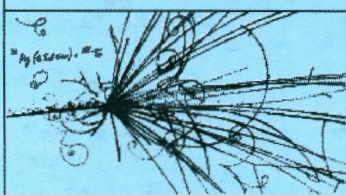


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**РЕЛЯТИВИСТСКАЯ ЯДЕРНАЯ ФИЗИКА:
ОТ СОТЕН МэВ ДО ТэВ**

**RELATIVISTIC NUCLEAR PHYSICS:
FROM HUNDREDS MeV TO TeV**

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

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RELATIVISTIC NUCLEAR PHYSICS: FROM HUNDREDS MeV TO TeV

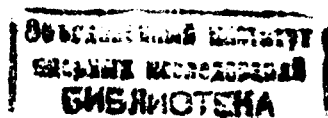
Proceedings of the International Workshop

Slovak Republic, Stara Lesna,
June 26 – July 1, 2000

РЕЛЯТИВИСТСКАЯ ЯДЕРНАЯ ФИЗИКА: ОТ СОТЕН МэВ ДО ТэВ

Труды международного совещания

Словакия, Стара Лесна,
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С 26 июня по 1 июля в Словакии (Стара Лесна) прошло традиционное рабочее совещание «Релятивистская ядерная физика: от сотен МэВ до ТэВ». Совещание было организовано ОИЯИ и Физическим институтом Словацкой академии наук и посвящено прогрессу исследований в области релятивистской ядерной физики. ФИ САН внес важный вклад в успех первых экспериментов на внутренней мишени нуклотрона. Успешный вывод пучка из нуклотрона сделал актуальным рассмотрение на этом совещании перспектив совместных исследований и решение практических вопросов проведения новых экспериментов. Был дан подробный обзор физической программы исследований на нуклотроне и развития ускорительного комплекса. Среди новых предложений, рассмотренных на совещании, перспективы исследований по структуре экзотических ядер на релятивистских пучках. В рамках обсуждения участия физиков ЛВЭ в экспериментах по ядро-ядерным соударениям были представлены результаты эксперимента NA49 в ЦЕРН по рождению легких ядер и антиядер и перспективы изучения глобальных характеристик реакций на LHC (коллаборация CMS). Участники совещания из США и Франции дали обзор первых физических результатов, полученных на ускорителях CEBAF и RHIC.

Relativistic Nuclear Physics: from Hundreds MeV to TeV: Proc. of the Intern. Workshop, Slovak Republic, Stara Lesna, June 26 – July 1, 2000. — Dubna: JINR, 2001. — 328 p.: photo.

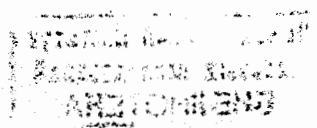
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The traditional Workshop «Relativistic Nuclear Physics from Hundreds of MeV to TeV» was held in Stara Lesna, Slovakia, from 26 June to 1 July. It was organized by JINR and the Institute of Physics (IP) of the Slovak Academy of Sciences and was devoted to general progress in relativistic nuclear physics research. The IP provided a significant contribution to the success of the first experiments with the Nuclotron internal target. The successful Nuclotron beam extraction made it topical to discuss prospects of further collaborative research, along with practical issues in the conduction of new experiments. A detailed review of the physics research programme at the Nuclotron and in the accelerator complex development was given. Among new suggestions considered at the Workshop one should mention prospects of exotic nucleus structure investigations by means relativistic beams. In the framework of LHE physic's participation in CERN's nucleus-nucleus collision programmes, the results of the NA49 experiments on the production of Light nuclei and anti-nuclei were presented, as well as prospects of global reaction characteristics measurements at the LHC (the CMS collaboration). The Workshop participants from the USA and France reviewed the first results obtained at the RHIC and CEBAF accelerators.

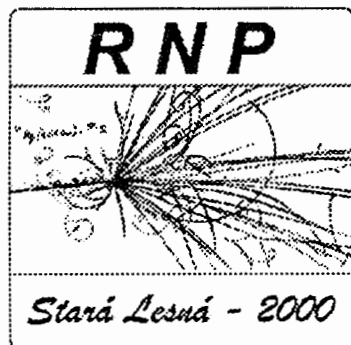
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Stará Lesná - 2000
Hotel "ACADEMIA"
June 26 - July 1, 2000
Slovak Republic



INTERNATIONAL WORKSHOP

"RELATIVISTIC NUCLEAR PHYSICS: FROM HUNDREDS MeV to TeV"

Organizers: Joint Institute for Nuclear Research, Dubna,
Russia.
Institute of Physics, Slovak Academy of
Sciences, Bratislava, Slovakia

Main topics:

- **The Research Programme at the Nuclotron beams.**
- **The JINR Programme in Nuclear and Particle Physics.**
- **Development of the Accelerator Complex of the Laboratory of High Energies.**
- **Experiments at other Accelerators: CERN (SPS, LHC), BNL (RHIC), HADES (GSI).**
- **Applied research**

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PREFACE

A series of international workshops „Relativistic Nuclear Physics: from Hundreds MeV to TeV” are traditionally held in various countries. This year, the RNP'2000 meeting has for the second time been held in Slovakia. It took place at a picturesque territory of the High Tatra Mountains in Stará Lesná on June 26-July 1, 2000. The meeting was organized jointly by the Laboratory of High Energies, JINR, Dubna (Russia) and the Institute of Physics, Slovak Academy of Sciences, Bratislava (Slovakia).

The aim of RNP workshops is to present and to discuss new theoretical, experimental and methodological achievements in the area of research with relativistic nuclear beams of the accelerator complex at the Laboratory of High Energies and other scientific centres such as CERN (SPS, LHC), BNL (RHIC) and the HADES experiment at GSI (Darmstadt), as well as to create good conditions for giving rise to new international collaborations and for enlarging the scope of the existing ones.

The successful Nuclotron beam extraction made it topical to discuss prospects of further collaborative research, along with practical issues in the conduction of new experiments. A detailed review of the physics research programme at the Nuclotron and in the accelerator complex development was given. Among new suggestions considered at the Workshop one should mention prospects of exotic nucleus structure investigations by means of relativistic beams.

In the framework of LHE physicists' participation in CERN's nucleus-nucleus collision programmes, the results of the NA49 experiment on the production of light nuclei and anti-nuclei were presented, as well as prospects of global reaction characteristics measurements at the LHC (the CMS collaboration). The Workshop participants from the USA and France reviewed the first results obtained at the RHIC and CEBAF accelerators.

The participants all felt and contributed to the friendly atmosphere at the meeting. We would like to thank all of them for their really hard work during the workshop. We also acknowledge warm hospitality, tireless work and technical support offered by the staff of the hotel "ACADEMIA" and the facilities of the Slovak Academy of Sciences.

We are grateful to Prof. A. Malakhov, Director of the Laboratory of High Energies, and Prof. S. Dubnička, Plenipotentiary of Slovakia at JINR, for their important contributions to the success of the meeting.

Dubna

Organizing Committee

DAILY PROGRAMME

MONDAY, June 26, 2000

Chair: S. Dubnička

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RESEARCH PROGRAM AT THE NUCLOTRON

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The present report contains information about experiments and projects at the Nuclotron in which collaborators of the Laboratory of High Energies of JINR are participating or will participate. The projects are worked out by groups, collaborations and divisions of the Laboratory of High Energies, as well as by other JINR laboratories and institutes of the JINR member-states and some other countries [1].

1. Introduction

The scientific program of the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR) is presently concentrated on investigations of interaction of relativistic nuclei in the energy region from a few hundred *MeV* to a few *GeV* per nucleon with the aim of searching for manifestations of quark and gluon degrees of freedom in nuclei, asymptotic laws for nuclear matter at high energy collisions as well as on the study of the spin structure of lightest nuclei. Experiments along these lines are being carried out using beams of the Synchrophasotron - Nuclotron accelerator complex. During last time investigations are going for the most part to the Nuclotron and we use Synchrophasotron practically only for research with polarized deuteron beams. In the nearest future we have plan to obtain polarized beams at the Nuclotron too.

2. Accelerator Complex

The accelerator complex at LHE is the basic facility of JINR for generation of proton, polarized deuteron (also neutron/proton) and multicharged ion (nuclear) beams in energy range up to 6 GeV/u. General view of the facility is shown in fig.1.

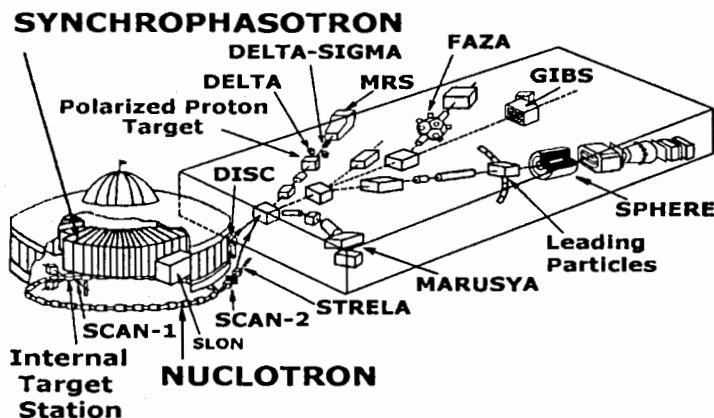


Fig.1. The accelerator complex of the Laboratory of High Energies, Joint Institute for Nuclear Research

The Nuclotron is based on the unique technology of superconducting magnetic system, which was proposed and investigated at Laboratory [2]. Before last year for physics experiments we have used only internal beam of the Nuclotron. In the end 1999 was obtained the external beam of the Nuclotron with help of the beam slow extraction system constructed on the base of the superconducting elements (fig.2).

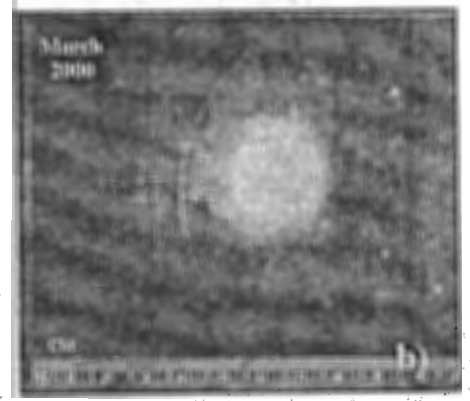


Fig.2. View of the Nuclotron beam extraction system (a) and image of the cross section of the Nuclotron extracted of deuterons beam with 4.5 GeV/c momentum and 10^9 d/cycle intensity (b)

Now we have begun the experiments at the Nuclotron external beams. Some parameters of the Synchrophasotron and Nuclotron beams are presented in table.

Table. Some beam parameters of the Synchrophasotron and Nuclotron

Beam	Intensity (particles per cycle)		
	Synchro- phasotron	Nuclotron	
		available	have to be
p	$4 \cdot 10^{12}$	$2 \cdot 10^{10}$	10^{13}
n	10^{10}		10^{13}
n↑	10^6		10^{11}
d	10^{12}	$5 \cdot 10^{10}$	10^{13}
d↑	$2 \cdot 10^9$	$3 \cdot 10^8$	$5 \cdot 10^{10}$
t	10^9	$4 \cdot 10^5$	10^{10}
^3He	$2 \cdot 10^{10}$		$5 \cdot 10^{11}$
^4He	$5 \cdot 10^{10}$	$8 \cdot 10^8$	$2 \cdot 10^{12}$
^7Li	$2 \cdot 10^9$		$5 \cdot 10^{12}$
^{12}C	10^9	10^8	$2 \cdot 10^{12}$
^{16}O	$5 \cdot 10^7$		10^{10}
^{20}Ne	10^4		$5 \cdot 10^9$
^{24}Mg	$5 \cdot 10^6$		$5 \cdot 10^{11}$
^{28}Si	$3 \cdot 10^4$		10^{10}
^{32}S	10^3		10^{10}
^{40}Ar			10^{10}
^{56}Fe			10^{11}
^{84}Kr		10^3	$5 \cdot 10^8$
^{131}Xe			$2 \cdot 10^8$
^{181}Ta			10^8
^{209}Bi			10^8
^{238}U			10^8
Energy, A·GeV	4.5	5.2	6.0

3. Basic Research

We have program of the first experiments at the Nuclotron external beams and long-range program. In the first runs of the Nuclotron with extracted beam we used two setups (STRELA and SCAN-2) for physical research. Simultaneously we continue the experiments at the internal beams of the Nuclotron.

3.1.The First Experiments at the Nuclotron

3.1.1.The Experiments at the Nuclotron External Beam

The experiment STRELA (fig.3) is proposed to study the spin dependent part of the nucleon scattering amplitude in the $np \rightarrow pn$ charge exchange process at the Nuclotron deuteron beams. The two-proton production cross section at small momentum transfers in the dp interactions is planned to measure in the range of the deuteron momentum from 3.0 GeV/c to 4.0 GeV/c.

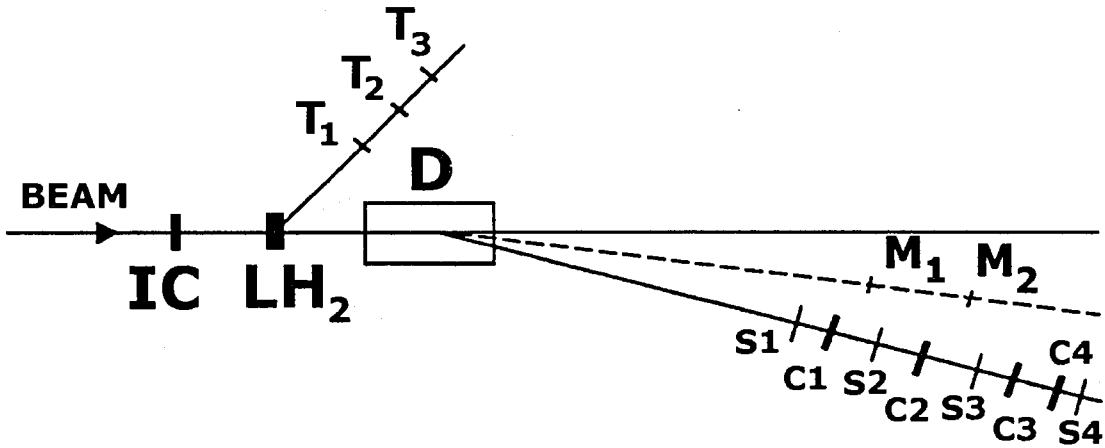


Fig.3. Layout of the STRELA experimental setup.
IC - ionization chamber, LH₂ - liquid hydrogen target, D- analyzing magnet, T1-T3 and M₁, M₂ - scintillator monitors, C1-C4 - Cherenkov counters, S1-S4 - scintillator counters

The possibility to get additional information about the amplitude of the elementary $np \rightarrow pn$ charge exchange reaction by means of the charge exchange process $dp \rightarrow (pp)n$ from the experiments with unpolarized deuteron was emphasized by A.B.Migdal and I.Y.Pomeranchuk.

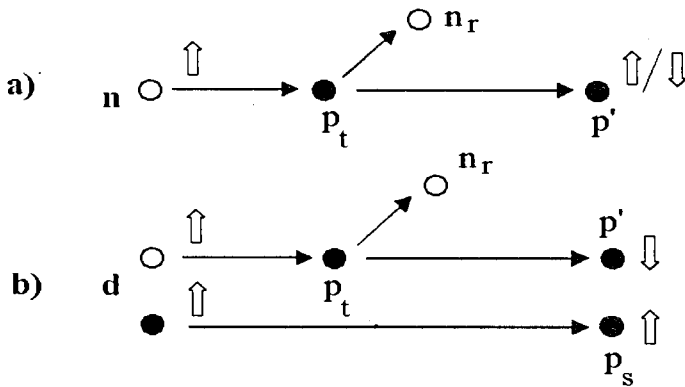


Fig.4. Elementary $np \rightarrow pn$ (a) and $dp \rightarrow (pp)n$ (b) charge exchange reactions

Simplified version of these two processes in the framework of the Impulse Approximation are shown in fig.4: a) the $np \rightarrow pn$ charge exchange process and b) the $dp \rightarrow (pp)n$ reaction, i.e. charge exchange one on the simplest nucleus - the deuteron. In the first case (a) both spin orientations are allowed while in the second one (b) at small angle scattering due to the produced charged symmetry (two protons move in the very forward direction with small relative momentum) the reaction can proceed only if the scattered proton spin flips (caused by the Pauli exclusive principle). At zero momentum transfers the differential cross section of $dp \rightarrow (pp)n$ reaction is determined by the spin flip part of the $np \rightarrow pn$ charge exchange process.

In the March 2000 Nuclotron run with the external deuteron beam were obtained experimental information which is now in process of analysis. Preliminary results on separation of events with two protons and one proton are presented in fig.5.

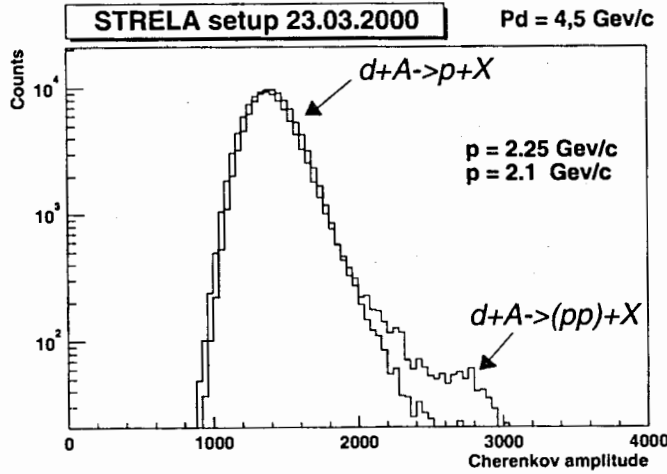


Fig.5. Preliminary results of STRELA experiment on separation of events with two protons and one proton

3.1.2. The Experiments at the Internal Nuclotron Beams

In the processes of investigation is a target fragmentation into two cumulative protons

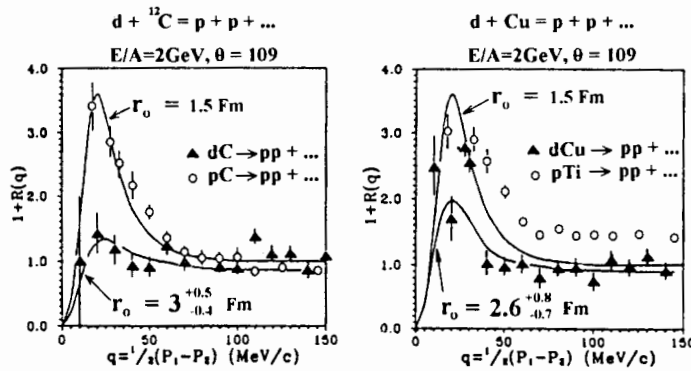


Fig.6. The correlations functions of cumulative protons emitted at small relative momentum q for dC and dCu reactions

with help of the SKAN-1 setup (Spokesman S.V.Afanasiev) at the internal beam of the Nuclotron (fig.6). The goal of experiment is measuring of transversal dimension of nucleus-nucleus interaction region. Method is the measurement correlation of cumulative protons,

emitted at small relative momentum. Correlations of protons, emitted in the angle interval between $106-112^\circ$ in laboratory system, are studied in the reactions $d + C \rightarrow p + p + \dots$ and $d + Cu \rightarrow p + p + \dots$ ($p_d = 2.4 \text{ GeV}$). Results of the measurements are presented in fig.6 [3].

As result were obtained approximately the same transversal radius for dC and dCu interactions: $r_{dC} = 3.0 \pm_{0.4}^{0.5} \text{ fm}$ and $r_{dCu} = 2.6 \pm_{0.7}^{0.8} \text{ fm}$.

These investigations will continue for the other projectiles and targets.

Group of the **MARUSYA** collaboration have began the investigations of the secondary fragments yield in the result of interaction of the internal Nuclotron beams with heavy targets using thin semiconductor detector. This group obtained good separation of secondary fragments with very low energies in region from 2 up 25 MeV in $d + Au$ interaction at 1.044 GeV deuteron energy (fig.7).

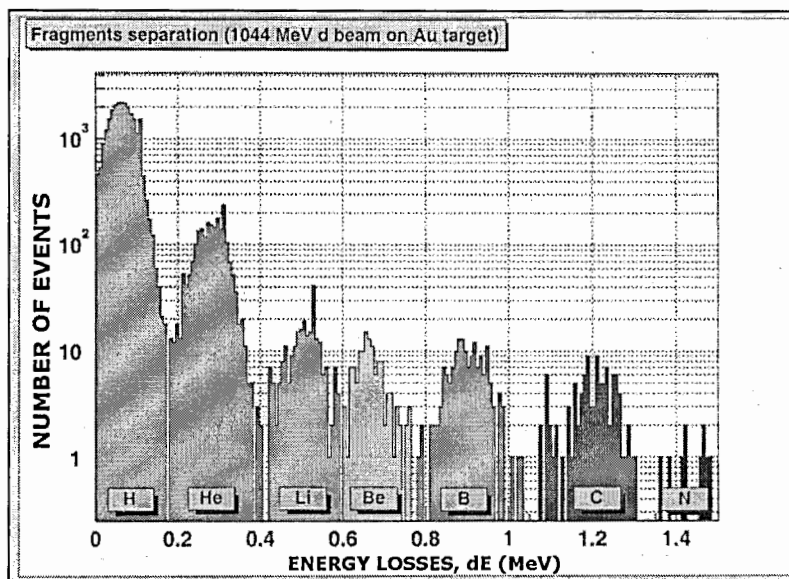


Fig.7. Separation of the secondary fragments for $d + Au$ reaction at 1.044 GeV deuteron energy

These data are in processes of analysis now and will use for study effect of the full destruction of the nuclei because of energies of the secondary fragments are very low.

3.2. Long-range Experimental Program at the Nuclotron

We have 12 setups at the Nuclotron now for carrying out of the basic research. There are **SPHERE**, **GIBS**, **FAZA**, **DELTA-SIGMA**, **DELTA**, **DISC**, **Leading Particles**, **MARUSYA**, **SCAN-1**, **SCAN-2**, **STRELA**, **SLON** (fig.1). And we have plan to use the Medium Resolution Spectrometer (**MRS**) from Los Alamos, USA at our Accelerator Complex. In these section are presented short review of the research program at these setups.

3.2.1 Experiments with Relativistic Nuclei

SPHERE project

The main goal of the project **SPHERE** is an investigation of fragmentation of the relativistic nuclei in geometry closed to 4π . A general layout of the spectrometer **SPHERE** is shown in fig.8.

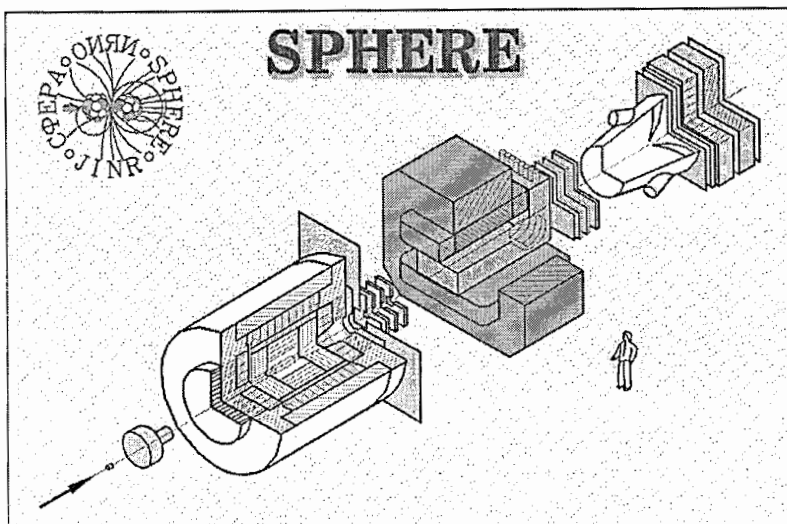


Fig.8. General layout of the SPHERE experimental facility

With forward detector of the SPHERE setup were obtained some new results at the Synchrophasotron. For example the inclusive spectra were measured for deuteron fragmentation into cumulative π^- mesons on a nuclear target, and the relevant cross section was investigated as function of the atomic number A of a target nucleus at SPHERE setup with Synchrophasotron beams. The deuteron beam momentum was varied between 7.3 and 8.9 GeV/c , and data were collected for the π^- meson momenta of $p_\pi = 3.0$ and 4.9 GeV/c . The shapes of the pion spectra are found to be similar for all investigated targets. The cross section shows a characteristic peripheral dependence on the target atomic number A for $A > 12$ ($d\sigma_\pi \sim A^{0.4}$) and a steeper decrease toward a hydrogen target (fig.9).

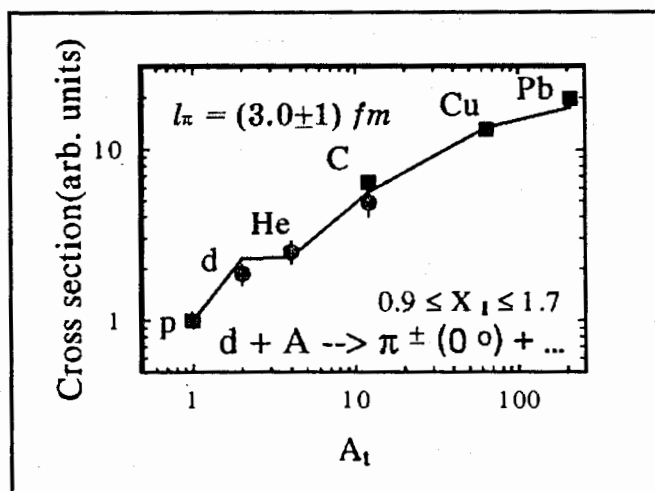


Fig.9. Cross section for production of cumulative pions as function of atomic number A of the nucleus

The proposed theoretical interpretation of the observed A dependence takes into account the interaction of the deuteron and of the emitted pion with target nucleons. The best description of the data is obtained under the assumption that the pion-formation length is $l_\pi = (3 \pm 1) fm$ [4].

The research program of the SPHERE setup at the Nuclotron includes the following:

1. Multiple cumulative particle production in 4π geometry:
2. Investigation of nucleus excitation in charge exchange reactions (together with GIBS collaboration).
3. Program with hypernuclei (together with GIBS collaboration).
4. Search for η -nuclei (together with FIAN).
5. Investigation of pion production (together with AMPIR collaboration)
6. Investigation of tensor analyzing power for cumulative hadron production (see section 3.2.1).

GIBS project

The GIBS setup is magnetic spectrometer on the base of the streamer chamber of $1.9 \times 0.8 \times 0.6 \text{ m}^3$ volume. Interesting results were obtained of GIBS collaboration at the Synchrophasotron. One of these is observation of the expansion of the volume from which irradiated narrow pion pairs in Mg-Mg interaction. M.I.Podgoretsky suggested a method to measure the velocity (and size) of the source by the interference method. This method allows one to get direct experimental evidence for the nonstationary state of the pion generation volume. This evidence was first obtained with the setup GIBS at LHE for central Mg-Mg interactions at 4.4 GeV/c [5]. The pictures were taken in streamer chamber with a magnesium target inside, exposed to the extracted magnesium beam from the Synchrophasotron.

The fig.10 displays rapidities ($Y = 0.5 \ln[(1+\beta)/(1-\beta)]$) of sources Y_{source} obtained by fitting the correlation function for subset of pions from different region of the kinematic spectrum.

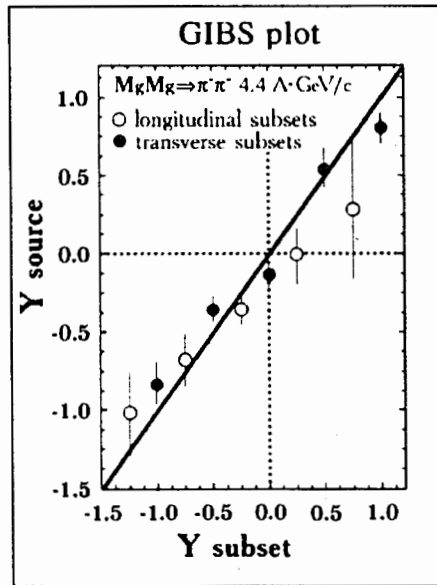


Fig.10. Rapidities Y_{source} of the pion production volume elements corresponding to different pion subset moving with different rapidities y_{subset} along and across the reaction axis in the Mg-Mg rest frame

Average rapidities of these subsets Y_{subset} are plotted on the horizontal axis. The data are given for subsets moving both along the reaction axis and across it. It is seen that pions from different regions of the kinematic spectrum are emitted by different «elements» of source, moving with respect to one another with almost highest possible velocities. For a stationary source, all points must be on the horizontal axis.

The GIBS collaboration have plan to investigate at the Nuclotron the charge exchange reaction ($t, {}^3\text{He}$) on carbon and magnesium targets using tritium beams of 2.2 to 3.0 $A\cdot\text{GeV}/c$.

The second experiment will be study production of hypernuclei with momerntum of several GeV/c . This implies that hypernuclei decay at a distance of the order of 20-30 cm from the production point. Thus, it is feasible to investigate hypernuclear interactions with different absorbers. In case of hypertriton, the method allows one to estimate bonding energy of Λ .

FAZA project

The aim of this project is the investigation of the mechanism of nuclear multifragmentation which takes place in nucleus-nucleus collisions at intermediate and high energies.

A number of experiments have been conducted with the proton and alpha beams of Synchrophasotron on 4π -device FAZA. The following main result is obtained: the hot target spectator expands before the fragment emission. The break-up density is found to be $\sim 1/3$ of normal one (fig.11) [6].

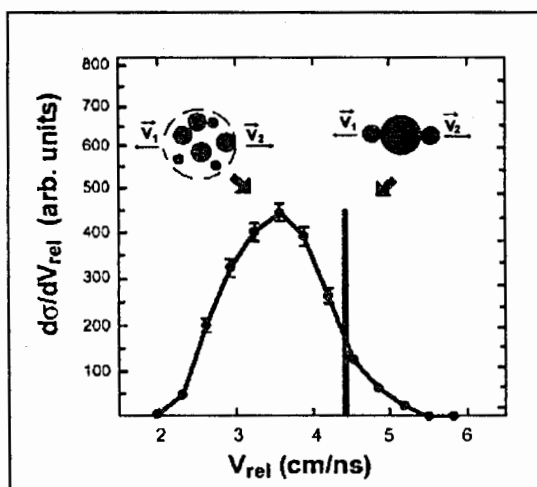


Fig.11. Distribution of relative velocities for the coincident fragments from $\alpha + Au$ collisions measured at correlation angles $150^\circ - 180^\circ$. The vertical line shows the expected maximum position for fragments evaporation from the nucleus surface. The experimental distribution is shifted to lower velocities, corresponding to the volume distribution of the expanded system

It is possible to interpreted this effect as observation of the gas - liquid faze transition in nuclear matter.

The research program of the FAZA collaboration at the Nuclotron is directed to further investigation of the mechanism of the copious fragment emission in very asymmetric nucleus-nucleus collisions. The most important expected results are:

- New data on the dependence of the decay time of the system upon the excitation energy and projectile mass will be obtained.
- Experimental data will be obtained on the evolution of the decay mechanism from pure thermal multifragmentation to more complicated one with increasing projectile mass.

MARUSYA project

This project has goal to investigate of the transition regime (transition from nucleon to quark-gluon degrees of freedom in nuclei) on basis of the experimental study of hadron

production in relativistic nuclear collisions. A schematic view of MARUSYA setup is presented in fig.12.

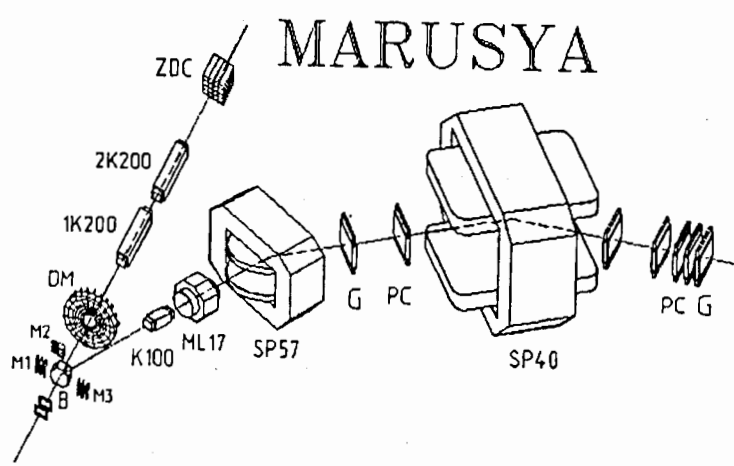


Fig.12. A schematic view of MARUSYA setup. M1-M3 - the beam monitoring system consists of three scintillation telescopes. K100, ML17 - magnetic lenses. SP57, SP40 dipole magnets. B- barrel system located around the target. PC - proportional chambers. G - scintillator hodoscopes. DM - multiplicity detector. ZDC - zero degree hadronic calorimeter

Leading Particles project

An investigation of leading particles from proton-nucleus interaction at the experimental apparatus SMS MSU («Scintillation magnetic spectrometer MSU») to illuminate the mechanism of strong interaction at the energies to 10 *GeV* is proposed. The experimental installation SMS is a single-arm magnetic spectrometer with variable geometry of its spectrometric section [7].

3.2.2. Experiments with Polarized Beams

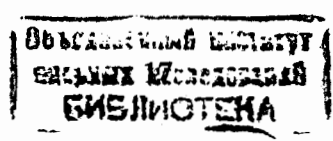
The Study of Polarization Effects in Collision of Relativistic Nuclei at SPHERE setup

The main goal of this project is to study the deuteron spin structure at short internucleon distances using hadronic probes and spin effects in hadron scattering in a few *GeV* region.

The tensor analyzing power A_{yy} for the cumulative pion production $d\uparrow + {}^{12}\text{C} \rightarrow \pi^{\pm} (0, 135, 178 \text{ mrad}) + \dots$ has been measured with tensor polarized deuteron beam of the Synchrophasotron at the SPHERE setup. This experiment is focused on «cumulatively produced pions», which are produced beyond the kinematically nucleon-nucleon collisions (Fig.13).

The measured values of A_{yy} are in disagreement with result of our impulse approximation calculation that is based on a single $NN \rightarrow \pi NN$ interaction and takes into account the internal motion of nucleons in the deuteron [8].

These investigations will be continued at the Nuclotron after obtaining polarized beam with enough intensity.



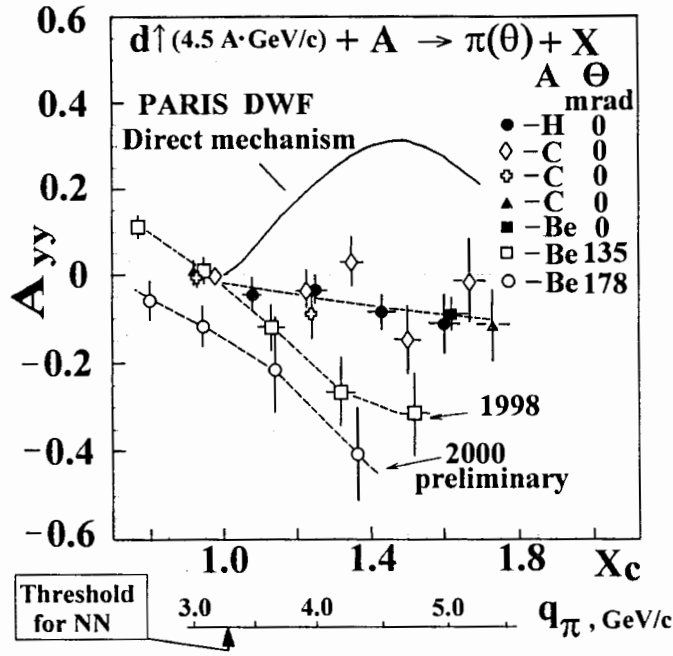


Fig.13. A_{yy} vs x_c , and q_π for the reaction $d + A \rightarrow \pi(0, 135, 178 \text{ mrad}) + \dots$

DELTA-SIGMA project

New results for the np spin-dependent total cross section difference $\Delta\sigma_L(np)$ at neutron beam kinetic energies 1.59, 1.79, and 2.20 GeV were obtained (Fig. 14).

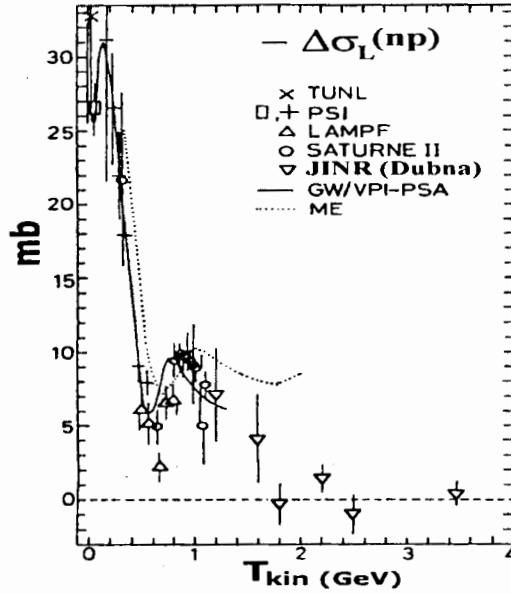


Fig.14. Energy dependence of the $\Delta\sigma_L(np)$ observables obtained with neutron polarized beam

A quasi-monochromatic neutron beam was produced by break-up of accelerated and extracted vector polarized deuterons from Synchrophasotron. The neutrons were transmitted through a large proton polarized target. The values of $\Delta\sigma_L(np)$ were measured as difference between the np total cross sections for parallel and antiparallel beam and target polarization, both oriented along the beam momentum. A fast decrease of $\Delta\sigma_L(np)$ with increasing energy above 1.1 GeV was confirmed [9].

To complete the measurements of the $\Delta\sigma_L(np)$ energy dependence one needs to measure it at 1.4, 1.6, 2.0 and 3,17 *GeV*. Also it need to measure the energy dependence of the $\Delta\sigma_T(np)$ with transverse polarized beam neutron and target protons. These experiments we propose to continue at the Nuclotron.

MRS project

It is proposed to use the Medium Resolution Spectrometer (LAMPF, Los Alamos, USA) at the our accelerator complex. This possibility arised after signing the agreement on the Scientific Collaboration between Los Alamos National Laboratory, the Institute for Nuclear Research of RAN and Joint Institute for Nuclear Research. Research program includes following:

- Study of spin-induced effects in few body system: backward elastic scattering
- Study of strange content of the nucleon
- Study of cumulative particle production using the polarized deuteron beam.

3.2.3. Study of the Asymptotic Laws in Relativistic Nuclear Physics

The principles of symmetry and self-similarity have been used to obtain an explicit analytical expression for inclusive cross section of production particles, nuclear fragments and antinuclei in relativistic nuclear collisions in the central rapidity region ($y = 0$). The result s are in agreement with available experimental data. It is shown that the effective number of nucleons participating in nuclear collisions decreases with increasing energy and the cross section tends to a constant value equal both for particles and antiparticles. The analysis of the obtained results makes it possible to predict asymptotic behaviour of production cross section of particles, nuclear fragments and antinuclei. One example of such prediction is presented in fig.15 from Dubna up to LHC energies [10, 11].

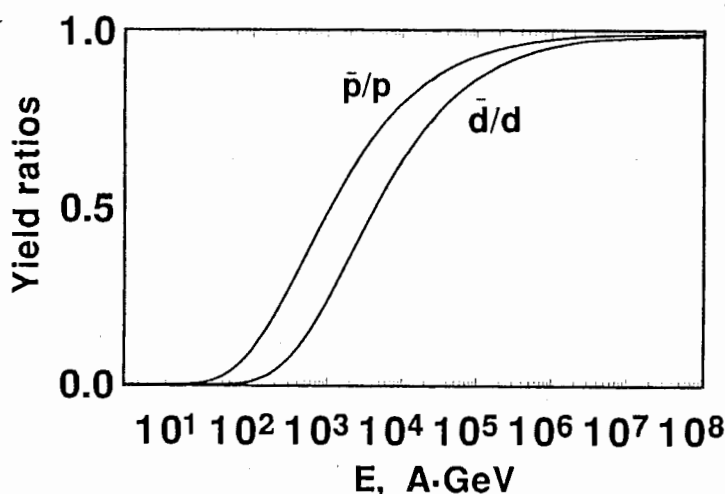


Fig.15. Predictions of the production cross section ratios for antiparticles to particles versus laboratory collision energy

4. Applied Research

We have used Synchrophasotron for applied research and will continue these investigations at the Nuclotron with more heavy ions. There are following applied research:

- radiobiology and space medicine (fig.16) [12]
- influence of nuclear beams on microelectronic components
- transmutation of radioactive waste products (fig.17) [13]

- aspects of the electronuclear method of energy generation (fig.17) [14]
- using carbon beam for tumor therapy and so on.



Fig.16. Chromosome 1 with fragment after irradiation with protons 1 GeV in interphase nucleus of human lymphocyte

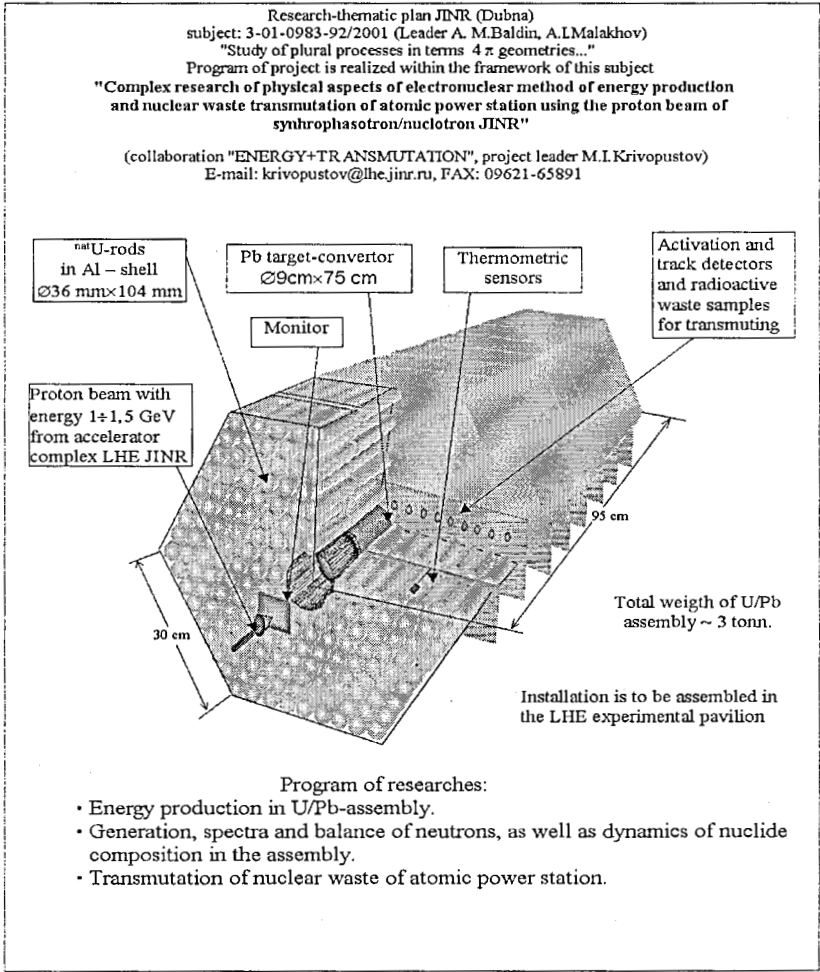


Fig.17. ENERGY-TRANSMUTATION project for investigations of aspects of the electronuclear method of energy generation and transmutation

5. Conclusions

We have the interesting research program with relativistic beams of nuclei, polarized deuterons and neutrons in JINR (Dubna) and the new perspectives of investigations with extracted nuclear beams of the Nuclotron.

6. Acknowledgements

I express my sincere gratitude to leaders of all projects at the Synchrotron-Nuclotron accelerator complex for assignment of information for this report. The work is supported by grants of the Russian Fund of Fundamental Research № 00-02-26109 and 00-02-16580.

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STATUS OF THE NUCLOTRON

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Abstract

The results of operation and development of the first superconducting synchrotron based on 2T cold iron fast cycling SC-magnets are presented. The essential news - beam resonance extraction from the Nuclotron is discussed.

1. INTRODUCTION

The Nuclotron accelerator complex at Laboratory of High Energies is the basic facility of JINR for generation of proton, polarized deuteron (also neutron/proton) and multicharged ion (nuclear) beams in energy range up to 6 GeV/amu.

The Nuclotron was built during 1987-92. This accelerator based on the unique technology of superconducting magnetic system, has been proposed and investigated at the Laboratory. All design, tests and assembling works were carried out at the LHE. Production of the structural cryomagnetic elements was done by the JINR workshops. The first results on the commissioning of the Nuclotron had been presented earlier [1,2].

Basically all of the design parameters have been achieved. Very high reliability of the liquid helium supply and the magnet cooling system were practically demonstrated. Data taking for physics was started at the internal target in 1994. The completion of the construction and first tests of beam extraction system as well as reassembling of the part of the accelerator ring 12 m in length were fulfilled in 1999. Pilot experiments at extracted beam were performed in March this year.

2 OPERATION

Seventeen runs of a total duration of 3930 hours were carried out up to now. Annual running time is limited by real budgetary resources. Total running time includes: cool down ~ 1692 h, the machine development and beam dynamic investigations ~ 1522 h, physics experiments ~ 716 h.

The achieved parameters are presented in Table 1. It should be mentioned additionally that an excellent flexibility of variation both as the accelerated beam energy and the magnetic field flat top duration were obtained. The discrepancy between design and achieved peak energy and repetition frequency is connected with the needed upgrade of a quench detection, power supply and energy dump systems. Sometimes extremely large losses of the beam were observed during the runs in 1994-1997. The reason was the partial local deformation of 0.5

mm stainless steel beam pipe due to the pressure difference between insulation volume of the cryostat and the beam pipe.

Table 1. General parameters

Parameter	Design	Achieved
Accelerated particles	$1 < Z < 92$	p, d, α , ^{12}C , ^{84}Kr
Energy, GeV/amu	6 ($A/Z=2$)	4.2
Magnetic field, B	2.0	1.5
Injection energy, MeV/amu	5	5
Beam intensity	(see Table.3)	
Vacuum pressure, Torr	$1 \cdot 10^{-10}$	$1 \cdot 10^{-10}$
Slow extraction	(see Table.2)	
Repetition frequency, Hz	0,5	0,2
Magnets ramp rate, T/s		
at stand tests	4	4.1
at the ring	2	1.0

3. BEAM EXTRACTION

The beam extraction system (BES) of the Nuclotron is intended to eject ion beams over the energy range from the unjection to about 6 GeV/amu. The extraction is realized by the excitation of the third order radial betatron oscillation resonance $Q_x = 20/3$. The resonance is provided by means of two pairs of sextupole lenses while four special quadrupole lenses, installed in the ring, make a shift of the radial betatron frequency from $Q_x = 6.78$ to $Q_x = 6.66$. The particles involved into the resonance cross the operating gap of the electrostatic septum (ES) and after that enter to the Lambertson magnet (LM). The electrostatic septum deflects the beam in horizontal plane at the angle of 5 mrad while the Lambertson magnet should provide deflection of the beam in vertical direction at the angle of 96 mrad. The last parameter was chosen to satisfy both as the needed displacement of a beam under extraction from the yoke of structural quadrupole installed after the LM and needed conjugation of the extracted beam with the existing system of transfer lines inside the experimental area. The main elements of the Nuclotron BES were described in [3]. The ES high voltage part is similar to the used at other laboratories. But in our case it has special design because superconducting electrical buses of the structural dipoles and quadrupoles are passing through its vacuum shell. The LM consist of two sections 1.5 m in length each. The iron yoke is cold and SC-winding made of a tube superconductor cable similar to the Nuclotron. So, the cross-section of the LM and its cryostat system is almost the same as for the



Figure 1. Transportation of the Lambertson magnet section in the tunnel

structural units (see Fig.1,2). The LM sections are supplied by current in series with structural dipoles. As a result of such connection all the particles entering in the operating gap of the LM at some energy will be extracted from the accelerator if the choice of the LM effective magnetic length was made correctly.

Special power supply connected with the first section of the LM and additional current leads were used to compensate a possible error of the extraction vertical angle over maximum expected value of ± 6 mrad.



Figure 2. The beam extraction area of the Nuclotron ring

The results of the BES commissioning are given in more details in the separate paper presented at the Conference. Briefly some of the parameters are shown in Table 2. The time structure of the extracted deuteron beam during the first tests is shown in Fig.3.

Table 2. Nuclotron Beam Slow Extraction

Parameter	Design	Achieved
Energy range, GeV/amu	$0.2 \div 6.0$	$0.2 \div 2.2$
Duration, s	up to 10	0.5
Efficiency of extraction, %		
at 0.2 GeV/amu	90	75
at 2.2 GeV/amu	95	60
Extraction beam intensity, ppc:		
at 0.2 GeV/amu		$3 \cdot 10^9$
at 2.2 GeV/amu		$1 \cdot 10^9$
Extraction angles, mrad		
horizontal	5	5
vertical	96 ± 6	96 ± 1
Nominal ES voltage, kV	200	150
Operating ES voltage, kV	up to 200	up to 40
LM supply current, kA	up to 6.3	6.3
Repetition rate, Hz	1.0	1.0

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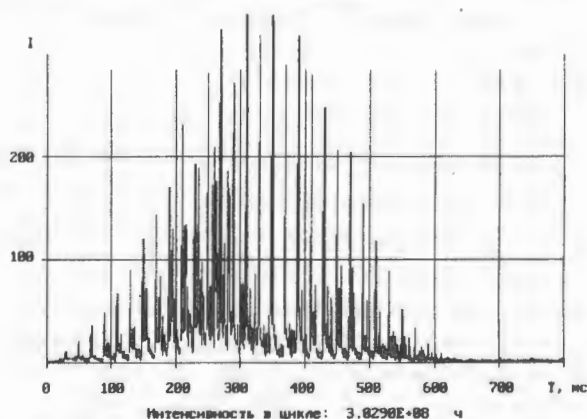


Figure 3. Time structure of the extracted deuteron beam

A lot of technical and technological problems were solved during the BES construction. In particular, the possibility of the displacement ± 20 mm in horizontal plane both as the LM and the ES under operating cold state was provided. Search for optimal position of the LM and ES has been performed several times during the test runs in December'99 and in March this year. Now we can conclude that the «hardware» of the Nuclotron slow beam extraction system is put into operation. So, the problem of the beam extraction from superconducting synchrotron is practically solved. Of course, we need make further improvement of the power supply sources, the closed orbit correction, the electrostatic septum operating parameters.

The works have to be carried out before the next Nuclotron run in October are in a progress.

4. FUTURE DEVELOPMENT

The main directions of the Nuclotron development during the nearest years are the following:

- Improvement of the Nuclotron beam slow extraction system.
- Development of the injector complex including ion sources, partial reconstruction of the linac LU-20, technical design and construction work on the Nuclotron booster.
- Upgrade of cryogenic supply, quench detection and energy dump as well as diagnostic, control and r.f. systems.

Some progress earlier mentioned has been reached. In particular:

- new CO₂ - laser for the laser driven source was designed and constructed;
- reflecting mode of the electron beam ionizer KRION operation was investigated as well as fast extraction (T ~ 30 mks) of ions from the KRION source was obtained;
- peak intensity of polarized deuteron beam from POLARIS ion source was increased by factor of 3;
- the front section of the LU-20 main cavity was reconstructed to decrease the minimal charge-to-mass ratio of accelerated ions from 0.33 to 0.28;
- conceptual design of the booster ring based on the Nuclotron-type technology was made. (The work is supported by the RFBR grant N.18 400);
- upgrade of the Nuclotron cryogenic supply system is carried out. All designed parameters of the Nuclotron cryogenic system were achieved. The reliability of the system as high as 95%. The average cool down time of the Nuclotron magnetic system (cold mass ~ 80 tons) is 100 hours. About (20 ÷ 25) tons/day of liquid N₂ are usually used during this period. After that the consumption of liquid N₂ is about (12 ÷ 15) tons/day. It can be decreased to (8-10) tons/day by means of special turbines cooled by helium flow instead of LqN₂ at the main refrigerators of liquid He. The set of such turbines was tested in June. The experimental results were closed to the predicted ones.

Construction of the booster will make it possible to increase significantly the intensity of accelerated beams (see Table 3). The cost of the project based on a conventional accelerator technology (published in 1991) was estimated at the level of \$3M. It can be decreased to about \$1.5M in the case of the Nuclotron technology application. The conceptual design of such accelerator has been made. The period of technical design and construction will take about 3 years after approval of the project.

The maximum energy of the booster is 250 MeV/amu. Multiturn injection of the beams from existing linac in the booster ring will be realized. The system of electron cooling is proposed to minimize the beam emittance. The designed repetition rate of the booster is 1 Hz. More detailed data on the booster design is presented in separate paper.

Table 3. The Nuclotron beams

Beam	INTENSITY (Particles per cycle)		
	Nuclotron (at present)	Nuclotron + Ion sources development	Nuclotron + Booster
P	$2 \cdot 10^{10}$	$1 \cdot 10^{11}$	$1 \cdot 10^{13}$
d	$2 \cdot 10^{10}$	$5 \cdot 10^{10}$	$1 \cdot 10^{13}$
³ He			
⁴ He	$8 \cdot 10^8$	$5 \cdot 10^9$	$2 \cdot 10^{12}$
⁷ Li		$2 \cdot 10^{10}$	$5 \cdot 10^{12}$
¹² C	$1 \cdot 10^8$	$7 \cdot 10^9$	$2 \cdot 10^{12}$
¹⁶ O			
²⁰ Ne		$1 \cdot 10^8$	$5 \cdot 10^9$
²⁴ Mg		$3 \cdot 10^8$	$5 \cdot 10^{11}$
²⁸ Si			
³² S			
⁴⁰ Ar		$3 \cdot 10^7$	$2 \cdot 10^9$
⁵⁶ Fe			$1 \cdot 10^{11}$
⁸⁴ Kr	$1 \cdot 10^3$	$2 \cdot 10^7$	$5 \cdot 10^8$
⁹⁶ Mo			$1 \cdot 10^{10}$
¹³¹ Xe		$1 \cdot 10^7$	$2 \cdot 10^8$
¹⁸¹ Ta			$1 \cdot 10^8$
²⁰⁹ Bi		$3 \cdot 10^6$	$1 \cdot 10^8$
²³⁸ U			$1 \cdot 10^8$

5. CONCLUSION

New technology of superconducting magnetic system has been tested during the Nuclotron construction and operation. The results obtained can be useful under design of a modern fast cycling superconducting synchrotrons of different applications.

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SCALING PROPERTIES OF MANYPARTICLE STOCHASTIC PROCESSES: AN EXAMPLE OF ELECTROMAGNETIC AND HADRONIC SHOWERS

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Abstract

We present some general reflections about scaling (or similarity) description of many-particle stochastic processes. As an example the results of the investigation of high-energy electromagnetic and hadronic showers behavior in dense and homogeneous materials are analyzed.

I. MOTIVATION

The search for the possibility of scaling (or, in more general, similarity) representation of main characteristics of processes and, especially, high energy many-particle cascade phenomena, has both cognitive and practical meaning. In the first case we deal with the so-called symmetry of solutions (of equations describing these processes). The second aspect concerns the chance of significant contraction of information in order to shorten the time of analysis of the processes of the same kind but occurring at different conditions (such as a primary energy and/or a type of initiated particles, as well as the characteristics of a concrete medium, in which the phenomenon develops) and to make a prediction about the consequences of such processes, such as energy release, radiation damage of the material or, finally, the possibility to make some estimations about the origin of the cascade initiating particle, its energy and the direction of flight.

In the present work we discuss the problem of the possibility of scaling description of two among most of all known high-energy many-particle cascade's processes developing in macroscopic and homogeneous (or fine granulated) media: electromagnetic and hadronic cascades. In consequence of this discussion some general conclusions about the origin of scaling properties revealed by several characteristics of such phenomena are drawn. In particular, the suggestion is set forth that purely stochastic factor, like in the case of the central limit theorem in the theory of probability but for stochastic processes, may often dominate, independently of concrete mechanism or nature of the phenomenon under consideration. Some remarks about other many-particle scaling phenomena (for instance, the KNO and the so-called nuclear scaling) are also made.

II. ELECTROMAGNETIC CASCADES

II.1. Process and its characteristics

The electromagnetic cascade (or shower) produced by a photon or electron in a dense enough material consists, in short, of a sequence and superposition of four basic elementary electromagnetic processes: pair production, bremsstrahlung, Coulomb multiple scattering and ionization of atoms. Other processes play a considerably smaller part in the energy balance and space structure formation of the shower, although, for example, Čerenkov radiation is widely used for the detection of photons and electrons. From the practical viewpoint discerned are the following shower characteristics: longitudinal and transverse (or lateral) distributions of average ionization loss (or profiles), the relevant fluctuations and correlations (see, for instance, [1] and references quoted herein).

II.2. Shower profiles

As a result of mainly experimental investigations performed using different techniques, as well as theoretical studies made by means of computer simulation, it has been found that the longitudinal shower profile can be satisfactorily approximated by the gamma function:

$$F_t(t) = a_1 t^{a_2} \exp(-a_3 t) \quad (1)$$

where the parameters a_1 , a_2 and a_3 are to be calculated as the best fit to the concrete experimental data [1]. Moreover, if the shower depth t (measured from the shower origin) is expressed by the dimensionless ratio $x=t/\langle t(E) \rangle$, where $\langle t(E) \rangle$ is the average cascade depth depending on the energy E of a cascade initiated particle, then the longitudinal profile displays a clear scaling with the energy at least when $E \geq 500$ MeV up to several hundred of GeV, where other processes gradually start, and at $x \geq 0.15$ [2].

Much more complicated is the situation concerning the transverse shower profile [1,2]. But again, if the shower width r is expressed by the similar as above dimensionless ratio $x=r/\langle p(t,E) \rangle$, where $\langle p(t,E) \rangle$ is the average width of a cascade at its depth t , then the transverse profile as well scales with E , at least for primary gamma quanta of energy 500-3500 MeV in liquid xenon [1,2], as shown in Fig.1 as the approximating function:

$$F(x) = \int_0^1 [(1/s) + (1/x)] / [s^2 \sqrt{1-s^2}] \exp[-(x/s)] ds.$$

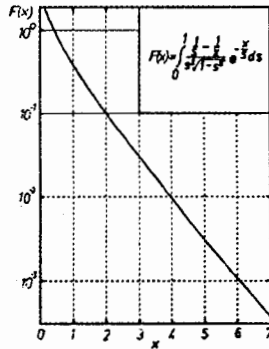


Fig.1. Scaling description of the transverse profile of electromagnetic showers produced in liquid xenon by gamma quanta of energy 100-3500 MeV (after [1])

II.3. Shower equations

In the simplest, i.e. one-dimensional approach, the diffusion equations for shower's electrons (and positrons, further also called electrons) and photons have been obtained about 60 years ago [3]. They describe the longitudinal distribution of average numbers of electrons, $n_e(E, E_0, t)$, and photons, $n_\gamma(E, E_0, t)$, along the direction of flight of a particle initiating the shower, as follows [3]:

$$\begin{aligned} \partial n_e(E, E_c, t) / \partial t &= 2 \int_E^\infty n_\gamma(E, E', t) \sum_p(E', E) dE' + \\ &+ \int_E^\infty n_e(E, E', t) \sum_b(E', E' - E) dE' - \int_0^E n_e(E, E', t) \sum_b(E, E') dE' + \epsilon \partial n_e(E, E_c, t) / \partial E; \\ \partial n_\gamma(E, E_c, t) / \partial t &= \int_E^\infty n_e(E, E', t) \sum_b(E', E) dE' - \int_0^E n_\gamma(E, E', t) \sum_p(E, E') dE' \end{aligned} \quad (2)$$

Here E_c is the cut-off energy of electrons (usually equal to 1-1.5 MeV), Σ_p and Σ_b are the differential cross-sections of pair creation and bremsstrahlung, correspondingly, ϵ is the average ionization loss of shower's electrons over 1 radiation length (r.l.). But the most often measured quantities are the numbers of electrons $N_e(E, E_c, t)$ with an energy greater then E_c at a shower depth t :

$$N_e(E, E_c, t) = \int_{E_c}^E n_e(E, E', t) dE',$$

or the quantities proportional to $N_e(E, E_c, t)$, such as the differential ionization loss and Čerenkov radiation. They practically correspond to the longitudinal shower's profile [1]. Note also that the above cited equations of electromagnetic showers have very limited practical meaning and apply chiefly to very high energies and light media, such as air and water, although surprisingly they reflects correctly the energy dependence of such important shower's characteristics as the position of average shower's depth (also called as the center of gravity) as a function of energy E , $\langle t(E) \rangle$, and the average position of shower's maximum $t(E)_{\max}$, both being proportional to $\ln E$.

The equations (2) are relatively simple as compared to the analytical description of many other known stochastic processes occurring in nature and having practical and cognitive significance (see, for example, [1,4-6]). However, they are not so transparent to notice whether the functions $n_e(E, E_c, t)$ and $n_\gamma(E, E_c, t)$, being divided by some energy dependent function, say $\langle t(E) \rangle$, $t(E)_{\max}$ or another quantile, become energy independent (and so $N_e(E, E_c, t)$), which is the case in actual fact. The situation is much more complicated when one considers the three-dimensional shower equation (see, for example, [7]).

II.4. Fluctuations

It turned out that as well longitudinal and transverse fluctuations of energy release of shower's electrons can be described in the approximately universal, i.e. energy independent form when they are expressed as the A-dependence of the rms deviation σ_A from the average fraction A of ionization energy loss deposited along the shower axis and in its transverse direction [1,2]. Unfortunately, such data have been obtained only for gamma quanta of energy 200-3500 MeV producing showers in liquid xenon. The relevant distributions are demonstrated in Fig.2.

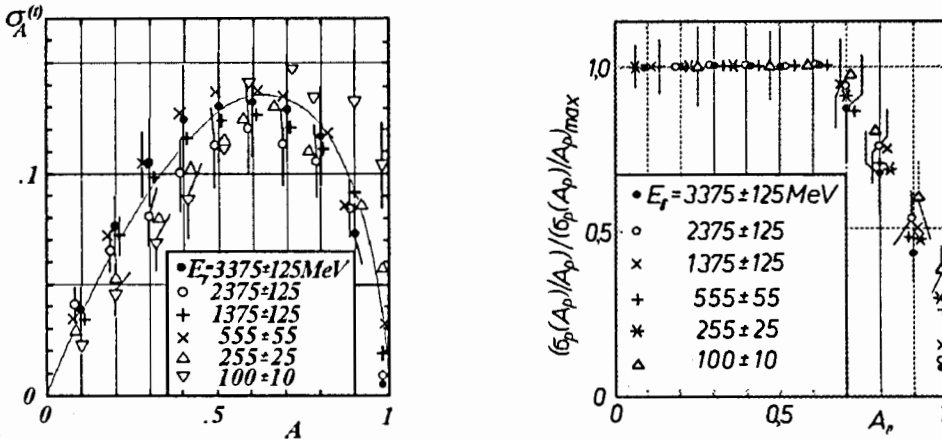


Fig.2. Scaling representation of longitudinal (left) and transverse (right) fluctuations of ionization loss of electrons in showers produced by gamma quanta of energy 100-3500 MeV in liquid xenon [1]

III. HADRONIC CASCADES

The knowledge of the development of hadronic cascades (also: showers) produced by different high-energy particles in various dense media is indispensable for many purposes, in particular, for hadron calorimetry, radiation protection and the investigation of radiation hardness of materials. So far a great deal of information concerning as well the longitudinal and transverse distribution of energy release in hadronic showers has been accumulated (see, for instance, [8,9] and references quoted herein). Below we reproduce the most important results from the point of view of scaling description of these important shower characteristics.

III.1. Longitudinal development

The well-known parameterization of the longitudinal development of a hadronic shower consists of the weighted superposition of two distributions, each being of the above indicated form (1) and describing respectively the electromagnetic and hadronic component of the shower [10]:

$$dE_s(x)/dx = N\{w(x/X_0)^{a-1}e^{-b(x/X_0)} + (1-w)(x/\lambda_I)^{a-1}e^{-d(x/\lambda_I)}\} \tag{3}$$

Here X_0 is the r.l. of the material, λ_I is the interaction length, a, b, d, w are parameters, N is the normalization constant, $w=0.4634$ and a and d linearly depend on $\ln E$. Mention also that often it is enough to use simply the one-component distribution, just like (1) only [9].

III.2. Transverse spread

The typical radial energy density in hadronic showers produced by 100 GeV pions in iron is shown in Fig.3 as the approximating solid curve [9]. One can notice its qualitative, at least, resemblance to the relevant distribution describing transverse profiles of electromagnetic showers (Fig.1).

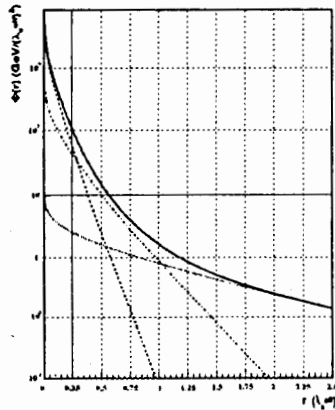


Fig.3. Radial energy density distribution for hadronic showers produced in iron by 100 GeV negative pions (solid line) [9]. (Other curves correspond to particular terms of approximating function [9])

IV. CONCLUSIONS

Although information about electromagnetic and hadronic showers, collected till now and adduced in this work is far from being exhaustive, nevertheless one can venture to suggest the following conclusions:

1. The fact that these processes so different in the main, but both being many-particle in essence, admit very similar formal description indicates that we are dealing with purely stochastic phenomena when the physics nature of these processes turns out of no importance (see also [6]). Moreover, the same suggestion seems to be supported by the fact that electromagnetic showers scale with energy in the very similar way as the well-known KNO scaling occurs (see, for instance, an overview article [11] and references herein), namely, using an average multiplicity of produced particles $\langle n \rangle$ or another central moment as a scaling parameter.

2. Usually when saying about scaling in high-energy physics (and not only) one means the possibility of the energy independent representation of some characteristics of the process under consideration. For example, dealing with nuclear reactions one says about nuclear scaling, KNO scaling, Z scaling (see, for example, [12]) etc. The case of electromagnetic and hadronic cascades has just been discussed earlier, and so on. But examining a macroscopic process it is also of equally great importance to investigate whether and to what extent one can describe this process as independent of the properties of the material in which the process takes place. It is evident, that to this purpose such quantities as radiation length, Molière unit and interaction length are too rough as scaling parameters. Unfortunately, the attempts to find the relevant scaling parameter for electromagnetic cascades developing in dense amorphous materials showed that this problem is more complicated [13]. Nevertheless, it seems that the so-called material scaling description of these macroscopic processes is to be achieved and the appropriate representation would be very useful as well for electronuclear processes and swift ion implantation into materials.

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Advanced multiparameter nuclear data acquisition, efficient storing, analysis and visualization

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1. Introduction

In the paper modular system to acquire, store, analyze and process nuclear data is described. The system allows to store in efficient way multidimensional histograms. The histograms can be processed using new developed sophisticated algorithms of background elimination, deconvolution, peak searching and fitting.

Spectrometers as GAMMASPHERE [1], EUROGAM [2], GASP [3] permit to obtain very interesting physical information, especially from heavy ion nuclear reactions, induced or spontaneous fission and others, where high-multiplicity γ -rays are registered. The future progress in the field of nuclear structure understanding depends on our ability to analyze correctly the coincidence data in multidimensional space. Thus, processing of many-fold experimental data deserves special attention.

As the final product in the data processing is the information on energies and intensities of γ -transitions, correct elimination of background and improvement of resolution represent problems common for all methods of spectral analysis regardless to how many-fold data are used. Recently, several sophisticated methods have been elaborated, which have been incorporated in software packages allowing efficient determination of the requested part of the many-parameter spectrum, created by partial absorption of γ -rays and Compton scattering on detector materials.

The requirements for using higher dimensions and resolutions in the field of nuclear experiments and data analysis are continuously increasing. Usually the classical techniques developed to analyze 1-parameter spectra cannot be directly extended to higher-fold data. The software described in the paper comprises a large number of conventional and new developed methods needed to analyze multiparameter nuclear data. It integrates coincidence multiparameter data taking [4], processing and visualization.

2. Data acquisition

The progress in detectors of nuclear radiation, particle sources and availability of powerful and relatively cheap personal computers opens new experimental possibilities in nuclear physics. It arises from the possibility to study correlations between the different properties of nuclear radiation and/or products of nuclear reactions.

The acquisition system is CAMAC oriented and modular so that the user can define any configuration of CAMAC modules in the crate. Data can be taken either from CAMAC modules

or from a file of events, which can be measured in previous experiments or brought from other laboratories. It means that the acquisition system can work either in on-line or off-line acquisition mode. At present the acquisition system supports several configurations. The CAMAC crate can be simply connected to PC. In this configuration it supports the following types of controllers:

- Hytec 1330,
- Wiener,
- KK 009, KK 012 (developed in JINR Dubna).

It supports also CCPC4 configuration, which represents integrated PC with CAMAC crate controller (the unit was developed in LHE JINR Dubna). Finally the acquisition subsystem was also implemented for VME FIC 8234 processor. The experimental equipment in CAMAC crate is connected via VSB to this processor. On the other hand the VME processor communicates with the processing subsystem via TCP/IP protocol. Then the measured data can be processed in the standard way.

3. Efficient data storing

The nuclear data taken from experiment can be stored either in the form of list of events or in the form of multidimensional histograms. The system supports analysis, storing and processing up to 4-dimensional histograms. Besides of our own event format our software supports also GAMMASPHERE format. Many practical problems arise in storing data. When storing nuclear data in the form of events enormous information is written on Exabyte tapes. Only to read one tape (4 GB) to the computer it takes about 2 hours. To handle and create different slices it is necessary the spectra to be available to the experimenter at hand. However on the other hand the resolution of ADCs e.g. in GAMMASPHERE experiments is 16k. If we assume that one channel is stored in 2 Bytes then to store 2-dimensional histogram in memory we need 512 MB, and 3-dimensional histogram would require 8 TB, 4-dimensional 128 PB (petaBytes). Obviously the memory requirements to store multidimensional data grow exponentially with the dimensionality. Therefore to fit the today's capacity of computer memory it is necessary to compress histograms in a way. The aim is to decrease the size of data to the size of available memory while preserving as much information as possible.

This can be achieved using different approaches. The simplest way is to bin neighboring channels together. However it implies the decrease of resolution and thus loss of information. On the other hand one can benefit from special properties of data. In multidimensional γ -ray spectra one can utilize the property of symmetry of the data where it holds:

- for 2-parameter spectra $E(\gamma_1, \gamma_2) = E(\gamma_2, \gamma_1)$,
- for 3-parameter spectra $E(\gamma_1, \gamma_2, \gamma_3) = E(\gamma_1, \gamma_3, \gamma_2) = E(\gamma_2, \gamma_1, \gamma_3) = E(\gamma_2, \gamma_3, \gamma_1) = E(\gamma_3, \gamma_1, \gamma_2) = E(\gamma_3, \gamma_2, \gamma_1)$.

This fact allows to decrease the size of memory for 2-parameter spectra by factor of 2 and for 3-parameter spectra by factor of 6. In general in the k -dimensional case by utilizing the property of symmetry the size of the memory can be decreased by factor of $k!$ without loss of information.

Then the size of spectra from GAMMASPHERE can be decreased to ≈ 256 MB in 2-dimensional case, to ≈ 1.25 TB in 3-dimensional case and to ≈ 5 PB in 4-dimensional case. Obviously one can conclude that even if utilizing property of symmetry of γ -ray spectra allows to decrease the size of data volumes to store data efficiently it is necessary to employ more

efficient compression method. For that purpose we have developed new adaptive transforms (Walsh, Cosine, Fourier) [5], [6], [7], which allow to compress spectra much more efficiently than classical transforms. Figs. 1a, b, c show original 2-dimensional spectrum, spectrum compressed by Cosine transform (compression ratio (CR) 64) and spectrum compressed by our adaptive Cosine transform (CR=64), respectively.

Moreover we have developed and implemented on-line compression method [8]. The algorithm allows to analyze (amplitude analysis) and subsequently compress each event separately. Compressed histogram is created from events coming sequentially one after the others. Later this compressed histogram, or slices of it, can be decompressed back to its original size. Obviously the decompressed spectrum must fit again the size of memory available. However user can create slices of lower dimensionalities and sizes and then to analyze these sliced spectra. To illustrate some results in Fig. 2a we show comparison of 1-dimensional slice from original 3-dimensional spectrum (solid line) and the same decompressed 1-dimensional slice from binned 3-dimensional spectrum (dashed line). One can observe the great distortion in decompressed spectrum. In Fig. 2b we show the same slice (original spectrum - solid line) and decompressed 1-dimensional slice from 3-dimensional spectrum compressed using our adaptive on-line compression method (dashed line). Now the distortion of the decompressed spectrum is much smaller. It should be realized that the compression ratio in this experiment was enormous (≈ 32000).

4 Processing

Processing of multiparameter spectra consists in the following steps:

- background elimination, i.e. separation of useless information (background, combination of coincidences of the background with peaks - ridges) [9],
- improving the resolution in the spectrum employing deconvolution methods [10],
- determination of peaks positions in spectrum [11],
- fitting of peaks.

Background estimation method is based on application of 2-nd order filter

$$\frac{y(i-k) + y(i+k)}{2}$$

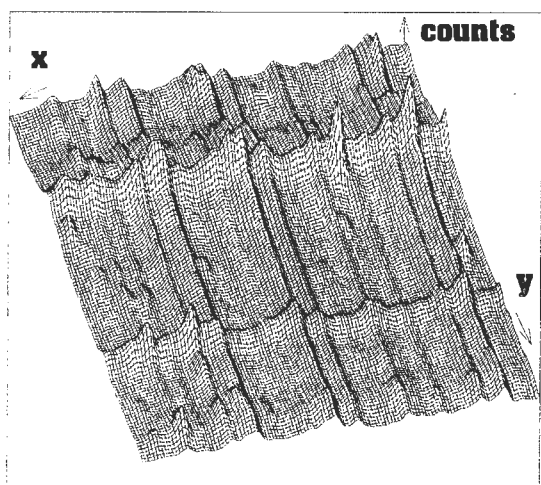
which is compared to $y(i)$, $k = 1, 2, \dots$. We accept minimum of both values. The method ignores linear component of background under peaks thus allowing to determine the background of the spectrum. The background elimination algorithm has been generalized to multidimensional data [9]. An example of 2-parameter spectrum before and after background elimination is given in Fig. 3a, b.

We have extended the method also for 4-th order filtering. Then

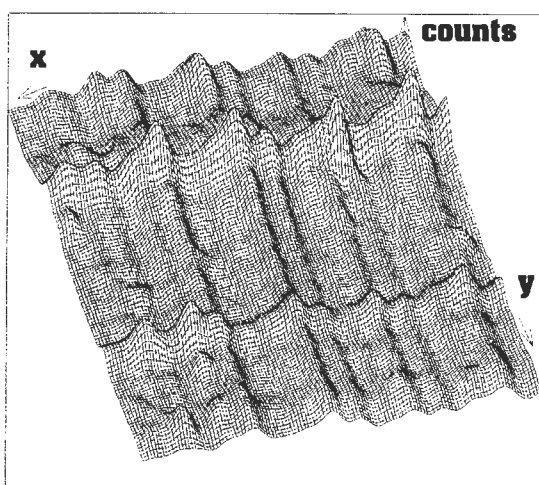
$$\frac{-y(i-2) - 4y(i-1) + 4y(i+1) - y(i+2)}{6}$$

is compared to $y(i)$. It ignores linear as well as cubic (like Compton edge) components of the background. We determine the boundary channels of a peak. Then the background itself under the peak is calculated as

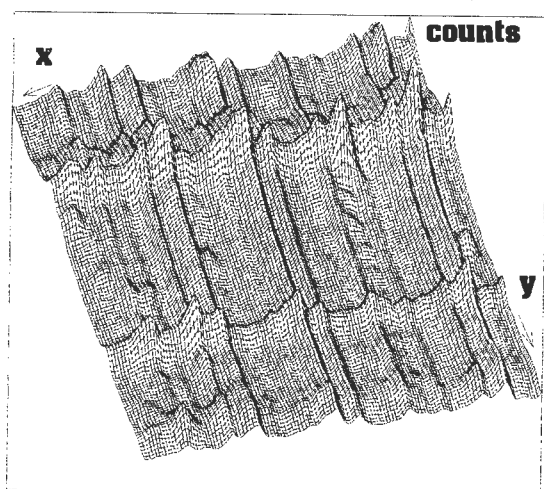
$$y'(i) = A \left(\sum_{j=b_1}^i [y(j) - y(b_1)] \right) + y(b_1)$$



(a)

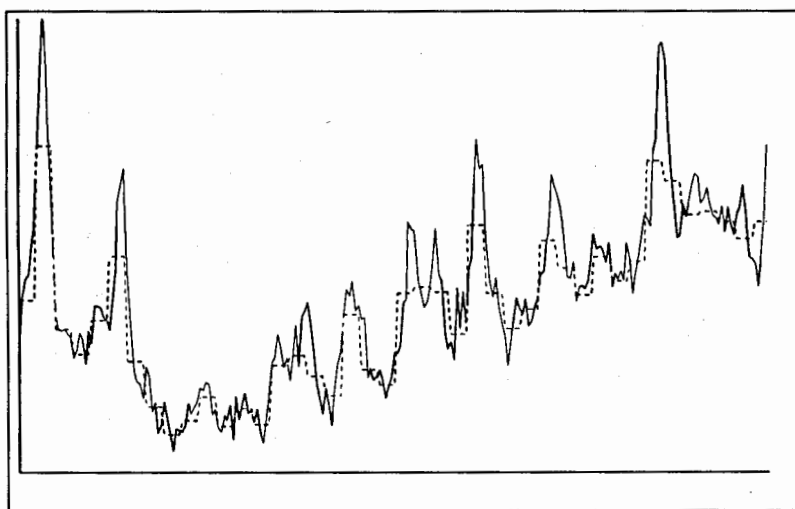


(b)

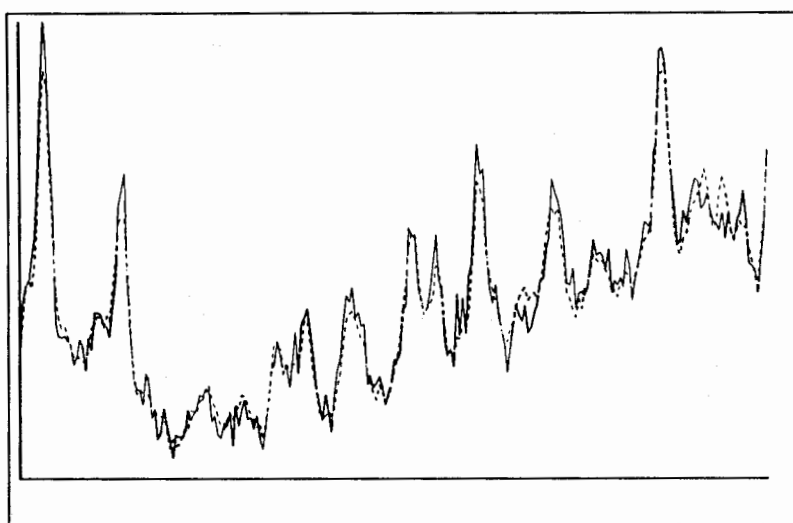


(c)

Figure 1. (a) Original two-dimensional nuclear spectrum, spectrum after the compression with $CR = 64$ using (b) classic Cosine transform and (c) adaptive Cosine transform

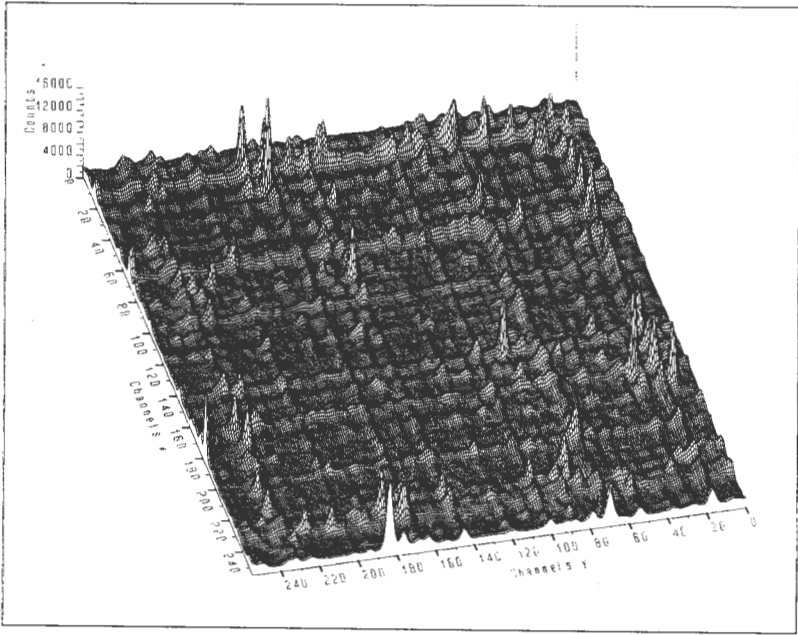


(a)

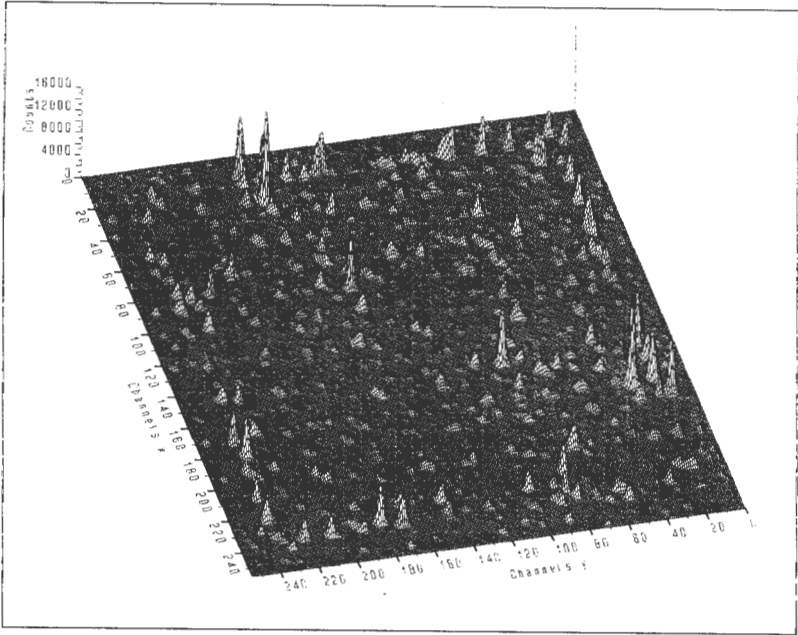


(b)

Figure 2. (a) One dimensional slice from 3-dimensional spectrum (solid line) and slice from binned 3-dimensional spectrum (dashed line), (b) one dimensional slice from 3-dimensional spectrum (solid line) and decompressed slice from our adaptive on-line compression method



(a)



(b)

Figure 3. Two-parameter spectrum (a) before and (b) after background elimination

where

$$A = \frac{[y(b_2) - y(b_1)]}{\sum_{k=b_1}^{b_2} [y(k) - y(b_1)]},$$

where b_1 is boundary channel number with lower counts, b_2 is boundary channel number with higher counts and $y'(i)$ is estimated background value in the channel i . The example of synthetic one-peak spectrum with background and noise is given in Fig. 4 (solid thin line). The background estimated using old 2-nd order filter method is shown as dashed thick line and using new 4-th order method as solid thick line.

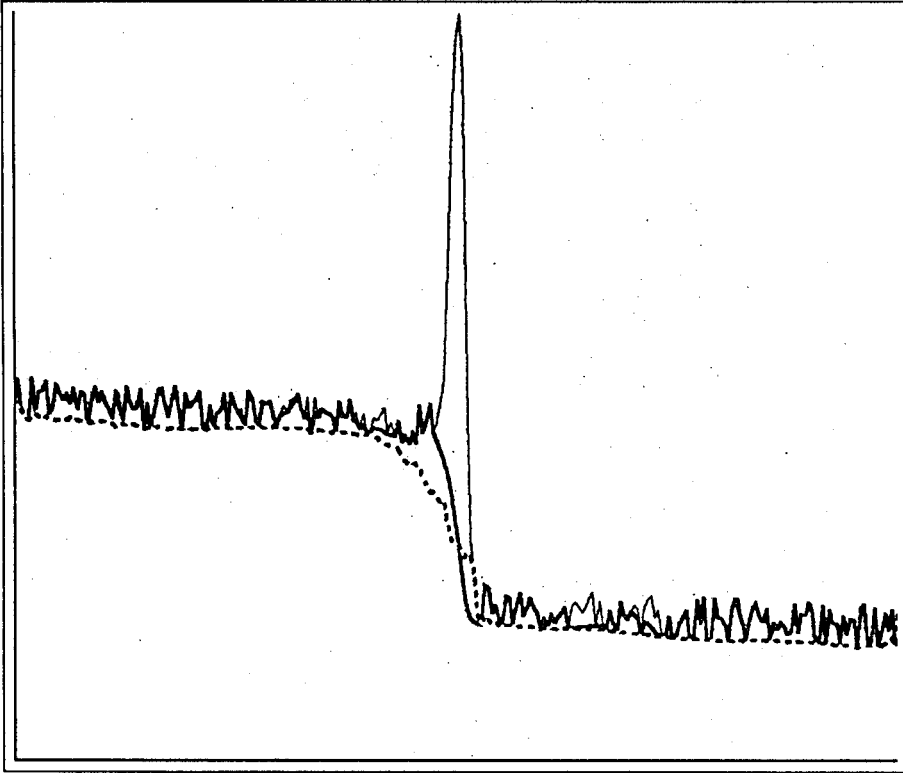
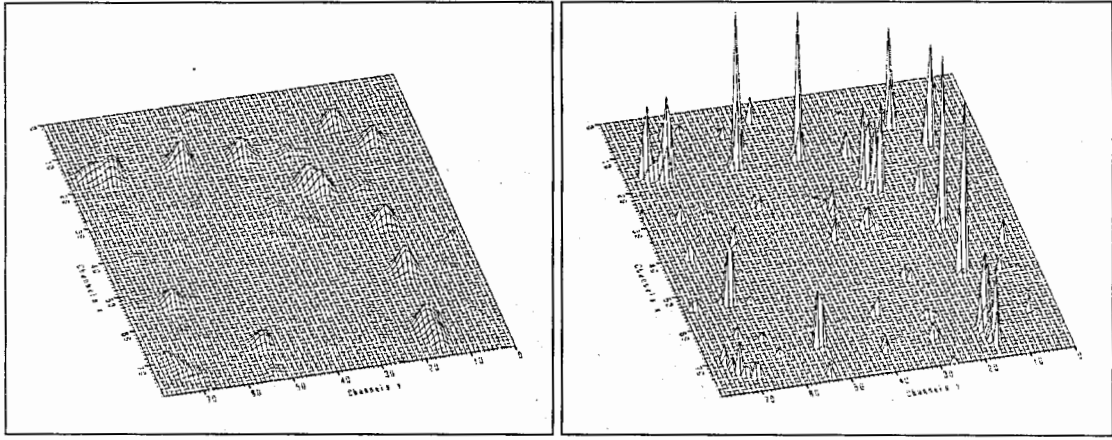


Figure 4. Synthetic one-peak spectrum with background and noise (solid thin line), background estimated using old 2-nd order filter method (dashed thick line) and using new 4-th order method (solid thick line)

After elimination of the background in multidimensional spectra the resolution can be improved by employing the deconvolution method. The Gold method of deconvolution [10] proved to be the most efficient for decomposition of multiplets in nuclear spectra. As example of the 2-dimensional spectrum before and after deconvolution is presented in Fig. 5.

The analysis of peaks in spectra consists in determination of positions of peaks and subsequent fitting, which results in estimation of peak shape parameters. The positions of peaks can be determined by employing peak searching algorithm implemented in our system [11]. They can also be determined simply by finding local maxima of well separated peaks after deconvolution. The positions of found peaks are fed as initial estimates into fitting procedure. Peaks in our system can be fitted either separately each peak (or multiplets) in a region or together



(a)

(b)

Figure 5. Two-parameter spectrum (a) before and (b) after deconvolution

all peaks found in a spectrum. To fit separately each peak one needs to determine the fitted region. However then it can happen that the regions of neighbouring peaks are overlapping and the results at fitting are very poor. On the other hand when fitting together all peaks found in a spectrum one needs to have a method that is stable (converges) and fast enough to carry out fitting in reasonable time.

According to numerical analysis it should be emphasized that direct inversion of matrices (especially large) should be avoided whenever possible. In our package we have implemented Slavic's method of fitting without matrix inversion. The method is based on the assumption that

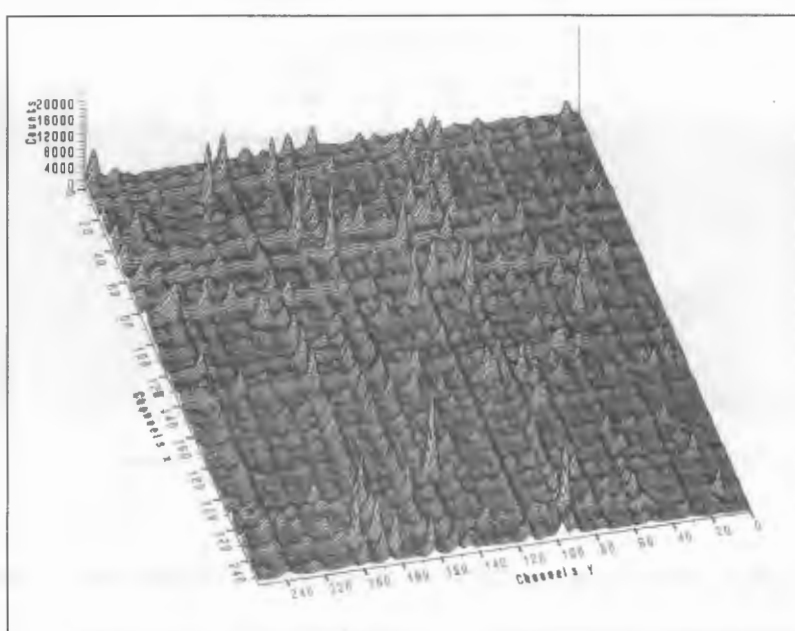
$$\sum_{i=1}^M \left(\frac{\partial y_i}{\partial b_j} \right) \frac{1}{y_i} \leq \frac{1}{\Delta b_j} \sum_{i=1}^M \left(\frac{\partial y_i}{\partial b_j} \right) \frac{e_i}{y_i},$$

where $e_i = y_i - Y_i$, y_i is the value of estimated data in channel i , Y_i is measured value in channel i , b_j are estimated parameters. Then

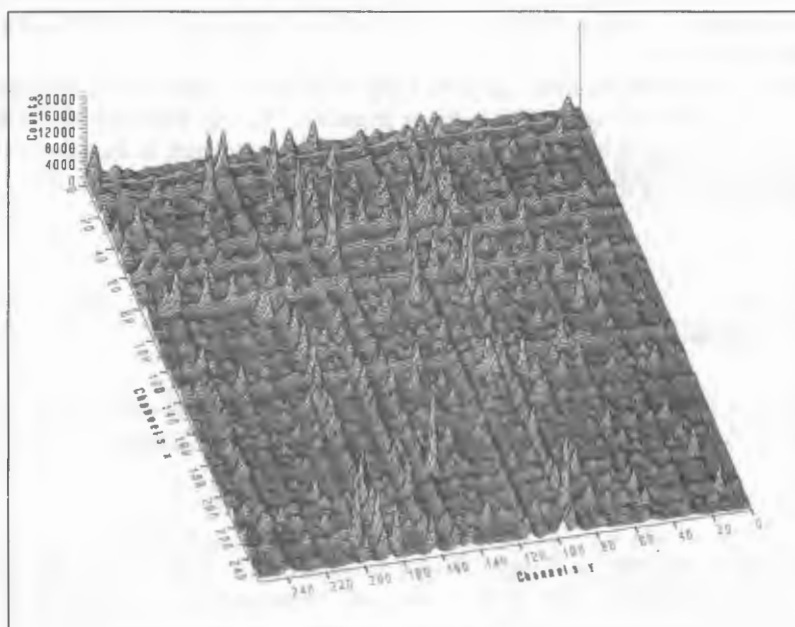
$$\Delta b_j^{(k)} = \frac{a^{(k)} \sum_{i=1}^M \left(\frac{\partial y_i^{(k-1)}}{\partial b_j} \right) \frac{e_i^{(k-1)}}{y_i}}{\sum_{i=1}^M \left(\frac{\partial y_i^{(k-1)}}{\partial b_j} \right)^2 \frac{1}{y_i}},$$

where k is iteration step and $\alpha^{(k)} \leq 1$. Slavic proposed that $\alpha^{(k)} = 1$ if the fitting process is convergent or $\alpha^{(k)} = 0.5\alpha^{(k-1)}$ if it is divergent. We have modified the algorithm

$$\alpha_j^{(k)} = \frac{\sum_{i=1}^M \left(\frac{\partial y_i^{(k-1)}}{\partial b_j} \right)^2 \frac{1}{y_i}}{\sum_{i=1}^M \left(\frac{e_i^{(k-1)}}{\Delta b_j^{(k-1)}} \right)^2 \frac{1}{y_i}} = \Delta b_j^{(k-1)} \frac{\sqrt{\sum_{i=1}^M \left(\frac{\partial y_i^{(k-1)}}{\partial b_j} \right)^2 \frac{1}{y_i}}}{\sqrt{\sum_{i=1}^M (e_i^{(k-1)})^2 \frac{1}{y_i}}}.$$



(a)



(b)

Figure 6. (a) Two-parameter spectrum and (b) spectrum generated from fitted parameters

The method proved to work fast. It is stable and always converges to the result. It allows to fit large blocks of data and lot of peaks. In the Fig. 6a we show original two dimensional spectrum (256×256 channels). Using peak searching method we have found 909 peaks. It represented 6366 parameters. The spectrum generated from fitted parameters is shown in Fig. 6b. One can observe good correspondence between both spectra. If using matrix inversion method in each iteration step the matrix inversion would be proportional to 6366^3 multiplications. The calculation could not be realized in reasonable time and the results due to rounding-off and truncation errors would be very probably worthless.

5. Conclusions

The software described so far integrates multiparameter data acquisition, sorting, analysis, processing and display. Its modular structure lends itself to set up the configuration of employed procedures according to specific needs of an experiment. A comprehensive number of both conventional and new developed algorithms were implemented in the software package.

The package allows to display 1, 2, 3, 4-parameter spectra using a great variety of visualization techniques. Also sophisticated methods like shaded isosurface, volumetric data presentation, with the possibility to smooth data using Bezier or *B*-spline techniques are implemented. It allows to display even 4-parameter spectra using new visualization model, which could be called volumetric data versus time. The pictures from screen can be printed on different printers or stored in a file in binary, postscript, PCX formats. PCX files can be also read onto screen. The package contains built-in graphical editor, which makes it possible to supplement pictures of spectra with additional drawings or texts. To write the graphical part of the package advanced graphics programming toolkit MetaWINDOWTM of the Metagraphics Software Corporation U.S.A. was used.

The presented software is suitable for acquisition of multiparameter data from small and medium sized experiments. However its processing part was used to analyze also data from Compact Pocket Ball (ORNL Oak Ridge), Gammasphere (LBL Berkeley) and Nuclotron (JINR Dubna).

Acknowledgments

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PROPOSITION OF INTERNATIONAL STANDARD: VME64 EXTENSIONS FOR PHYSICS AND OTHER APPLICATIONS (VME64xP)

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*In 1997 **VIPA** (VME International Physics Association) prepared the document VME64 Extensions for Physics and Other Applications (VME64xP) which was supplementary to VME64 and VME64x standards. It was addressed to physics community. Its aim was to make easier operation, maintenance and portability of VME equipment between laboratories. In 1998 this document was approved by American National Standard Institute (ANSI) and became American National Standard. The paper presents the main features of the Standard.*

Introduction

The VMEbus systems are used in many areas of industry and science resulting in volume production of variety of devices by numerous manufactures. For that reason they are used by physics community though the original VMEbus made certain problems when used in research applications. For example, noise as result of the shortage of ground pins in sensitive analog circuits. Because VMEbus supports a wide variety of options, incompatibilities would sometimes arise in systems with modules that did not support the appropriate subset of options. VME64x has greatly improved the VMEbus and mitigated most of the old problems and has generated interest in the wider use of VMEbus in physics research applications. The intent of the VME64x for Physics and Other Applications specification is to help the researcher to use the new features of VMEbus and thereby implement better and more reliable systems for the next generation of physics experiments. It has been produced as a supplement to VMEbus Specifications, particularly to the VME64 and VME64x Specifications.

Some of the features described in the VME64x for Physics and Other Applications specification had already been used for many years within physics community as popular extensions to VME. The specification clarifies the usage of such features and offers advice on implementation thereby limiting divergence through misunderstanding.

The following items are typical requirements to electronic systems used in research:

- Grounding

- High-frequency signalling
- Low noise for high-resolution analog signals
- User defined I/O pins
- Sparse data readout
- Geographical addressing
- Additional power supply voltages
- DC-DC on board converters
- Efficient block transfer protocols
- Provision for cooling
- Standard CSR registers
- Data space addressing rules
- Software
- Design guides

History

The original VMEbus standard was sponsored by the Technical Committee on Microprocessors and Microcomputers of the IEEE Computer Society. It was approved by ANSI (American National Standards Institute) and issued by IEEE as ANSI/IEEE Std 1014-1987. The maximum theoretical data rate on the backplane was 40 MB/sec. The VME64 Standard was developed in 1994 by the VME International Trade Association (VITA) and processed through (ANSI) by VME Standards Organization (VSO). It increased the data rate to 80 MB/sec. The next step was done by VMEx (VME Extensions) document developed by VITA and approved by ANSI which provided an increase to 160 MB/sec. VME64 Extensions for Physics and Other Applications (VME64xP) does not increase this transfer rate. In January 1998 VITA set up a task group to prepare the specification of the protocol which was called Two Edge Source Synchronous Transfer (2eSST). It bases on source synchronous transfer technology. The performance of 2eSST is determined not by propagation delay from source to destination, but by skew – the variation in propagation delay through the drivers, backplane and receivers. In the specification are proposed two new transfer rates 264 Mb/s and 320 MB/s. In theory, as technology improves, this protocol is virtually unlimited in potential transfer rate. VME performance has been enhanced 8 times since VME's introduction.

VIPA (VITA International Physics Association) is VITA Special Interest (User) Group that represents the international physics community in VSO. VIPA was formed to make VSO aware of the needs of the physics research community. This is not an association in the commercial sense. Most documentation is available on the Internet via ftp and www. VIPA has membership in VITA through CERN, the Fermilab National Accelerator Laboratory and JVP Working Group in Japan. The VIPA membership consists of:

- VMEbus Steering Committee. The VMEbus Steering Committee (VSC) is Study Group of ESONE (European Studies On Norms for Electronics). One of ESONE's aims is to promote the use of standards in research in Europe and to collaborate in the development of standards where none exist. ESONE developed CAMAC in collaboration with NIM. More recently it developed VICbus (ISO/IEC 11458)

- NIM VME-P. The NIM VME-P working group is the committee under NIM (Nuclear Instrumentation Module) that is concerned VME for physics applications in USA.
- JVP Working Group. JVP is the Japanese VME Physics working group concerned with VME for physics applications.

The VME64 Extensions (VME64x) Features

VME64x greatly enhances VME64 for its use in many fields. The following new features are defined in the VME64x :

- Addition of z & d rows to P1/J1 and P2/J2 connectors with associated pin assignments (Expended 160 pins connectors)
- An optional 2 mm hard metric P0/J0 connector between P1/J1 and P2/J2 with 95 user defined signal pins and a ground shield of either 19 or 38 pins for more user defined I/O
- 35 more signal grounds in P1/J1 and P2/J2
- 3.3 V power pins
- Nominal 48 V power for DC-DC converters
- Three more +5 V pins via the VPC power pins
- Slot geographical addressing
- 12 reserved bus lines and 2 reserved unbusd lines for future expansion
- 46 more user defined pins on P2/J2
- Pins allocated for test and maintenance bus (T&M bus)
- Two mate-first-break-last precharge pins in P1/J1 and one pin in P2/J2 for live insertion
- Two mate-first-break-last ground pins in P1/J1 and one pin in P2/J2 for live insertion
- Two reserved pins for individual slot power control live insertion applications
- Two bused serial lines for live insertion control
- Electromagnetic compatibility control (EMC) front panel
- Electrostatic discharge control (ESD) strips on boards and discharged clips on subrack card guides
- Solder side covers with ESD protection
- Injector/Ejector handles with optional locking feature
- User defined keying for boards and subrack slots
- Reserved area on front panel for ID and bar codes
- Multifunction alignment pin
- Rear I/O transition boards
- Added CR/CSR definitions
- Two edged transfer protocols for higher throughput (2eVME)
- Enhanced Transceiver Logic (ETL) for bus signals

The original VME, as well as VME64 uses a four edge handshake for all transactions. For each transfer, the handshake signal must be transferred four times across the backplane. The assertion by master of the strobe at edge 1 lets the slave know that data is valid. The slave acknowledge with edge 2. The assertion of edge 2 lets the master know that the slave has responded so that it rescinds its strobe at edge 3. The slave then finishes the cycle by rescinding its signal at edge 4.

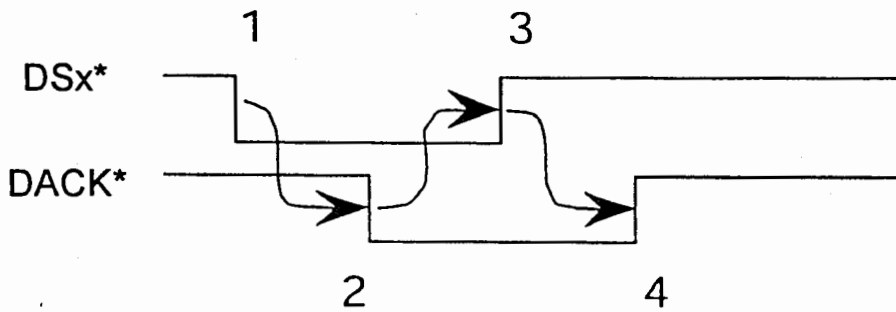


Fig. 1. Four Edge Handshake – Single Data Transfer

The 2eVME uses two edge handshake protocol. The master signals data valid on the falling edge of the strobe at 1 and the slave acknowledge data received by asserting its strobe at edge 2. The next transfer is signalled with the rising edge at 1 and the slave acknowledges with edge 2. Both address and data phases were speed up with this protocol. Another feature being added to the new protocol is a combination of either master or slave terminated block transfers.

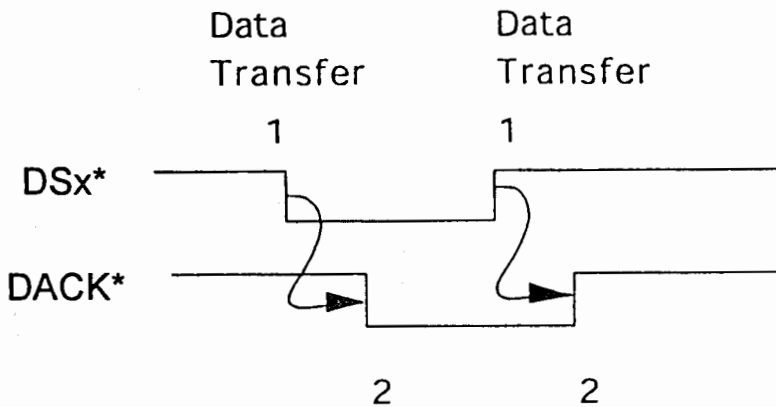


Fig.2.Two Edge Handshake – Single Data Transfer

The peak block data rate for 2eVME protocol is 160 MB/sec.

VMEx boards and backplane using 2eVME protocol should use ETL devices. These devices provide:

- Improved bus driver capability
- Improved bus receiver capability
- Precharge of bus transceiver signal pins during live insertion and withdrawal
- An independent forced high impedance mode.

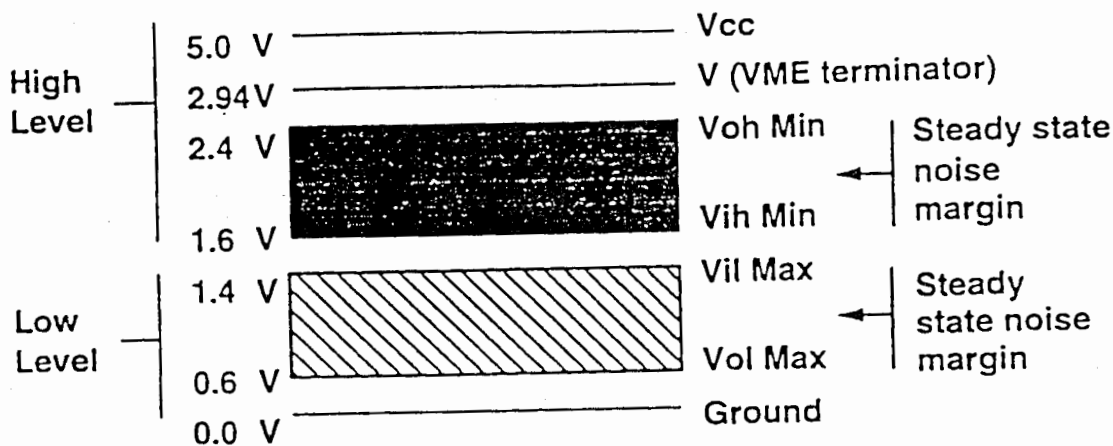


Fig.3. ETL Termination Voltage Levels

VME64 Extensions for Physics and Other Applications (VME64xP) Features

VME64xP modules and subracks are VME64x modules and subracks, respectively, in which many of the construction and protocol items given as options in VMEx are mandatory or recommended as physics applications require enhanced interchangeability and compatibility, increased I/O capability, and other characteristics.

Various backplane configurations are selectable and the backplane requirements (all in strict compliance with VME64x) are specified in more detail. Pin assignments are made for JO connector for extra power and power at other voltages while many pins are designated as grounds for enhanced signal quality. Also, pins are assigned as "user defined" in JO, that, together with those in the P2 connector, comprise an important feature of the VME64xP subrack for applications requiring a large number of I/Os.

VME64xP subracks are constructed to handle high power, for example for ECL circuitry. The high power requires busing assemblies together with design and construction that permits sufficient and uniform cooling of the modules inserted in the VME64xP subracks. In VME64x for Physics and Other Applications document are also included recommendations for EMC shielding of modules and subracks.

Injector/extractor handles, electrostatic discharge (ESD) provision, and keying (all optional in VME64x) are mandated in VME64xP modules and subracks. There are also included recommendations for EMC shielding of modules and subracks.

VME64xP designates specific requirements for implementations of Configuration ROM (CR) and Control Space Register (CRS) space as well as for Capabilities Register, and requires that data transfers to CR and CSR space be via D32. Addressing details are also specified or recommended both for operational efficiency and for uniformity.

The VME64xP standard includes also numerous recommended and suggested items and preferred implementations, many of which are readily available in VME64xP equipment.

Software is important part of VME systems. VME64x for Physics and Other Applications document does not deal with software. The following documents deal with software aspects of VME:

- VITA 19-1997
- VITA 25-1999

In the VME64x for Physics and Other Applications document are used the following keywords.

- **Rule:** indicates that that items are mandatory
- **Recommendation:** indicates an advice
- **Permission:** informs that certain approach is acceptable
- **Suggestion:** contains advice which is helpful
- **Observation:** explains the reader why the rule is to be followed
-

Address modes and data width

- The A32 and A64 address widths are recommended for all VME64xP modules
- The latching of addresses is recommended
- VME64xP modules shall support D32 transfers and it is recommended that they should support D64 block transfers
- All preferred AM codes are non-privileged access
- Module designers are encouraged to pack data into wide words for higher throughput

Data Acquisition Systems (DAC) have data stored in blocks of variable length. BLT and MBLT protocols require the Master to know how much to read from each Slave. Reading of information to determine the current data block size can slow the readout time considerably. Better solution is to inform Master that Slave has no data or it has sent the last data in the buffer. In such case Master can go to the next DAQ module and thereby reduce the total system readout time. The new 2eVME protocols defined in VME64x make possible that Slave can signal to the Master; no data, end of data, or suspend the transfer – with an implied “try again”. The other method is presented in Appendix E of VME64xP document. The technique called CBLT uses protocols defined in VME and VME64 with one exception. The IACK* daisy chain line is used as a token to indicate that the module is out of data. This nonstandard usage of IACK* puts some simple restrictions on placement of VME modules in the subrack.

CR/CSR registers

VME64xP modules follow Configuration ROM/Control and Status registers (CR/CSR) specified in VME64 and VME64x specifications. The Base Address Register (BAR) for access to CR/CSR space and VME64xP is loaded with the Modules Geographical Address at power on or with a board reset (including SYSRESET*). The Geographical Address is loaded into the BAR bits (7:3). This register can be reloaded to another address by system configuration software.

The location of CR and CSR registers, if used, follow the methodology in VME64 and VME64x. The requirement for certain locations to be standardized makes the system software simpler and opens the possibility of "plug-and-play". Some systems in High Energy Physics experiments have hundreds of subracks. The management of such a system is difficult. By having certain CR and CSR registers at known locations the management of these systems becomes much easier and less error prone. Large PROM's are cheap and they may be used to hold as much as possible information.

Modules and I/O transition modules

Data acquisition systems typically need large VME board. In physics domain the essential characteristic of almost all front-end modules is that of an array of many independent electronic channels whose outputs are scanned sequentially, with the results passed on through an interface to the backplane bus. Interface component costs and board occupancy tend to remain consistent regardless of number of channels supported and are better amortised when channel quantities per module are maximised.

VME64xP deals with the use not only the extremely popular 6U VME module, but also the 9U (366.7 x 400 mm) VME form factor as well. The design of 9U boards is more demanding than 6U boards. The 9U boards can be fitted with additional connectors. Optional items in VME64x such as injector/ejector/locking handles, ESD strips, provisions for EMI gaskets, keying and connector shields are made mandatory. They make system implementation and maintenance easier. Shields help reduce noise which could affect sensitive analog circuitry used in many data acquisition modules. Keying makes that the correct module is plugged into the correct slot. All VME64xP modules should have labels indicating which voltages and how much current is used.

Figure 4 shows the location of the various connectors and the nomenclature to identify each.

Two sizes of I/O transition modules are recommended. For 6U systems an 80 mm deep module is preferred. For 9U systems a 120 mm deep Transition Module is specified. The deeper 9U transition module gives more room for circuitry and trace routing to connectors and is sufficient for an adapter from 6U x 80 mm transition modules to 9U x 120 mm transition modules.

The new feature of transition modules is the use on them the DC-DC converters. Coding the front module to the associated rear transition module insures that the voltages produced matches the voltages required by the front module. If the code does not match the output of DC-DC converter no power is applied to the pins.

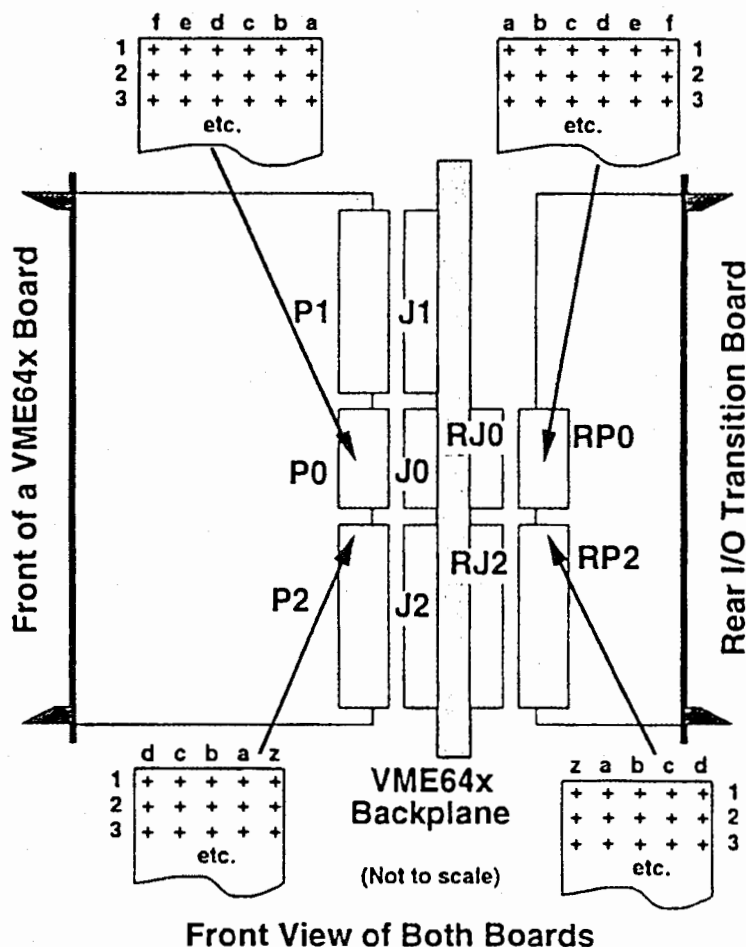


Fig.4. Front and Transition I/O Board

Mezzanine cards

A mezzanine card is a slim circuit board that is mounted in a module parallel to module circuit board and is attached to the module circuit board through one or more connectors. This gives users an easy way to customize their systems. Two types of mezzanine cards are recommended. The IP-module for lower performance and lower cost applications and PMC for higher performance applications. In the physics experiments using of mezzanine cards containing channel electronics mounted on a mother board interfaced to an appropriate backplane is very popular.

Subracks

A VME64xP subrack is an assembly that consists at least:

- A module card cage which holds the VMEbus modules, providing mechanical support and alignment of the modules with respect to the backplane;
- a backplane which provides power distribution, the VMEbus and, optionally, other communication paths;

- a power connection assembly which interfaces power supplies to the backplane

Optionally a VME64xP subrack may also include:

- A transition module card cage which provides mechanical support and alignment of transition modules which interface to the rear side of the backplane;
- Cooling apparatus (air or water flow)
- Power supplies which are integrated part of subrack mechanics

Subracks shall conform to VME64x and VME64x9U for details concerning the use of 2 mm hard metric connectors.

In the Appendix A and B of VME64xP document are defined new 7U and 10U subracks. 7U subrack accommodates twenty one 6U x 160 mm modules with field-removable 6U x 80 mm twenty one slot transition module cage, extra +5 V power, and four additional voltages for physics and other applications. This subrack includes VME64x features such as 5-row J1 and J2 connectors providing additional grounds, power for board-mounted DC-DC converters, Geographical Address pins, the J0 connector, optional EMC gaskets, compatibility with injector/ejector/locking handles, keying and alignment pins, and ESD protection.

10U subrack accommodates twenty one 9U x 400 mm VME modules with field-removable 9U x 120 mm twenty one slot transition module cage, extra +5 V power, and four additional voltages for physics and other applications. This subrack includes VME64x features such as 5-row J1 and J2 connectors providing additional grounds, power for board-mounted DC-DC converters, Geographical Address pins, the J0 connector, optional EMC gaskets, compatibility with injector/ejector/locking handles, keying and alignment pins, and ESD protection.

Subrack Backplanes

VME64xP systems generally use four types of backplanes:

- The J1/0/2 backplane which is monolithic backplane that includes connectors J1, J0 and J2 for all the slots. It may be used in subracks for 6U or 9U modules.
- J1/02/4/5/6 backplane which is monolithic backplane that includes connectors J1, J0, J2, J4, J5 and J6 for all the slots. It is used for subracks with 9U modules only.
- The J5/6 backplane which is used with J1/0/2 backplane in subracks for 9U modules.
- The J3 backplane configuration which is not recommended for new designs

The choice of the backplane for VME64xP is determined by system requirements. For systems which need voltages, other than those specified in VME64x, supplied to pins in the backplane, VME64xP has recommended special voltages on P0 for modules which are used in data acquisition systems. Six extra +5 V power pins are specified for the greater power consumption generally found in 9U VME modules. Two pairs of voltage buses and their common returns are also included. A typical use of these buses would be to assign three of them -5.2 V and one to -2 V. A maximum of 180 amperes could be delivered on the -5.2 V bus and 60 amperes on

the -2 V bus. DC-DC conversion technology, if used, gives the system designer freedom in utilising devices requiring various voltages.

9U models require high current connections to the backplane. Large bus bars are necessary to distribute high currents into the backplane at low voltage drops. In the table presented below are listed maximum currents that VME_xP backplane has to be desired carry on each bus.

Different combinations of voltage and current have different effects on the digital return current. In order to handle the worst case configuration the digital return current bus (COM) for 9U backplane is required to handle 530 amperes and for the 6U backplane it is specified for 170 amperes.

The backplane voltage drop between the same voltage or ground pins in a slot shall not exceed 10 mV when those pins are drawing the maximum allowed current.

The temperature rise in the backplane for any layer shall not exceed 5° C above ambient when the backplane is drawing the maximum currents imposed by limitations of the VME bus connectors.

9U subracks should so designed that they may dissipate 1.5 kW or more.

Table 1. Current ratings of 6U and 9U modules

Voltage	9U Current	6U Current
[V]	[A]	[A]
+3.3	200	50
+5	300	100
+12	30	20
-12	30	20
Vw, Vx, Vy, Vz	60 each	20 each
+/- V	30 A	20 A

Chained Block Transfers (CBLT) and Multicast Commands (MCST)

The Appendix E of VME64_xP document includes Chained Block Transfers (CBLT) and Multicast Commands (MCST) special protocols originally developed for High Energy Physics. The CBLT protocol reads data from adjacent set of modules on VME backplane without addressing each one individually. MCST is broadcast mechanism for controlling a group of modules in data acquisition system.

CBLT mechanism allows the fast readout of large blocks of data of undetermined size from series of modules housed in the same crate. At the start of CLBT transaction the Master has no knowledge of which of the slave modules contain data nor the quantity of data each. One block transfer is sufficient to read several modules containing the data for a single physics event.

Use of CBLT mechanism will have the greatest effect on read-out performance when data is "sparse", that is when modules tend to contain little or no data. When all of the modules tend to contain fixed amounts of data, the benefit will be minimal.

MCST transactions allow commands to be sent to chosen set of Slaves modules such that general commands such as reset, fast clear, trigger ready, event selection, etc. may be given to a number of modules in one DTB transaction.

A32 with either D32 or D64 is required for modules executing these protocols. The modules require two CR registers for controlling the operations. These registers enable/disable CBLT and MCST, define the first and last module in readout chain, flags to denote whether data is present, and a flag to tell if all data has been read.

Conclusions

VME64 Extensions for Physics and Other Applications (VME64xP) standard is natural development of VME, VME64 and VME64x standards. On its preparing had a large influence High Energy Physics Research Community. Its main aim is to make easier operation, maintenance and portability of VME equipment between laboratories. Besides it helps to ensure that the facilities required in physics experiments are not ignored in the interests of commercial marketing practice.

References

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- [3] VITA Draft 1.3 January 12, 1998: 2eSST Source Synchronous Transfer Draft Standard.

Search for Flow Effects in Relativistic Heavy Ion Collisions with Emulsion Nuclei

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Abstract

Various flow phenomena observed by unique emulsion method are reviewed. The experimental data of the emission of projectile and target fragments and relativistic particles in collisions of (1-160 A GeV/c) ^{16}O , ^{22}Ne , ^{28}Si , ^{32}S , ^{84}Kr , ^{197}Au and ^{208}Pb nuclei with ^{108}Ag (^{80}Br) targets are investigated. The transverse-momentum approach, the flow angle analysis using principal vectors, the azimuthal correlation functions, the method of the azimuthal correlations between the charged secondaries and the method of the Fourier expansion of the azimuthal angle distributions are applied. The evidence of the bounce-off of spectator fragments is observed in the medium-impact nuclear interactions accompanied with strong azimuthal correlations in the emission of fragments. In azimuthal distributions, with respect to the reaction plane, the squeeze-out and side splash of the participants are seen.

Introduction

Reactions between heavy nuclei at high energies have been investigated for a number of years at the Dubna, Brookhaven and CERN accelerators. A characteristic feature of nucleus-nucleus collisions is that the direction of the outgoing particles projected onto the transverse plane is correlated with the orientation of the impact parameter. These azimuthal correlations are usually referred to as "collective flow" [1].

The directed fluid-like emission of nuclear matter in energetic collisions of two nuclei was first predicted by [2]. Then many experiments have been devoted to the study of hydrodynamical behaviour of nuclear matter in nucleus-nucleus collisions [3].

The first conclusive evidence of collective sideward flow was provided by heavy-ion experiments around 1 A GeV/c [4]. Their 4π -detectors were able to measure event-by-event the four-momenta of all particles.

This phenomenon was also observed at ultrarelativistic energies by E877 Collaboration in Au+Au collisions at 11.4 AGeV/c [5] and only recently in 158 AGeV Pb+Pb collisions by NA49 and WA98 Collaborations [6]. One of the main motivations of such a study is that the experimental observation of asymmetries in azimuthal distributions for non-central collisions at ultrarelativistic energies could be sensitive to the formation of quark-gluon plasma [7]. At intermediate energies, they yield information on the nuclear compressibility [8] and on the in-medium nucleon-nucleon cross section [9].

The quantifying of the collective flow in nucleus-nucleus collisions starts usually with determining of the impact parameter b , the perpendicular distance from the target nucleus

to the initial line of motion of the incident nucleus. The impact parameter and the beam velocity vectors define a "reaction plane" for the collision. One expects collective phenomena to happen in this plane.

Different aspects of flow phenomena have been observed: the bounce-off of the spectator fragments and the side splash of participant matter which occurs in the reaction plane and the squeeze-out of nucleons perpendicular to the reaction plane [10].

The goal of the present paper is to review the various flow phenomena observed by unique emulsion method at energies between 1 AGeV and 160 AGeV.

Experiment

Stacks of NIKFI BR-2 nuclear emulsions were irradiated by 1.55 A GeV/c ^{84}Kr beam at SIS in Darmstadt, by ^{16}O , ^{22}Ne , ^{28}Si and ^{32}S at Dubna synchrophasotron (4.1-4.5 AGeV/c), by ^{28}Si and ^{197}Au beams at BNL AGS (14.6 and 11.6 A GeV/c) and by ^{208}Pb beams at CERN SPS (158 AGeV/c). The details of the experiments can be found in previous papers of the Dubna [11], Krypton [12] and EMU01 ([13], [14]) collaborations and in the references therein. In some cases, the experimental data were compared with cascade calculations [15].

Secondary charged particles were classified into the following groups:

1. Projectile fragments (PF) - with charges $Z_{PF} \geq 1$.
2. Target fragments (TF) - so called h-particles, they consists of fast g-particles, mainly recoil protons with kinetic energies $26 \leq T < 400$ MeV, and slow b-particles, target fragments with energy $T < 26$ MeV/nucleon.
3. Relativistic s-particles - fast singly charged particles with $\beta > 0.7$.

For all particles the polar (Θ) and azimuthal (Ψ) emission angles have been measured and charges of multiply charged projectile fragments have been determined.

For the present analysis we selected events of inelastic interactions of the projectile nucleus with Ag (Br) target nuclei at medium impact parameters. Selected events, if not saying else, are characterized by the number of target fragments $N_{TF} \geq 8$ (representing interactions with Ag or Br targets) and $N_{PF} \geq 4$, where N_{PF} is the number of projectile fragments (or $N_\alpha \geq 3$ in the case of ^{197}Au induced interactions, N_α is the number of projectile alpha fragments).

Results

There are many methods which are ideally suited to study emission patterns and event shapes in relativistic nuclear reactions. For our analysis we adopted: the transverse-momentum approach [16], the flow angle analysis using principal vectors [17], the azimuthal correlation functions [18], the method of the azimuthal correlations between the charged secondaries [19] and the method of the Fourier expansion of the azimuthal angle distribution [7].

In the transverse-momentum analysis the reaction plane is defined by the direction of the incident nucleus and the plane vector $\vec{R}_i$, which is constructed individually for each PF from the transverse momenta $\vec{P}_{t,j}$ of all remaining PFs in the same event as $\vec{R}_i = \Sigma A_j \vec{P}_{t,j}$, where $j \neq i$ ($i, j = 1, 2, \dots, N_{PF}$), N_{PF} is the number of PFs and A_j is

Tab.1

Momentum [AGeV/c]	Beam	$\langle P_R \rangle_{EXP}$ [AMeV/c]	$\langle P_R \rangle_{ME}$ [AMeV/c]	Selection Criteria	References
1.55	^{84}Kr	23.6 ± 2.3	0.6	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4^*$	[12]
4.1	^{22}Ne	16.1 ± 2.6	0.8	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[20]
4.5	^{16}O	12.8 ± 2.8	-0.7	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[20]
4.5	^{28}Si	6.1 ± 2.3	0.1	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[20]
4.5	^{32}S	18.4 ± 2.1	1.3	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[12]
11.6	^{197}Au	32.0 ± 1.8	-0.2	$N_{TF} \geq 8 \ \& \ N_{\alpha} \geq 3^*$	[13]
14.6	^{28}Si	7.2 ± 2.5	0.5	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[20]

* single charged PFs are not included in N_{PF}

the mass of the fragment. The definition of $\vec{R}$ ensures that the autocorrelations are removed by calculating $\vec{R}$ for each fragment separately from the transverse momenta of all remaining fragments, without including the fragment itself [16]. Assuming that each PF j has the same longitudinal momentum per nucleon P_L as the projectile nucleus, the transverse momentum per nucleon of the j th fragment is given by $P_{t,j} = P_L \tan \Theta_j$, where Θ_j is the emission angle of the j th fragment. Then we find the projection of $\vec{P}_{t,i}$ into the corresponding $\vec{R}_i$ by $P_{R,i} = (\vec{P}_{t,i} \cdot \vec{R}_i) / |\vec{R}_i|$. The average values $\langle P_R \rangle$ for nuclear interactions on Ag(Br) targets ($N_{TF} \geq 8$) are shown in Tab.1 as a function of beam mass and momentum. The mean value of P_R is zero if $P_{t,i}$ is randomly distributed in the azimuthal plane and is nonzero if the energy flow of fragments deviates from the zero-angle direction, i.e., if bounce-off of PFs occurs. One observes that our data significantly differ from zero and display the bounce-off of the PFs.

To investigate if the obtained value represents a significant flow of transverse momenta, the same procedure has been applied to mixed events (ME) which lack a dynamic effect in the reaction plane. The mixed events have been generated from the original total sample of fragments randomly distributed in the new events. The results are shown in Tab.1. The randomized events do not manifest this bounce-off effect.

Also the plane vector $\vec{R}$ of the TFs has been constructed for each event according to previously used formula. The coefficient $A_j = 1$ and instead of $\vec{P}_{t,j}$ a unit vector of the azimuthal direction of Ψ_j has been considered. The sum runs over all TFs in the given event. The distribution of the relative azimuthal angle ($\Delta\Psi_{PF-TF}$) between "projectile" and "target" plane vectors (Fig. 1a) shows strong correlation between them. The average azimuthal angles between them are $112^\circ \pm 4^\circ$ and $107^\circ \pm 3^\circ$ for ^{84}Kr and ^{197}Au primaries [12] [13]. The E877 Collaboration has previously reported [21] a corresponding pronounced event anisotropy.

In order to test the reaction plane determination the method proposed in [16] has been used. Each event was randomly divided into two parts and the reaction planes have been estimated separately for these sub-events. The distribution of the differences between the azimuthal angles of the two constructed reaction planes obtained in ^{197}Au induced collisions in emulsion [13] is shown in Fig. 1b. This distribution is peaked at 0° with a width $\sigma \approx 49.8^\circ$. The fact that the distribution is not flat and peaks at zero indicates that the obtained reaction planes are not accidental, but reflects physical correlations among the emitted fragments.

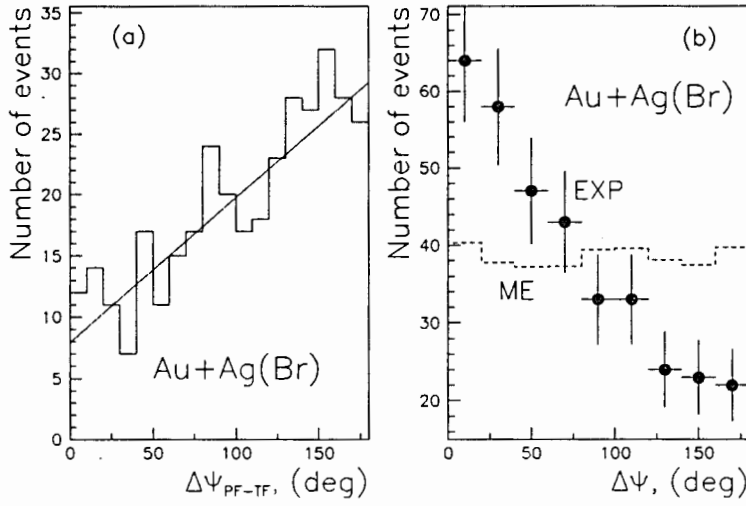


Figure 1. (a) The relative azimuthal angle between two reaction planes made from PFs and TFs in $^{197}\text{Au}+\text{Ag}(\text{Br})$ collisions at 11.6 A GeV/c, (b) test of the reaction plane determination

To verify this we have performed the same test using mixed events. The resulting distribution, shown as a dashed histogram in Fig. 1b is constant and does not show any correlations. The width σ was found to be related to the width σ_0 of the distribution of found reaction planes around the true reaction plane by $\sigma_0 = \sigma/2$ [22]. This value serves as a measure for the resolution of the plane vector $\vec{R}$. The obtained value $\sigma_0 \approx 24.9^\circ$ is comparable to the values reported in [23] and with the value $\sigma_0 \approx 23.1^\circ$ obtained in ^{84}Kr induced collisions with Ag(Br) targets [12].

Similar results have been obtained using the other methods. In the flow angle analysis proposed by Heckmann [17] the unit vectors in the directions of the emission of PFs and TFs are summed to give their principal vectors $\vec{V}_{PF}$ and $\vec{V}_{TF}$, respectively. These vectors are assumed to be in the direction of their sources with respect to the beam direction.

The values of the flow angle Θ_F for PFs (the polar angle of the vector $\vec{V}_{PF}$) are given in Tab.2 for different centrality groups (N_h is the number of TFs). One can see that the flow angles of PFs are small for all cases of centrality but they strongly increase at lower energies. On the other hand the increase of the mean value $\langle\Theta_F\rangle$ with decreasing impact parameter (increasing N_s , N_g or N_h) is clearly seen at all beam and energy combinations.

The experimental values are greater than the cascade calculations and ME sample (values in brackets). This fact can be considered as an indication of the sideward flow, i.e. the bounce-off of the PFs. It was also shown (but not illustrated here) that the tendency of the emission of PFs and TFs in the opposite directions in the azimuthal plane is reinforced with increasing centrality.

To avoid event-by-event estimate of the reaction plane we also tried an azimuthal correlation function analysis. Then the collective flow can be parametrized in terms of azimuthal angle distributions of projectile fragment pairs. Following [18], let us assume that the probability distribution $P(\Psi)$ of the angle Ψ between the transverse momenta of two correlated fragments is $P(\Psi) = A^2(1+0.5\lambda^2\cos(\Psi))$, where A is a normalization constant.

Tab.2

Momentum [AGeV/c]	Beam	Θ_F deg	Centrality Criteria	References
1.55	^{84}Kr	1.4 ± 0.1	$N_g = 1 - 6$	[12]
		2.0 ± 0.1	$N_g \geq 7$	
4.1	^{22}Ne	0.54 ± 0.03 (0.41)	$N_h = 7 - 13$	[25]
		0.80 ± 0.08 (0.41)	$N_h = 14 - 27$	
		1.26 ± 0.40 (0.40)	$N_h \geq 28$	
4.5	^{28}Si	0.51 ± 0.04 (0.33)	$N_h = 7 - 13$	[25]
		0.61 ± 0.04 (0.42)	$N_h = 14 - 27$	
		0.82 ± 0.15 (0.42)	$N_h \geq 28$	
11.6	^{197}Au	0.26 ± 0.02 (0.23*)	$N_s < 100$	[13]
		0.32 ± 0.02 (0.23*)	$N_s = 100 - 200$	
		0.47 ± 0.06 (0.30*)	$N_s > 200$	
14.6	^{28}Si	0.15 ± 0.02 (0.14)	$N_h = 8 - 13$	[26]
		0.15 ± 0.01 (0.15)	$N_h = 14 - 19$	
		0.23 ± 0.05 (0.17)	$N_h \geq 28$	

* ME calculations

The azimuthal correlation function $C(\Psi)$ is defined by $C(\Psi) = P_{\text{corr}}(\Psi)/P_{\text{uncorr}}(\Psi)$, where $P_{\text{corr}}(\Psi)$ represents the distribution of the angle Ψ for correlated fragment pairs occurring in the same event and $P_{\text{uncorr}}(\Psi)$ is obtained from the distribution of the uncorrelated fragment pairs generated by event mixing. If $C(\Psi) > 1$ at small values of Ψ and $C(\Psi) < 1$ at large Ψ , then it is an indication of collective flow. The magnitude of the observed flow can be characterised by the value of λ obtained from a fit of $A^2(1 + 0.5\lambda^2\cos(\Psi))$ to $C(\Psi)$ with $A = 1$.

The dependence of $C(\Psi)$ on Ψ in the case of Au induced collisions [24] is shown in Fig. 2. The fitted values of λ given in Tab.3 indicate the presence of the collective flow of nuclear matter. Within the errors the values of λ seem to be independent on the projectile mass and momentum. The inclusion of the singly charged PFs makes the value of λ smaller.

A complementary analysis of the azimuthal intra- and inter-group correlations has been made in part of data sample. Interactions of ^{12}C , ^{22}Ne , ^{24}Mg and ^{28}Si with Ag(Br) and Pb nuclei have been investigated ([11], [25] and references therein). The angle between the i -th and j -th particles ε_{ij} in the azimuthal plane was measured. Then the coefficient β_1 of asymmetry in the azimuthal plane was calculated by $\beta_1 = \Sigma \cos(\varepsilon_{ij}) / (n(n-1))^{1/2}$, $i = 1, \dots, n, i \neq j$, where $n > 2$ is the number of particles of a given type. The azimuthal asymmetry for s-particles and TFs was observed in nonperipheral collisions with Ag(Br) nuclei and it increases with increasing the centrality of nuclear collisions (measured by the total charge of noninteracting PFs).

It is now customary to extract information on flow by determination of the Fourier coefficients v_i [7] of the azimuthal distributions $F(\varphi) = F_0[1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi)]$. The $\cos(\varphi)$ term is sensitive to the yield within the reaction plane. The parameter v_1 is also denoted as "directed flow" and is a measure of the strength of the flow. The parameter v_2 (so called "elliptic flow") reflects the particle emission perpendicular to

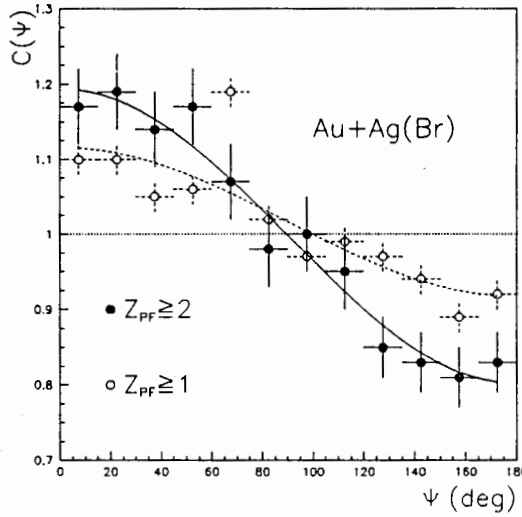


Figure 2. The variation of $C(\Psi)$ as a function of Ψ for PFs measured in $^{197}\text{Au}+\text{Ag}(\text{Br})$ collisions with $N_{TF} \geq 8$ and $N_\alpha \geq 3$

the direction of the reaction plane.

To exhibit agreement of the results of this analysis and those performed formerly, the values of the fit parameters v_1 and v_2 for different charged particles emitted in ^{84}Kr and ^{197}Au induced collisions in emulsion ([12], [13]) are shown in Tab.4. We observe the directed flow of spectator matter - the preferential emission of projectile fragments (with $Z_{PF} \geq 2$) in the direction of the reaction plane ($v_1 > 0$) and target spectator fragments (b-particles) opposite to this direction ($v_1 < 0$).

So far we discussed the flow of spectator fragments. Now we turn our attention to the participating nuclear matter. As participants we can consider s- and g-particles. As the squeeze-out is caused by hot matter which has been stopped it should be centered around midrapidity. For our analysis we define the relative pseudorapidity η_{rel} by $\eta_{rel} = (\eta - \eta_{CM})/\eta_{CM}$, where η_{CM} and η are the pseudorapidities of the CM system and of the detected particle in the laboratory frame, respectively. We tried to separate the s-particles into pions and protons by the method described in [28]. It was shown in [12] that pions are mostly produced at relative pseudorapidity $-0.6 < \eta_{rel} < 0.6$. The azimuthal distributions of s-particles around the central pseudorapidity, satisfying $-0.6 < \eta_{rel} < 0.6$, relative to the reaction plane, were examined. Clear visible double humped structure indicating the preferred emission perpendicular to the reaction plane was obtained in 1.55 AGeV/c $^{84}\text{Kr}+\text{Ag}(\text{Br})$ collisions ($v_2 < 0$). The result of fit according to formula for $F(\varphi)$ is shown in Tab.4. Hence the relativistic s-particles near central pseudorapidity exhibit the effect of squeeze-out or so-called "out-of-plane elliptic flow". This effect is possibly associated with final state interaction of relativistic particles produced in hot zone with spectator matter located in the reaction plane [29]. Thus only the direction perpendicular to the reaction plane is not blocked by the spectator nuclear matter.

In the EMU01 $^{197}\text{Au}+\text{Ag}(\text{Br})$ experiment at AGS energy no signal for the elliptic flow was detected and the value of v_2 is about zero. In ultrarelativistic EMU12 experiment performed at SPS energy 158 AGeV/c ^{208}Pb interactions with Ag(Br) targets in emulsion [14] were selected. In this case the reaction plane was constructed from the target fragments

Tab.3

Momentum [AGeV/c]	Beam	λ	Selection Criteria	References
1.55	^{84}Kr	0.474 ± 0.036 (0.706 ± 0.055)	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$ (*)	[27]
4.1	^{22}Ne	0.533 ± 0.058	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[24]
4.5	^{16}O	0.620 ± 0.085	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[24]
	^{28}Si	0.385 ± 0.097	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	
	^{32}S	0.544 ± 0.064	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	
11.6	^{197}Au	0.414 ± 0.020 (0.621 ± 0.029)	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$ (*)	[24]
14.6	^{28}Si	0.434 ± 0.103	$N_{TF} \geq 8 \ \& \ N_{PF} \geq 4$	[24]

* single charged PFs are not included in N_{PF}

Tab.4

	v_1	v_2	χ^2
$^{84}\text{Kr} + \text{Ag}(\text{Br})$ at 1.55 AGeV/c			
Projectile spectator fragments	0.227 ± 0.022	-0.006 ± 0.023	1.01
Target spectator fragments	-0.213 ± 0.018	0.016 ± 0.018	1.82
s-particles ($-0.6 < \eta_{rel} < 0.6$)	-0.022 ± 0.024	-0.094 ± 0.025	0.97
s-particles ($0.6 \leq \eta_{rel} < 2.13$)	0.148 ± 0.017	0.005 ± 0.017	1.39
g-particles	-0.169 ± 0.014	-0.025 ± 0.014	0.83
$^{197}\text{Au} + \text{Ag}(\text{Br})$ at 11.6 AGeV/c			
Projectile spectator fragments	0.222 ± 0.013	0.027 ± 0.013	1.38
Target spectator fragments	-0.082 ± 0.013	0.006 ± 0.013	0.76
s-particles ($-0.6 < \eta_{rel} < 0.6$)	-0.001 ± 0.005	0.006 ± 0.005	1.14
s-particles ($0.6 \leq \eta_{rel} < 1.56$)	0.060 ± 0.006	0.008 ± 0.006	0.91
g-particles	-0.069 ± 0.011	-0.009 ± 0.011	0.54

and the analysis of the azimuthal angle distributions of the relativistic s-particles relative to this reaction plane was performed. The preliminary value of $v_2 = 0.046 \pm 0.016$ was obtained at $-0.1 < \eta_{rel} < 0.1$, which indicate the signal of the "in-plane elliptic flow" for relativistic s-particles (mainly pions) with the values of η near η_{CM} .

The dependence of the v_2 parameter as a function of beam energy is shown in Fig. 3. The values of v_2 measured by the unique emulsion method are compared with the values from other experiments with different beams at different energies [30]. We can see that the squeeze-out effect in $^{84}\text{Kr} + \text{Ag}(\text{Br})$ experiment is stronger than in Plastic Ball Au + Au experiment at near energy. The value of v_2 measured in Pb+Ag(Br) collisions at CERN SPS [14] is smaller than one obtained in NA49 Pb+Pb data as shown in [30] which can be caused by smaller target mass in our experiment. Moreover the change of the sign of the elliptic flow measured at midrapidity is confirmed by the unique emulsion data.

The relativistic s-particles with projectile like pseudorapidities in 1.55 AGeV/c ^{84}Kr ($0.6 \leq \eta_{rel} < 2.13$) and in 11.6 AGeV/c ^{197}Au ($0.6 \leq \eta_{rel} < 1.56$) induced collisions on Ag(Br) targets in emulsion are preferentially emitted into the reaction plane ($v_1 > 0$, posi-

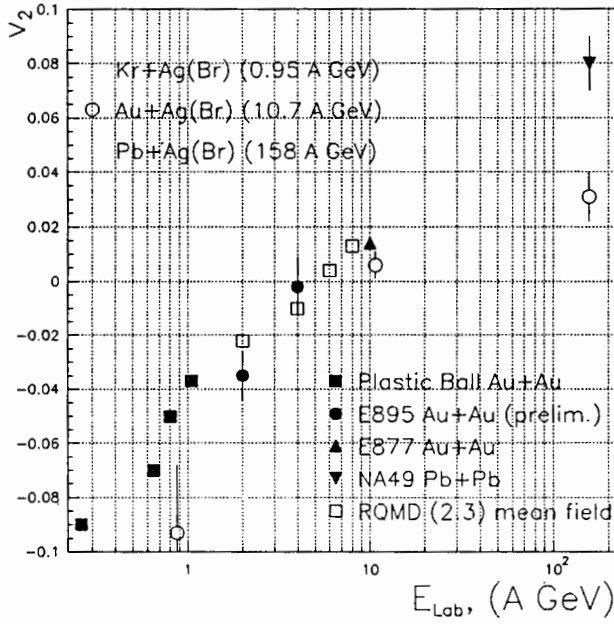


Figure 3. The systematics of v_2 as a function of beam energy

tive "directed flow"). Here $\eta_{rel} = 2.13$ and 1.56 are relative pseudorapidities corresponding to the fragmentation cone, see [31]. Projectile spectator protons were excluded from this analysis. On the other hand a clear emission of fast target fragments (g-particles), measured in the same experiments, opposite to the direction of the reaction plane ($v_1 < 0$, negative "directed flow") was registered. These two results demonstrate the side-splash of the participants at the projectile like pseudorapidity region ($\eta_{rel} \geq 0.6$) and of the target knocked out protons (g-particles). This directed flow of the projectile and target participants is significantly weaker at higher primary energy.

Conclusions

Investigations of ^{16}O , ^{22}Ne , ^{28}Si , ^{32}S , ^{84}Kr , ^{197}Au and ^{208}Pb induced nuclear interactions at (1-160) A GeV/c have been made using the unique emulsion track detector.

The methods of transverse momenta, principal vectors, azimuthal correlation functions, azimuthal correlations between the charged secondaries and the Fourier expansion of the azimuthal angle distributions have been applied. The bounce-off of the fragments of the projectile nuclei in their collisions with Ag(Br) target nuclei at middle impact parameters has been observed. The back-to-back correlation of the projectile and target fragments in the azimuthal plane has been obtained. With decreasing impact parameter this tendency becomes more pronounced. The mixed events and cascade calculations did not reproduce the observed effects. In azimuthal distributions, with respect to the reaction plane, the squeeze-out and side splash of the participants are seen.

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DAILY PROGRAMME

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Strong and electromagnetic interaction views on deuteron structure

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Abstract

The purpose of this contribution is to give an outlook of recent results connected with deuteron physics, with electromagnetic and strong interacting probes at intermediate energy. Special attention will be devoted to polarization observables.

I. INTRODUCTION

The deuteron (bound state of proton and neutron) with spin $\mathcal{J}$ and parity P : $\mathcal{J}^P = 1^+$, and with isospin $I=0$, has been investigated, theoretically and experimentally, since many decades. Few selected problems, which are very actual, will be discussed here according the following plan:

- The knowledge of the deuteron structure, itself, at the largest possible internal momenta (or at the shortest distances between the nucleons). The question which is addressed is the definition of the kinematical region where a description based on nucleons and mesons (basically impulse approximation (IA) with corrections due to

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meson exchange currents, isobars, relativistic effects..) has to be discarded in favor of a 'high energy view' in terms of quarks and gluons. Here, in particular, pQCD gives predictions concerning the asymptotic behavior of the deuteron form factors and assumes hadron helicity conservation for the amplitudes.

The transition region between these two regimes should be the privileged domain of intermediate energy machines. High intensity is required by exclusive measurements and/or studies with secondary beams (polarization etc..).

- The deuteron as a probe to investigate the nucleon or the heavy nuclei structure.
 - it can be used to study the properties of the neutron, which is not available as a target;
 - it is an isoscalar probe, which can be very selective in exciting specific states in nucleons and nuclei.

In order to illustrate the different points listed above, we will review some of the last data obtained at Jefferson Laboratory and Saturne. We will show few results from elastic electron-deuteron scattering and proton-deuteron elastic and inelastic scattering. Particular attention will be devoted to polarization observables.

II. THE DEUTERON ELECTROMAGNETIC FORM FACTORS

A. Recent determination of the elastic deuteron electromagnetic form factors

The measurement of the differential cross section of elastic ed -scattering, for a fixed value of Q^2 , at different scattering angles, allows to determine the structure functions $A(Q^2)$ and $B(Q^2)$:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_0 \cdot \mathcal{S}, \quad \mathcal{S} = A(Q^2) + B(Q^2) \tan^2(\theta_e/2)$$

with

$$\left(\frac{d\sigma}{d\Omega} \right)_0 = \frac{\alpha^2 \cos^2(\theta_e/2) E'}{4E^3 \sin^4(\theta_e/2)},$$

where E (E') is the electron beam (the scattered electron) energy and θ_e the electron scattering angle in the Laboratory system. The structure functions A and B can be expressed in terms of the three form factors, G_e (electric), G_m (magnetic) and G_q (quadrupole) as:

$$A(Q^2) = G_e^2(Q^2) + \frac{8}{9}\tau^2 G_q^2(Q^2) + \frac{2}{3}\tau G_m^2(Q^2), \quad B(Q^2) = \frac{4}{3}(1 + \tau)\tau G_m^2(Q^2), \quad \tau = \frac{Q^2}{4M^2},$$

where M is the deuteron mass. In case of unpolarized beam and target the outgoing deuteron is tensorially polarized and the components of the tensor polarization give useful combinations of form factors. In particular t_{20} allows, together with $A(Q^2)$ and $B(Q^2)$, the determination of the three form factors:

$$t_{20} = -\frac{1}{\sqrt{2}S} \left[\frac{8}{3}\tau G_e G_q + \frac{8}{9}\tau^2 G_q^2 + \frac{1}{3}\tau \left(1 + 2(1 + \tau) \tan^2(\theta_e/2) \right) \right] G_m^2,$$

At the Jefferson Laboratory (JLab), the elastic ed - cross section has been recently precisely measured up to large momentum transfer $Q^2 \simeq 6 \text{ (GeV/c)}^{-2}$, [1,2] and t_{20} has been measured for a momentum transfer up to $Q^2 = 1.9 \text{ (GeV/c)}^{-2}$ [4].

According to [1], the cross sections seems to scale as $(Q^2)^{-10}$, as previously pointed out [3], and predicted by pQCD. However, from the t_{20} data, it clearly appears that the pQCD limit is not yet reached, and that the data follow the trend suggested by IA. On the other hand, it is not possible, from these data, to constrain definitely different models or corrections. For a detailed comparison with theory, see, for example, [1,4].

The question is then, how to proceed further. On the experimental point of view, in the best presently achievable conditions of luminosity, about one month beam time was needed for the the polarization measurement and one week for the cross section at the largest values of Q^2 . It seems hard to foresee more favorable experimental conditions, with the present technology related to electron machines. One possibility is to investigate the inelastic deuteron form factors through the reaction $ed \rightarrow ed\pi^0$, where for the same momentum transfer for the electron, one accedes to shortest distances in the deuteron, compared to elastic scattering [5].

In next section we will focus on a conceptual problem, which is the limit of the validity of the assumption of the one photon exchange mechanism in electron-hadron scattering at

large momentum transfer. A related problem, that we will not discuss here, is that radiative corrections for polarization effects at large momentum transfer are not known.

B. Beyond the one-photon approximation

The formulas given above are valid if the momentum is transferred from the incident electron to the target by a virtual photon, with the underlying assumption that the possible two-photon contribution is small. The relative contribution of two photon exchange, from simple counting in α , would be of the order of the fine structure constant, $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137}$. However, more than 25 years ago it was observed that the relative role of two-photon exchange can increase significantly in the region of high momentum transfer [6–9]. If the transferred momentum is equally shared between two virtual photons, due to the steep decrease of the deuteron form factors, the simple rule of α -counting for the estimation of the relative role of two-photon contribution to the amplitude of elastic ed -scattering does not hold anymore. This effect would manifest already at momentum transfer of the order of 1 GeV^2 , in particular in the region of diffractive minima.

In Ref. [6] the two-photon amplitude is purely imaginary, at least at small scattering angles, so it cannot interfere with the one-photon exchange amplitude in the differential cross section for unpolarized particles scattering. However, in this case, the polarization observables in elastic ed -scattering have to be large, in particular the T-odd polarization observables. But the predicted increasing of the two-photon mechanism is so large that it may be observed even in the differential cross section of elastic ed -scattering, at relatively large momentum transfer square, $Q = 8 - 12 \text{ fm}^{-1}$. An evaluation of this contribution from the existing experimental data has been done in [10].

The crossing symmetry can provide a relation between the matrix elements $\mathcal{M}$ of the the elastic $e^- + h \rightarrow e^- + h$ scattering and the e^+e^- -annihilation: $e^+ + e^- \rightarrow \bar{h} + h$, in one-photon approximation.

$$|\overline{\mathcal{M}(eh \rightarrow eh)}|^2 = f(s, t) = |\overline{\mathcal{M}(e^+e^- \rightarrow \bar{h}h)}|^2. \quad (1)$$

The line over $\mathcal{M}$ denotes the sum over the polarizations of all particles (in initial and final states). The Mandelstam variable s is the total energy square and t is the momentum transfer square. They delimit different kinematical regions for the annihilation and the scattering channel.

The presence of a single virtual photon in the reaction $e^+ + e^- \rightarrow \gamma^* \rightarrow \bar{h} + h$ constrains the total angular momentum $\mathcal{J}$ and the P -parity for the $\bar{h}h$ -system to take only one possible value, $\mathcal{J}^P = 1^-$, the quantum number of the photon. In the framework of the one-photon approximation, in the general case, $|\overline{\mathcal{M}(e^+e^- \rightarrow h\bar{h})}|^2$ can be written (in CMS) as:

$$|\overline{\mathcal{M}(e^+e^- \rightarrow h\bar{h})}|^2 = a(t) + b(t) \cos^2 \tilde{\theta}, \text{ and } \cos^2 \tilde{\theta} = 1 + \frac{\cot^2 \frac{\theta_e}{2}}{1 + \tau}, \quad (2)$$

where $a(t)$ and $b(t)$ are definite quadratic combinations of the electromagnetic form factors for the hadron h and $\tilde{\theta}$ is the angle of the detected hadron.

In case of the presence of 2γ in the intermediate state, in the annihilation channel, any value of the total angular momentum and space parity is allowed, because the relative 3-momentum for the 2γ -state is nonzero, contrary to the case of the one-photon mechanism. The $\bar{h}h$ -system, produced through 1γ - and 2γ -exchanges has different values of C -parity, because $C(\gamma) = -1$ and $C(2\gamma) = +1$. Therefore the interference of one- and two-photon contribution must be an **odd** function of $\cos \tilde{\theta}$: $\overline{\mathcal{R}e\mathcal{M}_1\mathcal{M}_2^*} = \cos \tilde{\theta}(a_0 + a_2 \cos^2 \tilde{\theta} + \dots)$.

The SLAC results [3] were obtained at a fixed electron scattering angle. The odd contribution can then be estimated from the cross sections at two angles, for the same Q , one value being given from a fit of the data of ref. [3] and the other by the recent data [1,2]. We can then calculate separately the linear contribution or the cubic contribution in $\cos \tilde{\theta}$. It is expected that deviation from the linear $\cot^2 \frac{\theta_e}{2}$ formula would not appear for $Q \leq 5 \text{ fm}^{-1}$. The resulting ratios C/A and D/A are reported in Fig. 1 and 2 as functions of Q , as open circles [1] and open squares [2]. The data nicely agree: at large momentum transfer these ratios deviate from zero and show a dependence on the transferred momentum, which could result from two photon exchange. However the points had to be rescaled in order to have zero deviation at low Q (corresponding solid symbols) due to systematic errors in the measurement of the cross section between the two sets of data [1] and [2].

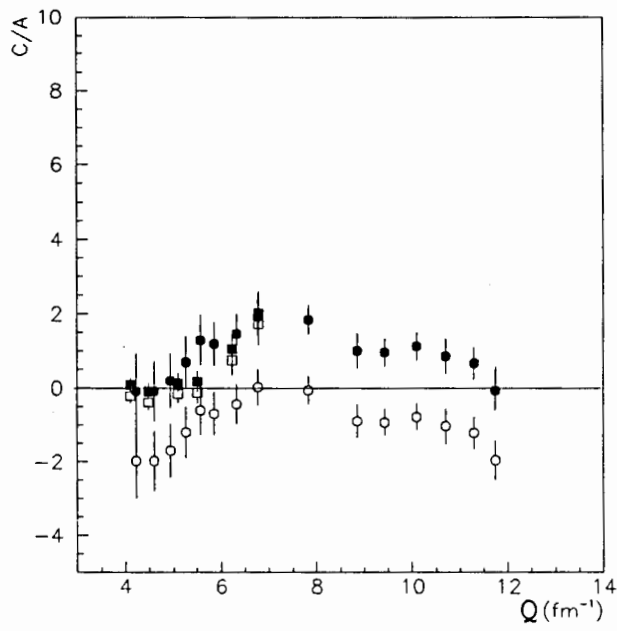


FIG. 1. Ratio C/A for the two sets of data, as a function of Q (fm^{-1}): squares from [2]; circles from [1], corresponding solid symbols after renormalization (see text)

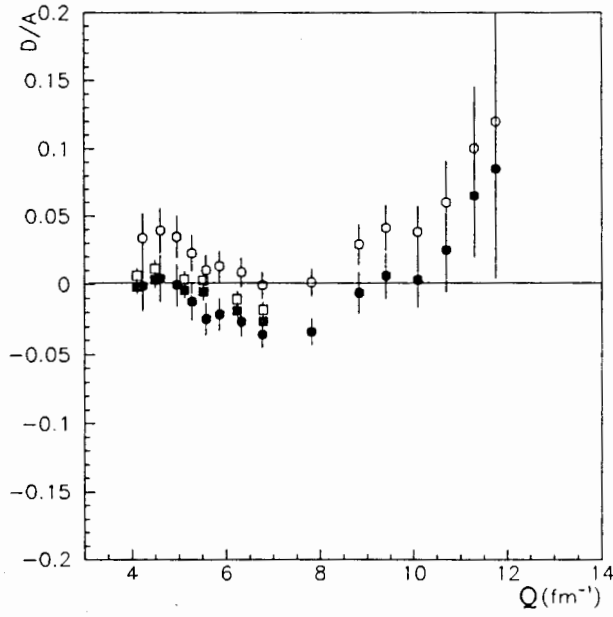


FIG. 2. Ratio D/A for the two sets of data, as a function of Q (fm^{-1}): squares from [2]; circles from [1], corresponding solid symbols after renormalization (see text)

While this can not be considered as a definite evidence for the presence of 2γ -exchange in ed -elastic scattering, it is the first attempt to obtain a quantitative upper limit of a possible 2γ -contribution, using a parameterization of the $1\gamma \otimes 2\gamma$ -interference and the existing experimental data.

The 2γ -exchange in elastic hadron scattering can be experimentally searched in different ways: - through the comparison of the cross section for scattering of unpolarized electrons and positrons (by protons or deuterons) in the same kinematical conditions, - looking to the deviation from a straight line on the Rosenbluth plot or measuring specific properties of polarization phenomena: as nonzero T - odd polarization observables, and violation of definite relations between T-even polarization observables and the SF $B(Q^2)$. The measurement of cross section and polarization observables bring complementary and independent pieces of information, as they test the real and imaginary part of the 2γ contribution.

III. THE DEUTERON STRUCTURE FROM DP BREAK-UP AND BACKWARD ELASTIC SCATTERING

We showed that the measurement of cross section and analyzing powers in ed -elastic scattering allows to determine all the three form factors (in one-photon approximation). These form factors, in IA, are integrals of the wave function over the radial coordinate. On the other hand, the reactions $\vec{d} + p \rightarrow \vec{p} + d$ (backward elastic scattering) and $\vec{d} + p \rightarrow p + X$ (deuteron break up) are directly related to the deuteron wave functions. In the IA, the tensor analyzing power T_{20} and the polarization transfer κ_0 can be written as:

$$T_{20} = \frac{1}{\sqrt{2}} \frac{\sqrt{8}uw - w^2}{u^2 + w^2},$$

$$\kappa_0 = \frac{u^2 - w^2 - 12uw}{u^2 + w^2},$$

from which one obtains a quadratic relation between T_{20} and κ_0 :

$$\left(T_{20} + \frac{1}{2\sqrt{2}}\right)^2 + \kappa_0^2 = \frac{9}{8}$$

Measurements have been performed at Saturne and Dubna [11,12]. The correlation between the two polarization observables is shown in Fig. 3. The full line is the IA prediction. The two sets of points correspond to backward elastic scattering (open circles) and deuteron break up (solid circles) and they show a very similar behavior. The deviation from IA, which gets larger at larger momenta has been interpreted in different models (see [13] and refs. herein). At this moment it seems fair to conclude that unambiguous signatures of quarks have not yet been found.

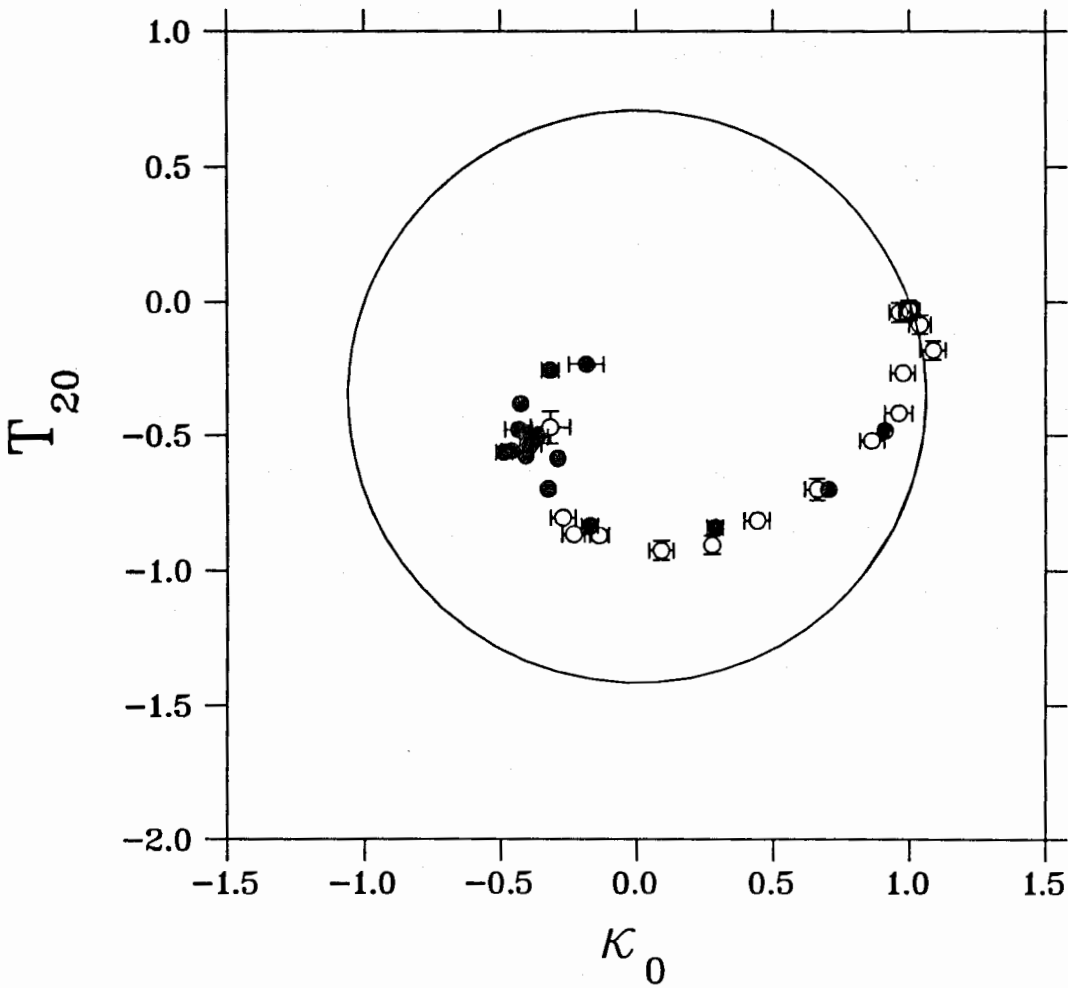


FIG. 3. Tensor analyzing power versus polarization transfer coefficient for dp backward elastic (filled circles) and for inclusive break-up (open circles). The solid curve is the IA prediction

A promising way of looking to deuteron at very short distances seems to be the measurement of the tensor analyzing power of pions emitted at 0° , in the reaction $\vec{d} + p \rightarrow \pi + X$, in the cumulative region [14].

IV. THE DEUTERON AS AN ISOSCALAR PROBE

A. The neutron electromagnetic form factors

Having high precision data on the differential cross section for ed - elastic scattering, and assuming a reliable model for their description, one can extract, in principle, the dependence of the electric neutron form factor G_{En} on the momentum transfer Q^2 . Such a procedure has been carried out in ref. [15], up to $Q^2=0.7$ (GeV/c) ^{2} . It can be extended at higher Q^2 using the elastic ed -scattering data mentioned above and recent data on the proton electric form factor [16]. These data have been obtain by the recoil proton polarization measurement in $\vec{e} + p \rightarrow e + \vec{p}$, following an idea suggested more than 30 years ago [17] and extend up to $Q^2=3.5$ (GeV/c) ^{2} . The large sensitivity to the nucleon form factors of the models which describe the light nuclei structure, particularly the deuteron, was already carefully studied in [18], and it was pointed out that the disagreement between the relativistic impulse approximation and the data could be significantly reduced if G_{En} were different from zero.

In the non relativistic IA, the deuteron form factors depend only on the deuteron wave function and on nucleon form factors:

$$G_c = G_{Es}C_E, \quad G_q = G_{Es}C_Q, \quad G_m = \frac{M_d}{M_p} \left(G_{Ms}C_S + \frac{1}{2}G_{Es}C_L \right), \quad (3)$$

where M_p is the proton mass, $G_{Es}=G_{Ep}+G_{En}$ and $G_{Ms}=G_{Mp}+G_{Mn}$ are the charge and magnetic isoscalar nucleon form factors, respectively. The terms C_E , C_Q , C_S , and C_L describe the deuteron structure and can be calculated from the deuteron S and D wave functions, $u(r)$ and $w(r)$ [19] :

$$\begin{aligned}
C_E &= \int_0^\infty dr \, j_0\left(\frac{Qr}{2}\right) [u^2(r) + w^2(r)], \\
C_Q &= \frac{3}{\sqrt{2}\eta} \int_0^\infty dr \, j_2\left(\frac{Qr}{2}\right) \left[u(r) - \frac{w(r)}{\sqrt{8}}\right] w(r), \\
C_S &= \int_0^\infty dr \left[u^2(r) - \frac{1}{2}w^2(r)\right] j_0\left(\frac{Qr}{2}\right) + \frac{1}{2} [\sqrt{2}u(r)w(r) + w^2(r)] j_2\left(\frac{Qr}{2}\right), \\
C_L &= \frac{3}{2} \int_0^\infty dr \, w^2(r) \left[j_0\left(\frac{Qr}{2}\right) + j_2\left(\frac{Qr}{2}\right)\right],
\end{aligned} \tag{4}$$

where $j_0(x)$ and $j_2(x)$ are the spherical Bessel functions. The normalization condition is $\int_0^\infty dr [u^2(r) + w^2(r)] = 1$.

With the help of expressions (3) and (4), the formula for $A(Q)^2$, can be inverted into a quadratic equation for G_{Es} . Then G_{Es} is calculated using the experimental values for $A(Q)^2$, assuming, for the magnetic nucleon form factors G_{Mp} and G_{Mn} the usual dipole dependence, which is in agreement with the existing data at a 3% level, up to $Q^2 \simeq 10 \text{ (GeV/c)}^2$.

In Fig. 4 we illustrate the behavior of the different nucleon electric form factors: G_{Es} , G_{Ep} and G_{En} . The nucleon isoscalar electric form factor, derived from different sets of deuteron data, decreases when Q^2 increases. The solid line represents the Gari-Krümpelmann parametrization [20] for G_{Es} . The dipole behavior, which is generally assumed for the proton electric form factor is shown as a dotted line. The new G_{Ep} data, which decrease faster than the dipole function, are also well reproduced by the Gari-Krümpelmann parametrization (thick dashed line).

The electric neutron form factor can be calculated from the isoscalar nucleon form factor, taking for G_{Ep} a dipole behavior (solid stars) or a fit based on the new data (open stars). The last option leads to values for G_{En} which are in very good agreement with the parametrization [20]. These results shows that the neutron form factor is not going to vanish identically at large momentum transfer, but becomes more sizeable than predicted by other parametrizations, often used in the calculations [15,21] (thin dashed line). Starting from $Q^2 \simeq 2 \text{ (GeV/c)}^2$ the form factor G_{En} becomes even larger than G_{Ep} . Let us mention that a recent 'direct' measurement [22] at $Q^2 = 0.67 \text{ (GeV/c)}^2$ finds $G_{En} = 0.052 \pm 0.011 \pm 0.005$ in agreement with the present values.

Let us mention that the $\gamma^* \pi^\pm \rho^\mp$ -contribution, which is a good approximation for the isoscalar transition $\gamma^* \rightarrow \pi^+ \pi^- \pi^0$ (γ^* is a virtual photon), is typically considered as the main correction to IA, necessary, in particular, to improve the description of the $SF A(Q^2)$ [3].

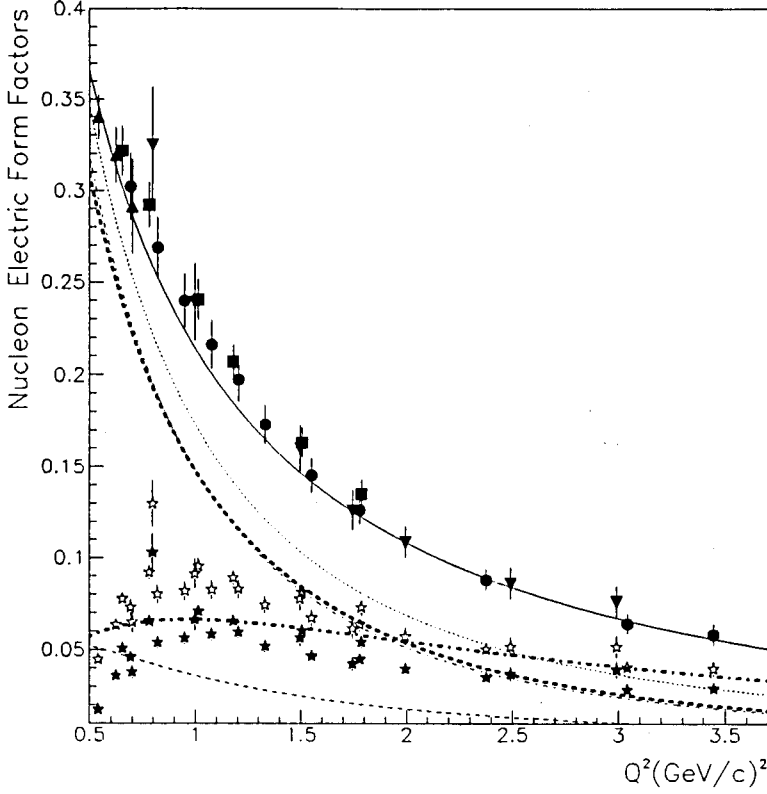


FIG. 4. Nucleon electric form factors as functions of the momentum transfer Q^2 . in the framework of IA with Paris potential. The isoscalar electric form factor is derived from the deuteron elastic scattering data: [15] (solid triangles), [1] (solid circles), [2] (solid squares), and [3] (solid reversed triangles). The electric neutron form factor is shown as solid stars when calculated from the dipole representation of G_E^p (dotted line) and open stars when Eq. (5) is taken for G_E^p (thin dashed-dotted line). The parametrization [20] is shown for G_E^s (solid line), for G_E^n (thick dashed-dotted line) and for G_E^p (thick dashed line). The thin dashed line is the parametrization [21] for G_E^n .

However the relative role of MEC is strongly model dependent [23] as the coupling constants for meson-NN-vertexes are not well known and arbitrary form factors are often added [24,25].

It should be pointed out that the $\gamma^*\pi\rho$ vertex is of magnetic nature and its contribution to $A(Q^2)$ has to be of the same order of magnitude as the relativistic corrections.

The forthcoming data about G_{En} , planned at JLab up to $Q^2=2$ (GeV/c)², [26] will be crucial in this respect. The large sensitivity of the deuteron structure to the nucleon form factors shows the necessity to reconsider the role of meson exchange currents in the deuteron physics at large momentum transfer.

B. The nuclear structure

The measurement of polarization transfer for inelastic $\vec{p}$ and $\vec{d}$ scattering by nuclei allows the study of the nuclear response and to disentangle the spin and isospin components. In particular it has been shown that the spin-flip probability is a very good signature of the presence of $\Delta S = 1$ in the continuum, as well as for discrete states. A systematic work has been carried on at LAMPF and at SATURNE, on several nuclei, from ¹²C to ²⁰⁸Pb. The nuclear response has been measured in different channels and compared to RPA calculations, in order to learn about correlations and collectivity in nuclei [27].

In order to go further, one should complete measurements at very small angles (with a zero degree facility) and with high statistics, and make a multipole analysis in the continuum.

C. The baryon resonances excitation in the inclusive $\vec{d}, p$ scattering

An application of this method based on the measurement of the spin-flip probability, is the study of nucleon resonances, in the reaction $\vec{d} + p \rightarrow \vec{d} + X$. The selectivity of reactions such as $p(d, d')X$ or $p(\alpha, \alpha')X$ [28] to the isoscalar part of the N^* -electroexcitation makes these processes complementary to electron-nucleon inelastic scattering, for the study of the N^* -structure. Particular attention has been devoted to the Roper resonance [29] In case of polarized deuteron beam, it has been shown [30] that the ω -exchange model gives a natural and simple description of the polarization phenomena for $\vec{d} + p \rightarrow d + X$. The main ingredients of such model are the existing information about the deuteron electromagnetic form factors [32] and the ratio r of the longitudinal and transversal isoscalar cross sections for the excitation of the N^* -resonances [31].

The ω -meson is preferred, among the isoscalar mesons as σ or η , for several reasons. The ωNN - coupling is large; the ω -meson, being a spin 1 particle, can induce strong polarization effects and an energy-independent cross section. When it is considered as an *isoscalar photon*, then the cross sections and the polarization observables can be calculated from the known electromagnetic properties of the deuteron and N^* , through the vector dominance model.

The tensor analyzing power in $d+p \rightarrow d+X$, T_{20} , can be written in terms of the deuteron electromagnetic form factors as:

$$T_{20} = -\sqrt{2} \frac{V_1^2 + (2V_0V_2 + V_2^2)r(t)}{4V_1^2 + (3V_0^2 + V_2^2 + 2V_0V_2)r(t)}, \quad (5)$$

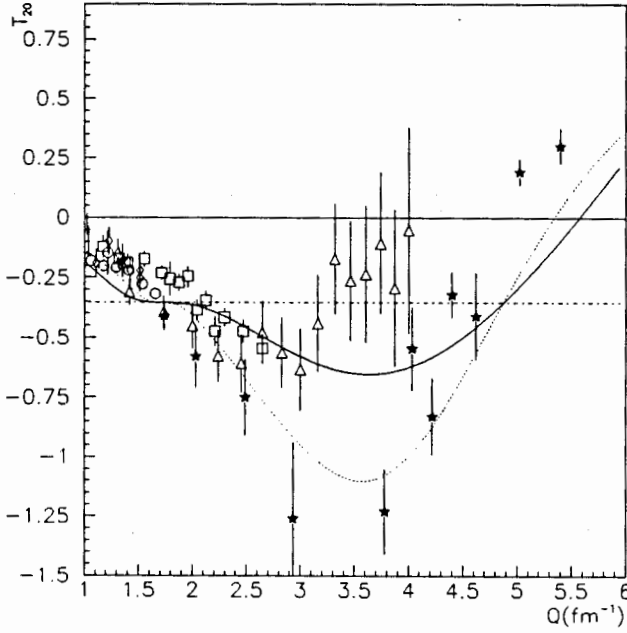


FIG. 5. Experimental data for T_{20} for $e^- + d \rightarrow e^- + d$ elastic scattering (filled stars) [35] and $d + p \rightarrow d + X$ at incident momenta of 3.75 GeV/c (open diamonds) [33], 5.5 GeV/c (open circles), 4.5 GeV/c (open squares), 9 GeV/c (open triangles) [34]. Prediction of the ω -exchange model for $r = 0$ (dashed-dotted line). Calculations are shown for the case when only the Roper resonance is considered (dotted line) and for the case when all the four resonances (6) are considered (solid line)

where $V_0(t)$, $V_1(t)$ and $V_2(t)$ are linear combinations of the standard electric, G_e , magnetic G_m and quadrupole G_q deuteron form factors. The ratio r characterizes the relative role of longitudinal and transversal isoscalar excitations in the transition $\omega + N \rightarrow X$.

From Eq. (5) one can see that all information about the ωNN^* -vertex is contained in the function r only. A zero value of r results in a t - and ω -independent value for T_{20} , namely $T_{20} = -1/\sqrt{8}$, for any value of the deuteron electromagnetic form factors. The ratio r is calculated using the collective string model in [31], assuming $SU_{sf}(6)$ symmetry, including the contributions of the following resonances: $N_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$ and $S_{11}(1650)$, which are overlapping in this energy region.

In Fig. 5 we report the theoretical predictions for T_{20} , in framework of ω -model, together with the existing experimental data. In such approximation T_{20} is a universal function of t only, without any dependence on the initial deuteron momentum. The experimental values of T_{20} for $p(\vec{d}, d)X$ [33,34], for different momenta of the incident beam are shown as open symbols. These data show a scaling as a function of t , with a small dependence on the incident momentum, in the interval 3.7-9 GeV/c. On the same plot the data for the elastic scattering process $e^- + d \rightarrow e^- + d$ [35] are shown (filled stars).

These different data show a very similar behavior: negative values, with a minimum in the region $|t| \simeq 0.35 \text{ GeV}^2$ and their value increase toward zero at larger $|t|$. The lines are the result of the ω -exchange model for the $d + p \rightarrow d + X$ process: for $r = 0$ (dashed-dotted line), the calculation based on [31] for the Roper excitation only is represented by the dotted line and for the excitation of all the four resonances by the the full line. The deuteron electromagnetic form factors have been taken from [32], a calculation based on relativistic impulse approximation, and they reproduce well the T_{20} -data for ed elastic scattering [35]. When $r \gg 0$ or if the contribution of the deuteron magnetic form factor $V_1(t)$ is neglected, then T_{20} does not depend on the ratio r , and coincides with t_{20} for the elastic ed -scattering (with the same approximation).

From Fig. 5 it appears that the t -behavior of T_{20} is very sensitive to the value of r especially at relatively small r , $r \leq 0.5$. The values of r , predicted by model [31], give a

very good description of the data, when taking into account the contribution of all four resonances. These data, in any case, exclude a very small value of r , $r \ll 0.1$ as well as very large values of r . Only the Roper resonance has a nonzero isoscalar longitudinal form factor. Without excitation of the Roper resonance, $r = 0$, (in the considered kinematical region) and the value for T_{20} becomes t -independent: $T_{20} = -1/2\sqrt{2}$, in evident disagreement with existing data.

Due to their specific quark structure, the resonances lying in the concerned mass region, such as $S_{11}(1535)$, $D_{13}(1520)$ and $S_{11}(1650)$, are characterized by a pure isovector nature of longitudinal virtual photons absorbed by the nucleons. The isoscalar longitudinal amplitudes of $S_{11}(1535)$ and $D_{13}(1520)$ electroexcitation vanish due to a specific spin-flavor symmetry, while both isoscalar and isovector longitudinal couplings of $S_{11}(1650)$, $D_{15}(1675)$ and $D_{13}(1700)$ vanish identically.

This behavior of the isoscalar form factors is essential for the correct description of the existing experimental data on the t -dependence of T_{20} for the process $d + p \rightarrow d + X$.

One could improve the model taking into account for example, other meson exchanges, or the effects of the strong interaction in initial and final states. However these corrections are strongly model- and parameter- dependent and the existing experimental data are not good enough to constrain the additional parameters which have to be added.

The successful description of the polarization observable T_{20} can be considered as a strong indication that the ω - exchange is the main mechanism for the considered process and that the Roper resonance is excited in this process.

V. CONCLUSIONS

Some of the recent results obtained in the study of the deuteron structure have been reviewed. Despite the large precision and the new region of internal momentum explored, questions arised many decades ago are still actual:

- The relative role of different possible components in the deuteron wave function: isobar configurations, six-quark components, etc..;
- The relativistic description of the deuteron structure: the number of independent components of the deuteron wave functions as well as the number and the nature of their arguments;
- The relative role of the different possible mechanisms in the simplest reactions with deuterons: for example the role of meson exchange current in the description of the electromagnetic form factors of the deuteron;
- The kinematical region corresponding to the transition regime in the deuteron structure: i.e. from the nucleon-meson picture of the deuteron to the quark-gluon description.

These problems are far from being solved. The experimental study of polarization phenomena remains the most fruitful way in this investigation. If, in the case of elastic ed -scattering we are near the limits of the experimental possibilities, in reactions such as the deuteron photodisintegration, $\gamma + d \rightarrow n + p$ or the coherent pion photoproduction on the deuteron $\gamma + d \rightarrow d + \pi^0$, a wide program of polarization experiments can be realized, due to the rich spin structure of the corresponding matrix elements. Moreover the experimental study of new reactions, such as the coherent neutral pion production on the deuteron, $e + d \rightarrow e + d + \pi^0$, in the near threshold region and in the Δ -region (for large momentum transfer) can bring useful information.

These conclusions apply to the hadronic sector, too. The complete experiment for the simplest case, the dp backward elastic scattering, requires further steps which can be realized in principle in the nearest future. The study of the nucleon resonances through reactions induced by isoscalar probes as deuterons and α particles seems to be very promising, in particular the polarization observables.

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Prediction of $\sigma_{tot}(e^+ e^- \rightarrow \text{hyperon} - \text{antihyperon})$ behaviour

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Abstract

Universal unitary and analytic model, defined on four-sheeted Riemann surface, for all members of the $1/2^+$ baryon octuplet is constructed simultaneously, in which from all coupling constant ratios under consideration only $(f_{\rho BB}^{(i)}/f_{\rho})$, $(f_{\omega BB}^{(i)}/f_{\omega})$ and $(f_{\phi BB}^{(i)}/f_{\phi})$ ($i=1,2$) are to be free parameters. For nucleons they are evaluated numerically by a comparison of the model with experimental data on nucleon electric and magnetic form factors. For hyperons they are found by means of the SU(3) symmetry from nucleon coupling constant ratios. As a result the corresponding total cross-sections of electron-positron annihilation into hyperon-antihyperon pairs are predicted and compared with existing data.

The electromagnetic structure of the $1/2^+$ octet baryons $[p,n]$, $[\Lambda^0]$, $[\Sigma^+, \Sigma^0, \Sigma^-]$ and $[\Xi^0, \Xi^-]$ is completely described by the electric $G_E^B(t)$ and magnetic $G_M^B(t)$ form factors (FF's) to be related to the Dirac $F_{1B}(t)$ and Pauli $F_{2B}(t)$ FF's by the relations

$$\begin{aligned} G_E^B(t) &= F_{1B}(t) + \frac{t}{4m_B^2} F_{2B}(t) \\ G_M^B(t) &= F_{1B}(t) + F_{2B}(t), \end{aligned} \tag{1}$$

where $t = -Q^2$ is four momentum transfer squared and m_B is the baryon mass. The total cross-section of electron-positron annihilation into baryon-antibaryon pairs takes

the following form

$$\sigma_{tot}(e^+ e^- \rightarrow B\bar{B}) = \frac{4\pi\alpha^2\beta_B}{3t} \left[|G_M^B(t)|^2 + \frac{2m_B^2}{t} |G_E^B(t)|^2 \right], \quad (2)$$

where $\alpha = 1/137$ is the fine structure constant and $\beta_B = [1 - 4m_B^2/t]^{1/2}$ is the velocity of the produced B ($\bar{B}$).

So, as soon as the behaviour of $G_E(t)$ and $G_M(t)$ is known for $t \geq 4m_B^2$, then one can predict the behaviour of $\sigma_{tot}(e^+ e^- \rightarrow B\bar{B})$.

This is, however, an unsolvable problem from the first principles, except for very short distances, where PQCD applies and predicts

$$|G_E^B(t)| < |G_M^B(t)|, \quad \text{but} \quad |G_{E,M}^B(t)|_{|t| \rightarrow \infty} \sim t^{-2} \quad (3)$$

and one has to resort to phenomenological models. The most suitable FF's for construction of such models are the isoscalar $F_{1B}^s(t)$, $F_{2B}^s(t)$ and isovector F_{1B}^v , F_{2B}^v parts of the Dirac and Pauli FF's with the following properties:

i) they are normalized at the $t=0$

$$F_{iB}^I(0) = N_{iB}^I, \quad i = 1, 2; \quad I = s, v, \quad (4)$$

where normalization constants N_{iB}^I are reviewed in Table

ii) They are complex functions of a complex variable t :

$F_{iB}^s(t)$, $i = 1, 2$ are analytic in the t -plane besides cuts on the positive part of the x -axis

B	N_{1B}^s	N_{1B}^v	N_{2B}^s	N_{2B}^v
N	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}(\mu_p + \mu_n)$	$\frac{1}{2}(\mu_p - \mu_n)$
Λ	0	—	μ_Λ	—
Σ	0	1	$\frac{1}{2}(\mu_{\Sigma^+} + \mu_{\Sigma^-})$	$\frac{1}{2}(\mu_{\Sigma^+} - \mu_{\Sigma^-})$
Ξ	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}(\mu_{\Xi^0} + \mu_{\Xi^-})$	$\frac{1}{2}(\mu_{\Xi^0} - \mu_{\Xi^-})$

from t_{0B}^s to $+\infty$, where t_{0B}^s is the lowest normal (i.e. $9m_\pi^2$) or anomalous threshold.

$F_{iB}^v(t)$, $i = 1, 2$ are analytic in the t -plane besides cuts on the positive part of the x -axis from t_{0B}^v to $+\infty$, where t_{0B}^v is the lowest normal (i.e. $4m_\pi^2$) or anomalous threshold

iii) discontinuity across cuts is given just by $ImF_{iB}^s(t)$ and $ImF_{iB}^v(t)$

iv) from Hermitivity of the electromagnetic current $J_\mu^{EM}(x)$ the reality of $F_{iB}^I(t)$ from $-\infty$ to t_{0B}^I follows

v) by an application of the Schwarz reflection principle the reality condition

$$F^*(t) = F(t^*) \quad (5)$$

is obtained, giving relation between values of FF's at the upper and lower half-planes.

A special case is

$$F^*(t + i\epsilon) = F(t - i\epsilon) \quad (6)$$

for $t > t_{0B}^I$ and $\epsilon \ll 1$

vi) an experimental fact of a creation of vector-meson resonances in the $e^+e^- \rightarrow$ *hadrons* is taken into account by means of complex poles on unphysical sheets of $F_{iB}^I(t)$, where the position of these poles $t_r = (m_r - \Gamma_r/2)^2$ is determined by the mass m_r and the width Γ_r of the resonance

vii) from reality condition (5) it follows that to every resonance pole also a complex conjugate pole has to exist on the same sheet of the Riemann surface

viii) the quark model of hadrons predicts the following asymptotic behaviour

$$F_{1B}^{s,v}(t)_{|t| \rightarrow \infty} \approx t^{-2}, \quad F_{2B}^{s,v}(t)_{|t| \rightarrow \infty} \approx t^{-3} \quad (7)$$

for the isoscalar and isovector parts of the Dirac and Pauli FF's.

On the other hand a decomposition of $G_{E,M}^B(t)$ into $F_{iB}^I(t)$ is as follows

$$\begin{aligned}
G_E^{p,n}(t) &= [F_{1N}^s(t) \pm F_{1N}^v(t)] + \frac{t}{4m_{p,n}^2} [F_{2N}^s(t) \pm F_{2N}^v(t)] \\
G_M^{p,n}(t) &= [F_{1N}^s(t) \pm F_{1N}^v(t)] + [F_{2N}^s(t) \pm F_{2N}^v(t)] \\
G_E^\Lambda(t) &= F_{1\Lambda}^s(t) + \frac{t}{4m_\Lambda^2} F_{2\Lambda}^s(t), G_M^\Lambda(t) = F_{1\Lambda}^s(t) + F_{2\Lambda}^s(t) \\
G_E^{\Sigma^+, \Sigma^-}(t) &= [F_{1\Sigma}^s(t) \pm F_{1\Sigma}^v(t)] + \frac{t}{4m_{\Sigma^+, \Sigma^-}^2} [F_{2\Sigma}^s(t) \pm F_{2\Sigma}^v(t)] \\
G_M^{\Sigma^+, \Sigma^-}(t) &= [F_{1\Sigma}^s(t) \pm F_{1\Sigma}^v(t)] + [F_{2\Sigma}^s(t) \pm F_{2\Sigma}^v(t)] \\
G_E^{\Sigma^0}(t) &= F_{1\Sigma^0}^s(t) + \frac{t}{4m_{\Sigma^0}^2} F_{2\Sigma^0}^s(t), G_M^{\Sigma^0}(t) = F_{1\Sigma^0}^s(t) + F_{2\Sigma^0}^s(t) \\
G_E^{\Xi^0, \Xi^-}(t) &= [F_{1\Sigma}^s(t) \pm F_{1\Sigma}^v(t)] + \frac{t}{4m_{\Xi^0, \Xi^-}^2} [F_{2\Sigma}^s(t) \pm F_{2\Sigma}^v(t)] \\
G_M^{\Xi^0, \Xi^-}(t) &= [F_{1\Sigma}^s(t) \pm F_{1\Sigma}^v(t)] + [F_{2\Sigma}^s(t) \pm F_{2\Sigma}^v(t)] .
\end{aligned} \tag{8}$$

Then the universal unitary and analytic model of all members of the $1/2^+$ baryon octet, reflecting all properties *i) - viii)* and depending from all coupling constant ratios under consideration only on $(f_{\rho BB}^{(i)}/f_\rho)$, $(f_{\omega BB}^{(i)}/f_\omega)$ and $(f_{\phi BB}^{(i)}/f_\phi)$ ($i = 1, 2$) as free parameters, is given by the expressions

$$\begin{aligned}
F_{1B}^s[V(t)] &= \left(\frac{1 - V^2}{1 - V_N^2} \right)^4 \left\{ N_{1B}^s \cdot \prod_{n=\omega'}^{\omega''} H_n^1(V) + \right. \\
&+ \left[L_\omega^1(V) H_{\omega''}^1(V) \frac{(C_{\omega''}^1 - C_\omega^1)}{(C_{\omega''}^1 - C_{\omega'}^1)} - L_\omega^1(V) H_{\omega'}^1(V) \frac{(C_{\omega'}^1 - C_\omega^1)}{(C_{\omega''}^1 - C_{\omega'}^1)} - \right. \\
&- \left. \prod_{n=\omega'}^{\omega''} H_n^1(V) \right] (f_{\omega NN}^{(1)}/f_\omega) + \\
&+ \left[L_\phi^1(V) H_{\omega''}^1(V) \frac{(C_{\omega''}^1 - C_\phi^1)}{(C_{\omega''}^1 - C_{\omega'}^1)} - L_\phi^1(V) H_{\omega'}^1(V) \frac{(C_{\omega'}^1 - C_\phi^1)}{(C_{\omega''}^1 - C_{\omega'}^1)} - \right. \\
&- \left. \prod_{n=\omega'}^{\omega''} H_n^1(V) \right] (f_{\phi BB}^{(1)}/f_\phi) \left. \right\}
\end{aligned} \tag{9}$$

$$F_{1B}^v[W(t)] = \left(\frac{1-W^2}{1-W_N^2} \right)^4 \left\{ N_{1B}^v \cdot L_{\rho'}^1(W) H_{\rho''}^1(W) + \right. \\ \left. + \left[L_{\rho}^1(W) H_{\rho''}^1(W) \frac{(C_{\rho''}^1 - C_{\rho}^1)}{(C_{\rho''}^1 - C_{\rho'}^1)} - L_{\rho}^1(W) L_{\rho'}^1(W) \frac{(C_{\rho'}^1 - C_{\rho}^1)}{(C_{\rho''}^1 - C_{\rho'}^1)} - \right. \right. \\ \left. \left. - L_{\rho'}^1(W) H_{\rho''}^1(W) \right] (f_{\rho BB}^{(1)} / f_{\rho}) \right\}$$

$$F_{2B}^s[U(t)] = \left(\frac{1-U^2}{1-U_N^2} \right)^6 \left\{ N_{2B}^s \cdot \prod_{n=\omega'}^{\phi'} H_n^2(U) + \right. \\ \left. + \left[L_{\omega}^2(U) H_{\omega''}^2(U) H_{\phi'}^2(U) \frac{(C_{\omega''}^2 - C_{\omega}^2)}{(C_{\omega''}^2 - C_{\omega'}^2)} \frac{(C_{\phi'}^2 - C_{\omega}^2)}{(C_{\phi'}^2 - C_{\omega'}^2)} - \right. \right. \\ \left. - L_{\omega}^2(U) H_{\omega'}^2(U) H_{\phi'}^2(U) \frac{(C_{\omega'}^2 - C_{\omega}^2)}{(C_{\omega''}^2 - C_{\omega'}^2)} \frac{(C_{\phi'}^2 - C_{\omega}^2)}{(C_{\phi'}^2 - C_{\omega''}^2)} + \right. \\ \left. + L_{\omega}^2(U) H_{\omega'}^2(U) H_{\omega''}^2(U) \frac{(C_{\omega'}^2 - C_{\omega}^2)}{(C_{\phi'}^2 - C_{\omega'}^2)} \frac{(C_{\omega''}^2 - C_{\omega}^2)}{(C_{\phi'}^2 - C_{\omega''}^2)} - \right. \\ \left. - \prod_{n=\omega'}^{\phi'} H_n(U)^2 \right] (f_{\omega BB}^{(2)} / f_{\omega}) + \\ \left. + \left[L_{\phi}^2(U) H_{\omega''}^2(U) H_{\phi'}^2(U) \frac{(C_{\omega''}^2 - C_{\phi}^2)}{(C_{\omega''}^2 - C_{\omega'}^2)} \frac{(C_{\phi'}^2 - C_{\phi}^2)}{(C_{\phi'}^2 - C_{\omega'}^2)} - \right. \right. \\ \left. - L_{\phi}^2(U) H_{\omega'}^2(U) H_{\phi'}^2(U) \frac{(C_{\omega'}^2 - C_{\phi}^2)}{(C_{\omega''}^2 - C_{\omega'}^2)} \frac{(C_{\phi'}^2 - C_{\phi}^2)}{(C_{\phi'}^2 - C_{\omega''}^2)} + \right. \\ \left. + L_{\phi}^2(U) H_{\omega'}^2(U) H_{\omega''}^2(U) \frac{(C_{\omega'}^2 - C_{\phi}^2)}{(C_{\phi'}^2 - C_{\omega'}^2)} \frac{(C_{\omega''}^2 - C_{\phi}^2)}{(C_{\phi'}^2 - C_{\omega''}^2)} - \right. \\ \left. - \prod_{n=\omega'}^{\phi'} H_n^2(U) \right] (f_{\phi BB}^{(2)} / f_{\phi}) \right\}$$

$$F_{2B}^v[X(t)] = \left(\frac{1-X^2}{1-X_N^2} \right)^6 \left\{ N_{2B}^v \cdot L_{\rho'}^2(X) H_{\rho''}^2(X) H_{\rho'''}^2(X) + \right. \\ \left. + \left[L_{\rho}^2(X) H_{\rho''}^2(X) H_{\rho'''}^2(X) \frac{(C_{\rho'''}^2 - C_{\rho}^2)}{(C_{\rho'''}^2 - C_{\rho'}^2)} \frac{(C_{\rho''}^2 - C_{\rho}^2)}{(C_{\rho''}^2 - C_{\rho'}^2)} - \right. \right. \\ \left. - L_{\rho}^2(X) H_{\rho'}^2(X) H_{\rho'''}^2(X) \frac{(C_{\rho'''}^2 - C_{\rho}^2)}{(C_{\rho'''}^2 - C_{\rho''}^2)} \frac{(C_{\rho''}^2 - C_{\rho}^2)}{(C_{\rho''}^2 - C_{\rho'}^2)} + \right. \\ \left. \left. - L_{\rho'}^2(X) H_{\rho''}^2(X) H_{\rho'''}^2(X) \frac{(C_{\rho'''}^2 - C_{\rho'}^2)}{(C_{\rho'''}^2 - C_{\rho''}^2)} \frac{(C_{\rho''}^2 - C_{\rho'}^2)}{(C_{\rho''}^2 - C_{\rho'}^2)} \right] \right\}$$

$$\left. \begin{aligned} & + L_{\rho'}^2(X) H_{\rho'}^2(X) H_{\rho''}^2(X) \frac{(C_{\rho'}^2 - C_{\rho}^2)}{(C_{\rho''}^2 - C_{\rho'}^2)} \frac{(C_{\rho'}^2 - C_{\rho}^2)}{(C_{\rho''}^2 - C_{\rho'}^2)} - \\ & - L_{\rho'}^2(X) H_{\rho''}^2(X) H_{\rho'''}^2(X) \left[(f_{\rho BB}^{(2)} / f_{\rho}) \right] \end{aligned} \right\} ,$$

where

$$L_k^1[V(t)] = \frac{(V_N - V_k)(V_N - V_k^*)(V_N - 1/V_k)(V_N - 1/V_k^*)}{(V - V_k)(V - V_k^*)(V - 1/V_k)(V - 1/V_k^*)}, \quad k = \omega, \phi$$

$$H_n[V(t)] = \frac{(V_N - V_n)(V_N - V_n^*)(V_N + V_n)(V_N + V_n^*)}{(V - V_n)(V - V_n^*)(V + V_n)(V + V_n^*)}, \quad n = \omega', \omega''$$

$$V(t) = i \frac{[(t_{in}^1/t_{0B}^s - 1)^{1/2} + (t/t_{0B}^s - 1)^{1/2}]^{1/2} - [(t_{in}^1/t_{0B}^s - 1)^{1/2} - (t/t_{0B}^s - 1)^{1/2}]^{1/2}}{[(t_{in}^1/t_{0B}^s - 1)^{1/2} + (t/t_{0B}^s - 1)^{1/2}]^{1/2} + [(t_{in}^1/t_{0B}^s - 1)^{1/2} - (t/t_{0B}^s - 1)^{1/2}]^{1/2}} \quad (10)$$

$$V_s = V(t_s), \quad t_s = (m_s - i\Gamma_s/2)^2, \quad s = \omega, \phi, \omega', \omega''; \quad V_N = V(t) \Big|_{t=0}$$

$$C_k^1 = \frac{(V_N - V_k)(V_N - V_k^*)(V_N - 1/V_k)(V_N - 1/V_k^*)}{-(V_k - 1/V_k)(V_k^* - 1/V_k^*)}, \quad k = \omega, \phi$$

$$C_n^1 = \frac{(V_N - V_n)(V_N - V_n^*)(V_N + V_n)(V_N + V_n^*)}{-(V_n - 1/V_n)(V_n^* - 1/V_n^*)}, \quad n = \omega', \omega''$$

and similarly for $L_v^1(W)$, $H_v^1(W)$, C_v^1 ; $L_s^2(U)$, $H_s^2(U)$, C_s^2 and $L_v^2(X)$, $H_v^2(X)$, C_v^2 .

Now, how to predict the $\sigma_{tot}(e^+e^- \rightarrow \text{hyperon} - \text{antihyperon})$ behaviour.

The main idea consists in the following. From the trace of SU(3) invariant Lagrangian for vector-meson-baryon-antibaryon vertex

$$\begin{aligned} Tr(L_{VB\bar{B}}) &= \frac{i}{\sqrt{2}} f^F \left[\bar{B}_{\beta}^{\alpha} \gamma_{\mu} B_{\gamma}^{\beta} - \bar{B}_{\gamma}^{\beta} \gamma_{\mu} B_{\beta}^{\alpha} \right] (V_{\mu})_{\alpha}^{\gamma} + \\ &+ \frac{i}{\sqrt{2}} f^D \left[\bar{B}_{\gamma}^{\beta} \gamma_{\mu} B_{\beta}^{\alpha} + \bar{B}_{\beta}^{\alpha} \gamma_{\mu} B_{\gamma}^{\beta} \right] (V_{\mu})_{\alpha}^{\gamma} + \\ &+ \frac{i}{\sqrt{2}} f^S \bar{B}_{\beta}^{\alpha} \gamma_{\mu} B_{\alpha}^{\beta} \omega_{\mu}^0, \end{aligned} \quad (11)$$

with B , $\bar{B}$ and V baryon, antibaryon and vector-meson octuplet matrices, ω_μ^0 omega-meson singlet, f^F , f^D , f^S SU(3) coupling constants, one can derive the relation between $f_{V B \bar{B}}^{(i)}$ and f^F , f^D , f^S as follows

$$\begin{aligned} f_{\rho NN}^{(1,2)} &= \frac{1}{2}(f_{1,2}^D + f_{1,2}^F) \\ f_{\omega NN}^{(1,2)} &= \frac{1}{\sqrt{2}} \cos \vartheta f_{1,2}^S - \frac{1}{2\sqrt{3}} \sin \vartheta (3f_{1,2}^F - f_{1,2}^D) \\ f_{\phi NN}^{(1,2)} &= \frac{1}{\sqrt{2}} \sin \vartheta f_{1,2}^S + \frac{1}{2\sqrt{3}} \cos \vartheta (3f_{1,2}^F - f_{1,2}^D) \end{aligned} \quad (12)$$

$$\begin{aligned} f_{\omega \Lambda \Lambda}^{(1,2)} &= \frac{1}{\sqrt{2}} \cos \vartheta f_{1,2}^S + \frac{1}{\sqrt{3}} \sin \vartheta f_{1,2}^D \\ f_{\phi \Lambda \Lambda}^{(1,2)} &= \frac{1}{\sqrt{2}} \sin \vartheta f_{1,2}^S - \frac{1}{\sqrt{3}} \cos \vartheta f_{1,2}^D \end{aligned} \quad (13)$$

$$\begin{aligned} f_{\rho \Sigma \Sigma}^{(1,2)} &= -f_{1,2}^F \\ f_{\omega \Sigma \Sigma}^{(1,2)} &= \frac{1}{\sqrt{2}} \cos \vartheta f_{1,2}^S - \frac{1}{\sqrt{3}} \sin \vartheta f_{1,2}^D \\ f_{\phi \Sigma \Sigma}^{(1,2)} &= \frac{1}{\sqrt{2}} \sin \vartheta f_{1,2}^S + \frac{1}{\sqrt{3}} \cos \vartheta f_{1,2}^D \end{aligned} \quad (14)$$

$$\begin{aligned} f_{\rho \Xi \Xi}^{(1,2)} &= \frac{1}{2}(f_{1,2}^D - f_{1,2}^F) \\ f_{\omega \Xi \Xi}^{(1,2)} &= \frac{1}{\sqrt{2}} \cos \vartheta f_{1,2}^S + \frac{1}{2\sqrt{3}} \sin \vartheta (3f_{1,2}^F + f_{1,2}^D) \\ f_{\phi \Xi \Xi}^{(1,2)} &= \frac{1}{\sqrt{2}} \sin \vartheta f_{1,2}^S - \frac{1}{2\sqrt{3}} \cos \vartheta (3f_{1,2}^F + f_{1,2}^D) . \end{aligned} \quad (15)$$

Then comparing (8) and (9) for N with data on G_E^N , G_M^N , one finds $f_{V N \bar{N}}$. Substituting the latter into (12) and solving the obtained system of 3 algebraic equations, one finds f^F , f^D and f^S . As a result, by (13)-(15) one finds numerical values of the vector-meson-hyperon coupling constants which allow to determine all hyperon electric and magnetic FF's and corresponding total cross sections. The latter are graphically presented in Figs. 1-8.

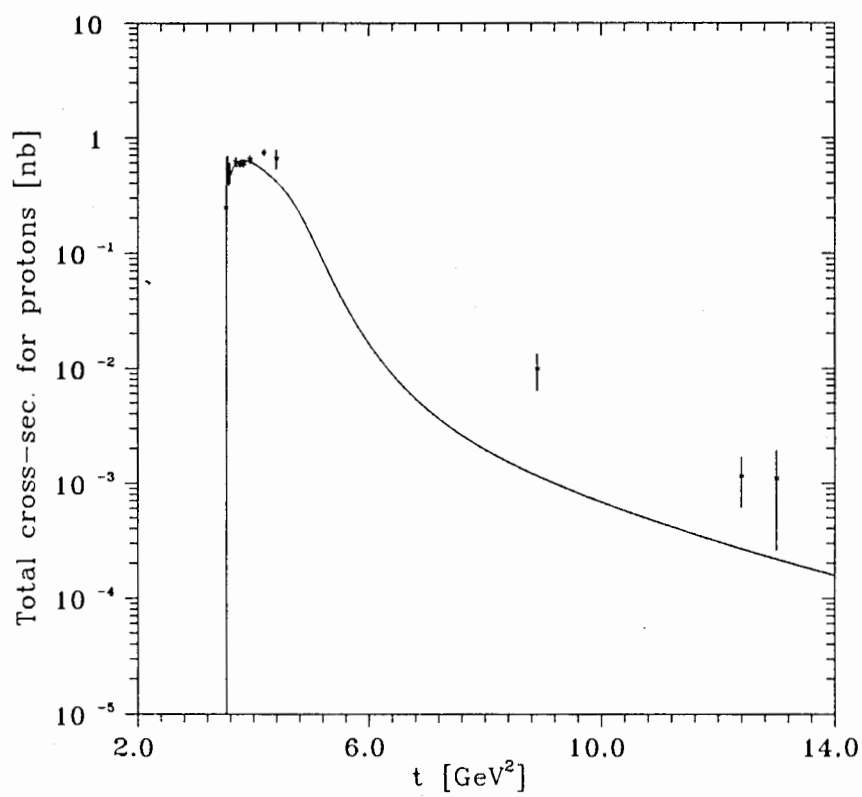


Fig. 1

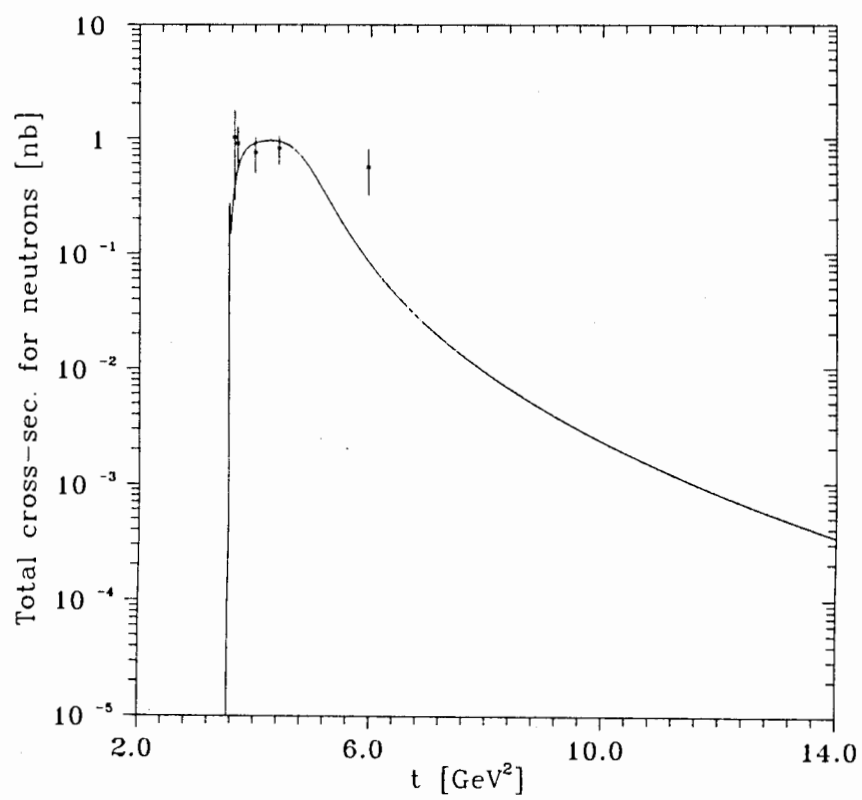


Fig. 2

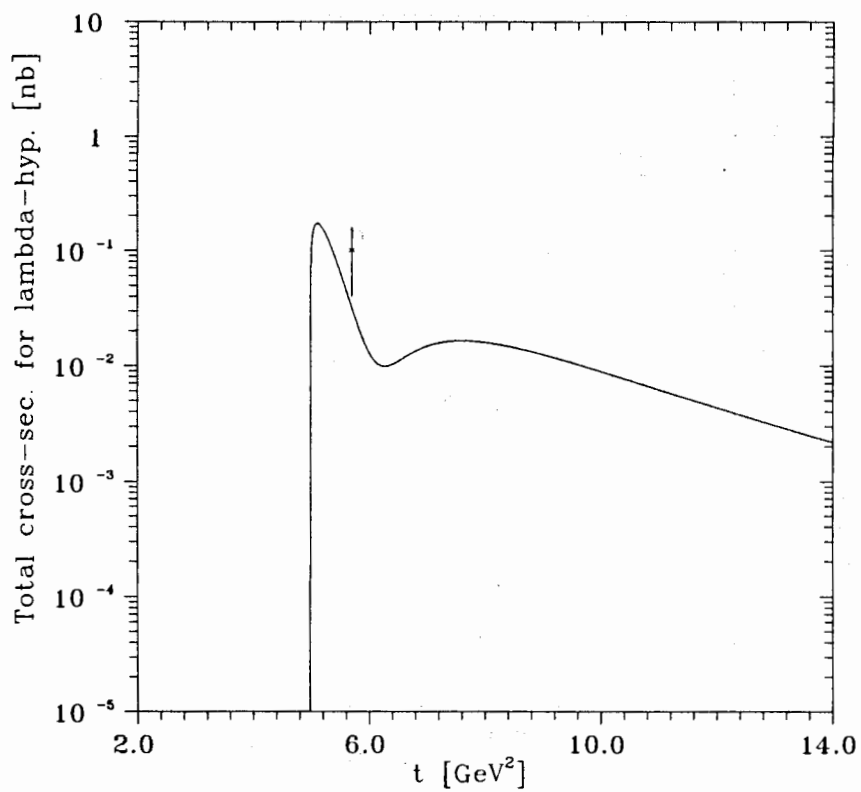


Fig. 3

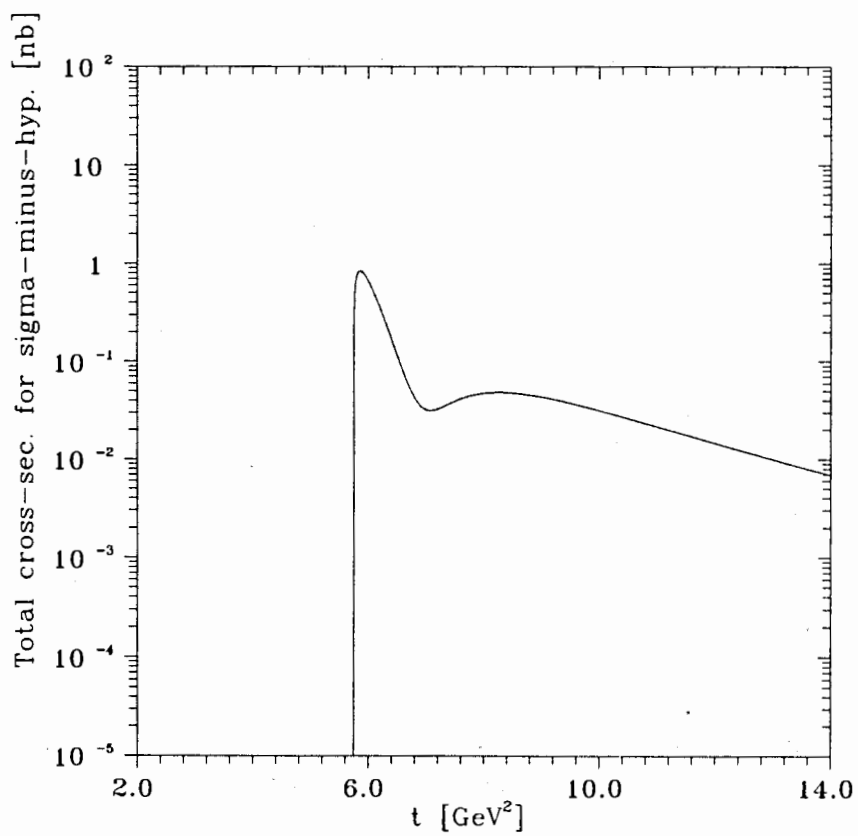


Fig. 4

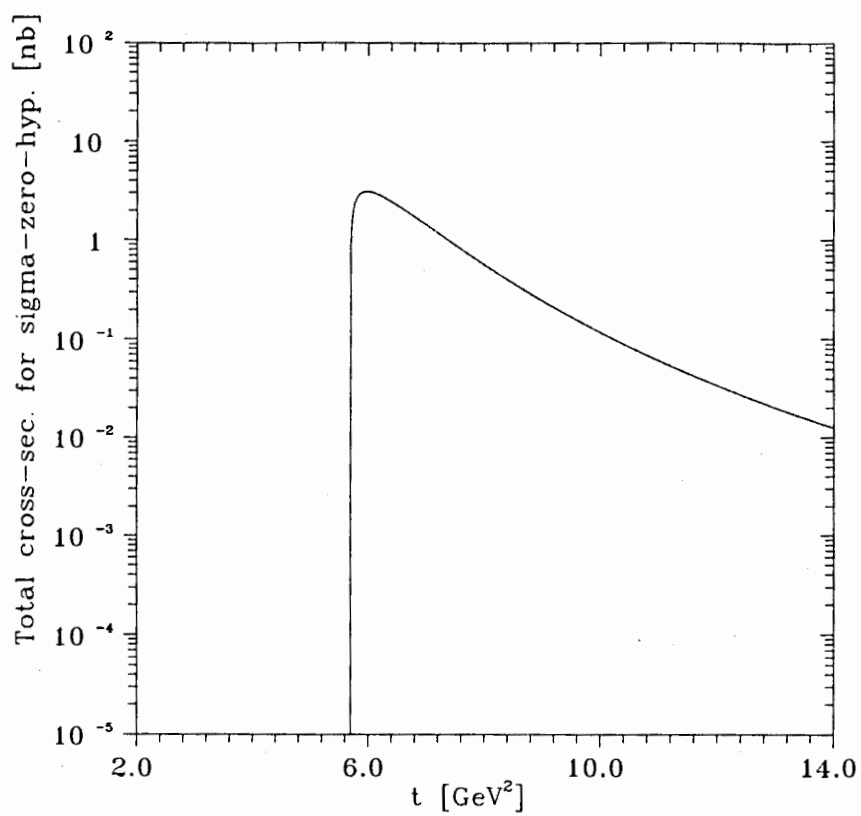


Fig. 5

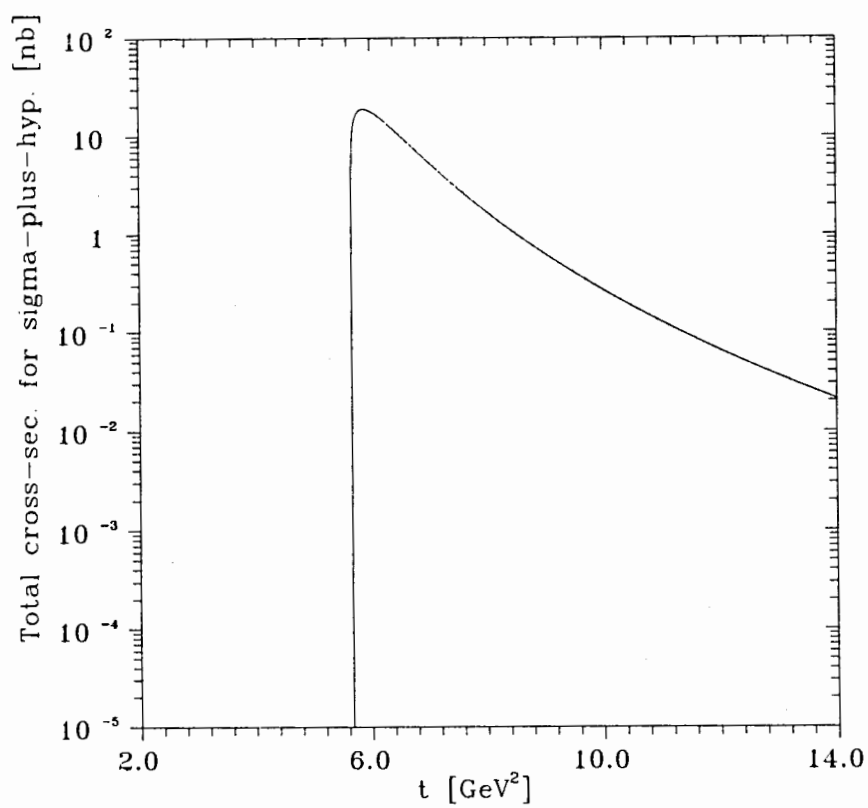


Fig. 6

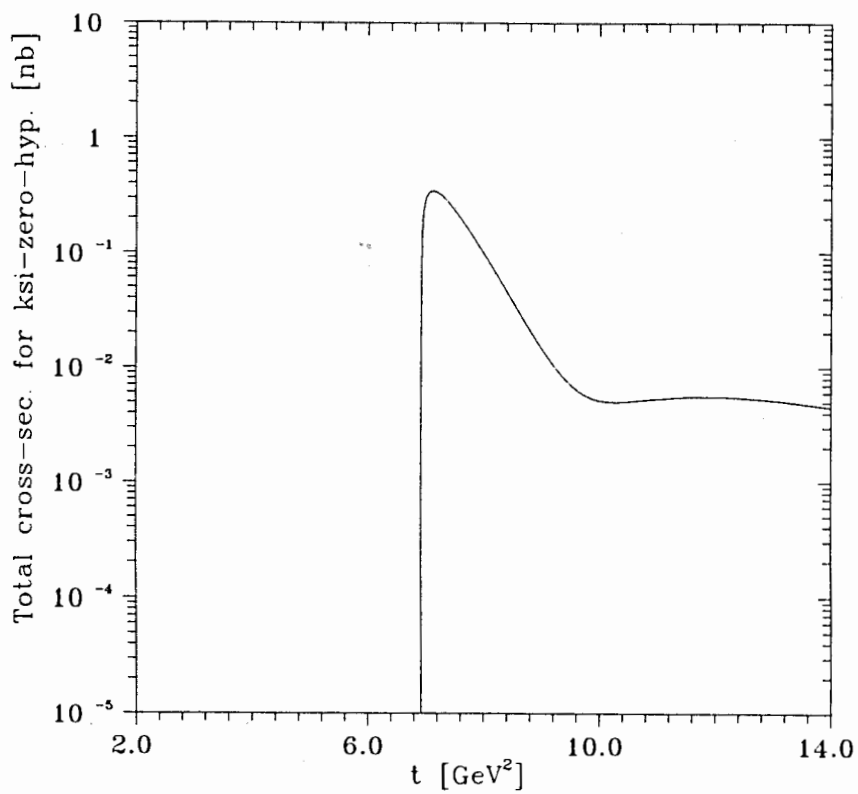


Fig. 7

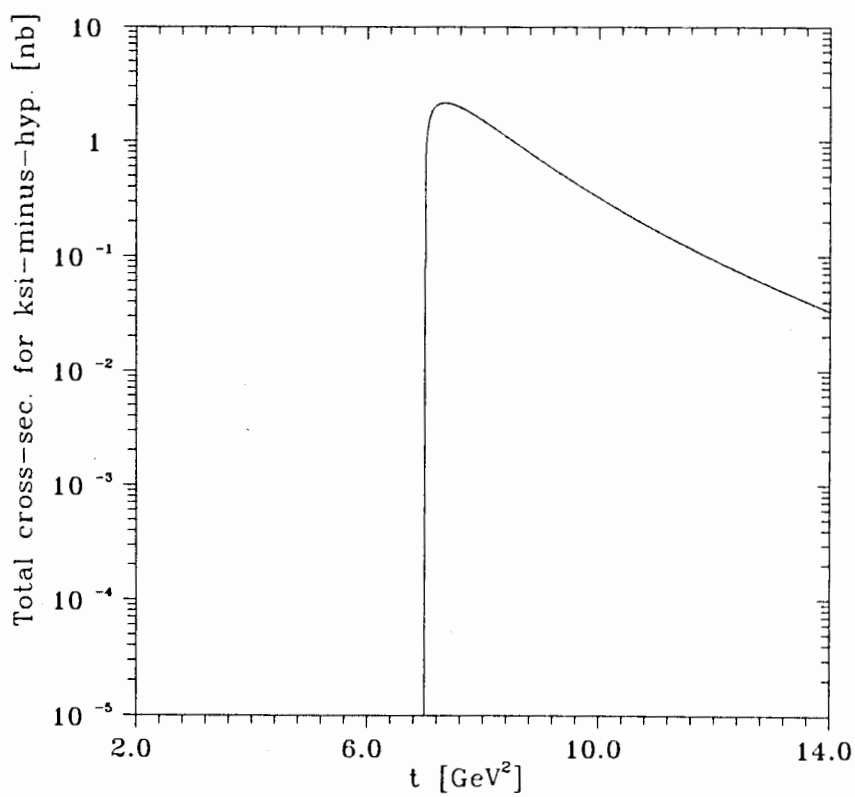


Fig. 8

Measurement of the Ratio G_{Ep}/G_{Mp} Interesting New Results from Jefferson Lab

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Abstract

The electromagnetic form factors of the nucleon describe charge and current distributions inside the nucleon and thus are intimately related to its structure. The ratio of the proton's elastic electromagnetic form factors G_{Ep}/G_{Mp} was obtained by measuring P_t and P_l , the transverse and longitudinal recoil proton polarization, respectively. For the elastic reaction $\vec{e}p \rightarrow e\vec{p}$, G_{Ep}/G_{Mp} is proportional to P_t/P_l . Simultaneous measurement of P_t and P_l provides good control of the systematic uncertainty. The results for the ratio G_{Ep}/G_{Mp} show a systematic decrease as Q^2 increases from 0.5 to 3.5 GeV². These data have unprecedented precision, and show for the first time that the Q^2 dependence of the spatial distributions of charge and magnetization currents in the proton are very different.

1. Introduction

The understanding of the structure of the nucleon has been of fundamental importance for the past several decades in nuclear and particle physics; ultimately such an understanding is necessary to describe the strong force. For any QCD based theory, its ability to predict the pion and nucleon form factors correctly is perhaps the most important test of its validity, and hence *precise data are required to test the models*. The region of Q^2 from 1 to 20 GeV² has been anticipated to be where a transition from mesonic to quark-gluon degrees of freedom takes place. Measurements of the nucleon form factors in this region will directly test theories of the strong interaction.

The internal structure of the nucleon, proton and neutron, is revealed by properties like their r.m.s. radius, anomalous magnetic moment, charge and current distributions, polarizabilities and transition amplitudes to excited baryonic states. Nucleon elastic form factors, at least in the non-relativistic

limit, are linked to the charge and current distribution inside the nucleon: they are the Fourier transforms of the charge and current densities. At higher energies or momentum transfers this connection is blurred because the form factor-density relation holds true only in the Breit frame, and the connection to the laboratory frame densities is non-trivial. Even though this simple connection to charge and current is lost at large momentum transfer, the elastic form factors are fundamental properties of the nucleon which must be quantitatively reproduced by any realistic model of the nucleon structure.

The electromagnetic interaction provides a unique tool to investigate the structure of the nucleon. The measurement of electromagnetic form factors in elastic and inelastic scattering of electrons, has been a rich source of information on the nucleon structure. The experimental quantities of interest here are the elastic electric and magnetic form factors, G_{Ep} and G_{Mp} , known as the Sachs form factors; they are connected to the Dirac and Pauli form factors F_{1p} and F_{2p} , which describe the deviation from a point-like Dirac particle, and the corresponding non-point-like nature of the anomalous magnetization, respectively, as follows:

$$G_{Ep} = F_{1p} - \tau \kappa F_{2p} \text{ and } G_{Mp} = F_{1p} + \kappa F_{2p}, \quad (1)$$

where τ is a dimensionless four-momentum transfer squared defined as:

$$\tau = \frac{Q^2}{4M_p^2}, \text{ where } Q^2 = -(E_e - E_{e'})^2 + (\vec{p}_e - \vec{p}_{e'})^2 \quad (2)$$

where M_p is the mass of the proton, and E_e and $\vec{p}_e$, and $E_{e'}$ and $\vec{p}_{e'}$, are the energies and momenta of the incident and scattered electron, respectively. κ_p is the anomalous part of the magnetic moment of the proton, μ_p ; both κ_p and μ_p are in units of the nuclear magneton.

Both the elastic cross section and polarization observables of the reaction can be expressed in terms of either the Sachs or the Dirac and Pauli form factors; in the one photon exchange approximation, these form factors depend only upon the four-momentum squared, Q^2 , of the reaction. The elastic ep cross section in terms of the Sachs form factors can be expressed as:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{ns}} \left[G_{Ep}^2 + \frac{\tau}{\epsilon} G_{Mp}^2 \right] \frac{1}{1 + \tau} \quad (3)$$

where $\epsilon = \left[1 + 2(1 + \tau) \tan^2(\frac{\theta_e}{2}) \right]^{-1}$ is the longitudinal polarization of the virtual photon; $0 \leq \epsilon \leq 1$; θ_e is the electron scattering angle in the laboratory frame. Until now almost all data for G_{Ep} and G_{Mp} have come from the Rosenbluth separation method. The separation of G_{Ep}^2 and G_{Mp}^2 is achieved by fitting data at a given Q^2 over a range of ϵ obtained by changing the

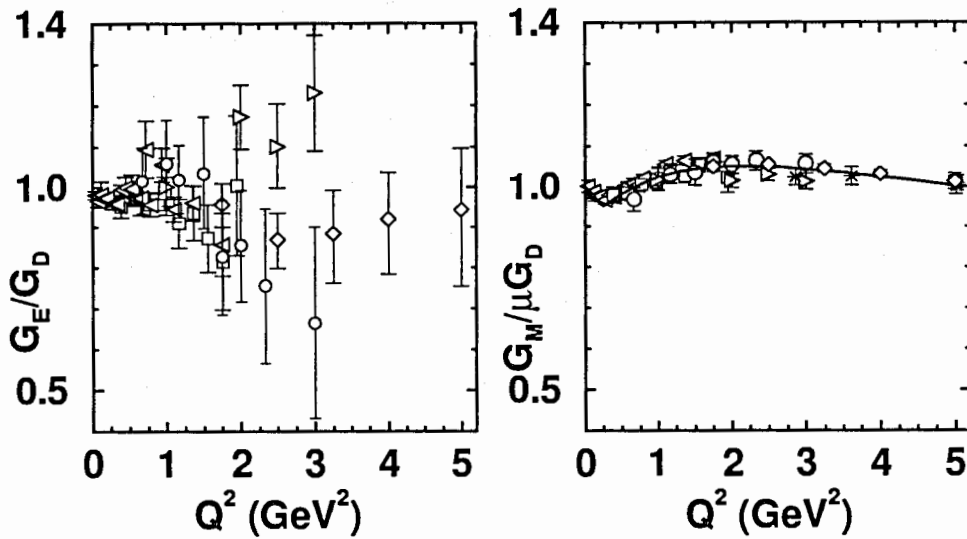


Figure 1. World data for (a) G_{Ep}/G_D and (b) $\mu_p G_{Mp}/G_D$. Refs. [1]□, [2]◁, [3]○, [4]▷, [5]◇ and [6]*. The solid curve in (b) is a fit to G_{Mp} data by Bosted [7]

beam energy and θ_e . Based on the extensive data base available before this experiment, it was customary to assume that $G_{Ep} = G_D$ and $G_{Mp} = \mu_p G_D$, where G_D , known as the dipole form factor is given by:
 $G_D = m_D^4(m_D^2 + Q^2)^{-2}$, with the constant m_D^2 empirically determined to be 0.71 GeV^2 .

Figure 1 shows previous data of G_{Ep} and G_{Mp} , plotted as the ratio G_{Ep}/G_D and $\mu G_{Mp}/G_D$ versus Q^2 , up to 5 GeV^2 . This representation is justified empirically in the low Q^2 region up to about 1 GeV^2 , where the data indicate that $G_{Mp}/\mu \sim G_{Ep} \sim G_D$. The G_{Ep} data start to have large errors bars above $Q^2 = 1 \text{ GeV}^2$, where results from different experiments begin to diverge. The ratio G_{Ep}/G_D is consistent with unity only at the 20-30% level for large Q^2 values. Even if $G_{Mp}/\mu \sim G_{Ep}$, the factor τ in front of G_{Mp} in the cross section tends to boost the contribution due to G_{Mp} , compared to that of G_{Ep} for increasing Q^2 . This means that G_{Mp} dominates the cross section at large Q^2 , thus measuring G_{Ep} with high precision above $Q^2 = 1 \text{ GeV}^2$ by the Rosenbluth separation method is difficult.

A better way to obtain the proton form factors G_{Ep} and G_{Mp} is by measuring the polarization observables in the elastic ep reaction, with longitudinally polarized electrons, as first suggested by Akhiezer and Rekalov [8], and later discussed in detail by Arnold, Carlson and Gross [9]. The polarization observables of the reaction are the beam-target polarization asymmetry and the

beam-recoil proton polarization transfer coefficient; both contain an interference term proportional to $G_{Ep} G_{Mp}$. That is the main reason why polarization experiments are more sensitive to small amplitudes than cross section measurements. In this work, we have measured the polarization transferred to the recoil proton, with longitudinally polarized electron beam on an unpolarized hydrogen target. We will show that the ratio of the two polarization components, transverse and longitudinal P_t and P_l , respectively, relative to the proton momentum, is directly proportional to the ratio G_{Ep}/G_{Mp} , but is independent of the electron beam polarization and the analyzing power of the polarimeter. Systematic asymmetries of the polarimeter itself are canceled by the use of electron of positive and negative helicity, in an alternating mode. As will be explained in the experimental description, the systematic uncertainties are mostly related to the transport of spin through the various magnetic elements used to detect the proton.

In this paper, we present the G_{Ep}/G_{Mp} -ratio obtained at Jlab using the recoil polarization technique, the technique is described in section II, and the spin transport method is described in section III. In section IV, experimental setup is discussed. The main results of the experiment, which are 9 measurements of G_{Ep}/G_{Mp} at $0.5 \leq Q^2 \leq 3.5$, are presented in section V, and a discussion of the theoretical predictions available at this time is also presented in this part.

2. The Recoil Polarization Technique

In experiment 93-027 we used the recoil polarization method successfully to measure the ratio G_{Ep}/G_{Mp} up to $Q^2 = 3.5 \text{ GeV}^2$. The main advantage of polarization observables over cross sections is that, for a given Q^2 , a single measurement directly gives the form factor ratio; the Rosenbluth separation requires at least two cross section measurements made at different energy and angle combinations at the same Q^2 .

For one-photon exchange, in a $^1\text{H}(\vec{e}, e' \vec{p})$ reaction, the scattering of longitudinally polarized electrons results in a transfer of polarization to the recoil proton with only two non-zero components, P_t perpendicular to, and P_l parallel to the proton momentum in the scattering plane, given by the following relations [8, 9]:

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_{Ep} G_{Mp} \tan \frac{\theta_e}{2} \quad (4)$$

$$I_0 P_t = \frac{1}{M} (E_e + E_{e'}) \sqrt{\tau(1+\tau)} G_{Mp}^2 \tan^2 \frac{\theta_e}{2} \quad (5)$$

where E_e and $E_{e'}$ are the energy of the incident and scattered electrons, respectively, θ_e is the scattered electron angle and I_0 is:

$$I_0 = G_{Ep}^2(Q^2) + \tau G_{Mp}^2(Q^2) [1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2}] \quad (6)$$

Eqns. 4 and 5 show that the transverse and longitudinal components of the proton polarization are proportional to $G_E G_M$ and G_M^2 , respectively and together these equations give:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M} \tan\left(\frac{\theta_e}{2}\right) \quad (7)$$

The ratio G_{Ep}/G_{Mp} is obtained from a simultaneous measurement of the two recoil polarization components in the polarimeter. Neither the beam polarization nor the polarimeter analyzing power needs to be known which results in small systematic uncertainties.

The recoil polarization method was first used to obtain the neutron form factors in the $^2H(\vec{e}, e'\vec{n})$ reaction (Bates 88-05[10]). Bates experiment 88-21 also used the polarization transfer method to measure the form factor ratio G_{Ep}/G_{Mp} in $\vec{e}p \rightarrow e\vec{p}$ for the free proton [11], as well as for the proton in the deuteron at small Q^2 - values [12].

With a focal plane polarimeter, one measures the azimuthal angular distribution after a second scattering in a graphite analyzer. This distribution has two components only, corresponding to the two projections of the polarization in the plane of the analyzer. It can be written as:

$$N_p^\pm(\theta, \varphi) = N_p^\pm(h=0) \epsilon(\theta) (1 \pm |h| A_c(\theta) [P_t^{fpp} \sin \varphi - P_n^{fpp} \cos \varphi]) \quad (8)$$

where $|h|$ is the electron beam polarization, and the $\pm$ stands for the two possible orientations of the electron beam helicity, $N_p(h=0)$ is the number of protons incident on the polarimeter, θ , φ are the polar and azimuthal angles after scattering in the analyzer, $\epsilon(\theta)$ is the differential efficiency, and $A_c(\theta)$ the analyzing power of the graphite; P_t^{fpp} and P_n^{fpp} are the in-plane components, transverse and normal, respectively, of the polarization at the analyzer. The physics quantities are obtained by a Fourier analysis of the difference in the normalized angular distributions yields $\frac{N^+(\theta, \varphi)}{N_p^+(h=0)} - \frac{N^-(\theta, \varphi)}{N_p^-(h=0)}$, and the instrumental asymmetries are helicity independent and hence cancel.

3. The Spin Transport Method

The proton spin precesses as it travels from target to the focal plane through the magnetic elements of the spectrometer, and therefore the polarization components at the target and the FPP are different. We measure the polarization of the proton in the focal plane of the spectrometer, so to obtain the polarization at the target, the spin transport method through the spectrometer was developed.

For a spectrometer consisting of a single dipole with homogeneous field, the relation between polarizations at the analyzer and at the target can be written in terms of a spin transport matrix as:

$$\begin{pmatrix} P_n^{fpp} \\ P_t^{fpp} \\ P_t^{fpp} \end{pmatrix} = \begin{pmatrix} \cos \chi & 0 & \sin \chi \\ 0 & 1 & 0 \\ -\sin \chi & 0 & \cos \chi \end{pmatrix} \begin{pmatrix} P_n \\ P_t \\ P_t \end{pmatrix}$$

In the case of elastic ep scattering, $P_n=0$ in the single photon exchange approximation. Thus, in this case, in the single dipole approximation the relationship between target and focal plane components are:

$$P_t^{fpp} = P_t \quad \text{and} \quad P_n^{fpp} = P_t \sin \chi \quad (9)$$

where $\chi = \theta_B \gamma (\mu_p - 1)$, is the spin precession angle in the spectrometer.

The Fourier analysis of the experimental azimuthal distribution $\frac{N^+(\theta, \varphi)}{N_p^+(h=0)} - \frac{N^-(\theta, \varphi)}{N_p^-(h=0)}$, gives the two physical amplitudes for each bin of θ :

$$a(\theta) = h A_c(\theta) P_t^{fpp} \quad \text{and} \quad b(\theta) = h A_c(\theta) P_t^{fpp} \quad (10)$$

from which P_t and P_t can be obtained.

The hadron HRS in Hall A consists of 3 quadrupoles and one dipole with shaped entrance and exit edges, as well as a radial field gradient. As a consequence further spin rotation occurs in these higher order magnetic fields (quadrupole, sextupole...). Therefore, the actual spin transfer matrix (S_{nm}) has nine non-zero matrix elements. These matrix elements are different for every event, because they depend on $(\theta, y, \phi, \delta)_{tgt}$. To extract the physical quantities P_t and P_t one must correct for spin precession for each event. The method we have been using in the analysis is directly based on the Fourier analysis[13]: one can show that the quantities $a(\theta)$ and $b(\theta)$ in Eq. 10 are the sums over all events in the azimuthal distribution, as follows:

$$a(\theta) = \frac{2}{N} \left[\sum_i^N (S_{nt}^{(i)} h A_c(\theta) P_t \cos^2 \varphi_i + S_{nt}^{(i)} h A_c(\theta) P_t \cos^2 \varphi_i) \right] \quad (11)$$

$$b(\theta) = \frac{2}{N} \left[\sum_i^N (S_{tt}^{(i)} hA_c(\theta) P_t \sin^2 \varphi_i + S_{tt}^{(i)} hA_c(\theta) P_t \sin^2 \varphi_i) \right] \quad (12)$$

where index i numbers the events. The equations can be solved for the 2 unknowns $(hA_c(\theta)P_t)$ and $(hA_c(\theta)P_\ell)$. The S_{nm} matrix elements have to be calculated from a model of the spectrometer. The spectrometer has been modeled with COSY[14], a differential analysis based code, and SNAKE[15], a ray-tracing code. Both these codes reproduce the optics of the spectrometer.

The ratio G_{Ep}/G_{Mp} can then be obtained directly from the ratio of $r(\theta) = \frac{hA_c(\theta)P_t}{hA_c(\theta)P_\ell}$:

$$\frac{G_{Ep}}{G_{Mp}} = -r(\theta) \frac{(E_e + E_{e'})}{2M} \tan\left(\frac{\theta_e}{2}\right) \quad (13)$$

The definition of P_t and P_ℓ (Eqns. 5 and 4) can then be used to calculate these two components from G_{Ep}/G_{Mp} , leading to a calculation of the quantity $hA_c(\theta)$. The beam polarization is measured independently with the Mott polarimeter at the injector, and with the Møller polarimeter in Hall A, thus providing a calibration of the polarimeter's analyzing power for each of the proton energies.

4. The Experiment

The experiment was done using the Hall A facility at Jefferson Lab. Longitudinally polarized continuous electron beams with energies between 0.934 GeV and 4.090 GeV were scattered in a 15 cm long, circulating liquid hydrogen (LH_2) target, refrigerated to 19 K. The longitudinal beam polarization for the four highest Q^2 data points was ~ 0.39 with currents up to $\sim 115 \mu A$; for the lower Q^2 data points typical polarizations of ~ 0.6 were achieved with currents between 5 and 15 μA . For the four highest Q^2 data points a bulk GaAs photo-cathode was used to produce polarized electron beams; the helicity was flipped at 30 Hz. For the lower Q^2 points, a strained GaAs crystal was used; the helicity was flipped at 1 Hz. The polarization was measured periodically with a Mott polarimeter in the injection line, and a Møller polarimeter in Hall A, located up stream of the LH_2 target.

In this experiment the longitudinal and transverse polarizations of the outgoing proton were measured for the $^1H(\vec{e}, e'\vec{p})$ reaction, in Q^2 range of 0.5–3.5 GeV^2 . The two identical High Resolution Spectrometers (HRS) of Hall A[16] were used to select elastic ep events by detecting the scattered

electrons and recoiling protons in coincidence. Each HRS deflects particles vertically by 45° and accepts a maximum central trajectory momentum of 4 GeV/c with a 6.5 msr angular acceptance, $\pm 5\%$ momentum acceptance and $\sim 10^{-4}$ momentum resolution. A schematic of the hadron detector stack is shown in Fig. 2.

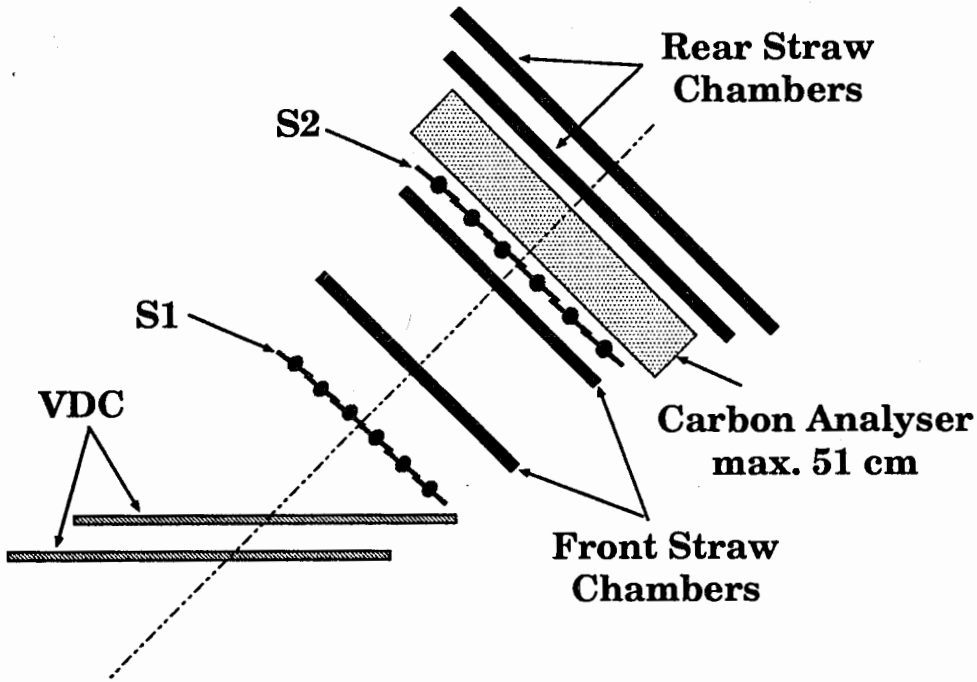


Figure 2. Schematic of hadron detector stack

As shown in the Fig. 2, on the proton side the detector stack in the focal plane contains two vertical drift chambers (VDC's), two scintillator planes, S_1 and S_2 , and a Focal Plane Polarimeter (FPP)[17]. The two vertical drift chambers (VDC) installed close to the focal plane of each HRS define position and angle with high precision. The trigger was defined by a coincidence between the signals from scintillator planes S_1 and S_2 in the two HRS's. The FPP consists of the two front and two rear straw-tube drift chambers, and a graphite analyzer. The two front chambers in the FPP are used to define the incident proton trajectory and the rear chambers define the proton trajectory after scattering in the graphite. The active areas of the two front chambers are $60 \times 209 \text{ cm}^2$, for chambers 3 and 4 they are $124 \times 272 \text{ cm}^2$ and $142 \times 295 \text{ cm}^2$, respectively. The spatial resolution of the tracks in straw-tube drift chamber is about $250 \text{ } \mu\text{m}$. The graphite analyzer consists of 5 sets of graphite plates that can be moved out to collect straight-through trajectories for alignment of the FPP chambers.

5. Results and Discussion

The data from our experiment are shown with filled circles in Fig. 3a as the $\mu G_{Ep}/G_{Mp}$ ratio and in Fig. 3b as the ratio $Q^2 F_2/F_1$ [18], obtained from Eq. (1); in both figures only the statistical uncertainties are shown. Three sources contribute to the systematic uncertainty: measurement of the target variables, positioning and field strength of the HRS magnetic elements, and uncertainties in the dipole fringe field characterization. The systematic uncertainties would shift all data points in the same direction, either up or down.

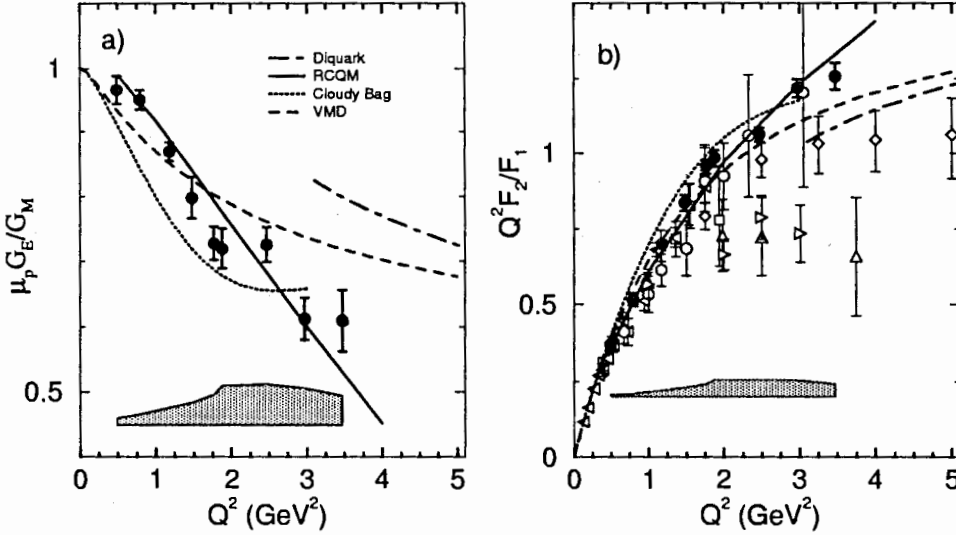


Figure 3. (a) The ratio $\mu_p G_{Ep}/G_{Mp}$ from this experiment, compared with theoretical calculations; the absolute value of σ_{sys} is shown by the shaded area. (b) The ratio $Q^2 F_{2p}/F_{1p}$ for the same data, compared to the same theoretical models as in 3a and world data; Refs. [1]□, [2]◁, [3]◊, [4]▷, [5]◊, [11]*, [19]△

The most important feature of the data is the sharp decline of the ratio $\mu G_{Ep}/G_{Mp}$ from 1 starting at $Q^2 = 0.5 \text{ GeV}^2$ to a value of ~ 0.60 at $Q^2 = 3.5 \text{ GeV}^2$, which indicates that G_{Ep} falls faster than G_{Mp} . This is the first experimental indication that the Q^2 dependence of G_{Ep} and G_{Mp} is definitely different.

The $Q^2 F_2/F_1$ ratio shown in Fig. 3b indicates a continuing increase with Q^2 , contradicting earlier observations based on the data of refs. [4, 5] that it might have reached a constant value as predicted in pQCD: $F_1 \sim \frac{1}{Q^4}$ and $F_2 \sim \frac{1}{Q^6}$. It would be of great interest to explore the larger Q^2 region where

pQCD will dominate. Extension of this experiment to larger Q^2 has become a very interesting prospect and is planned in the near future.

Results from this experiment are consistent with the earlier results of refs. [1, 2, 3] which have much larger uncertainties. Our results are compatible with the SLAC data of Ref. [5] up to about Q^2 of 2.5 GeV², considering the larger uncertainties, but our results are in definite disagreement with the older results of Ref. [4] from SLAC, as shown in Fig. 3b.

The much improved quality of the data from the Jefferson Lab will have an impact on theoretical models. The new data already help to eliminate theoretical models which predict $\mu G_{Ep}/G_{Mp}$ greater than one for $Q^2 > 1$ GeV². The fundamental understanding of the nucleon form factors in terms of QCD is one of the outstanding problems in nuclear physics. So far all theoretical models of the nucleon form factors are based on effective theories; they all rely on a comparison with existing data and their parameters are adjusted to the data. There are two quite different approaches to calculate nucleon form factors; one is based on Vector Meson Dominance, known as VMD[20, 21, 22], and the other is QCD based and includes models like the relativistic constituent quark[23, 24], light-front quark[25, 26], diquark[27], cloudy bag model[28], QCD sum rule[29] and skewed parton distribution[30, 31, 32]. Calculations of the nucleon form factors from lattice QCD are also in progress [33]. In the VMD approach, the photon couples to the nucleon via vector mesons, whereas in QCD based models the photon couples to the quarks directly. It is believed that the transition from hadron-meson to quark-gluon degrees of freedom occurs somewhere in the Q^2 region between 1 and 20 GeV²; this transition region is a difficult area for theoretical models; this explains why so much theoretical work has been done in this domain.

In Fig. 3 we show as a dashed curve the ratios of $\mu_p G_{Ep}/G_{Mp}$ and $Q^2 F_{2p}/F_{1p}$ calculated from the latest published fit to the proton and neutron form factors of Mergell *et al.*[22] based on VMD (not including data from this experiment). These authors use dispersion relations for the form factors, with spectral functions taking into account the dominant vector meson poles as well as the two-pion channel; an asymptotic behavior consistent with pQCD was also included. The VMD models have been successful in describing the data at lower Q^2 values[20, 21] and perturbative QCD has had success at high Q^2 [34].

In the earliest study of the RCQM, Chung and Coester[23] investigated the effect of the constituent quark masses, the anomalous magnetic moment of the quarks, F_{2q} , and the confinement scale parameter. Recently Coester introduced a form factor for F_{2q} to reproduce the present data; the result is the solid curve in Fig. 3[35]. This demonstrates how the new G_{Ep}/G_{Mp} data can help constrain the basic inputs to a particular model.

The dashed-dot curve in Fig. 3 shows the recently re-evaluated di-quark model prediction of Kroll *et al.* [27]. In the limit $Q^2 \rightarrow \infty$ this model is equivalent to the hard-scattering formulation of pQCD. The version of the cloudy bag model used by Lu *et al.* [28] couples a pion field to the quarks inside a bag. As shown in Fig. 3 by the dotted curve, the prediction is low compared to the new data, but this is a simplified version of the model. The authors suggest that one possible future development would be to include $\pi\pi$ interactions.

It is important to compare the theoretical predictions to both the proton and neutron form factors. G_{Mp} has been measured to <5% experimental uncertainty up to $Q^2 = 15 \text{ GeV}^2$. This experiment has reduced the error on G_{Ep}/G_{Mp} to a level comparable to G_{Mp} up to $Q^2 = 3.5 \text{ GeV}^2$. With the new data tighter constraints will be placed on theory to fit both form factors of the proton. In addition, at Jefferson Lab, experiments are planned to measure G_{En} and G_{Mn} , and G_{Ep} to higher Q^2 , together these experiments will further constrain theory.

To conclude, we have presented a new measurement of G_{Ep}/G_{Mp} obtained in a polarization transfer experiment with unprecedented accuracy. The results demonstrate for the first time that the Q^2 dependence of G_{Ep} and G_{Mp} is significantly different. The quality of the JLab data will place a tight constraint on the theoretical models. Results from this experiment combined with future measurements of the neutron form factors will bring us closer to a single description of the structure of the nucleon.

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Recent Results in Deuteron Photodisintegration

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Abstract

Experimental and theoretical studies of deuteron photodisintegration at photon energies above 1 GeV are presented. The cross section might best be explained in a quark picture of the reaction, rather than in a meson-baryon picture, but this result is not definitive. A more stringent constraint results from measurements of the recoil proton polarization at $\theta_{\text{cm}} = 90^\circ$ for photon energies up to 2.5 GeV. The induced polarization is found to vanish above 1 GeV, contrary to meson-baryon model expectations, in which resonances lead to large polarizations. However, the polarization transfer observables do not vanish, in contradiction with hadron helicity conservation and thus with asymptotic perturbative QCD expectations. Additional measurements are planned for clarification.

1. Introduction

The main goal of the experiments is to find a signature of the role of quarks and gluons in nuclei and in nuclear reactions. In the nuclear standard model nuclei and nuclear reactions are described in terms of effective nucleon-nucleon interactions which are mediated by the exchange of mesons. These models have been extended into the GeV region by explicitly including excited nucleon states. At very high energies, the features of nuclear reactions are expected to become simple, yielding distinct signatures for quantum chromodynamics (QCD) effects. In the intermediate energy regime, nonperturbative QCD models, incorporating e.g. quark exchange, quark rescattering,

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and the quark-gluon string model, may become valid. The energy scale at which QCD effects become dominant must be determined experimentally.

2. Theoretical considerations

Two signatures of quark effects will be considered to establish that an exclusive nuclear reaction is in the perturbative regime: the energy dependence of the cross section should be consistent with the constituent counting rules (CCR) [1] and polarization observables should be consistent with hadron helicity conservation (HHC) [2]. HHC arises from the fact that vector interactions (photon or gluon coupling with the quarks) conserve chirality. With HHC, the sum of the components of the hadronic spins along their respective momentum directions is conserved; this leads to predictions about spin observables.

The pQCD prediction of helicity conservation leads to p_y - (coordinate system defined in Figure 1) - vanishing and can be further tested with polarization transfer observables. The induced polarization p_y is given - rewriting the expression from [3] - by:

$$f(\theta)p_y = 2\Im \sum_{i=1}^3 [F_{i,+}^* F_{i+3,-} + F_{i,-} F_{i+3,+}^*]. \quad (1)$$

In this expression, the four amplitudes that conserve hadronic helicity, $F_{1,+}$, $F_{3,-}$, and $F_{5,\pm}$, are multiplied by amplitudes that do not conserve hadronic helicity. However, p_y can systematically vanish without helicity conservation, if, for example, the two amplitudes in each product term have the same phase - as would happen in a meson-baryon calculation without resonances or final state interactions.

The transverse in-plane polarization transfer C_x results from the real part of the same combination of amplitudes as p_y , and also vanishes with HHC. The longitudinal in-plane polarization transfer C_z is given by

$$f(\theta)C_z = \sum_{i=1}^6 \sum_{\pm} \pm |F_{i\pm}|^2, \quad (2)$$

and is generally nonzero. However, applying the assumptions of [4] about relations between the helicity conserving amplitudes at $\theta_{cm} = 90^\circ$, one finds that C_z also vanishes.

It has long been known that many reactions are consistent with the CCR [5], including deuteron photodisintegration [6, 7, 8, 9], but no exclusive reactions have been shown to satisfy HHC. The difficulties of determining spin observables have limited the number of studies. The most detailed investigation was performed for proton-proton elastic scattering [10]. Although the $p - p$ elastic scattering is consistent with CCR, the failure to observe HHC could be attributed to long distance phenomena in which there are three independent scatterings of quarks in the beam proton from quarks in the target proton [11, 12]. This long distance (Landshoff) mechanism is probably strongly suppressed in photoreactions because the incoming photon can only interact with a single quark in the target [13].

The present work is the first direct test of HHC in a photoreaction in a kinematic region where the cross section exhibits scaling behavior. We measured the $\gamma d \rightarrow \bar{p}n$ reaction in the photon energy range 0.5 to 2.5 GeV. Quantities measured included the induced polarization normal to the scattering plane, and the polarization transfer coefficients for transverse and longitudinal spin components in the reaction plane.

3. Experiment

The measurements were performed at the Thomas Jefferson National Accelerator Facility (JLab) Hall A. A polarized electron source was used with a strained GaAs crystal to produce a $\approx 30 \mu\text{A}$ polarized electron beam. The beam helicity state was flipped pseudo-randomly, at 30 Hz. Charge asymmetries between the two helicity states were negligible. The beam polarization was measured with the Hall A Møller polarimeter. The thirteen measurements, taken every few days, averaged about 70%, with typical uncertainties of $\pm 0.3 \%$ (statistics) and $\pm 3.0 \%$ (systematics).

A schematic of the layout of the experiment is shown in Figure 1. Circularly polarized bremsstrahlung photons were generated when the electron beam impinged on a copper radiator 6% of a radiation length thick (4% for the lowest energy, 0.5 GeV), positioned ≈ 73 cm upstream of a 15-cm liquid deuterium target. The polarization of these near endpoint photons can be directly calculated [14]; the ratio P_γ/P_e is 98.4 - 99.8 % under our experimental conditions.

Protons from the target were detected in the Hall A high resolution hadron spectrometer. The detectors used in the focal plane are symbolized in Figure 2.

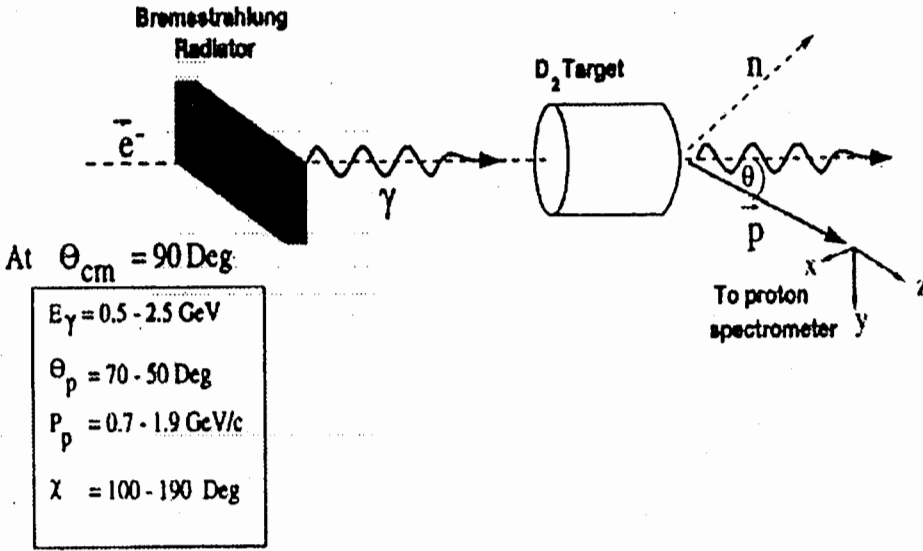


Figure 1. Experimental setup. Note that if the photon momentum is $\vec{k}$ and the proton momentum is $\vec{q}$, the coordinate system is: $\hat{z} = \hat{q}$, $\hat{y} = \hat{k} \times \hat{q}$, $\hat{x} = \hat{y} \times \hat{z}$

The trajectories were measured with the Vertical Drift Chambers (VDCs). Scattering angles, momentum, and interaction position at the target were calculated from the VDC tracks. Two planes of plastic scintillators provided triggering and time of flight information for particle identification. An aerogel Cerenkov counter was used to identify and reject pions, which constitute a $\approx 1\%$ background in these measurements.

The final element in the detector stack was the polarimeter, consisting of front and rear straw chambers that determined the scattering angles of protons in a carbon analyzer. Transverse components of the proton polarization in the focal plane led to azimuthal asymmetries in the scattering distribution. All triggering scintillators were located before the analyzer, to prevent possible false asymmetries, at the expense of reading in events in which the protons were absorbed in the analyzer. The efficiency was large because of the large rear chambers, which detected all protons scattered at angles less than 15° , and had high geometric acceptance for scatterings up to 30° in the analyzer. The induced (transferred) polarization was determined by the

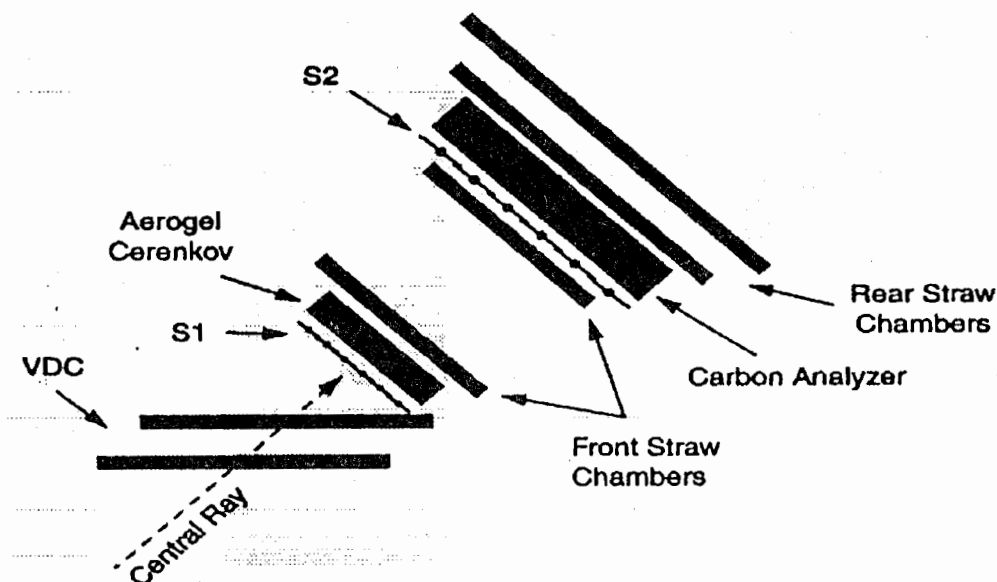


Figure 2. Detector stack in the focal plane of the proton spectrometer

sum (difference) of the azimuthal asymmetry distributions for the two beam helicity states.

The determination and subtraction of background processes, from electrodisintegration and from interactions with the target cell walls, was very similar to the procedures used for previous cross-section measurements [6, 7, 8, 9]. Additional backgrounds included cosmic rays and neutral particles. Cosmic rays were easily rejected with scintillator time-of-flight cuts. Neutral particles interacted with the scintillators to generate triggers, but no tracks in the VDC or polarimeter chambers. The incident photon energy was reconstructed from the scattered proton energy and angle, using two-body photo-disintegration kinematics. Events between the bremsstrahlung endpoint and the onset of π^0 production background were analyzed.

Determination of the proton polarization required a careful treatment of polarimeter systematics. The alignment of the chambers was determined with straight-through trajectories, with the carbon analyzer removed. Additional systematic studies were performed with $\vec{e}p$ elastic scattering measurements at each of the eight spectrometer momentum settings used for the data of this experiment, since the analyzer thickness was varied to optimize the figure of merit for each setting. Polarization transfer in $\vec{e}p \rightarrow e\vec{p}$ allows deter-

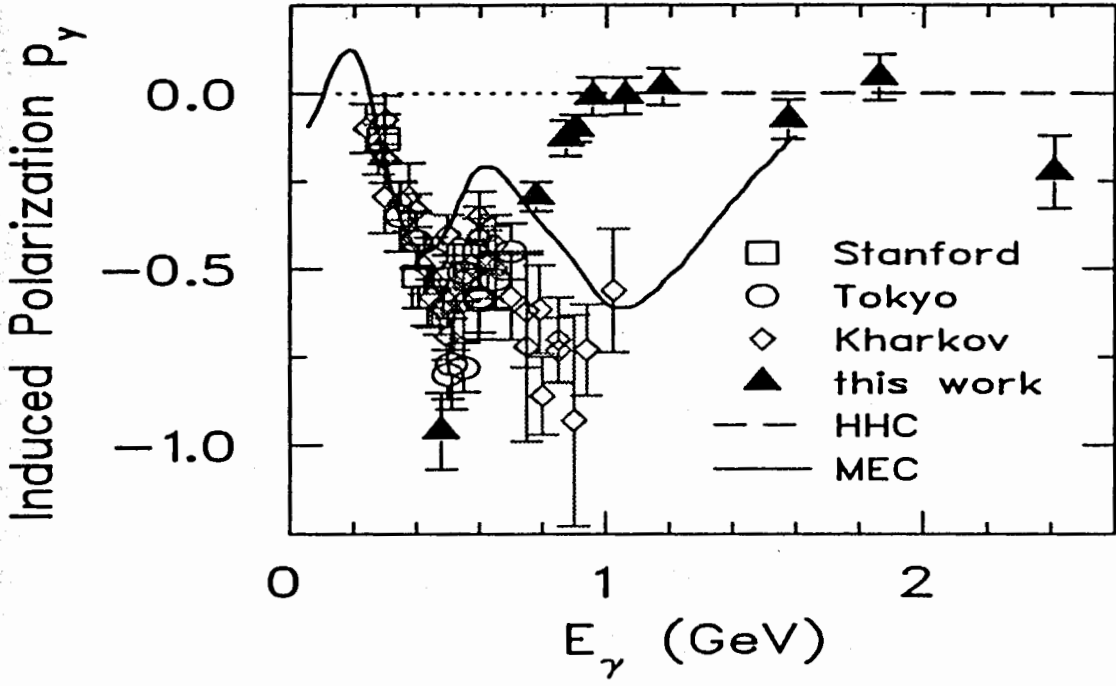


Figure 3. Induced polarization p_y in deuteron photodisintegration at $\theta_{cm} = 90^\circ$. Only statistical uncertainties are shown. The curves are described in the text

mination of both the ratio of the proton's electromagnetic form factors [15] and the carbon analyzing power, after accounting for spin transport through the spectrometer and the beam polarization. The spin transport analysis is similar to that of [16]. Our measurements [17] agree well with previous data for the form factor ratio [16] and for the carbon analyzing power [16, 18, 19]. Neglecting small corrections from two-photon exchange, the induced polarization in ep elastic scattering vanishes, allowing a direct measurement of the false asymmetries in the polarimeter. The induced polarization data are corrected for the measured false asymmetries. The use of the helicity difference largely cancels out the false asymmetries in the polarization transfer data.

4. Results

Here are new results to be considered as the first direct test of HHC in a photoreaction in a kinematic region where the cross section exhibits scaling behavior. For the $\vec{\gamma}d \rightarrow \vec{p}n$ reaction, in the photon energy range 0.5 to 2.5

GeV, the measured quantities were the induced polarization, normal to the scattering plane, p_y , and the polarization transfer coefficients for transverse and longitudinal spin components in the reaction plane, C_x and C_z .

Figure 3 shows our results for the normal component p_y of the induced polarization in deuteron photodisintegration. These data are compared to previous measurements,[3, 20, 21, 22, 23] and theoretical predictions. Similar resonance structure is evident in both the previous data and the Bonn calculation[24] (solid line). The polarization peak near 500 MeV in the calculation results from interference of the Δ resonance with the Born term, while the peak near 1 GeV results from interference of the $D_{1,3}$ and $D_{3,3}$ resonances with the Born term. While our low-energy data are in good agreement with previous measurements, the disagreement of our data with the highest energy Kharkov measurements is evident. Above about 1 GeV, the induced polarization is small, consistent with zero. While the 2.5-GeV point might indicate a deviation from zero, the six highest energy points are consistent with zero, averaging to -0.02 ± 0.02 , with $\chi^2_{\text{total}} = 6.6$, not including systematic uncertainties. Analysis of different false asymmetry models and alignment / tracking procedures, sensitivity to cuts and spin transport, and uncertainty in the carbon analyzing power, leads to an estimated systematic uncertainty of about ± 0.04 for these induced polarizations.

The disagreement of our data with the Bonn prediction is striking, implying a breakdown in the meson-baryon reaction picture, as there appear to be no resonance contributions to the induced polarization above 1 GeV beam energy. The consistency of our measurements above 1 GeV with the pQCD helicity conservation prediction that $p_y = 0$ suggests a systematic vanishing of the polarization, rather than a chance cancellation of amplitudes. The Bonn calculation includes π , ρ , η , and ω exchange, plus all the well-established nucleon and Δ resonances with mass less than 2 GeV and $J \leq 5/2$. Earlier polarization calculations [25, 26], which included only the Δ resonance, have similar predictions at low energies, giving further confidence in the Bonn resonance treatment. While sensitivities in these models make precise calculations difficult, it appears very unlikely that such a model can yield a consistently vanishing polarization while including the baryon resonances. These observations suggest that meson-baryon theories are not an appropriate physical model for high-energy photodisintegration data.

Our data for C_x and C_z are shown in Figure 4. No previous data, and no calculations, exist for these observables. Estimated systematic uncertainties for these data are generally in the range 0.01 - 0.03; the 2.5-GeV C_x and

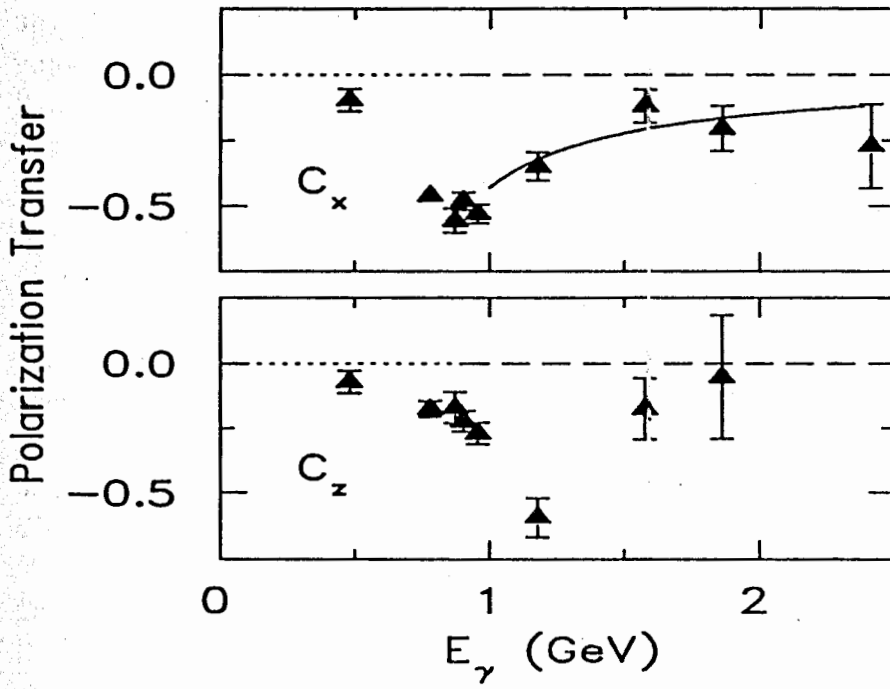


Figure 4. Polarization transfers C_x and C_z at $\theta_{cm} = 90^\circ$. Only statistical uncertainties are shown. The curve is described in the text

1.9-GeV C_z data points have systematic uncertainties of 0.06. No points are shown at 1.1 GeV, as these data were taken with unpolarized beam. The longitudinal polarization transfer data appear to decrease with energy above 1 GeV, and could become consistent with zero near 2 GeV, but uncertainties are large. No point is reported at 2.4 GeV for C_z , due to the unfavorable spin transport which makes the uncertainties here ≈ 1 .

The transverse component C_x is nonzero in the energy range of this experiment, showing clearly that HHC is not valid. Perturbative arguments suggest that spin-flip amplitudes should decrease faster than non-spin-flip amplitudes by one power of t , leading to a $1/t$ dependence for C_x . (This result is well known for the nucleon form factors, for which it is expected that $-tF_2/F_1 \rightarrow \text{constant}$ at large $-t$.) Figure 4 also shows that the C_x data are consistent with this t dependence - the curve is normalized to the data - but more precise data over a wider range are clearly desirable. The scaling of the cross section, starting near $E_\gamma \approx 1$ GeV, coincides with the vanishing of the induced polarization, in strong disagreement with the Bonn calculation. Since it is hard to understand how one can reproduce these data in a meson-

baryon calculation, we suggest that quark model degrees of freedom are more appropriate to understand these data above about 1 GeV. Although scaling of the cross section and vanishing of the induced polarization p_y agree well with the pQCD prediction, the polarization transfer data show violations of HHC, while possibly indicating an approach to this limit [27].

It appears likely that an explanation of these data will require some non-perturbative quark model. Examples of such models include the QCD rescattering, quark-gluon string, and quark exchange models.

The QCD rescattering model [28] calculates deuteron photodisintegration as a convolution of the deuteron wave function, a hard photon-quark coupling, and the proton-neutron scattering amplitude, taken from data. It reproduces the cross section reasonably well, for energies above about 1.5 GeV, although the nominal range of validity for the model requires $-t > 2 \text{ GeV}^2$ and $E_\gamma > 2.4 \text{ GeV}$. Polarization calculations are underway [29].

Polarization calculations are also underway [30] in the quark-gluon string model [31], a low t Regge phenomenology model that reproduces the small angle photodisintegration cross section well. However, the polarization (and cross section) at $\theta_{cm} = 90^\circ$ may be outside the range of validity of this model.

Radyushkin [32] has independently proposed a model similar to the QCD rescattering model, in which the photon is absorbed on two quarks exchanged between the neutron and proton. In this model, the cross section depends approximately on the product of nucleon form factors and phase space factors, which largely reproduces the angle and energy dependence of the data. More detailed calculations in the framework of generalized parton distributions are underway.

5. Future measurements

Plans exist to extend the current experimental results[33]. The recoil proton polarization has been observed to vanish at $\theta_{cm} = 90^\circ$ for photon energies higher than 1 GeV. This is a region where the CCR applies. It is important to measure the angular distribution of this polarization and look for deviation from zero, particularly in regions where the CCR does not work. These measurements would be straightforward with the existing setup and would require only a limited amount of beam time. Uncertainty also remains on the energy from where pQCD and HHC can be apply. We have shown that the results up to 2.5 GeV on the polarization transfer observables are

not interpretable as hadron helicity conservation whereas those on induced polarisation are. An extension of the same measurements to higher energies would get closer to the expected limit of validity of pQCD and may lead to unified results. Both proposals have been recently approved.

6. Summary

The recoil proton polarization in deuteron photodisintegration at $\theta_{cm} = 90^\circ$ has been recently measured for photon energies from 0.5 to 2.5 GeV. The induced polarization vanishes above $E_\gamma \approx 1$ GeV. This surprising behavior, in contrast with expectations from a meson-baryon calculation, suggests that one should employ a quark model picture to understand the data. The observation of nonzero polarization transfer C_x and C_z indicates a violation of hadronic helicity conservation. However, the general trend of the measured polarization observables as E_γ increases above 1 GeV is consistent with the perturbative expectation of a monotonic decrease with increasing $-t$; if precise higher energy measurements were to confirm this behavior, the data would be strongly suggestive of pQCD. Nonperturbative quark models have shown rough agreement with cross section data, and results for the polarization calculations in progress are eagerly awaited.

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The Study of Reaction of Deuteron Fragmentation into Cumulative Pions

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Abstract

The possibility to use the reaction of deuterons fragmentation into cumulative (subthreshold) pions emitted forward is analyzed. The inclusive relativistic invariant spectrum of pions and tensor analyzing power T_{20} and A_{yy} are calculated in the framework of relativistic impulse approximation for different kinds of the nucleon models of deuteron. These calculations shown that T_{20} and A_{yy} have weak dependence from amplitude of pion production in hadron-hadron collisions. The results of calculations are compared with experimental data.

Introduction

The study of nuclei component at short ($1 < fm$) internucleon distances (high internal momentum $> 0.2 GeV/c$) is interesting for understanding what has happened when nucleons are separated by distances less or equal to nucleon size. This information can be obtained in experiment with leptonic or hadronic probes. Reactions with leptonic probes are easy than reactions with hadronic probes for theoretical interpretation but have less cross section. In more popular deep inelastic scattering of leptons high internal momentum corresponds to the region of Bjorken variable $x_b \geq 1$ where the cross section is too small [1]. The small cross section is one of the reason way at present time the data for nuclei structure in deep inelastic scattering are obtained only for $x_b \leq 1$ [1, 2]. One of possible way to study high momentum components in nuclei are the reactions with cumulative particle production. Cumulative particles [3, 4] are meant particles produced in the fragmentation region of one of the colliding particles beyond the kinematic limit of free nucleon-nucleon collisions.

The deuteron nucleus is of the particular interest as more studied from the experimental (static characteristics, formfactors and so on) and theoretical points of view. The non trivial spin structure of deuteron (connected with non-zero quadruple momentum) give the easy way to take additional information from studing spin structure at short internucleon distances.

The investigation of polarization phenomena by fragmentation of deuterons at middle and high energies in the kinematical region forbidden for the emission of hadrons by free $N - N$ scattering has recently become very topical. This kinematical region corresponds to the values of the light cone variable $x = 2(E' + p')/(E_D + p_D) \geq 1$ where E', E_D and p', p_D are the energies and moment of the final hadron and deuteron respectively. The polarization effects can be considered as the more precise tool for the study of the deuteron structure at small distances in comparison to the inclusive spectra of hadrons produced by the deuteron fragmentation. It can be seen from the experimental and theoretical study about the fragmentation of deuterons to protons [5, 6] and [7]. The theoretical analysis of such processes has shown very large sensitivity of the deuteron tensor analyzing power T_{20} and polarization transfer κ to the used deuteron wave function (DWF) and especially to the reaction mechanism. It has been shown, not one relativistic form of the DWF can describe T_{20} at $x \geq 1.7$ measured by $Dp \rightarrow pX$ striping. On the other, hand the inclusion of the reaction mechanism: the impulse approximation and the secondary interaction of produced hadrons can describe

both the inclusive spectrum and T_{20} at $x \leq 1.7$ using only the nucleon degrees of freedom. The inclusion of the non-nucleon degrees of freedom, it can be either six quark state or the composition of $\Delta\Delta$, NN^* , $NN\pi$, etc. states in the deuteron, allowed to describe the experimental data about the inclusive proton spectrum at $x \geq 1.7$ [7]. Many papers were dedicated to the theoretical analysis of the deuteron stripping to protons, see for example Refs. in [4, 7]. However till now there is not the unified theoretical description of T_{20} at the whole kinematic region of protons emitted forward by the $Dp \rightarrow pX$ deuteron break-up reaction.

For the small internucleon distances (equal or less of hadron size) the use of nucleon as a quasy-particle seems to be groundless, and effects of manifestation of non-nucleon degrees of freedom in deuteron could be expected [17, 3, 10, 7]. In order to study this effects is natural to use as a probe hadrons with different quarks contents.

From this point of view recently published [8] the experimental data about T_{20} in the reaction $Dp \rightarrow \pi X$ with the pion emitted at zero angle looks like additional to the data on deuteron break-up reaction. They show very small approximately constant value of the tensor analyzing power T_{20} for the fragmentation of deuteron to pions $Dp \rightarrow \pi X$ at $x \geq 1$. The mechanism of this reaction is mainly impulse approximation, as it is shown in [9] the secondary interaction or the final state interaction (FSI) is very small and can be neglected. The quite big yield of high momentum pions produced by $p-D$ and $p-A$ collisions in the kinematical region forbidden for the free $N-N$ scattering was explained by both few-nucleon correlation

models [4] and [10] or multiquark bags one [11, 12]. However the polarization phenomena by deuteron fragmentation to pions were out side of these models.

In this paper we present a relativistic invariant analysis of the deuteron tensor analyzing power T_{20} and unpolarized pion spectrum in backward inclusive $p + D \rightarrow \pi(180^\circ) + X$ reaction. The main goal is to describe this reaction in a consistent relativistic approach based on nucleon model of deuteron. A fully covariant expression for all quantities is obtained within the Bethe-Salpeter (BS) formalism. This way is possible to come to general conclusions about the amplitude of the process not to seen in the non-relativistic approach. On the other hand, the non-relativistic limit will be recovered and some links to the non-relativistic corrections can be established. Such analysis of the deuteron models is in our opinion very important assuming the searching the deviation the experimental from calculations based on nucleon model in order to understand the possible value of effects of non-nuclnucleon degrees of freedom.

Relativistic impulse approximation

We consider the inclusive reaction of the type $D + p \rightarrow \pi(0^\circ) + X$, where the typical initial energy of the polarized deuteron (D) in the order of a few GeV, and the final pion is detected in the forward direction beyond the kinematic limit of free nucleon-nucleon collisions.

In the impulse approximation this reaction is presented by the Feynman diagram shown in Fig.1. The amplitude of this process $\mathcal{T}_{pD}^\pi$ can be written in the following relativistic invariant form:

$$\mathcal{T}_{pD}^\pi \equiv \mathcal{T}(Dp \rightarrow \pi X) = (\bar{U}_Y \Gamma_{NN})_{\alpha\beta} \bar{u}_\gamma^{(\sigma_{p'})}(p') \left(\frac{\hat{n} + m}{n^2 - m^2} \right)_{\beta\delta} u_\alpha^{(\sigma_p)}(p) (\Gamma_\mu(D, q) C)_{\delta\gamma} \xi_M^\mu(D). \quad (1)$$

where μ is a Lorentz index and $C = i\gamma_2\gamma_0$ is a charge conjugation Dirac matrix, M is the deuteron spin projection. Here the deuteron vertex $(\Gamma_\mu(D, q)C)$ satisfies the BS equation and depends on the

relative momentum $q = (n - p')/2$ and total momentum $D = n + p'$ of the deuteron, $\xi_M^\mu(D)$ is the four-vector of the deuteron polarization. It satisfies to the following equations:

$$\begin{aligned} \xi^{\mu M}(D)D_\mu &= 0, \quad \xi^{\mu M}(D)\xi_{\mu M'}(D) = -\delta_{M'}^M, \\ \sum_M (\xi_{\mu M}(D))^* \xi_{\nu M}(D) &= -g_{\mu\nu} + \frac{D_\mu D_\nu}{M^2}, \end{aligned} \quad (2)$$

Squaring this amplitude one can write the relativistic invariant inclusive pion spectrum of the reaction $Dp \rightarrow \pi X$ in the following form:

$$\rho_{pD}^\pi = \varepsilon_\pi \frac{d\sigma}{d^3p_\pi} = \frac{1}{(2\pi)^3} \int \frac{\sqrt{\lambda(p, n)}}{\sqrt{\lambda(p, D)}} \rho_{pN}^\pi(s_{pn}, p_\pi) \cdot [\rho_{\mu\nu}(D)\Phi^{\mu\nu}(D, q)] \frac{m^2 d^3p'}{\varepsilon'}, \quad (3)$$

where $s_{pN} = (p + n)^2$, p, n are four-momenta of the proton-target and intra-deuteron nucleon respectively, $\rho_{pN}^\pi \equiv \varepsilon_\pi \frac{d\sigma}{d^3p_\pi}$ is the relativistic invariant inclusive spectrum of pions produced by interaction of the intra-deuteron nucleon with the proton-target, $\rho_{\mu\nu}(D)$ is the density matrix of the deuteron [43]:

$$\begin{aligned} \rho_{\mu\nu}(D) &= (\xi_{\mu M}(D))^* \xi_{\nu M}(D) = \frac{1}{3} \left(-g_{\mu\nu} + \frac{D_\mu D_\nu}{M^2} \right) + \frac{1}{2} (W_\lambda)_{\mu\nu} s_D^\lambda - \\ &\left[\frac{1}{2} \left((W_{\lambda_1})_{\mu\rho} (W_{\lambda_2})_{\rho\nu} + (W_{\lambda_2})_{\mu\rho} (W_{\lambda_1})_{\rho\nu} \right) + \frac{2}{3} \left(-g_{\lambda_1\lambda_2} + \frac{D_{\lambda_1} D_{\lambda_2}}{M^2} \right) \left(-g_{\mu\nu} + \frac{D_\mu D_\nu}{M^2} \right) \right] p_D^{\lambda_1\lambda_2} \end{aligned} \quad (4)$$

with $(W_\lambda)_{\mu\nu} = i\varepsilon_{\mu\nu\gamma\lambda} D^\gamma / M$; s_D is the spin vector and p_D is the alignment tensor of the deuteron.

The full symmetrical tensor $\Phi_{\mu\nu}(D, q)$ in Eq.(3) reads

$$\Phi_{\mu\nu}(D, q) = \frac{1}{4} \text{Tr} \left[\bar{\Psi}_\mu \left(\frac{\hat{n} + m}{m} \right)^2 \Psi_\nu \frac{\hat{p}' - m}{m} \right] = -f_0(n^2)g_{\mu\nu} + f_1(n^2) \frac{q_\mu q_\nu}{m^2}. \quad (5)$$

By the proof of eq.(5) we introduced the modified vertex, $\Psi_\mu(D, q)$:

$$\Psi_\mu(D, q) = \frac{\Gamma_\mu(D, q)}{m^2 - n^2 - i0} = \varphi_1(n^2)\gamma_\mu + \varphi_2(n^2)\frac{n_\mu}{m} + \frac{\hat{n} - m}{m} \left(\varphi_3(n^2)\gamma_\mu + \varphi_4(n^2)\frac{n_\mu}{m} \right). \quad (6)$$

Substituting Eq.(6) into Eq.(5) and calculating the trace, one can find explicit forms of the invariant functions $f_{0,1}$

$$\begin{aligned} f_0(n^2) &= \frac{M^2}{m^2} \left(\varphi_1 - \frac{m^2 - n^2}{m^2} \varphi_3 \right) \varphi_1 - \left(\frac{m^2 - n^2}{m^2} \right)^2 (\varphi_1 - \varphi_3) \varphi_3; \\ f_1(n^2) &= -4 \left\{ \varphi_1 + \varphi_2 - \frac{m^2 - n^2}{m^2} \left(\frac{\varphi_2}{2} + \varphi_3 + \varphi_4 \right) \right\} (\varphi_1 + \varphi_2) \\ &+ \frac{M^2}{m^2} \left(\varphi_2 - \frac{m^2 - n^2}{m^2} \varphi_4 \right) \varphi_2 - \left(\frac{m^2 - n^2}{m^2} \right)^2 (\varphi_2 + 2\varphi_3 + \varphi_4) \varphi_4. \end{aligned} \quad (7)$$

The corresponding invariant scalar functions $\varphi_i(n^2)$ of the deuteron vertex with one on-shell nucleon can be computed in any reference frame. Let us note that in our case, when one particle is an on-mass shell, only four partial amplitudes contribute to the process, namely in the ρ spin classification,

$u = {}^3S_1^{++}$, $w = {}^3D_1^{++}$, $v_s = {}^1P_1^{-+}$ and $v_t = {}^3P_1^{-+}$. We can write φ_i in the deuteron rest frame in order to relate them to the non-relativistic S -, D - and P -waves of the deuteron. In this case, the invariant functions take the following forms:

$$\begin{aligned}\mathcal{N}\varphi_1 &= u - \frac{w}{\sqrt{2}} - \sqrt{\frac{3}{2}} \frac{m}{|\mathbf{q}|} v_t ; \\ \mathcal{N}\varphi_2 &= -\frac{m}{(E_q + m)} u - \frac{m(2E_q + m)}{|\mathbf{q}|^2} \frac{w}{\sqrt{2}} + \sqrt{\frac{3}{2}} \frac{m}{|\mathbf{q}|} v_t ; \\ \mathcal{N}\varphi_3 &= -\sqrt{\frac{3}{2}} \frac{mE_q}{|\mathbf{q}|(2E_q - M)} v_t ; \\ \mathcal{N}\varphi_4 &= \frac{m^2}{M(E_q + m)} u - \frac{m^2(E_q + 2m)}{M|\mathbf{q}|^2} \frac{w}{\sqrt{2}} - \sqrt{3} \frac{m^2}{|\mathbf{q}|(2E_q - M)} v_s ,\end{aligned}\quad (8)$$

where all the vertex functions are determined in the deuteron rest frame and all the kinematic variables in Eqs.(8) have to be evaluated in this system; $E_q = \sqrt{|\mathbf{q}|^2 + m^2}$. The normalization factor $\mathcal{N}^{-1} = \pi\sqrt{2/M}$ is chosen according to non-relativistic normalization DWF: ¹

$$\int_0^\infty |\mathbf{q}|^2 d|\mathbf{q}| (u^2(|\mathbf{q}|) + w^2(|\mathbf{q}|)) = 1$$

The relativistic invariant functions $f_{0,1}(|\mathbf{q}|)$ (7) can be rewritten in terms of these spin-orbit momentum wave functions as

$$\begin{aligned}f_0(|\mathbf{q}|) &= \mathcal{N}^{-2} \frac{M^2}{m^2} \left\{ \left(u - \frac{w}{\sqrt{2}} \right)^2 + \sqrt{6} \frac{|\mathbf{q}|}{m} \left(u - \frac{w}{\sqrt{2}} \right) v_t - \frac{3}{2} v_t^2 \right\} ; \\ \frac{2}{3} \frac{|\mathbf{q}|^2}{m^2} f_1(|\mathbf{q}|) &= \mathcal{N}^{-2} \frac{M^2}{m^2} \left\{ 2\sqrt{2}uw + w^2 + v_t^2 - 2v_s^2 - \frac{4}{\sqrt{3}} \frac{|\mathbf{q}|}{m} \left[\left(u - \frac{w}{\sqrt{2}} \right) \frac{v_t}{\sqrt{2}} + (u + \sqrt{2}w) v_s \right] \right\} .\end{aligned}\quad (11)$$

Then, all the observables can be computed in terms of positive- and negative-energy wave functions u, w and v_s, v_t , respectively. The contribution of the positive-energy waves u, w to the observables results in the non-relativistic limit. The parts containing the negative-energy waves v_s, v_t have a pure relativistic origin, and consequently they manifest genuine relativistic correction effects.

Using an explicit form of the density matrix (4), one can write

$$\Phi \equiv \rho_{\mu\nu} \Phi^{\mu\nu} = \Phi^{(u)} + \Phi_{\lambda}^{(v)} s_D^{\lambda} + \Phi_{\lambda_1 \lambda_2}^{(t)} p_D^{\lambda_1 \lambda_2} .\quad (12)$$

¹Note, the Gross definition [44] of DW $\tilde{\Psi}_\mu(q)$ is related to the BS vertex $\Psi_\mu(q)$ (6) as the follows:

$$\tilde{\Psi}_\mu(q) = \Psi_\mu(-q) .\quad (9)$$

Comparing it with Eqs.(46) of Ref. [44], one can see that the Gross wave functions $\tilde{u}(q), \tilde{w}(q)$ and $\tilde{v}_s(q), \tilde{v}_t(q)$ are connected with our wave functions (8) as

$$\begin{aligned}\tilde{u}(q_0, |\mathbf{q}|) &= u(-q_0, |\mathbf{q}|) ; \quad \tilde{w}(q_0, |\mathbf{q}|) = w(-q_0, |\mathbf{q}|) ; \\ \tilde{v}_s(q_0, |\mathbf{q}|) &= -v_s(-q_0, |\mathbf{q}|) ; \quad \tilde{v}_t(q_0, |\mathbf{q}|) = -v_t(-q_0, |\mathbf{q}|) ,\end{aligned}\quad (10)$$

where $q_0 = M/2 - E_q$.

The superscripts (u, v, t) denote unpolarized, vector polarized and tensor polarized cases, respectively:

$$\begin{aligned}\Phi^{(u)}(\mathbf{q}) &= f_0 + \frac{1}{3} \frac{|\mathbf{q}|^2}{m^2} f_1 ; \\ \Phi^{(v)}_{\lambda}(\mathbf{q}) &= 0 ; \\ \Phi^{(t)}_{\lambda_1 \lambda_2}(\mathbf{q}) &= \left[\frac{1}{3} \frac{|\mathbf{q}|^2}{m^2} \left(-g_{\lambda_1 \lambda_2} + \frac{D_{\lambda_1} D_{\lambda_2}}{M^2} \right) - \left(-g_{\lambda_1 \mu} + \frac{D_{\lambda_1} D_{\mu}}{M^2} \right) \left(-g_{\lambda_2 \nu} + \frac{D_{\lambda_2} D_{\nu}}{M^2} \right) \frac{q^{\mu} q^{\nu}}{m^2} \right] f_1 .\end{aligned}\quad (13)$$

Let us consider now the case when the deuteron has a tensor polarization. If the initial deuteron is only aligned due to the p_D^{zz} component, then the inclusive spectrum of the reaction $\mathbf{D} + p \rightarrow \pi + X$ (3) can be written in the form:

$$\rho_{pD}^{\pi}(p_D^{zz}) = \rho_{pD}^{\pi} [1 + \mathcal{A}_{zz} \cdot p_D^{zz}] , \quad (14)$$

where ρ_{pD}^{π} is the inclusive spectrum for the case of unpolarized deuterons and $\mathcal{A}_{zz} \equiv \sqrt{2} T_{20}$ ($-\sqrt{2} \leq T_{20} \leq 1/\sqrt{2}$) is the tensor analyzing power. One can write:

$$\rho_{pD}^{\pi} = \frac{1}{(2\pi)^3} \int \frac{\sqrt{\lambda(p, n)}}{\sqrt{\lambda(p, D)}} [\rho_{pN}^{\pi} \cdot \Phi^{(u)}(|\mathbf{q}|)] \frac{m^2 d^3 q}{E_q} ; \quad (15)$$

$$\rho_{pD}^{\pi} \cdot \mathcal{A}_{zz} = -\frac{1}{(2\pi)^3} \int \frac{\sqrt{\lambda(p, n)}}{\sqrt{\lambda(p, D)}} [\rho_{pN}^{\pi} \cdot \Phi^{(t)}(|\mathbf{q}|)] \left(\frac{3 \cos^2 \vartheta_{\mathbf{q}} - 1}{2} \right) \frac{m^2 d^3 q}{E_q} . \quad (16)$$

where

$$\begin{aligned}\Phi^{(u)}(|\mathbf{q}|) &= f_0(|\mathbf{q}|) + \frac{1}{3} \frac{|\mathbf{q}|^2}{m^2} f_1(|\mathbf{q}|) \\ &= \mathcal{N}^{-2} \frac{M^2}{m^2} \left\{ u^2 + w^2 - v_t^2 - v_s^2 + \frac{2}{\sqrt{3}} \frac{|\mathbf{q}|}{m} [(\sqrt{2} v_t - v_s) u - (v_t + \sqrt{2} v_s) w] \right\} ;\end{aligned}\quad (17)$$

$$\begin{aligned}\Phi^{(t)}(|\mathbf{q}|) &= \frac{2}{3} \frac{|\mathbf{q}|^2}{m^2} f_1(|\mathbf{q}|) \\ &= \mathcal{N}^{-2} \frac{M^2}{m^2} \left\{ 2\sqrt{2} u w + w^2 + v_t^2 - 2v_s^2 - \frac{4}{\sqrt{3}} \frac{|\mathbf{q}|}{m} \left[\left(u - \frac{w}{\sqrt{2}} \right) \frac{v_t}{\sqrt{2}} + (u + \sqrt{2} w) v_s \right] \right\}\end{aligned}\quad (18)$$

It is intuitively clear that the nucleons in the deuteron are mainly in the states with angular momenta $L = 0, 2$ (see also a numerical analysis of the solutions of the BS equation in terms of amplitudes within the ρ -spin basis [41]), the probability of states with $L = 1$ ($v_{s,t}$) in Eqs.(17,18) is much smaller than the probability for the u, w configurations. Moreover, it can be shown that the u and w waves directly correspond to the non-relativistic $\mathcal{S}$ and $\mathcal{D}$ ones. Therefore, Eqs.(17,18) with only u, w waves can be identified as main contributions to the corresponding observables, and they can be compared with their non-relativistic analogies. The other terms possessing contributions from $\mathcal{P}$ -waves are proportional to $\mathbf{q}/m$ (the diagonal terms in $v_{s,t}$ are negligible). Due to their pure relativistic origin, one can refer to them as relativistic corrections.

In a many work relativistic effects were considered in a so-called minimal relativization scheme [51, 4]. In this scheme the following (i) replacing the argument of the non-relativistic wave functions

by the light-cone variable $k = (k_{\perp}, k_{\parallel})$

$$k^2 = \frac{m^2 + k_{\perp}^2}{4x(1-x)} - m^2; \quad k_{\parallel} = \sqrt{\frac{m^2 + k_{\perp}^2}{x(1-x)}} \left(\frac{1}{2} - x \right). \quad (19)$$

where $x = (E_{\pi} + |q| \cos \vartheta(q))/M = (\varepsilon' - p'_{\parallel})/M$; $|k_{\perp}| = p'_{\perp}$ in the deuteron rest frame, and (ii) multiplying the wave functions by the factor $\sim 1/(1-x)$. It results in a shift of the argument towards larger values, and the wave function itself decreases more rapidly. This effect of suppressing the wave function is compensated by the kinematic factor $1/(1-x)$. In this work the calculation in the framework of minimal relativization scheme have been performed also.

In the *BS* approach the relativistic effects are of a dynamic nature [42] and not reduced to a simple shift in arguments. In addition to *S* and *D* waves, it contains negative energy components, i.e., *P* waves. From calculation it followed that they play a more important role for the polarization observables.

Results and discussion

Below, the calculated results of the inclusive relativistic invariant pion spectrum and the tensor analyzing power in the fragmentation process $Dp \rightarrow \pi X$ are presented and compared with the available experimental data [3, 8]. These experimental data are presented as a functions of the so-called cumulative scaling variable x_c ("cumulative number") [14]. For our reaction, this variable is defined as follows:

$$x_c = 2 \frac{(p\pi) - \mu^2/2}{(Dp) - Mm - (D\pi)} = 2 \frac{t - m^2}{(t - m^2) + (M + m)^2 - s_X} \leq 2. \quad (20)$$

In the rest frame of the deuteron $D = (M, 0)$, it can be rewritten in the form:

$$x_c = 2 \frac{EE_{\pi} - pp_{\pi} \cos \vartheta_{\pi} - \mu^2/2}{M(E - E_{\pi} - m)} \rightarrow 2 \frac{E}{T_p} \frac{\alpha}{1 - E_{\pi}/T_p}, \quad (21)$$

where $\alpha = (E_{\pi} - \pi \cos \vartheta_{\pi})/M$ is a light-cone variable. The value of x_c corresponds to a minimum mass (in nucleon mass units) of part of the projectile nucleus (deuteron) involved in the reaction. The value of x_c larger than 1 corresponds to the a cumulative pion. The meaning of this variable is closed to the Bjorken variable x_b commonly used in deep inelastic scattering.

In our discussion we will compare the obtained results with that, what is known for deuteron (polarized and unpolarized) fragmentation into proton $D + A \rightarrow p(0^\circ) + X$. It is one of the more intensively studied reaction with hadronic probe because it has a big cross section and rather a simple relation of the inclusive spectrum (ρ_{Dp}^p) and polarization observables to the *S*- and *D*-waves of the DWF obtained within in spectator mekhanizm for IA. For example, the invariant cross-section and the tensor analyzing power T_{20} within IA can be written in the following simple form:

$$\rho_{Dp}^p \sim \sigma_{NN}^{tot} (u^2 + w^2) \quad (22)$$

$$T_{20} = -\frac{1}{\sqrt{2}} \frac{2\sqrt{2} u w + w^2}{u^2 + w^2} \quad (23)$$

Invariant Spectrum of Pions
 $D + p \rightarrow \pi^+(0^\circ) + X; P_p = 9 \text{ GeV}/c$

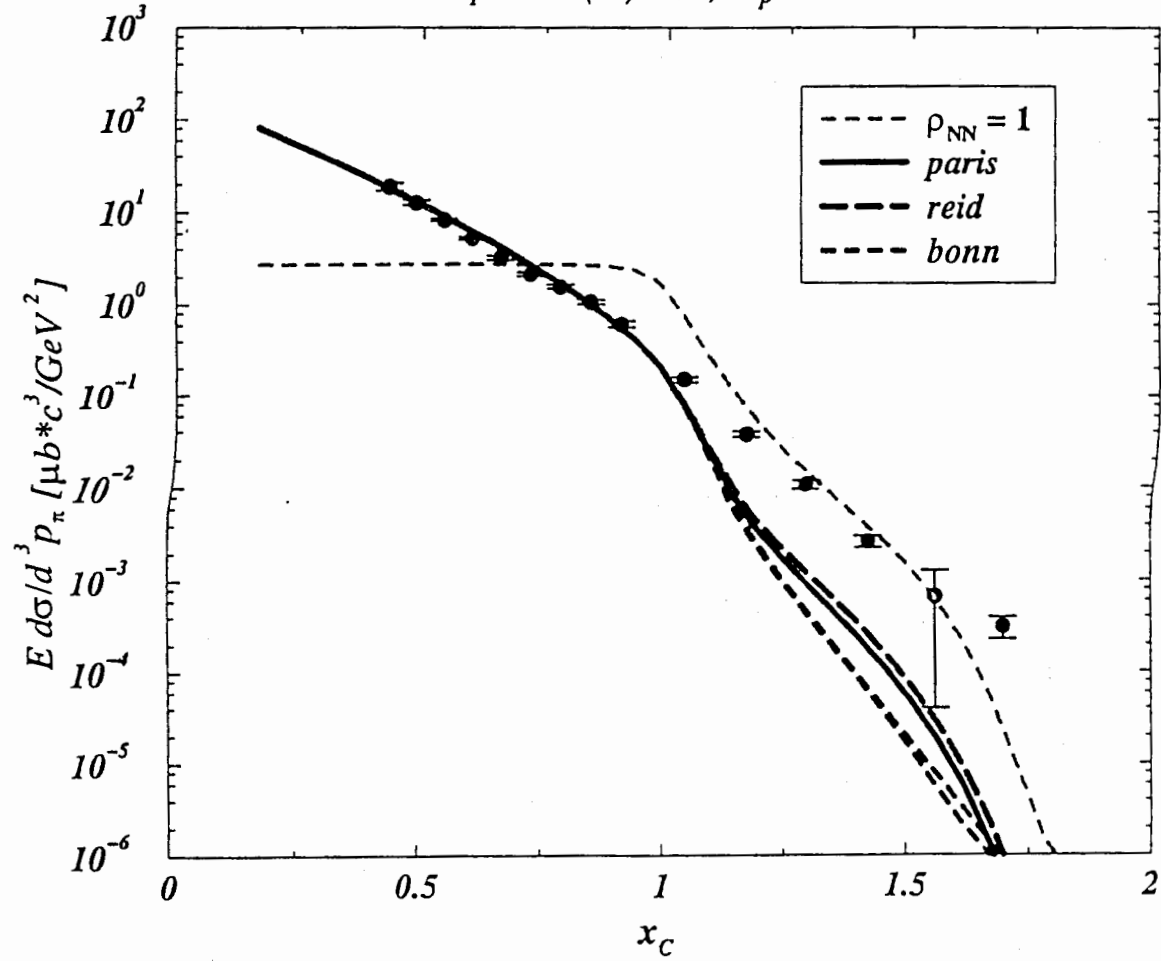


FIG.1. The invariant spectrum of the backward pions in the deuteron fragmentation reaction calculated in the relativistic impulse approximation using various types of the nonrelativistic DWF. The calculation results are compared with the experimental data from [3] for the value of the projectile proton momentum $P_p = 9 \text{ GeV}/c$. The thin dashed curve corresponds to the calculus by neglecting the dependence of the elementary vertex $NN \rightarrow \pi Y$ on the relativistic invariant variables

This relation does not depend on the amplitude of elementary reaction $pn \rightarrow pX$ which is taken in IA as an off-mass shell. As shown in [7], both the differential cross section and T_{20} for fragmentation $D + p \rightarrow p(0^\circ) + X$ can be described within the IA at internal momentum $k \leq 0.2 \text{ GeV}/c$ only. At larger momenta k , secondary interactions, in particular the triangle graphs with a virtual pion, have to be taken into account in order to describe these observables least satisfactorily.

However, as shown in [27] for the pion production $D + p \rightarrow \pi(0^\circ) + X$ at the cumulative over region the rescattering mechanism is kinematically suppressed. It is way we believe that IA have to give us resonable discription of this rection. One of the main usertanties of this calculation is connected with

the vertex $NN \rightarrow \pi Y$ which is taken off-mass shell and over wide range off initial energies S_{NN} . In order to understand this uncertainty the calculations with two kind of this vertex was carried out. In more realistic calculation the vertex was taken on-mass shell corresponding differential cross section proposed in [37] was used. In unrealistic calculation the corresponding differential cross section was taken as a constant.

The results of our calculations for the invariant spectrum of pions produced in the $D + p \rightarrow \pi(0^\circ) + X$ reaction are presented in Fig. (1-3) for different kind of DWF and different relativization schemes. From Fig. 1 one can see a large sensitivity of the inclusive spectrum to the $NN \rightarrow \pi Y$ vertex.

Invariant Spectrum of Pions
 $D + p \rightarrow \pi^+(0^\circ) + X ; P_p = 9 \text{ GeV}/c$

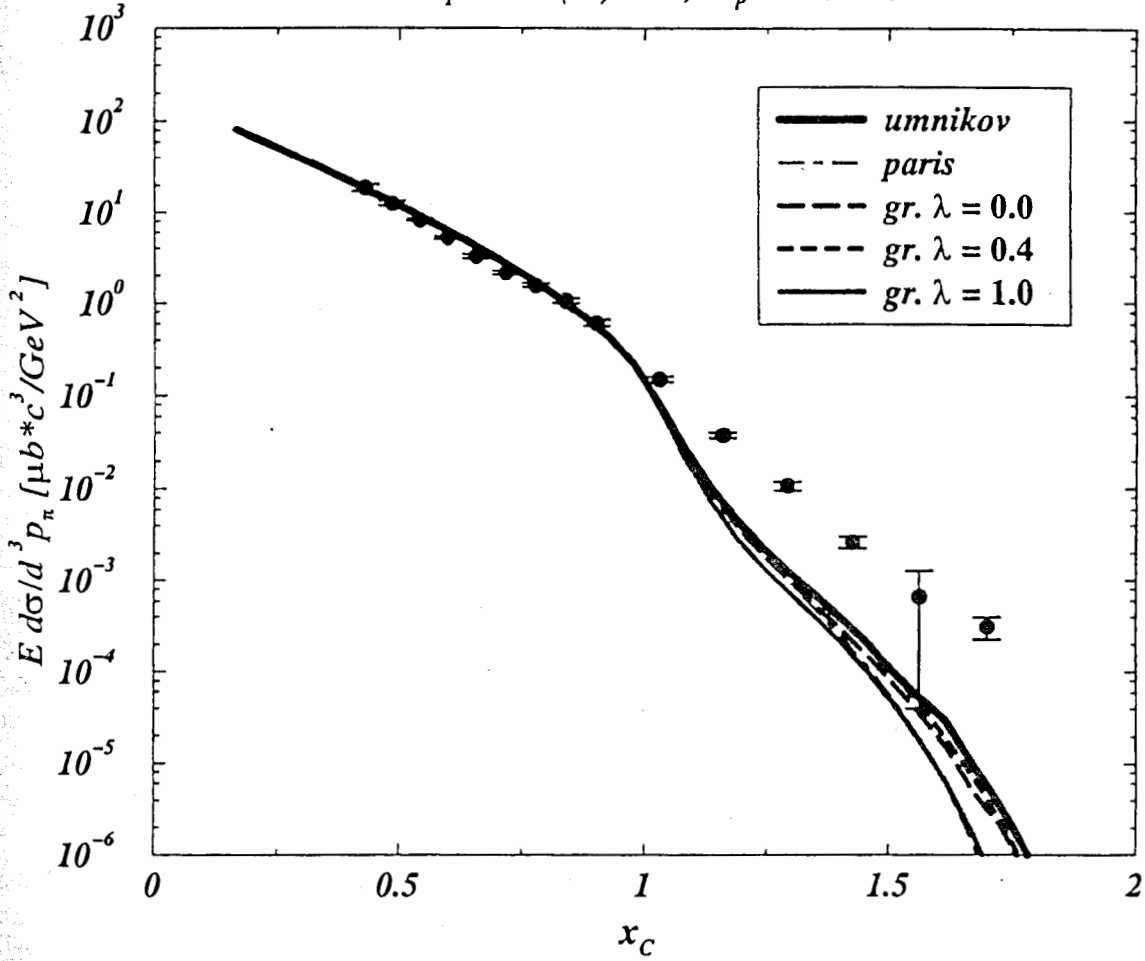


FIG.2. The invariant spectrum calculated by using two forms of the relativistic DWF's, [39] and [44]. The experimental data are taken from [3]. The thin solid line corresponds to the DWF [39], where the total probability of the small components: $P_v = \int_0^\infty p^2 dp \cdot [v_t^2 + v_s^2] \simeq 0.2 \%$. The long-dashed, dashed and thick solid lines represent the calculations with Gross's DWF by using the mixing parameter $\lambda = 0.0, 0.4$ and 1.0 respectively [45] that correspond to the small component probabilities $P_v = 0.03 \%, 0.44 \%$ and 1.46% . The dot-dashed line corresponds to the nonrelativistic Paris DWF

Invariant Spectrum of Pions
 $D + p \rightarrow \pi^+(0^0) + X; P_p = 9 \text{ GeV}/c$

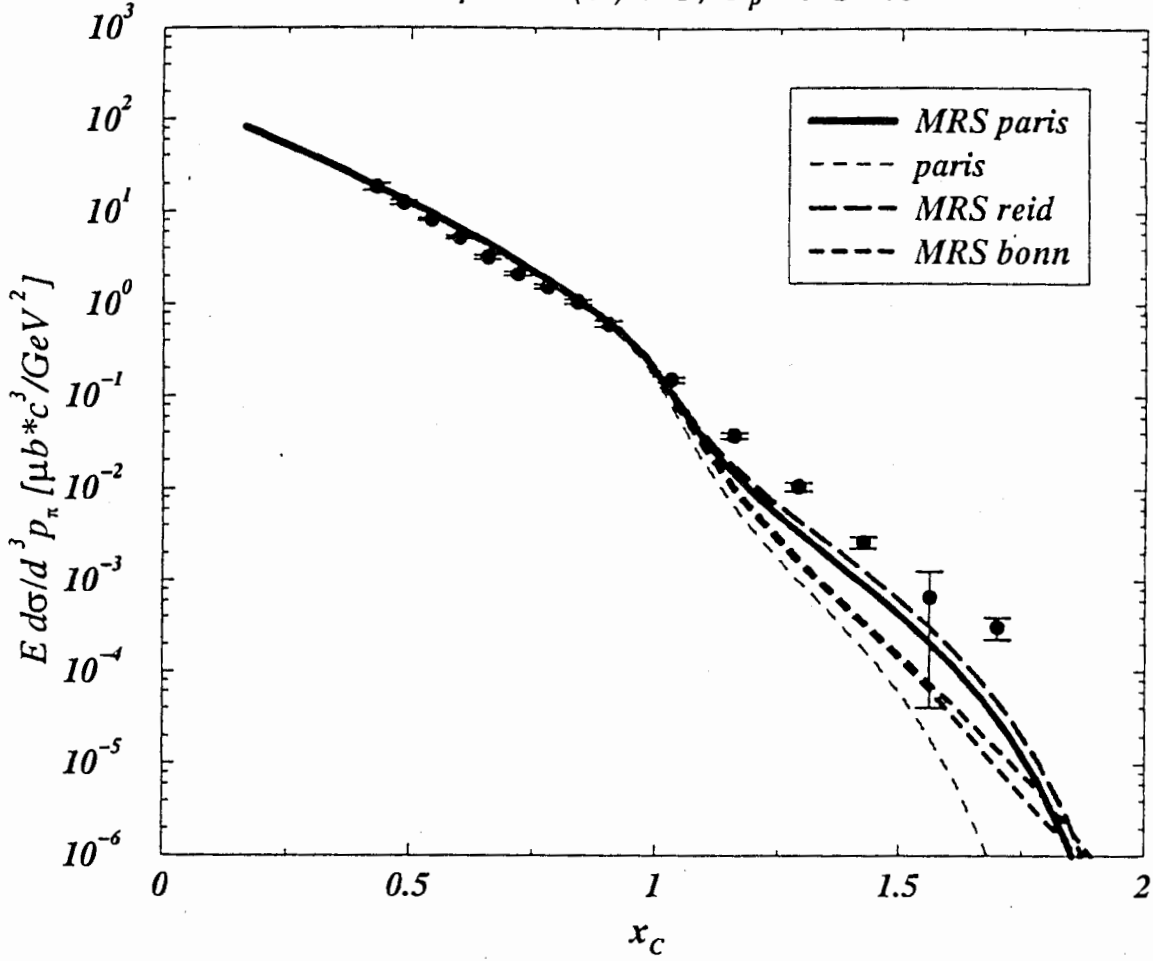


FIG.3. The invariant pion spectrum calculated by using the nonrelativistic DWF's obtained by the minimal relativisation scheme (MRS) [4, 51]. The solid, dashed and long-dashed lines correspond to the various DWF forms: the Paris one, the RSC and the Bonn DWF. The experimental data are taken from [3]

The Fig. 2 shows that the inclusion of the $\mathcal{P}$ -waves contribution to the DWF within the Bethe-Salpeter or Gross approaches results in a better (but not satisfactory) description of the experimental data over the cumulative region. From Fig. 3 one can see the effects of calculation using the minimal relativization scheme [4].

The calculated results of T_{20} for the reaction of polarized deuteron fragmentation into cumulative pions are shown in Fig. (4-6). From these figures one can see a small sensitivity of T_{20} to the vertex corresponding to the $NN \rightarrow \pi Y$ process. It is also seen that T_{20} is more sensitive to the DWF form than the invariant spectrum. The experimental data on T_{20} are not described by any DWF used in this paper even for internal momentum $k \leq 0.2 \text{ GeV}/c$.

Tensor Analysing Power T_{20}
 $D + p \rightarrow \pi^-(0^0) + X ; P_p = 4.46 \text{ GeV}/c$

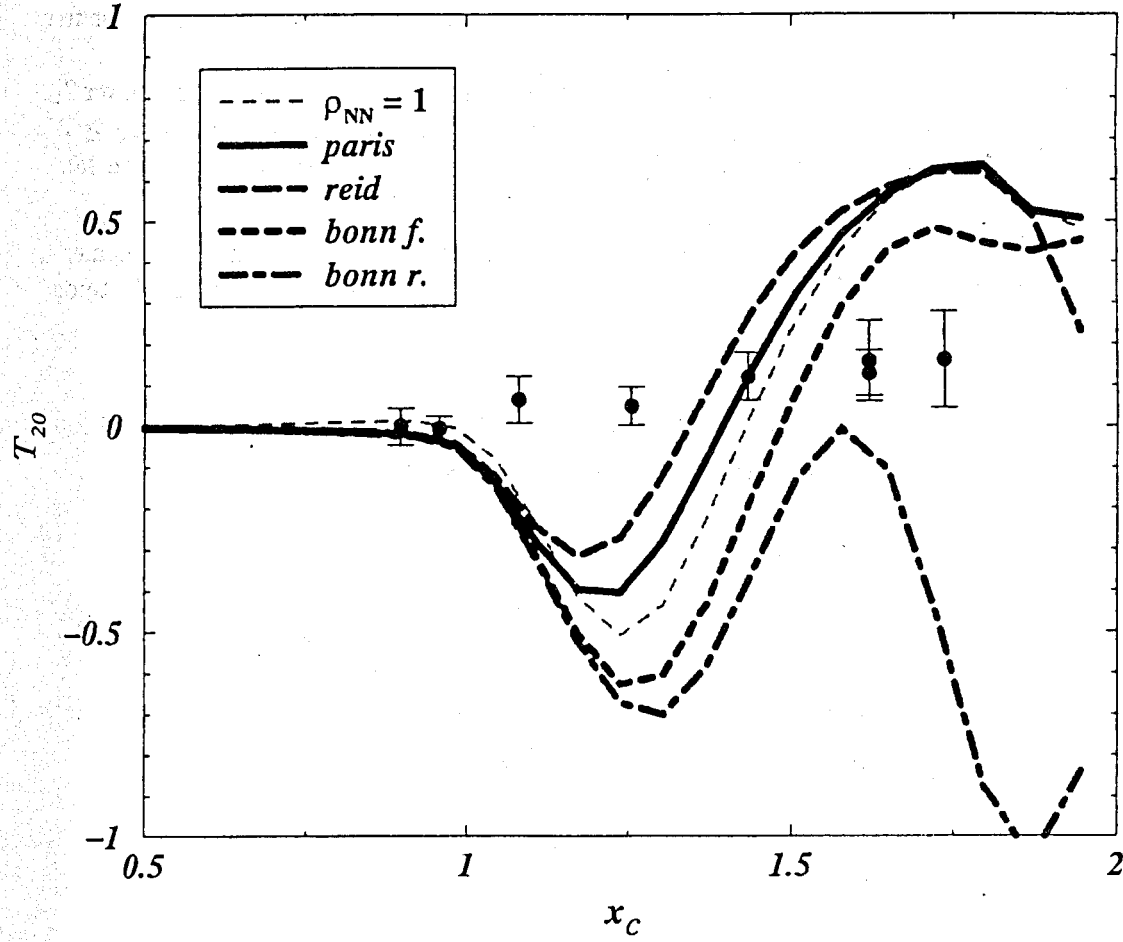


FIG.4. Tensor analyzing power T_{20} of the deuterons. The calculation results are compared with the experimental data from [8] at the projectile proton momentum $P_p = 4.46 \text{ GeV}/c$. The thin dashed curve corresponds to the calculus by neglecting of the internal structure of the elementary vertex $NN \rightarrow \pi Y$. The solid, long-dashed, dashed and dot-dashed lines correspond to the calculus by using various types of the nonrelativistic DWF: the Paris one, the RSC and two Bonn types, the relativistic Bonn DWF and the full Bonn DWF respectively

Main results can be summarized as follows.

1. It is quite incorrect to use the nonrelativistic deuteron wave function for the analysis of $D - N$ fragmentation into hadrons, in particular pions. Relativistic effects are sizable, especially in the kinematic region corresponding to short intra-deuteron distances or large x . It is seen from the behavior of the inclusive pion spectrum and particularly the tensor analyzing power T_{20} at large x .
2. At the present time, the state of theory is such, that the unique procedure to include relativistic effects in the deuteron has not been found yet. An extreme sensitivity to different methods of the relativization deuteron wave function is found for T_{20} at $x \geq 1$.
3. A large sensitivity of the inclusive spectrum of pions to the vertex of the $NN \rightarrow \pi X$ process can be seen from Fig. 1. In contrast to this the small sensitivity of T_{20} to this vertex is found, as seen from Fig. 4. This polarization observable is very sensitive to the DWF form (Fig. (4-6)).

4. The experimental data on T_{20} are not reproduced by a theoretical calculus using even different kinds of the relativistic DWF. This may indicate a possible existence of non-nucleon degrees of freedom or basically new mechanism of pion production in the kinematic region forbidden for free $N - N$ scattering.

5. For the deuterons fragmentation into protons emitted forward, the tensor analyzing power T_{20} is not described by the standard nuclear physics using the nucleon degrees of freedom at $x_c \geq 1.7$ [7]. On the contrary, T_{20} for the fragmentation $Dp \rightarrow \pi X$ can not be described within the same assumptions over all region $x_c \geq 1$.

Note that experimental and theoretical study of polarization observables of deuteron fragmentation into hadrons containing of different quarks is powerful tool for understanding the deuteron structure at small distances.

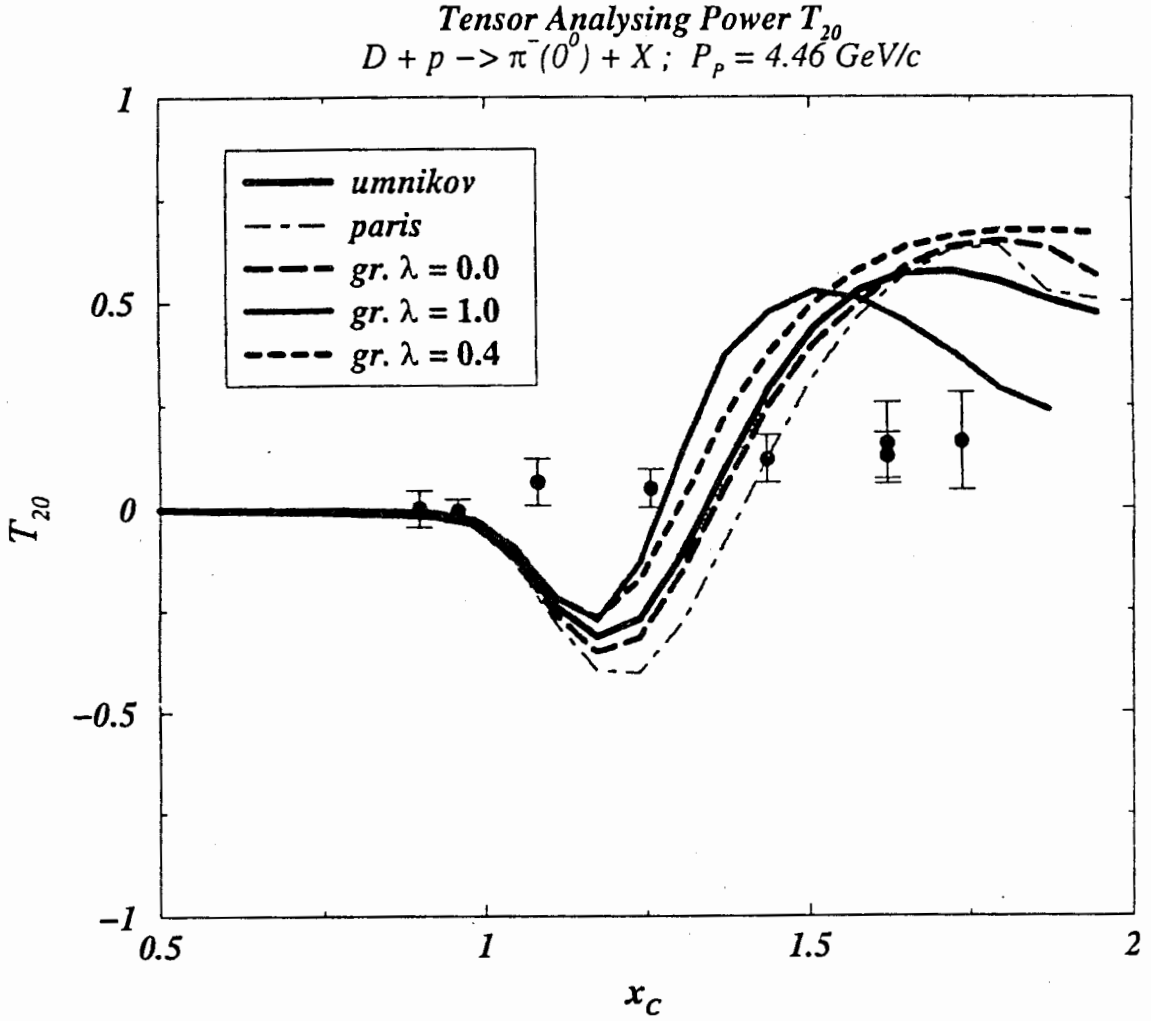


FIG.5. T_{20} calculated by using two forms of the relativistic DWF's, [39] and [44]. Notation as in FIG. 2. The experimental data are taken from [8]

Tensor Analysing Power T_{20}
 $D + p \rightarrow \pi^-(0^0) + X ; P_p = 4.46 \text{ GeV}/c$

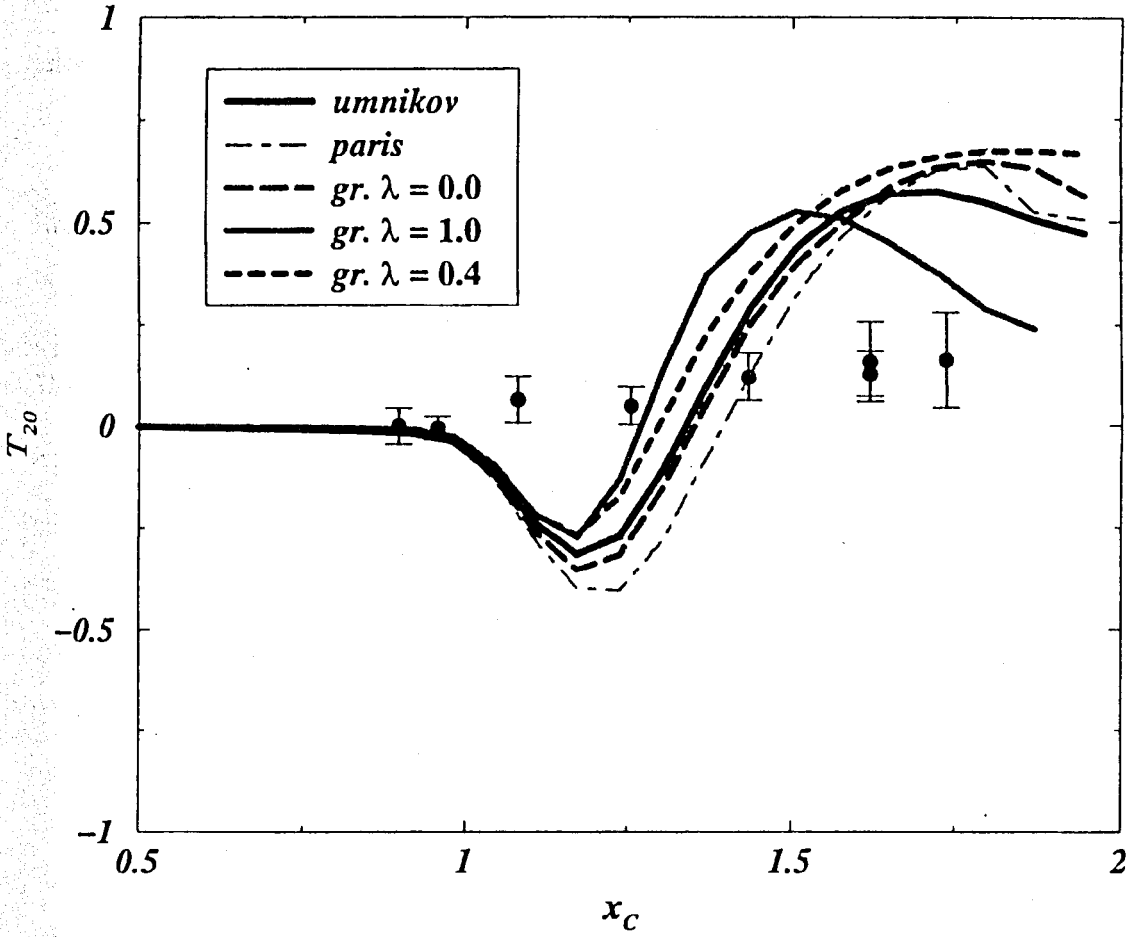


FIG.6. T_{20} calculated by applying the nonrelativistic DWF's using the minimal relativisation scheme (MRS) [4, 51]. The solid, thick dashed, thin dashed and long-dashed lines correspond to the various DWF forms: the Paris one, the RSC and the two Bonn DWF's, the full Bonn and the relativistic one. The experimental data are taken from [8]

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Experimental study of polarized deuteron fragmentation into cumulative pions

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Availability of polarized deuteron beams in GeV region in Saclay and Dubna stimulated a number of experiments to obtain information about deuteron spin structure at small distances. One of the goals was to verify applicability of deuteron wave function (DWF), based on the standard NN potentials (Reid, Paris, Bonn and others), to describe spin observables behaviour in $dp(dA)$ -interactions. The experiments with polarized beams performed in Saclay [1] and Dubna [2] showed that the Impulse Approximation (IA) predictions for spin observables were confirmed in deuteron breakup $A(d,p)X$ and $dp \rightarrow pd$ backward scattering only in the region of small internal momenta in the deuteron $k \leq 0.25$ GeV/c (Fig.1). The same results are found in the polarization transfer in deuteron breakup [3]. Discrepancy with the calculations with the standard DWF revealed at higher k can be related to manifestation of non-nucleonic degrees of freedom (NNDF) in the region of short-range nucleon correlations (SRC) in nucleus as well as with distortions due to interactions in final states (FSI). The accounting FSI allows to decrease discrepancy in region of middle k in case of deuteron breakup [4] but did not remove disagreement at the highest k reached (Fig.1). To distinguish between different reasons governing spin observables behaviour is highly desirable to compare behaviour of observables in different reactions under kinematic conditions allowing to probe SRC in nuclei.

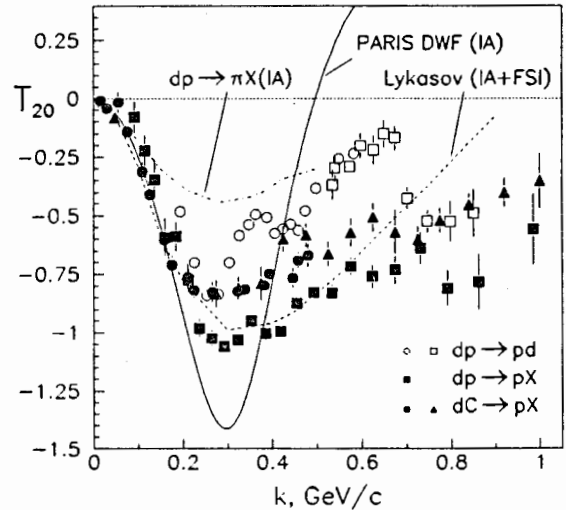


Fig.1. The experimental data for reactions induced by tensor polarized deuterons in GeV region: deuteron breakup $H, C(d,p)X$ [1] and $dp \rightarrow pd$ [2]. The solid curve presents IA with the Paris DWF [5] for both breakup and backward elastic, and the dashed line presents the results from [4] for 9 GeV/c breakup. IA prediction for cumulative pion production $^{12}C(d,\pi)X$ [6] is shown with dash-dotted line

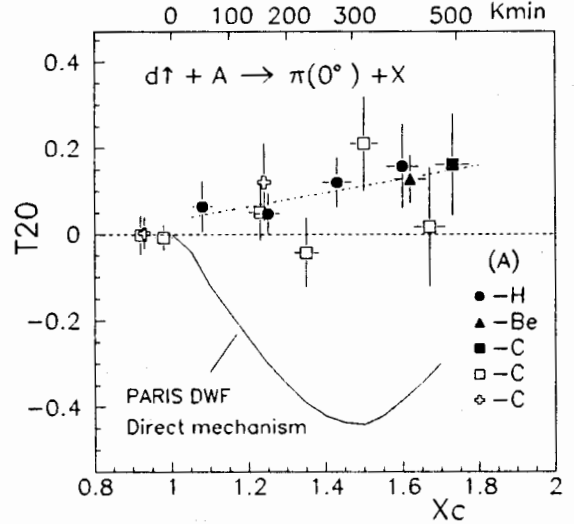
A well-known reaction to probe SRC is cumulative hadron production where a hadron can be produced only by strongly correlated nucleons in fragmenting nucleus (subthreshold production) [7]. In case of deuteron fragmentation into pions a cumulative meson

is produced at small internucleonic distances in the deuteron where contribution of the D-state in DWF is noticeable. In accordance with D-state domination one can expect to observe remarkable spin effects at fragmentation of tensor polarized deuterons in cumulative pions [8]. For cumulative pion production in the reaction

$$\vec{d} + A \rightarrow \pi + X \quad (1)$$

IA-calculations [6] predict (Fig.1) the sign and behaviour of tensor analyzing power at 0° , T_{20} , vs k .

Fig.2. Tensor analyzing power T_{20} vs x_c at fragmentation of 9 GeV deuterons on H-, Be-, and C-targets. Two points for π^+ are marked by crosses. k_{min} is the minimum internal momentum (in light cone dynamics) in the deuteron to produce a pion at corresponding x_c through the direct mechanism. The solid curve shows calculations with Paris DWF [6]



Our first measurements at $\theta = 0^\circ$ [9] on H-, Be-, and C-targets showed (Fig.2) that the sign and the value of T_{20} contradict with the IA-predictions based on hypothesis of dominating the direct mechanism of pion production on a high momentum nucleon in the deuteron ($NN \rightarrow NN\pi$). In contrast to the deuteron break-up reaction $Dp \rightarrow pX$ here we come across with complete failure of IA-approach. In Fig.2 the T_{20} -data are presented vs the cumulative variable x_c which is the minimum fragmenting mass in units on nucleon mass required to produce a pion with momentum q_π . The spectra of cumulative hadrons produced at different kinematical conditions demonstrate a scaling behaviour in x_c -presentation and a weak dependence on atomic mass number of fragmenting nucleus. In case of deuteron fragmentation, x_c -es ranging from 1 to 2 correspond to the region of cumulative production. In the framework of the direct mechanism of pion production, x_c can be related to k_{min} – the minimum internal momenta k of nucleon N_f in the deuteron required to produce $\pi(q_\pi)$ in $N_f N \rightarrow NN\pi$ process. IA predicted D-state effect should be observed as increasing the analyzing power around of maximum of D/S-ratio which, for instance, takes place at $k \simeq 300$ MeV/c for the Paris DWF. However, the $T_{20}(0^\circ)$ -data do not demonstrate such an effect. Obviously, to understand features of SRC in nuclei other approaches considering non-nucleonic degrees of freedom also have to be considered. A successful attempt in this direction was undertaken by A.Kobushkin [8]. Working in the framework of a constituent quark model of the deuteron, he showed that estimation

of contribution of $\Delta\Delta$ -states in the deuteron allowed to reproduce the average value and the sign of T_{20} in $Dp \rightarrow \pi(0^\circ)X$ at $k \geq 300$ MeV/c.

However, if the direct mechanism isn't excluded, a strong discrepancy of IA and our $T_{20}(0^\circ)$ -data could be due to a strong role of pion absorption diagram at zero angle when momenta of pion and spectator nucleon are collinear. This motivated measurements at non-zero angle. At $\theta \neq 0$ preferably to use cartesian analyzing power A_{yy} which related to spherical T_{20} as $A_{yy}(\theta) = -\frac{1}{\sqrt{2}}T_{20} - \sqrt{3}T_{22}$ (at $\theta=0$ $A_{yy} = -T_{20}/\sqrt{2}$).

For reaction (1), A_{yy} is determined by difference of pion production cross sections at different tensor polarizations (p_{zz}) of deuteron beam

$$\bar{\sigma}(\theta) = \sigma_o(\theta)(1 + \frac{3}{2}p_z A_y(\theta) + \frac{1}{2}p_{zz} A_{yy}(\theta)). \quad (2)$$

We carried out measurements at $\theta = 135$ mrad and 180 mrad at the same setup as at 0° -measurements [6] using the head bending magnet for selection of pion emission angle. As the measurements at $\theta = 0^\circ$ with H -, Be -, and C -targets showed a weak dependence on atomic mass number of target, new measurements were performed with Be -target only. At the fixed deuteron beam momentum $p_d = 9.0$ GeV/c the pion momentum was changed from 1.5 to 4.5 GeV/c at $\theta = 180$ mrad. The range of x_c from 0.96 to 1.52 was covered at $\theta = 135$ mrad and from 0.40 to 1.58 at $\theta = 180$ mrad. New data for $\theta = 135, 180$ mrad along with the old 0° -data are shown in Fig.3.

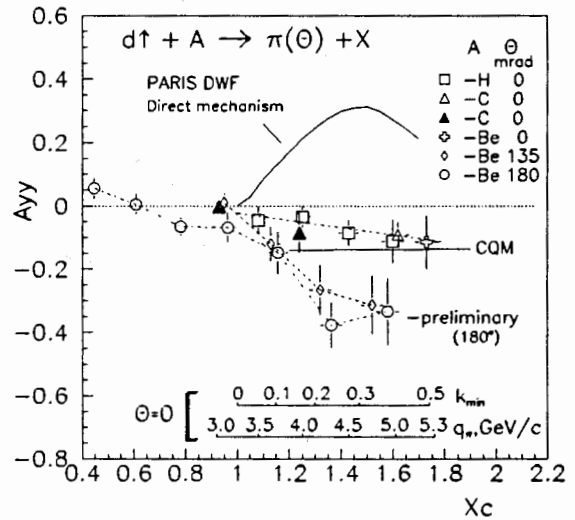


Fig.3. A_{yy} vs x_c at fragmentation of 9 GeV deuterons into pions at $\theta = 0, 135$, and 180 mrad. For $\theta = 0^\circ$ there are shown the scales of q_π , pion lab. momentum, and k_{min} . The solid curves show calculations with Paris DWF [6] and the estimation according with the constituent quark model (CQM) of A. Kobushkin [10]

The presented data of $A_{yy}(135, 180 \text{ mrad})$ at fragmentation of 9 GeV tensor polarized deuterons into negative pions demonstrate a more dramatic dependence on x_c compared to the 0° -data. A_{yy} increases with growing contribution of D-wave reaching -0.4 around internal momenta $k = 0.3-0.4$ GeV/c where D/S-ratio has its maximum. The pion transverse momentum p_T ranges up to 0.90 GeV/c in our measurements. Preliminary analysis of π^+ -data at 180 mrad shows that $A_{yy}(\pi^+)$ demonstrates a similar behaviour with the same sign of A_{yy} . The sign of A_{yy} at $x_c > 1$ remains the opposite to the one predicted by Paris DWF in the cumulative production region. This indicates that pion production

on the deuteron core can not be described in the framework of the direct mechanism ($NN \rightarrow NN\pi$). It means that a pion cloud around the deuteron core has such a structure that is substantially different from that of free nucleon. We suppose to continue the study of A_{yy} in extended x_c - and p_T -regions.

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The first experiments for the SPHERE-GIBS collaboration

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Recently (in March 2000), the beam extraction system of the new Nuclotron accelerator was tested successfully at LHE JINR. Now, it is a good reason to discuss first possible experiments for the SPHERE-GIBS collaboration. It was suggested [1,2] to investigate the properties of the lightest hypernuclei and the charge exchange reactions of tritium nuclei using the SPHERE spectrometer as well as the GIBS one.

The experiments, which include the measurement of the binding energy of the lightest hypernuclei – ${}^3_{\Lambda}\text{H}$, ${}^6_{\Lambda}\text{He}$ and the lifetimes of light hypernuclei, can be of interest for the hypernuclear item.

The hypernuclear production cross sections and lifetimes of ${}^3\text{H}$ and ${}^4\text{H}$ were measured in our previous experiments [3] using the synchrophasotron ion (${}^3\text{He}$, ${}^4\text{He}$, ${}^6\text{Li}$) beams. However, the experiments were interrupted because of low available statistics. In future experiments, the data collection rate can increase by a factor of 200-300 due to an excellent Nuclotron duty cycle and the use of proportional chambers instead of the streamer chamber. However, the approach will be generally the same. As target nuclei are usually excited to produce hypernuclei, we use excited beam nuclei as a source of relativistic hypernuclei. If a beam nucleus (${}^3\text{He}$, see fig.1) of a 6 GeV energy interacts in the target T, the ${}^3\text{H}$ hypernucleus, which energy is slightly lower 6 GeV, can be produced. Due to the Lorentz factor, hypernuclei decay at quite a large distance from the target. This means that we will obtain a "hypernuclei beam" which allows us to investigate interactions of this beam, for example, in an absorber A inserted downstream the target.

We propose to employ a substantially new method to determine the binding energy of ${}^3\text{H}$ - to investigate the Coulomb dissociation cross section of weakly bounded hypernuclei depending strongly on the value of absorber's nucleus charge and lambda binding energy [4]. The method can be effective in case of low values of binding energy.

It is also important to emphasize that hypernuclei lifetimes can be measured with small systematic errors. Our experiment is the only one in which the lifetime is calculated using the spatial distribution of relativistic hypernuclei decay points. The measurement of this distribution is quite simple, reliable, precise and adequate to the task. In such an approach, the influence of systematic errors does not exceed 1% of the result, and the statistical errors can be reduced to 2-3%.

Considering charge exchange reactions, we offer two experiments. Oset et al. [5] have shown that one of the diagrams describing the charge exchange of ${}^3\text{He}$ nuclei on a nucleon with delta excitation should be strongly expressed in case of a neutron target (experimentally impossible) or in an isotopically reversed reaction of tritium charge exchange on a hydrogen target. Meanwhile, the diagram is practically suppressed for nuclear target. So, we think that the measurement of inclusive cross section of a charge exchange reaction of tritium on a hydrogen target can be an interesting task for the SPHERE spectrometer. A layout of the slightly modified spectrometer is presented in Fig. 2. It should be noted that such an experiment is of interest from the methodical point of view as well because it is simple enough to be a good test of the SPHERE proportional chamber spectrometer.

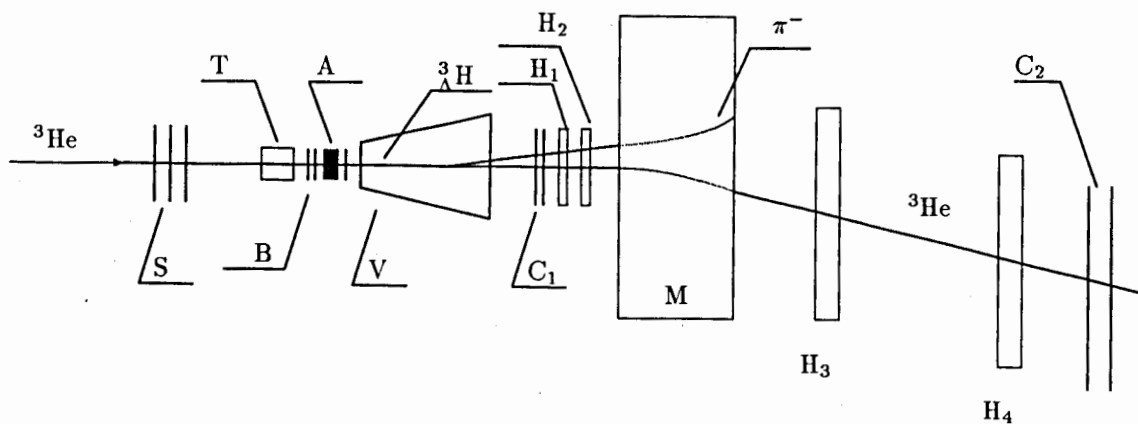


Figure 1. SPHERE spectrometer adapted for hypernuclear experiments. T – target; A – absorber for the study of Coulomb dissociation of hypernuclei; S, B, C_{1,2} – trigger counters; V – vacuum decay volume; M – the magnet; H₁₋₄ – proportional chambers

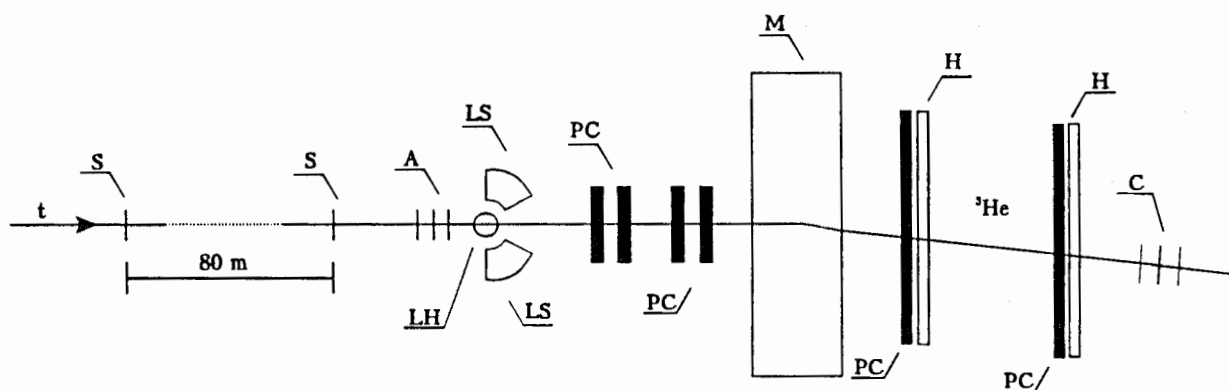


Figure 2. SPHERE spectrometer adapted for the inclusive cross section measurement in case of the charge exchange on the proton (liquid hydrogen) target LH. S – TOF counters, A, C – trigger counters; M – the magnet; PC, H – proportional chambers; LS – the lead glass spectrometer

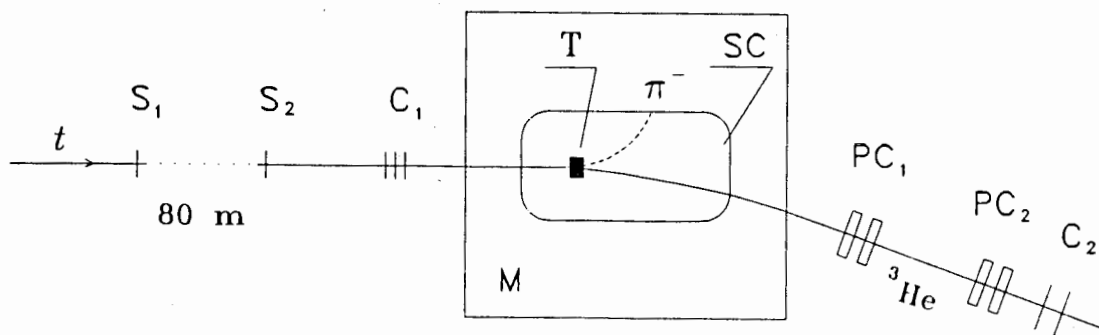
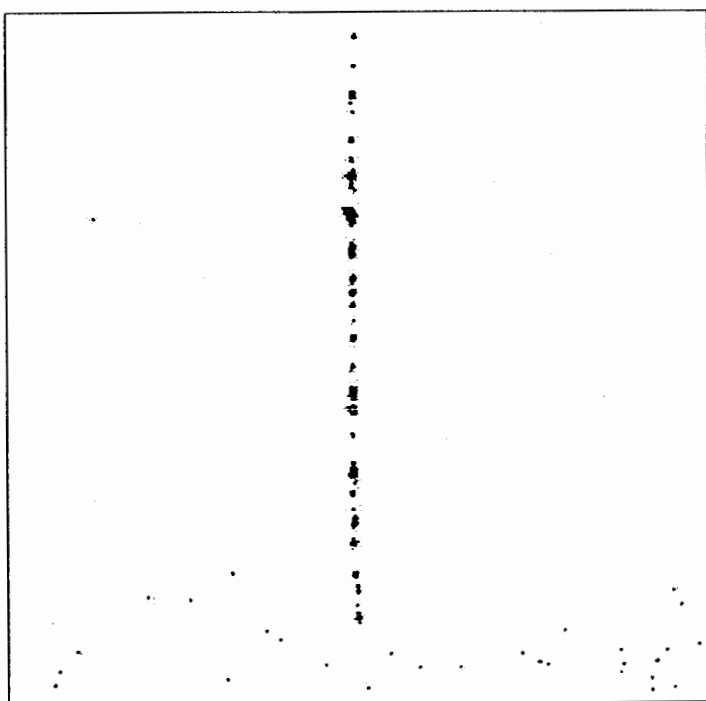


Figure 3. A schematic display of the GIBS spectrometer with the streamer chamber SC, target T (inside the streamer chamber), analyzing dipole magnet M; S₁, S₂ – time-of-flight counters TOF, C_{1,2} – trigger counters, PC_{1,2} – proportional chambers

At the same time, it would be interesting to continue a detailed research of charge exchange reactions of tritium on nuclear (carbon) targets at the GIBS spectrometer. In the previous experiments, a strong evidence was found out [6] in favor of the idea that a significant part of pions is produced without delta as an intermediate state. However, more statistics and precise measurements of transferred momentum are required. To improve the accuracy of the measurements we shall use the time of flight spectrometer for projectile (tritium) nuclei and proportional chambers downstream the analyzing magnet (see Fig. 3) for outgoing helium. The streamer chamber will be used as a vertex detector to measure the properties of negative pions and other secondary particles (protons). Over the last period, the main technical problem, which we had to overcome in order to increase statistics, was solved successfully – the readout system, based on CCD TV cameras, was elaborated and tested. A streamer chamber track, registered and stored on a hard disk, is presented in Fig. 4. Serious efforts of V.Aksinenko, L.Krasnov, V.Kondratiev, V.Matyushin and M.Anikina in solving technical and software tasks should be emphasized. However, we must elaborate a program, which will allow us to calculate pion momenta, before the beginning of experiments.

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Figure 4. A track
in the test streamer
chamber registered
with digital
TV camera



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RESEARCH ON THE NUCLOTRON INTERNAL TARGET

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Abstract

Correlation of protons, emitted in angle interval between $103^\circ \div 109^\circ$ in laboratory system, are studied in reactions $pA \rightarrow ppX$, $dA \rightarrow ppX$ at small relative momentum of secondary protons. The analysis of the experimental data on correlation between cumulative particles has been done. The analysis is based on both correlation data and inclusive spectra.

Key-words: cumulative, proton, correlation, nucleus

1. Introduction

The experimental data of particles correlation are a source of information about dynamics of nuclear reactions. From the analysis of these data a spatial - temporal information from interaction is extracted [1, 2, 3].

The first correlation experiments in the field of generation of cumulative particles were performed in Institute for Theoretical and Experimental Physics (ITEP). The processes of hadron-nuclear interaction were investigated, in which two cumulative particles with small relative momentum [5, 6, 7] were detected. The analysis of experimental data carried out in ITEP has shown that " The area, from which the cumulative particles take off, is not spherically-symmetric. Longitudinal, in relation to momentum of primary hadron, sizes of this area are comparable on magnitude to sizes of the target nucleus. The transverse dimension is less than longitudinal one and is close on an order of magnitude to characteristic hadron size " [9]. It has allowed to formulate the following conclusion: " the cumulative particles are produced sequentially along a trajectory of initial hadron in the nucleus when an initial particle interacts with nuclear substance " fig.1(a) [8, 9].

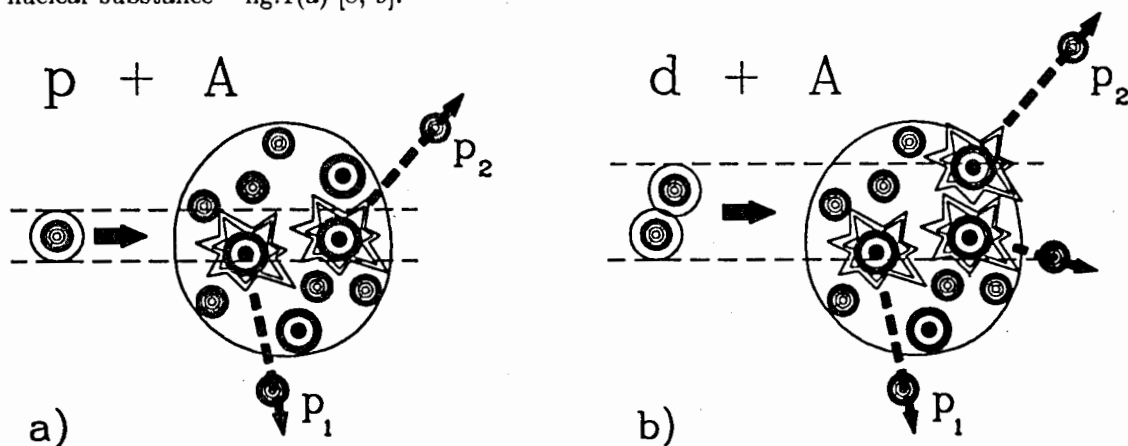


Figure 1. The schematically view of cumulative particles production; (a) in $p+A$ reaction, (b) in $d+A$ reaction

Consequence of this conclusion is that the transverse dimensions of cumulative particles production area should depend on sizes of a primary particle. The accuracy of similar statement can be experimentally tested in the nuclear - nuclear interactions. Varying atomic number of nucleus beam, it is possible to receive a dependence of a transverse dimension of area of cumulative particles production from sizes of a nucleus of beam fig.1(b). In this case the dependence from a type of a target should not be, or it will be insignificant. The condition of experiment, in this case, should be determined.

2. Technique of the experiment

A two-arm scintillation spectrometer SCAN, obtaining a title SCAN (a Spectrometer of Cumulative Hadron on Nuclotron) has been created for research of cumulative particle production source. The spectrometer is based on registration charged particles in scintillation detectors, using time of flight and energy loss in detectors (the method of dT-E). Similare spectrometers work on many accelerators in the world [4, 10].

The experiment was been done on internal target of the superconducting accelerator of the nucleus Nuclotron. The geometry of experiment was as follows (fig.2). The station with a set of targets was installed on rectilinear gap of Nuclotron. The selection of a target and positioning in the accelerated beam was carried out remotely. The carbon fibers with a diameter of $8\text{ }\mu\text{m}$ and copper wire - diameter $70\text{ }\mu\text{m}$ were used as targets.

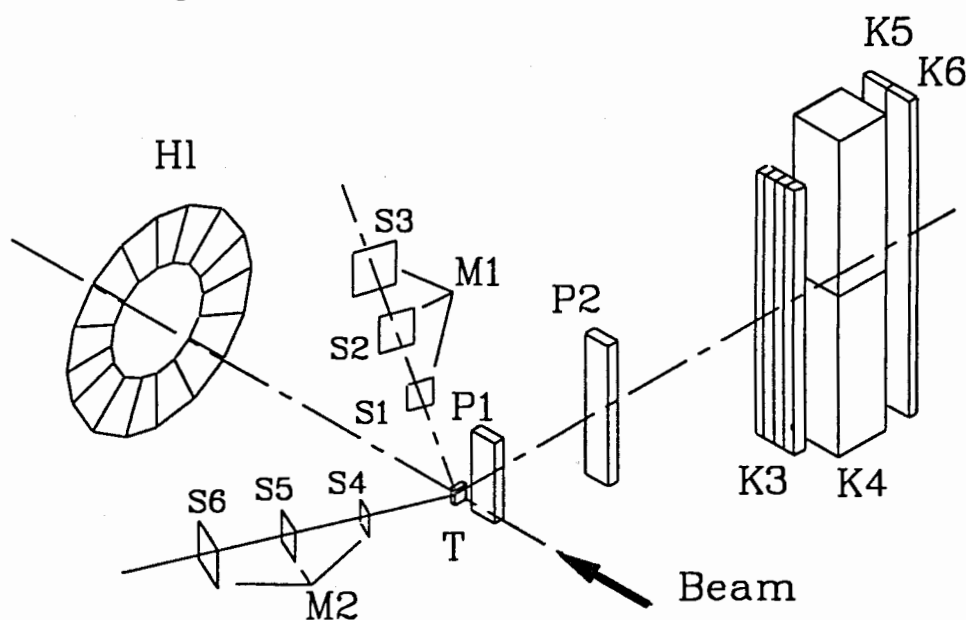


Figure 2. The experimental setup

Structure of the equipment included the following elements: a scintillation spectrometer, detector of multiplicity and two monitors.

The scintillation two-arm spectrometer is used for registration of two protons in momentum range $0.28 \div 0.72\text{ GeV/c}$ and relative difference of momentum of two protons $q_T = P_1 - P_2 < 0.2\text{ GeV/c}$. The spectrometer was assembled at two independent frames. The detectors P1-P2 and K3-K6 were installed on them. The detectors P1, P2 and K3 were used for development of a trigger signal and definition of time of flight (TOF-system); K4 - for detection of a kinetic energy of particles; K5 and K6 - for selection of high energy particles passing through all stratum of substance. All detectors are made of plastic scintillator. Light was registered from two ends of plastic by means of photomultipliers. The spectrometer was installed at angle $\Theta = 106^\circ$ concerning an axis of a beam.

The 16 channel scintillation hodoscope H_1 detecting charged particles in angular range $15^\circ < \phi < 30^\circ$. It represents a ring divided into 16 segments. Each segment is looked through by separate photomultiplier. The hodoscope has used for selection of impact parameter.

Two triple monitors M1 (counters S1-S3) and M2 (counters S4-S6) are used for luminosity monitoring. They installed at angles $\Theta_1 = -32^\circ$ and $\Theta_2 = 68^\circ$, correspondingly.

In setup the spectrometer allows to carry out as registration and identification of secondary particles as to select conditions of experiment. Particles have been detected in a spectrometer when the signals from detectors P1, P2 and at least one element of K3 (trigger on a single particle), or at least two elements of K3 (trigger on a pair) where presented.

For definition of time of flight of secondary particles, the difference in times of flight between K3-P2 and P1-P2 is used.

$$t = t_{K3-P2} - t_{P1-P2} = t_{K3} - t_{P1} \quad (1)$$

The full time resolution of spectrometer is determined by a time resolution of detectors P1 and K3 and it has an average absolute value of 150ps. The signal from the counter P2 was been used as a starting pulse for time to digital converters and does not added in the additional contribution to timing parameters of the system. The using of two time intervals t_1 and t_2 on the different basis of flight L_1 and L_2 allows to separate real events from background. Magnitudes t_1 and t_2 are bound by a simple functional dependence: $F(t_2) = \frac{L_2}{L_1} t_1$ and are good selectable for two-dimensional $t_1 - t_2$ analysis.

The time of flight data are used also for definition of a Y-coordinate of hit in the detector K3. The Y-coordinate is determined as a difference in time of arrival of light from a place of a scintillation to FEU installed on opposite side of scintillator and is defined as follows:

$$Y = \frac{1}{2}(\tau_1 - \tau_2)V_{sc} \quad (2)$$

Where τ_1 and τ_2 are times of arrival of light to FEU1 and FEU2, and V_{sc} - velocity of light in scintillator. The X-coordinate is defined as the K3 element number and is taken in account a coordinate of a center of the element.

The measure of energy loss E in a spectrometer is a magnitude of charges Q_3 and Q_4 read - out with FEU K3 and K4 when a particle passing through active volume of the detectors $E = k_1 Q_1 + k_2 Q_2$. The absolute value of magnitudes E and t was normalized so that the value δ was minimum.

$$\delta = \min \sum | f_{theor}(E, t) - f_{exp}(E, t) | \quad (3)$$

Here $f_{theor}(E, t)$ and $f_{exp}(E, t)$ are theoretical and experimentally obtained values for each pair E, t. The values E and t allow to calculate an effective mass of a particle and by that to determine a type of a particle. As have shown by more detailed calculation, the level of reliability of identification of protons in a working momentum range had more than 98%. The particles, which reconstructed mass was in an interval from 500 MэB up to 1350 MэB, were considered as protons and were used for the further analysis.

The events in which only two elements of K3 were active and their y-coordinates had a different sign were used for correlation analysis.

The correlation function for two protons was defined in this case as follows:

$$R_2(p_1, p_2) = \frac{\sigma_{inel} d^2\sigma / dp_1 dp_2}{d\sigma / dp_1 d\sigma / dp_2} = C \frac{N_{12}(\mathbf{q})}{N_1 N_2(\mathbf{q})}, \quad (4)$$

Where $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$, C - a constant factor, $N_{12}(\mathbf{q})$ - distribution of two-particle events on $\mathbf{q}$ and $N_1 N_2(\mathbf{q})$ - background distribution on $\mathbf{q}$, obtained by mixing of single protons registered in inclusive condition.

3. Experimental results

The first measurements of correlation function of two cumulative protons were carried out on a beam of relativistic deuterons with momentum 5.5 GeV/c [12]. The accelerated deuterons during two seconds were kept by a magnetic field of the accelerator. The target was moved into a primary beam and the products of interaction were registered in this moment. The velocity of driving of a target selected so that the counting rate of the detectors, nearest to a target, did not exceed 10^6 of pulses per second. Typical magnitude of count intensity was $(1 \div 2) \cdot 10^5$ pulses per second.

The measurements were carried out in two conditions: one-particle - the event with at least one hit registered and two-particles - the double hit events are registered only.

The one-particle regime was used for the definition of conditions of experiment and for testing an equipment. In this condition the background distributions were checked. It was marked, that the conditions of experiment allow to measure of correlation and accidentals give the insignificant contribution.

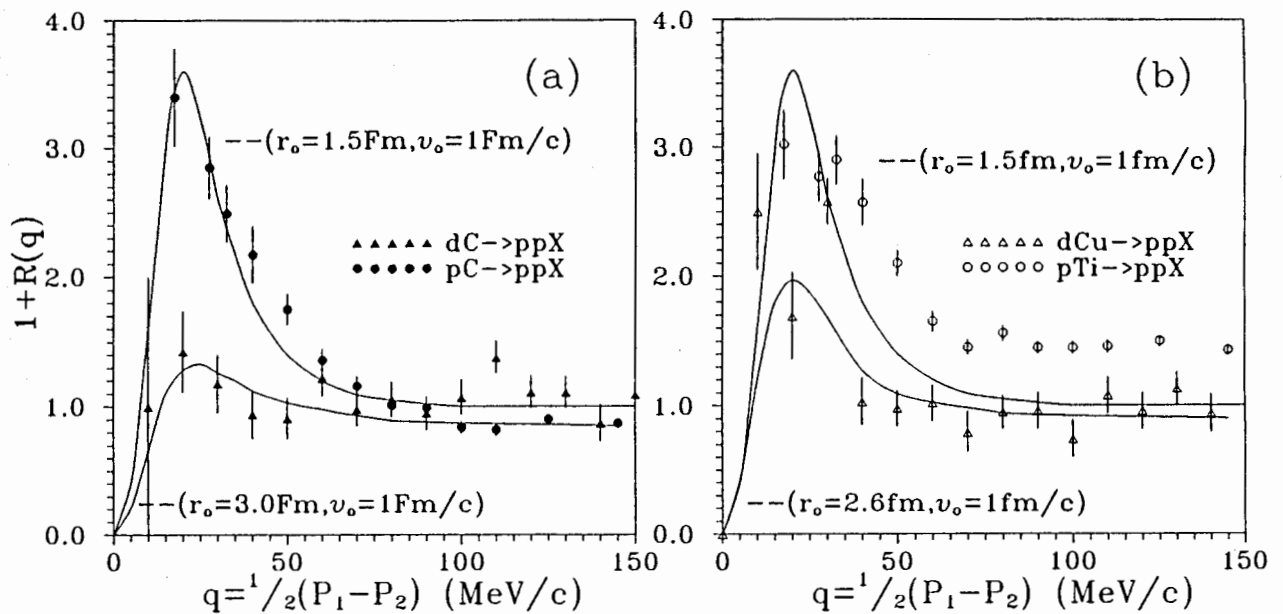


Figure 3. Correlation function, obtained for reactions, $dC \rightarrow ppX$ and $dCu \rightarrow ppX$. For example the data for reactions $pC \rightarrow ppX$ and $pTi \rightarrow ppX$ from work [8] are reduced

In an outcome of exposure of carbon and copper targets, $2 \cdot 10^4$ and $5 \cdot 10^3$ of two-particle events are registered, correspondingly. The events, in which both particles were identified as protons, were selected from these data. Correlation functions for these events are submitted in fig.3(a),(b) for a reaction $d + C \rightarrow ppX$ and $d + Cu \rightarrow ppX$, correspondingly. Our data are shown on the graph with triangles. For a comparison the data for reactions $p + C \rightarrow ppX$ and $p + Ti \rightarrow ppX$ taken from work [8] are used. It is well-visible that our data and data of ITEP are noticeably differ despite of the large errors. Fitting of data using method offered in [11], has shown that the transverse radius of area of two generation protons is close to a radius of a deuteron (carbon) and is equal to $R_t(d + C) = 3^{+0.5}_{-0.4}$ fm. It two is greater than magnitude obtained in the hadron-nuclear interaction [8], approximately by factor. A radius of area of generation in $d + Cu \rightarrow p + p$ reaction the close value $R_t(d + Cu)$ has $2.6^{+0.8}_{-0.7}$ fm.

As it is visible from obtained data, the correlation function for $d + A$ interaction noticeably differs from correlation function for $P + A$ interaction. This difference takes place in both reactions.

However these results could not be used for final conclusions. The data are obtained in different conditions, on various detectors and in various times. Also they can contain systematic errors which we can not calculate in the analysis correctly.

For correction of these point we have carried out the measurement on deuterons and protons beams with momentum of 5.5 GeV/c during one experimental run.

The experiment was carried out with primary intensity of $2 \cdot 10E^9$ of particles in a cycle on a target of 10 carbon fibers with diameter of 8 μ m.

The result of the analysis of data for $d + C$ - reaction is shown in fig.4(a). As one can see, the data practically does not vary. The data differ a little from that obtained by us in the previous case. However, last data have essentially smaller statistical errors. Fitting of data has given a value for a radius of interaction equal to $R_t = 2.7 \pm 0.1$ fm.

The similar picture is observed for $p + C$ - reaction also. The result is shown in fig.4(b). Fitting of data has given a value for a radius of interaction equal $R_t = 2.8 \pm 0.2$ fm. This value, despite of the large error in a measurement, practically coincides with magnitude R_t for $d + C$ reaction and hardly differs from a value published in [8].

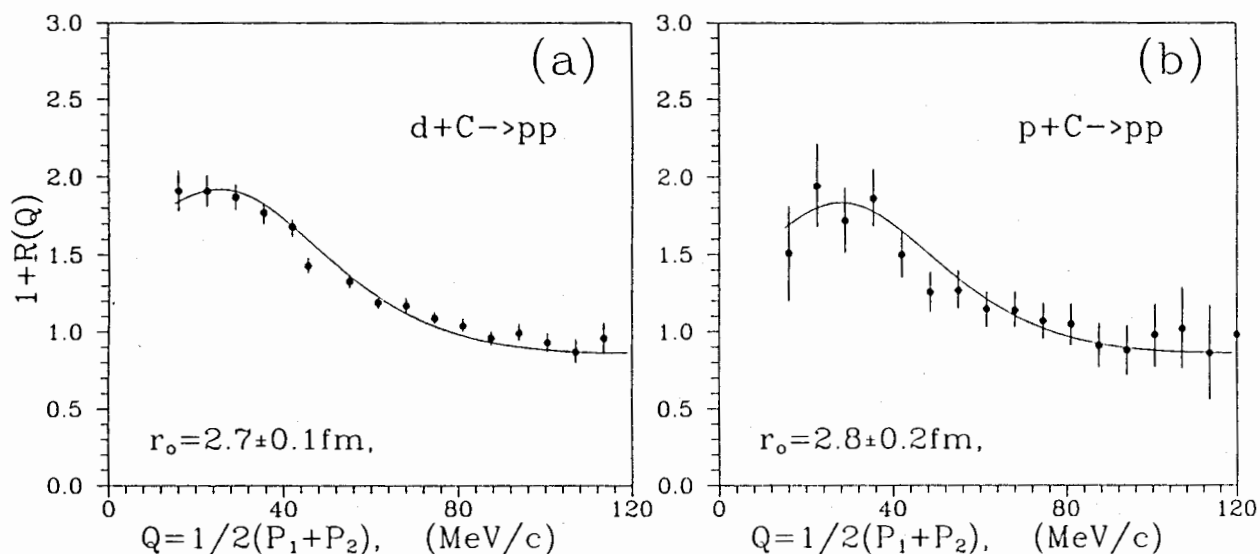


Figure 4. Correlation function, obtained for reactions, $dC \rightarrow ppX$ (a) and $pC \rightarrow ppX$ (b)

4. Summary

Conducted researches of $d + A$ interactions with production of two cumulative protons at angle 106° have shown noticeable difference in a behavior of correlation function from data obtained in $p + A$ reaction in ITEP [8]. Fitting of data $R_t(q)$, using parametrization corresponding to particle emission from Gaussian source, has shown that transverse dimension of cumulative protons source is approximately corresponding to a radius of nucleus used as a target.

The comparison of our data with data published in [8] has shown noticeable difference between them. This disagreement is important and requires realization of the further researches in this area.

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Some features of support of physical installations by beam of charged particles

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The carrying out of physical experiments in LHE JINR now concentrated in main in two measuring pavilions. It is so-called Old measuring pavilion and building 205 (see fig. 1).

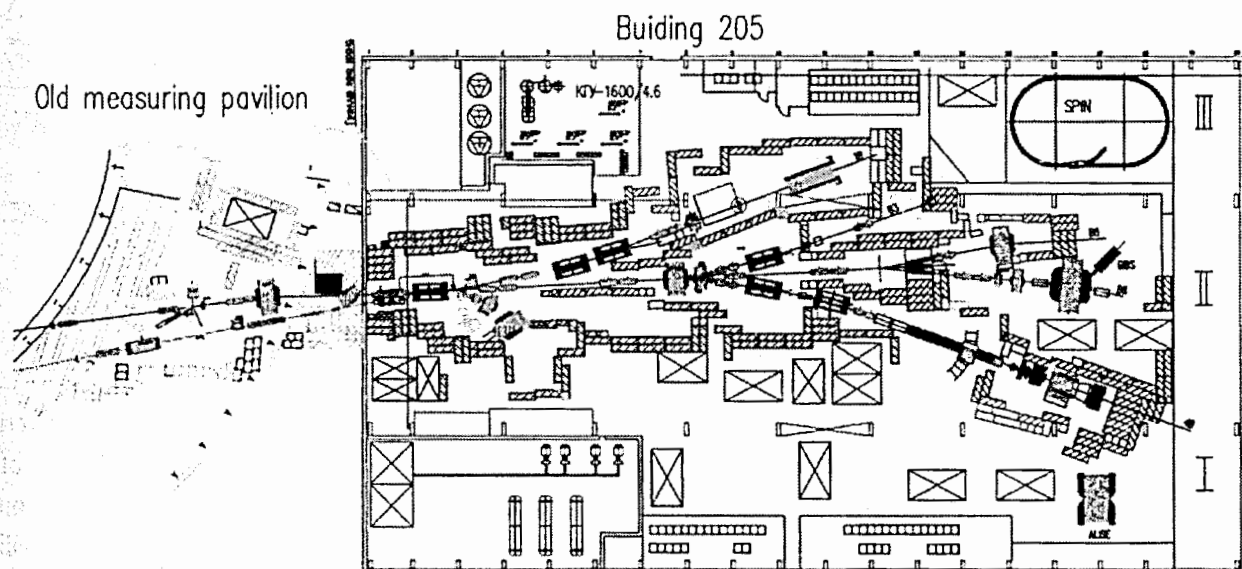
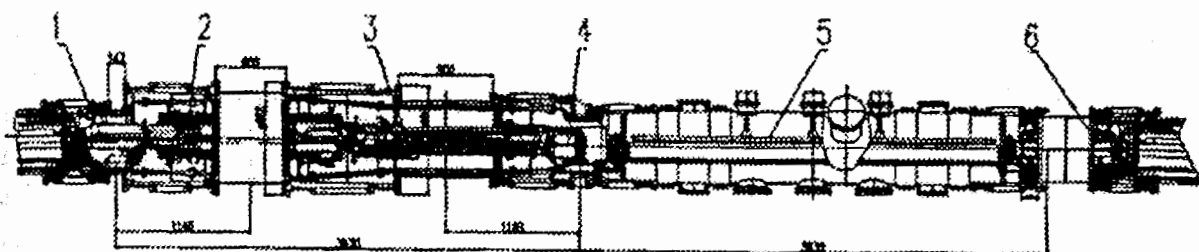


Fig. 1

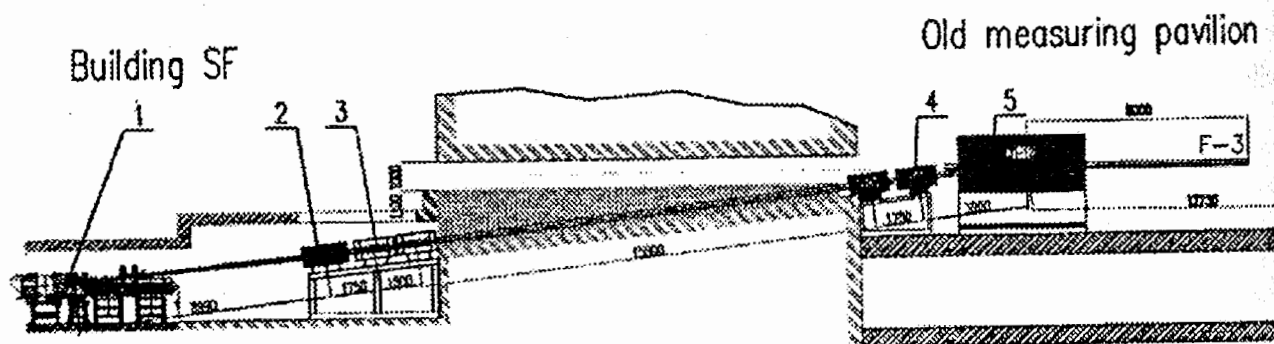
The installations are provided with accelerated bundles of positive protons and relativistic nucleus from two operating accelerators. It is of a synchrophasotron (SF) - the old computer with weak focusing of a magnet system, major aperture of a vacuum chamber and major expenditure of an electrical power. Created as the accelerator of positive protons on energy 10 GeV, it by the beginning of the 70-tenth years, on sentence A. M. Baldin, was transformed into the accelerator of relativistic nucleus. On SF the bundles of polarized deuterons were obtained Nuclotron, framed as the accelerator of relativistic nucleus on energy 6 GeV/nucleons, work on physical experiments since 1993. It is the accelerator with a strong focusing. Its magnet system is fulfilled on the basis of magnets with windings from a superconductor and field shaped iron. In past 1999 the system of the beam slow extraction from Nuclotron is put into operation. It is fulfilled on a basis of "cold" units, built-in in a ring of the accelerator and in 5-th rectilinear interval (see fig. 2).



1. Lens 5F2; 2. Lambertson-type magnet LM 2; 3. Lambertson-type magnet LM 1; 4. Lens 501; 5. Electrostatic septum; 6. Lens 5F1.

Fig. 2

The accelerator is disposed in a cellar of building of a synchrophasotron, around of its foundation. A level median of a plane Nuclotron on 3.765 meters of a below median plane SF. The output of a bundle and transporting it in a building 205 (see fig. 3) is stipulated by this circumstance.



1. 5-th rectilinear section; 2. Corrector VCM; 3-4. Lenses 20K100; 5. Magnet SP-12A

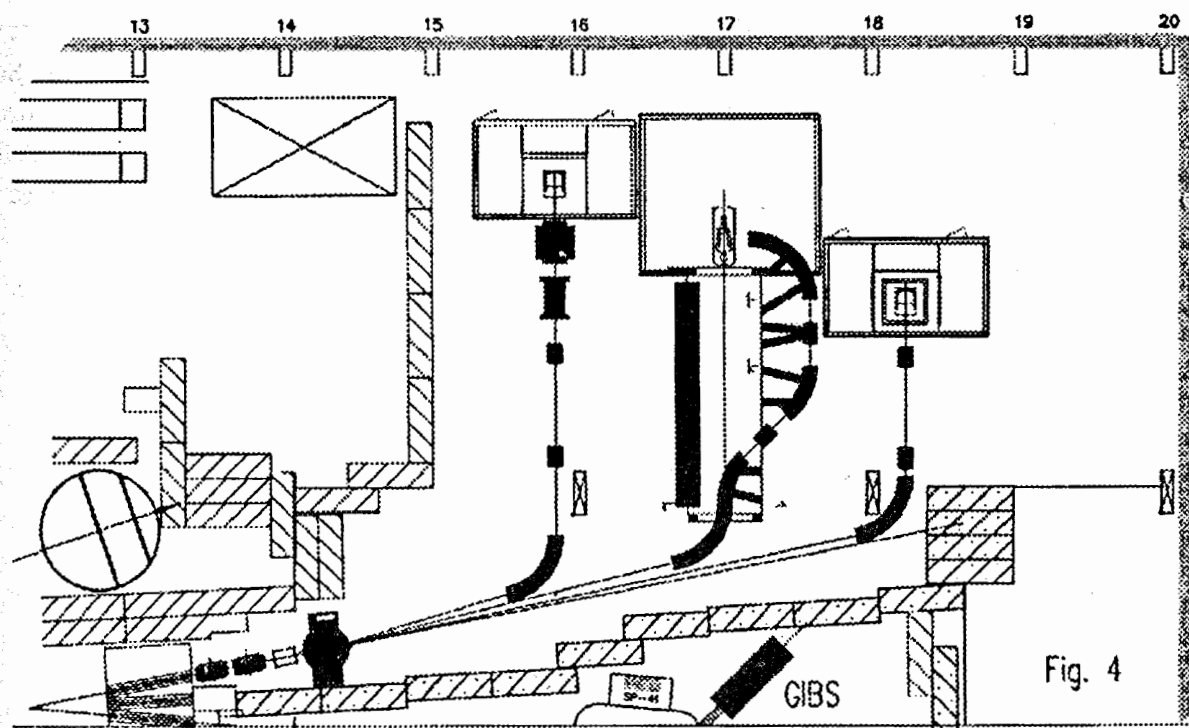
Fig. 3

A magnet VCM yields the adjustment of deviation of the output bundle on a corner in a vertical plane. The beam is focalized by doublets from lenses 20K100. The rotational displacement of its (bundle) in bridge to floor height is yielded by a magnet SP-12A, for what it is turned around on 90 degrees around of a horizontal axis. Optician of the output and transported beam in measuring pavilions is fulfilled on the basis of doublets from "warm" reference lenses 20K100. For a direct bundle EB-1 it is lenses 20K200, which one allow to stage focusing a beam in points F4, F5 and F6. For opticians of channels of secondary particles other types of lenses of the major aperture will be utilized also.

The tract of transporting of a beam is arranged with the system of monitoring of parameters of a bundle and control of its position. The control of parameters of bundles is yielded by the monitoring system on the basis of transparent proportional cameras, meters of a beam intensity and control of parameters of a field in rotary magnets. The control of a field in magnetic units is fulfilled with the help of sensors of the Hall that allows automating a management system of operation of channels with use of a computer. The working on by such system started and it is supposed to complete it in following year. The monitoring system of parameters of bundles is entered also by a polarimeter permitting to spot a degree of polarization of a bundle after transporting it in measuring pavilion. Now the polarimeter is installed in F4. The variant of installation of polarimeters in district F3 SF and FS' Nuclotron is considered. The transporting of the output bundle is yielded in vacuum conductor (ion conductor), composed from tubes a dia of 200 mm - sites inside lenses and free intervals - and vacuum boxes, rotary magnets, installed in splits. The channels of bundles and physical installations allocate inside rebuilt biological are hardwired from concrete cubes and upper beams. The protection allows being in building in a bum-time of accelerators with the output bundle.

The header of the channel is easily rebuilt for transporting a bundle to physical installations from both accelerators. It is reached for the score to roll of a doublet of lenses 20K200, installed on a mobile platform, on a direction of the working accelerator and magnet SP-12A. The building 205 is equipped with all indispensable production equipment for support of normal operation of channels of bundles and physical installations. There is a system of forvacuum rollout ion conductors of channels of transporting of bundles, system of support of cooling of magnetic units for the score to break of demineralised water at pressure four atmospheres and ramified haulage system of a current supply through cabinets of a

current supply posed at the left and on the right along walls of building. The feeding cables and control behind operation of unit's magnetic opticians allocate in cable ducts below than floor height. For allocation measuring and the monitoring equipment's near to installations will widely be utilized block of the experimenter Now on channels of bundles the installations DISK, MARUSYA, Alpha -3C, LEADING PARTICLES, SPHERE, GIBS-SPHERE, DELTA-SIGMA, DELTA, MPPT, FASA, CONUS and so on are installed. The most saturated and used zone of building 205 is the central bay (bay II). In bay III on the channel 1B there is equipment of the Movable proton polarized target (MPPT) and the installation of a magnet system MRS is planed. The creation of the channel for radial therapy-treatment of oncology swellings is planed. The feature placement of the channel, biological protection and cabs for an exposure of the patients represented on Fig. 4.



The carrying out of operations on implementation of this project will be carried out without damage to operation of operating physical installations. In bay 1 is planed to dispose a dipole magnet fulfilled on the project ALICE, for carrying out of test trials before a sending off in CERN.

Usage Nuclotron instead of SF for support of operation of physical installations allows in 3 times to diminish expenditure of an electrical powers going on power supply immediately of the accelerator and systems of its support. The expenditure of an electrical power on carrying out of experiments, nevertheless, is great, as for transporting a bundle the power-intensive magnetic units will be utilized. It is possible to determine the value of consumed energy by these units from data's, reduced in the table 1.

Table 1

a) Dipole magnets

The naming of unit	Magnetic density	Rated current	Voltage rating	Consumed power
	Ersted	A	V	Kw
SP-12A	18000	1600	205	328
SP-12	14000	1100	190	209
SP-40	18000	1100	220	242
SP-57	16000	600	171	102.6
SP-94	18000	635	212	134.62

b) Quadruple lenses

The naming of unit	Lapse rate	Rated current	Voltage rating	Consumed power
	E/sm	A	V	Kw
20K200A	1300	3500	189	630
20K100A	1300	3500	75	262.5
ML-16	650	1280	200	256
ML-17	650	1280	106	135.68
ML-15	800	508	80	40.64
ML-14	800	508	41	20.828

The decrease of expenditure of an electrical power is possible to reach, utilizing magnetic units with superconductor (SC) windings. Our Lab has wide experience of creation of magnet systems with SC by magnets, the field in which one is shaped by a ferrous yoke, and the winding is fulfilled from a superconductor. The operations on development of a lens with a superconductor winding intended for replacement of lenses 20K200 in channels of transporting of charged bundles would now be carried out. The variant of such construction of a lens represented in a fig. 5.

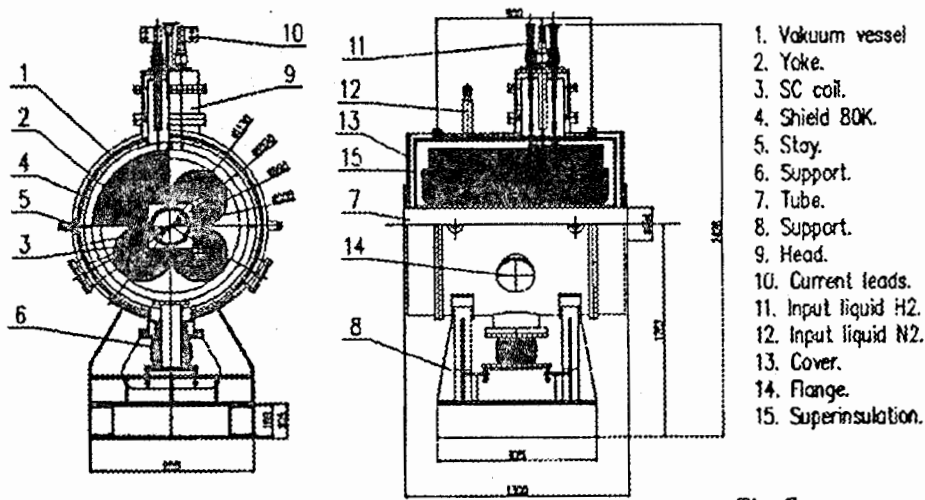


Fig.5

Under the similar scheme the rotary magnet is fulfilled also, probable fulfillment's which one is reduced in a fig. 6.

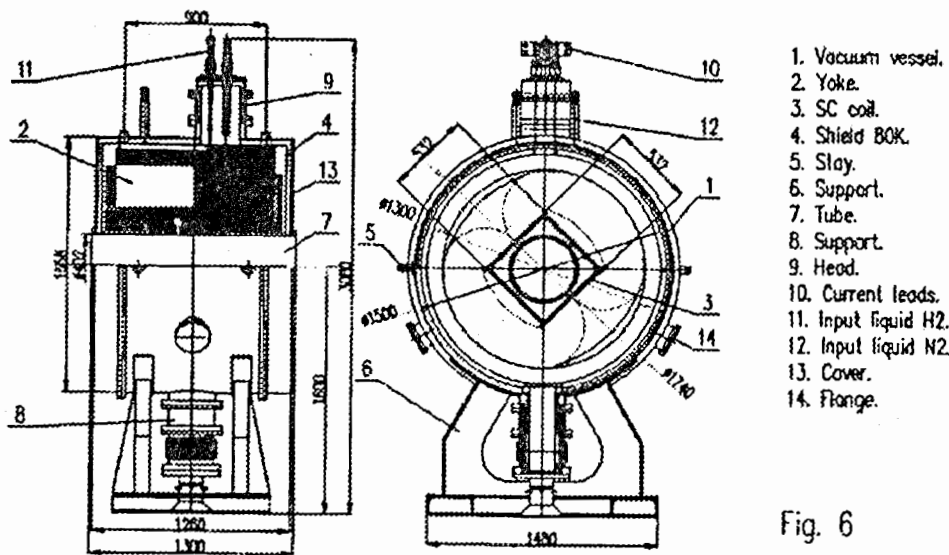


Fig. 6

The magnet system of these magnetic units is disposed in separate cryostats and represents the mobile block, which one substitutes by itself an appropriate "warm" magnet. For operation of such blocks it is required to provide with their liquid nitrogen and helium. The solution of this task in conditions LHE is quite possible. The Lab has wide experience on transporting condensed gases in tank cars and on transport pipelines. Use of SC magnetic units will allow to lower power consumption's on building 205 approximately three times, and expenditures on support of operation of channels of charged particles approximately twice. The main expenditures will be determined in this case by expenditures on a liquefaction of nitrogen both helium and losses of helium for technological reasons. In Lab is used the best efforts for the extension of possibilities on carrying out of physical experiments on the output bundles of accelerators and increase of a bum-time of operating installations.

Beam transport lines from the Nuclotron to the experimental set-ups

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Joint Institute for Nuclear Research, Dubna

Currently Lab of High Energies has an accelerating complex of two machines: the eldest synchrophasotron accelerating ions up to ^{32}S and the new superconducting accelerator Nuclotron capable to accelerate nuclei with 6 GeV/nucleon [1].

Now while running the Nuclotron a great success has been achieved: slowly extracted beam of deuterons was transported to experimental hall 205. The beam profiles measured are shown on Fig.1. Beam intensity achieved at the end of slow extraction line MV-1 in crossover F3 was 10^8 deuterons/spill.

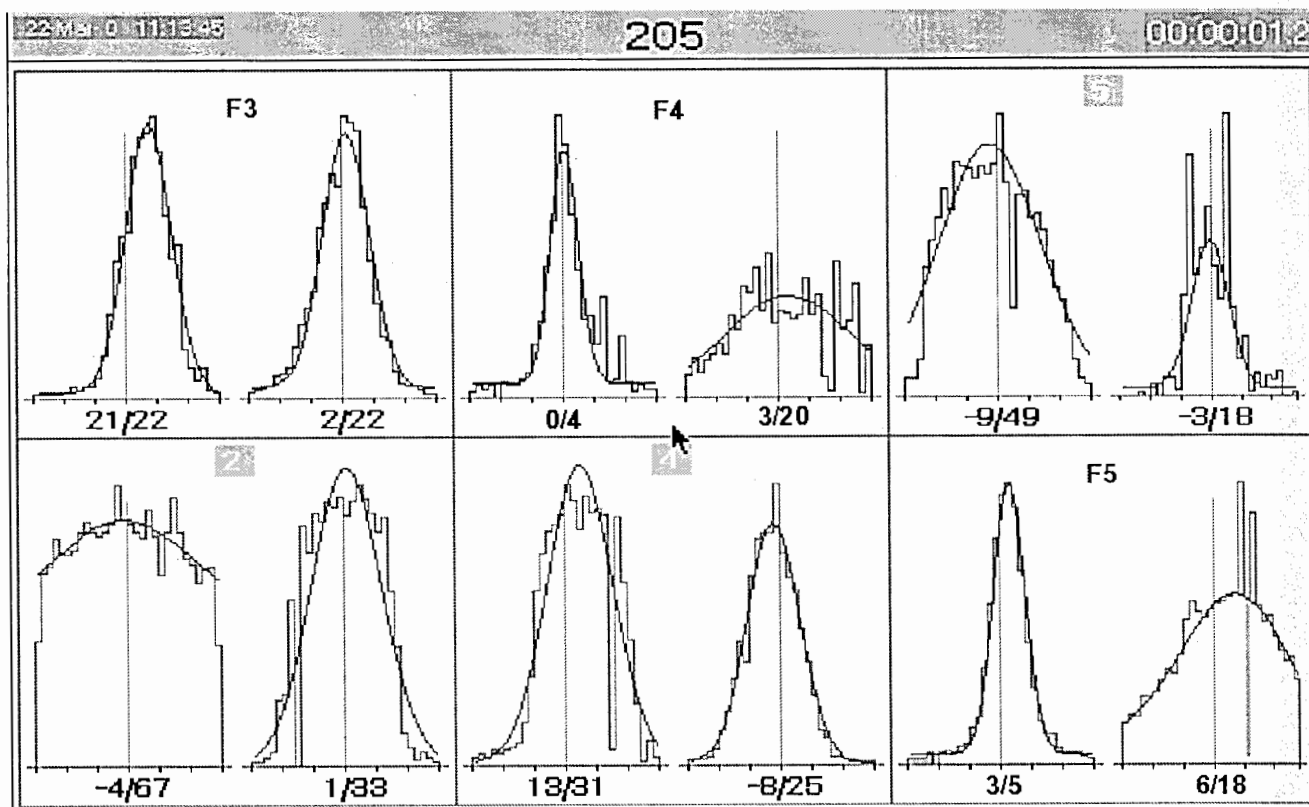


Fig.1. Preliminary test beam slowly extracted from Nuclotron: deuterons, $T=1\text{ GeV/n}$

The Nuclotron ring is mounted in the tunnel right below the synchrophasotron ring. Thus aiming to use the same experimental set-ups for both machines one need to make a rise-up of the beam extracted from the Nuclotron to the standard synchrophasotron horizontal plane. The sketch of this beam transport line scheme is shown in Fig.2.

The key element used to combine synchrophasotron and Nuclotron beams for the same set of experimental targets is 5SP-12A magnet. After it the two slow extraction beam lines merge and further the beam particles are transported to various set-ups using the same set of magnets and lenses of the main beam line VP-1. But magnetic field in the magnet has to be increased to bend a particle with maximum Nuclotron beam momentum at the nominal angle of 140 mRad. At the first step the pole gap in it was narrowed to 15 cm. Then the pole gap of the magnet has been prepared for connection with global vacuum system of VP-1 beam line. To make it possible two side plates were installed inside the pole. Magnetic field measurements resulted a good quality of magnetic field along the pole axis as well as vacuum tests achieved nominal vacuum value. The comparison of a new vacuumized pole construction with previous non-vacuumized pole without side plates is shown in Fig.3. Thus a value $B \cdot L = 6.71 \text{ T} \cdot \text{m}$ at $I = 1752 \text{ A}$ with effective length $L_{\text{eff}} = 3.12 \text{ m}$ was

achieved. This step allowed to reduce material along the beam line (reduce beam losses) and to keep vertical acceptance as large as possible for passage of beam particles from both machines, which is very important for secondary beams forming.

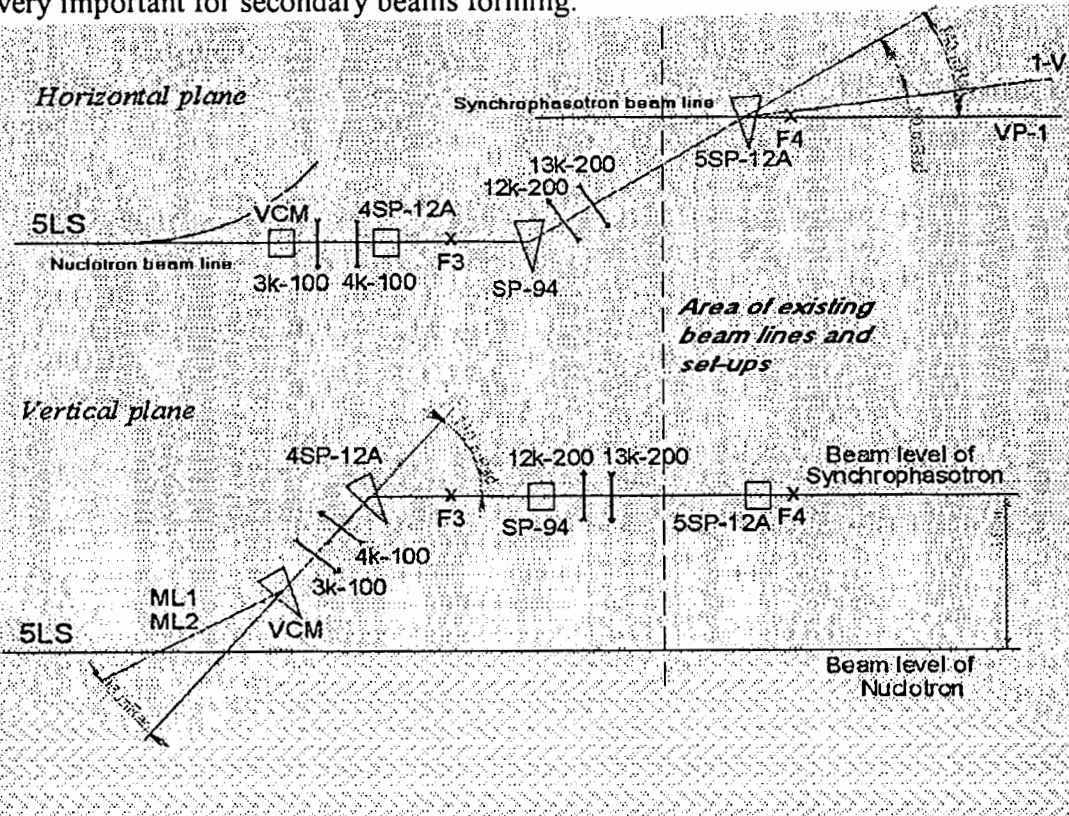


Fig.2. Nuclotron slow extraction beam line MV-1

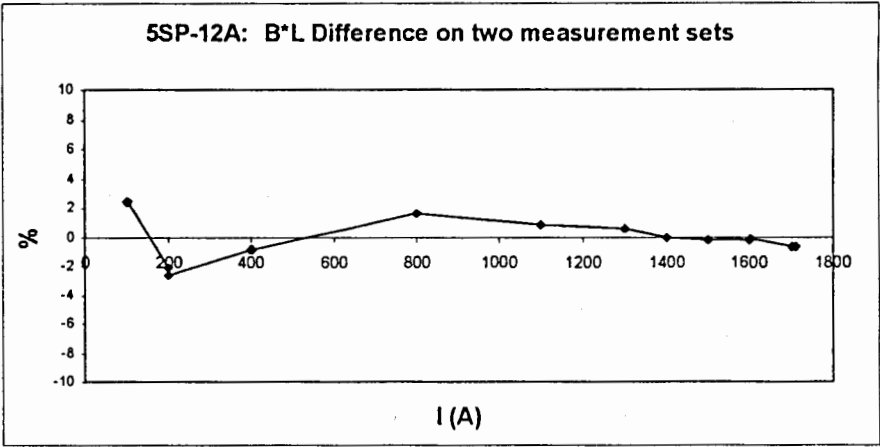


Fig.3. Comparison of 5SP-12A magnetic field along the axis with and without vacuumization

Looking closer at the current beam transport facilities installed in the experimental hall 205 one can see a few bottlenecks. These come from the limitation of maximum possible beam momentum along the lines below the maximum beam momentum available from the Nuclotron. The main constraints are summarized in Tab.1. Bold-typed elements denote the difficulty and corresponding bold-typed values produce a limitation while transporting beams with maximum Nuclotron beam momentum. The proposed solutions are not expensive and do not need global reconstruction of the whole beam line system in the experimental hall 205. They are mainly magnets pole reconfiguration and movement of some of the elements upbeam or downbeam. Replacement of some of the elements by superconducting ones also can be considered as a possible solution if the new elements

Tab.1. Experimental hall 205. Beam line reconstruction for the Nuclotron

Line, Pmax [GeV/c]	Element	φ [mRad]	B*L [Tesla*m]	Comments
1V, 12.5	5SP-12A	76	6.7	
	1SP-94	72	3.0	Move, pole reconfiguration
	1SP-12A	160	6.7	Narrow gap by 2x50mm
	2SP-12A	110		
3V, 13.8	2SP-40	120 (100)	+30%	Pole reconfiguration
	1SP-94	45 (65)	3.0	Move, narrow gap
	1SP-12A			
4V 12.5	2SP-40	110	+30%	Pole reconfiguration
	1SP-94	65		Move, pole reconfiguration
	1SP-12A	80		
	2SP-12A	165	6.7	Narrow gap by 2x50mm
	1,2ML-16			Replace by 1,2K-100 lenses
6V 13.8	3SP-12	150	6.7	Narrow gap

will have appropriate dimensions to be installed at the places. But this way is more expensive and needs longer time of construction and creation.

One of the side channels coming from VP-1, so called 1V channel, is used for experiments with neutron beams on the basis of a slowly extracted deuteron beam [2]. Now this line is modernized to be able to form both neutral and charged particles beams. A set of insertions for a final dublet of quadrupole lenses (3, 4K-100) was constructed. Putting these insertions inside the lenses one can get a lengthy collimation system for neutron beams. Removing them and turning the lenses on the line can be used to form a beam of charged particles. So in a couple of hours without termination of acceleration run and usage of complex installation equipment the line can be transformed from neutron beam transport line to a charged particles beam transport line.

Data acquisition and beam monitoring system also requires a lot of improvements. The nearest needs and requests for modernization of external beam control system can be summarized as follows:

- Modernization/production of preliminary electronics for ionization chambers; Production of ionization chambers;
- Monitors of intensity; Absolute calibration;
- Modernization of preliminary electronics for proportional chambers, TOF, q-analysis;
- Development of the magnetic field control system for beam line elements (first for 4V, SPHERE set-ups);
- Development of the automated currents control system in magnetic elements (first for 4V, SPHERE set-ups).

The whole work totals to \$40000US and can be done in a few stages (for example, \$20000US + \$20000US). This calculation does not include a computerized currents control system in magnets, which should be considered separately.

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DAILY PROGRAMME

WEDNESDAY, June 28, 2000

Chair: E. Tomasi-Gustafsson

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Deuteron Production in Central Pb+Pb Collisions at 158A GeV

G.L. Melkumov

(NA49 Collaboration)

Athens (Greece), Berkeley (USA), Birmingham (England), Bratislava (Slovakia), Budapest (Hungary), Geneva (Switzerland), Cracow (Poland), Darmstadt (Germany), Davis (USA), Dubna (Russia), Frankfurt (Germany), Houston (USA), Kent (USA), Los Angeles (USA), Marburg (Germany), Munich (Germany), Warsaw (Poland), Seattle (USA), New Haven (USA), Zagreb (Croatia)

Abstract

Experimental results on deuteron emission from central Pb+Pb collisions ($E_{beam} = 158A$ GeV, fixed target), obtained by NA49 at the CERN SPS accelerator, are presented. The transverse mass m_t distribution was measured near mid-rapidity ($2.0 < y < 2.5$) in the range of $0 < m_t - m_0 < 0.9$ GeV/ c^2 ($0 < p_t < 2.0$ GeV/ c) for the 4% most central collisions. An exponential fit gives an inverse slope $T_d = (450 \pm 30)$ MeV and a yield $dN_d/dy = 0.34 \pm 0.03$. The coalescence factor $B_2(m_t = m_0) = (3.5 \pm 1.0) \cdot 10^{-4}$ GeV² and its m_t -dependence are determined and discussed in terms of a model that includes the collective expansion of the source created in a collision. The derived Gaussian size parameter R_G of the emission volume is consistent with earlier HBT results on the source of pion emission.

INTRODUCTION

Nucleus-nucleus collisions at ultrarelativistic energies offer the unique possibility to study hot and dense nuclear matter (for recent overviews see [1]). Among a variety of species produced in the collisions deuterons form a minor fraction of the emitted particles. The bulk consists of pions with an admixture of kaons and nucleons. This matter forms a hot fireball which cools by expansion. The particles decouple or freeze out from the fireball region at a temperature of $T = 120 - 140$ MeV [2, 3]. Because of their low binding energy of 2.2 MeV deuterons cannot exist within the hot and dense reaction phase; they are only formed very late at freeze-out by nucleons in close proximity and with small relative momenta by means of a coalescence process [4]. Therefore, a measurement of deuteron production allows to study the freeze-out configuration in phase space.

The coalescence picture [5] suggests to relate the phase space density of the emitted deuterons - or, in general, of nuclear clusters with mass number $A = Z_{protons} + N_{neutrons}$ - to those of nucleons. This is formulated by the equation

$$E_A \frac{d^3 N_A}{dP_A^3} = B_A (E_p \frac{d^3 N_p}{dP_p^3})^Z (E_n \frac{d^3 N_n}{dP_n^3})^N, \quad (1)$$

$$P_p = P_n = P_A/A$$

where dN is the number of emitted particles, E and P are their energies and momenta. The dependence on the density in configuration space is absorbed into the coalescence factor B_A . Under the assumption of a constant B_A this relation successfully describes the scaling of the yields of light nuclei in nucleus-nucleus collisions at BEVALAC and SIS energies of 0.2 – 2.0A GeV [6–8] independently of the beam energy and the size of colliding nuclei, as well as in high energy p+p and p+A collisions at FNAL [9]. At the typical AGS energy of 10 – 15A GeV [10–12] B_A was found to be smaller by an order of magnitude. This was interpreted as evidence that for high energy heavy ion collisions it is also necessary to consider the spatial distribution of the nucleons [3, 13]. In such a picture the decrease of B_A with increasing beam energy observed in nuclear collisions with large ions can be understood in terms of a collective expansion of the collision zone before break-up [14].

Recently, the coalescence model was refined by Scheibl and Heinz [15]. They employed the similarity of the physics of coalescence and the final state momentum correlations, earlier stressed in [16], extending the investigation to a system with strong collective expansion. Using a hydrodynamically motivated parametrization for the source at freeze-out which implements rapid collective expansion of the collision zone formed in the relativistic heavy ion collisions, they calculated the coalescence probability and invariant momentum spectra for deuterons and antideuterons. To compare the numerical results of the model with experimental data, they used the fireball size and flow parameters obtained from the HBT analysis of two-pion correlations and negative particle spectra measured in the NA49 experiment in central 158A GeV Pb+Pb collisions [2]. The present study of deuteron production in the same experimental conditions provides an important test of the model.

EXPERIMENTAL METHOD

The experiment was carried out at the CERN SPS using the NA49 large acceptance hadron detector (Fig.1) [17, 18]. It mainly consists of four large Time Projection Chambers (TPCs). They provide tracking in the magnetic field and information on the specific energy loss dE/dx in the gas of the TPCs with a resolution of about 4% [17, 19].

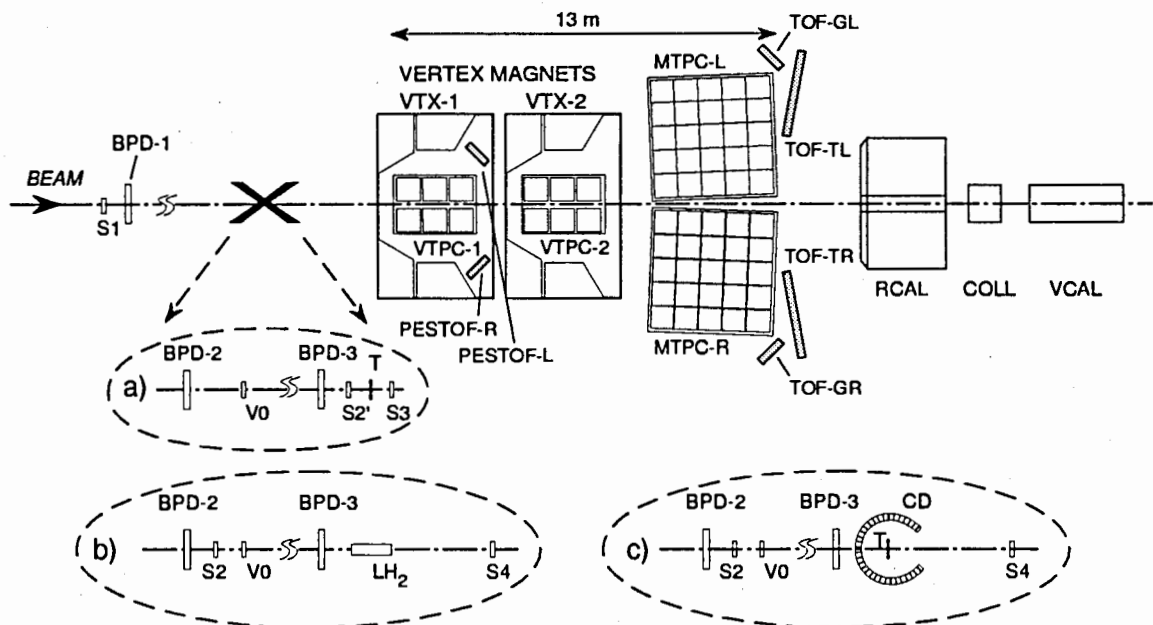


Figure 1. Set-up (not to scale) of NA49 experiment with different beam definitions and target arrangements for a) Pb+Pb, b) p+p and c) p+A collisions. The target position is at the front face of the Vertex Magnet (VTX-1)

The tracks of the charged particles emerging from the collision of the ^{208}Pb ion beam with a Pb target of 224 mg/cm^2 in thickness are measured in two Vertex TPCs located in the magnetic field of two superconducting dipole magnets (total bending power 9 Tm) and in two large Main TPCs placed behind the magnet 11 m downstream from the target on either side of the beam axis.

In the present study the particle identification and the separation of the deuterons from the background relies on the particle mass information obtained from two 2.2 m^2 Time-of-Flight (TOF) walls containing 891 pixels each and situated behind the Main TPCs on both sides of the beam. The pixels are scintillator tiles of $60/70/80 \text{ mm} \times 34 \text{ mm} \times 23 \text{ mm}$ size viewed by single photomultipliers. The overall time resolution is about $60 - 70 \text{ ps}$. The particle identification capability in the experiment is shown in Fig.2a, where the dE/dx value measured in the Main TPC is plotted against the particle mass squared m^2 derived from the TOF information. Whereas deuterons would be completely overshadowed by kaons and protons in the dE/dx projection, they can be cleanly separated on the basis of the TOF information. The acceptance of the TOF system for deuterons (protons) covers the laboratory rapidity range $2.0 < y < 2.5$ ($2.4 < y < 3.0$) and transverse momenta $p_t < 2.0 \text{ GeV}/c$.

The central Pb+Pb collisions were selected by a trigger employing the

measurement of the forward-going energy in the Veto Calorimeter, located 27 m downstream of the target. It was set to accept only the 4% most central events of all inelastic Pb+Pb reactions, corresponding to an impact parameter range of $b < 3.5$ fm.

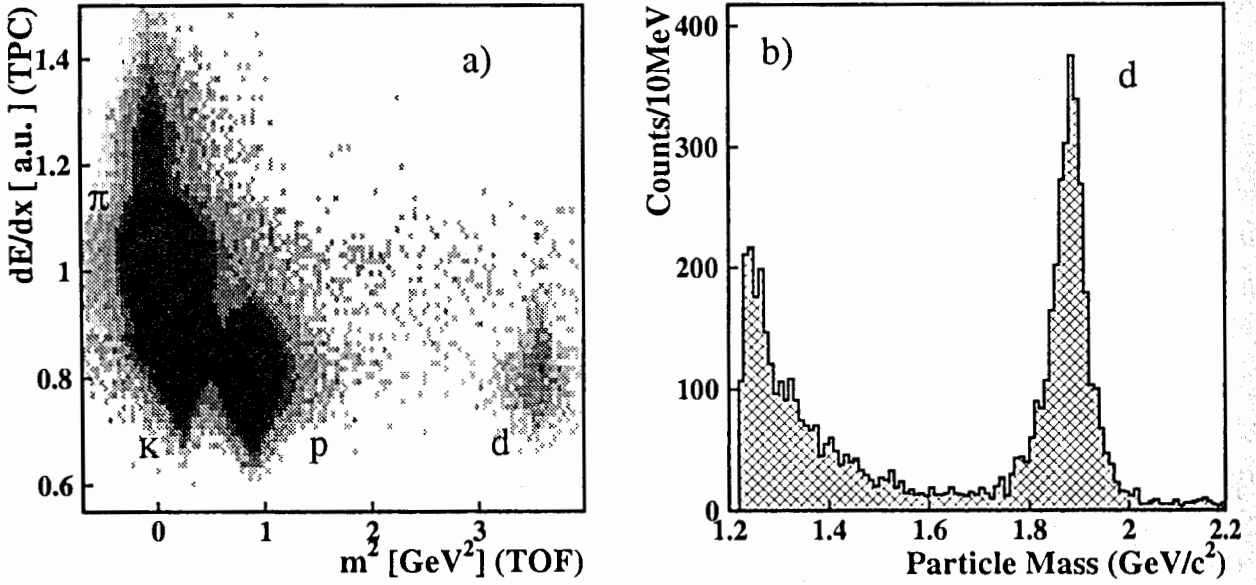


Figure 2. a) Particle identification by time-of-flight and dE/dx measurements and b) Invariant mass distribution after dE/dx cuts in the momentum range $p = 3 - 10$ GeV/c

DATA ANALYSIS AND RESULTS

For the present study 205,000 events were used. In the following, we outline briefly the main steps of the data analysis, in which the information from the TPC and TOF detectors have been used simultaneously. The reconstruction of tracks was performed by a global tracking technique forming track segments in the Main and Vertex TPCs. The reconstructed tracks were extrapolated to the TOF detector plane and were subjected to a number of cuts to reduce the background. Due to the finite granularity of the TOF walls their efficiency for detection of a single particle is less than 100% because of double hits, edge effects as well as conversion pairs created in the scintillator from event-correlated gammas. The sum of all losses, as determined experimentally by comparison with the TPC tracking data, amounts to 25% on average, with a maximum of 32% in the central region closest to the beam. The relevant efficiency corrections have been applied to the data.

The next step of the analysis was the selection of deuterons and the reconstruction of their transverse mass m_t distribution. We defined windows in dE/dx and m^2 which simultaneously maximized the number of deuterons

and minimized the background contribution mostly coming from the other particles, i.e. pions, kaons and protons. This selection was performed for (p_t, p) bins of $\Delta p_t = 0.5$ GeV/c and $\Delta p = 1.0$ GeV/c widths in the full kinematical range of deuterons accepted by the TOF detector $0 < p_t < 2.0$ GeV/c and $3.0 < p < 14.0$ GeV/c. The background was negligible over most of the covered phase space reaching about 20% in the region of momenta $p > 12.0$ GeV/c at $p_t > 1.0$ GeV/c. The correction factors for the deuteron loss and background contamination due to the cuts were estimated separately for each (p_t, p) bin. Fig.2b shows the resulting distribution of the particle mass after dE/dx cuts.

Geometrical acceptance and tracking efficiency was obtained from a Monte-Carlo simulation of the detector in GEANT. The tracking efficiency was 95% over all the TOF acceptance.

The transverse mass ($m_t = \sqrt{p_t^2 + m_0^2}$, m_0 = particle mass) spectrum for deuterons obtained after all corrections is shown in Fig.3.

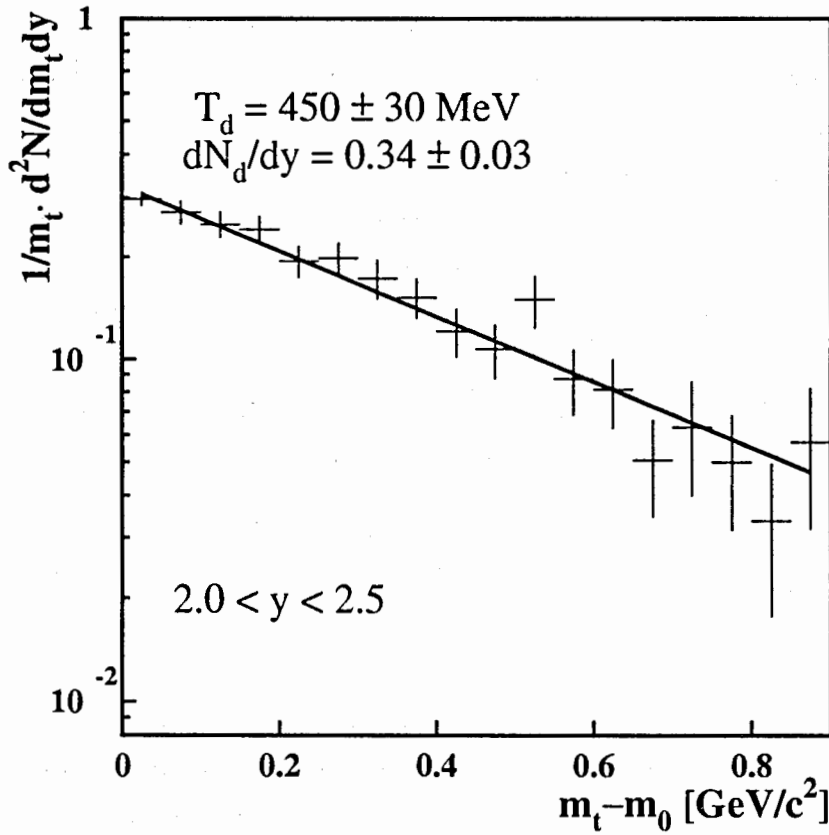


Figure 3. Transverse mass spectrum for deuterons produced in the 4% most central Pb+Pb collisions at 158A GeV

The m_t distribution was fitted with the exponential function:

$$\frac{d^2N}{m_t dm_t dy} = C e^{-(m_t - m_0)/T}, \quad (2)$$

yielding the following parameters :

$$T_d = 450 \pm 30 \text{ MeV},$$

$$dN_d/dy = 0.34 \pm 0.03,$$

where T_d and dN_d/dy are the inverse slope and the deuteron yield respectively. The errors are statistical. dN_d/dy was obtained by integrating the exponential function over the full m_t range. The total errors including systematical ones are estimated to be about 10% for both parameters.

DISCUSSION

The transverse mass spectrum of deuterons is observed to be significantly flatter than that of protons. Quantitatively, this is expressed by the inverse slope parameter $T_d \approx 450$ MeV for deuterons compared to $T_p \approx 330$ MeV for protons [24]. Fig.4 shows the deuteron inverse slope along with those obtained from TOF-identified particles π , K and p near mid-rapidity by fitting the m_t spectra in the range $0 < m_t - m_0 < 1.0$ GeV/ c^2 for K and p, and $0.3 < m_t - m_0 < 1.0$ GeV/ c^2 for π respectively. The inverse slopes for ϕ meson and Ξ -hyperon measured by the NA49 are also presented in Fig.4. The increase of T with particle mass [20, 21] is commonly interpreted as an evidence for a strong collective transverse expansion of the fireball [22].

For deuterons, the shape of the transverse mass spectrum also depends on the coalescence mechanism. A very simple coalescence model assuming an independent source functions in configuration and momentum space predicts the inverse slope of the m_t spectrum of deuterons to be similar to that of protons. However, if the space-momentum correlation is included in the coalescence model the inverse slope of deuterons may deviate from the prediction of the simple coalescence model in the case of strong transverse flow [3, 13]. As was shown by Polleri et al. [23] the different slopes of nucleon and deuteron transverse mass spectra require a transverse density profile of the source which is closer to a box than to a Gaussian shape.

In order to obtain the coalescence factor B_2 for deuterons as defined by Eq.1 the invariant yields for nucleons are needed, to be taken at the same

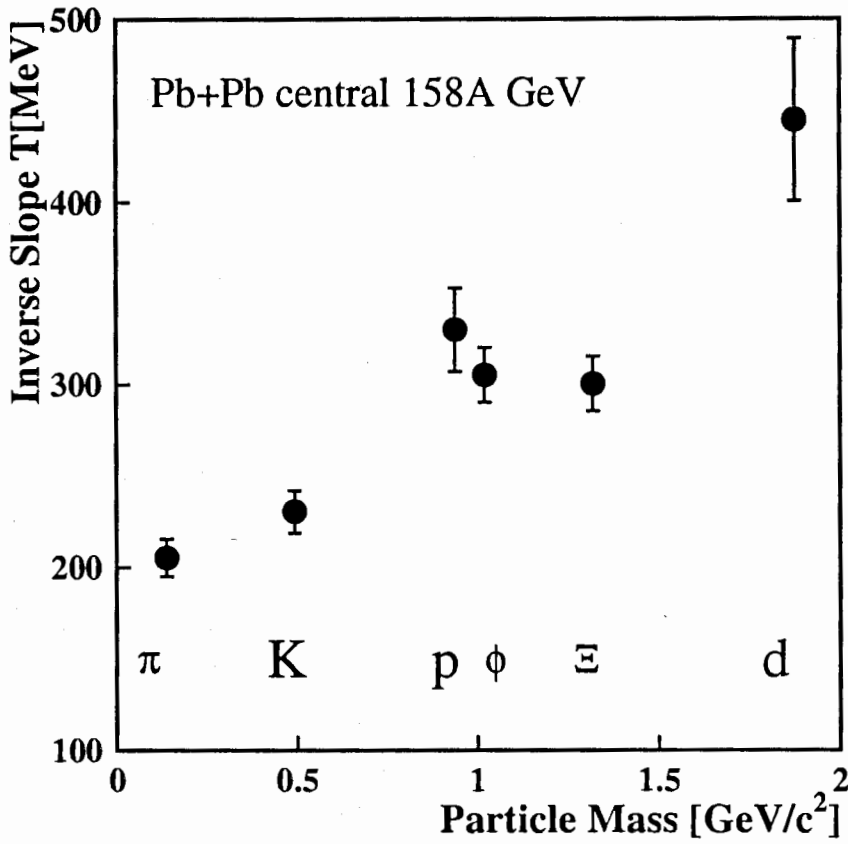


Figure 4. Inverse slopes for various hadron species near mid-rapidity in central Pb+Pb collisions at 158A GeV

rapidity as for deuterons. As usual it is assumed that neutrons behave identically to the protons under our experimental conditions. Data for the latter can be obtained from the NA49 experimental results on net protons, have already been corrected for feed-down from weak decays of Λ and Σ hyperons [24], and revalued for a small fraction of antiprotons ($\bar{p}/p = 5 - 7\%$ as estimated from TOF data). This procedure yields $T_p = 330$ MeV and $dN_p/dy = 32$, with estimated errors of 10% for both quantities.

Eq.1 applied to the deuteron case reads

$$E_d \frac{d^3 N_d}{dP_d^3} = B_2 \left(E_p \frac{d^3 N_p}{dP_p^3} \right)^2, \quad P_d = 2P_p, \quad (3)$$

where B_2 [GeV²] is the coalescence factor for deuterons. Assuming azimuthal isotropy and an exponential m_t -dependence as in Eq.2 the invariant particle yield at a given rapidity can be written as

$$E \frac{d^3 N}{dP^3} = \frac{1}{2\pi} \frac{d^2 N}{m_t dm_t dy} = \frac{1}{2\pi} \frac{dN}{dy} \frac{1}{m_0 T + T^2} e^{-(m_t - m_0)/T}. \quad (4)$$

$B_2(m_t)$ is obtained from (3) and (4):

$$B_2(m_t) = 2\pi \frac{dN_d/dy}{(dN_p/dy)^2} \frac{(m_p T_p + T_p^2)^2}{m_d T_d + T_d^2} e^{-(m_t - m_0)/D}, \quad (5)$$

where $D = T_p * T_d / (T_p - T_d) = -1.24$ GeV, and m_t is the transverse mass of the deuteron. Inserting the experimental values for the proton and deuteron parameters, we derived for $p_t = 0$

$$B_2(m_t = m_0) = (3.5 \pm 1.0) \cdot 10^{-4} \text{ GeV}^2,$$

with an m_t -dependence determined by the parameter D . This result is displayed in Fig.5. Above error for B_2 includes both the statistic and systematic errors.

Our result for B_2 is somewhat smaller than the values obtained by other SPS experiments for the same collision system under similar centrality conditions: NA52 [25] reported $B_2 \simeq 6 \cdot 10^{-4} \text{ GeV}^2$ (at $y = 3.75$, which is equivalent to $y = 2.1$); NA44 [26] presented $B_2 \simeq 8 \cdot 10^{-4} \text{ GeV}^2$ ($1.8 < y < 2.2$). All three experimental results are in the same range as the value $B_2(m_t = m_0) = (6_{-2}^{+4}) \cdot 10^{-4} \text{ GeV}^2$ predicted by the coalescence model [15] mentioned earlier. It should be emphasized that the B_2 -values measured at the SPS energy are smaller (by a factor of about 2) than those measured in central Au+Au collisions at the AGS [11, 12], while the latter are again smaller by one or two orders of magnitude than the values measured at BEVALAC energies [8]. This can be interpreted as a consequence of the large radial flow and large freeze-out volume reached at higher energies.

In a simplified coalescence model based on the assumption of a static Gaussian nucleon source [27] a relation between the source radius R_G and the B_2 -value defined in Eq.3 can be derived:

$$R_G^3 = \frac{3}{4} (\sqrt{\pi} c \hbar)^3 \frac{m_d}{m_p^2} \frac{1}{B_2}. \quad (6)$$

Inserting the measured B_2 -values one obtains $R_G(m_t)$ as shown in Fig.5. R_G becomes m_t -dependent as a consequence of transverse flow. Although the underlying assumptions are only crude approximations, in particular for a source expanding differently in longitudinal and transverse directions, the advantage of this relation is that the resulting "effective" size parameter R_G can be compared directly to pion interferometry results. In Ref. [2] NA49 reported a transverse Gaussian radius $R_G(HBT) = (6.5 \pm 0.5) \text{ fm}$ (for transverse velocity $\beta_t = 0$) for the same reaction under identical trigger conditions.

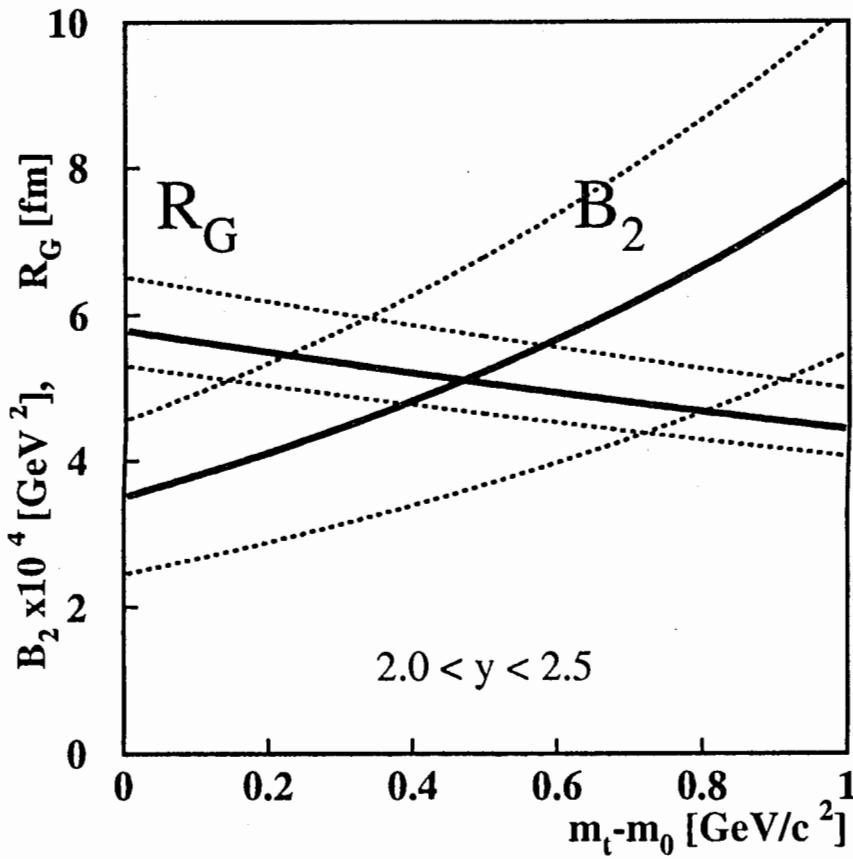


Figure 5. Coalescence factor B_2 and radius parameter R_G as a function of the deuteron transverse mass for the 4% most central Pb+Pb collisions at 158A GeV (solid lines). The bands indicate the uncertainties (dotted lines)

The agreement with the deuteron result shown in Fig.5 ($R_G = (5.8 \pm 0.7)$ fm at $m_t - m_d = 0$) is reasonable. On the other hand, we estimate from our measurement of the two-proton correlation function [28] a smaller effective source radius for proton emission of $3.85 \pm 0.15(stat.)^{+0.60}_{-0.25}(syst.)$ fm.

SUMMARY

The transverse mass distribution for deuterons produced in the 4% most central Pb+Pb collisions at 158A GeV in the region $2.0 < y < 2.5$ and $0 < p_t < 2.0$ GeV/c shows an inverse-slope parameter $T_d = (450 \pm 30)$ MeV, which is considerably larger than that of protons. The deuteron yield in this rapidity is measured to be $dN_d/dy = 0.34 \pm 0.03$.

The coalescence scaling factor $B_2(m_t)$ and a Gaussian size parameter $R_G(m_t)$ were derived from comparison to proton invariant m_t spectra. B_2 is found to be at least an order of magnitude smaller than for comparative systems at BEVALAC energies (SPS: 158A GeV, BEVALAC: below 1A GeV). This is consistent with the presence of a strong collective expansion

in nucleus-nucleus collisions at SPS energies. The size parameter R_G agrees with the transverse freeze-out radius obtained by pion interferometry for the same collision system.

The values of T_d and B_2 are consistent with the inverse slope and the coalescence probability predicted by a newly developed coalescence model which uses hydrodynamically motivated parameters of the particle emission source and implements rapid collective expansion for central heavy ion collisions.

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Global Event Characteristics in Ultrarelativistic Nuclear Collisions

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Global characteristics of nucleus-nucleus collisions available in the CMS experiment [1] are differential distributions of total transverse energy flows, $dE_T/d\eta$, in a pseudorapidity range $-5 < \eta < 5$ as well as electromagnetic and charged multiplicity ones, $dE_0/d\eta$ and $dN_{ch}/d\eta$. For instance, the CMS calorimeter system will be able to cover about 80% of a total transverse energy flow. Use of the CMS apparatus for studies of global observable distributions allow one to establish a quite general rules of nucleus-nucleus collision dynamics up to the highest energy frontier with a huge rapidity coverage and to verify some crucial predictions of quark-gluon plasma formation models in a sufficiently simple way.

One of the predicted features of such state of a nuclear matter is energy losses of scattered partons in final state interactions with a dense nuclear matter called jet quenching [2]. The HIJING Monte Carlo generator developed by M. Gyulassy and X.-N. Wang [3, 4] provide an opportunity to study various manifestations of this mechanism. Among other effects originated by a jet quenching one may expect a significant modification in the differential distributions mentioned above. Indeed a strong indication is found on appearance of a wide bump in the interval $-2 < \eta < 2$ over a pseudorapidity plateau of such distributions for the case when jet quenching is switched on [5].

The problem of existence of this bump rise the question of principal importance - whether a asymptotic behaviour of basic distributions established already at lower energy scale will be broken in new energy domain or not. A wide pseudorapidity plateau provided by the LHC machine and the CMS acceptance give a chance to obtain a definite answer to the question.

Even in absence of such modifications a conservation of similarity in a behaviour of global observable distributions with respect to lower energy ones make it possible to derive a conclusion on colour transparency of colliding nuclear matter. This circumstance is of a special meaning since already $\approx 80\%$ of total transverse energy flow in LHC energy scale are calculated in the framework of application of pQCD to the HIJING [4].

So, a well defined choice between two possible scenarios make these distributions interesting for dedicated experimental study and for definition of future explorations. Below we shall present most important results of our study.

In addition to a general physics interest the global event characteristics provide a basis for estimation of a collision impact parameter and inelasticity characterization for correlated measurements in other reaction channels like jet and lepton pair production. For instance this measurement might provide a basis for searches of manifestation of spacial variation of nuclear structure functions [6]. Besides, in the framework of global energy simulations one can work out practical suggestions on a fast inelastic event selection with various collision centrality in order to enreach most central event sample ($\approx 3\%$).

In this respect it's interesting to note that such secondary effect as a jet quenching can modify only the central rapidity part leaving both fragmentation regions ($3 < \eta < 5$) unchanged. This circumstance is useful for definition of nuclear collision geometry (i.e. impact parameter) by means of the very forward calorimeters with minimal dependence on collision dynamics details in the central region (fig. 1).

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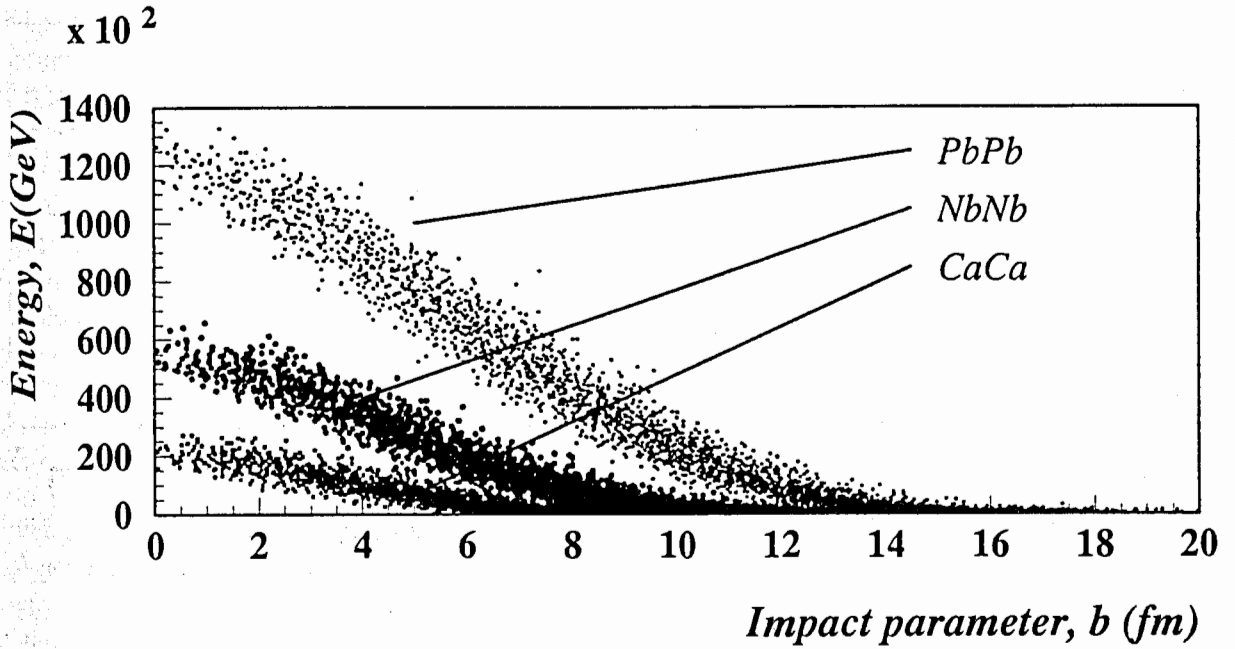


Figure 1. Correlation between total energy flow per collision (vertical axis in GeV; full scale 100,000 GeV) in very forward calorimeter direction ($3 < \eta < 5$) and collision impact parameter (horizontal axis in fm). HIJING Model. From top to bottom: 10,000 Pb-Pb, Nb-Nb, Ca-Ca collisions at 5.5 TeV/nucleon (cms)

Let's turn back to results of the global energy flow simulations. In the HIJING generator [3] soft hadron-hadron processes are simulated as classical strings with kinks and valence quark ends following the FRITIOF model [8]. Hard parton processes and the jet production are based on the PYTHIA program package [9]. The number of jets in inelastic pp-collisions is calculated in the eikonal approximation. The HIJING model provides a dependence of the parton structure function on a collision impact parameter.

One of the most important features of the HIJING model is the inclusion of energy losses dE/dx mechanism of a parton traversing dense nuclear matter. High energy quark and gluon losses in a hot chromodynamic matter are estimated in [10]. It was shown that a dominant mechanism of energy losses is radiative ones induced by a gluon emission in soft final state interactions (bremsstrahlung). In the HIJING model this mechanism is fulfilled as consecutive transmissions of a part of the quark and gluon energy from one string configuration to another. It is supposed that the energy losses are proportional to a distance traversed by a jet after last interaction and occur only in a transverse direction within a nucleus radius. An interaction proceeds until a parton jet stays inside the considered volume and the jet energy exceeds the jet production energy limit. Let's note that a space-time picture of parton shower evolution is not considered in the HIJING, and the effect of dense matter formation is introduced by a phenomenological way.

The HIJING generator was used to produce large samples of events (up to 10,000) of minimal bias PbPb, NbNb, CaCa, OO interactions. In fig. 2 differential transverse energy distributions $dE_T/d\eta$ are presented for Pb-Pb collisions at energy values $\sqrt{s_{nn}}$ equal to 5.5, 3, 1, 0.5, 0.2, 0.1 TeV/nucleon (center of mass). A distinctive feature of the distributions is the presence of the bump in central pseudorapidity ($-2 < \eta < 2$) region starting from the energy value larger than 3 TeV/nucleon. For lower energy values this effect is not so profound due to smaller rapidity difference between fragmentation regions. Verification of such dependences impose a task of feasibility of colliding beam energy scanning with the LHC machine from few hundred GeV to few TeV region.

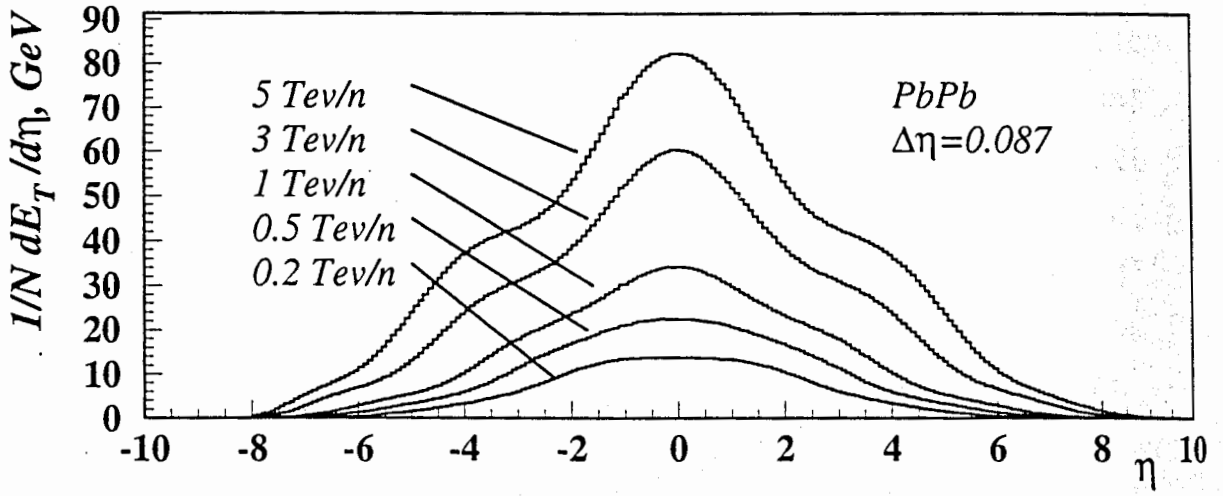


Figure 2. Differential distribution of total transverse energy $dE_T/d\eta$ (GeV) over pseudorapidity for Pb-Pb minimal bias collisions at energy values $\sqrt{s_{nn}}$ equal to 5.5, 3, 1, 0.5, 0.2 TeV/nucleon (cms). Jet quenching is on. Normalized per number of events; η bin size is 0.087

The existing CERN heavy ion injection system can provide sufficient luminosity for whole variety of fully stripped nuclei with rapid transition from one type ion to another [11]. This makes it possible to study a mass number dependence of the distribution modifications. Reduction of the colliding nucleus radii must lead to a bump reduction. This provides an additional test of jet quenching existence. Fig. 3 shows that lead-lead collisions demonstrate maximum quenching dependence while in lighter ion cases the bump becomes less and less profound. It's interesting to note that a degree of shadowing modification of PDFs can be estimated by measurement of absolute value of absolute value of transverse energy flow for various ion species.

A collision impact parameter dependence was followed for a Pb-Pb case from most central collisions to peripheral ones. It was shown that a bump stay distinguishable until parameter values about 12 fm. So, this gives additional option to study effect by a global approach making impact parameter tagging by the very forward calorimetry. As it follows from fig. 2 fluctuations in nucleus-nucleus collisions of an impact parameter definition at a level of 2 fm which is sufficient to explore transverse energy correlations over an available pseudorapidity range on event-by-event basis.

It was found in the framework of this study that the qualitatively the same picture of a bump formation are obtained in differential distributions of transverse electromagnetic energy and charged multiplicity flow. This gives experimental alternatives to search for the effect.

Our preliminary results indicate that the qualitatively same modification of a distribution shape can be obtained in the VENUS Monte Carlo model [12] in the case when rescattering of nucleons is switched on. It's appears to be very fruitful to compare the discussed distributions with predictions of other models and their options.

We note that among global characteristics available for measurements with the CMS a high transverse momentum muon flow might be noted as potentially interesting to search for modifications in open heavy flavours and IVBs production in nucleus-nucleus collisions with respect to proton-proton ones (see for example in [14]). Such approach based on integral flow of hard muons and dimuons demands careful study of contributions of lighter hadrons. This study is in a progress now.

Let's discuss some practical requests needed to be resolved for the global observable studies with CMS.

First of them is availability of heavy ion beams for the CMS at LHC during period when the CMS solenoid isn't switched yet. This circumstance is critical to allow one to measure undistorted distributions of total energy and charged multiplicity flows. Heavy ion option might be attractive

of alignment of the tracking detectors. Otherwise it's necessary to prove that for a case of gamma-quantum energy flow a distortion produced in the electromagnetic calorimeter by charged hadron flux is small enough.

Another practical problem is sufficiency of CMS calorimeter resolution for a bump observation. One of the CMS calorimeter practical problems is energy resolution depletion on boundaries of the major calorimeter part, i.e. barrel, forward, and very forward ones. This problem can be overcome in case nucleus-nucleus collision by normalisation of the distributions to proton-proton ones having the same dependence of calorimeter response. It is shown in the paper [13] that application of this idea allow one to observe the bump with the CMS calorimetry resolution even on a sample of 100 Pb-Pb events without complicated corrections.

So, it might be concluded that the CMS experiment with a wide calorimeter and tracker (pixel part) acceptance is able to observe the described modification of global observable distributions. From experimental point of view this option to search for jet quenching is specially attractive due to the positive correlation - than more jet quenching is than more transverse energy "repumped" toward $\eta = 0$. In fact this leads to effective increase of energy density or "stopping power" in the central region.

These differential distributions can be obtained with a practically unlimited accuracy for various colliding nuclei by a direct counting of differential energy and charged multiplicity flow. The special

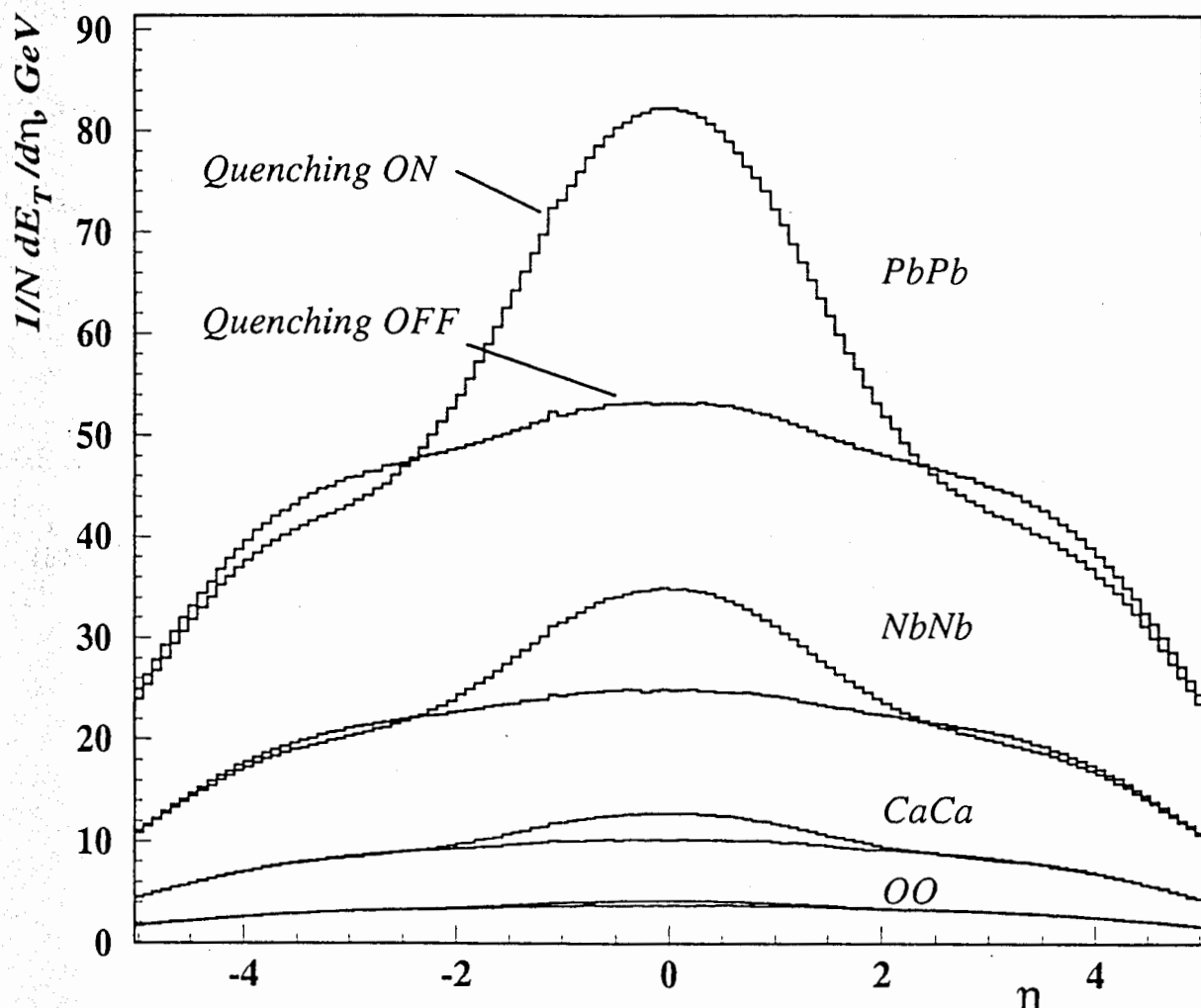


Figure 3. Differential distribution of total transverse energy flow $dE_T/d\eta$ (GeV) over pseudorapidity for Pb-Pb, Nb-Nb, Ca-Ca, O-O minimal bias collisions at 5.5 TeV/nucleon (cms) with and without jet quenching. Normalized per number of events; η bin size is 0.087

demand of this study is availability of a brief period of CMS running with the solenoid switched off and, as addition, variation of an LHC collision energy value and a type of accelerated nuclei. By these reasons global observable measurements of nucleus-nucleus collisions in ultrarelativistic domain demanding minimum beam time might pretend to become a candidate on "Physics of LHC first seconds".

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Polarization transfer in the $^{16}\text{O}(\vec{e}, e'\vec{p})^{15}\text{N}$ and $^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$ reactions

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Abstract. The first $(\vec{e}, e'\vec{p})$ polarization transfer measurements on nuclei heavier than deuterium have been carried out over the last several years at Jefferson Laboratory and MAMI at Mainz. The reactions studied were $^{16}\text{O}(\vec{e}, e'\vec{p})^{15}\text{N}$ and $^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$. The data are sensitive to possible modifications of the nucleon form factors and to relativistic distortions of the lower components of the nucleon wave function (spinor distortions) in the nuclear medium.

1. Introduction

The combination of a high intensity, high polarization, continuous electron beam and a focal plane polarimeter makes possible a new generation of studies of the effects of the nuclear medium on the properties of the nucleon. ¹ Polarization transfer in the $(\vec{e}, e'\vec{p})$ reaction on a proton target is a direct measure of the ratio of the electric and magnetic form factors of the proton, G_E^p/G_M^p , as shown below. When such measurements are carried out on a nuclear target, the polarization transfer observables are sensitive to the form factor ratio of the proton embedded in the nuclear medium. Because such experiments involve the measurement of ratios of polarizations at a single kinematic setting, the systematic errors can be very small, in contrast to the usual Rosenbluth separations which require different kinematic settings.

The issue of possible modification of the properties of hadrons in the nucleus has been attracting experimental and theoretical attention for some years. It remains unsettled. Interpretations of inclusive (e, e') cross-section measurements in the y -scaling regime suggest ² that the radius of the nucleon is changed by less than a few percent at least for values of the four-momentum transfer squared (Q^2) up to about 1 (GeV/c)². These measurements are primarily sensitive to the magnetic form factor. Measurements of the Coulomb sum rule over a similar region in Q^2 indicate that the electric form factor in ^3He is close to its free value, ³ and some studies suggest that this is true in ^{12}C and ^{56}Fe as well, ⁴ but recent work disputes this conclusion. ⁵ Measurements of the form factor ratio of the nucleon in nuclei by Rosenbluth separations in $(e, e'p)$ reactions indicated changes of about 25% at low Q^2 , ⁶ but some other experiments and theoretical analyses disagree. ⁷

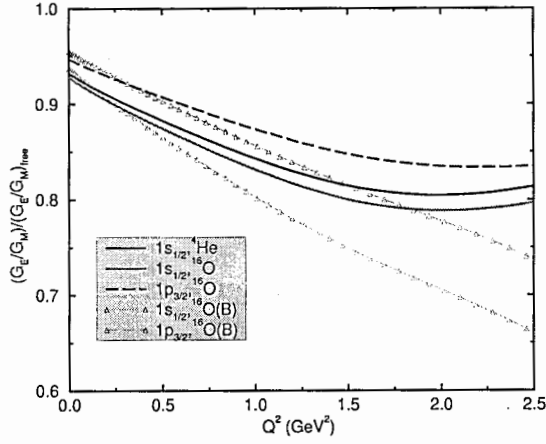


Figure 1. Predicted super-ratios of the in-medium form-factor ratios to the free form-factor ratios for states in ^{16}O and ^4He as a function of Q^2 . The three curves that are highest at 2.5 GeV^2 have been calculated with a fixed bag constant; the two lower curves assume a density-dependent bag constant

An example of possible changes apparently consistent with all previous data is shown in Fig. 1. The curves are predictions by the Adelaide group ⁸ based on the quark-meson coupling model (QMC), a mean-field calculation using the bag model to describe the nucleons. The super-ratio of the predicted in-medium form-factor ratio to the free form-factor ratio is shown as a function of four-momentum transfer for several states in ^{16}O and ^4He . The curves with the triangles were calculated with density-dependent bag constants; the others were based on free values of the bag constant. At the momentum transfer of the ^{16}O experiment, 0.8 GeV^2 , the predicted changes are of the order of 10-15%; at the highest values of Q^2 , changes up to about 30% are predicted. Changes of this magnitude have also been suggested previously. ⁹

Polarization transfer data are also sensitive to relativistic effects of the nuclear medium on the wave function of the nucleon. Recent theoretical calculations have shown that the lower components of the nucleon wave function may be changed from their plane wave values. ^{10,11} Evidence for such "spinor distortions" has been observed in cross section measurements for the $^{16}\text{O} (e, e'p)^{15}\text{N}$ reaction. ¹² The A_{LT} response functions extracted from the data show significant structure at large values of the missing momentum p_m attributed to these effects of relativistic dynamics.

Here I describe three $(\vec{e}, e'\vec{p})$ experiments on ^{16}O and on ^4He in which I have been involved along with a large number of collaborators. The oxygen experiment was the first measurement of this sort carried out on a nucleus heavier than deuterium.¹³ The experiment, E89-033 at the Thomas Jefferson National Accelerator Facility (JLab),¹⁴ was part of the commissioning effort for Hall A. It was the first experiment requiring the use of polarized beam at the Laboratory, and the first to use the focal plane polarimeter (FPP) mounted on the High Resolution (hadron) Spectrometer. The many difficulties involved in commissioning limited the statistical precision of the results we were able to achieve in a fixed beam time.¹⁵ More recently, data with much higher statistical precision have been obtained on ^4He , at low momentum transfer at Mainz ($Q^2 = 0.4 (\text{GeV}/c)^2$), and up to $2.6 (\text{GeV}/c)^2$ at JLab. While only preliminary results of the ^4He experiments are available at this time, they indicate that high precision polarization transfer data are a sensitive measure of the effects of the nuclear medium on the structure of the nucleon.

2. The Recoil Polarization Technique

For the free nucleon, the polarization transfer can be written in terms of the form factors as¹⁶

$$I_0 P'_l = \frac{E + E'}{m_p} \sqrt{\tau(1 + \tau)} G_M^2 \tan^2(\theta/2)$$

$$I_0 P'_t = -2\sqrt{\tau(1 + \tau)} G_M G_E \tan(\theta/2)$$

$$I_0 = G_E^2 + \tau G_M^2 [1 + 2(1 + \tau) \tan^2(\theta/2)]$$

$$\tau = Q^2/4m_p^2,$$

where E and E' are the energies of the incident and scattered electron, θ is the electron scattering angle, and m_p is the proton mass. P'_l is the longitudinal polarization transfer, the polarization of the scattered proton P_l in the direction of its momentum for a 100% polarized electron beam. P'_t is the transverse polarization transfer, the polarization of the scattered proton P_t transverse to its momentum in the scattering plane for a 100% polarized electron beam.

The ratio of the transferred polarizations is then

$$\frac{P'_t}{P'_l} = \frac{-2m_p}{(E + E') \tan(\theta/2)} \frac{G_E}{G_M}.$$

The actual polarizations are hP'_l and hP'_t , where h is the electron beam polarization. The measured polarizations change sign when the electron helicity changes sign, so these polarization transfer quantities are insensitive to false asymmetries in the detectors.

For a free proton target, then, the ratio of polarizations can be used to determine the ratio of the form factors without measuring an absolute cross section (although determination of the individual values of the form factors still requires knowledge of the cross section). The ratio is also independent of the beam polarization (assuming it is not zero) and of the analyzing power of the proton polarimeter. Because the measurement is made at a single angle, most systematic problems associated with absolute cross section measurements are eliminated. The integrated luminosity, spectrometer acceptance, and dead time are common and cancel in the ratio. The ratio also eliminates the kinematic factors which suppress G_E in the cross section measurement.

For nuclear targets, the polarization transfer observables depend sensitively on the nucleon form factors, but they depend also on the motion of the nucleon and on the nuclear wave functions. Even in the plane wave impulse approximation (PWIA), the simple expression above for the ratio of transferred polarizations is modified by the change in kinematics. In addition, the observables may also be modified by other effects not included in the PWIA, such as final-state interactions of the outgoing proton, meson exchange, isobar currents, and off-shell effects.^{17,18,19,20} The possible distortion of the nucleon spinors by the strong Lorentz scalar and vector potentials was mentioned already in the introduction.^{10,11}

The nuclear target also allows for an induced polarization normal to the scattering plane P_n . This polarization is zero in the PWIA. It depends on the final state interactions of the outgoing proton, and so it is a measure of how well the reaction model describes the passage of the nucleon out of the nucleus. P_n is independent of the electron helicity, and thus is present even for an unpolarized electron beam. This means, however, that it is also sensitive to false asymmetries in the detector. I will not be discussing P_n further here.

3. Experiment 89-033 at Jefferson Lab

Experiment 89-033 was a measurement¹⁴ of polarization observables in the reaction $^{16}\text{O}(\vec{e}, e'\vec{p})^{15}\text{N}$. The beam energy was 2.445 GeV with a polarization of about 30%, the electron scattering angle was 23.4° and the central scattered electron energy was 2.000 GeV, the quasielastic peak. The central proton momentum was 973 MeV/c. The recoil proton was detected in quasi-perpendicular kinematics at angles of 50.8° , 53.3° , 55.7° , and 60.5° , corresponding to missing momenta of -85, 0, 85, and 140 MeV/c. Positive missing momentum corresponds to the case where the missing momentum vector points to smaller scattering angles on the proton side. Elastic scattering from hydrogen can be seen at spectrometer angles of 53.3° (where it dominates the spectrum so that no useful data could be taken on ^{16}O) and 55.7° . The target was a waterfall consisting of three foils with a total thickness of about 0.5 g/cm². The use of three separated foils allowed sufficient

energy resolution to easily distinguish the $p_{1/2}$ ground state of ^{15}N from the first excited state ($p_{3/2}$). In the continuum, excitation of the $s_{1/2}$ shell rises weakly above the (physics) background presumably related to multiparticle knockout.

The JLab focal plane polarimeter was designed and built by a collaboration of Rutgers, William & Mary, Georgia, Norfolk State, and Regina^{21,22,15} and funded by the U.S. National Science Foundation. The polarimeter, consisting of four tracking straw chambers and a graphite analyzer, is mounted in the hadron spectrometer behind the spectrometer VDC's. The FPP has been used successfully now in a large number of experiments in Hall A. The analyzing power of the FPP, A_c , was taken from the parametrization by McNaughton *et al.*²³ Measured values of A_c , obtained by analyzing data from scattering from hydrogen, have been shown to agree well with this parameterization.²⁴ The beam polarization was measured at varying intervals with a 5 MeV Mott polarimeter in the injector. For the 85 MeV/c data point on ^{16}O , where hydrogen appeared on the focal plane, values of the beam polarization determined from the Mott polarimeter and from the FPP results for hydrogen agreed very well, well within the 5% systematic error we assign to the beam polarization in the subsequent analysis of the oxygen data.

The polarization of the outgoing proton was measured for each electron-helicity state. By subtracting data for the two states, the polarization transfers P'_l and P'_t can be found, while the sum gives P_n . The result for the ratio $\mu \frac{G_E}{G_M}$ in hydrogen measured in this experiment at a Q^2 of 0.8 GeV^2 is 0.92 ± 0.05 . This value is in agreement with previous results and with values subsequently measured in Experiment 93-027 at JLab with much higher precision.²⁴

4. Results

Results for the transverse and longitudinal components of the polarization at the two central values of the missing momentum for the two bound states, $p_{1/2}$ and $p_{3/2}$, and for the region of the unbound $s_{1/2}$ state are shown in Fig. 2. The missing energy cuts on the latter extended from about 29 to 55 MeV. The polarizations are given in the scattering (lab) frame, defined by the incident and outgoing electron.^{25,18} The errors shown are statistical. Systematic errors on the individual polarizations are about $\pm 6\%$, primarily due to the uncertainty in the polarization of the beam. Small acceptance averaging corrections are included,²² as are the effects of corrections to the dipole approximation for spin transport of the proton in the hadron spectrometer.^{22,15} Both corrections are generally less than about 2%. Radiative corrections to the polarizations, expected to be much smaller than the statistical errors here, have not been made.²⁶

The curves in Fig. 2 represent theoretical calculations based upon one-body currents and free (MMD)²⁷ proton form factors. PWIA results, shown as dotted lines, are identical for the three states and, at $p_m = 0$, are equal to those for the free proton.¹⁸ The p_m dependence in the PWIA calculations is dominated by the rotation of the spin axes to bring the $\hat{\ell}$ direction parallel to the ejectile momentum. Convection currents proportional to the initial momentum of the bound proton also produce small changes of the recoil polarizations. Final-state interactions included in DWIA calculations produce small state-dependent deviations from PWIA. The DWIA calculations by Kelly¹⁸ are based upon a relativized Schrödinger equation and an effective momentum approximation (EMA) to the current operator. The dashed curves assume that lower and upper components of bound and ejectile spinors are related in the same way as for free protons.¹⁸ The dash-dotted curves include relativistic dynamics (spinor distortions) through the effect of Dirac scalar and vector potentials upon the effective current operator.¹⁰ The solid curves show the results of calculations by Moya de Guerra and Udias¹¹ who solve the Dirac equation directly without using the EMA. All DWIA calculations shown used the same input as the calculations of unpolarized observables in Ref. ¹². These include the EDIAO optical model of Cooper *et al.*,²⁸ NLSH bound-state wave functions,²⁹ the Coulomb gauge, and the cc2 off-shell cur-

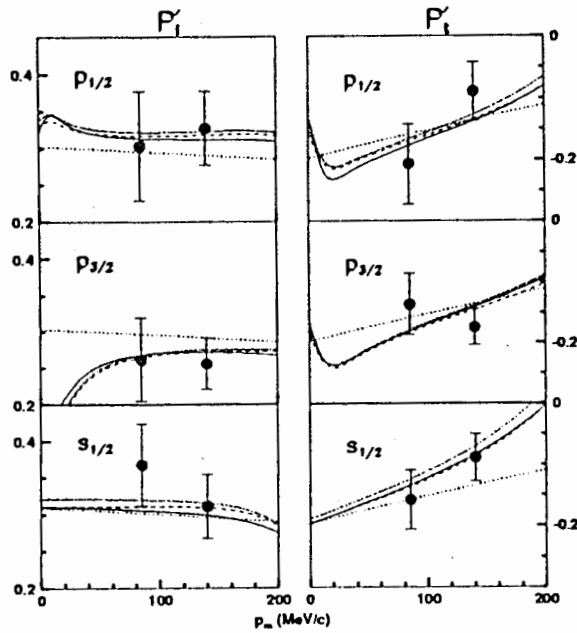


Figure 2. Measured values of the polarization transfer observables P'_1 and P'_t for the $^{16}\text{O}(\bar{e}, e'p)^{15}\text{N}$ reaction at $Q^2 = 0.8 \text{ (GeV/c)}^2$. The theoretical curves represent plane-wave calculations (dotted) and distorted-wave calculations without spinor distortions (dashed) and with spinor distortions (dash-dot) by Kelly¹⁰ and by Udias *et al.*¹¹ (solid)

rent operator. For modest p_m , the recoil polarization is relatively insensitive to variations of these choices.

All DWIA calculations are in reasonable agreement with the measured data. The two calculations which include relativistic dynamics are very similar over the relevant range of p_m . This is expected, since the results of the calculation of unpolarized observables in Ref. ¹² suggested that Kelly's formulation is a good approximation to the more accurate approach of Udias *et al.* for $p_m \leq 300$ MeV/c. The effects of relativity on the recoil polarization are small for this range of p_m in comparison with the statistical errors of the data; they are dominated by distortion of the ejectile spinor.

Contributions from meson exchange (MEC) and isobar (IC) currents can also affect the recoil polarizations. Early calculations of the effects of MEC and IC were carried out by the Pavia group ¹⁷, and preliminary calculations by M. Radici ¹⁹ of this group for the present kinematics have been made.

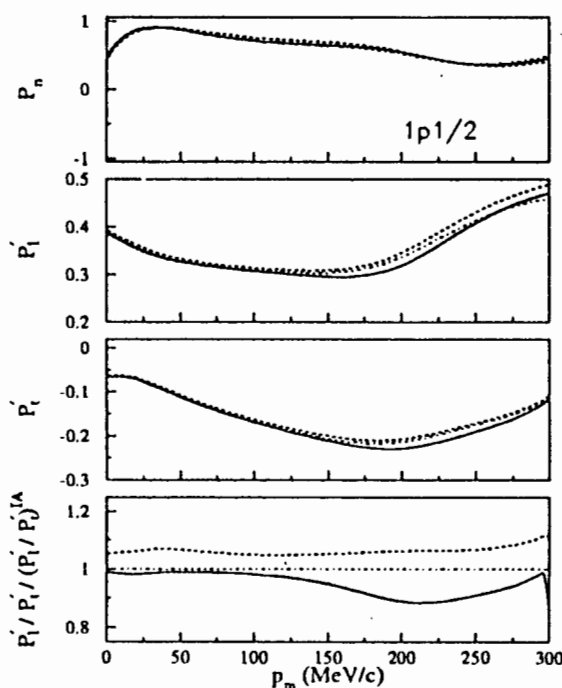


Figure 3. Effects of two-body currents on the polarization transfer observables predicted by Ryckebusch for the $p_{1/2}$ state in ^{16}O . The dot-dashed curves show the IA results. MEC effects have been included for the dashed curves. The solid curves show the full results including also IC

Predictions of these effects using a different approach have been published recently by J. Ryckebusch *et al.* ²⁰ for the present kinematics. An example of these calculations is shown in Fig. 3. The scale of these effects is typically comparable to the differences among the three DWIA curves shown. The

DWIA with small corrections thus provides a firm baseline for considering changes in the form factor.

The ratios of the P_t' to P_l' data for the three states are plotted in Fig. 4. Three of the theoretical curves shown there correspond to those in Fig. 2, namely the PWIA (dots), and the DWIA without spinor distortion (dashes) and with spinor distortion (dash-dot) by Kelly.¹⁰ The data are in good agreement with the three predictions, as expected from Fig. 2. The ratio of the experimental and theoretical values of P_t'/P_l' for the summed p state data is 0.95 ± 0.18 using either DWIA calculation.

Deviations from unity significantly outside theoretical and experimental uncertainties would be evidence for changes in the nucleon form factor ratio

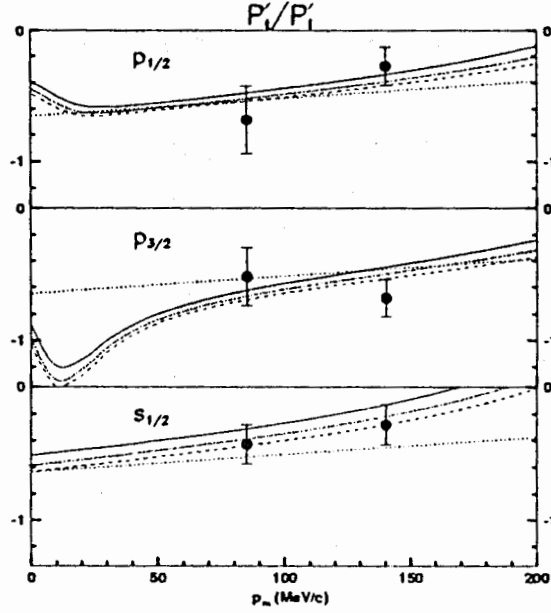


Figure 4. Measured values of the ratio of polarization transfer observables P_t'/P_l' for the $^{16}\text{O}(\bar{e}, e'\bar{p})^{15}\text{N}$ reaction at $Q^2 = 0.8 \text{ (GeV/c)}^2$. The theoretical curves represent plane-wave calculations (dotted) and distorted-wave calculations without spinor distortions (dashed) and with spinor distortions (dash-dotted).¹⁰ The solid curves use a modified current operator in which nucleon form factors depend upon local density as predicted by Lu *et al.*;⁸ spinor distortions are included

in the nuclear medium. As noted in the introduction, the Adelaide group⁸ obtained density-dependent form factors using a quark-meson coupling model and found changes in the form factor ratio for ^{16}O of about 10% for $Q^2 = 0.8 \text{ (GeV/c)}^2$. The sensitivity of the $(e, e'p)$ reaction to such changes has been estimated by Kelly using a local density approximation to the current operator. The fourth curve (solid) in Fig. 4 shows that the 10% change in the form factor ratio translates into changes of roughly 5% in the P_t' to P_l' ratio.¹⁰ The reduced sensitivity of knockout at small p_m can be understood

by comparing the averaging procedure used by Lu *et al.* with one more closely related to the matrix elements involved in the (e,e'p) reaction.

Lu *et al.* ⁸ estimated the effect of density dependence upon the electromagnetic form factors for a bound nucleon in orbital ϕ_α by using average form factors of the form

$$\bar{G}_\alpha(Q^2) \propto \int d^3r w_\alpha(r) G(Q^2, \rho_B(r)) \quad (1)$$

where ρ_B is the ground-state baryon density for the residual nucleus. Here proportionality denotes division by a similar integral omitting G . The static weighting factor $w_\alpha(r) = |\phi_\alpha(r)|^2$ determines the effective density for different orbits. For the (e, e'p) reaction, however, a more realistic weighting factor is that suggested by van der Steenhoven *et al.*: ³⁰

$$w_\alpha = \exp(i\mathbf{q} \cdot \mathbf{r}) \chi^{(-)}(\mathbf{p}', \mathbf{r})^* \phi_\alpha(\mathbf{r}) \quad (2)$$

where χ is the distorted wave for ejectile momentum $\mathbf{p}'$, $\mathbf{q}$ is the momentum transfer, and $\mathbf{p}_m = \mathbf{p}' - \mathbf{q}$. In the interests of simplicity, recoil corrections and details of the current operator have been suppressed. In the plane-wave approximation, the weighting factor becomes

$$w_\alpha^{(\text{PWIA})} = \exp(-i\mathbf{p}_m \cdot \mathbf{r}) \phi_\alpha(\mathbf{r}) \quad (3)$$

and for $p_m \rightarrow 0$ reduces to simply ϕ_α . In kinematic regimes explored thus far, this linear dependence upon ϕ_α reduces the effect of density dependence in the reaction, although the effect does increase with p_m . In the actual calculations shown here, Kelly ¹⁰ applies a local density approximation to the current operator itself and performs an unfactorized DWIA calculation without using these simple weighting factors. Furthermore, absorption and nonlocality corrections also reduce interior contributions to the average form factor.

The oxygen results thus confirm the accuracy of the DWIA description of the reaction mechanism in this kinematical regime. For someone like myself with a long history of applying the DWIA to polarization measurements in hadron reactions, the success of the DWIA here seems remarkable. The measured ratio of the transverse to longitudinal polarization transfers for the proton embedded in ¹⁶O at a Q^2 of 0.8 (GeV/c)² is in good agreement with calculations based on the free form factor within an experimental uncertainty of about 18%. As discussed above, the systematic errors on the polarization measurements are much smaller than the present statistical errors.

The good agreement with the prediction based on the free ratio suggests that changes in the form factor ratio are not very large in these kinematics. The present results are not, however, inconsistent with the predictions of the Adelaide group, ⁸ which translate into somewhat smaller percentage changes on polarization ratios in the (e,e'p) reaction. The predicted effects of spinor distortions are somewhat smaller than the predicted effects due to changes in

the form factor. High precision data will be needed to see such effects, and I will describe now our initial efforts to provide just such data.

5. ${}^4\text{He}(\bar{e}, e'\bar{p}){}^3\text{H}$

Thus we turn to higher statistics experiments on ${}^4\text{He}$ targets. The first measurements of polarization transfer in the ${}^4\text{He}(\bar{e}, e'\bar{p}){}^3\text{H}$ reaction were done recently at the Mainz Microtron MAMI at the Johannes Gutenberg-Universität, Mainz, Germany by the A1 Collaboration there, including the Rutgers group.³¹ Data were also taken with a hydrogen target, to reduce systematic errors in the ratio of helium and hydrogen data. The results shown below are preliminary; the data reduction and theoretical analysis are not yet finalized.

The measurements were done with spectrometers A and B in Hall A1, described in Ref. ³². A proton focal plane polarimeter was installed in Spectrometer A, ³² in place of the Čerenkov detector. The beam energy was 854.5 MeV. The nominal settings were 625 MeV/c central momentum at 50.24° for the electron arm (Spectrometer B) and 660 MeV/c and 46.56° for the proton arm (Spectrometer A). This corresponds to the quasielastic peak and parallel kinematics at $Q^2 = 0.4 \text{ (GeV/c)}^2$. The FPP includes a graphite analyzer with a thickness of 11.9 g/cm^2 (7 cm). The spectrometer vertical drift chambers (VDC) serve as the tracking detectors before the analyzer and two horizontal drift chambers track scattered protons after the analyzer. The basic design of the FPP is similar to several used previously.³³ For all further details see Ref. ³⁴.

The helium target consisted of a gas cell 8 cm long, at a temperature of 19 K and pressure of 19 bar, with a thickness of about 250 mg/cm^2 . The same cell was used for hydrogen, although the hydrogen was in liquid form, with a thickness of about 560 mg/cm^2 . The current used for hydrogen was typically $0.5 \mu\text{A}$ and for helium $14 \mu\text{A}$. The data acquisition could handle rates of up to about 200 Hz, which limited the maximum usable current for hydrogen. The beam polarization was approximately 75%, as determined from the polarization measured for hydrogen using the analyzing power from Ref. ²³.

The invariant mass resolution was approximately 0.8 MeV, which allowed clear separation of the p - ${}^3\text{H}$ final state from the pnd and $ppnn$ final states. In the data analysis events were selected that satisfy criteria of spectrometer acceptance, target geometry, missing mass, and FPP polar scattering angle ($7^\circ < \theta_c < 35^\circ$). The polarizations, P'_x and P'_z (corresponding to the notation P'_t and P'_l used above for the ${}^{16}\text{O}$ data) were determined by means of a maximum likelihood technique, utilizing the azimuthal distribution of the protons scattered from the graphite analyzer. The systematic uncertainty in the determination of the ratio of polarizations, P'_x/P'_z , was estimated by introducing artificial shifts in various parameters. The total systematic uncertainty was estimated to be about ± 0.03 on this ratio, for both the helium and hydrogen ratio.

Table 1 lists the extracted polarization ratios for ^4He and ^1H . No radiative corrections have been applied, but they are expected to have an effect of order 1%, which is less than the statistical uncertainty.²⁶ The hydrogen ratio was found to be in agreement with the polarization ratio derived from the world average of $\mu G_E/G_M$.^{13,24,35}

Table 1. Polarization ratios with statistical and systematic uncertainties

Target	P'_x/P'_z	Ref.
^1H	-0.952 ± 0.008	13,24,35
^1H	$-0.978 \pm 0.044 \pm 0.03$	this work
^4He	$-0.862 \pm 0.020 \pm 0.03$	this work

Since systematic effects on the polarization ratio for hydrogen and helium were nearly identical, the effect of systematic uncertainties on the ratio of helium to hydrogen

$$R = (P'_x/P'_z)_{\text{He}} / (P'_x/P'_z)_{\text{H}}$$

nearly canceled. This “super-ratio” is estimated to have a systematic uncertainty of less than 1%. The uncertainty in R is then limited by the statistical uncertainty on the hydrogen ratio measured in this experiment. Although the ratio derived from world data on hydrogen has a smaller statistical uncertainty, the systematic uncertainty on the super-ratio would be larger. Because the hydrogen ratio measured in this experiment is very close to the world average, both methods give nearly the same result. Table 2 lists the super-ratio as a function of missing momentum in four bins, along with the value averaged over the entire data set, using the hydrogen ratio determined in this experiment. Note that the total error on the ratio is about 5%, compared to the error of about 18% on the oxygen data shown above; the systematic error is still negligible.

To consider the significance of the fact that the super-ratio is different from unity, we have to compare it to theoretical predictions that include the effect of final state interactions, the off-shell interaction, relativity, etc., as

Table 2. Polarization double ratios

p_m (MeV/c)	$(P'_x/P'_z)_{\text{He}} / (P'_x/P'_z)_{\text{H}}$
-70.6	$0.898 \pm 0.063 \pm 0.01$
-38.1	$0.858 \pm 0.055 \pm 0.01$
38.4	$0.956 \pm 0.062 \pm 0.01$
71.9	$0.832 \pm 0.052 \pm 0.01$
mean	$0.882 \pm 0.044 \pm 0.01$

discussed above for oxygen. For example, the binding energy alone, which causes the effective interaction energy to shift, will shift the ratio from unity even for PWIA.

Fig. 5 shows a comparison of the experimental data with the acceptance-averaged calculations of the ^4He polarization ratio normalized to the hydrogen ratio, ie, the super-ratio. Note that the scale is highly expanded. Calculations for both targets are based on the same model of the nucleon form factor, though some of the calculations for helium include modifications of that form factor as noted. Apart from the plane wave calculation (dotted), all the calculations shown are based on LEA, the distorted wave code by J.J. Kelly^{18,10} as described above for the oxygen calculations. We used the van Oers' optical potential for $A = 3$.³⁶ LEA does not include MEC or IC, but calculations by Laget indicate such effects are very small.³⁷ The similarity of the PWIA curve and the calculation of Kelly (dash-dotted) that does not include negative energy components of the wave function (spinor distortions) or modification of the form factor indicates that final state interactions have only a small effect. Note that both curves deviate significantly from the data. The difference (not shown) between LEA calculations (without spinor distortions) with different off-shell current operators $cc1$ and $cc2$ is negligible.

Inclusion of spinor distortions in LEA (two dashed curves) changes the result significantly. The fact that the error bars here are so much smaller than for ^{16}O means that even the modest effects of spinor distortion make a noticeable difference in the quality of the agreement with the data. However, the difference between the $cc1$ and $cc2$ prescriptions for the off shell behavior is no longer negligible either. Finally, the form factor modifications predicted in the QMC model of Lu *et al.*⁸ have been included in LEA using both $cc1$ and $cc2$ with spinor distortion (solid curves). As in oxygen, the change in the ratio attributable to the QMC form factor modification is less than that given in Ref. ⁸ because of the different averaging. The size of the QMC induced changes (roughly 3%) is comparable to the size of the changes induced

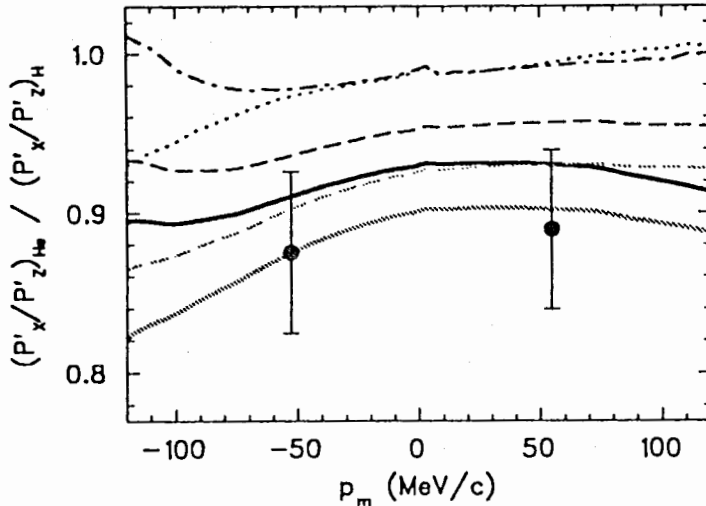


Figure 5. Comparison of the preliminary measured polarization ratios for ^4He with theoretical calculations. PWIA (dotted); J.J. Kelly LEA with $cc2$ and no spinor distortions "NoSV" (dot-dashed), with spinor distortions "SV" (thick-dashed), SV + QMC (dark solid), LEA with $cc1$ and SV (thin dashed), SV + QMC (light solid)

by spinor distortions. The net change attributable to these two effects of the nuclear medium brings the full theory curves (solid) into good agreement with the data.

High statistics data have also been taken for the ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ reaction at JLab at values of Q^2 of 0.4, 1.0, 1.6, and 2.6 (GeV/c) ^{2} . This was E93-049 that was run in April of this year,³⁸ and only the results of an on-line data reduction are available. Except at the highest Q^2 , the total errors should be comparable to or better than those of the Mainz data. At this stage, the super-ratio extracted at 0.4 (GeV/c) ^{2} appears to be in excellent agreement with the Mainz data point; the super-ratios at the higher momentum transfers do not show a clear trend with Q^2 . The Q^2 dependence of form factor changes and spinor distortions is expected to be different, and provide a possible method of separating the two effects.

6. Conclusion

The results of the first polarization transfer measurements for the reactions ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ and ${}^{16}\text{O}(\vec{e}, e'\vec{p}){}^{15}\text{N}$ reveal the potential power of the technique as a measure of medium-induced modifications of the nucleon in the nucleus. The preliminary analysis of high precision data on helium, in particular, provides some evidence for such modifications. However, although recoil polarization provides a direct signal for medium modifications of nucleon form factors, the effect in (e,e'p) reactions is smaller than first expected. It is the combined effect of medium induced changes in the wave function and in the form factor which appears visible in the helium data. A rigorous interpretation will require a unified relativistic treatment of the reaction and form factor models, including two-body currents. Even better statistical accuracy in the data would also be very desirable.

Acknowledgments

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Are narrow mesons, baryons and dibaryons evidence for multiquark states ?

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Several narrow structures have been progressively observed since the last fifteen years, in dibaryonic invariant mass spectra or missing mass spectra. More recently, narrow structures were observed in baryonic and now in mesonic mass spectra. Since these small peaks appear at fixed masses, independently of the experiment, they are associated with real states. There is no room to explain these states within classical nuclear physics taking into account baryonic and mesonic degrees of freedom.

An interpretation is proposed, which associate these narrow structures with two coloured quark clusters.

I. INTRODUCTION

It is usually believed that the observation of quark degrees of freedom cannot start at energies lower than several GeV (≈ 10 GeV). However such limit is somewhat unprecise. A relation was proposed by Baldin [1] some years ago. In this theory, the deconfinement is determined as being a process allowing particle creation for $b_{ij} \geq 5$, where

$$b_{ij} = -(P_i/m_i - P_j/m_j)^2 \quad (1)$$

and P_i, P_j are the four momentum of both particles involved in the reaction, and m_i, m_j their masses. If we consider a N-N reaction, the previous relation reduces in the laboratory system to $T_i \geq 2.35$ GeV.

The search for possible signatures of the beginning of the quark deconfinement, could therefore be significant at energies close to 2 GeV. These will be the energies of the experiments discussed in this paper. This paper will start to describe experimental results, rather than calculations, for the following reasons :

- several accelerators exist (or existed), where the experiments usefull for such studies were already performed and must be repeated,
- calculations must be done using non perturbative QCD. This is a difficult task.

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The beginning of this work will be dedicated to show the most precise experimental results where narrow hadronic structures were observed. Some of these results were already published, but not all, and the presentation will emphasize recent, unpublished, and sometimes preliminary data. These results were obtained during the study of the $\bar{p} p \rightarrow a^+ b^+ X$ reaction.

The paper will be divided into the following parts. The experiment will be shortly described. Some spectra will be presented, showing various checks and studies done in order to control all possible spurious effects. Then several results will be shown, corresponding to narrow dibaryons, narrow baryons and narrow mesons. The third part will describe an attempt to rely these structures to coloured quark clusters. Finally a discussion will be presented, trying to reproduce the masses of **all observed hadronic narrow structures** inside two phenomenological relations and a minimum number (three) of free parameters.

II. EXPERIMENTAL RESULTS

The reaction $\bar{p} p \rightarrow a^+ b^+ X$ was studied using the SPES3 beam line and detection at SATURNE. The proton beam was accelerated at three energies ($T_p=1520, 1805$ and 2100 MeV) and the spectrometer put at several angles between 0° and 17° in the lab. Several papers were already published, describing the experiment [2]. Therefore a general description will not be repeated here. However since the objective of these experiments is to look for small peaks lying over a background, spacial care on possible experimental errors must be done. Some of these checks are described now.

A. Misidentified particles

The electronical device included two time of flights. The first one, on a 3 meter basis, identified the particles. The second one between both detected particles, controled the random events, and rejected the small amount of misidentified particles. Indeed, the distance inside the spectrometer, from target up to detection, of the order of 7 meters, induced a shift ≈ 21 channels (of 250 ps/channel), if the nature of the detected particle was changed from proton to pion. This is much larger than the window used to keep two particle real events (± 9 channels). Only some **random** coincidences between a real proton and a misidentified pion - when a $p p \rightarrow p p X$ reaction was studied - were not suppressed by our electronical selection. There were very few such events, without any peak, as shown in Fig. 1.

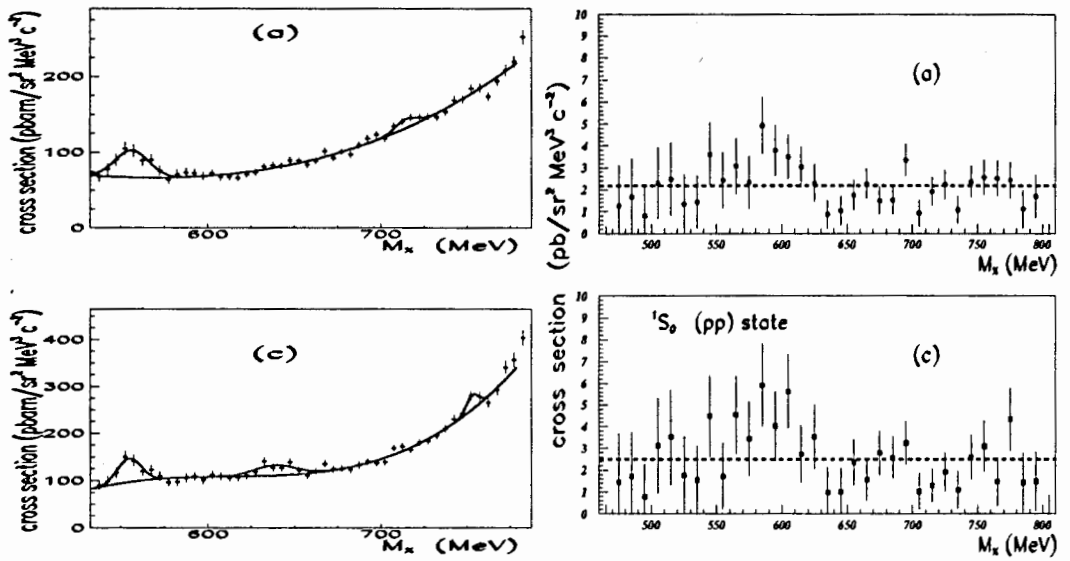


Fig. 1. The figure shows cross sections versus the missing mass M_X of the $p p \rightarrow p p X$ reaction at $T_p=2.1$ GeV, $\theta=9^\circ$ lab. Real events are shown on left part of the figure and misidentified events are shown on right part. The two cases (a) and (c) correspond to different conditions on the invariant mass M_{pp} of both detected protons.

B. Range of scatterplot selection

The scatterplot of the momenta of the first detected particles against the momenta of the second detected particles, displayed sharp angles (Fig. 2). These were due to cuts induced by physics and by the spectrometer momenta limits. They were also lost events, induced mainly by those events when both momenta were equal. This explains the empty narrow region inside the filled area in top of Fig. 2. A simulation code was written in order to correct all lost events. However when the correction function displayed peaks, the measured range was limited in order to eliminate such regions and to avoid to introduce eventual fake effects (see Fig. 2).

C. Empty target contribution

Fig. 3 shows the missing mass spectra M_X of the $p p \rightarrow p \pi^+ X$ reaction, after removal of all events corresponding to n and Δ^0 missing masses, in order to enhance the intermediate region corresponding to narrow baryons. The empty target data, normalized on the same number of incident protons, are shown at the bottom of the figure. We observe here a low count rate ($\leq 5\%$) and a flat distribution without

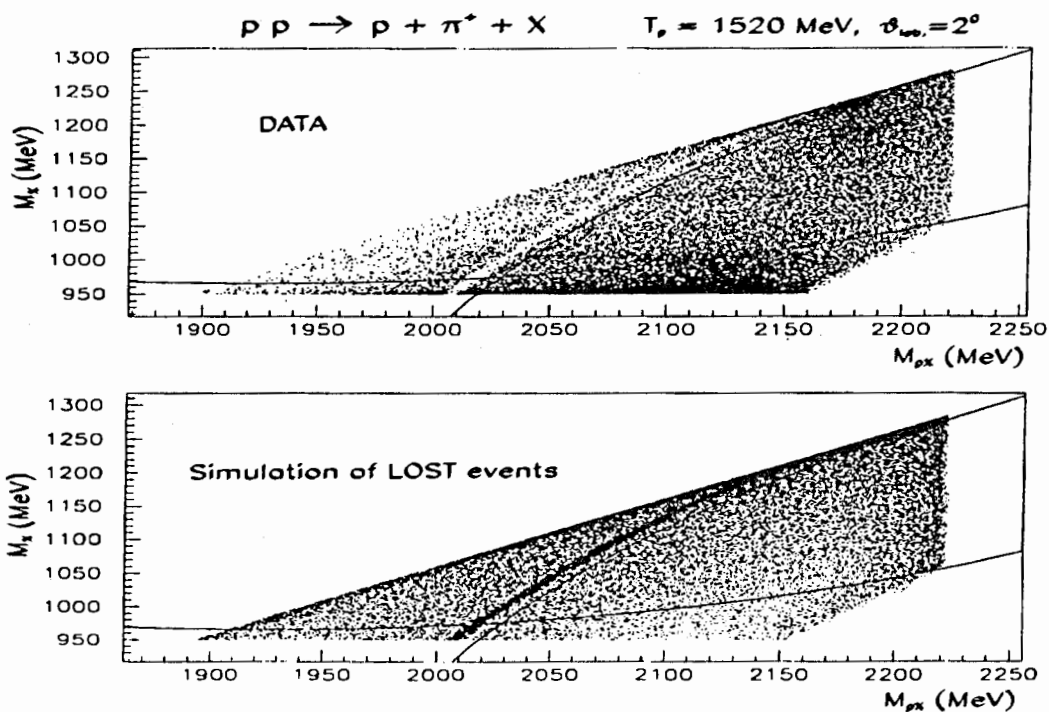


Fig. 2. Scatterplot of the missing mass M_X versus the invariant mass M_{pX} events for the $pp \rightarrow p\pi^+X$ reaction at $T_p = 1520 \text{ MeV}$ and $\theta = 2^\circ$. The area between both curves was selected, at the expense of statistics, in order to avoid sharp corrections. The intense region corresponding to n missing mass peak was removed in these data.

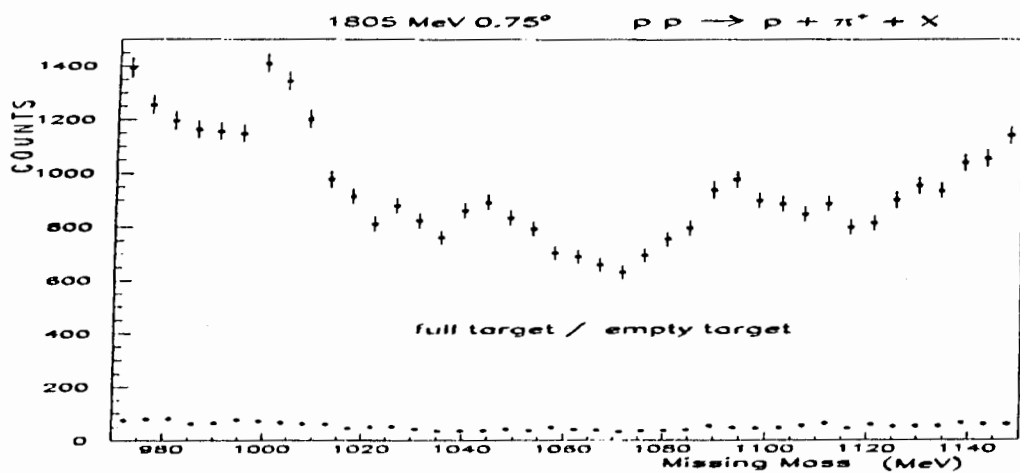


Fig. 3 Comparison of full versus empty target countings.

structure. We deduce from this observation that our data were not spoiled by a beam tail scattering inside some thick side of the cryogenic target or the scattering chamber.

D. Random events

The incident proton flux was adjusted in order to keep, during the acquisition, the number of random events at a rate lower than 10 %. Then the contamination of randoms, in the window of real events, was small for $p p \rightarrow p \pi^+ X$ and $p p \rightarrow p p X$ reactions. Fig.4 shows the small and smooth distribution of these events for $p p \rightarrow p \pi^+ X$ reaction. The number of true events in case of $p p \rightarrow \pi^+ \pi^+ X$ reaction was small, and therefore the amount of random events was large. For this last reaction, the results corresponding to random events only, will also be shown for comparison.

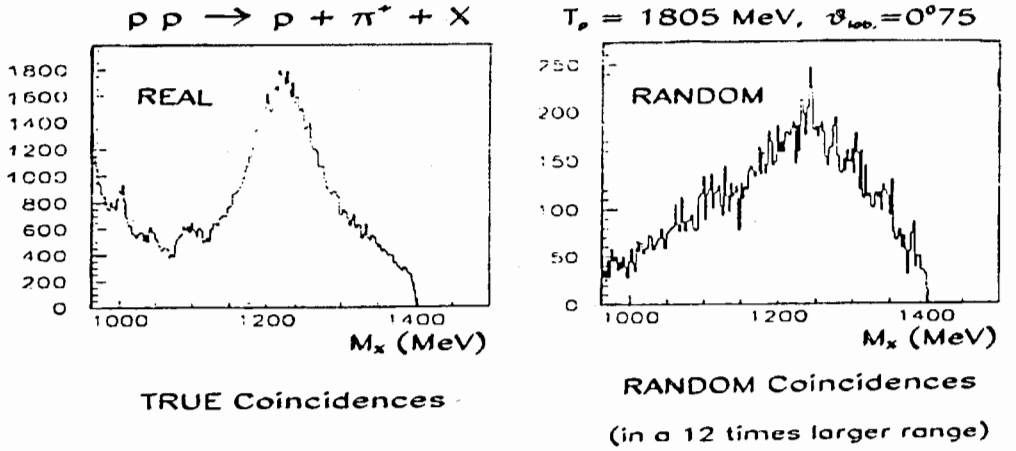


Fig. 4 Comparison of real with random events.

III. RESULTS

Three reactions were studied simultaneously. They were :

- 1) $p p \rightarrow p \pi^+ X$. Here the baryonic missing mass M_X was studied in the range $940 \leq M_X \leq 1470$ MeV. All ranges depended on the incident energy and angle of measurement. In the same reaction, the dibaryonic invariant mass M_{pX} was studied in the range $1950 \leq M_{pX} \leq 2400$ MeV.
- 2) $p p \rightarrow p p X$. Here the mesonic missing mass M_X was studied in the range $135 \leq M_X \leq 800$ MeV. The dibaryonic invariant mass M_{pp} was studied in the range $1877 \leq M_{pp} \leq 1920$ MeV.
- 3) $p p \rightarrow \pi^+ \pi^+ X$. Here the dibaryonic missing mass M_X was studied in the range $1880 \leq M_X \leq 2138$ MeV.

The results will be presented now, using a classification by hadronic species and not by reactions.

A. Narrow dibaryons

The observation of narrow structures, which correspond to non classical physics, started more than 15 years ago in the dibaryonic sector. A classification of the observed masses was reported 10 years ago in a review talk [3]. These first results were progressively confirmed. Recently new precise data were published [2] which correspond to the reaction $p p \rightarrow p \pi^+ X$ from the experiment described before. A selection of typical spectra are shown in Fig. 5, 6 and 7 where the dibaryons were observed in M_{pn} and

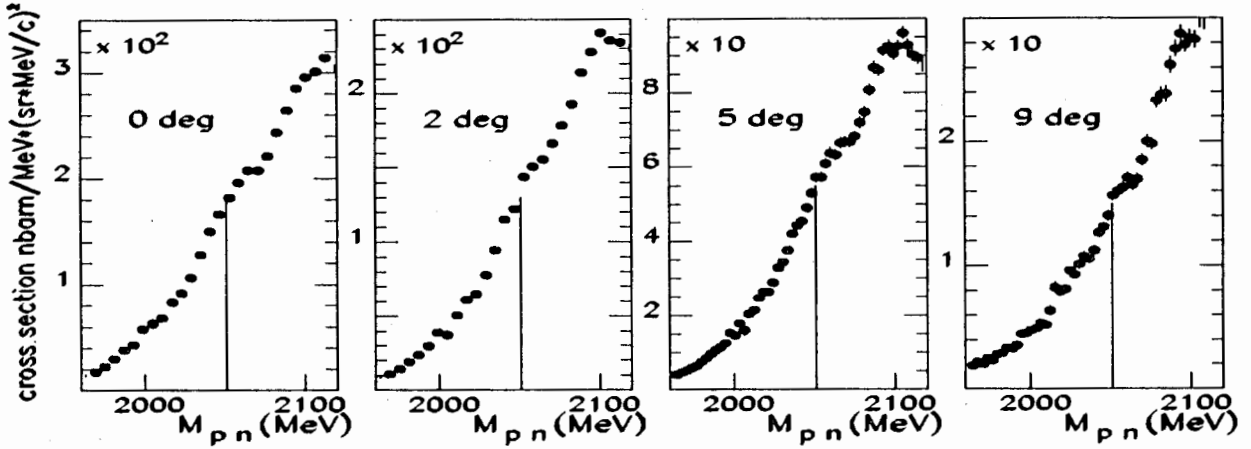


Fig. 5. $p p \rightarrow p \pi^+ n$ reaction at $T_p = 1520$ MeV, showing a narrow dibaryon at 2050 MeV.

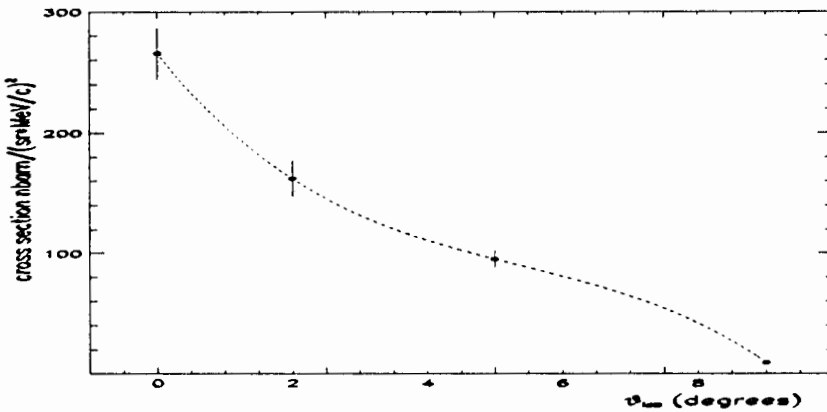


Fig. 6. Forward angle angular distribution of the $M = 2050$ MeV dibaryon produced in the $p p \rightarrow p \pi^+ n$ reaction at $T_p = 1520$ MeV.

M_{pX} invariant masses in reaction 1). Narrow dibaryons were observed in the invariant mass spectra at 2050, 2122 and 2150 MeV. The corresponding numbers of standard deviations vary between 3.2 and 12.6. display any structure.

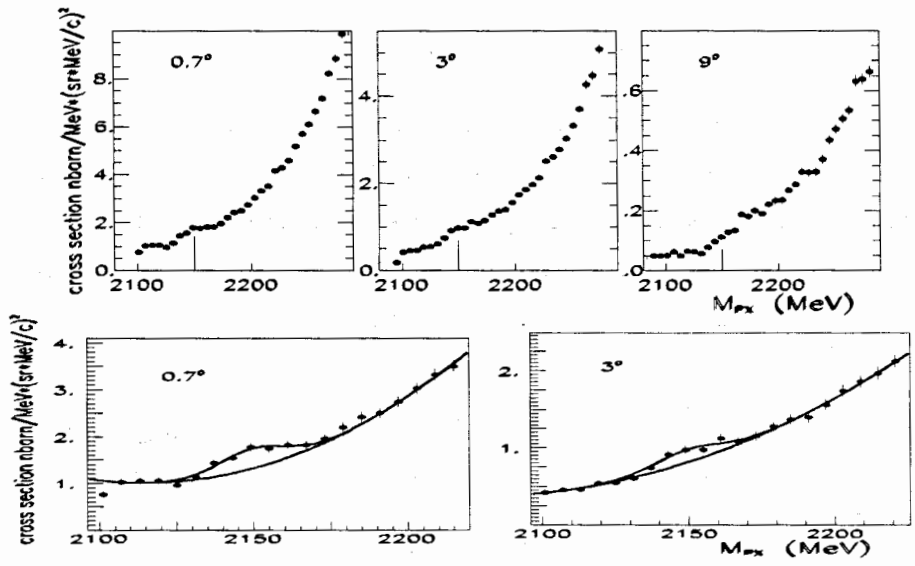


Fig. 7. $p p \rightarrow p \pi^+ X$ reaction at $T_p = 2100$ MeV, showing a narrow dibaryon at 2150 MeV. The number of standard deviations (S.D.) at $\theta_{lab.} = 0.7^\circ$ (3°) is equal to 8.1 (5.5).

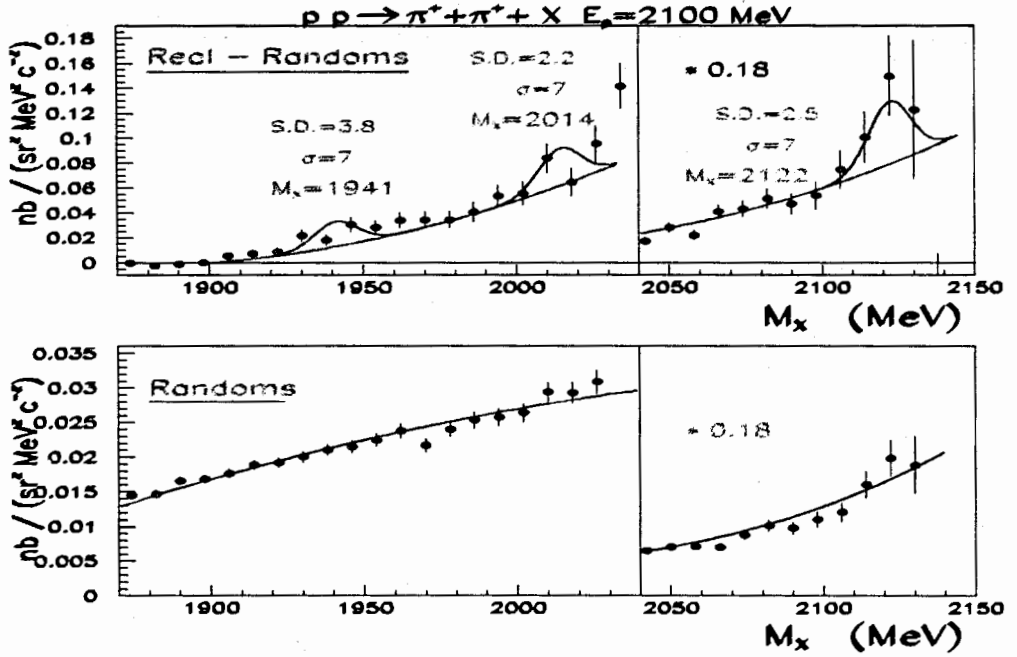


Fig. 8. $p p \rightarrow \pi^+ \pi^+ X$ reaction at $T_p = 2100$ MeV. Narrow dibaryons at 1941, 2014 and 2122 MeV are observed in the real minus random events spectrum (sum of all three angles measured at this energy). The random spectrum, normalized on the same coincidence window width, is more precise and does not

The masses of these narrow dibaryons agree with systematic studies of dibaryonic masses experimentally observed through many experiments performed by various collaborations.

The $p p \rightarrow \pi^+ \pi^+ X$ reaction was only analyzed at $T_p = 2100$ MeV, since the number of two pion produced events, already low at this energy, is still less at smaller energies. Preliminary results are shown in Fig. 8. We observe that the results of this new reaction, are rather imprecise. They are however in agreement with the previous results. Indeed the three dibaryon masses observed at 1941, 2014 and 2122 MeV were already obtained previously in several different experiments [3].

The actual classification of narrow dibaryons, including the presently shown results are displayed in Fig. 9 and summarized in Fig. 10. Here the experiments performed with electronics are noted with squares, and those from bubble chamber chambers are noted with triangles. Full symbols correspond to data with $S.D. \geq 3.07$ (confidence level $\geq 99\%$), and open symbols to data with $S.D. \leq 3.07$.

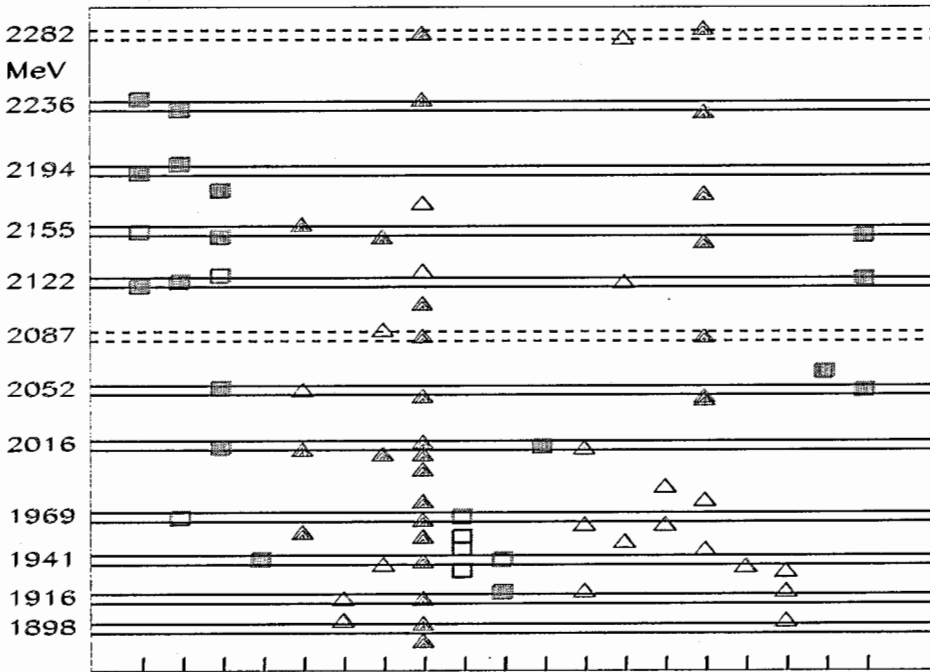


Fig. 9. Masses of experimental narrow dibaryons observed in previous and present experiments, versus the corresponding reference quoted in [2].

Fig. 9 shows that two regions can be roughly observed. In the first region : $2 \text{ GeV} \leq M_{pp}$, nearly all dibaryonic experimental masses fall into narrow bands which correspond to a well fixed mass ± 3 MeV. In the second region, for masses lower than 2 GeV, the situation is somewhat confused. The threshold for $pp\pi$ desintegration is 2.016 GeV.

experimental		calculated			
..... (2282.)	2296.	_____	1	(0,1)	1,2,3 (1,2)
_____ 2236.	2261.	_____	0	(0,0)	1,2,3 (1,2)
_____ 2194.	2191.	_____	1,2,3	(1,2)	0,1,2 (1,1)
_____ 2155.	2156.	_____	2	(0,2)	0,1,2 (1,1)
_____ 2122.	2121.	_____	0,1,2	(1,1)	0,1,2 (1,1)
..... (2087.)	2086.	_____	1	(1,0)	0,1,2 (1,1)
_____ 2052.	2051.	_____	0	(0,0)	0,1,2 (1,1)
_____ 2016.	2016.	_____	2	(0,2)	1 (0,1)
_____ 1969.	1981.	_____	0,1,2	(1,1)	1 (0,1)
_____ 1941.	1946.	_____	1	(0,1)	1 (0,1)
_____ 1916.			0	(0,0)	1 (0,1)
..... (1902.)					
d	1876.	1876.	_____	1	(0,1)
				0	(0,0)
				Spin (s1,s2)	Iso. (i1,i2)

Fig. 10. Experimental spectra of narrow dibaryons and calculated masses. before precise study of the region $2M_p \leq M_{pp} \leq 2.0$ GeV. The calculations will be discussed later.

We need a precise experiment dedicated to this mass region. This was done by the study of the invariant M_{pp} mass spectra through the reaction 2) : $p p \rightarrow p p X$. A selection of typical spectra from such reaction is presented in Fig. 11. These data are preliminary. The cross sections do show small peaks or shoulders. Since all statistics was concentrated in a relatively narrow range, it was possible to extract structures with a large S.D. although in this mass range, the dibaryon production cross sections are small. Since the electromagnetic disintegration only is allowed, the widths of the observed structures are experimental. Due to the fast decrease of the counting for increasing M_{pp} , the statistical precision in that experiment was too small for masses larger than 1920 MeV.

As it was the case in all reactions described, the analyzing powers were measured simultaneously with the cross-sections. Although the corresponding error bars are larger than those obtained for cross sections, their shape in several cases display an oscillatory pattern shown in Fig. 12. These oscillations **may be** the consequence of an interference between the classical NN amplitude and another amplitude, quickly varying for different M_{pp} invariant masses. The existence of several narrow dibaryons in this mass range **could be** at the origin of such behaviour.

Fig. 13 shows the spectrum of low mass dibaryons obtained from this experiment, and compared with previously observed low mass dibaryons.

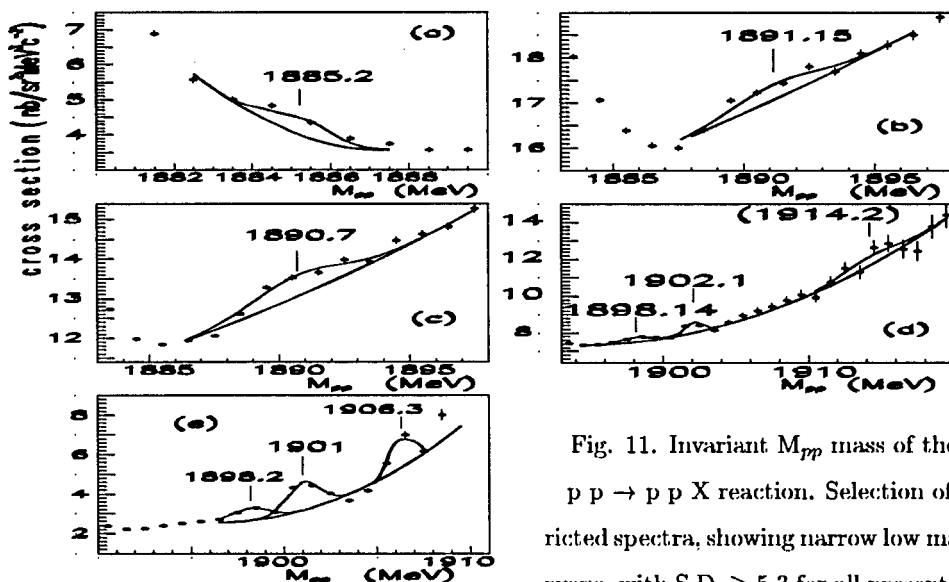


Fig. 11. Invariant M_{pp} mass of the $p p \rightarrow p p X$ reaction. Selection of restricted spectra, showing narrow low mass dibaryons, with S.D. ≥ 5.3 for all presented peaks

(except those close to 1915 MeV, and the 1902.1 structure in part (d)). The five parts of the figure correspond to : (a) $T_p=1520$ MeV; (b) all energies and angles; (c) $T_p=1520$ and 1805 MeV; (d) $T_p=1520$ MeV and forward c.m. data at $T_p=1805$ MeV; (e) $T_p=1805$ MeV, backward c.m. data at 0.75° and 3.7° .

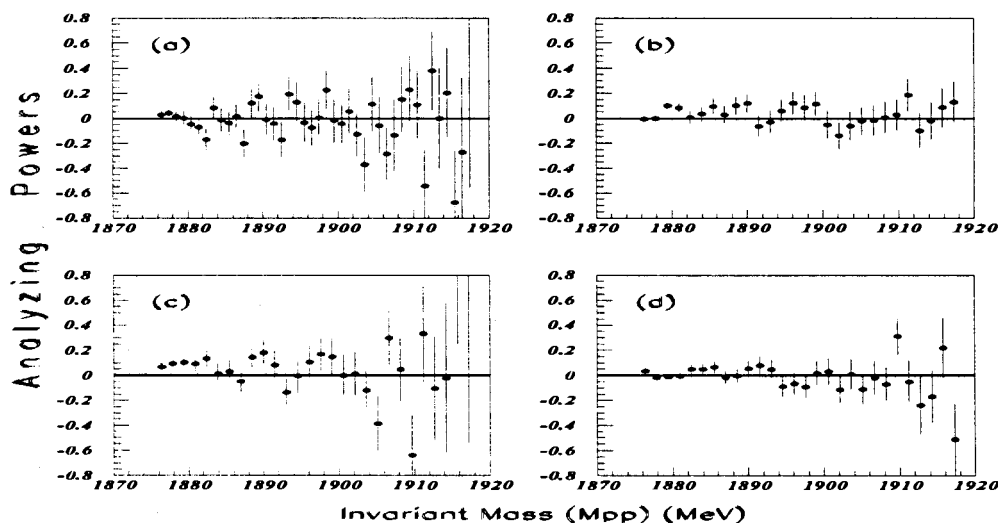


Fig. 12. Analyzing powers for the $\bar{p} p \rightarrow p p X$ reaction, at $T_p=1805$ MeV: (a) and (c), and at $T_p=2100$ MeV: (b) and (d). (a) and (b) are for 0.75° lab. (backward solution in c.m.), (c) for 6.7° lab. (also backward) and (d) for 9° lab. forward solution in c.m. system.

experimental		calculated	
previous	present		
1916	1915	1915.2	2,3 (1/2,5/2) 1,2 (1/2,3/2)
1905	1905.7	1906.4	1,2 (1/2,3/2) 1,2 (1/2,3/2)
1902	1901.3	1901.1	0,1 (1/2,1/2) 1,2 (1/2,3/2)
	1898.2	1899.3	2,3 (1/2,5/2) 0,1 (1/2,1/2)
	1891.	1890.5	1,2 (1/2,3/2) 0,1 (1/2,1/2)
	1885.2	1885.2	0,1 (1/2,1/2) 0,1 (1/2,1/2)
		Spin (s1,s2)	Iso. (i1,i2)

Fig. 13. Masses of low mass dibaryon spectrum, experimental and calculated (mean values from different data). The calculations will be discussed later. The previous masses correspond to references : [5], [6], [7].

B. Narrow Baryons

Narrow exotic baryons at $M_x = 1004, 1044$ and 1094 GeV, were observed in the missing mass of the $p p \rightarrow p \pi^+ X$ reaction [4]. Fig. 14 shows a selection of spectra at both smaller energies and forward angles. Filled data are for $T_p = 1805$ MeV and empty data are for $T_p = 1520$ MeV. We observe that the structures appear at constant missing masses : $1004, 1044$ and 1094 MeV. Fig. 15 shows the new baryonic spectra in the range $M_N \leq M_X \leq M_{Roper}$.

C. Narrow Mesonic Structures

They were studied in the missing mass of the $p p \rightarrow p p X$ reaction. The range was cut into two parts : a first part, in the ABC region (below the η meson (550 MeV)), deserves a special discussion since several peaks are not separated. This discussion will be presented elsewhere [9]. We present here the results [10] corresponding to the range $550 \text{ MeV } (\eta \text{ meson}) \leq M_X \leq 783 \text{ MeV } (\omega \text{ meson})$. A selection of typical spectra is shown in Fig. 16 at $T_p=1.805$ GeV and Fig. 17 at $T_p=2.1$ GeV.

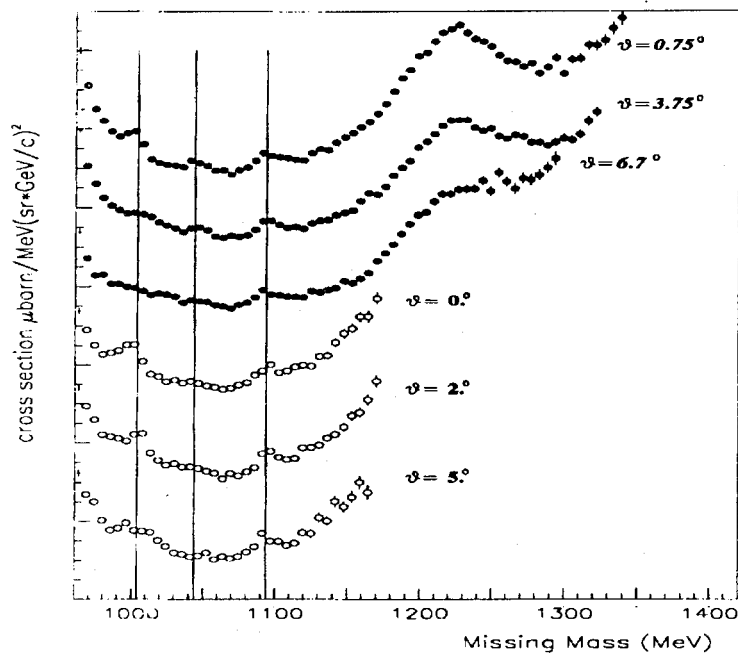


Fig. 14.
Cross sections of the $p p \rightarrow p p X$ reaction, at forward angles, after cuts on the neutron missing mass. We observe peaks at fixed masses, indicated by vertical lines.
Filled data are for $T_p = 1800$ MeV and empty data are for $T_p = 1520$ MeV.

1/2	<u>N(P₁₁)</u>	1/2 1440.	1440. 3 $\frac{1}{2}...7/2$	_____	$\frac{1}{2}, 3/2$
			1407. $\frac{1}{2}...5/2$	_____	$\frac{1}{2}...5/2$
			1407. $\frac{5}{2}$	_____	$\frac{1}{2}, 3/2$
			1340. $\frac{3}{2}, 5/2$	_____	$\frac{1}{2}, 3/2$
			1340. $\frac{3}{2}$	_____	$\frac{3}{2}$
			1306. $\frac{1}{2}, 3/2$	_____	$\frac{3}{2}$
			1306. $\frac{1}{2}...5/2$	_____	$\frac{1}{2}, 3/2$
			1273. $\frac{3}{2}...7/2$	_____	$\frac{1}{2}$
			1273. $\frac{1}{2}...7/2$	_____	$\frac{1}{2}$
3/2	<u>Δ</u>	3/2 1232.	1239. $\frac{1}{2}...7/2$	_____	$\frac{3}{2}$
			1239. $\frac{3}{2}$	_____	$\frac{1}{2}, 3/2$
			1206. $\frac{1}{2}, 3/2$	_____	$\frac{1}{2}, 3/2$
			1139. $\frac{3}{2}, 5/2$	_____	$\frac{1}{2}$
			1139. $\frac{1}{2}$	_____	$\frac{1}{2}, 3/2$
		(1094.)	1106. $\frac{1}{2}...5/2$	_____	$\frac{1}{2}$
	_____	1044.	1039. $\frac{3}{2}$	_____	$\frac{1}{2}$
	_____	1004.	1005. $\frac{1}{2}, 3/2$	_____	$\frac{1}{2}$
1/2	<u>N</u>	1/2 939.	939. $\frac{1}{2}$	_____	$\frac{1}{2}$
Spin		Isospin	Spin		Isospin
Experimental			Calculated		
BARYONIC MASSES (MeV)					

Fig. 15. Baryonic level scheme. The calculated values will be discussed later.

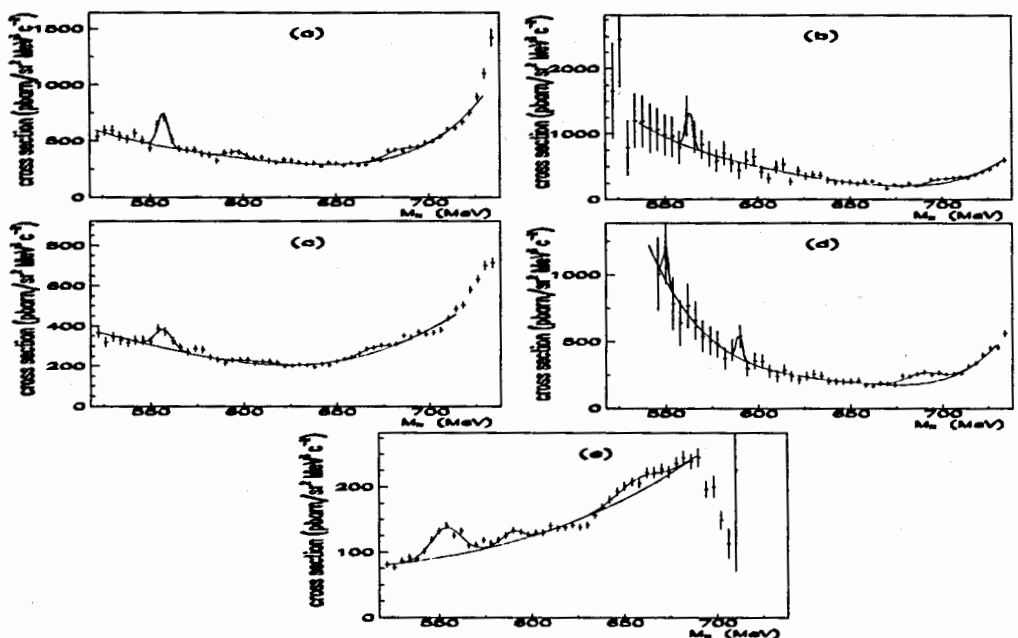


Fig. 16. Differential cross sections (in lab. system) at $T_p = 1805$ MeV. (a) and (b) correspond to 0° lab. data, (c) and (d) correspond to 3° lab. data and (e) corresponds to 9° lab. data. (a), (c) and (e) correspond to forward kinematics whereas (b) and (d) correspond to backward kinematics.

The spectrum of narrow exotic mesons (between 550 and 800 MeV) is shown in Fig. 18. The left column shows our results which are compared to other data (next column). Narrow mesons were looked for previously in the invariant mass $M_{\pi^+\pi^-}$ ($M_{\pi^-\pi^-}$) [13] from the reaction $p n \rightarrow p p \pi^+ \pi^- \pi^- \pi^0$ ($p n \rightarrow n p \pi^+ \pi^+ \pi^- \pi^-$) at Dubna using a 5.10 GeV/c neutron beam. Here the statistics was not rich since bubble chamber slides were analyzed. Another experiment was performed at Protvino with 40 GeV π^- beam. Invariant masses $M_{\pi^+\pi^-}$ from the $\pi^- C \rightarrow \pi^- \pi^- \pi^+ C$ reaction were studied. Several structures were not pointed out by the authors, since they exhibit a too small number of S.D. However their masses are rather close to ours. The masses (in MeV) of these structures compared to our masses between parenthesis, are : 355(350), 440(430), 510, 588(588), 640(647) and 753(750). Although these structures cannot be used by themselves (small S.D.), they however confirm our results.

IV. INTERPRETATION

A. General Description

An interpretation is suggested within the assumption of two coloured constituent quark clusters.

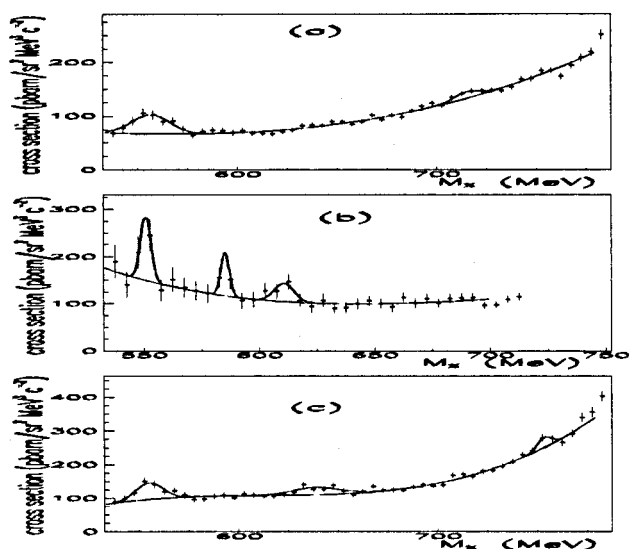


Fig. 17. Differential cross sections (in lab. system) at $T_p = 2100$ MeV, $\theta = 9^\circ$ lab. (a), (b) and (c) correspond respectively to: forward c.m. kinematics, backward c.m. kinematics and selected $2M_p \leq M_{pp} \leq 2M_p + 5$ MeV events with forward c.m. kinematics.

(---)753	759 750 748	— $p p \rightarrow p + p + X$ M_x This work Saturne
----- 715	720	----- $\pi^- C \rightarrow \pi^- \pi^- \pi^+ C$ $M_{\pi^+ \pi^-}$ M.A. Ananjeva et al. IHEP (Protvino)
----- 700		----- idem $M_{\pi^+ \pi^- \pi^-}$
----- 681		$\pi^- A \rightarrow \pi^- \pi^- \pi^+ A$ $M_{\pi^+ \pi^-}$ Yu. Ivanshin et al. IHEP (Protvino)
----- 647	650 640	$p n \rightarrow \pi^- \pi^+ p n$ $M_{\pi^+ \pi^-}$ Yu.A. Troyan et al. JINR (Dubna)
----- 608		 $n p \rightarrow n p \pi^+ \pi^+ \pi^- \pi^-$ $M_{\pi^+ \pi^-}$ $n p \rightarrow n p \pi^+ \pi^- \pi^- \pi^0$ $M_{\pi^+ \pi^-}$ Yu.A. Troyan et al.
----- 588	588 580	
----- 550		

Fig. 18. Masses of narrow exotic mesons. The left column shows the results of this work, when next to the right column shows masses from other experiments [11], [12], [13].

The mass formula used - which involves a large degeneracy - was derived many years ago [14]:

$$M_{exp} = M_{0 exp} + M_{1 exp} [i_1(i_1 + 1) + i_2(i_2 + 1) + (1/3)s_1(s_1 + 1) + (1/3)s_2(s_2 + 1)] \quad (2)$$

where i_1 (i_2) and s_1 (s_2) are the isospin and spin values of the first (second) quark cluster. We have two sets of quarks in a bag stretched for orbital excitations. All quarks are in the lowest bag mode (1s ground state of a spherical bag). There is no orbital, neither radial excitation. The spectra is given by the color-magnetic energy. The fine structure is determined by the coloured quark configurations at the ends of the bag.

The experimental results were fitted using the previous formula as a phenomenological one. Both parameters $M_{0 exp}$ and $M_{1 exp}$ were adjusted to the data. Depending on the hadrons considered, these parameters will be adjusted in order to get known mass, spin and isospin of some stable hadrons. Therefore we have either two, one or zero free parameters.

B. Results

For **narrow exotic mesons** we do the assumption that the simplest (lowest) configurations are favoured. We have two free parameters and the following clusters :

$q^2 - \bar{q}^2$ clusters with $M_{0 exp} = 310$ MeV, and $M_{1 exp} = 30$ MeV describe the ABC mass region (not discussed here), up to $M = 470$ MeV.

$q^3 - \bar{q}^3$ clusters with the same values of both parameters, describe the mesonic mass range up to 610 MeV.

$q^4 - \bar{q}^4$ clusters, $M_{0 exp} = 357$ MeV, and $M_{1 exp} = 27$ MeV describe the mesonic mass range up to 790 MeV. The comparison between these calculated masses and those observed experimentally, is shown in Fig. 19.

The parameters for **narrow exotic baryons** are adjusted in order to get the N and N* (1440) (Roper Resonance) masses, spins and isospins. There is no free parameter here. We get : $M_{0 exp} = 838.2$ MeV, and $M_{1 exp} = 100.3$ MeV. The calculated mass values are compared to the experimental ones in Fig. 15. The possible spin and isospin values are shown. The parity depends on the clusters : $P = +$ for $[q - q^2]$ clusters, $P = -$ for $[(q\bar{q}) - q^3]$ clusters and $P = +$ for $[(q\bar{q})^2 - q^3]$ clusters. The masses of the two first (3/2, 3/2) states are found to be close to 1232 MeV, a little below and a little above the mass of the known Δ^{++} resonance.

Two sets of clusters are considered for **narrow exotic dibaryons**. The mass region between 1940 and 2300 MeV is described by $q^2 - q^4$ clusters, with $M_{0 exp} = 1841$ MeV and $M_{1 exp} = 52.5$ MeV.

calculated $q^3 - \bar{q}^3$ parity (-)	experimental	calculated $q^4 - \bar{q}^4$ parity (+)
	(-----)759	----- 753 (1)(1..3) (1..3)(0..4)
	(-----)750	----- 735 (0)(1..3) (2)(0..4)
	----- 715	----- 717 (0..2)(2) (0..2)(0..4)
	----- 700	----- 699 (1)(2) (1)(0..4)
	----- 681	----- 681 (0)(2) (0)(0..4)
		(0..4)(1) (0..4)(1..3)
	----- 647	----- 645 (1..3)(1) (1..3)(1..3)
		----- 627 (2)(1) (2)(1..3)
		(0..4)(0) (0..4)(2)
----- 610 (0..3)(0..3)	----- 608	
(0..1)(2..3)		
----- 580 (1..2)(0..3)	----- 588	
----- 550 (0..1)(0..3)	----- 550	
(Spin)(Isospin)		(Spin)(Isospin)

Fig. 19. Experimental and calculated mesonic mass spectrum.

Since these values allow to get deuteron mass, spin and isospin values, only one parameter is free. Fig. 10 shows the comparison between the experimental and calculated masses. We notice here the very good agreement between both, in the mass range $2.0 \leq M \leq 2.2$ GeV.

The mass region between the threshold and 1920 MeV is described by $q - q^5$ clusters, with two free parameters : $M_{0 \text{ exp.}} = 1874.6$ MeV and $M_{1 \text{ exp.}} = 5.3$ MeV. The comparison is shown in Fig. 13.

C. Attempt for an unification

In order to strengthen our results, we tried to connect the different $M_{0 \text{ exp.}}$ and $M_{1 \text{ exp.}}$ found for the various following quark clusters :

$$q - q^2, q(q\bar{q})^2 - q^2, q^2 - q^4, q - q^5, q^2 - \bar{q}^2, q^3 - \bar{q}^3 \text{ and } q^4 - \bar{q}^4.$$

In order to get a completely general formula for M_0 and M_1 , we consider the following two quark clusters :

$$q^m \bar{q}^m - q^n \bar{q}^n \quad (3)$$

where m ($\bar{m}$) and n ($\bar{n}$) are respectively the number of quarks (antiquarks) of both clusters. Let us define the two following variables :

$$u = |(m - \bar{m}) - (n - \bar{n})| \quad (4)$$

and

$$v = |(m - \bar{m}) + (n - \bar{n})| \quad (5)$$

describing the difference and the sum of the number of quarks (minus antiquarks) of both clusters. We calculate $M_{0 \text{ cal.}}$ and $M_{1 \text{ cal.}}$ using the following expressions :

$$M_{0 \text{ cal.}} = M_{00} + M_{01}/v^v - M_{1 \text{ cal.}} \quad (6)$$

and

$$M_{1 \text{ cal.}} = M_{10} + M_{11}/u^u \quad (7)$$

where $M_{00} = v.m_q$, $m_q=313$ MeV being the mass of the constituent quarks. We choose $M_{01} = 340$ MeV, $M_{10} = 30$ MeV and $M_{11} = 70.5$ MeV in order to fit the parameters for $q^3 - \bar{q}^3$ clusters. Then the calculated $M_{0 \text{ cal.}}$ and $M_{1 \text{ cal.}}$ values are compared, for all quark cluster combinations, to the corresponding experimentally determined values in table 1 and Fig. 20.

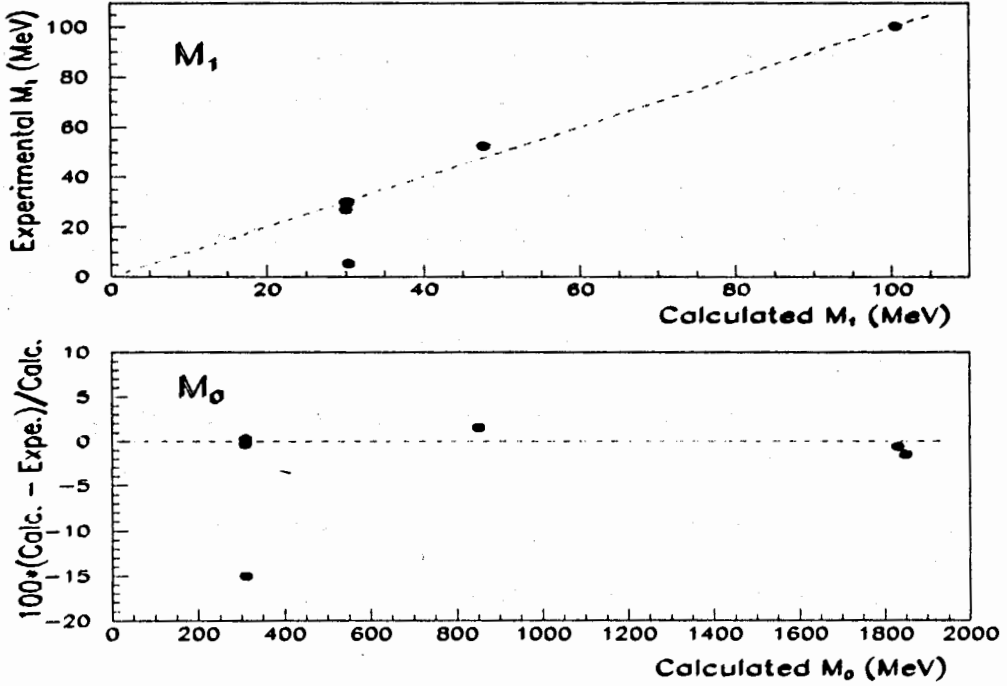


Fig. 20. Comparison of experimentally found M_0 and M_1 values with the corresponding ones obtained from previous equations.

Therefore three adjustable parameters : M_{01} , M_{10} and M_{11} - and the previous formula, allow to reproduce nearly all values reported in table 1. The only parameter which is badly reproduced is the smaller one, M_1 for $q - q^5$ clusters. We observe that the narrow structure masses remain the same when $(q\bar{q})^k$ configurations are added in one or both clusters, (k) being an arbitrarily integer. This appears in $q(q\bar{q})^2 - q^2$ configuration which gives the same mass as the $q - q^2$ configuration.

The formula and parameters give also with high precision the masses of all nuclei. For example the three nucleon mass is obtained within $\Delta M = (M_{cal.} - M_{exp.}) / M_{exp.} \leq 0.003$. On the other hand, the pion mass is badly reproduced (387.6 MeV). In conclusion with the use of our mass formulas and three free parameters, we reproduce the masses of many narrow mesons, baryons and dibaryon experimentally observed.

V. CONCLUSION

The evidence concerning the real existence of narrow hadronic structures, once uncertain, is now clearly established. Indeed the number of standard deviations for narrow peak against background, vary up to 4.6 for mesons, up to 16.9 for baryons and up to 8.1 for dibaryons. The stability of the corresponding masses, independently of the experiments, allows to consider them to be new exotic states, which have no room in classical meson-baryon physics. Therefore this work can be considered as an attempt to go beyond the physics of mesons and baryons in interaction.

After having presented the last and more precised experimental results, we have shown the possibility to rely these observations to possible colored quark clusters. In such case, these states will be associated to possible partial precursor quark deconfinement.

It is clear that more work is needed.

Theoretically it corresponds to an important and difficult field, since the energy is low, and therefore involves non-perturbative QCD calculations.

New experiments are essential. They must be precise, with small both systematical and statistical errors. A necessary good resolution ($\sigma \approx 1-2$ MeV) is more easy to be obtained with not too large energy beams. An incident energy of $T \approx$ several GeV, is well suited for such purpose. These structures must be looked for in inelastic channels. It is not the place here to give an exhaustive list of possible experiments. Some studies were already performed but must be repeated with better accuracy, using the Nuclotron, COSY, CELSIUS... beams. They correspond to the following experiments :

- Isospin zero narrow dibaryons :
 $d d \rightarrow d X$ reactions (Saturne) [15]

• Isospin two narrow dibaryons :

$d (\pi^\pm, \pi^\mp) X$ (Lampf) [16]

$\bar{p} p \rightarrow \pi^- X$ (Saturne) [17]

stopped π^- in D_2 (Triumf) [18]

• Isospin three narrow dibaryons :

$\bar{p} p \rightarrow \pi^- \pi^- X$ (Saturne) [19]

In the same way, the electromagnetic probe can be used for such studies, at TJNAF for example. Precise and simple reactions as $p [d] (e, e') X$ must be done in order to look for narrow structures in the missing mass. Of course, many experiments with nucleons and pions in the final state, can be used to the same studies in the invariant masses.

Table 1. Calculated masses using equations (4) $\rightarrow$ (7), and experimental masses of narrow hadronic structures. ΔM_0 and ΔM_1 are defined by the relation : [(calculated-experimental)/calculated] values between M_0 and M_1 masses

		M_0 cal.	M_0 exp.	ΔM_0		M_1 cal.	M_1 exp.	ΔM_1
$q - q^2$		851.1	838.2	0.015		100.5	100.3	0.002
$q^2 - q^4$		1830.4	1841	-0.006		47.6	52.5	-0.10
$q - q^5$		1847.7	1874.6	-0.015		30.3	5.3	0.82
$q^2 - \bar{q}^2$		309.7	310	-0.001		30.3	30	0.01
$q^3 - \bar{q}^3$		310	310	0		30	30	0
$q^4 - \bar{q}^4$		310	357	-0.15		30	27	0.1
$q(q\bar{q})^2 - q^2$		851.1	838.2	0.015		100.5	100.3	0.002

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Status of the experimental investigation of the η -mesic nuclei

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Abstract

Short history of ideas concerning a possible existence of bound states of the η -meson and nucleus is considered. First experiments at BNL and LAMPF on searching for these states are discussed. Another recent experiment using the photon beam of the 1 GeV electron synchrotron of LPI is described. Possible experiments on studying η -mesic nuclei using a proton beam (at Nuclotron of Dubna) and a γ -beam (CEBAF, JLAB) are suggested.

Key words: η -meson, η -mesic nuclei, $a_{\eta N}$ -scattering length, $S_{11}(1535)$ nucleon resonance, $E_g(\eta)$ -binding energy of η -meson into nucleus, time of flight method, bremsstrahlung photons.

I. INTRODUCTION

This is a status report of experimental investigations of new objects of nuclear physics - η -mesic nuclei, ${}_{\eta}A$, a bound system of η -meson and nucleus (fig. 1). The η -nuclei are a new kind of the atomic nuclei and their research has the fundamental significance in studying the interaction of the η -meson with nucleons and nucleon resonances into the nucleus.

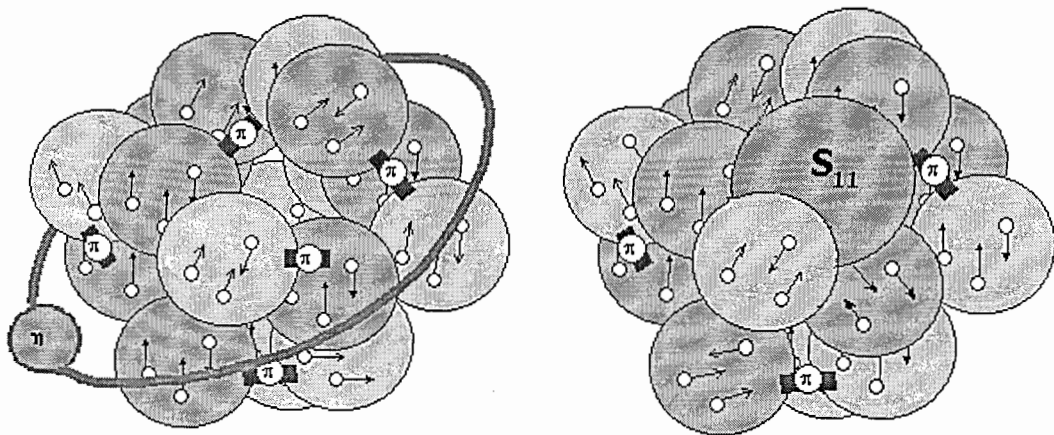


FIG. 1. η -nuclei as η -meson in nuclei field (left) and as S_{11} -resonance inside nuclei(right)

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A. Short history

Beams of the η -mesons cannot be obtained because of very short life-time of the η -mesons ($t_{1/2} \sim 5,5 \cdot 10^{-19}$ sec). So the study of the interactions of the η -mesons with nucleons in elementary processes of $\eta N \rightarrow \eta N$, $\eta N \rightarrow \pi N$ type is not possible. The interaction ηN can be investigated only in the final state of the elementary processes, for example $\pi N \rightarrow \eta N$, $\gamma N \rightarrow \eta N$.

The η -mesic nuclei give us unique possibility to study ηN -interaction in nuclear matter.

The possibility of the existence of the η -meson and nucleus bound state was firstly noted by J.C. Peng [1] in connection with the analysis of the $\pi N \rightarrow \eta N$ reaction. As one noted, this reaction is characterized by nonrecoil kinematics for a η -meson. Then assuming that the reaction proceeds on a nuclear nucleon providing that:

- the ηN -interaction has attractive character in a s-wave and
 - the reaction time of η -meson in the nucleus is not small
- the η -mesic nuclei can be formed.

B. The scattering length $a_{\eta N}$

The interaction of the η -meson in a s-wave with nucleon can be describe by $a_{\eta N}$. The analysis of the scattering lengths of reactions $\pi N \rightarrow \pi N$; $\pi N \rightarrow \pi \pi N$ and $\pi N \rightarrow \eta N$ carried out by R. Bhalerao and L. Liu [2] has shown that scattering length $a_{\eta N}$ calculated for the reaction $\eta N \rightarrow \eta N$ is equal to:

$$a_{\eta N} = (0,27 + i \cdot 0,22) fm. \quad (1.1)$$

A positive value of $Rea_{\eta N}$ means that

- the interaction in s-wave has attractive character and
- the existence of quasi-bound states of the η -meson with a nucleus for $A \geq 11$ is possible at this value $Rea_{\eta N}$.

The widths of these levels were estimated by Q. Haider and L. Liu [3]. The calculated values of width $\Gamma_g(\eta) \approx 10$ MeV mean that the life-time of these states is approximately 10 times larger then the typical nucleus time (10^{-23} sec), corresponding to the flight of relativistic particle through the nucleus.

The values of $\Gamma_g(\eta) \simeq 30 \div 80$ MeV for the widths of the bound states of the η -nuclei are obtained by E. Oset et. al [4].

New calculations [5] of the scattering length $a_{\eta N}$ for the $\eta N \rightarrow \eta N$ reaction were then carried out and the values of $Rea_{\eta N}$ were found to be 3 times larger then those from paper [2].

This means that the existence of the η -meson bound states with lighter nuclei having atomic number $A = 4 \div 5$ [6] and even $A=2$ [7] is possible.

Fig. 2 shows energy dependence of $Rea_{\eta N}$ and $Ima_{\eta N}$ [5].

C. The first experiments for search of the η -nuclei

First experiments on direct reseach for η -nuclei were carried out just after calculation of $a_{\eta N}$ [2] with using π^+ beams at BNL [8] and LAMPF [9]. The criterion of η -nuclei selection

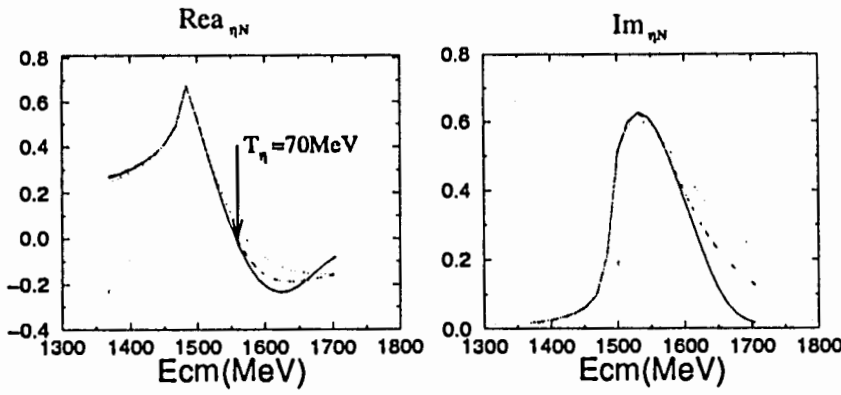


FIG. 2. Energy dependence of $Re a_{\eta N}$ and $Im a_{\eta N}$ for process $\eta N \rightarrow \eta N$ [5]

in the BNL experiment was the observation of narrow kinematic peak ($\Gamma_g \sim 9$ MeV) in the spectrum of proton arising in the final state of the 2-particle reaction:

$$\pi^+ + A \rightarrow p + {}_{\eta}(A-1). \quad (1.2)$$

The peak width $\Gamma_g(\eta)$ corresponded to the width of the η bound state in ${}_{\eta}(A-1)$ nuclei [3]. The trigger of the events was detection only one particle-proton. The experiment was carried out on a π^+ meson beam with momentum of 800 MeV/c using Li, C, O and Al targets. A narrow peak, 9 MeV in width, was assumed to be observed in the spectrum of protons for $\Theta_p = 15^\circ$. However, no narrow kinematic peak was observed for any target in the spectrum p in the expected area. The authors of paper [8] would like to note that these negative results can be explained by:

- a larger width of the expected peak than it was assumed.
- a smaller cross section, than it was assumed.
- a very bad ratio: effect/background < 1 .
- a too high energy of primary π^+ -mesons.

As noted in [6] $Re a_{\eta N}$ is decreased with energy and can become negative at higher energies. This means that "attraction" in the ηN system can be replaced by "repulsion".

Of course, all reasons above are important, but in our opinion, the negative results in [8] can be due to in principle the fermi-motion of nucleons in the nucleus. Really, a reaction of the (1.2) type at a fixed energy of π -mesons but with the nucleon moving in the nucleus (fermi-motion) is equivalent that on the nucleon at rest, but with energy "spread" of π -beam. This naturally leads to a sharp energy spread of protons detected at fixed angle Θ_p . LAMPF experiment [9] was carried out on a π^+ -meson beam with a momentum of 640 MeV/c and a harder trigger for event selection corresponding to the production of η -nuclei was used: proton p was detected on coincidences with π -meson from the decay of the $S_{11}(1535)$ resonance in the η -nucleus. As noted in report [9], in this experiment an excess of counts was observed in the expected area for a kinematic peak of protons. However, the experiment was not completed, as so the results were not published.

Thus, first direct experiments on the search of the η -nuclei have not given the expected results. At the same time, some results were obtained in the study of reaction $p + d \rightarrow {}^3\text{He} + \eta$ [10]. There interpretation required to use of the representations of nucleus interaction of η -meson with the nucleus in the intermediate stage of the reaction [10]. The characteristic properties of this reaction was:

- a very large cross section in a 10 MeV interval at threshold, by two orders greater than the cross section of the reaction with π^0 -meson production.

- practically an isotropic angular distribution of η -mesons over this energy range (at threshold), which assumed a multiplicity of interaction of η -mesons with nucleons inside the nucleus.

An indication of nuclear interaction of η -meson with the nucleus in the intermediate stage of the reaction was also obtained in the analysis of double charge-exchange reaction $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ [12], where a peak was observed in the excitation curve at energy $E_{\pi^+} = 410$ MeV corresponding to η -meson production threshold.

II. FIRST RESULTS CONCERNING FORMATION OF η -MESIC NUCLEI IN PHOTOREACTIONS

The problem of the η -nuclei existence for long time (~ 10 years) remained open after experiments at BNL and LAMPF with negative results. Only in 1998 in the experiment carried out on the 1 GeV electron synchrotron at Lebedev Physical Institute the results were obtained which can be interpreted as a direct experimental evidence of the existence of bound η -meson-nucleus states [13].

A. Method of the identification η -nuclei

The experiment was performed on a bremsstrahlung photon beam and correlated π^+n pairs, arising from the reaction

$$\gamma + {}^{12}\text{C} \rightarrow p(n) + {}_{\eta}^{11}\text{B}({}_{\eta}^{11}\text{C}) \rightarrow p(n) + \pi^+ + n + {}^{10}\text{Be}({}^{10}\text{B}) \rightarrow \pi^+ + n + X. \quad (2.1)$$

The experiment was carried out at 2 energies $E_{\gamma\text{max}} = 650$ and 850 MeV, i.e. below and above η -meson production threshold. As noted earlier in paper [14], the registration of (πN) -pairs and the analysis of angular and energy characteristics can be a good criterion of production and consequent decay of quasi-bound state of η -meson and nucleus in an intermediate stage of reaction (2.1).

The η -nucleus formation in the reaction (2.1) followed by its decay is shown schematically in fig. 3. There, the first stage of the reaction, i.e. production of η by photon, second stage i.e. formation of bound state η -meson with nucleus, and the third stage, i.e. annihilation of η and creation of a pion, proceeds through single-nucleon interactions (either with a proton or a neutron in the nucleus), mediated by the $S_{11}(1535)$ nucleon resonance. According to modern representations, the bound state of η -meson and nucleus can be considered as a sequence of production and decay into ηN -pairs of the $S_{11}(1535)$ resonance in the nucleus

$$\eta + N \rightarrow S_{11} \rightarrow \eta + N \rightarrow S_{11} \rightarrow \dots \rightarrow S_{11} \rightarrow \eta + N \quad (2.2)$$

where N is nucleon, proton or neutron.

As result, the full averaging of the energy and angular characteristics of pair components

are arised. The decay of the η -nucleus is via the decay of the "last" practically "thermalized" $S_{11}(1535)$ resonance in this nucleus into πN -pair.

$$\eta N \rightarrow S_{11}(1535) \rightarrow \pi N. \quad (2.3)$$

Due to the Fermi motion, πN pairs from η -nucleus decays have the characteristic opening angle $\langle \Theta_{\pi N} \rangle = 180^\circ$ with the width of $\simeq 25^\circ$. The kinetic energies are $\langle E_\pi \rangle = 300$ MeV and $\langle E_N \rangle = 100$ MeV with the widths of $\simeq 10\%$. It should be noted that the average energies $\langle E_\pi \rangle$ and $\langle E_N \rangle$ of the decay components were estimated for the $S_{11}(1535)$ resonance bound in the nucleus. Its energy is reduced to binding energy $E_g(S_{11})$ which can reach $20 \div 30$ MeV.

In the case when the momentum (or energy) of produced η is high (> 150 MeV/c), the attraction between η and the nucleus is not essential and the η -meson propagates freely (up to an absorprion, see Fig. 3b).

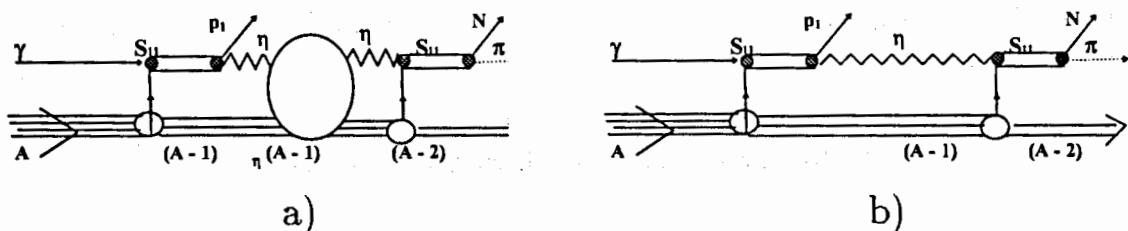


FIG. 3. (left) Mechanism of formation and decay of an η -nuclei in photoproduction process ($E_\eta \leq 70$) MeV. (right) Mechanism of production and annihilation of η 's in the nucleus ($E_\eta > 70$ MeV)

In this case, the final πN -pairs also carry a high momentum and their kinematic characteristics, such as the opening angle $\langle \Theta_{\pi N} \rangle$ and average energies $\langle E_\pi \rangle$, $\langle E_N \rangle$, differ from those for pairs produced through the stage of the η -nucleus formation.

The kinematics suggests photon energies $E_\gamma = 650 - 850$ MeV as the most suitable for creating the η -mesic nuclei.

B. Experimental set-up

An experimental set-up consisted of two the time of flight scintillator spectrometers having a time resolution of $d\tau \simeq 0,1$ ns (fig. 4). Carbon target $\varnothing 4 \times 4$ was used. A plastic anticounter A of charged particles (of the 90% efficiency), placed in-front of the neutron detectors, and dE/dx layers, placed between "start" and "stop" detectors in the pion spectrometer, were used for a better identification of particles. The time of flight spectra in the pion and neutron spectrometers shown in fig. 4. Two-dimensional distributions over the time of flight particles were obtained for $(\pi^+ n)$ -coincidence by combination their individual distribution events.

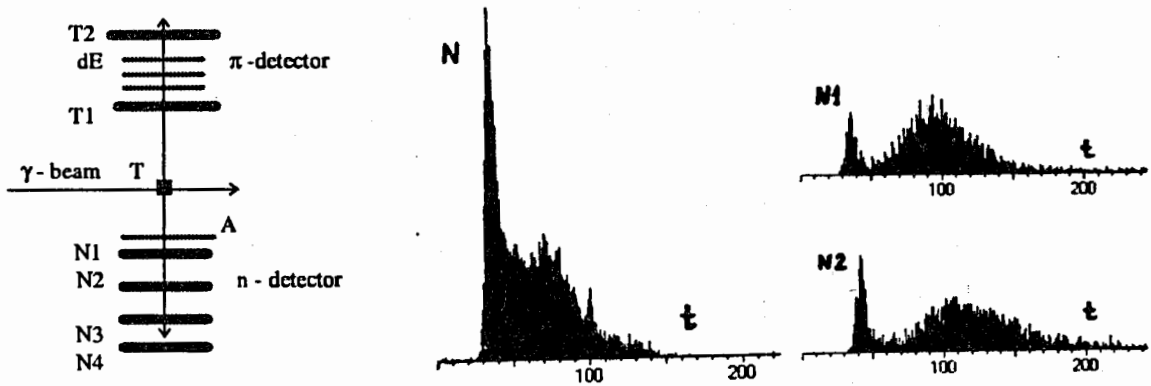


FIG. 4. Layout of the experimental setup. Shown also time-of-flight spectra in the π (left) and n (right) spectrometers

C. Procedure of measurements

Strategy of measurements was as follows. Two bremsstrahlung-beam energies were used, $E_{\gamma\max} = 650$ MeV and 850 MeV, i.e. well below and well above η production threshold (707 MeV on the free nucleon). The first "calibration" run was performed at 650 MeV with spectrometers positioned at angles $\Theta_\pi = \Theta_n = 50^\circ$ around the beam. In that run, this was a quasi-free photoproduction $\gamma p \rightarrow \pi^+ n$ which dominated, the observed yield of the $(\pi^+ n)$ pairs. Then, at the same "low" energy 650 MeV, the spectrometers were positioned at $\Theta_\pi = \Theta_n = 90^\circ$ (the "background" run), In such kinematics the quasi-free production did not contribute and the observed counts were presumably dominated by double pion production. At last, the third run (the "effect + background") was performed at the same $90^\circ/90^\circ$ position, however with the higher photon beam energy of 850 MeV, at with η mesons are produced too.

D. Handling of raw results

In accordance with measured velocities of particles detected by the spectrometers all candidates to the $(\pi^+ n)$ -events were separated into three classes: fast-fast (FF), fast-slow (FS), and slow-slow (SS) events. The FF events mostly correspond to $\pi^0 \pi^0$ production with results in hitting detectors by photons or e^+/e^- . The FS events mostly emerge from $(\pi\pi) + (\pi^+ n)$ -pairs. The SS events arised from $(\pi\pi)$ pairs. Comparing yields and time spectra in these runs we have found a clear excess of the FS events which appeared when the photon energy exceeded η production threshold. (see [13] for more details). The raw experimental spectrum over the particles velocities had unphysical region with $\beta_i > 1$. So happened the velocities $\beta_i = L_i/t_i$ are subject to fluctuations stremming from errors δt_i and δL_i in the time-of flight t_i and the flight base L_i . Such fluctuations are cleary seen in the case of the ultra-relativistic FF events. Therefore, an experimental β -resolution of the set-up can be directly inferred from the FF events. Then, using this information and applying an inverse-problem statistical method discribed in Ref [15], one can unfold the experimental spectrum, obtain a smooth velocity distribution on the physical region $\beta_i \leq 1$. (fig. 5), and eventually find a distribution of the particle's kinetic energies

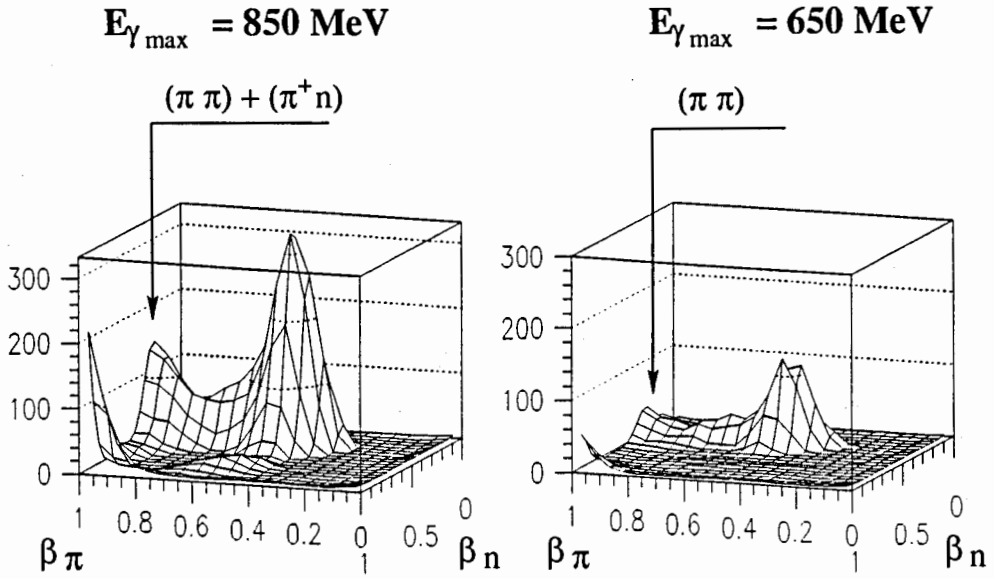


FIG. 5. Corrected two-dimensional distributions over the velocities (β) for the (π^+n) -events with end-point energy of the bremsstrahlung spectrum $E_{\gamma\max} = 650$ and 850 MeV

$E_i = M_i[(1 - \beta_i^2)^{-1/2} - 1]$. Finding E_i , we introduced corrections related with every energy losses of particles in absorbers and in the detector matter. It is worth to say that the number of the (π^+n) FS events visibly increases when the photon beam energy becomes sufficient for producing η mesons.

E. Results

The most interest is the distribution of the (π^+n) -events over their total energy $E_{tot} = E_n + E_\pi$, because creation and decay of η -mesic nuclei is expected to produce a relatively narrow peak in E_{tot} (see [13, 16]). Such a peak was indeed observed.

At fig. 6 we see an excess of the FS events appears when the photon energy exceeds the η -production threshold. These (π^+n) pairs arise from creation and decay of captured bound η in the nucleus, i.e. they arise through the stage of formation of an η -mesic nucleus. The second important results is a "shift" of the position of $S_{11}(1535)$ resonance decayed into nuclei.

On fig. 7 we have a 1-dimensional energy distribution of the (π^+n) events presumably coming from bound η decaying in the nuclei. The experimental width of this distribution is about 100 MeV including the apparatus resolution. Its center lies by $\Delta E = 40$ MeV below the energy excess $m_\eta - m_\pi = 408$ MeV in reaction $\eta N \rightarrow \pi N$, and it is well below the position of the $S_{11}(1535)$ resonance too.

Up to effects of binding of protons annihilated in the decay subprocess $\eta p \rightarrow \pi^+n$, the

$$E_{\gamma\max} = 850 \text{ MeV}$$

$$E_{\gamma\max} = 650 \text{ MeV}$$

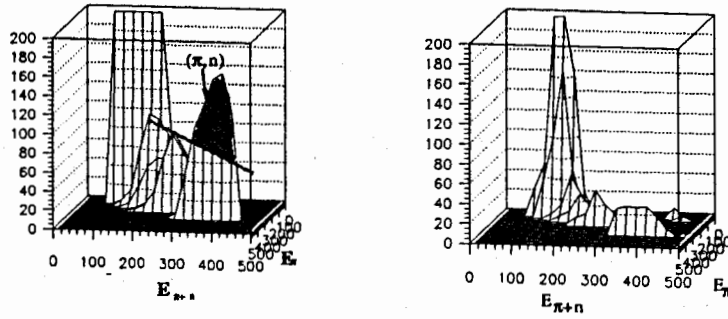


FIG. 6. Distribution over the total kinetic energy of the (π^+n) pairs for the “effect+background” run (the left panel) and for the “fon” run (the right panel) obtained after unfolding raw spectra

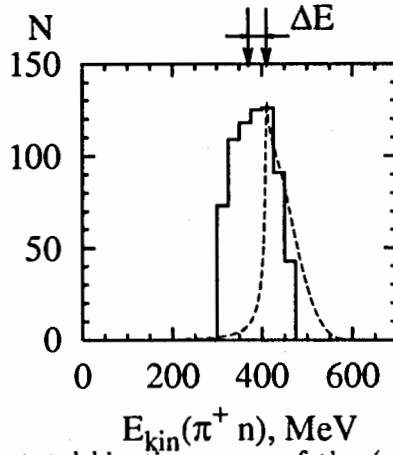


FIG. 7. Distribution over the total kinetic energy of the (π^+n) pairs after subtraction of the background. An arrow indicates the threshold of 408 MeV (see in the text). For a comparison, a product of free-particle cross sections of $\gamma N \rightarrow \eta N$ and $\eta N \rightarrow \pi N$ is shown with the dashed line (in arbitrary units)

value ΔE characterizes the binding energy of η in the nucleus. The width of that peak is determined both by the width of the η -bound state and by the Fermi motion.

F. Conclusions

The first results which gives the evidence for existence of the bound state of η -meson and nucleus in intermediate stage photomesonic processes are obtained at LPI [13].

III. STUDY FOR THE η -MESIC NUCLEI IN PA-COLLISIONS AT JINR NUCLOTRON (PROPOSAL)

A. Experimental conditions

The use of intensive monochromatic beams of protons with energies of some GeV may look promising to study η -mesic nuclei. The possibility of the η -nuclei production in the reaction

$$p_0 + A \rightarrow p_1 + p_2 + \eta (A - 1) \rightarrow p_1 + p_2 + p_3 + \pi^- + X \quad (3.1)$$

for light nuclei with $A \geq 12$ (^{12}C , ^{14}N , ^{16}O) is considered in this suggestion.

Fig. 8(a) presents a diagram of process describing the stage of η -meson production in nucleus with formation of the bound state of η -meson and nucleus and at last the stage of the η -nucleus decay. The diagram corresponding to process where the η -mesic nucleus is not production is shown in fig. 8(b). One can assume that the kinetic energy of the η -meson is rather great ($T_\eta > 70$ MeV) in this case and there is not attraction between η -meson and nucleon [6].

The production cross sections of η -meson in elementary processes $\pi p \rightarrow \eta p$ and $pp \rightarrow \eta pp$ are practically similar. However, the advantage of p-beams consist in their much greater intensity (by 2-3 orders) in comparing with π -meson beams (the latter are secondary beams of proton accelerators). This circumstance is important as the production cross sections of η -nuclei in pA -collisions are expected at a level of some tens microbarns.

The event selections of η -mesic nuclei production in pA -collisions are assumed to be made by registering 4 particles: p_1 and p_2 protons produced in the 1-st stage of the reaction (3.1) and (π^-, p_3) pairs from the decay of the η -mesic nucleus (fig. 8). To separate from the process shown by the diagram in fig. 8b should be detected the 4 particles in the corresponding energy and angular intervals.

For a bound state of η -meson and nucleus the angular distribution of the (π^-, p_3) components from the $S_{11}(1535)$ resonance decay is characterized by isotropy at an everagy angle of $< \Theta_{\pi p} > \simeq 180^\circ$ and an increased yield of such pairs a 3-5 times fold in comparison with the case without ηA -interaction.

B. Experimental setup

The experiment is supposed to be performed on an internal beam of protons at the JINR NUCLOTRON.

The use of the internal beam affords unique opportunities to study processes with small cross sections through the full interaction of the beam with a "wire" target so the total intensity can reach $\sim 10^{14}$ p/hours and a low nouse level since the background particles are not practically multiplied into the target.

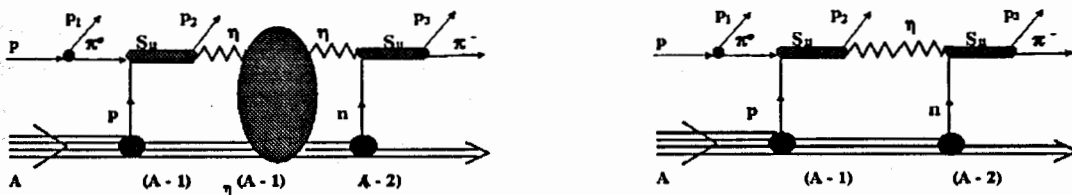


FIG. 8. (left) Mechanism of formation and decay of an η -nuclei in pA -collisions ($E_\eta \leq 70$ MeV). (right) Mechanism of production and annihilation of η 's in the nucleus ($E_\eta > 70$ MeV).

The scheme of the experimental setup and its deposition on the ring of the accelerator is shown in fig. 9. According to the chosen algorithm of event selection of the η -nuclei production in pA -collisions, the setup consists of 3 types detectors. All the detectors are made of the plastic scintillation counters. This is determined by the necessity of the realization of fast coincidences and the measurement of the time-of-flight of particles in the picosecond range. The detectors of p_1 and p_2 represent an assembly of counters W1-W8 placed around the axis of an incident beam at an angle $\langle \Theta \rangle$ of $\sim 10^\circ$.

The function of detectors p_1 and p_2 is to measure the coordinate of the detected protons, angle $\Theta(p)$ and time-of-flight. The detector used to register the proton p_3 is a scintillation telescope of the $\Delta E - E$ type. The detector of π^- -mesons is scintillation telescope of 2 counters TC1 and TC2. The time resolution of all detectors is about 150-170 psec. The first counter of the π^- -spectrometer is used as a "start" counter for all the time-of-flight system.

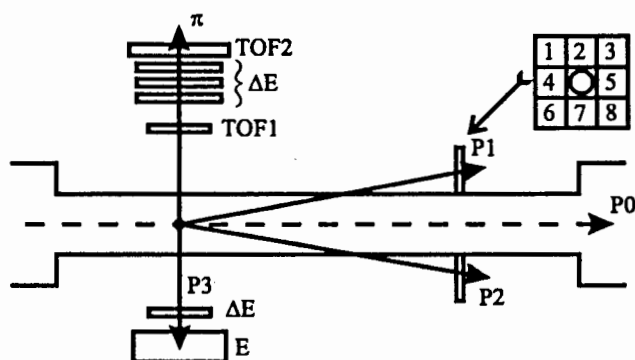


FIG. 9. The scheme of the experimental setup and its deposition on the ring of the accelerator

C. Estimates of the $\Delta Y(p_1, p_2, p_3, \pi^-)$ yield

As the production of the η -nuclei is preferable for slow η -mesons ($E_\eta \leq 70$ MeV) the reaction yield is determined by threshold values of the cross sections for elementary processes

of the η -meson production. A favourable circumstance is that production cross sections are rather significant. It is due to the disposition of the η -meson production threshold inside the energy region of the $S_{11}(1535)$ resonance, having a large width of $\Gamma \sim 150$ MeV in an elementary $pp \rightarrow pS_{11}(1535) \rightarrow pp\eta$ reaction. The total production cross section of η -meson near threshold is equal to [17, 18] :

$$\sigma_t(pp \rightarrow \eta pp) \simeq 100 \mu kb (10^{-28} cm^2). \quad (3.3.1)$$

The yield of the 4 multiple coincidences $\Delta Y(p_1, p_2, p_3, \pi^-)$ for $50 \mu m^{12}C$ target wire can be estimated from the following relation:

$$\Delta Y(p_1, p_2, p_3, \pi^-) = \sigma_t(p^{12}C \rightarrow p_1 p_2 {}^{11}_\eta B) \cdot N_n \cdot N_p \cdot Br(\pi, N) \cdot \xi \cdot \Omega_\pi \cdot f(\Omega_p/\Omega_\pi) \cdot \eta_\pi \cdot \eta_p \cdot \chi_{p_1} \cdot \chi_{p_2}. \quad (3.3.2)$$

In this expression:

$\sigma_t(p^{12}C \rightarrow p_1 p_2 {}^{11}_\eta B)$ is taken as part of σ_t for the η -meson production on the ^{12}C nucleus. This part is the same as for photoreactions, i.e. $\sim 5\%$. Then the production cross section of the η -nuclei in the interaction of p-beam with the ^{12}C nucleus is equal:

$$\bullet \sigma_t(p^{12}C \rightarrow p_1 p_2 {}^{11}_\eta B) = [6 \cdot \sigma(pp \rightarrow \eta pp) \cdot F({}^{11}B)] \cdot 0,05 = 3 \cdot 10^{-3} mb = 3 \mu kb$$

where $F({}^{11}B)$ is the form factor of the nucleus ${}^{11}B$, assumed to be $\sim 0,1$.

$$\bullet N_n = \frac{N_a}{A} \cdot \rho(g/cm^3) \cdot \Delta x(cm) = \frac{6 \cdot 10^{23} \cdot 1,7 \cdot 5 \cdot 10^{-3}}{12} = 4,25 \cdot 10^{20} nucleus/cm^3$$

$$\bullet N_p = I_p \cdot n \cdot K = 10^{11} \cdot 800 \cdot 2 = 1,6 \cdot 10^{14} p/hour$$

Where $n=800$ -number of acceleration cycles per hour, $k=2$ is the average multiplicity of the passages of the proton beam through the target.

$$\bullet \Omega_\pi = \left(\frac{50}{150}\right)^2 \frac{1}{4\pi} = 9 \cdot 10^{-3}$$

$$\bullet Br(\pi N) = 0,5$$

$$\bullet \xi = 1/3 - \text{the part } (\pi^- p) \text{ decay } S_{11} \text{ of all kind decay.}$$

$$\bullet f(\Omega_p/\Omega_\pi) - \text{is the correlation function} = 0,2$$

$$\bullet \eta_\pi = 0,8 - \text{efficiency of } \pi\text{-detection}$$

$$\bullet \eta_p = 0,8 - \text{efficiency of } p\text{-detection}$$

$$\bullet \chi(p_1) \text{ and } \chi(p_2) \text{ are the geometric factors describing the fraction over angle interval of } \Delta\Theta = 10 \pm 5^\circ.$$

This fraction is registered by the p_1 and p_2 detectors of the total number of p_1 and p_2 produced in the $pp \rightarrow \eta pp$ reaction. The kinematic calculations give the following values:

$$\chi(p_1) = 0,185; \chi(p_2) = 0,233.$$

Substituting these numerical values to formula (3.3.2) we obtained:

$$\Delta Y(p_1 p_2 p_3 \pi^-) \cong 4 \frac{\text{events}}{\text{hour}} \simeq 100 \text{ events/day}.$$

The value of the expected yield can be considered as rather high under the condition of the small background level.

D. Conclusion

The research of the η -mesic nuclei in pA-collisions can be interest from point of view of development of the presentations about interaction adrons (η -meson) with nuclear matter

and a research of the new kind of atomic nucleus - η -mesic nuclei. In these research one can have possibility to formation two- η -mesic nuclei and mesic nuclei with other mesons (ρ, ω, φ).

IV. SEARCH FOR A FEW-BODY η -MESIC NUCLEI AT JLAB (CEBAF) (SUGGESTION FOR EXPERIMENT)

A. Experimental conditions

Performance of study for η -mesic nuclei at CEBAF can be very favourable consequently high intensity and continuous e-beam of accelerator. The experiment can be performed at bremsstrahlung photons in region of energy $E_{\gamma max} = 600 \div 1000$ Mev.

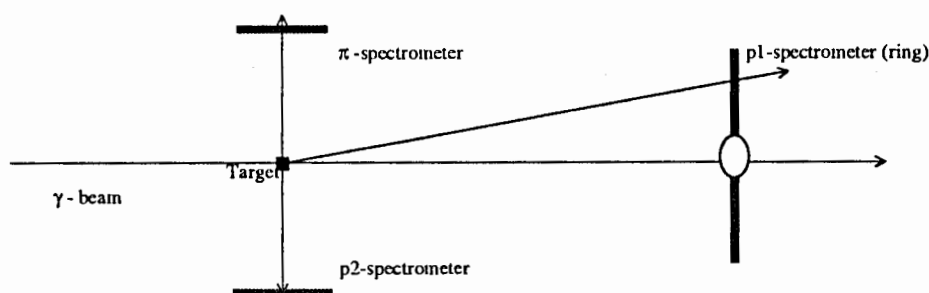


FIG. 9. Sketch of the experimental setup

The main task of experiment may be to measure of energy and A-dependence cross section for photoproduction of light η -mesic nuclei (up $A=12$ to $A=3$).

The method of η -nuclei identification consist of the detection 3-particles: one particle, from first stage of reaction (see fig.10) (n or p) and two-particles from second stage -decay of η -mesic nuclei: (π^+n) or (π^-p)-pairs. Detection of 3-ple coincidence is guarantee of selection of events connecting with formation η -mesic nuclei. The experimental set-up must have 3 type scintillation time-of-flight spectrometers (Fig. 10). The yeild of 3-ple councendence events can be to compose about 10 events/hour. One can receive the experimental results about energy bounding $E_g S_{11}(1535)$ resonance in light nuclei.

One of interested results can be evidence of existence lightest η -mesic nuclei (${}^3_{\eta}H, {}^3_{\eta}He, {}^4_{\eta}He$).

V. CONCLUSIONS

Study of the η -mesic nuclei is new very interesting field of nuclear physics and particle physics. One can receive a new information for interaction of the η -meson with nucleon and

nucleon resonance in the nuclear matter. The measurement of the bonding energy $E_g(\eta)$ and $E_g(S_{11})$ can be used in chiral symmetry theories in problem for origin of the elementary particle masses.

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Deuteron Beam Polarimetry at LHE Accelerator Facility

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The spin physics program of the Laboratory of High Energies, JINR (Dubna), is based on use of the slowly extracted deuteron beam with momentum up to 9 GeV/c [1]. To control operation of the polarized ion source POLARIS as well as vector and tensor polarization of deuteron beam, the following four types of polarimeters are used:

1. Low energy polarimeters. These are used to measure vector and tensor polarization of deuteron downstream the 10 MeV linac with ${}^4\text{He}(\vec{d}, d){}^4\text{He}$ and ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ reactions correspondingly. The design of detector boxes of vector (LEPV) and tensor (LEPT) polarimeters is shown in Fig.1. In both cases the gaseous target and detectors are combined in the hermetic box which can be brought in 10 MeV deuteron beam by means of a mechanical supporting device.

The vector polarization of deuterons is defined by means of measuring left-right asymmetry of yields of alpha-particles at $d^4\text{He}$ elastic scattering at the angle 150° in c.m. frame. The collimated deuteron beam is scattered on the helium nuclei in the target part of the detector box and recoiled alpha-particles are registered at the lab. angles of 15° with two thin ($55\mu\text{m}$) silicon detectors. The 4.5 MeV alpha particles are easily separated from deuterons, ΔE - losses of which are about 1.2 MeV in silicon. The beam polarization is related to the left-right asymmetry $A_{LR} = \frac{N_L - N_R}{N_L + N_R}$ by the equation

$$p_z = \frac{2A_{LR}}{3A_y}.$$

where analyzing power of the reaction ${}^4\text{He}(\vec{d}, d){}^4\text{He}$ is known with accuracy as low as 5% [2]: $A_y = 0.328 \pm 0.015$ at $T_d = 6.7$ MeV - the deuteron energy after losses in the mylar window and in helium.

To measure the tensor polarization of deuteron beam in the LEPT - polarimeter the detector box is designed in the form of a stainless steel cylinder ($\phi 37\text{mm}$ by 80mm) the forward part of which is filled with ${}^3\text{He}$ at 2 atm. The fast protons ($T_p = 20$ MeV) emitted at 0° in the reaction ${}^3\text{He}(\vec{d}, p){}^4\text{He}$ are detected by $500\mu\text{m}$ silicon detector after crossing the filter of $2.3 \frac{\text{G}}{\text{cm}^2}$, rejecting other lower energy particles. The tensor polarization is defined by difference of yields of the protons in polarized (N_p) and unpolarized (N_0) deuteron beam:

$$p_{zz} = 2\sqrt{2} \frac{I_0 N_p - I_p N_0}{T_{20} I_p N_0}.$$

where I_p, I_0 - beam intensities are monitored by means of the $d\text{Au}$ -scattering at the thin Au -target. The tensor analyzing power, T_{20} is known with accuracy as low as 2% [3]: $T_{20} = 1.254 \pm 0.014$ at $T_d = 6$ MeV (deuteron energy in the center of ${}^3\text{He}$ -target).

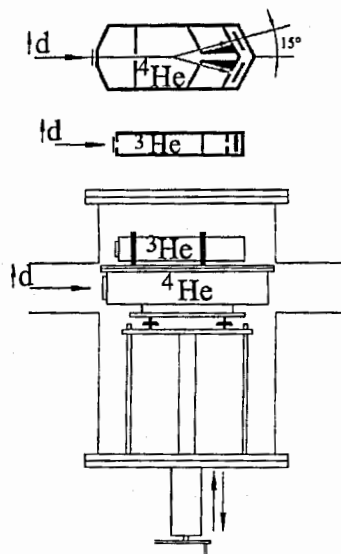


Figure 1. Detector boxes of low energy vector and tensor polarimeters, LEPV and LEPT, based on using $^4\text{He}(d, d)^4\text{He}$ (LEPV) and $^3\text{He}(d, p)^4\text{He}$ (LEPT) reactions. In accordance with vector or tensor mode of beam polarization, the LEPV- or LEPT-detector box is inserted downstream LINAC in 10 MeV deuteron beam

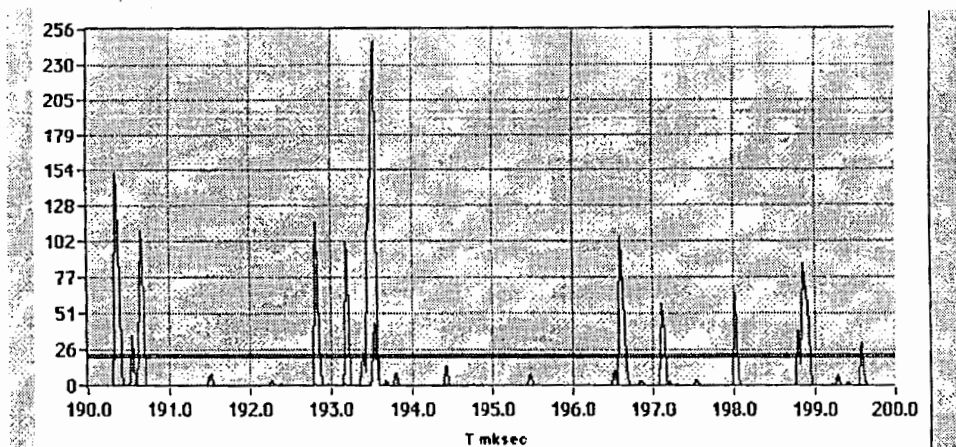


Figure 2. Signals of the fast proton Si-detector of LEPT-polarimeter digitized by flash-ADC with step of 20ns

To register amplitudes of signals of the silicon detectors a standart electronic line is used:

preamplifier-cable line(30m)-amplifier-amplitude to digital convertor (ADC).

At first, during POLARIS testing and tuning, ADCs of conventional type, with conversion time of about $30\mu s$, were used. At LINAC beam burst of $300\mu s$, it limited an available count rate at the level of 3-4 counts per a burst. Correspondingly, to measure a beam's polarization with accuracy of 5% it required about 3-hour data taking for the low repetition time of LHE LINAC equals to 10s. To overcome this disadvantage a new data acquisition system was developed [4]. It is based on using a fast ADC of flash type with the 32 Kwords memory. The system allows to increase count rate to 100 counts/burst. The flash ADC codes an input potential with the step of $20 ns$. This allows to cover the time interval of $0.02\mu s \cdot 32K = 640\mu s$. That is enough to fix one burst's picture. Between two bursts all information is processed by the CCPS personal computer controller.

An amplitude spectrum reproduced in the time scale is shown in Fig.2 as an example. Signals width is within $0.2\mu s$ at using a fast output of preamplifiers. Fig.3 displays amplitude spectra from the monitor detector, the right wide peak, and from the detector registering fast protons in the reaction $d^3He \rightarrow pX$, the left narrow peak (they are presented in different colours at a colour display). In three quadrates there are replaced the spectra at different deuteron beam polarization states (+, -, 0) and in the fourth one there are shown the subtracted spectra ("+"-"0"), ("-"-"0").

At present, measurements at the LEPT and LEPV polarimeters are produced in pauses between deuteron acceleration sessions in the main ring because the polarimeter detector box is placed at the LINAC-main-ring ionoguide. Installation of a switching magnet and doubling LINAC bursts will make continuous monitoring of deuteron beam polarization possible.

2. Two arm high energy polarimeter ALPHA with momentum selection of dp-elastic scattering events [5]. This measures vector and tensor polarization of accelerated deuteron beam. The polarimeter operates with the 10 cm hydrogen target. Measurements are produced periodically at the fixed deuteron momentum of 3 GeV/c where the vector and tensor analyzing powers were precisionally studied at the SATURN accelerator: $A_y = 0.0338 \pm 0.004$, $A_{yy} = 0.598 \pm 0.016$.

The polarimeter setup is schematically shown in Fig.4. The elastically scattered forward-deuterons are selected in coincidences with the recoil-protons according to the kinematical constraint $d + p \rightarrow d(7.5^\circ) + p_{recoil}(72^\circ)$. Polarimeter azimuth angular acceptance corresponds to the transverse momentum of $t = -0.150 \pm 0.017(GeV/c)^2$. According to the precise Saclay data [6] for dp-elastic at $P_d=3.0 GeV/c$ the vector and tensor analyzing powers at selected t are equal to $A_y = 0.338 \pm 0.004$ and $A_{yy} = 0.598 \pm 0.016$.

The ALPHA-polarimeter is the most precise tool to control the p_z and p_{zz} of extracted deuteron beam. Disadvantages of its using are due to a) a requirement to adjust an extracted beam at fixed momentum, b) a necessity to recollect magnetic arms at run with experimental setups located downstream the polarimeter, c) an arbitrary long time to obtain p_z, p_{zz} with a small uncertainty (it takes about 3h to have $\Delta p_z^{stat} = 2\%$ at extracted

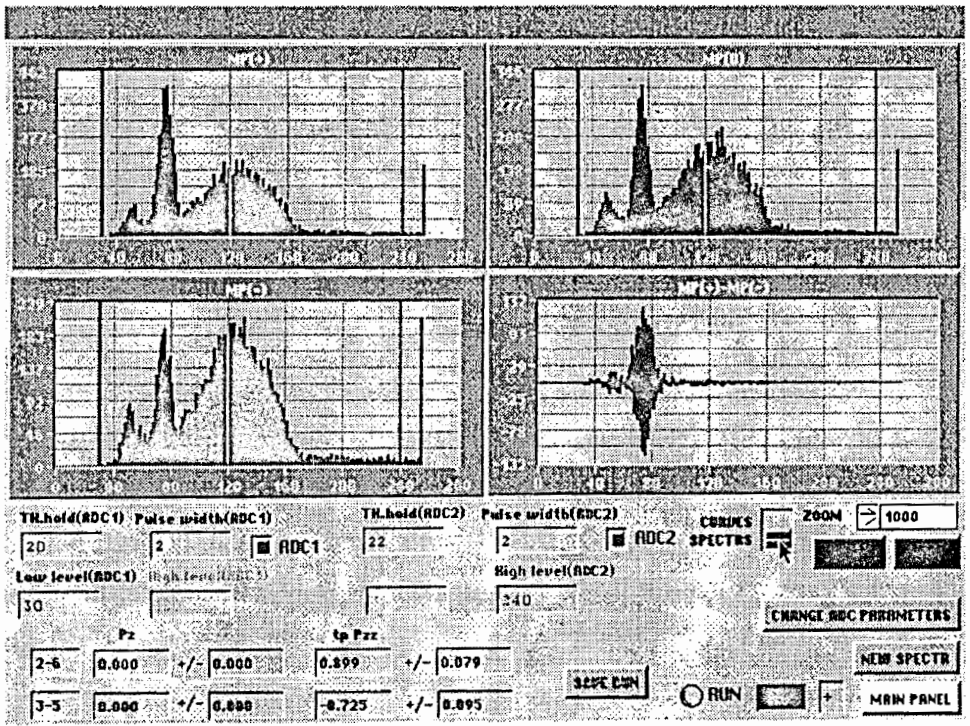


Figure 3. Amplitude spectra of the proton and monitor detectors of LEPT-polarimeter sorted according to the sign of tensor polarization (+, -, 0) are on display screen (laid on in different colors)

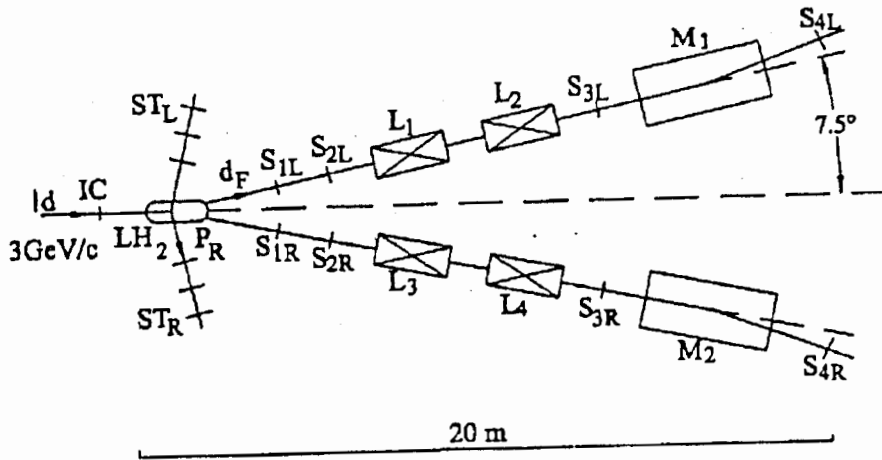


Figure 4. A schematic view of the two-arm ALPHA-polarimeter with momentum selection of dp -elastic scattering events at $|t|=0.15(\text{GeV}/c)^2$.

LH₂ is a liquid hydrogen target (0.7-2 g/cm²); IC is a ionization chamber beam monitor; ST_{L,R} are recoil proton telescopes; S_{iL}, S_{iR} are scintillation counters of forward left-right spectrometers; M_i, L_i are magnetic dipoles and quadrupoles correspondingly

beam spill of 400ms). The ALPHA-polarimeters is usually used for p_z, p_{zz} measurements at the beginning and at the end of data taking run.

3. Two-arm scintillation counter polarimeter with a thin polyethylene target. It is used to continuously monitor vector polarization of extracted deuteron beam [7]. Polarimeters of the type those based on measurement of the asymmetry in the quasi-elastic pp -scattering on hydrogen in polyethylene, are widely used in many intermediate energy laboratories. The polarimeter's geometry is shown in Fig.5. The vector analyzing power of CH_2 -polarimeter was studied for the fixed arm angles of 14° at $P_d = 3 - 6$ GeV/c and of 8° at $P_d = 6 - 9$ GeV/c. The $A_y(CH_2)$ ranges from 0.466 ± 0.008 at 3 GeV/c to 0.138 ± 0.010 at 9 GeV/c [7]. At tensor polarization of deuteron beam the CH_2 -polarimeter might be used only to watch stability of polarized ion source operation measuring the vector component in the beam.

4. Tensor polarimeter based on using of the deuteron break-up reaction $dA \rightarrow p(0^\circ)X$ measures tensor polarization of the deuteron beam at the fixed ratio of the proton to the deuteron momentum [8]. Experience of study of tensor analyzing power T_{20} in the deuteron break-up at Saclay and Dubna showed the next features of T_{20} -behaviour in $dA \rightarrow p(0^\circ)X$ [8]:

- $|T_{20}|$ reaches its maximum at a ratio of proton to deuteron momenta $P_p/P_d \simeq 2/3$ corresponding to internal momenta about $k=0.3$ GeV/c;
- A -dependence of T_{20} for light nuclei is absent at k up to 0.28 within the error limit and does not exceed 10% at $k \leq 0.33$;
- T_{20} is independent of a deuteron momentum at $2.5 \leq P_d \leq 9.0$ GeV/c and no theoretical reasons for revealing P_d -dependence at higher energies;
- $T_{20}(k)$ is constant at k from 0.23 to 0.33 in the $dC \rightarrow p(0^\circ)X$ reaction the according to the Saclay and Dubna data:
 $T_{20}^{Saclay}(k = .3) = -0.825 \pm .025 \pm 0.025$, $T_{20}^{Dubna}(k = .3) = -0.820 \pm .040 \pm 0.033$;

A tensor polarization of deuteron beam is determined with measurement of proton 0° -yields at different polarization states (n^+, n^-, n^0)

$$p_{zz}^\pm = \frac{2\sqrt{2}}{T_{20}} \left(1 - \frac{n^\pm}{n^0}\right),$$

where $T_{20} = -0.82 \pm .04$ according to Saclay-Dubna data.

The measurement of the tensor component in the deuteron beam can be realized in the simplest way as measurement of count rate in a beam-line focus located downstream a carbon target at beam-line momentum adjusted to momentum of $P_p = 0.65P_d$. A typical arrangement is shown at Fig.5. At the beam-line momentum resolution of 2-3% an admixture of deuterons is about 6% that can be accounted with a corresponding few % correction. At more accurate measurements one can reject deuterons using TOF-technique.

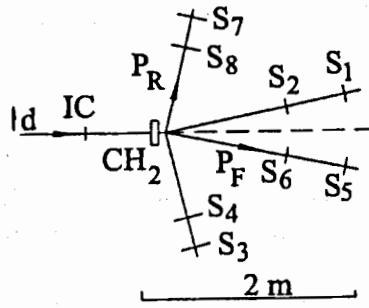


Figure 5. Two-arm scintillation counter polarimeter with a thin polyethylene target (CH_2 , 0.5 g/cm^2) based on measurement of the left-right asymmetry in the quasi-elastic pp-scattering on hydrogen in polyethylene

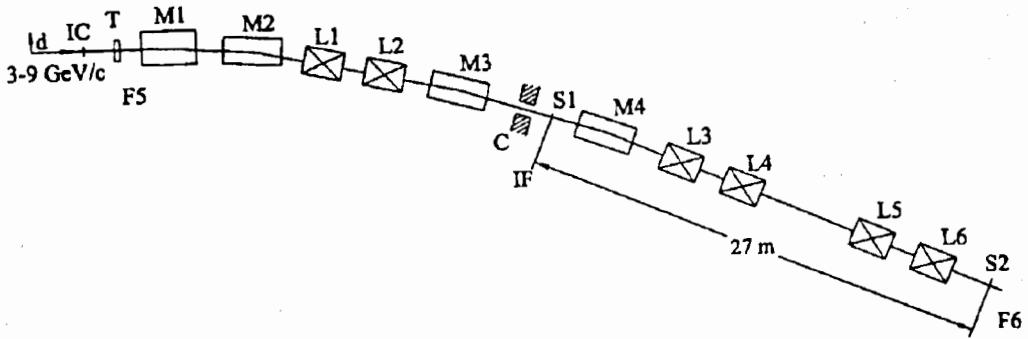


Figure 6. Setup of the 4V beam-line polarimeter to measure tensor polarization of high energy deuteron beam by means of measuring the difference of stripping proton yields at 0° in the deuteron breakup on carbon target at fixed ratio $P_p/P_d=0.65$. T is a C(Be)-target (up to 30 g/cm^2); IC is an ionization chamber beam monitor; C is a collimator in an intermediate focus IF; S1,S2 are scintillation counters for TOF-selection of stripping protons, M_i, L_i are magnetic dipoles(M) and quadrupoles(L)

The yield of stripping protons is rather high: $\frac{d\sigma}{dpd\Omega}(dC \rightarrow pX) \simeq 300\text{mb}/(\text{GeV}/c \text{ sr})$ at $P_d = 9, P_p = 6 \text{ GeV}/c$ (so it allowed us to reach $\delta_{stat} \simeq 3\%$ at 10-min run using the beam line 4V arrangement, Fig.5). The yield grows as P_d^2 at increasing the deuteron energy. This method of polarization monitoring was first applied at the 1997 run with tensor polarized beam, the p_{zz} -measurements were repeated 24 times during 5-days and, as results, a long time stability of the polarized ion source POLARIS operation was confirmed [9].

In conclusion:

Considering an arbitrary simplicity of realization, a high counting rate and an analyzing power energy independence, one can recommend using the deuteron breakup reaction as an effective express method to monitor the tensor polarization of deuteron beams at several GeV and higher energies.

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Charge Exchange Processes on the Deuteron

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Abstract

An estimate of the spin dependent part of the $np \rightarrow pn$ exchange amplitude has been made on the basis of the $dp \rightarrow (pp)n$ data, taken by the 1m hydrogen bubble chamber in a full solid angle arrangement. At the momentum of 1.67 GeV/c per nucleon, as it has been shown, the $np \rightarrow pn$ amplitude is entirely spin dependent. This result opens new possibilities for the experiments in polarized deuteron beams and polarized proton target.

An experiment is proposed to study the spin dependent part of the nucleon scattering amplitude in the charge exchange process at the Nuclotron deuteron beams. The two-proton production cross section at small momentum transfers is intended to investigate in the range of the deuteron momentum from 3.0 GeV/c to 4.0 GeV/c. The experimental arrangement, the event selection methods and first test of STRELA setup on the NUCLOTRON are briefly reported.

1. INTRODUCTION

The task to build up the theory of the nucleon-nucleon scattering, specially for the region above 1 GeV, remains still actual. To have a complete sample of data what enables to carry out such

informations as e.g. the phase analysis, experiments with double and triple scatterings are necessary. However, for investigation of the spin-flip contribution into the $np \rightarrow pn$ charge exchange, the deuteron interacting with proton can be used, where the neutron is in a defined spin-orbital state.

During the charge exchange process (the $dp \rightarrow (pp)n$ reaction) of the deuteron breakup reaction, one of the two protons produced in a symmetrical spatial state has to change its spin state due to Pauli exclusive principle. So, the spin dependence of the elementary $np \rightarrow pn$ charge exchange amplitude can be connected with the differential cross section at $t=0$. In this way the experiments in the deuteron beams can replace those with triple scatterings and enlarge the efficiency.

Application of the above method to polarized deuteron beams can be used for proton tagging. Protons in aligned spin states allow to carry out experiments with polarized proton targets on a much higher level.

2. EXPERIMENT

The experimental data have been taken by the JINR 1m hydrogen bubble chamber [1] in a full solid angle geometry, at a deuteron momentum of 3.35 GeV/c. The use of nuclear beams impinging on a fixed proton target makes all the fragments of the incoming nuclei fast in the laboratory frame and, thus, they can be detected, well measured and identified practically without losses. On the other hand, almost all the losses due to the chamber threshold momenta are concentrated in the elastic channel. These conditions allow to study the reactions containing not more than one neutral particle in an exclusive approachs.

The $dp \rightarrow ppn$ reaction can be divided into two channels:

1. the charge retention channel, where the proton is the fastest secondary particle with respect to the deuteron rest frame and
2. the charge exchange channel, where the neutron is the fastest secondary particle with respect to the deuteron rest frame.

The separation of these two channels is illustrated in Fig. 1, showing the distribution of the four momentum transfer squared t , between the impinging proton and the secondary neutron. Quantity defined in such a way does not depend on the final proton state, whether it is a spectator or it participates in the reaction (indifferent to the proton interferency).

The first attempt to determine the contribution of the spin dependent amplitude of the $np \rightarrow pn$ elementary charge exchange from the differential cross section of the $dp \rightarrow (pp)n$ reaction [2], using the available pp and np scattering data, was carried out in the initial stage of the experiment on a relatively small part of the processed events. The data obtained as well as the estimate were ambiguous because of the poor statistics. Nevertheless the enhanced role of the spin flip amplitude in the $np \rightarrow pn$ charge exchange has been shown.

We returned to this problem on the final statistics of over 10^5 events of the $dp \rightarrow ppn$ reaction for two reasons:

1. To estimate the $dp \rightarrow (pp)n$ differential cross section at $t=0$ for the further use of the Dean formalism [3].
2. To predict the capabilities and limitations of a prepared counter experiment [4].

3. RESULTS AND DISCUSSION

The possibility to use the charge exchange reaction on the unpolarized deuteron for determining the spin dependent part of the $np \rightarrow pn$ charge exchange has been proposed by A.B. Migdal [6] and I.Y. Pomeranchuk [5]. The effect can be qualitatively understood in the following way. The nucleons bound in the deuteron may be in $^3S_1$ and $^3D_1$ ($T=0$) spatial and spin symmetric states but their charge states should be antisymmetric. In the charge exchange process a charge symmetric state of two protons is produced and to fulfill the Pauli principle at a conserved spatial symmetry, the spin flip ($^1S_0$ or $^1D_2$ states of the two final protons) of the scattered nucleon ensures the asymmetric total wave function. In this way, the spin dependent part of the elementary charge exchange will be reflected through the probability of the charge exchange on the deuteron.

The mathematical formalism within the impuls approximation was developed by Dean [3] and others. The general formula for the differential cross section of the $dp \rightarrow (pp)n$ looks like:

$$\left(\frac{d\sigma}{dt}\right)(pd \rightarrow n(pp)) = [1 - F_d] \left(\frac{d\sigma_{nf}}{dt}\right) + [1 - \frac{1}{3}F_d] \left(\frac{d\sigma_f}{dt}\right), \quad (1)$$

where F_d stands for the deuteron form factor, $\frac{d\sigma_{nf}}{dt}$ and $\frac{d\sigma_f}{dt}$ are non-spin flip and spin flip parts, respectively, of the $np \rightarrow pn$ differential cross section. At zero transfers ($|t| \sim 0$), when $F_d=1$ the expression (1) simplifies to:

$$\frac{d\sigma}{dt}(pd \rightarrow n(pp)) = \frac{2}{3} \frac{d\sigma_f}{dt}(np \rightarrow pn). \quad (2)$$

The last formula is applicable if at least two conditions are fulfilled:

1. the momentum transfer of the quasielastic np scattering is small,
2. the intrinsic momenta q of the nucleons in the deuteron are small.

The second condition means S-wave dominance in the deuteron wave function. It can be seen, e.g. in Fig 2, where the S wave probability distribution is shown as a function of the nucleons intrinsic momenta. In the region below $p=0.07$ GeV/c this probability practically does not depend on the nucleon intrinsic momenta.

Both the above mentioned conditions can be fulfilled simultaneously, if one selects events in the laboratory frame (fast deuteron impings on the proton target) containing two fast protons at small production angle, with momenta close to the half of the deuteron's one. We would like to emphasize, that this task can be realized successfully in the beams of accelerated deuterons. In the case of a deuteron target the two protons are too slow to be detected and the reaction cannot be identified.

To answer the question of the spin flip contribution of the $np \rightarrow pn$ process as it follows from expression (2), it is necessary to turn to the experimental data on $np \rightarrow pn$ charge exchange differential cross section at $t=0$. Such data have been obtained at Brookhaven [7] for the region of 1-8 GeV and could be reasonably approximated by the function $1/p^2$, where p is the momentum of the incoming neutron. The data imply $\frac{d\sigma}{dt}(0)=(36,9 \pm 3,0) (GeV/c)^2$ at 1.67 GeV/c. The task now is to compare the differential cross section of the exchange on the deuteron, obtained in our experiment at $t=0$ with those for the $np \rightarrow pn$ at the corresponding beam energy.

For a reasonable approximation of $d\sigma/dt$ to $t=0$, it is inevitable to select a region of production angles, excluding the high momentum tails of the nucleon intrinsic motion and also the region of momentum transfers, where other more complicated mechanisms than the quasielastic scattering come into play. The differential cross sections for four different values of the two selected protons production angles are illustrated in Fig. 3. The shape of the distribution at small $|t|$ does not change with the increase of the production angle while the contribution of higher $|t|$ increases.

A typical value of the production angle is $\Theta = \arctg(p_f/p_0) = 1.6^\circ$, where the experimental and theoretical maxima ($p_f=50$ MeV/c) of the Fermi momentum distribution of the nucleons in the deuteron state as a measure of transverse momentum and the longitudinal momentum per nucleon in the laboratory frame is $p_0=1.67$ GeV/c. It leads to the result that the optimal value for the opening angle of a cone within the two protons are produced is around 3° .

In this connection we remind the used definitions: the slowest proton in the deuteron rest frame is referred to as a spectator; the other is the scattered one. If no cuts are imposed on the production angles of protons, their momentum distributions essentially differ as it is shown in Fig. 4. The spectator proton momentum distribution (full line) is of a shape, typical for the Fermi momentum distribution of the nucleon in the deuteron. When the above mentioned cut of 3° is applied to the spectator and scattered proton production angles, their momenta distributions, as one can see in Fig. 5, overlap. Their angular distributions are shown in Fig. 6. The quantity t is indifferent to the two proton interferency, as it has already been mentioned.

The differential cross sections for small values of $|t|$ are displayed in Fig. 7 together with the curves, corresponding to a fit of $\frac{d\sigma}{dt} = ae^{bt}$ to the data. The fit gives the following results: $a = 19,0 \pm 1,1$ ($\chi^2/ND = 4,3/8$) for the interval of $|t| = \{0, 0 - 0,02\}$ and $a = 23,1^{+3,6}_{-3,1}$ ($\chi^2/ND = 1,0/2$) for the interval $|t| = \{0, 0 - 0,004\}$. Fig. 8 demonstrates the differential cross section at $t=0$ as a function of the cut, imposed on the proton production angles. It can be seen, that around $\theta = 3^\circ$ the quantity $\frac{d\sigma}{dt}(0)$ reaches the level of $\frac{2}{3} \frac{d\sigma}{dt}(0)$ of the elementary $np \rightarrow pn$ process. For the value of $\theta = 3^\circ$ we get the contribution of the spin flip part to the elementary $np \rightarrow pn$ of 0.94 ± 0.15 . The obtained contribution of course depends on the unknown systematical errors of the differential cross section of the elementary $np \rightarrow pn$ charge exchange. In any case the contribution obtained is large enough and does not exclude the full spin flip in the $np \rightarrow pn$ process. It means, that in the beams of vector polarized deuterons one can get an additional possibility to use the studied reaction for more sophisticated purposes, e.g. to explain the interference mechanism in the two protons system. The spectator and the scattered protons are then tagged, because the first one conserves the beam polarization and the latter (scattered) is then polarized oppositely.

4. The new STRELA setup

The geometry, detectors and the background were estimated using: 1) Monte Carlo simulations of the reaction, 2) real events from 17 different channels of dp interactions. The following parameters were used as inputs to the model: the spot of the deuteron beam at the target - 1 cm; the beam momentum - 3.5 GeV/c; the thickness of the liquid hydrogen target - 10 cm; the length of the magnet - 1m and the magnetic field fixing at 1 T; the distances from the target to the magnet 1m and to the first detector 7 m; the transverse size of the detector 5 cm; the Gartenhaus-Moravcsik deuteron wave function and the experimental slopes of the Nd and NN elastic scattering.

These parameters can be optimized according to the geometrical requirements of the setup. The experimental and Monte Carlo estimations of the background from the one-proton events of the reaction, i.e. from the charge retention deuteron breakup, gave approximately the same results. It is expected not more than 400 one-proton events per one two-proton event, when the aperture of the event selection is 0.5° . The effect-background ratio improves by increasing this angle.

In the case of one-proton events, the detected protons are spectators and they can give a good basis for the cross section normalization.

Thus, two protons, each with half of the deuteron beam momentum, must be detected. This ensures that events at 0° with respect to the beam direction with small relative momentum of the nucleon internal motion in the deuteron and small transferred momentum to the scattered neutron are selected. Therefore the minimal necessary conditions for the detection of the proposed effect are possible to realize. On the first stage the experimental scheme, shown in Fig. 9, is proposed. The slow extraction deuteron beam is incident on a 10-cm liquid hydrogen target LH2 and the analyzing magnet D separates the primary deuterons and secondary particles. The ionization chamber IC measures a flux of the deuteron beam. The scintillator monitors T1-T3 and M1-M2 control the intensity and position of the beam. The scintillator counters S1-S4 with diameters of 48 mm determine the angular and momentum acceptances (10%) and trigger the event. The Cherenkov counters C1-C3 with polystyrol radiators of the size $50 \times 50 \times 16 \text{ mm}^3$ select the two-proton events. The expected resolution about 10% allows to separate reliably the two and one-proton events. The Cherenkov counter C4 with a quartz radiator serves for pion suppression. The signal amplitudes from all counters are recorded for all the trigger events. To make the event selection more efficient, the possibility to include the signal amplitude from one of the Cherenkov counters in the trigger logic is foreseen.

5. Proposed data points, rates and first test of STRELA setup

With 510^{-2} msr angular acceptance and a momentum acceptance of 5% of the setup the proposed data points (2000 two proton events per energy) at the deuteron intensity of 10^7 per spill are given in the Table below. Each data point requires tuning of the Nuclotron and the additional time to check detectors and conditions of beam parameters, neither of them is included in to the time shown in the last coloumn of the table.

N	Td (GeV)	Deuteron momentum (GeV/c)	One proton event	Two proton events	Time (min)
1	1.41	2.7	3100	8	50
2	1.49	2.8	3100	8	50
3	1.58	2.9	3100	8	50
4	1.66	3.0	3200	9	50
5	1.75	3.1	3200	9	50
6	1.83	3.2	3300	10	40
7	1.92	3.3	3400	10	40
8	2.00	3.4	3600	10	40
9	2.09	3.5	3800	11	40
10	2.18	3.6	4200	11	40
11	2.27	3.7	4400	12	40
12	2.36	3.8	4800	13	30
13	2.45	3.9	5100	14	30
14	2.54	4.0	5400	15	30

In March,2000 the first run of STRELA setup on the extraction beam of NUCLOTRON has passed. The key possibility of adjustment of a telescope on a maximal stripping (Fig.10) and selections of two-proton events was shown (Fig.11).

6. CONCLUSION

The study of the $dp \rightarrow (pp)n$ reaction in full solid angle conditions has shown, that the amplitude of the elementary $np \rightarrow pn$ charge exchange is fully spin dependent. The obtained result gives new possibilities for experiments in polarized deuteron beams and polarized proton target.

The first run of new experimental setup STRELA has been performed and the key possibility of obtaining new information about spin dependent amplitude $np \rightarrow pn$ reaction in a wide range of energies has been shown.

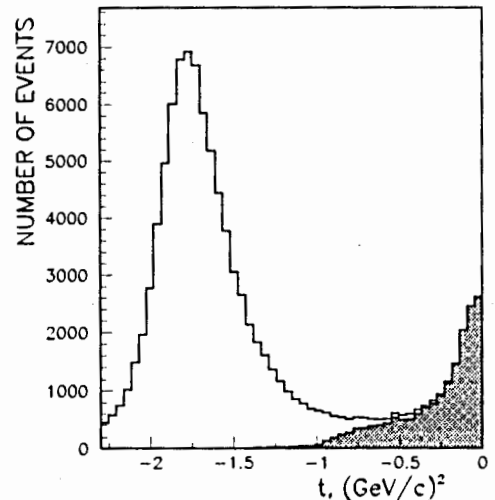


Fig.1.Distribution of four momentum transfer squared from the target proton to neutron for the $dp \rightarrow ppn$ events

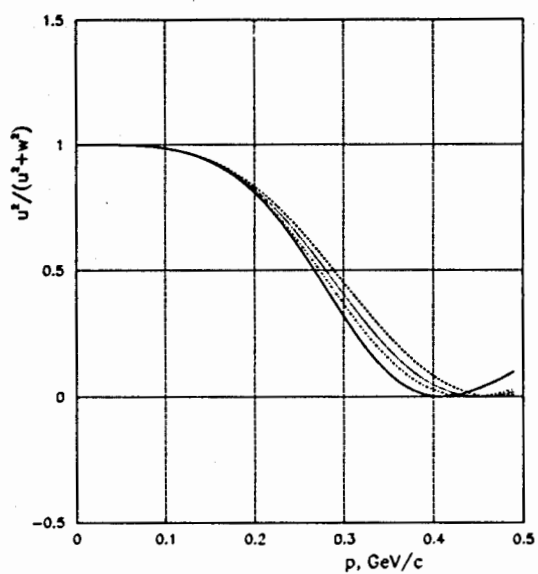


Fig.2. The S wave probability as a function of the nucleon Fermi momentum

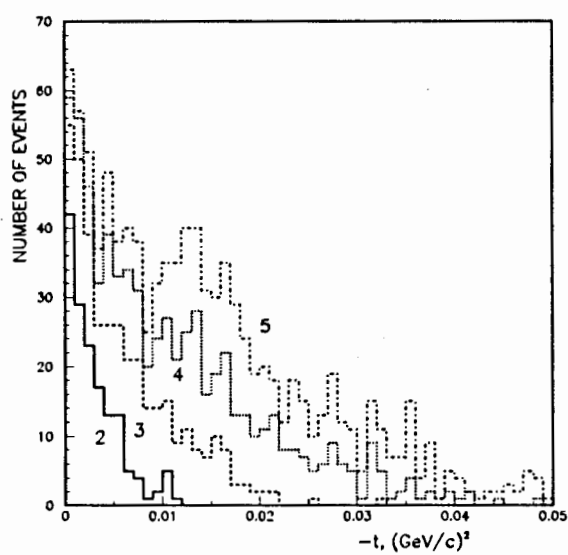


Fig.3. Distribution of $|t|$ for the charge exchange channel with the production angles of both protons below 2,3,4 and 5 degrees

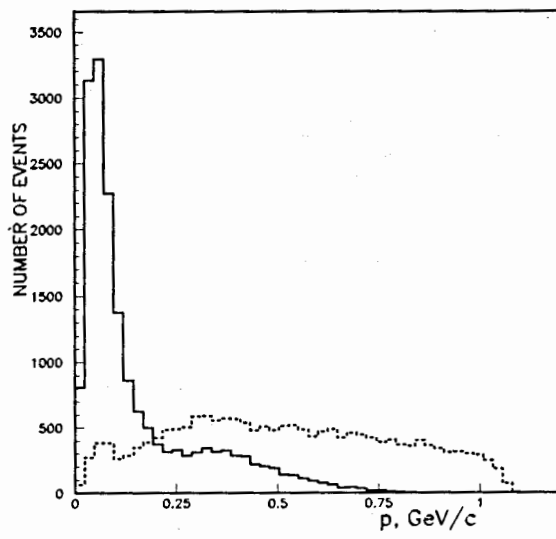


Fig.4. Momentum distributions of the spectator (full line) and the scattered proton (dashed line) in the deuteron rest frame

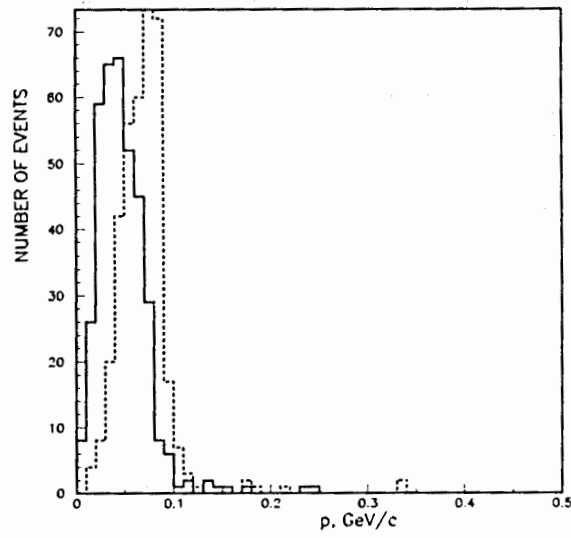


Fig.5. Momentum distributions of the spectator (full line) and the scattered proton (dashed line) in the deuteron rest frame. The proton production angles in the laboratory frame are below 3°

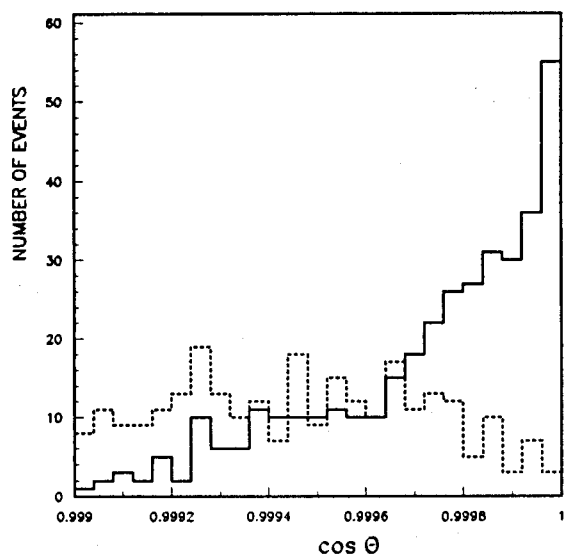


Fig.6 Angular distribution of the spectator proton (full line) and that of the scattered one (dashed line) in the deuteron rest frame, for the case when their production angle in the laboratory frame is in the interval $0-3^\circ$

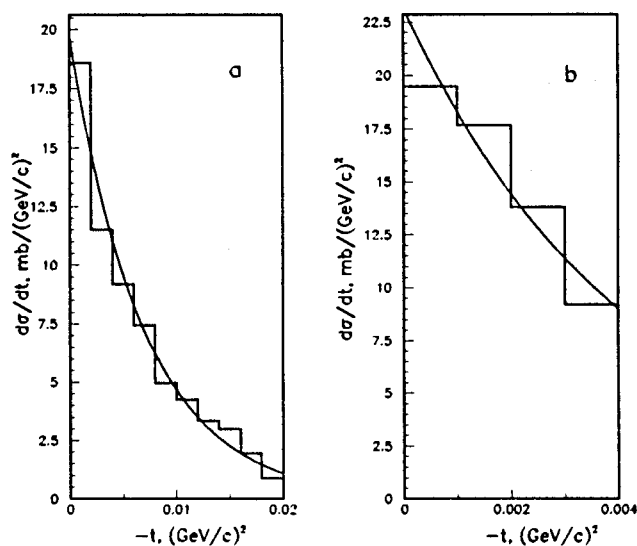


Fig.7. Differential cross section of the charge exchange reaction in the region of small $|t|$. The production angle of both protons in the laboratory frame is in the interval $0-3^\circ$

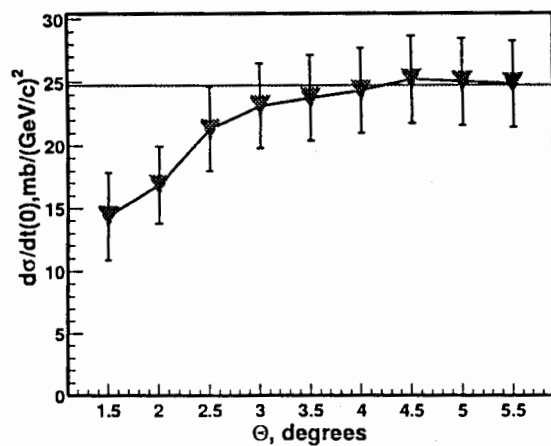


Fig.8. Differential cross section at $t=0$ when both protons are within a cone of opening angle Θ

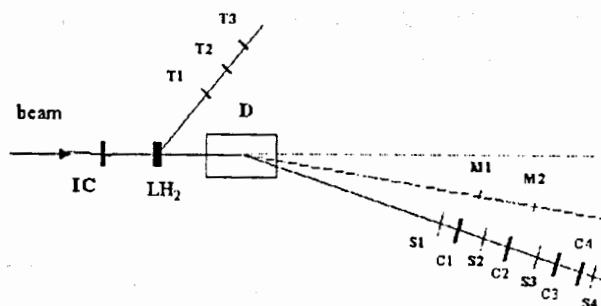


Fig.9. Layout of the experimental setup

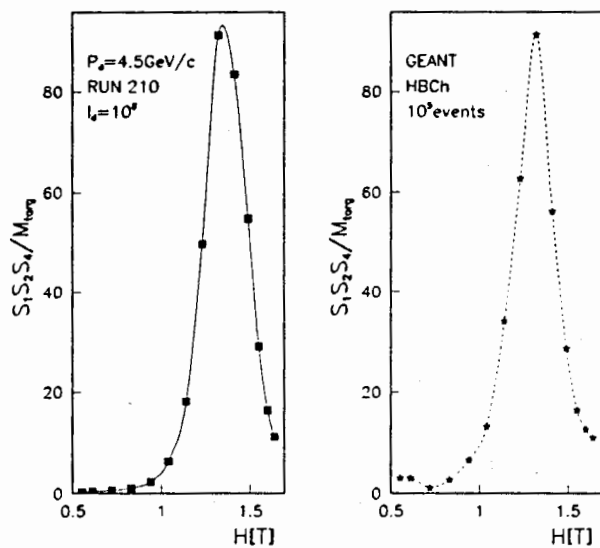


Fig.10. Experimental and Monte Carlo distributions of stripping protons

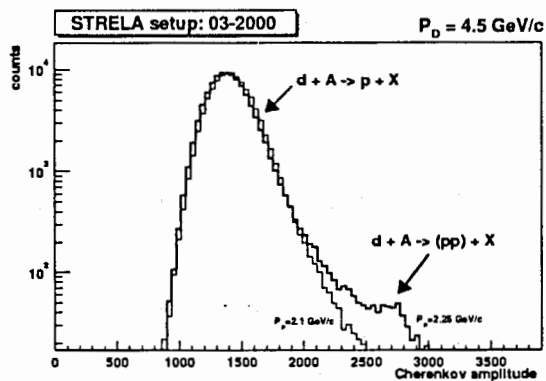


Fig.11. Cherenkov amplitude for one- and two-proton events

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OPERATION OF THE NUCLOTRON REFRIGERATORS WITHOUT USING OF LIQUID NITROGEN

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The calculated data for the refrigerators of superconducting synchrotron Nuclotron [1,2] are presented. The data are obtained for various modes of the simultaneous production of refrigeration and liquid helium. The technique for calculating is based on the joint solution of the heat-transfer equations and the equations for the energy balance of the heat exchangers.

INTRODUCTION

Cryogenic helium refrigerators are designed on the basis of calculations of the corresponding thermodynamic cycle. If it is desired to use the refrigerator in several different modes, then all the versions of the cycle are analysed and the design is worked out using the one which requires the largest heat-transfer surface area of the heat exchangers. A real refrigerator operating cycle can differ significantly from the calculated one, both owing to deviations in the actual parameters of the devices from those used in the calculation, and owing to changes in the operating conditions required by the user. In cooling of superconducting magnet systems, helium refrigerators operate in various combined modes, when helium is liquefied at the same time as refrigeration is produced. The dependence of the refrigerating capacity on the amount of liquid helium simultaneously produced is called refrigerator characteristic. Such characteristics give a clear methodological basis for analysing cryogenic systems consisting of a refrigerator and a cooled object. They can be used, for example, to determine the rate at which liquid is accumulated for a given heat inflow and, consequently, to estimate quantitatively the part of the start-up period which corresponds to the time needed to accumulate a required amount of liquid helium in a cryostat. Characteristics can be also very useful to analyse systems with cooled current leads.

Refrigerator characteristics can be obtained both experimentally and theoretically. Obtaining characteristics theoretically is rather complicated, but necessary for at least two reasons. First, the experimental study of the characteristics of large-scale installations entails a large consumption of electrical energy and other operating expenses. Second, this is the only way of studying those cases where the modes of interest have not yet been realized in practice.

TECHNIQUE OF CALCULATION

The technique for calculating refrigerator modes is based on the joint solution of the heat-transfer equations and the equations for the energy balance of the heat exchangers. For a double-flow heat exchanger (Fig. 2a) a quantity of heat can be written as $Q = W' \delta T' = W'' \delta T''$ and $Q = W \delta T$, where W' is a product of specific heat and mass flow rate between points 1-2, W'' is the same for the return flow, $\delta T' = T_1 - T_2$, $\delta T'' = T_4 - T_3$, and $\delta T = T_1 - T_3$ is the greatest temperature difference in the heat exchanger. If specific heat of the flows does not change the value of W can be given by:

$$W = [\exp(kF/W') - \exp(kF/W'')]/\{[\exp(kF/W')]/W' - [\exp(kF/W'')]/W''\},$$

where k is a heat transfer coefficient, and F is a surface area of the heat exchanger.

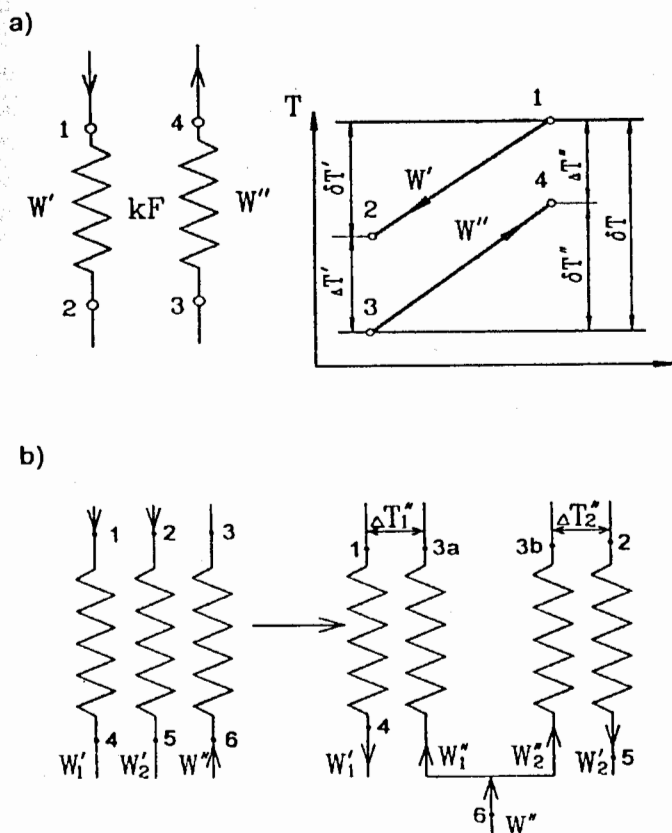


Figure 1. Calculating of heat-exchangers: a – double-flow heat exchanger, b – triple-flow heat exchanger

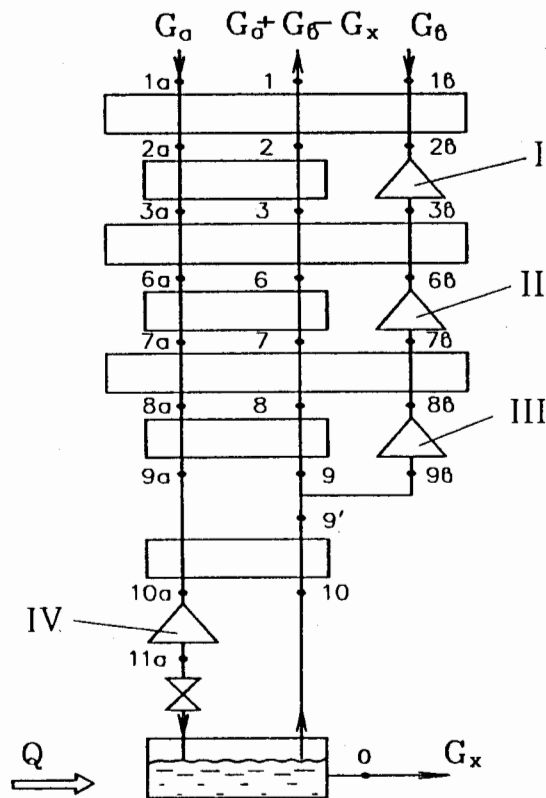


Figure 2. Flow diagram of the KGU-1600/4.5 refrigerator

Having as the initial data temperature in two any points (inlet or outlet) of heat exchanger, the temperatures in two of the rest points can be easily calculated. So, if the temperature in points 1 and 2 is given, it is possible to write down: $Q = W'(T_1 - T_2) = W''(T_4 - T_3) = W(T_1 - T_3)$, from where the temperatures in points 3 and 4 are $T_3 = T_1 - (T_1 - T_2) W'/W$, $T_4 = T_3 + (T_1 - T_2) W'/W''$. In case of triple-flow heat exchanger the system can be analysed as two double-flow devices (Fig. 2b). The parts of the return flow are calculated by the iteration method from the condition $T_{3a} = T_{3b}$.

For the scheme Fig. 2 having as the initial data temperatures T_{1a} , T_{1b} , T_{2b} , T_{6b} , T_{8b} , T_{10} , the temperatures T_1 , T_2 , T_{2a} , T_3 , T_{3a} , T_{3b} , T_6 , T_{6a} , T_7 , T_{7a} , T_{7b} , T_8 , T_{8a} , T_{9a} , $T_{9'}$, T_{10a} are calculated sequentially. The value of G_a and G_b for the given G_x must be obtained by the iteration method from the condition $i_{9'}(G_a - G_x) + i_{9b}G_b = i_9(G_a + G_b - G_x)$, where $i_{9'}$, i_{9b} , and i_9 are enthalpies at the specified points. Expansion ratio of turbines I and II are calculated by the equations for energy balance. It is necessary to execute the forecited calculations several times (usually 7-9) and precise after each one specific heat, mass flow rate, heat transfer coefficient, pressure loss of the heat exchangers. The heat exchanger of the final stage of the refrigerator is divided into smaller parts due to the sharp changing of specific heat.

RESULTS OF CALCULATION

Below, we present the calculated data for the KGU-1600/4.5 refrigerator [3] in modes without liquid nitrogen at various points of the characteristic, obtained with the goal of finding the most rational design of the turbo-expanders. The computational scheme is shown in Fig. 2. As the initial data we used the values of the surface area of the KGU-1600/4.5 heat exchangers. To a first approximation, the heat transfer coefficients and the pressure losses of the heat exchanges were taken as for the basic mode of the KGU-1600/4.5. The refrigerator is designed to produce simultaneously 1850 W of refrigeration and 50 l/h

of liquid helium in that mode. The flow rate of compressed helium was taken to be 0.17 kg/sec, the pressure after the compressors - 2.5 MPa, and the adiabatic efficiency of all the expanders - 0.65.

If we use the notation G_k for the amount of compressed helium supplied by the compressor, G_x - for the amount of liquid helium extracted from the cycle, Q_R - for refrigerating capacity, $q=Q_R/G_k$ - for the specific refrigerating capacity, and $x=G_x/G_k$ - for the coefficient of liquefaction, the optimization of the parameters reduces to determining the maximum of function of three variables for the given value of x : $q=f(T_{2b}, T_{6b}, T_{8b})$, where T_{2b} , T_{6b} , and T_{8b} are temperatures of the compressed helium at the inflow to the gas-expansion turbines I, II, and III.

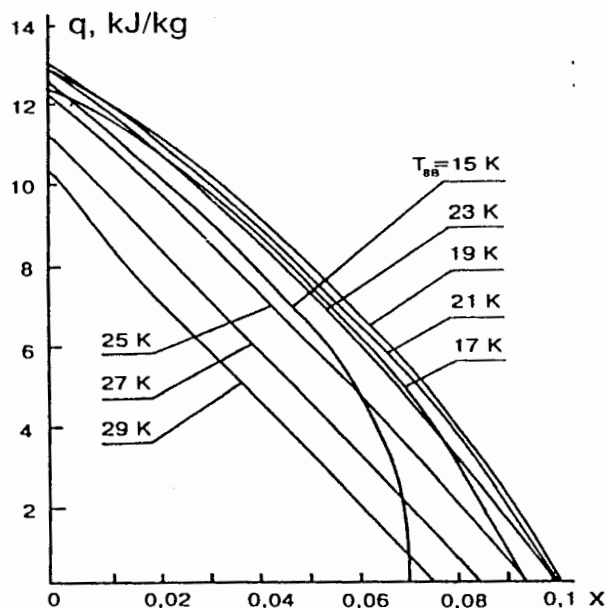


Figure 3. Calculated characteristics of the KGU-1600/4.5 refrigerator for various values of the temperature T_{8b} before gas-expansion turbine III and the use wet expander IV. The optimal values of the temperatures are $T_{6b} = 50$ K and $T_{2b} = 140$ K

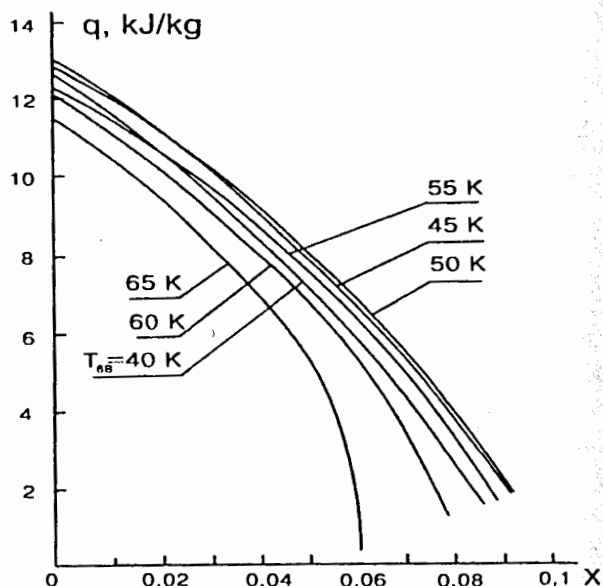


Figure 4. Calculated characteristics of the KGU-1600/4.5 refrigerator for various values of the temperature T_{6b} before gas-expansion turbine II and the use wet expander IV. The optimal values of the temperatures are $T_{8b} = 19$ K and $T_{2b} = 140$ K

The results of the optimisation for the case of using a wet expander are shown in Figs. 3-4. We see that for the relatively low efficiency, which we have used for the gas-expansion turbines, efficient operation can be achieved at all the points of the characteristic. In the purely refrigerator mode at the maximum value $q=12.8$ kJ/kg the refrigerating capacity of the KGU-1600/4.5 is $Q_R = qG_k = 12.8 \times 0.17 = 2.18$ kW. The maximum value $x=0.10$ corresponds to the capacity in the liquefaction mode equal to $G_x = xG_k = 0.1 \times 0.17 = 0.017$ kg/sec = 490 l/h. Here the efficiency of the device is fairly high. The actual costs of obtaining refrigeration and liquid helium are 306 W/W at 4.5 K and 1.36 kW×h per litre of liquid (for isothermal efficiency of the compressor equal to 50%, in case of a screw machine).

It follows from these results that the temperatures at which the gas-expansion turbine should operate to ensure the optimal characteristic are 140, 50, and 19 K. They are practically independent of the value of x , i.e., they are nearly identical both for the pure refrigerator mode and for the liquefaction one. Near the optimal point the function $q = f(T_{2b}, T_{6b}, T_{8b})$ is fairly flat, and it can be quite possible to obtain high efficiency with no better than 10% accuracy of a temperature distribution: $T_{2b} = 140 \pm 20$ K, $T_{6b} = 50 \pm 5$ K, and $T_{8b} = 19 \pm 2$ K. The optimal values of temperature T_{2b} , T_{6b} , and T_{8b} determined for the case where a wet expander is used remain practically unchanged even when J-T valve is used at the final cooling stage (Fig. 5). This suggests that these values can be recommended independently not only of the amount x , but also of the efficiency of the wet expander. For using of J-T valve in the final cooling stage, the maximum refrigerating capacity is only $q = 5.6$ kJ/kg, and the liquefaction coefficient is $x = 0.08$.

Since turboexpanders cannot be regulated, operation at each point of the characteristics given above requires its own set of three gas-expansion devices. The rate of flow through a turbine is roughly determined by the geometry of the flow part of the machine and the parameters at the inflow: the pressure

and temperature. Approximate dependencies for the flow rate as a function of the pressure and temperature at the inflow are given in [4]. The dash lines in Fig. 6 show the results of the calculations taking into account these constraints. We see that to the left and right of the maxima the efficiency of the system is sharply reduced. Thus as x changed, the optimal parting of compressed gas G_b/G_a (Fig.2) changes, and this optimal parting cannot be ensured, since the turbines cannot be regulated. Therefore, the device parameters rapidly deviate from the optimal values.

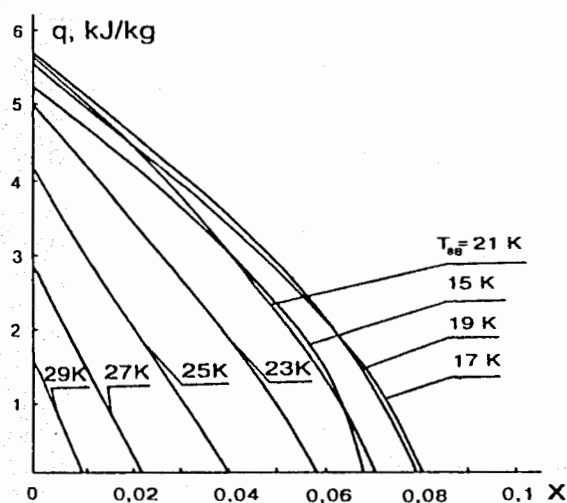


Figure 5. Calculated characteristics of the KGU- 1600/4.5 refrigerator for various values of the temperature T_{0b} before gas-expansion turbine III and the use J-T valve instead of wet expander IV. The optimal values of the temperatures are $T_{0a} = 50$ K and $T_{2b} = 140$ K

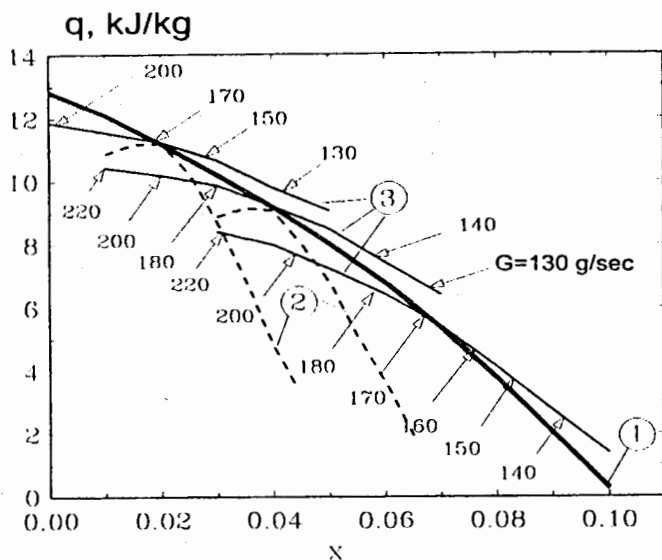


Figure 6. Comparison of the optimal characteristic (1) of the KGU-1600/4.5 with the characteristics for given sets of gas-expansion turbines at constant (2) and variable (3) flow rate of compressed helium

The efficiency of the refrigerator operating with a single set of gas-expansion turbines can be raised over a fairly large segment of the characteristic by changing the amount of gaseous helium input to the system from the compressors. This version is shown by curves 3 in Fig. 6. On the middle curve at $x = 0.01$ the amount of compressed gas is 0.22 kg/sec, while for $x = 0.07$ it is reduced to 0.13 kg/sec. This method of obtaining the optimal characteristic was first demonstrated in the experiment using a similar refrigerator of smaller scale [5]. In the cryogenic system of the Nuclotron it can be used fairly simply, because the system contains as a reserve seven relatively small piston compressors, which allow changing of the total amount of compressed gas easily and efficiently.

SUMMARY

Keynotes of the computer simulation of helium refrigerators have been presented. This kind of simulation enables to escape the experimental study, which in case of large-scale installations entails a large consumption of electrical energy and other operating expenses. The calculation results for the KGU-1600/4.5 refrigerators have been discussed.

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Structure of Exotic Oxygen Isotopes in the Relativistic Mean-Field Theory

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Abstract

We have calculated ground-state properties of oxygen isotopes in the framework of the relativistic mean-field approach. The binding energy, two neutron separation energy, energy levels, root-mean-square radius and density distribution have been calculated for even-even isotopes from ^{12}O to ^{28}O . The model still predicts the particle stability of heavy isotopes ^{26}O and ^{28}O , systematical decreasing of spin-orbit splitting and great extension of density distribution for nuclei far from the stability line.

1. Introduction

Great progress in experimental technique, especially in accelerator technology has opened a new exciting area in nuclear physics. In the past years many experiments using radioactive nuclear beams have provided new information on structure of nuclei far from the stability line.

These exotic nuclei have many unusual properties. The well known phenomenon is a developing of structure with a dilute density distribution, extended very far away from the nuclear core as a consequence of extremely small separation energy of the last nucleon or several nucleons. Such structures are referred as nuclear halo in light nuclei and nuclear skin in heavier

nuclei. In addition, the existence of nuclear skin should lead to new collective vibration modes in these nuclei. The shell structure of some exotic nuclei is characterized by decreasing of spin-orbit splitting leading to more equable distribution of energy levels without big energy gaps between nuclear shells. This phenomenon is referred as shell gap melting and it is a consequence of modification in nuclear density distribution and increasing importance of the pairing effects [1, 2].

Unusual structure of exotic nuclei represent a great challenge for testing nuclear many-body theories. In recent years the relativistic mean-field theory (RMF) have been very frequently used for these calculations with great success [3, 4, 5, 6, 7]. The RMF is a relativistic quantum field theory, based on hadronic degrees of freedom. It describes nucleons as relativistic particles interacting through meson exchange [8, 9, 10]. The RMF is as successful as very complicated nonrelativistic many body theories in describing bulk and single-particle properties of nuclei from the lightest to superheavy elements.

Oxygen isotopes far from stability line represent very interesting area, because many mass formulas and nuclear shell model calculations assume stability of very heavy isotopes ^{26}O and ^{28}O contrary to experimental results [11, 12, 13]. We can consider that oxygen isotopes are unable to minimize their energy by adopting strong deformation as done very heavy isotopes in neighbourhood ^{25}N and ^{31}F [13]. Heavy oxygen isotopes are also good candidates for existence of the neutron halo structure [14, 15, 16].

2. The Relativistic Mean-Field Theory

The starting point for a relativistic theory is a Lagrangian density which includes nucleon field (ψ), isoscalar-scalar meson field (σ), isoscalar-vector meson field (ω), isovector-vector meson field (ρ) and electromagnetic field (A).

$$\begin{aligned} \mathcal{L} = & \bar{\psi} \left[i\gamma_{\mu} \partial^{\mu} - M + g_{\sigma} \sigma - g_{\omega} \gamma_{\mu} \omega^{\mu} - g_{\rho} \gamma_{\mu} \vec{\rho}^{\mu} \cdot \vec{\tau} - e\gamma_{\mu} \frac{(1 - \tau_3)}{2} A^{\mu} \right] \psi + \\ & + \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - m_{\sigma}^2 \sigma^2 - \frac{1}{3} b_{\sigma} \sigma^3 - \frac{1}{4} c_{\sigma} \sigma^4 - \frac{1}{4} O^{\mu\nu} O_{\mu\nu} + \frac{1}{2} m_{\omega}^2 \omega_{\mu} \omega^{\mu} + \\ & + \frac{1}{4} c_{\omega} (\omega_{\mu} \omega^{\mu})^2 - \frac{1}{4} \vec{R}_{\mu\nu} \vec{R}^{\mu\nu} + \frac{1}{2} m_{\rho}^2 \vec{\rho}_{\mu} \vec{\rho}^{\mu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad (1) \end{aligned}$$

The first line describes free nucleon field and nucleon-mesons interactions. The g_σ , g_ω , g_ρ and M are nucleon-meson coupling constants and nucleon mass. Next two lines describe σ -meson, ω -meson, ρ -meson and electromagnetic parts of the Lagrangian density. The Lagrangian density also contains cubic and quartic self-interaction terms for σ -meson field and quartic self-interaction term for ω -meson field. The strengths of these couplings are given by constants b_σ , c_σ and c_ω . The arrows denote the isovector quantities and m_σ , m_ω and m_ρ denote meson masses. The field tensors are given by standard expressions

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad O_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \quad \vec{R}_{\mu\nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu. \quad (2)$$

The field equations for this model follow from the Euler-Lagrange equations by a standard way. For a practical application two approximations are necessary. The first is to replace the field operators for meson and electromagnetic fields by their expectation values (the mean-field approximation). The second is exclusion of the filled Dirac sea of negative energy states (no-sea approximation).

The Dirac spinor for positive energy solution in spherical case can be written in standard form

$$\mathcal{U}_{n\kappa mt}(r) = \begin{pmatrix} i \frac{G_\alpha(r)}{r} \Phi_{\kappa m} \\ -\frac{F_\alpha(r)}{r} \Phi_{-\kappa m} \end{pmatrix} \zeta_t, \quad (3)$$

where $\Phi_{\kappa m}$ is a spherical harmonics function, α denotes quantum numbers n, κ, t , where t is the isospin and κ is the Dirac quantum number given by

$$\kappa = \begin{cases} -\left(j - \frac{1}{2}\right) & \text{for } j = l + \frac{1}{2} \\ +\left(j - \frac{1}{2}\right) & \text{for } j = l - \frac{1}{2} \end{cases}. \quad (4)$$

Using this ansatz we obtain two coupled Dirac equations for upper, G_α , and lower, F_α , components of nucleon wave functions

$$\left(\frac{d}{dr} + \frac{\kappa}{r}\right) G_\alpha(r) - [M - U(r) - V(r) + E_\alpha] F_\alpha(r) = 0, \quad (5)$$

$$\left(\frac{d}{dr} + \frac{\kappa}{r}\right) F_\alpha(r) - [M - U(r) + V(r) - E_\alpha] G_\alpha(r) = 0, \quad (6)$$

where $U(r)$ and $V(r)$ denote the scalar and vector potentials given by

$$U(r) = g_\sigma \sigma(r), \quad (7)$$

$$V(r) = g_\omega \omega_0(r) + g_\rho \tau_3 \rho_0^{(3)}(r) + e \frac{(1 - \tau_3)}{2} A_0(r). \quad (8)$$

The meson and electromagnetic fields obey the radial Laplace equations

$$\frac{d^2}{dr^2} \sigma(r) + \frac{2}{r} \frac{d}{dr} \sigma(r) - m_\sigma^2 \sigma(r) = -g_\sigma \rho_S(r) - b_\sigma \sigma^2(r) - c_\sigma \sigma^3(r), \quad (9)$$

$$\frac{d^2}{dr^2} \omega_0(r) + \frac{2}{r} \frac{d}{dr} \omega_0(r) - m_\omega^2 \omega_0(r) = -g_\omega \rho_V(r) - c_\omega \omega_0^3(r), \quad (10)$$

$$\frac{d^2}{dr^2} \rho_0^{(3)}(r) + \frac{2}{r} \frac{d}{dr} \rho_0^{(3)}(r) - m_\rho^2 \rho_0^{(3)}(r) = -g_\rho \rho_I(r), \quad (11)$$

$$\frac{d^2}{dr^2} A_0(r) + \frac{2}{r} \frac{d}{dr} A_0(r) = -e \rho_C(r). \quad (12)$$

The source terms on right hand of foregoing equations are the scalar density ρ_S , vector density ρ_V , isovector density ρ_I and charge density ρ_C :

$$\rho_S(r) = \sum_{\alpha}^{occ} \bar{U}_{\alpha}(r) U_{\alpha}(r) = \sum_{\alpha}^{occ} \left(\frac{2j_{\alpha} + 1}{4\pi r^2} \right) [|G_{\alpha}(r)|^2 - |F_{\alpha}(r)|^2], \quad (13)$$

$$\rho_V(r) = \sum_{\alpha}^{occ} U_{\alpha}^{+}(r) U_{\alpha}(r) = \sum_{\alpha}^{occ} \left(\frac{2j_{\alpha} + 1}{4\pi r^2} \right) [|G_{\alpha}(r)|^2 + |F_{\alpha}(r)|^2], \quad (14)$$

$$\rho_I(r) = \sum_{\alpha}^{occ} U_{\alpha}^{+}(r) \tau_3 U_{\alpha}(r) = \sum_{\alpha}^{occ} \left(\frac{2j_{\alpha} + 1}{4\pi r^2} \right) \tau_3 [|G_{\alpha}(r)|^2 + |F_{\alpha}(r)|^2], \quad (15)$$

$$\rho_C(r) = \sum_{\alpha}^{occ} U_{\alpha}^{+}(r) \frac{(1 - \tau_3)}{2} U_{\alpha}(r) = \sum_{\alpha}^{occ} \left(\frac{2j_{\alpha} + 1}{4\pi r^2} \right) \frac{(1 - \tau_3)}{2} [|G_{\alpha}(r)|^2 + |F_{\alpha}(r)|^2]. \quad (16)$$

Table 1. Values of the parameters in the NL-BA, NL-Z2 and NL3 parameterizations

parameter	NL-BA [17]	NL-Z2 [18]	NL3 [19]
M	939.0	938.9	939.0
m_σ	506.28	483.15	508.1941
m_ω	782.6	780.0	782.5010
m_ρ	789.0	763.0	763.0
g_σ	10.129758	10.1369	10.2169
g_ω	12.722198	12.9084	12.8675
g_ρ	4.508614	4.55627	4.4744
b_σ	-11.480161	-13.7561	-10.4307
c_σ	-32.277332	-41.4013	-28.8851

The expression for total energy can be derived from Lagrangian density and it has a structure

$$E = \sum_{\alpha}^{occ} E_{\alpha} (2j_{\alpha} + 1) - \frac{1}{2} \int (g_{\sigma} \sigma_0 \rho_S + g_{\omega} \omega_0 \rho_V + g_{\rho} \rho_0^{(3)} \rho_I + e A_0 \rho_C) d^3x + \int \left(\frac{1}{3} b_{\sigma} \sigma_0^3 + \frac{1}{4} c_{\sigma} \sigma_0^4 - \frac{1}{4} c_{\omega} \omega_0^4 \right) d^3x. \quad (17)$$

In the case of open shell nuclei, the BCS pairing has been applied using a constant gap approximation and the pairing energy has been added to the total energy. In addition, the total energy has been corrected for the spurious centre of mass motion. The set of Dirac equations (5 - 6) for nucleons and Laplace equations (9 - 12) for mesons and electromagnetic field with expressions for source terms (13 - 16) have to be solved self-consistently.

3. Results and discussion

All calculations have been performed using NL-BA [17], NL-Z2 [18] and NL3 [19] parameters for even-even oxygen isotopes from ^{12}O to ^{28}O . The values of the parameters are listed in Table 1.

For all parameterizations the binding energy, two neutron separation energy, energy levels, root-mean-square radius and density distribution were calculated.

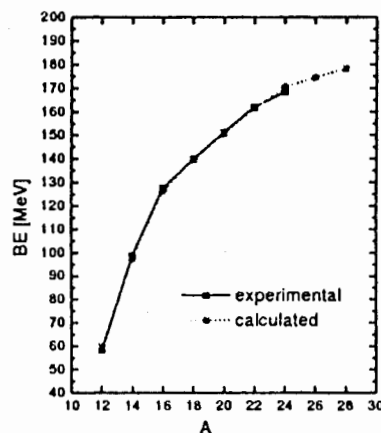


Figure 1. Experimental and theoretical binding energy calculated with NL3 parameters for oxygen isotopes

Calculated binding energies were compared with experimental values. Good agreement for all parameterizations was confirmed, therefore we expect good agreement for other theoretical calculations with experimental data. Calculated data obtained with NL3 parameters are compared with experimental data in Figure 1.

Good agreement with experimental values was confirmed also for two neutron separation energies for all parameterizations. Calculated two neutron separation energy of ^{26}O and ^{28}O are very small, however there are still positive contrary to experimental observed particle instability of these nuclei. Calculated data with NL3 parameters are shown in Figure 2.

In single-particle energies we can see the systematic decreasing of spin-orbit splittings with increasing number of protons. The spin-orbit splittings between $1p_{3/2}$ and $1p_{1/2}$ calculated with NL-BA parametrization are listed in Table 2.

We calculated proton, neutron and total root-mean-square (RMS) radii of nuclei, all parameterizations provide similar results. We can see an evident great increase of proton RMS radius in ^{12}O and neutron RMS radii in ^{24}O , ^{26}O and ^{28}O which are also reflected in increasing of total radii. Values calculated with NL-BA parameters are in Figure 3.

Density distributions with all parameters also provide analogous results. Calculated density distributions for nuclei far from stability line are characterized by long density tail. We can see a structure with a dilute neutron

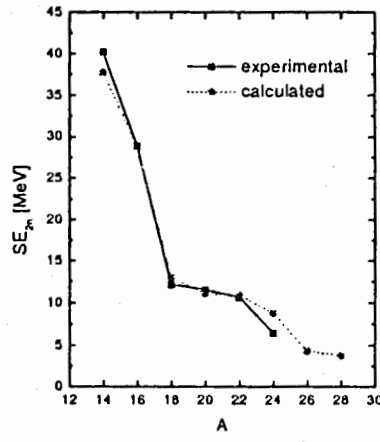


Figure 2. Experimental and theoretical two neutron separation energy for different oxygen isotopes calculated with NL3 parameters

Table 2. Calculated spin-orbit splitting between $1p_{3/2}$ and $1p_{1/2}$ obtained with NL-BA parameterization

isotop	Δ_P [MeV]	Δ_N [MeV]
^{16}O	6.376	6.299
^{18}O	6.141	6.179
^{20}O	5.914	6.070
^{22}O	5.646	5.922
^{24}O	6.046	6.232
^{26}O	5.327	5.501
^{28}O	4.423	4.591

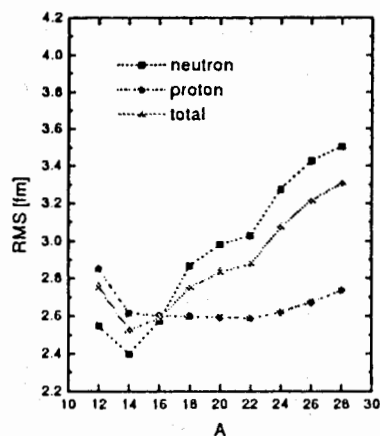


Figure 3. Calculated proton, neutron and total RMS radii obtained with NL-BA parameterizations

density distribution extended very far away from the nuclear centre for ^{24}O , ^{26}O and ^{28}O and the same effect for proton density distribution for ^{12}O . Density distributions of ^{12}O , and ^{28}O compared with density distribution of ^{16}O calculated with NL-Z2 parameters are drawn in Figures 4, 5 and 6.

4. Summary

We can summarize our results as follows. The relativistic mean-field theory with the NL-BA, NL-Z2 and NL3 parametrizations is successful in describing ground-state properties of exotic oxygen isotopes. The model still predicts particle stability of heavy isotopes ^{26}O and ^{28}O in contrary to experimental results. The approaches beyond the mean-field model should be used to explain this phenomenon. Calculated energy levels refer to systematical decreasing of spin-orbital splittings in exotic nuclei. This effect is a indication of the shell gap melting in these nuclei. The model predicts great increase of neutron RMS and extended neutron density distribution for ^{24}O , ^{26}O and ^{28}O . Analogous conclusion we can pronounce about the proton density in the case of ^{12}O . This structure is a indication of halo effect in oxygen nuclei far away from stability line.

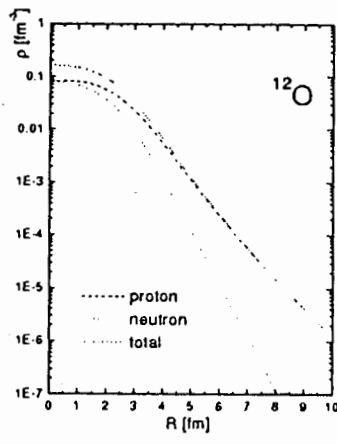


Figure 4. Proton, neutron and total density distributions of ^{12}O calculated with NL-Z2 parameters

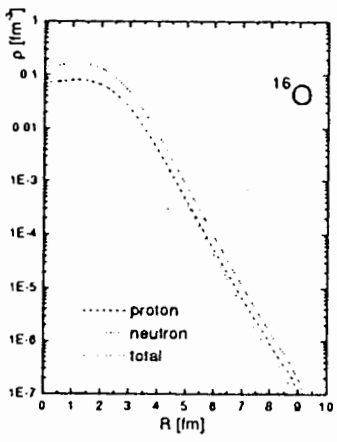


Figure 5. Proton, neutron and total density distributions of ^{16}O calculated with NL-Z2 parameters

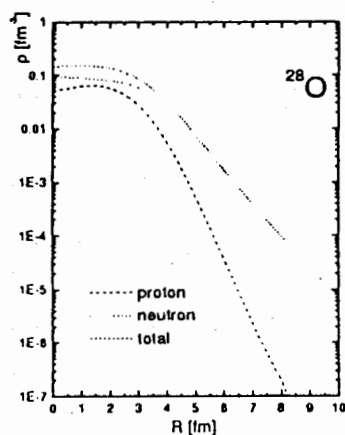


Figure 6. Proton, neutron and total density distributions of ^{28}O calculated with NL-Z2 parameters

5. Acknowledgments

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Monte-Carlo simulation of experimental setup used in experiment with polarized deuterons

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Abstract

The results of the Monte-Carlo simulation of the SPHERE setup for experiments with a polarized and nonpolarized deuteron beams are presented. An acceptance of the magnetic channel was calculated for cumulative and twice cumulative pions [5] for a different target lengths along the beam.

Setup description

The SPHERE setup used for the measurements of the cross sections and polarization observables for the reaction of a (polarized and nonpolarized) deuteron fragmentation into cumulative hadrons (h): $D + A_t = h + X$ (see, for example, [1], [2], [3], [4]) is shown in Fig.1. The main element of this setup is a magnetic channel containing four banding magnets and three doublets of quadrupole lenses.

In such experiments the trigger was generated if secondary (detected) hadron hits each of $F56_1$, $F56_2$, F_{61} , F_{62} , and F_{63} counters. Hodoscope HT was used for Time-of-Flight (ToF) measurements. The ToF between counters situated in foci $F56$ and $F6$ and, optionally, signals from Cherenkov counters $\check{C}_1$ or (and) $\check{C}_2$ was used for particle identification. The H0XY and H0UV hodoscopes were used for measurements of secondary particles beam profile. Because of all counter signals were taken into account in the data analysis, the detected particle have to hit all detectors along magnetic channel during a Monte-Carlo simulation (see Fig.1).

Simulation procedure description

The software package GEANT3 [6] was used for simulation of a particle interactions with materials in channel, decays and tracking along channel. The constant field and constant gradient approximations have been used for banding magnets and quadrupole lenses, respectively. As a secondary particles a twice cumulative pions were taken.

The number N_h of detected particles obtained from exposition with total deuteron beam intensity I on target with length along the beam l (in g/cm³) given by the following equation:

$$N_h = \frac{N_{Av} I}{A_t} \int_0^l dl \int_{p_{min}}^{p_{max}} \frac{d\vec{p}}{E} \left(E \frac{d\sigma}{d\vec{p}}(E_D(l), \vec{p}) \right) W_{D\pi}(l) W_c(l, \vec{p}) W_{dc} , \quad (1)$$

where A_t is a target mass number, N_{Av} – Avogadro number, $W_{D\pi}(l)$ – probability for deuteron to reach point at distance l along a target, and for pion to come out a target both without inelastic collisions, $W_c(l, \vec{p})$ – probability for hadron produced on point l to hit all counters, and W_{dc} – probability for secondary particle to avoid decay.

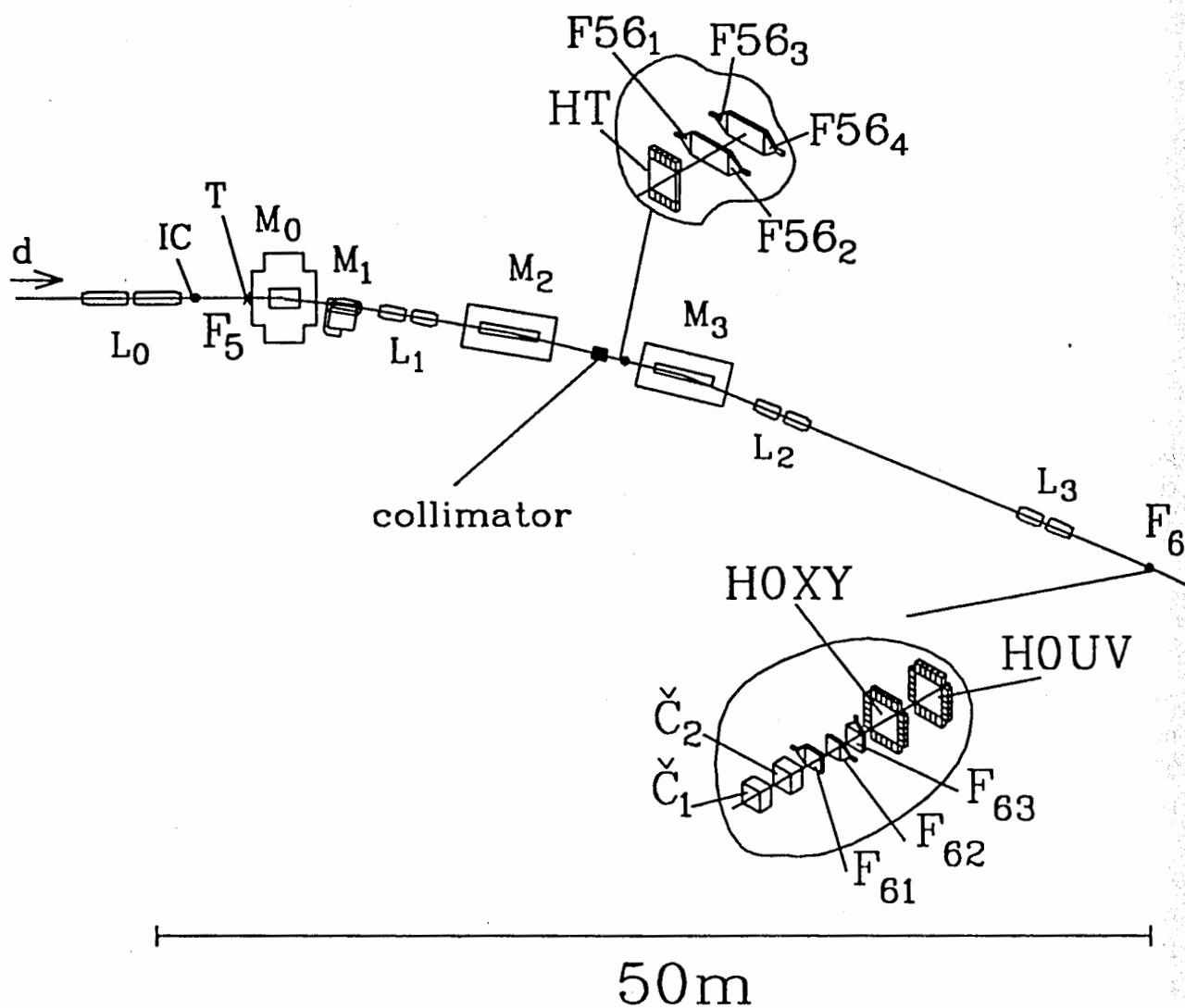


FIG.1. The layout of SPHERE setup. M_i - i -th bending magnet; L_i - i -th duplet of quadrupole lenses; IC - ionization chamber; T - target; F_{61-3} and F_{561-4} - scintillation counters; HT, H0XY and H0UV - hodoscopes; $\check{C}_1$, $\check{C}_2$ - Cherenkov counters

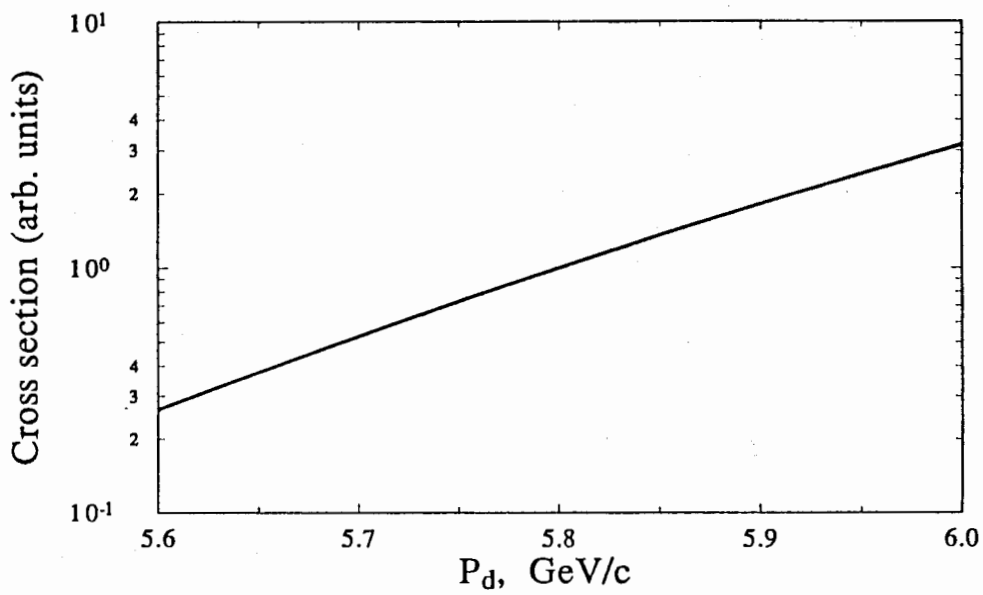


FIG.2. The cross section of twice cumulative pion production in the $D + Be = \pi(0^\circ) + X$ reaction as a function of deuteron momentum

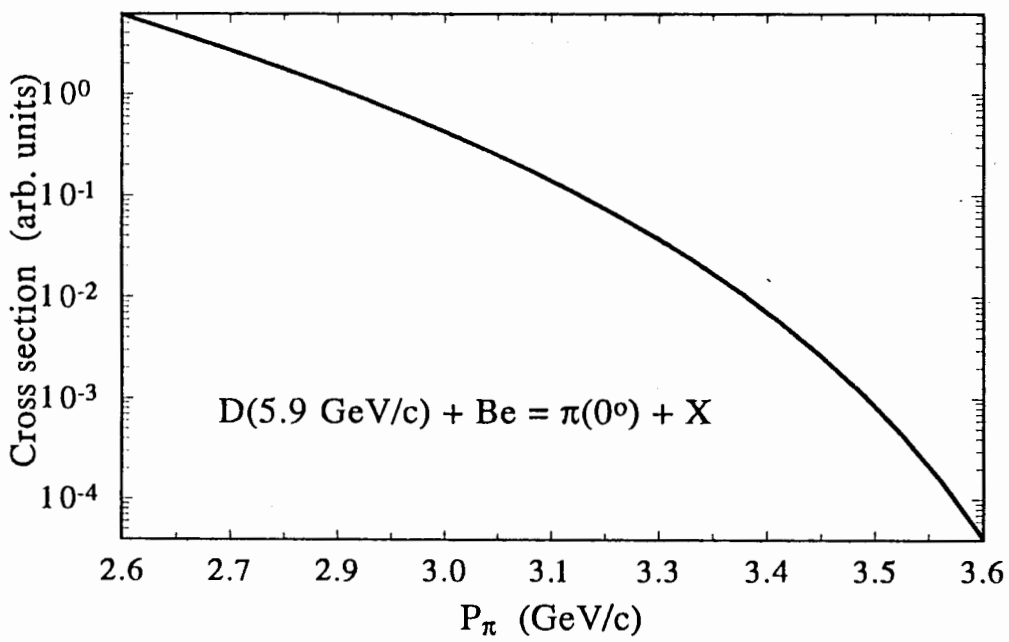


FIG.3. The cross section of twice cumulative pion production in the $D + Be = \pi(0^\circ) + X$ reaction as a function of pion momentum

From equation (1) one can see that it is necessary to know cross section as a function of initial energy $E_D(l=0)$ and momentum $\vec{p}$ of detected particle, because of an energy losses of deuteron and secondary particle during passing through a target. The present simulation have been performed for so called twice cumulative region (see [5]) when the detected hadron (h) is produced in kinematic region forbidden not only for $p + A_t = h + X$ reaction, but also for $D + p = h + X$. The cross section was taken in the form proposed in [5]. It decreases with deuteron energy decreasing and with secondary pion momentum increasing (see Fig.2 and Fig.3). The corresponding generator for secondary particle production have been designed.

The acceptance for target with length l was calculated using the following expression:

$$Acc(l) = \left(\int_0^l dl \int_{p_{min}}^{p_{max}} \frac{d\vec{p}}{E} \left(E \frac{d\sigma}{d\vec{p}}(E_D(l), \vec{p}) \right) W_{D\pi}(l) W_c(l, \vec{p}) W_{dc} \right) / \left(l E \frac{d\sigma}{d\vec{p}}(E_D(0), \vec{p}_c) \right) , \quad (2)$$

where $E \frac{d\sigma}{d\vec{p}}(E_D(0), \vec{p}_c)$ is the cross section for the production of a secondary hadron¹ by deuteron with initial energy. Such acceptance as a function of the secondary particle momentum for Be target with $l = 6.3 \text{ g/cm}^2$ is shown in the Fig.4. From this picture one can see that momentum acceptance of the channel $\Delta p/p \simeq 2\%$.

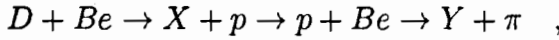
Results and discussion

The calculated acceptance is shown in Fig.5. From this picture one can see that the acceptance decreases with target length increasing. The dependence of acceptance Acc from target length l can be approximated with accuracy better than 2% by the following empirical dependency:

$$Acc(l(\text{g/cm}^2)) = Acc(l=0) \exp(-0.024l(\text{g/cm}^2)) . \quad (3)$$

The reasons for acceptance behaviour mentioned above are follows:

- The deuterons and pions can be lost due to inelastic collisions. After inelastic collision of deuteron on Be the cumulative pion can be produced only by the following cascade process (on a different nuclei in target):



where the proton momentum have to be big enough for production of a twice cumulative pion. Using designed secondary particle generator was shown, that per 100000 cumulative pion events such cascades doesn't encountered (on the target with $l = 4 \text{ g/cm}^2$), so it's probability less than 0.1% is assumed. One can estimate that all inelastic collisions (for deuterons and for pions) follows to lost of the corresponding particle. The inelastic collisions probability can be estimated as follows:

$$W_{inel.}(l_t) = \frac{\lambda_D \lambda_\pi}{l(\lambda_D + \lambda_\pi)} (\exp(-l_t/\lambda_\pi) - \exp(-l_t/\lambda_D)) , \quad (4)$$

where λ_π and λ_D are inelastic collision length for pion and deuteron, respectively.

- The cross section depend from the energy of deuterons and pions (see Fig.2 and Fig.3). Assuming that pion is produced in the middle point of target along beam direction, one can estimate probability of such process:

¹With momentum, which provides trajectory close to axis of the magnetic channel.

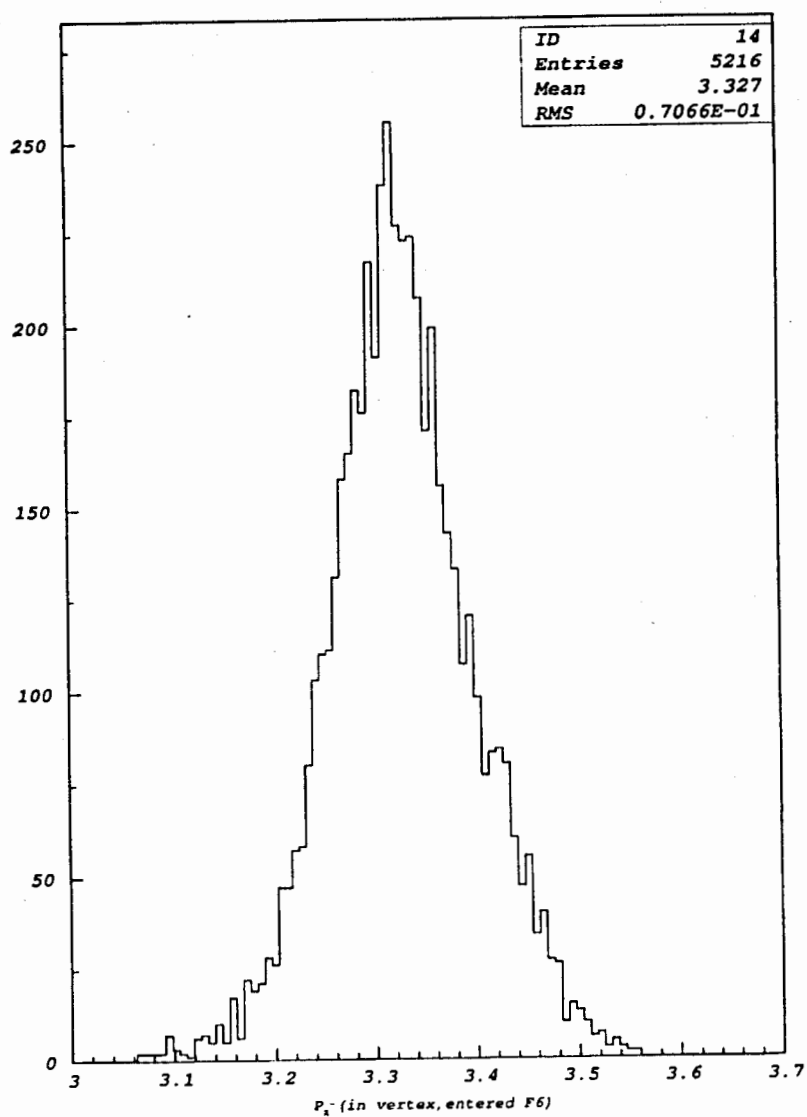


FIG.4. The acceptance of channel as a function of the secondary pion momentum for Be target with $l = 6.3 \text{ g/cm}^2$

$$W_{cross.}(l_t) = \frac{d\sigma}{d\vec{p}}(E_D - \frac{dE_D}{dx}l_t/2, E_\pi - \frac{dE_\pi}{dx}l_t/2) / \frac{d\sigma}{d\vec{p}}(E_D, E_\pi) , \quad (5)$$

where $\frac{dE_D}{dx}$ and $\frac{dE_\pi}{dx}$ are the deuteron and pion energy losses in a target, respectively.

The total efficiency of this two processes can be estimated as a production of $W_{cross.}$ and $W_{inel.}$:

$$W_{tot.}(l_t) = W_{inel.}(l_t)W_{cross.}(l_t) , \quad (6)$$

and is shown in Fig.6. From Fig.5 and Fig.6 one can see that the results of simulation and proposed estimation of efficiency are in a good agreement.

Main results can be summarized as follows:

1. The generator for twice cumulative particles is designed.
2. The simulation procedure for SPHERE setup (Fig.1) used in the inclusive experiment on studying of a cumulative particle production have been performed for different target lengths in the case of twice cumulative pion production.
3. From this simulation obtained that acceptance decreases rapidly with target length increasing. For example, in the case of target length $l_t = 20$ g/cm² and $l_t = 40$ g/cm² numbers of detected particles differ only on 20%. It have to be taken into account in order to find optimal relation between background and count rate.

This investigation was supported by Russian Foundation for Basic Research under grant No. 99-02-16528a.

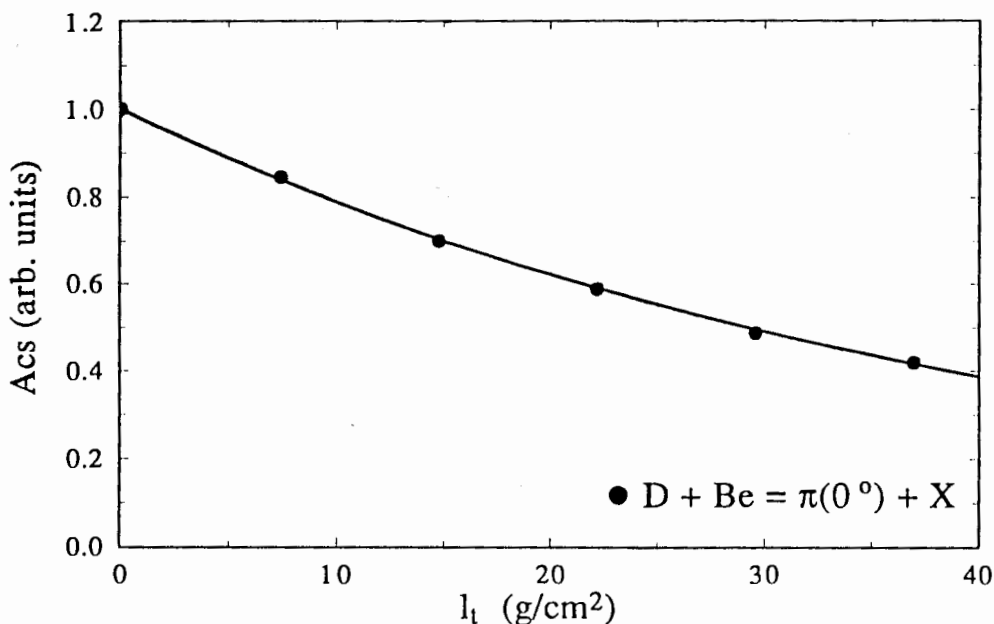


FIG.5. The calculated acceptance as a function of target length.
Solid line – approximation by empirical dependency (3)

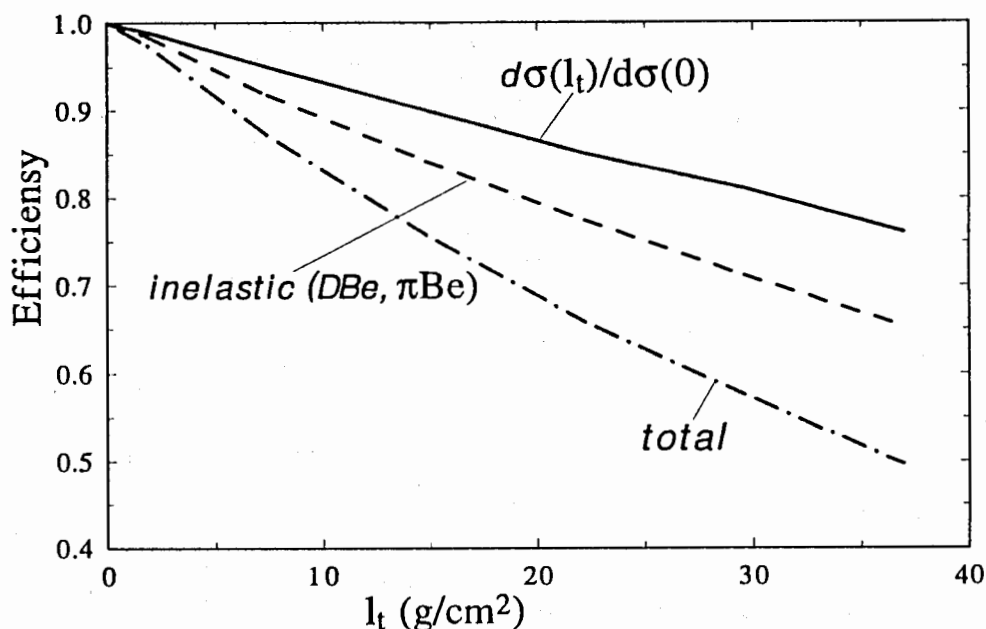


FIG.6. The estimation of the pion detection efficiency as a function of target length.

Solid line – efficiency due to an energy losses of deuteron and pion in target;

dashed line – efficiency connected with particle lost due to inelastic interaction of deuterons and pions;

dash-dotted line – efficiency due to the sum of two mentioned factors

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DEVELOPMENT OF THE BEAM INJECTION INTO THE NUCLOTRON

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Abstract

The system for the injection of 5 MeV/u heavy ions into the Nuclotron is described. The system comprises a superconducting septum-magnet, kick electric plates, beam diagnostic apparatus and magnet correctors.

The septum magnet has an iron yoke. The coil and septum made of a hollow superconductor, are cooled with a two-phase helium flow. The magnetic field is 1 T. The electric field is 7 kV/cm and its fall time in the fast kicker about 100 ns.

The beam diagnostics are composed of the Faraday cups and multi-wire collector chambers for current and profile measurements over a wide range of intensities. The magnetic correctors in the beam line and the Nuclotron ring are used for injection adjustment.

1. INTRODUCTION

The superconducting heavy ion synchrotron Nuclotron was commissioned into operation in 1992 as planned replacement of the 35-year-old Synchrophasotron. The Nuclotron ring was placed in the ground tunnel -3.76 m below the median planes of the Synchrophasotron and the injector (the Alvarez type linac). The latter accelerates ions with a charge-to-mass ratio of $0.28 < q/A < 0.5$ up to 5 MeV/u and protons up to 20 MeV.

The existing set of heavy ion sources: a duoplasmatron (protons, deuterons, and α -particles), a source of polarized deuterons, a laser source and an electron beam ion source (EBIS) allows us to get ion beams over a wide range of masses up to xenon.

There are two reasons why the single turn injection was chosen:

- beam pulse duration of the laser source and EBIS are comparable to the time of one turn;
- the minimization of the structure magnet apertures and cross section sizes allow substantially the power consumption to decrease. As for the storage of light ions (protons, deuterons and α -particles), we are planning to include booster into the Nuclotron layout.

2. SINGLE-TURN INJECTION LAYOUT

Taking into account the features of the Nuclotron position, the injection scheme was chosen to provide the beam deflection in the vertical plane.

A standard layout of the single-turn injection comprises two main elements: a deflecting septum-

magnet and a kicker. In our case, the principal requirement to these devices is to have low levels of warm and gas discharges. The superconducting septum magnet and kick electric plates obviously satisfy these conditions better than their warm magnetic analogs.

The parameters of these devices for the injection of protons and heavy ions with a charge-to-mass ratio of 0.5 are presented in Table 1.

Table 1

No	Parameters		Ions	Protons
1.	Energy	MeV/u	5	20
2.	Charge-to-mass ratio	q/A	0.5	1
3.	Magnetic rigidity	T·m	0.647	0.649
4.	Electric rigidity	MV	19.95	39.58
5.	Revolution time	μ s	8.152	4.125
6.	Magnetic field in the septum-magnet	T	0.120	0.121
7.	Length of the septum-magnet	m	0.5	0.5
8.	Electrical tension in the plates	kV/m	250.9	497.7
9.	Length of the plates	m	1.5	1.5

A scheme of the beam injection is given in Fig. 1:

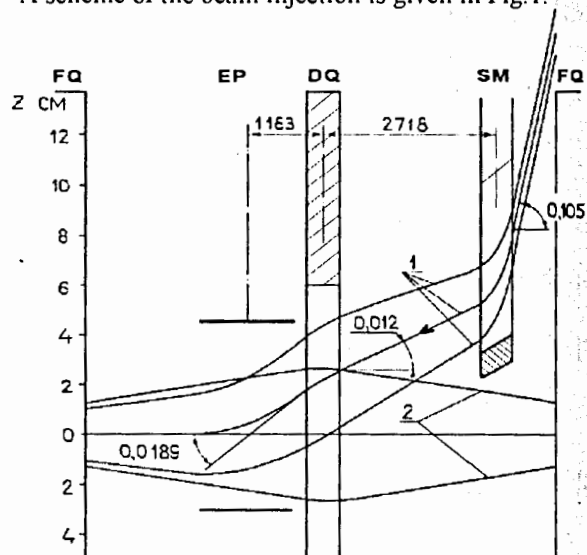


Figure 1. The injection scheme. 1 - injected beam, 2 - circulating beam

A low level of the magnetic field and a large thickness of the septum allow one to make the coil and septum of the superconducting cable. A traditional magnetic kicker was also substituted by an electric one because of the low magnetic permeability of a ferrite yoke under cryogenic

temperature. The cross sections of the septum-magnet and plates were determined by parameters of the injected and circulating beam parameters:

- transverse emittance of the injected beam $30\pi \text{ mm} \cdot \text{mrad}$,
- horizontal emittance of the circulating beam $40\pi \text{ mm} \cdot \text{mrad}$,
- vertical emittance of the circulated beam $45\pi \text{ mm} \cdot \text{mrad}$,
- relative momentum spread 10^{-3} .

3. DEPOLARIZATION OF THE BEAM ON THE NUCLOTRON

The analytical and numerical simulations of the deuteron depolarization in the Linac, beam transport lines and Nuclotron have shown that most resonances are not dangerous. The exception is the resonance $\nu = -1$ at the energy of 5.62 GeV/u. Its crossing during acceleration time and slow extraction near this energy is impossible without taking of special measures.

It is known, that to keep the beam polarization in the accelerator ring is difficult due to the crossing of spin resonances. Their perturbation conditions are determined by the relationship:

$$\nu = k_0 + k_x Q_x + k_y Q_y,$$

where ν is the number of spin precession per orbit revolution, k_0 , k_x , k_y - integer numbers and Q_x , Q_y - betatron tunes.

Table 2 shows possible spin resonances up to the second order ($|k_x| + |k_y| \leq 2$) over the beam energy range from 5 MeV/u to 6 GeV/u and betatron tunes $Q_x \approx 6.8$, $Q_y \approx 6.85$. The results of computer simulations of resonance depolarization at a guide magnetic field velocity of $dB/dt = 1 \text{ T/sec}$ are shown in Table 2. The high lattice periodicity (32 cells and 8 superperiods) have allowed to avoid excitation of the most dangerous lattice resonances. The influences of magnetic field imperfections and correcting fields (normal and skew dipole, quadrupole, sextupole and octupole) are taken into account. Among non-perfect resonances in the Nuclotron, the most powerful one is $\nu = -1$ at the energy of 5.6 GeV/u. Its crossing is dangerous without taking special measures.

The task of beam polarization keeping under stationary conditions is appeared, when the spin and betatron tunes do not change much arises from a 10 second slow extraction. The beam depolarization degree under stationary conditions depends on closeness to spin resonance. A maximum effect appears when the particles are in the resonance band. In a real accelerator, it is very difficult to realize these resonance conditions exactly

because of synchrotron modulation and betatron tune spread.

Table 2. Spin resonances at the acceleration

k_0	k_x	k_y	ν	$W_{kin}, \text{GeV/u}$	$D, \%$
-7	0	1	-0.15	0.005	8
-7	1	0	-0.20	0.37	8
-14	0	2	-0.30	1.02	0.5
-14	1	1	-0.35	1.35	0.5
-14	2	0	-0.40	1.68	0.3
13	-2	0	-0.60	2.99	0.1
13	-1	-1	-0.65	3.32	0.1
13	0	-2	-0.70	3.65	0.1
6	-1	0	-0.80	4.30	0.3
6	0	-1	-0.85	4.63	0.73
-1	0	1	-0.95	5.29	0.06
-1	0	0	-1.00	5.62	40

The data on beam depolarization for a 10 second spill of slow extraction are presented in Table 3.

The resonance $\nu = -1$ is dangerous for all the regimes

The same situation occurs for experiments with the internal target.

Table 3. Spin resonances at the slow extraction

k_0	k_x	k_y	ν	$W_{kin}, \text{GeV/u}$	D
-7	1	0	-0.20	0.37	16
-14	1	1	-0.35	1.35	0.7
6	-1	0	-0.80	4.30	4
6	0	-1	-0.85	4.63	1.5
-1	0	0	-1.00	5.62	100

4. CHARGE-EXCHANGE INJECTION

Since early 80^{ies}, the spin physics program at the JINR Synchrophasotron has been going successfully. The next step of this program is to accelerate the polarized beams at the Nuclotron. The first test run of polarized deuteron injection and acceleration has been carried out. Computer simulation of charge exchange injection into the accelerator is also considered.

The intensity of polarized deuterons at the Synchrophasotron is now equal to $5 \cdot 10^9$ particles per cycle by using multiturn injection. Without a special procedure, the intensity at the Nuclotron is approximately by an order lower because of single-turn injection into the latter. To increase the intensity of a polarized deuteron beam, three ways are considered at the Laboratory of High Energies:

- the formation of a particle short pulse comparable to the revolution time in the new POLARIS ionizer,
- charge exchange ($\uparrow D^- \rightarrow \uparrow D^+$) injection into the Nuclotron
- construction of a booster used to store and preaccelerate ions up to 200 MeV/u.

The last one is most effective and very useful for other ions, but it is the most expensive one, of course. Below the second possibility of increasing the intensity, the charge exchange injection of polarized deuterons into the Nuclotron, is studied by computer simulations.

After all calculations carried out with a specially designed simulation code SINSIM - Monte Carlo object-oriented C++ program for Windows, carbon was chosen as a stripping foil material.

The growth of emittance and relative momentum spread was simulated by 100 macroparticle during 100-turn stripping injection. The intensity gain (I/I_0) during 100 turn stripping injection with the Nuclotron acceptance restriction is shown in Fig.2 below.

This work is based on the previous results for simulations of heavy ion stripping injection into synchrotrons, where advantages of storing ions with a small atom mass unit (up to carbon) by this method were shown.

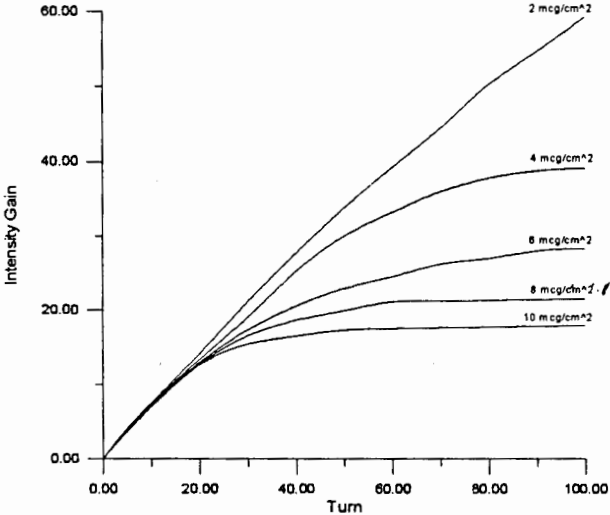


Figure.2. The intensity gain (I/I_0) during 100 turn stripping injection with the Nuclotron acceptance restriction.

4.1.CHARGE-EXCHANGE INJECTION SCHEME

The version of the multiturn injection technical realization is considered below.

The Nuclotron first straight section should be reconstructed sufficiently (see Fig.3a). Four pairs of the pulse electrical plates (IP1, IP2, IP3, IP4), two additional correcting magnets (C1, C3), carbon stripper (T) and two profile monitor (P1, P2) are supposed to be installed there. The position of the inflector magnet does not change. The stripper and multiwire profilemonitor are assembled on the mechanical drivers.

During the injection period the plates (IP1, IP2, IP3, IP4) produce the bump of direction (see Fig.3a) for passing through the stripper. At the end of the injection

the plate voltage decreases to zero very fast (about 100 ns). The correcting magnets C1 and C3 together with the existing corrector C2 produce the local closed orbit (bump), directed to the accelerator center (see Fig. 3b) to avoid the charge-exchange target and not to interfere with circulation of the injected beam.

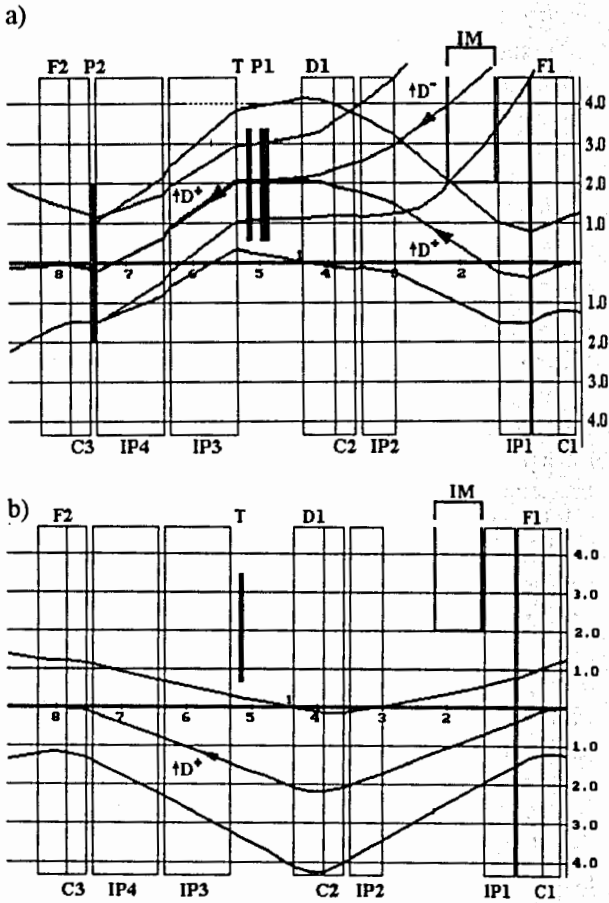


Figure 3. Charge-exchange injection scheme

The axis beam trajectory is considerably shifted in the D1 lens region during the injection. Therefore a new profile of a specialized vacuum chamber was made (Fig. 4).The new vacuum chamber is now under construction and testing.

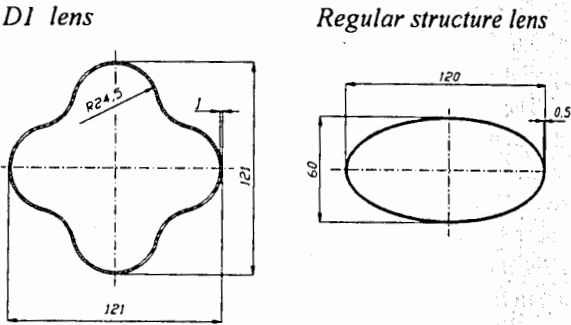


Figure 4. Vacuum chamber profile

Besides, it is necessary to define technical refinements for new devices and to choose places for their mounting on the Nuclotron.

Preliminary meanings of the technical parameters of new devices are presented in Table 4 .

Table 4.Charge-exchange injection elements parameters

Element	Length, m	Magnetic field, (Gs)	Current, (A)	Electrical Field, (kV/cm)	Voltage, (kV)
Corrector C1 (8K4)	0.3	120	9.2		
Electrical Plates IP1	0.5			6.7	54
Electrical plates IP2	0.5			3.9	31
Corrector C2 (1K1)	0.3	120	9.2		
Electrical plates IP3	1.0			4.8	38
Electrical plates IP4	1.0			6	48
Corrector C3	0.3	135	10.4		

5. CONCLUSION

We have considered an optimistic possibility to get sufficient quantity of the polarized $\uparrow D^-$ in the improved POLARIS.

At the charge exchange injection of $\uparrow D^-$ into the Nuclotron, it is possible to gain at least a factor of more than 10 for increasing the polarized deuteron intensity.

Principal tasks for 2000 year as follows:

1. To carry out numerical simulation polarized deuterons accumulation in real magnetic fields at the Nuclotron.
2. To determine physics motivation of the project and technical tasks for engineering the multiturn injection elements; to carry out modelling and bench-testing researches of the devices.
3. To obtain polarized $\uparrow D^-$ on bench-testing.

6. ACKNOWLEDGEMENTS

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Organization and Synchronization of Data Acquisition in Multiprocessor System for the First Detector on the SPHERE Setup

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While preparation of the SPHERE electronics to experiments on Nuclotron beams in March 2000 it was found that DAQ system is not operating properly because system HDD failure on VME station controlling FASTBUS electronics. They decided to move front-end electronics to CAMAC crates for experiments on SYNCHROPHASOTRON polarized deuteron beams. It was necessary to have 25 channels of ADC, 20 channels of TDC and 10 scalers in this setup. We put this front-end electronics in 3 CAMAC crates. The readout of data was performed by intelligent CAMAC crate controllers CCPC5. It is more powerful version of the previous controller CCPC4 with embedded PC known by previous similar meeting RNP-1999.

CCPC5 parameters:

CPU	AMD K6-2 350 MHz
RAM	64 MB
HDD	4GB
Video	PCI 2MB
CAMAC	ISA bus
Width	3M

It was necessary to organize synchronization of data readout within 3 crates with accelerator spill and trigger and to provide access to data taken for network connected PCs. As a result of 2-month efforts we have built new data acquisition system shown on Fig. 1.

The synchronization system is built with specially designed trigger logic unit LT-3320 based on in-system programmable microchip LATTICE-3320. Synchronization block has NIM level 16 inputs and 16 outputs, 16 channel bi-directional TTL level bus and CAMAC bus buffers.

One can attach parallel port connector to program trigger logic including CAMAC interface directly from PC. For SPHERE setup we programmed the block in the following way. Inputs SoS, EoS and TRIG are for Start-of-Spill, End-of-Spill and Trigger pulses, and CR1, CR2 inputs are for reading status of crates. The output EV indicates event and ResetTRIG output is for unblocking of trigger system. The controller in crate with LT-3320 operates in MASTER mode and other crate controllers are in SLAVE mode. Besides specified the SFS output signals spill time interval when event data taking is enabled.

The dedicated PC referred as EB performs the event reconstruction. It controls data taking process including event data format, service parameters, run start and stop and merges data files created by all controllers, performs real-time data processing and graphical representation of data. The format of event data and service parameters is given by special NAF file containing functions and addresses for CAMAC blocks.

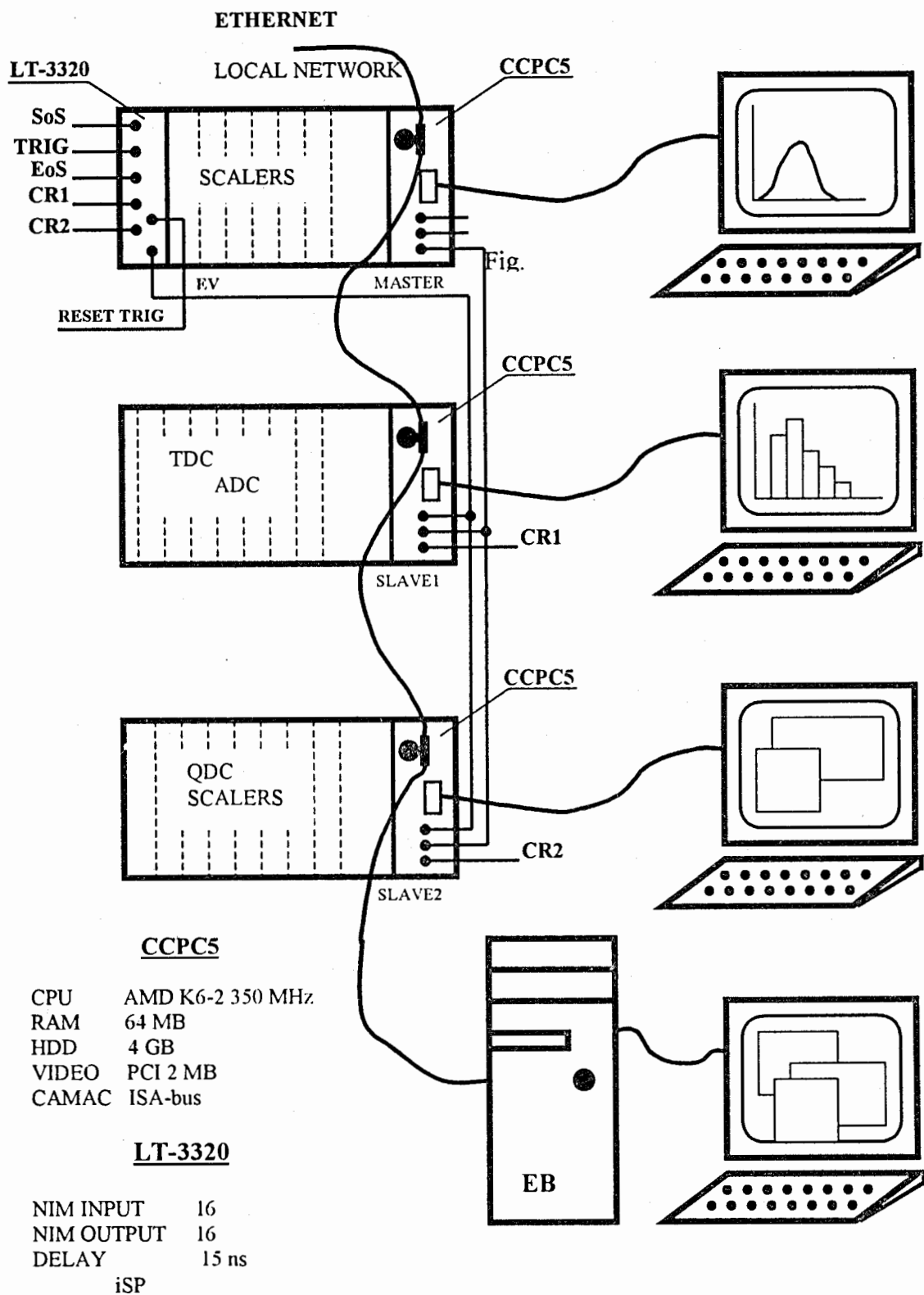


Fig. 1

All controllers and event builder use same network file system. There is one special service data file for software synchronization which is used together with hardware handshake to guarantee correct event reconstruction and binding to accelerator cycle. The synchronization algorithm is shown on Fig. 2, where main processes in MASTER and SLAVE controllers are illustrated and their sequence given by control signals. All controllers and EB are run under Linux OS, which gives us the possibility of remote control of the whole data acquisition system. It is flexibly enough to operate in real-time mode as well as in multitask, which allows one to readout data and do its processing and graphical representation simultaneously.

This system has been shown its full operating during last SYNCHROPHASOTRON run and demonstrated the following parameters:

intercrate synchronization time	15 <i>us</i>
2-byte word readout time	1.6 <i>us</i>

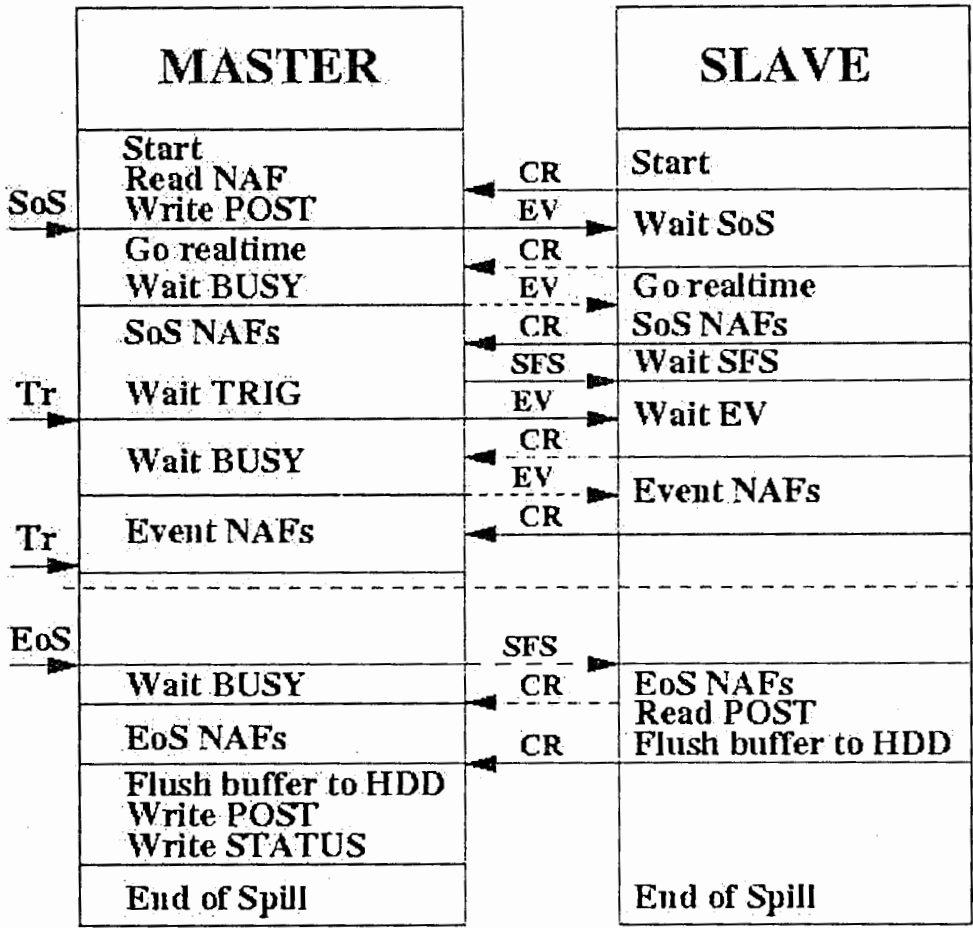


Fig.2

Status and Upgrade Capabilities of Magnetometry System of LHE Experiments and Beam Channels

S.A.Dolgij, A.V.Karpunin,
G.P. Nikolaevskij, A.Yu. Starikov

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Abstract

Carrying out physics experiments requires a knowledge with a high accuracy of a three-dimensional map of the magnetic fields of analysing and spectrometric magnets, the magnetic optical elements of transmission channels for charged particles and magnetic field control in these elements during the experiment.

Hall generators of the ПХЭ(ПХЭМ) 602(605) type constructed at the A.F. Ioffe Physico-technical institute are used as sensors of magnetic field induction. Thermostatic and nonthermostatic one- and three-component magnetometric probes are developed and made. They are calibrated by means of a NMR-magnetometer within a range of up to 2 Tl.

Simple not complicated, easily repeated schemes of source power and sensor thermostabilization (Fig.1,2) ensuring a permanent parameter stability of no worse than 10^{-5} , are developed.

The system used to measure the spatial distribution of magnetic fields (Fig.3) includes three-component measuring and support one-component probes with corresponding electronics, a coordinate device with a controller and PC measuring-registering electronics.

One- component probes are used for magnetic monitoring. Thermostatic probes (Fig.4) are mounted into the dipole magnets, and nonthermostatic ones (Fig.5), but selected by the value of Hall's voltage temperature coefficient, into the magnetic lenses.

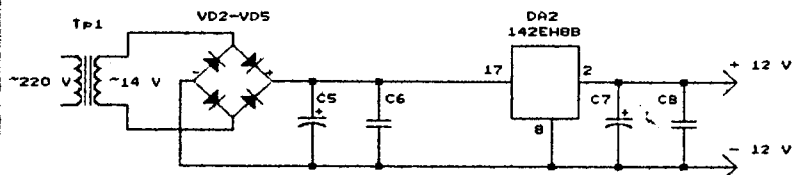
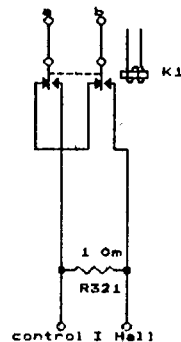
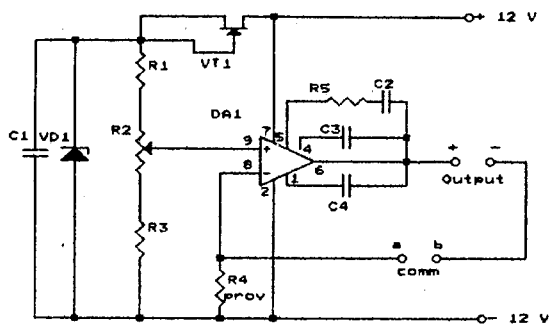


Figure 1

JINR LHE		
Title	Hall's power supply	
Size Document Number	REV	
A		
Date:	July 4, 2094	Sheet 1 of 1

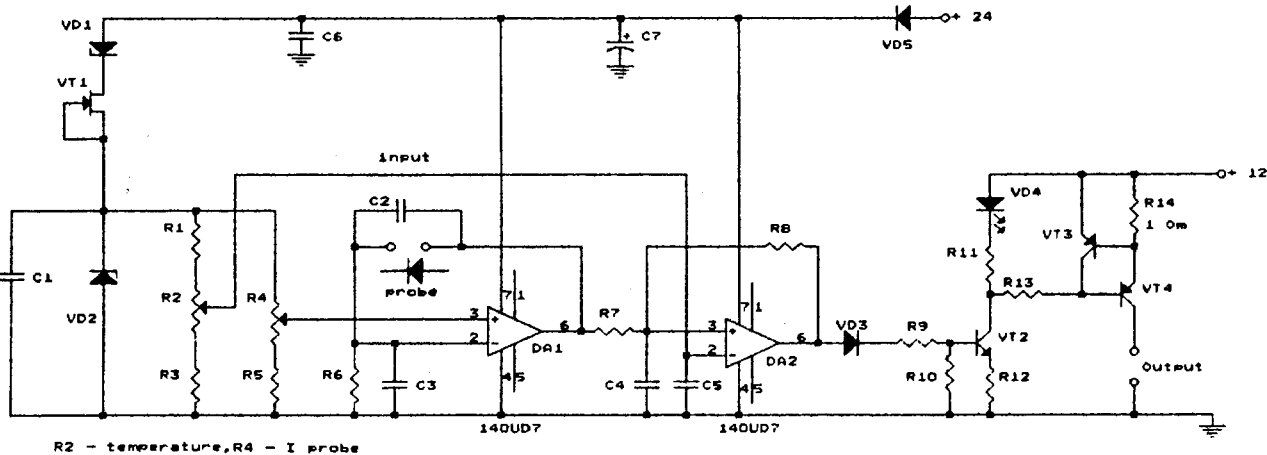
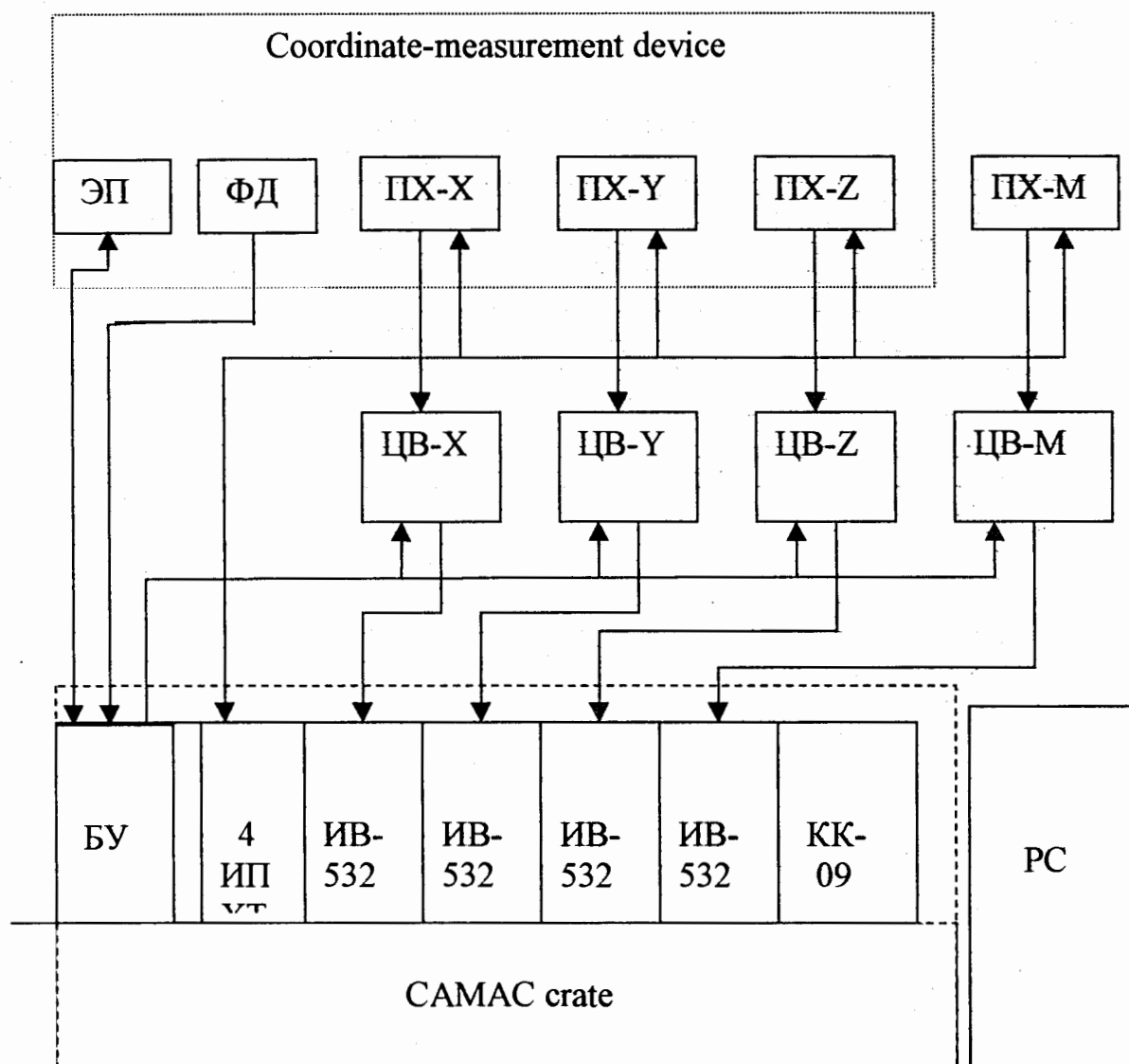


Figure 2

JINR LHR		
Title	Hall's thermostat	
Size Document Number	REV	
A		
Date:	July 4, 2094	Sheet 1 of 1



ЭП – electric drive of the coordinate device

ФД – photosensor

ПХ-X – ПХ-M – Hall generators

ЦВ-X – ЦВ-M – digital voltmeters

БУ – controller of the coordinate device

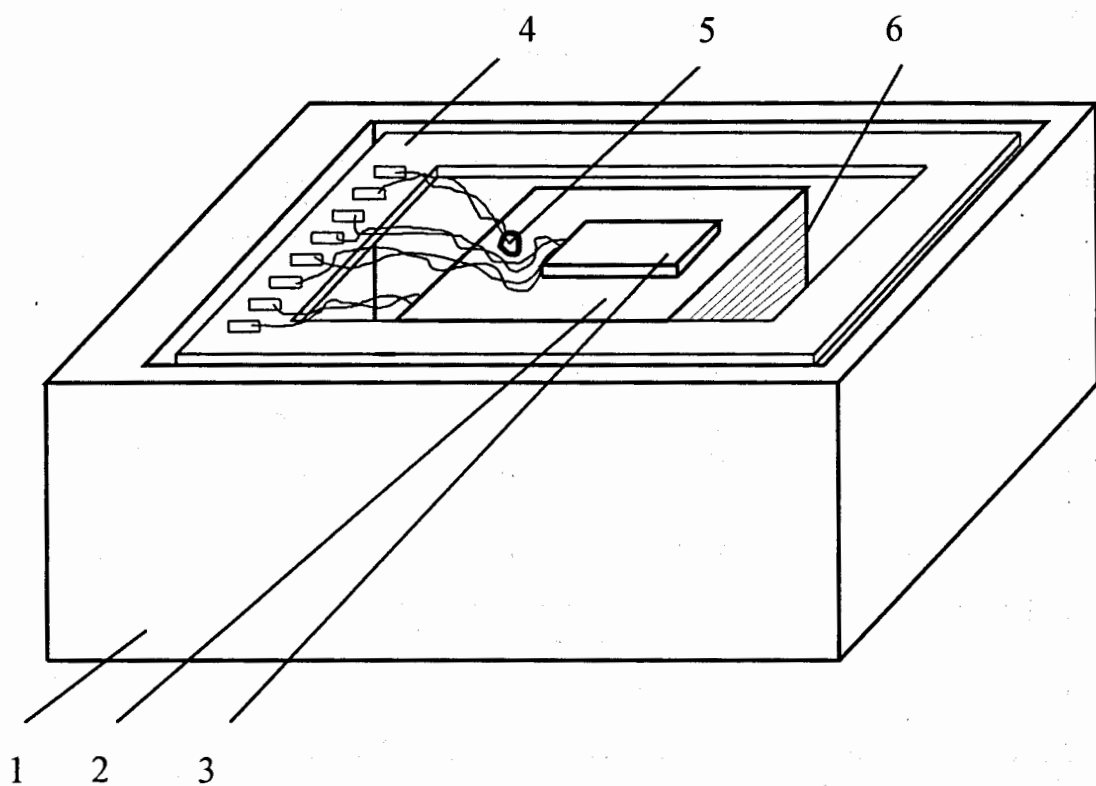
4 ИПХТ – 4-chanel power supply and thermostating Hall generators

ИБ-532 –interface of the digital voltmeters

КК-09 – CAMAC crate-controller

PC – personal computer

Fig. 3



- 1 – box
- 2 – cube-base
- 3 – Hall generator
- 4 – distributing collector (cross)
- 5 – packageless diode-thermosensor
- 6 – heater winding

Fig. 4

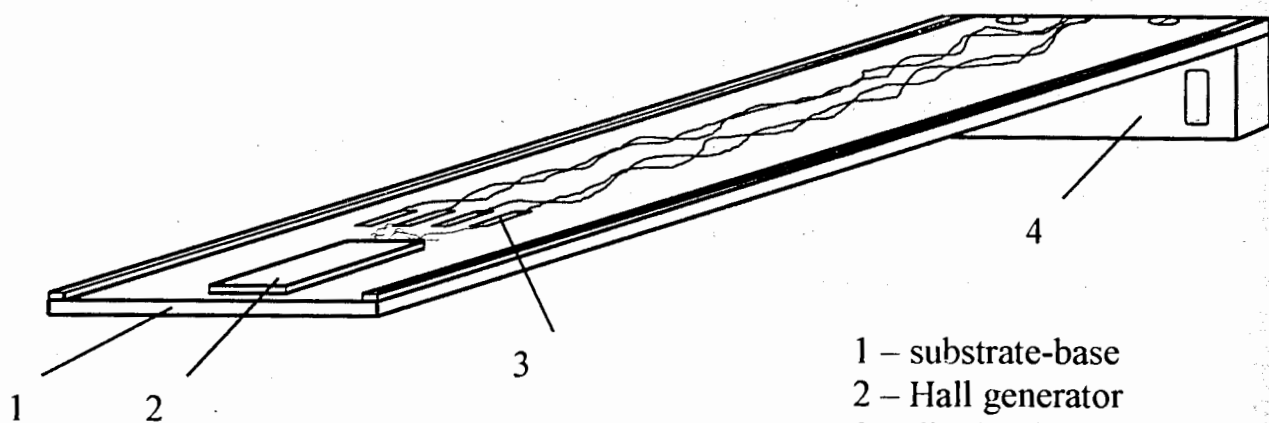


Fig. 5

- 1 – substrate-base
- 2 – Hall generator
- 3 – distributing collector
- 4 – pole based support

Main results:

1. We have built up the magnetometry system which allows one to measure the space distributions of magnetic fields in electromagnets of various types with an accuracy better than 0.1%. The system is based on a three-component Hall generator.
2. We have constructed the magnetic monitoring system for physics setups and beam channels. This system allows one to:
 - decrease the time of setting working parameters in experiments;
 - control the stability of set parameters during experiments;
 - enlarge the control accuracy of magnetic fields in the elements operating with pulsed energy supply.

We are planning to use Hall generator signals for energy supply control.

SLOW BEAM EXTRACTION FROM THE NUCLOTRON: FIRST RESULTS, FUTURE DEVELOPMENT

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Abstract

First experiments on the extraction system of the Nuclotron, a superferric heavy ion synchrotron, were carried out in March 2000, and the obtained results are described. The resonance $Q_x=20/3$ used for a horizontal betatron amplitude growth, provides beam entering the Electrostatic Septum (ESS), where it obtains an initial deflection to avoid losses on the septum of the Lambertson Magnet (LM). The latter bends the beam in the vertical plane to the level of experimental halls. An extraction coefficient of about 70% and a spill time 0.4s were obtained in the first experiments performed at the deuteron beam energy from 200MeV/amu to 1.5GeV/amu. Tentative experiments were performed on the external physics setups. The updating, which permit to improve the extracted beam parameters till the designed ones, is discussed.

1. INTRODUCTION

The Nuclotron [1], a superconducting heavy ion synchrotron for the energy of 6GeV/amu with iron shaped magnets has been under operation since 1994 and physics experiments were carried out only on the internal circulating beam before March 2000. Preparation of the extraction equipment for the final bench tests and installation into the ring started early 1999. Extraction equipment assembling required to reconstruct the regular dipoles and quadrupoles in the area of the 5-th, extraction, straight section. Last year the works were completed and the equipment was installed into the ring that permitted to start the commissioning of the Slow Extraction System [2].

2. EXTRACTION SYSTEM

Figure 1 shows the location of the slow extraction system elements. Two pairs of sextupole lenses S1 and S2 are used to produce the 20-th harmonic of quadratic nonlinearity to excite the resonance $Q_x=20/3$. The first pair (S1) is located in the 2-nd and 6-th octants and

second pair (S2) in the 4-th and 8-th octants. The lenses of each pair connected in series are located in antipode points of the ring and supplied from separated sources. One pair is turned relatively the other one by the angle of $7\pi/16$. It permits to have an arbitrary phase of the sextupole disturbance.

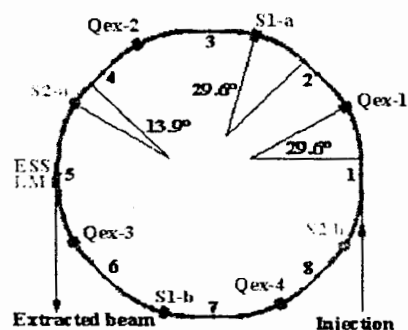


Figure 1. Location of the slow extraction system elements

Four additional quadrupole lenses Q_{ex} supplied in series are used to reach the resonance frequency $Q_x=20/3$ and to carry out control of the extraction process. The lenses are located in the 1-th, 3-th, 5-th and 7-th octants. The beam spill rate defining the extraction duration is controlled by a current slope, di/dt , in these lenses.

The bending system separating and deflecting the blown up part of the beam is located in the 5-th extraction straight section. Its first device is the electrostatic septum, ESS placed in the first half of the section. The septum is made of tungsten-rhenium wires of 0.1 mm thick and separates the region of the circulating beam from the region of the deflecting electrostatic field. The gap between the septum and the negative electrode can be changed from 10 to 30 mm. A HV tension up to 200 kV is supplied to the negative titanium electrode. The beam in the gap is deflected outside in the horizontal plane at an angle of ≈ 2 mrad to avoid losses on the septum of the Lambertson magnet

located in the second half of the extraction straight section.

The second device is a Lambertson magnet LM containing two stages of 1.5 m each. It bends the deflected beam in the vertical plane at the angle of 96 mrad to the level of the experimental halls. Its superconducting windings are connected in a series with the ones of the regular dipoles. This technical decision permanently provides the LM field for deflecting the beam by the constant angle at any time of the magnetic ramp. The idea to compensate the LM leakage field in the gap for the circulating beam by means of the superconducting short-connected coil, proposed at [3], was successfully confirmed. The bench measurements of the field inside the gap have shown the field compression up to the negligible value.

According to the calculations, an optimal radial operational position of the ESS and ML should be $R_0+19\text{mm}$. That is why in the area of the 5-th straight section it is necessary to have a horizontal orbit bump at the beginning of the accelerating cycle to meet requirements for unhampered beam injection and acceleration. Meanwhile, non-operational positions ($R_0+63\text{mm}$) of the ESS and the ML are foreseen in case of tentative experiments with a fully free aperture. The devices are movable both in warm and cold states keeping the ultra-high vacuum inside the beam chamber. This also provides a possibility of their accurate adjustment in case of the orbit distortion.

3. EXPERIMENTAL RESULTS

According to our estimations, the most acceptable working point lies in the vicinity of $Q_x=6.73$ and $Q_z=6.89$ (Fig.2). The approach to the resonance stop-band begins by means of additional current change in the regular quadrupoles. Then the subsequent current increasing in Q_{ex} (line segment 1-2, Fig.3) provided a smooth control of the resonance process in the extraction time, while the betatron oscillation frequency changes from the value corresponding to the edge of stop-band for one end of the momentum distribution to the value of $Q_x=20/3$ - for another end.

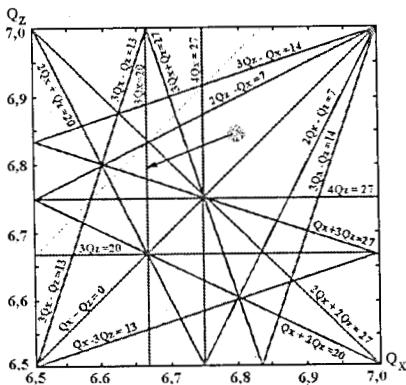


Figure 2. Resonance diagram near the working point

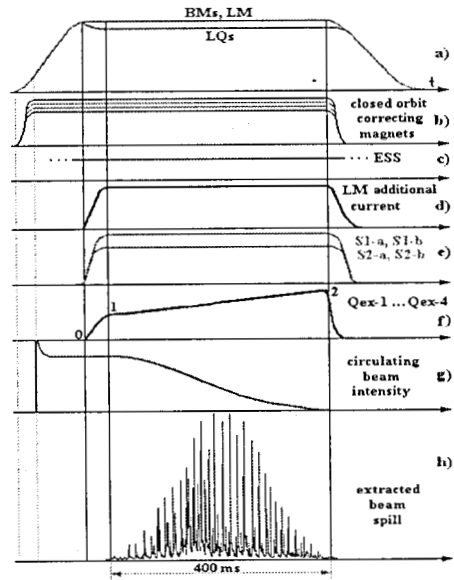


Figure 3. Timing diagram of the extraction processes

The experiments on the amplitude growth at the resonance for the deuteron beam were performed during the previous Nuclotron run before the installation of the bending system in the ring. The lenses were driven by tentative sources having small currents that limited the energy of the beam for the investigation, i.e. the main magnetic flat-top field was 0.2T corresponding to the particle energy of 204MeV/amu. A fluorescent TV-screen to observe the blown up beam was placed in a more accessible warm straight section number 7 at a distance of +20mm from the central orbit. The screen was movable to release the vacuum chamber aperture during the beam injection and acceleration. The observation of the resonance growth of the betatron amplitude resulting in hitting the beam unstable part on the TV-screen (Fig.4) has confirmed the capacity of the Resonance System operation.



Figure 4. Image of the beam on the fluorescent screen

The first extraction run began in March 2000, when the bending system was installed in the ring and the beam transport line was mounted to the nearest external setups.

The experiments on introducing the beam into the resonance were performed under conditions similar to

the previous ones, but the sextupole lenses currents corresponded to the maximum amplitude gain in the extraction straight section.

A typical time regime of the beam extraction process corresponding to the energy of 1.5 GeV/amu is shown in Fig. 2, which illustrates the extracted beam spill and relevant currents. There is considerable inhomogeneity on time due to ripples in current supplies of the extraction lenses and in the main magnetic flattop field.

At the correct orbit position the beam blown up in the horizontal plane and deflected in the ESS, was observed on a fluorescent screen at the entrance of the ML (Fig. 5a). It was also observed on the outside window of the ring vessel (Fig 5b).

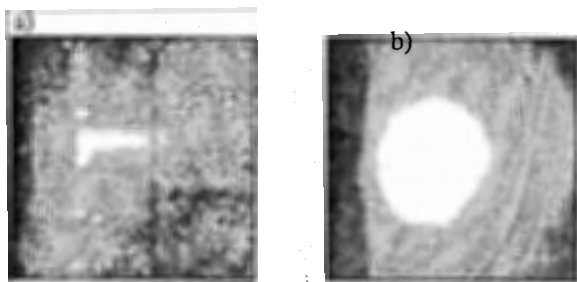


Figure 5. Beam image a) at the entrance LM, b) at the exit window

The layout of the extracted beam position in the fifth straight section is shown in Fig. 6.

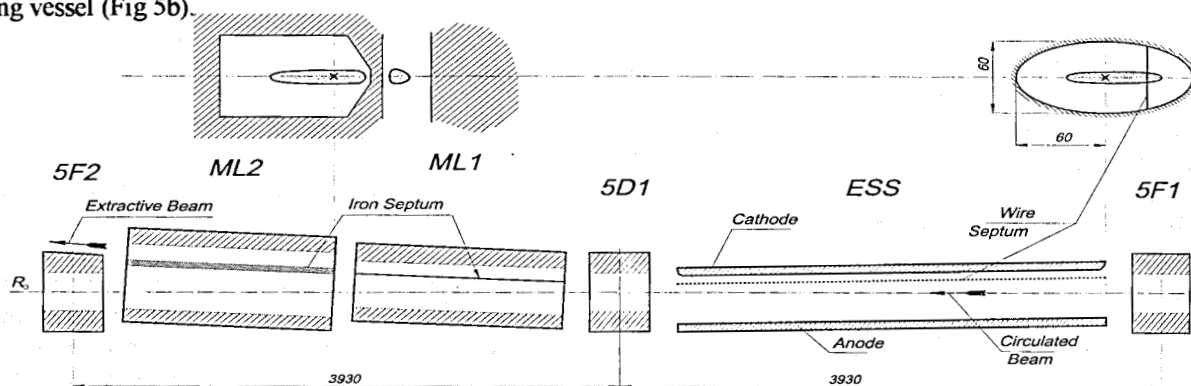


Figure 6. Layout of the extracted beam position in the fifth straight section

The measurements have shown that the envelope of the extracted beam in the horizontal plane is in a good agreement with the design, while the obtained vertical envelope has a greater size. It can be explained by the position of the working point (Fig. 2) close to the coupling resonance $2Q_x - Q_y = 7$, caused by the 7-th harmonic of the sextupole nonlinearity which appears due to the regular magnets field. The big value of this harmonic is confirmed by the observed blowing up (and even the low efficiency extraction) of the beam if to move towards this resonance when the sextupole lenses are switched off.

The energy range of the extracted beam was from 200 MeV/amu to 1.5 GeV/amu at the evaluated efficiency of about 70%. The duration of the extraction was 0.4 s.

Though the main task of the run has been solved quite well, the obtained beam characteristics have not achieved their project values. One of the reasons was the lack of time for tuning the extraction system since we had to share it with the physicists who were pressing us by their requests to receive the external beam for their experiments.

4. NEXT STEPS OF DEVELOPMENT

To obtain the designed parameters of the external beam, it is planned to carry out the following:

- Damping the ripples in current supplies of extraction lenses and of the main magnets;

- Using feedback between the external beam signal and the quadrupole current to "straighten" and stretch the beam spill up to 10 s and longer;

- Raising the extraction energy and receiving the extracted beams of other nuclei;

- Investigation of the influence of the initial position of the working point on the extraction process and finding optimal ways of the approach to the resonance (This way we hope to decrease, first of all, the effects of the resonance $2Q_x - Q_y = 7$);

- Providing the permanent orbit angle at the ESS azimuth by using a controlled bump during extraction to reduce losses on the septum and to increase the extraction coefficient up to the designed value (not less than 90%).

ACKNOWLEDGMENT

The authors greatly appreciate the contribution of many LHE employees to the implementation of the Nuclotron slow beam extraction.

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DAILY PROGRAMME

FRIDAY, June 30, 2000

Chair: Ch. Glashausser

9 ⁰⁰	L. Bimbot	Tracking Muons on ALICE's Arm	Page 285
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19 ⁰⁰		FAREWELL DINNER	



Tracking muons on Alice's arm

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Abstract

Alice is one of the four detectors to be used at LHC. Devoted mainly to heavy ions physics it will be equipped with a special arm for muon detection. After physics considerations on the interest of detecting two muons in coincidence, we will discuss : the requirements for the detection, the selected detectors and the plans for realisation of the tracking system. The status of specific R.& D. on CPC and associated electronics, done by the Institute of Nuclear Physics of Orsay will be exposed.

1. Introduction

The first new accelerator of the third millenium in Europe will be LHC (Large Hadron Collider) to be acheived at CERN in 2005. There will be four interaction points with four experimental setups: ALICE, ATLAS, CMS and LHCb as it shown on Figure 1.

ALICE (A Large Ion Collider Experiment) is the only detector dedicated to the study of nucleus-nucleus collisions. It will investigate the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma (QGP) is expected. One of the most sensitive probes of the plasma is expected to be the production of heavy quark vector mesons, i.e. J/Ψ , Ψ' , Υ , Υ' , Υ'' , which could be measured through their muonic decay in a forward muon arm [1]. A detailed description of the envisaged spectrometer was given in 1996 in an addendum [2] to the ALICE Technical Proposal (TP)[3]. The identification of the different heavy mesons requires a good background rejection and an excellent overall resolution. Apart of the shielding the tracking chambers play a crucial role.

*member of the Alice Collaboration

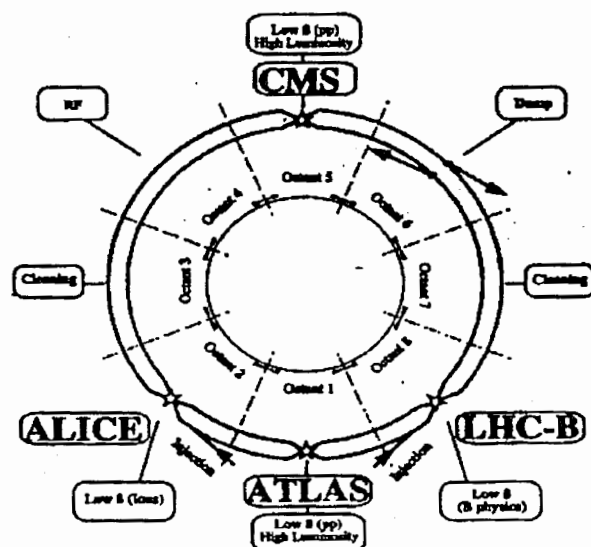


Figure 1. Schematic view of the experimental areas planned for LHC

They must be able to work at very high counting rate and they must be thin enough to keep the resolution to enable the separation of the different mesons analyzed. Different aspects - technical, mechanical and electronical - of developments will be presented in which the groups of the Orsay Institute of Nuclear Physics (IPN-Orsay) played an major role.

2. Physics goals and consequences

The physics goals of the full ALICE detector cannot be summarized in this modest contribution. A complete review can be found on the website at CERN[5]. I will concentrate on the role of the dimuon arm. By the name itself it is clear that it is built to detect two muons in coincidence. What can be expected from this signal has been reviewed recently[6]. I want to emphasize it as a sign of the muonic decay of heavy mesons - on a background - which is interesting to give access to study of QGP formation. Already promising within the NA50 experiment[7] and to be studied at RHIC[8], the process of Debye flavor screening [1, 9] will give, at the energies and lumi-

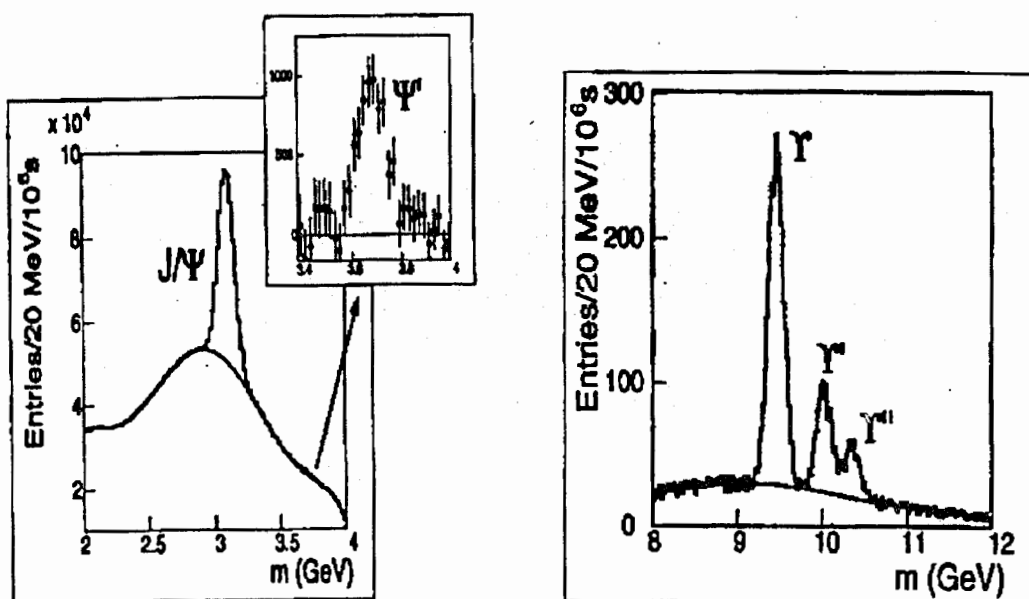


Figure 2. Simulations of production signal for J/Ψ , Ψ' , and Υ family

nosities of LHC, information on new state of nuclear matter. In addition to the current measurements at Cern it will be possible to access the Υ family to complement the observations made on J/Ψ and Ψ' at lower energy. The results of simulations of these reactions are shown in Figure 2, assuming specific characteristics of beam and detection. One must note that the resolution is crucial for discrimination between Υ , Υ' and Υ'' .

The meson identification is the missing mass calculated from muon energies and implies a good resolution in muon energy measurement, i.e. good localisation tracking chambers. The 'magic' numbers resulting from simulations is to obtain a resolution of the order of 100 μm on each plane in the deflecting direction, less than 2mm in the perpendicular direction and less than 3% of radiation length for each chamber. Another characteristic of the ion-ion collisions is the very high multiplicity of produced secondary particles what is expected to be up to 8000 per events and this requires a very sensitive and robuste detectors.

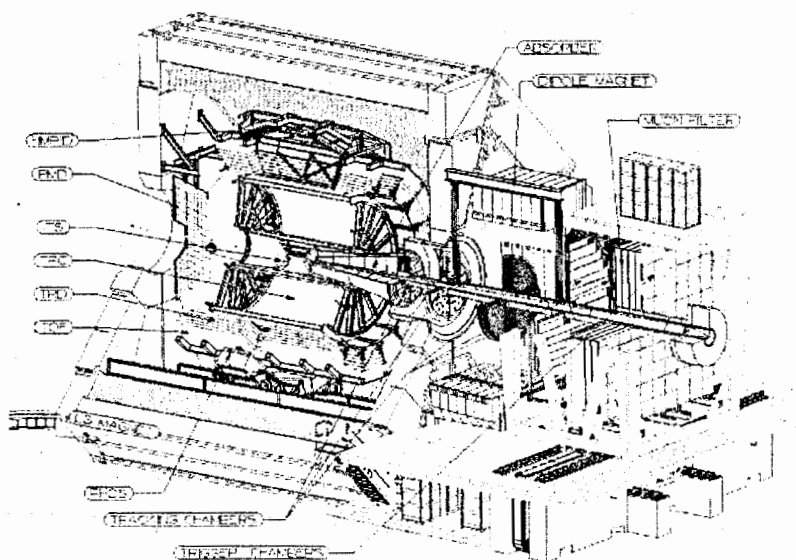


Figure 3. Artist view of Alice detector

3. The muon arm

The complete ALICE detector is shown in Figure 3. It consists of the magnet of the L3 experiment - a large solenoid with a week field - equipped with the following detectors:

- * The inner tacking system (ITS) made of silicum detectors.
- * The time projection chamber (TPC) for a robust tracking of up to 8000 particles per rapidity unit.
- * The barrel for particle identification (PID) using time of flight technology.
- * The high momentum particle identification detector (HMPID), a ring imaging Cerenkov counter.
- * The photon spectrometer (PHOS) made of PbWO₄ cooled at 25°.
- * The charged particles veto (CPV) for the PHOS with MWPC technology.

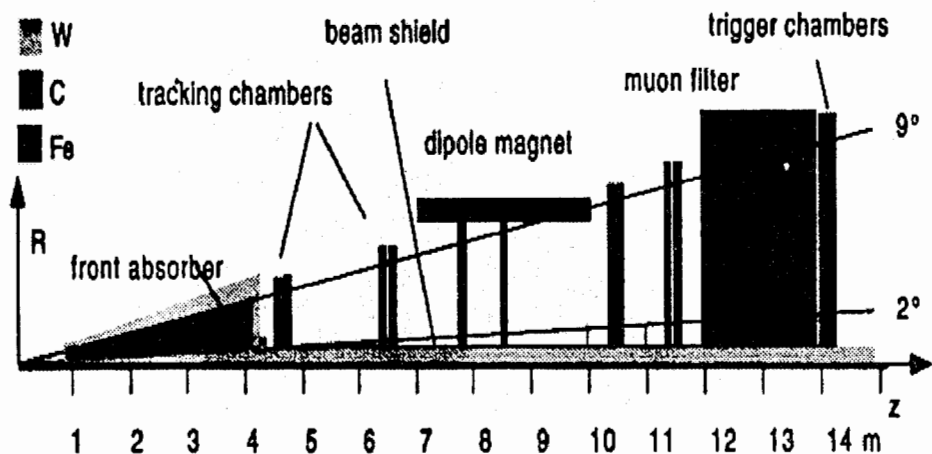


Figure 4. Schematic view of the dimuon arm. The acceptance is for an angle θ between 2° and 9° corresponding to a rapidity η between 2.5 and 4. There is 10 tracking chambers and 2 trigger chambers

- * The forward multiplicity detector (FMD) made of of micro channel plates and multipad Si detectors.
- * The zero degree calorimeter (ZDC) for proton and neutron calorimetry based on spaghetti type of quartz fibers.
- * The muon arm that is schematically presented in Figure 4 and detailed below.

All these systems have to be built but the technical design reports are now available [10]. The presentation today is more about the tracking system of the muon arm but it is important to remind the different other parts that will contribute to a high quality setup:

- the magnet (to be built at JINR Dubna[11]).
- the absorber.
- the shielding.
- the tracking chambers.
- the trigger chamber.
- the muon filter (1.2m of Iron representing $7.2 \lambda_{interaction}$).

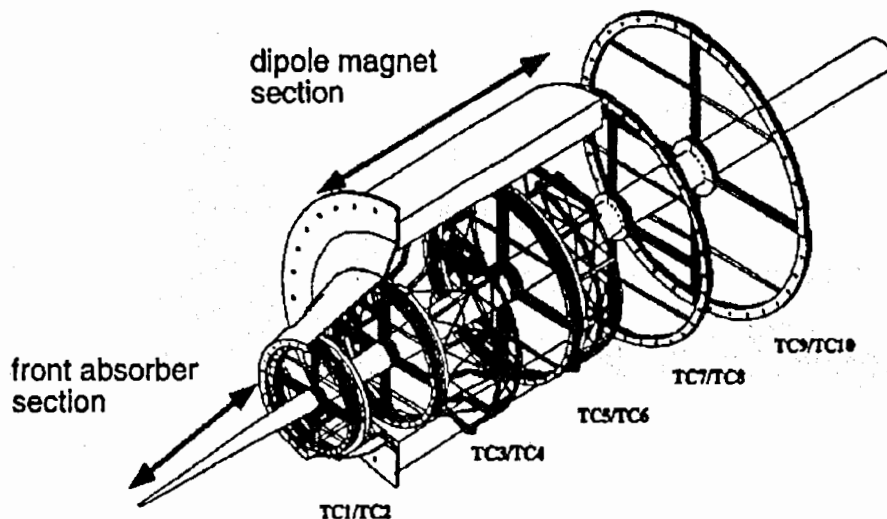


Figure 5. General layout of the tracking system

The figure 5 gives an idea of what the assembly of the tracking system will be, but nothing is yet finalized. The maintenance is an important criterium because of the lack of accessibility. The dead zones and material thickness are dominant issues. Progress and adaptations are made continously.

4. Tracking sytem

At the early stage it was necessary to choice the detector type. The requirements from the different stations are summarized in Figure 6. From litterature and simulations[12] it was decided to test on beam CPC (Cathode Pad Chamber) because these detectors offer a lot of flexibilty by changing the geometry parameters and can be adjusted to new requirements. They are also well studied , already used for experiments and robuste.

The building technique and physical principle are illustrated on Figure 7. The measured quantity is the induced charge distribution on different pads of a segmented cathode plane. The main difficulty when changing granularity is to find a path to extract signal from each pad. Two different prototypes have been built in Orsay, first to test the response of this type of detector

Station	Total hits	dN/dA max (0.01 cm ²)	Internal diameter (cm)	External diameter (cm)
TC 1/2	320	4.0	36	177
TC 3/4	340	1.6	46	224
TC 5/6	230	0.6	66	317
TC 7/8	380	1.0	67	440
TC 9/10	620	1.2	67	513

Figure 6. Requirements for the different tracking stations

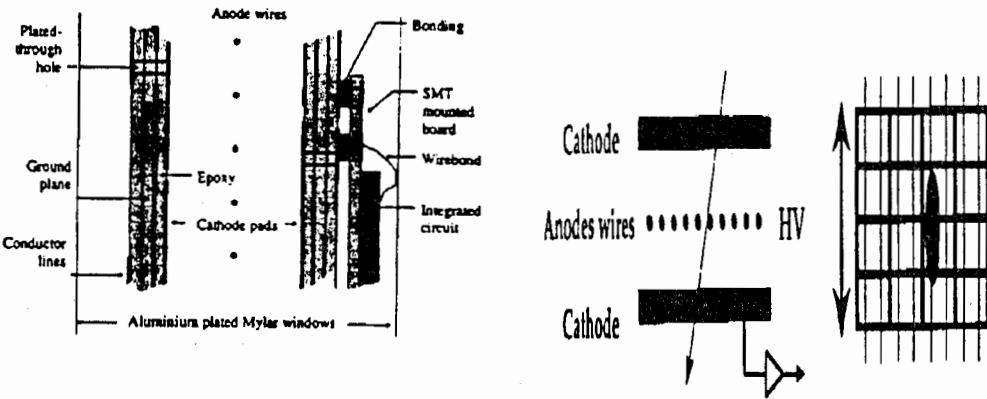


Figure 7. CPC structure and CPC principle

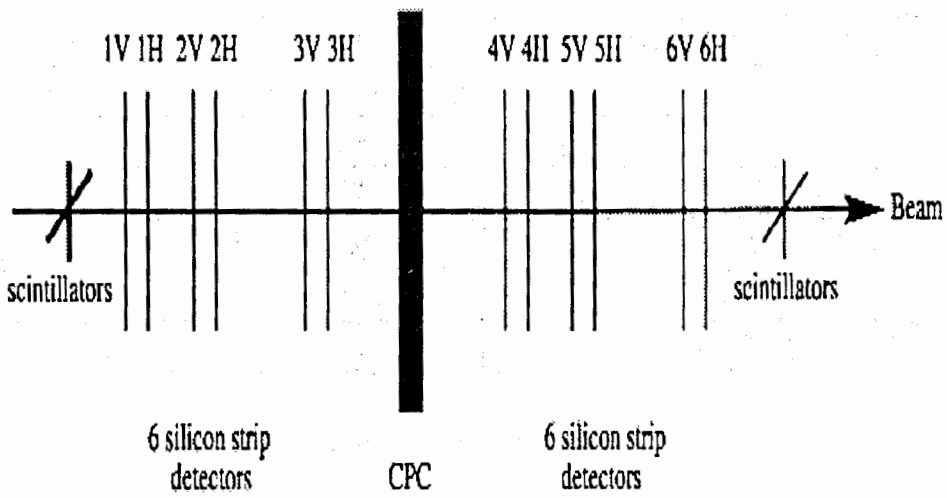


Figure 8. Experimental setup use to test prototypes at CERN

versus the different parameters: pitch, gap, wire diameter, gaz mixture, HV , etc... and then a real size one [13] to develop the skills for a complete design and construction.

5 Tests on beam

Tests have carried out at CERN with PS and SPS test beams. The general setup for these tests is shown in Figure 8.

For resolution studies, very precise Si micro-strips detector telescopes were use in front and behind the prototypes to determine the trajectory of particles to project at the CPC position and compare with the result the CPC itself deduced of the charges on pads. The results [14] have been exposed in details in the muon spectrometer TDR[4]. I will just present on Figure 9 the results on resolution studies. The crude comparison made on the left side of the picture shows a structure correlated with the position of the impact relative to the pad. If you introduce a polynomial correction function the residuals are reduced to a sigma of $28\mu\text{m}$, less than the required value of $100\mu\text{m}$. In the other direction the result of the measurement is less than $800\mu\text{m}$ (not shown).

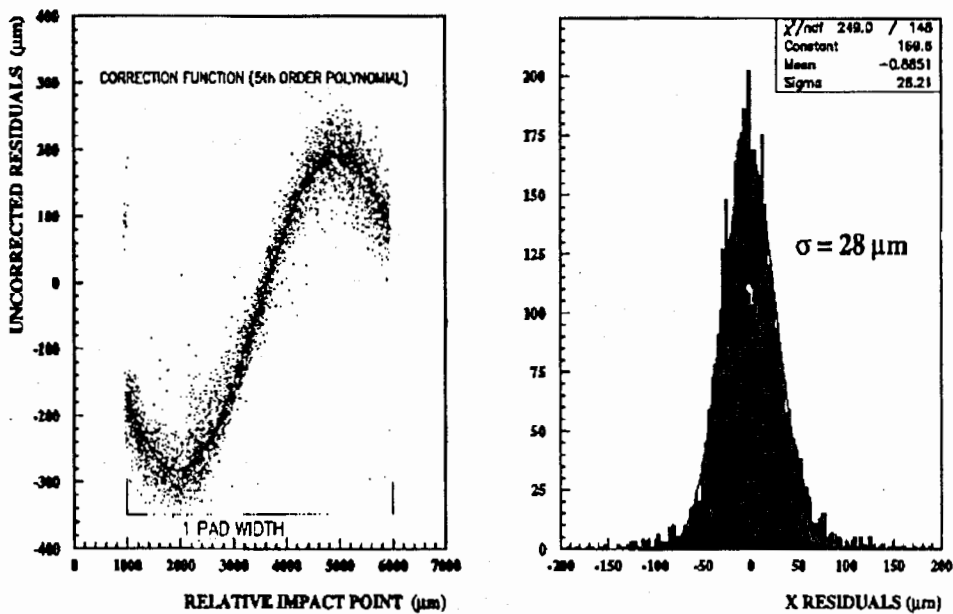


Figure 9. Resolution study of CPC prototype

The consequences on the resolution of the non perpendicularity of the tracks were of an acceptable amount (see Figure 10).

Other tests have proven that the behaviour of the detector is good agreement with model predictions and that the physical constraints help to determine the chamber geometry. A gaz mixture of 80% Argon and 20% CO₂ is the best compromise with safety and efficiency but the final composition may still vary lightly. Other tests have been developped in parallel by other groups [15] and all the expertises will be combined for the final realisation. The building by assembly of four quarters for each stations 1 and 2 has to be formalized and the technique for stations 3 to 5 is orientated towards a slat structure[16].

For the final detector the chamber geometries have been determined so as to be able to cope with the simulated particle densities and background levels. As may be expected modifications in the surrounding environment, such as beam-pipe shielding, external supports and absorber materials, all influence background contributions and impose modification on the chamber design. Mechanical solution will be different and adapted to the particular constraints imposed on each station.

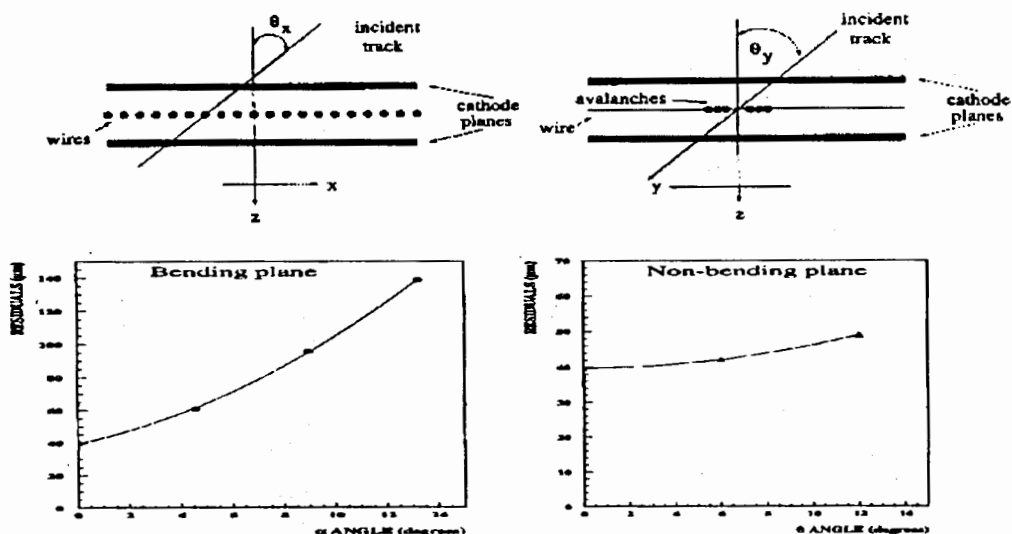


Figure 10. Angular dependence of the residual values

6. Electronics

On the contrary the electronic solution will be common to all detectors. It will be the fruit of research and development carried out in the past years by different participating institutes. For convenience of size, price and realisation a dominant part of the electronics will be on the detector itself. The full chain included :

- A MultiChip Module (MCM), the closest to the cathod pads. One module handles up 64 analog inputs. The MCM performs analog processing, ADC conversion, pedestal subtraction, zero suppression, data formating and transmission to the upper level via (DSP) via the digital local bus.
- A Digital Signal Processor (DSP). The local buses collect the data from up to 24 MCMs (depending on chamber and plane). Several buses run through each plane, making the data available to Digital Signal Processors located on the edge of the chambers. Each DSP can handle up to six buses.

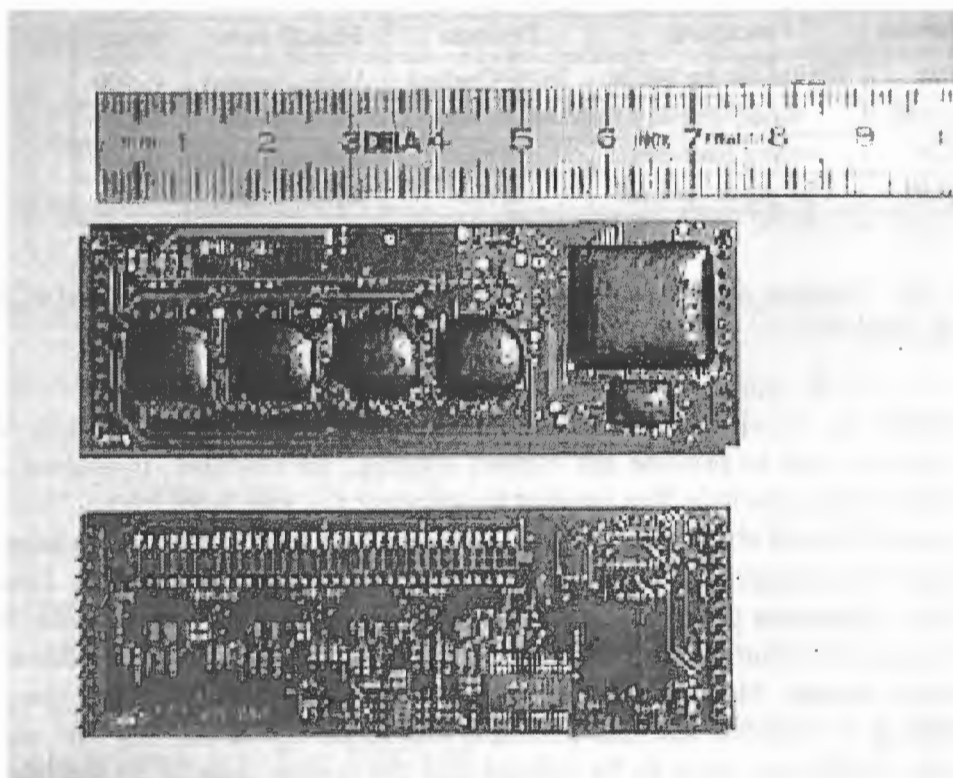


Fig. 11. View of the two sides of the fully package MCM

- The Cluster board. The DSPs are assembled onto cluster boards. Each cluster contains up to six DSPs. The whole cluster board can hence process 36 buses, i.e. 864 MCMs or 55,296 channels. The cluster boards communicate with the spectrometer top-level RORC cards through optical DDL links.

A prototype of the MCM is shown on Figure 11. It composed of three sections: a set of four GASSIPLEX preamplifier/shaper/multiplexers (MA-NAS-16 for **M**ultiplexed **A**NAlog **S**ignal-processor 16 channels), a 12 bits ADC and a complex custom-designed digital processor (MARC for **M**uon **A**rm **R**eadout **C**hip).

The list of the various designers and manufacturers is given in Figure 13 and illustrates the internationality of the project.

Future developments

For the electronics : the new asics, modules, processors, buses and connections have to be produced and tested. For the mechanics, the new open questions within the collaboration are : to decrease the Station 1 occupancy,

Component	Description	Designer	Manufacturer	Volume
Marc	Digital asic for MCM	INFN Cagliari	AMS (Austria)	15,000
Manas-16	GASSIPLEX	SAHA Calcutta	SCL (India)	60,000
MCM	Analog front-end	IPNO	IPNO (France)	15,000
Cluster	DSP processor card	IPNO	IPNO (France)	20

Figure 12. Various electronic components to be produced for the ALICE dimuon project

to decrease the dead zones in stations 1 and 2, to reduced the weight of these stations and to provide the correct cooling. As example, in station 1 an increase of the particle flux implies to decrease the gap from 2.5 to 2 mm, to decrease the pad sizes from 5×7.5 to $4 \times 6 \text{ mm}^2$ and to decrease the number of hit pads by staggering. These new geometry has just been tested in June at CERN. To reduce the weight and the dead zones, SINP[17] and IPNO[18] perform common studies, with overlap of the different quadrants and without aluminium frames. Mechanical prototypes will be available and tested soon. For stations 3, 4 and 5 the slat principle has to be validated, the size and assembly of different parts to be defined and the cooling also to be solved.

Summary

I have described the detector ALICE, giving the main lines but it must be clear that changes will occur before completion to adapt new technologies and/or new physics goals. Many R. & D. programs have been developped and I have given results concerning the tracking chambers of the dimuon arm. It had been proved by test experiments at CERN that a technical solution based on CPC will meet the physical requirements on counting rates and space resolution, given a constraint from simulations[2] and this choice seems flexible enough to enable better performances in changing the geometry parameters at the price of increasing the number of channels by chamber plane. The necessary characteristics of the electronics on board had also been defined and an international collaboration is organise to reach the goals and minimize the prize. This is now a long time plan that must be acheived by the year 2005 if we want to be ready in time to take benefit from the first heavy ion beams of LHC.

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The spectrometer HADES tracking system

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The High Acceptance Di Electron Spectrometer (HADES) is a detector system for lepton pair spectroscopy presently built up at GSI (Darmstadt) by a European collaboration involving groups from 22 institutions in 10 different countries. (<http://www-hades.gsi.de>).

The HADES Physics Program [1,2]

1. The study of lepton pair emission in relativistic heavy ion collisions.
2. Di-lepton production in elementary reactions (πp , pp).
3. Experiments aimed at studying the structure of hadrons.

As leptons do not undergo strong interactions but interact only electromagnetically they are considered penetrating probes of compressed hadronic matter formed within the collision zone of relativistic heavy ion reactions. Predominant dilepton sources for $m_{e^+e^-} \geq 500 \text{ MeV}$ are direct or Dalitz decays of vector and pseudoscalar mesons produced in these collisions. The very weak final state interaction allows a measurement of vector meson masses in the hot and compressed hadronic environment by reconstruction of the invariant mass from the lepton momenta. This provides the possibility to test theoretical predictions for a partial restoration of chiral symmetry at elevated temperatures and baryon densities which - as an experimentally observable consequence - would lead to reduced meson masses.

The HADES detector is specifically designed to provide excellent mass resolution ($\delta m/m \approx 1\%$) and very large acceptance for comprehensive studies of the behaviour of ρ , ω and ϕ - mesons in the nuclear medium. With a lifetime of $\approx 1 fm/c$ the ρ -meson is ideally suited for probing vector meson properties in the transient high density phase ($\approx 10 fm/c$) of heavy ion reactions. Possible mass shifts of vector mesons at normal matter density - predicted within the same theoretical frame work as well - can be tested with ω ($\tau \approx 22 fm/c$) and ϕ -mesons ($\tau \approx 44 fm/c$) which predominantly decay within the target nucleus if produced almost recoil free using a π -beam.

These series of experiments, exploiting the full range of primary and secondary beams available at GSI, will make important contributions to our understanding of Quantum Chromodynamics in the non-perturbative regime and, in particular, will provide information on the origin of hadron masses.

Below $500 \text{ MeV}/c^2$ dilepton spectra in heavy ion collisions are dominated by η -Dalitz decays, Δ -decays and nucleon-nucleon as well as π -nucleon bremsstrahlung. For a quantitative interpretation of dilepton spectra in heavy ion collisions the latter contributions have to be measured separately in elementary p - and π -induced reactions while the η -Dalitz decay contribution can be identified by measuring γe^+e^- coincidences employing an additional photon detector, e.g. TAPS.

The electromagnetic structure of mesons and baryons can be studied by measuring their time-like formfactors which are important ingredients in any modelling of hadrons. Transition form factors can be deduced from the shape of the dilepton invariant mass spectra from γe^+e^- or $\gamma\gamma e^+e^-$ Dalitz decays of neutral mesons. A precise knowledge of these formfactors is also important for a quantitative understanding of dilepton spectra from heavy-ion and π -induced reactions. To perform such measurements with HADES the present set up has again to be combined with an electromagnetic calorimeter for photon detection.

Design of the Spectrometer

HADES is comprised of the following main components: Cherenkov detector (RICH), Multi-layers Drift Chambers (MDC), Superconducting toroid with 6 coils (Coil), Time-of-flight detectors (TOF), Electromagnetic shower detector (Shower).

Spectrometer consists of six identical sets of detectors (sectors), one sector covers 60 degrees in azimuthal angle. The particles created in target without scattering for large angles provide track only in one sector. This feature allows searching tracks independently in each sector.

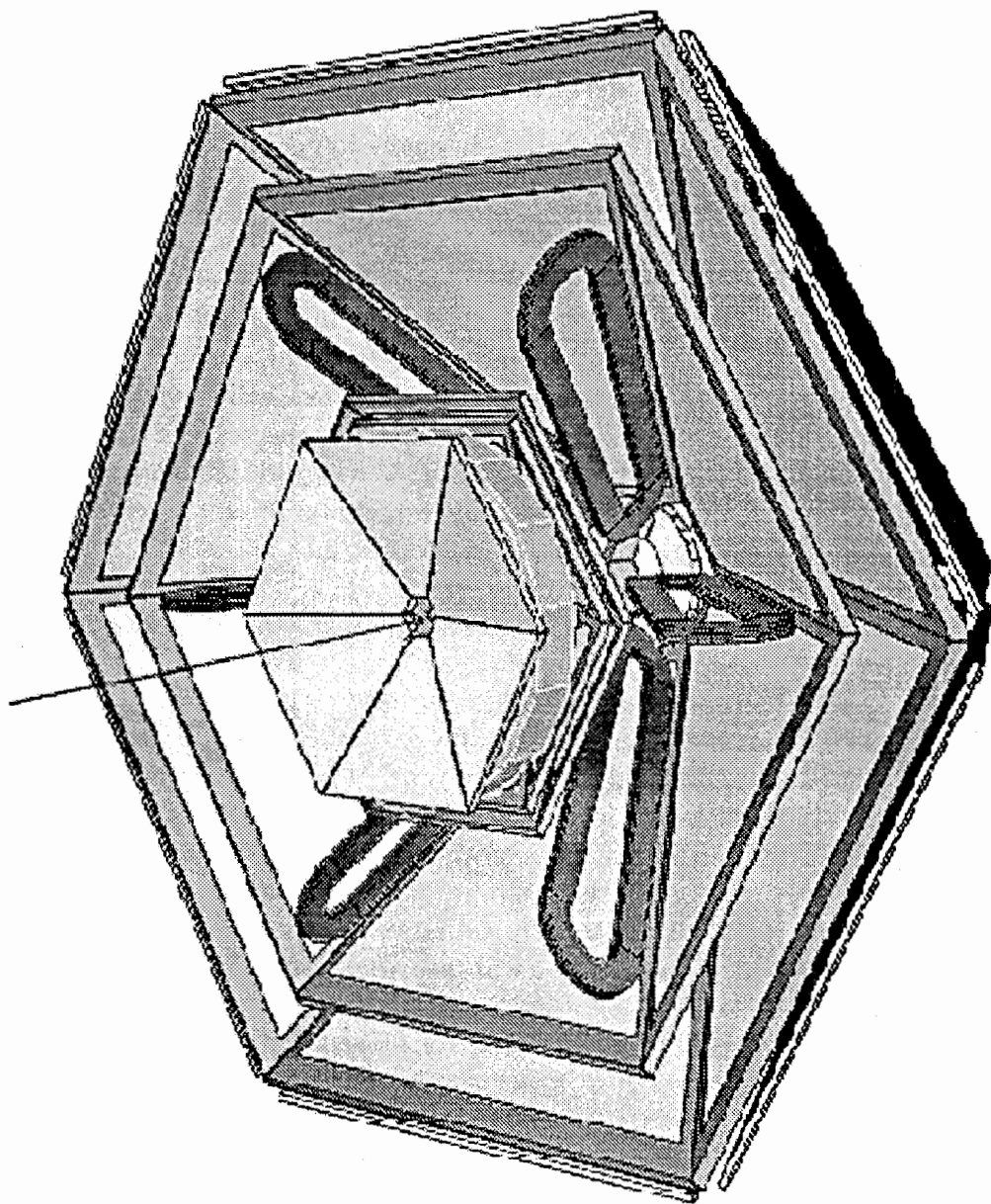


Figure 1. The spectrometer HADES

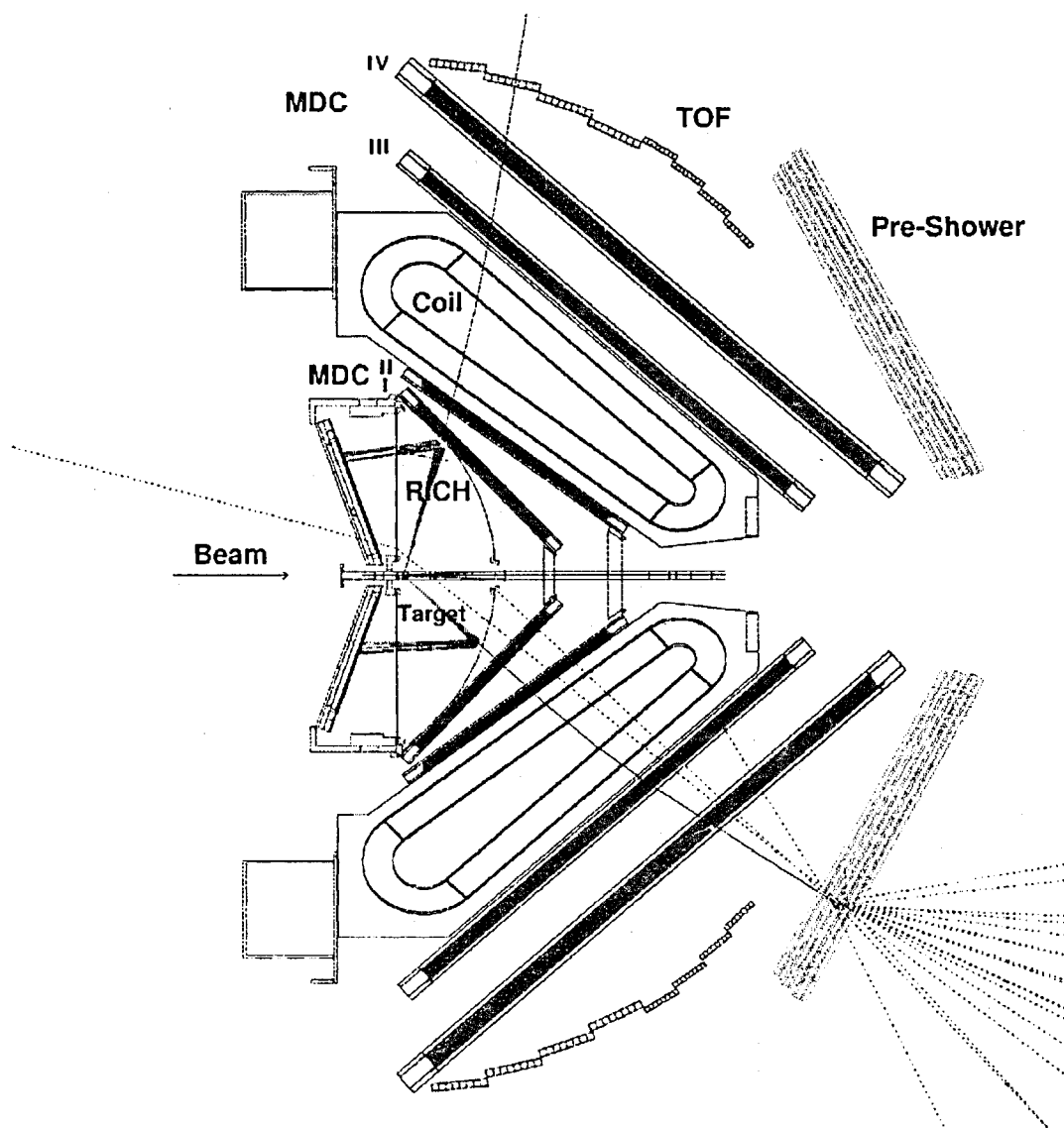


Figure 2. Azimuthal cross section of the HADES setup

The system of Multilayers Drift Chambers [3,4]

The system of Multilayers Drift Chambers is the main tracking part of the spectrometer. Each sector contains four MDC chambers (two inner and two outer chambers). In the current design each chamber module consists of six drift cell layers and seven cathode planes. The wire planes have orientations $+40^\circ, -20^\circ, 0^\circ, 0^\circ, +20^\circ, -40^\circ$, with respect to the normal on the symmetry axis of the module. All (anode) are separated from each other by field (cathode) wires.

Table 1 contains the distances between sense wires (H), distances between cathode planes (W), geometrical sizes of MDC, (MDC has trapezoidal shape).

As an output MDC information provides number of fired wire and drift time. After calibration procedure the drift time information is converted to distance between track and sense wire. The space resolution of MDC is about $70 \div 100$ microns. Six sense planes in each MDC module and high efficiency allow to reconstruct pieces of tracks (position and orientation) independently in each module.

Table 1

MDC module	H (mm)	W (mm)	Dimensions (mm)			Num. of sense wires					
			A	B	C	+40°	-20°	0°	0°	+20°	-40°
I	5	5	144	800	880	168	173	156	157	176	176
II	6	5	205	905	1088	184	192	172	172	192	192
III	12	8	359	1905	2186	187	191	171	170	191	188
IV	14	10	395	2338	2748	192	200	184	184	208	200

Tracking in MDC's.

The algorithm for searching and reconstruction of tracks is base on the two main features of HADES spectrometer:

a) The maximum calculated multiplicity is $20 \div 25$ charged particle per module. It is ease to estimate that in case of selection of all possible combinations fired wires we have about 10^6 combinations in one module. That is way it is desirable to have preliminary filter program for reducing of combinations.

b) The magnet is constructed in such a way that magnetic field practically don't penetrate into MDC modules and in the first approximation parts of tracks before and after the magnet one can describe with a straight line. It allows to reconstruct pieces of tracks simultaneously in 2 modules (inner I-II and outer III-IV).

Tacking into account above information we can mark out the following steps in this algorithm:

1) The searching of track candidates in MDC-I and MDC-II (preliminary filter). As a track candidate we assume the number of fired wires which corresponds to one track and the initial approximation for coordinate of this track.

2) The fitting of this pieces tacking into account drift time information. During this step fitting procedure defines either the considered candidate is a real or false one and with numbers of fired wires are corresponded to this track.

3) The vertex definition and correction for track parameters tacking is into account vertex information.

4) The searching of track candidates in MDC-III and MDC-IV (after magnetic field) assuming that these tracks should continue tracks before magnetic field. In the other words for tracks which have been find in MDC-I and MDC-II the continuation of these tracks will be searching in MDC-III and MDC-IV.

5) Fitting of found candidates tacking into account drift time information and checking of correspondence between tracks from inner and outer part of MDC.

6) Fitting of all track and definition of particle momentum.

Method for searching of track candidates.

The method is base on the two main features of HADES spectrometer. Firstly, the size of target is small enough in beam direction respectively to distance from the target to MDC (> 40 cm) and straight-line shape of the tracks with good approximation between target and magnet.

The basic idea which is behind of this method is the projection of sensitive volumes from fired wires to one plane (see fig.3). Due to non point-like shape of the target, the projection for each wire is done respect to the first (in beam direction) and last point of the target. Projections of sense volumes for fired wires from one particle (which is going from the target) provide overlap

region on this plane. For searching such regions on the projection plane the 2-dim plot is created. The bins of this plot are increased for 1 in case them "darken". So, in the overlap region of the projection from the fired wires we have a spike (see fig.4).

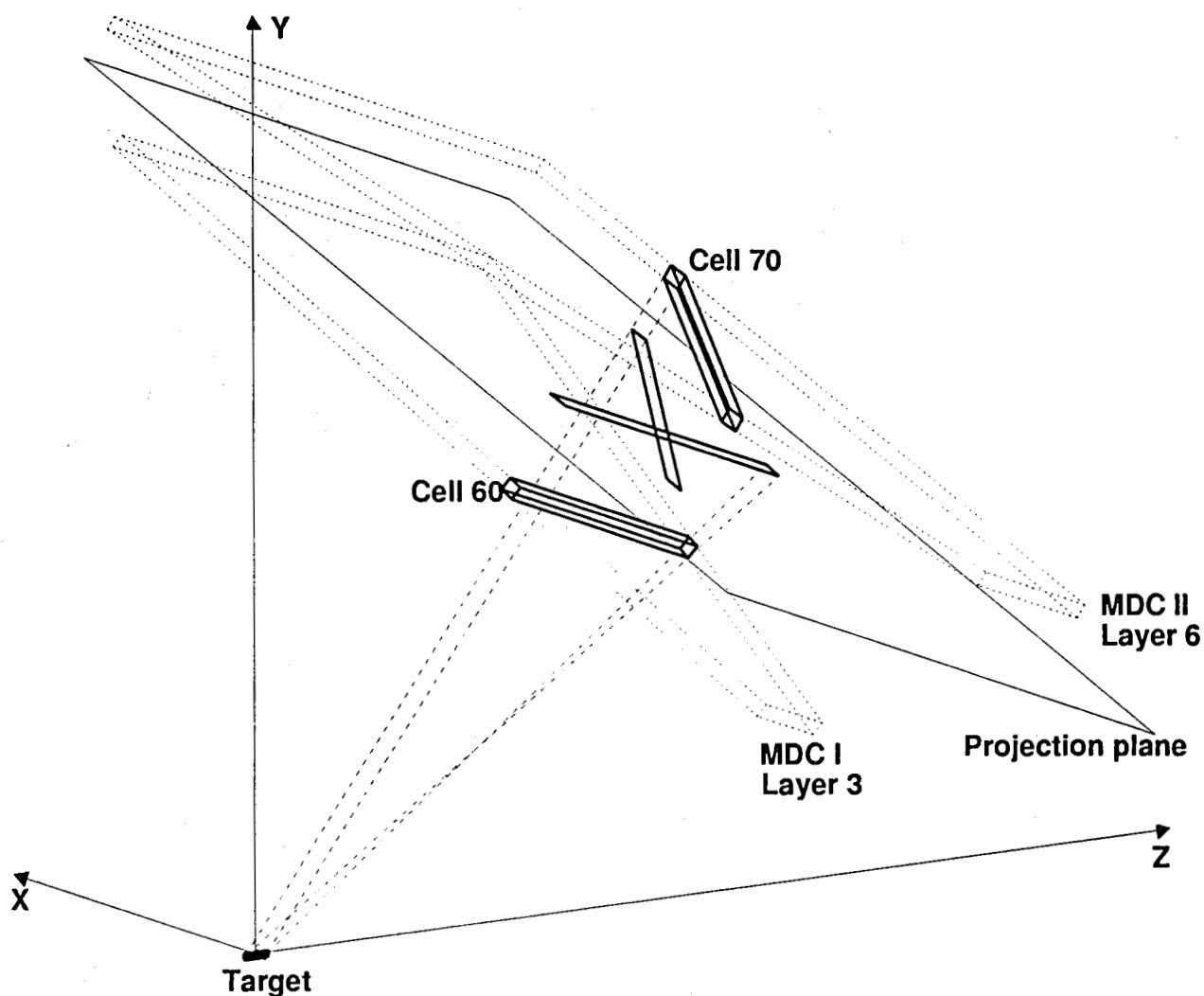


Figure 3. The scheme for projection of the sense volumes of the wires to one plane respectively to the target. The beam of accelerated nucleons has direction in Z-axis. MDC I Layer 3 and MDC II layer 6 are volumes of drift gas for 3-rd and 6-th planes of sense wires in MDC-I and MDC-II, respectively. Cell-60 and Cell-70 are sense volumes for wires with number 60 and 70, respectively. The thickness of drift gas volumes and geometrical sizes of sense volumes are increased in 3 times. Projection plane is the plane for projection of sense volumes from the fired wires. The projections from two sense volumes of fired wires are depicted. Target consists of 12 planes. Dotted lines depict the projection procedure

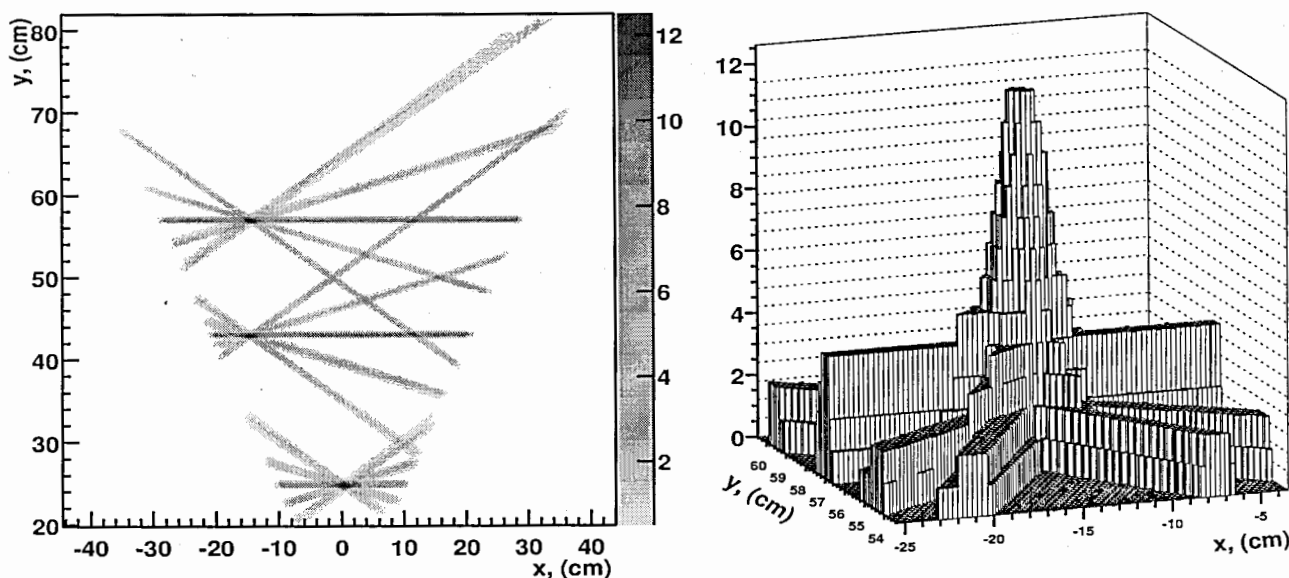


Figure 4. Left picture shows 2-dim plot obtained for one sector of spectrometer with 3 passed particles (simulated data). The scale on the right side shows correspondence between value and color (gray scale) bin in plot. Right picture shows 3-dim presentation of the left picture for 1 passed particle

The testing of the method on simulated data

For checking of the method we used 200 simulated data for central $Au - Au$ collisions (the average multiplicity is about 15 particles per sector) (see fig.5). The simulated events were proceeded by GEANT package, where the passage of the particles from the detector materials, air and magnetic field was simulated. The GEANT output information was transformed into detector responses.

Table 2 contains results of analyze as a function of occupancy. In the table the following designations are used. $N_{tr.}$ - number of fired wires from one track in MDC-I and MDC-II in one sector. $N_{cl.}$ - number of wires provided one cluster. $N_{cl.(tr.)}$ - number of wires from the track which provides this cluster.

Table 2

Occupancy per one sector	5	15	25
$\langle N_{cl.(tr.)}/N_{tr.} \rangle$	99.8%	99.6%	99.2%
$\langle N_{cl.(tr.)}/N_{cl.} \rangle$	90%	82%	72%
Fraction of false clusters	4%	10%	24%
Fraction of clusters contained 1 track	98%	95%	92%
Fraction of "lost" clusters	3%	6%	6%

The first line in this table shows the average ratio of wires selected by studying method from the total part of wires fired from one track as a function of occupancy. It is seen that practically all wires have been found. Some wires could be lost due to scattering on large angles.

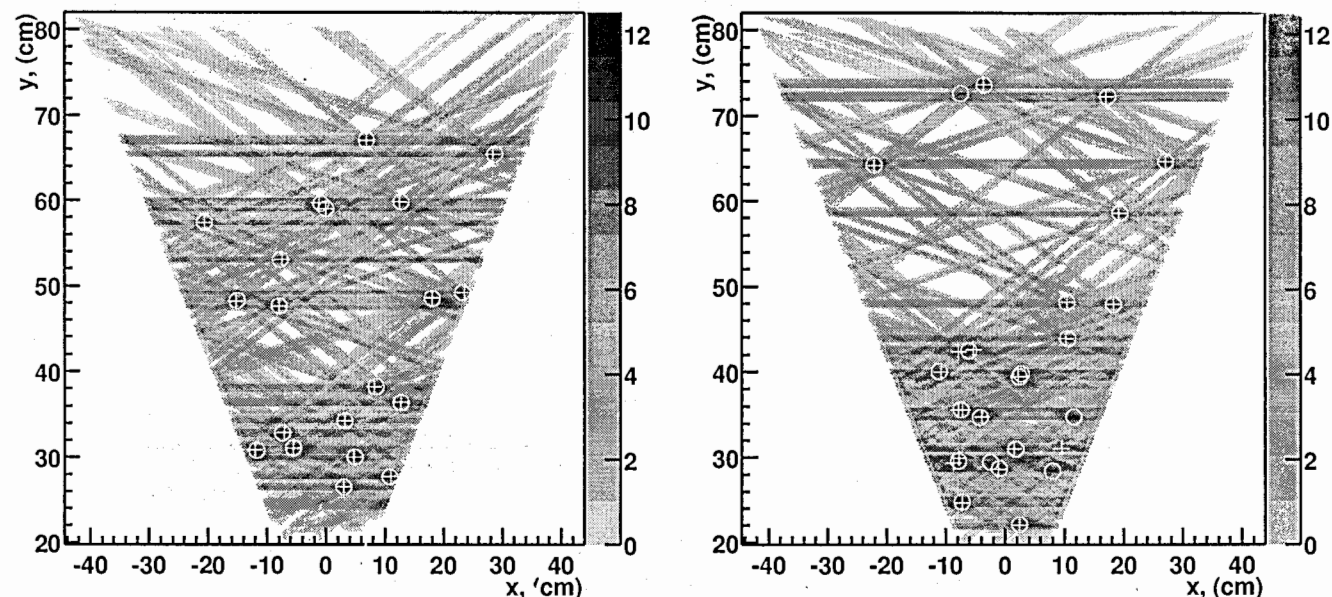


Figure 5. 2-dim. projection plots. White crosses correspond to intersections of tracks and projection plane. White circles marks track candidates which have been found by the program. On the left picture 20 particles (going from the target) and one δ - electron (is not marked by cross) are shown. All tracks have been found. Right picture shows 22 particles (from the target) and δ - electron. 23 clusters have been found, 5 of them are false, 3 contain 2 tracks, one track is lost

Second line shows the average ratio of the fired wires from one track in the cluster from the total number of wires in the cluster. It could be easily seen that number of "alien" wire is getting more in case of occupancy increasing.

Third line indicates the average ratio of false track candidates.

Forth - ratio of clusters contained one track only.

Fifth - ratio of lost tracks (the reason is the scattering for large angles). In case of occupancy equal to 5 the ratio of lost tracks is less due to threshold for searching of clusters is decreased up to $H_{min} = 10$.

Figure 6 shows the resolution for candidate search method in X and Y directions. The average values of coordinate differences and RMS are presented on this picture. The fitting with gauss function provides the following values $\sigma_{x_g-x_c} = 0.16$ cm and $\sigma_{y_g-y_c} = 0.07$ cm

If the second point of the track is the center of the target, than one can calculate the cross point with sense planes and compare with known values from GEANT package. Table 3 contains resolutions (defines in this way) for some different planes. Plane 1 MDC-I is the nearest to the target, plane 6 MDC-II - the most remote.

Table 3

	$RMS_{x_g-x_c}$ (cm)	$\sigma_{x_g-x_c}$ (cm)	$RMS_{y_g-y_c}$ (cm)	$\sigma_{y_g-y_c}$ (cm)
MDC I, Layer 1	0.249	0.162	0.158	0.131
MDC I, Layer 6	0.248	0.161	0.138	0.112
Projection plane	0.241	0.158	0.108	0.072
MDC II, Layer 1	0.294	0.196	0.144	0.100
MDC II, Layer 6	0.305	0.208	0.162	0.122

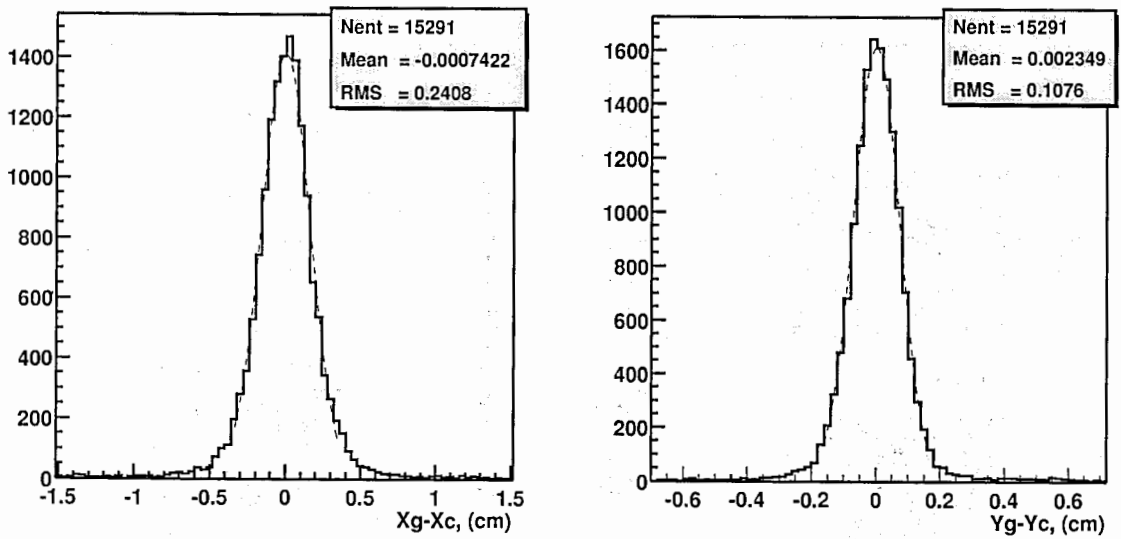


Figure 6. The resolution of the candidate search method. $(x_g - x_c)$ and $(y_g - y_c)$ - difference of coordinate of cross point the projection plane (x_g, y_g) and cluster position on this plane (x_c, y_c) . Dotted lines are the fitting with gauss

Testing and using of candidate search method on real data

First tests of HADES spectrometer have been done in 1999. During these tests two chambers of MDC-II was operated (which has been fabricated in LHE Dubna). The maximum height of spike for this data can't be more than 6 (see fig.7). For projection plane the first sense plane of MDC-II was taken. The same geometry as for simulated data was used, because the measurements with good accuracy for definition of position MDC have not been done.

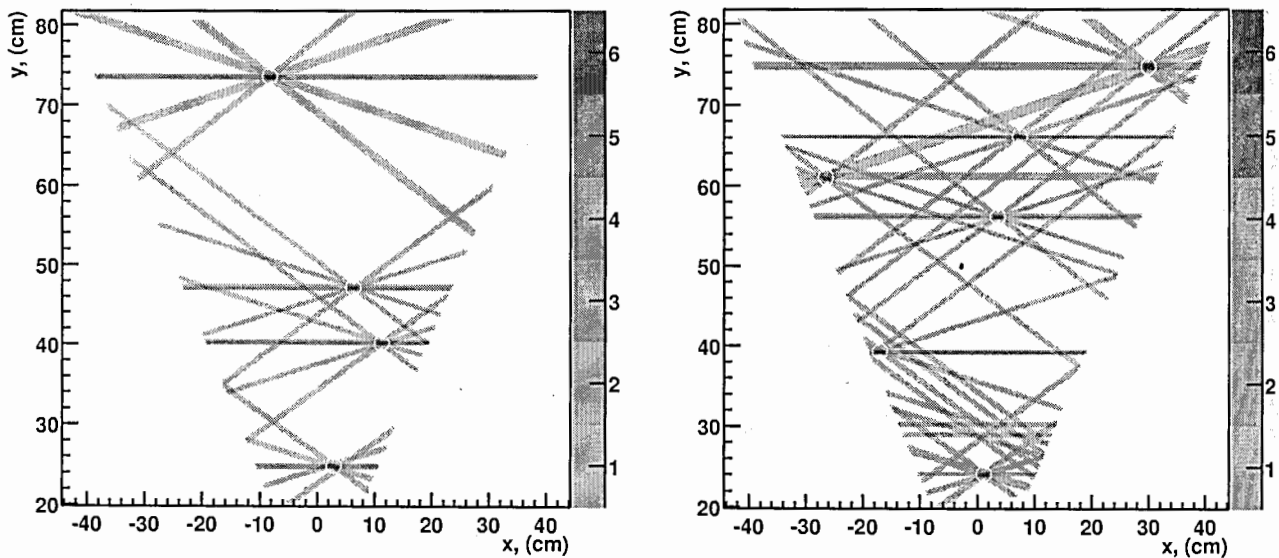


Figure 7. 2-dim plots. White rings are the track candidates, which have been found by program. Experimental data

Together with Time-of-Flight (TOF) the comparison of tracks in TOF and MDC detectors has been done (see fig.8). TOF detector consists of 64 scintillator strips which are parallel to X -axis. The scintillators rods are read-out from both sides by photomultiplier tube. Using time of flight information the x coordinate can be reconstructed. Coordinate y could be found using position of the strip in the space. TOF covers region of projection plane with y coordinate large than 50 cm. The experimental data without magnetic field were used. For coordinate calculation the assumption that tracks are started from the target has been used. For this comparison only events with one track in TOF and MDC in the region with y -coord. large than 50 cm (this region is covered by TOF detector) were used.

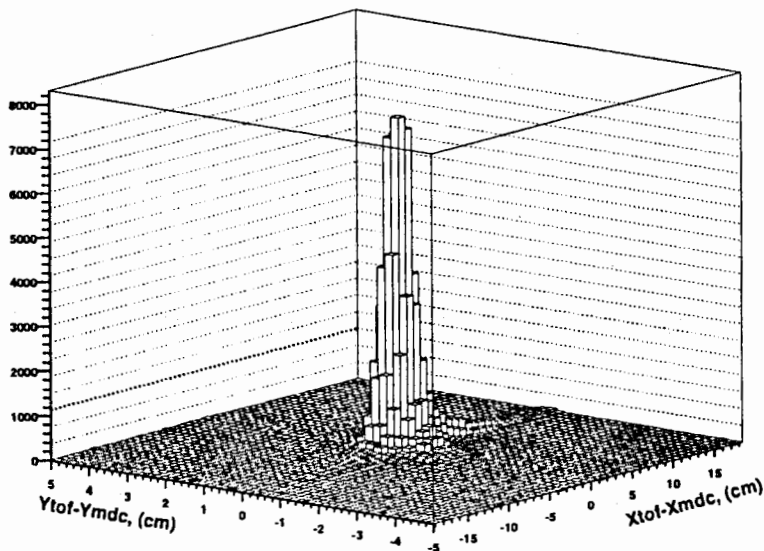


Figure 8: x_{tof} and y_{tof} - track coordinate obtained by TOF detector and transformed to the projection plane coordinate system . x_{mdc} and y_{mdc} - coordinates of cluster on the projection plane.

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Low-Energy Fragments Research in $d+Au$ Reactions

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1. Scientific novelty

The investigation of inclusive fragmentation processes in nucleus-nucleus collisions at relativistic energies has been taken over more than 20 years. Many phenomenological models are built on their basis.

Professor Nikitin's group has been investigated cross-sections of emission of heavy fragments of energies from 20 to 200 MeV at Synchrophasotron beams. Cross-sections' behavior in energy range higher 50 MeV is in accordance to theoretical predictions, but at fragment energies lower 50 MeV theoretical model is in discrepancy with experimental data.

In framework of MARUSIA collaboration we have taken an experiment ITELEF to study low-energy heavy fragments production. The experiment was not planned specially.

2. Experimental setup

2.1. Fragments detection problem

The investigation of heavy low-energy fragments is problematic due to difficulties of their detection. Low fragment energy binds us to make thin targets that leads to low fragments production cross-section and makes it impossible to take experiment on extracted beam. Use of internal target allows us to reach high luminosity by multiple passes of accelerated beam through target material.

A common problem in nuclear physics experiment is the charge identification of the fragments emitted. Usual technique of Time-Of-Flight becomes unacceptable. It is almost impossible to know time when particle interacts with target. On internal target experiments for identifying heavy fragments a two-stage detector telescope technique is adopted. A thin first stage detector measures the energy loss of particle ΔE , the second stage detector measures the residual energy E . Combining two signals, one can identify the particle charge, and in some cases also mass, using energy loss dependence.

There are commercially available detectors with only up to $5\text{ }\mu\text{m}$ as minimum thickness. They are also quite expensive due to manufacturing difficulties. This didn't allow them to study fragments with energy lower 20 MeV because energy loss in first stage of telescope becomes comparable to the energy of fragment.

Professor Nikitin's group used telescopes of silicon semiconductor detectors with thickness of first stage detector as low as $6\text{ }\mu\text{m}$. This limited investigation of heavy fragments to energies higher 20 MeV, leaving region of fragments energy lower 20 MeV untouched.

2.2. Silicon detector telescopes

The progress in microelectronic technologies in last years allowed building principally new type of semiconductor telescopes - monolithic silicon telescope [2]. An ultrathin silicon detector of $1\text{ }\mu\text{m}$ thick implanted on a standard $400\text{ }\mu\text{m}$ Si-detector has been manufactured by SGS Thomson in Catania (Italy) with the collaboration of the CNR-IMETEM laboratory. Telescopes are built with ion implantation technology and thermodiffusion. 4 experimental samples of that telescope were kindly allowed to us for experiments on internal target of Nuclotron in framework of MARUSIA collaboration.

2.3. Front-end electronics restrictions

Electrical capacitance of $1\text{ }\mu\text{m}$ thin ΔE stage detector and active area 12 mm^2 is 2 nF. This restricts usage of standard Si-detector electronics and lead to build new amplifier. Energy loss in ΔE stage for α -particle with characteristic energy 5 MeV is 140 keV [1], this induces voltage step of amplitude $3\text{ }\mu\text{V}$ on detector capacitance, so usage of standard spectrometer is not acceptable.

Another specialty of monolithic telescope is reciprocal induction between the two stages of the detector due to intrinsic resistivity of common implanted anode. In fact, when high charge is collected from E stage, a large negative signal is induced in the ΔE detector. The decay time of this signal is relatively small with respect to one of the true ΔE signal, then, using a large integration constant in the amplifier, the processed signal results nearly independent of the E one.

3. Amplifier

The signal produced by thin silicon detector is necessary to amplify to satisfy ADC input range. The amplifier should not dramatically decrease energy resolution presented by detector itself.

3.1. Shaping

Besides its main function, spectrometer amplifier also shapes the signal. It is necessary for optimization the signal/noise ratio of spectrometer and as a result energy resolution. The moments of interaction of particle with detector are random distributed and increment of event rate leads to effect of superposition of pulses. To decrease the effect one use differentiating circuit and by decreasing differentiation time constant it is possible to eliminate the superposition effect. The dependence of shape of signal and geometrical place of interaction of particle with detector usually makes necessary to use second integrator stage in amplifier to eliminate the induction effect.

So, it is important to optimize time constants in amplifier to reach optimal signal/noise ratio and next energy resolution.

3.2. Noise sources

Main noise sources in Si-detector spectrometer are fluctuations of detector background current and front stage amplifier current.

3.3. Amplifier schematics

Both ΔE and E channels of amplifier are build by similar design with the difference that in ΔE channel parallel FET input transistors are used to reach necessary signal/noise ratio and capacitance matching between detector and amplifier. In order to reduce the effects of the mismatching between 10 FETs in parallel, each one has been source degenerated through a resistor and a by-pass capacitor.

Besides linear spectrometric output the amplifier has fast output used to start trigger and to count number of particles detected by telescope.

3.4. Calibration at vacuum stand

To measure linearity and noise resolution of detector-amplifier system we take some runs at special vacuum stand chamber at pressure of 10^{-6} Torr. The spectra taken when irradiating the telescope with α -particles from ^{226}Ra source were matched with known spectrum of ^{226}Ra . The noise resolution of E channel was 30 keV and linearity in energy range up to 8 MeV was better than 0.04%.

Main difficulty is calibrating of ΔE channel with absence of low-energy beams of heavy ions. Sensitivity of ΔE channel was measured by energy losses of α -particles in thin first stage detector. Energy resolution of ΔE channel limited by noise was 40 keV.

4. ITELEF Experiment

4.1. Setup placement

Detector and preamplifier modules are situated on Nuclotron internal target setup. DAQ electronics are situated at a distance of 60 m in internal target operator's hall. The near presence of high-voltage acceleration stations lead us to use of special filters in analog signal transmission lines and optimization of grounding to prevent high-frequency induction on detector signal.

4.2. DAQ electronics

DAQ system is done in CAMAC standard. System is controlled with intellectual CAMAC crate controller CCPC4 [?]. It is based on AMD 5x86 133MHz processor. 10-bit Ortec ADC 811 together with spectrometric amplifier-shaper performs digitizing of analog signals. The ADCs we had available didn't let us to extend integration time as large as 1 μs which in turn limited ΔE channel energy resolution.

4.3. Online data processing system

The choice of OS for real-time data processing was limited by functionality of CCPC4 crate controller and MSDOS was optimal for our needs. The development of online data processing program was held in framework of Borland Pascal 7.0 with integrated debugger which with very high compilation speed allowed us to make corrections to program and modifications of data processing algorithm just on the fly.

Developed data processing package also presents data on monitors connected in convenient graphical view. One can see 2-D $E - \Delta E$ scatter plot with data captured in real time, the magnitude of magnetic field during acceleration cycle, beam intensity and instantaneous detector load.

4.4. Beam monitoring

Operator defines the trajectory of target. The position and intensity of beam in Nuclotron chamber is monitored by beam profile ionisation probe that is read every accelerating cycle. Beam and target interaction in real-time is presented on the graph which allows us to optimally adjust the trajectory of target for optimal detectors' load.

4.5. Target

The investigation of low energy heavy fragments imposes limitations on target thickness. In our experiment we used Nuclotron internal target station [3] with thin target made by vacuum injection of $0.045\mu\text{m}$ Au layer on $3\mu\text{m}$ polyester strip of 3 mm width.

4.6. Calibration and stability monitoring

We put an weak intensity ^{241}Am α -radioactive source near detectors that allowed us to monitor stability of setup parameters and calibrate signal circuits. During 10 days system collected 10^6 events from α -particles from this probe radioactive source. The stability of its spectral line was better than 100 keV which is comparable to noise level in E channel. The short-period E channel resolution was 50 keV.

4.7. Fragments separation, energy resolution

We take a series of experiments on deuteron beams with energies from 170 up to 1500 MeV. The setup showed the ability of identification of fragments with $E - \Delta E$ method.

5. Results

The build experimental setup allows the investigation of heavy fragments with energies in range from 1 MeV to 100 MeV and their identification by energy losses in $1\mu\text{m}$ Si layer with energy resolution of 50 keV with help of monolithic Si telescope. This opens a new area of investigation of heavy fragment with energies, not studied earlier.

In ITELEF experiment we got new data for emission of low-energy heavy fragments in interaction of relativistic deuteron beam with thin Au target on Nuclotron acceleration complex.

Experimental data taken at ITELEF experiment is shown to be crucial to theoretical models.

6. Perspectives

It is easy to improve energy resolution with help of special integrating ADC in ΔE channel which will allow integrating time constant as large as $10\mu\text{s}$. The investigation of fragments with energies below 1-2 MeV requires trigger to be started from ΔE signal.

In experiment performed we couldn't detect fragments heavier than N due to limitation in time by 1 hour.

The increasing of target thickness will increase fragments emission rate but will lead to performance decrease due to energy losses by heavy fragments in target material.

7. Conclusion

We are planning to participate in investigation of transmutation problems. In particular it is important to know which beam energy is optimal for transmutation. Next point of problem is what beams are most efficient - deuteron, alpha or another. The investigation of full nucleus collapse is important for future technologies in energy production area.

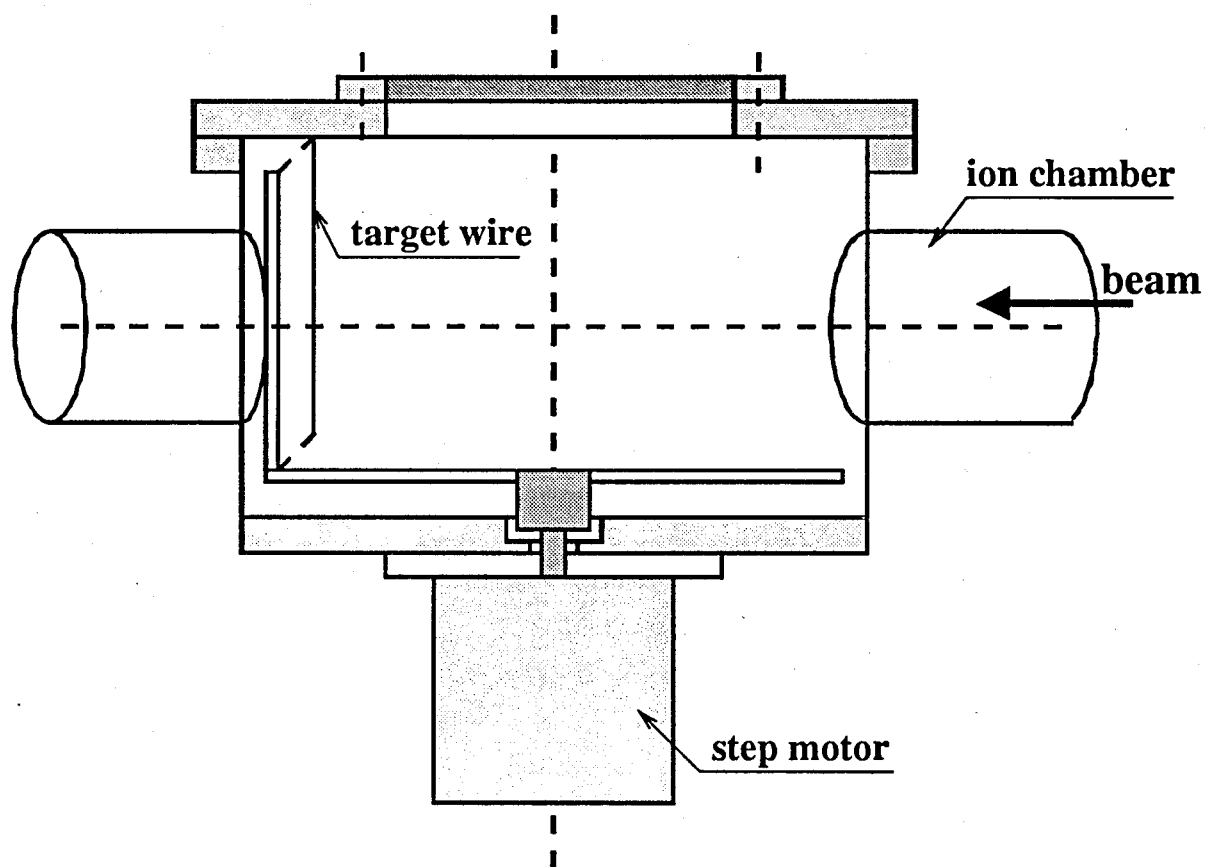


Fig. 1. Internal target chamber

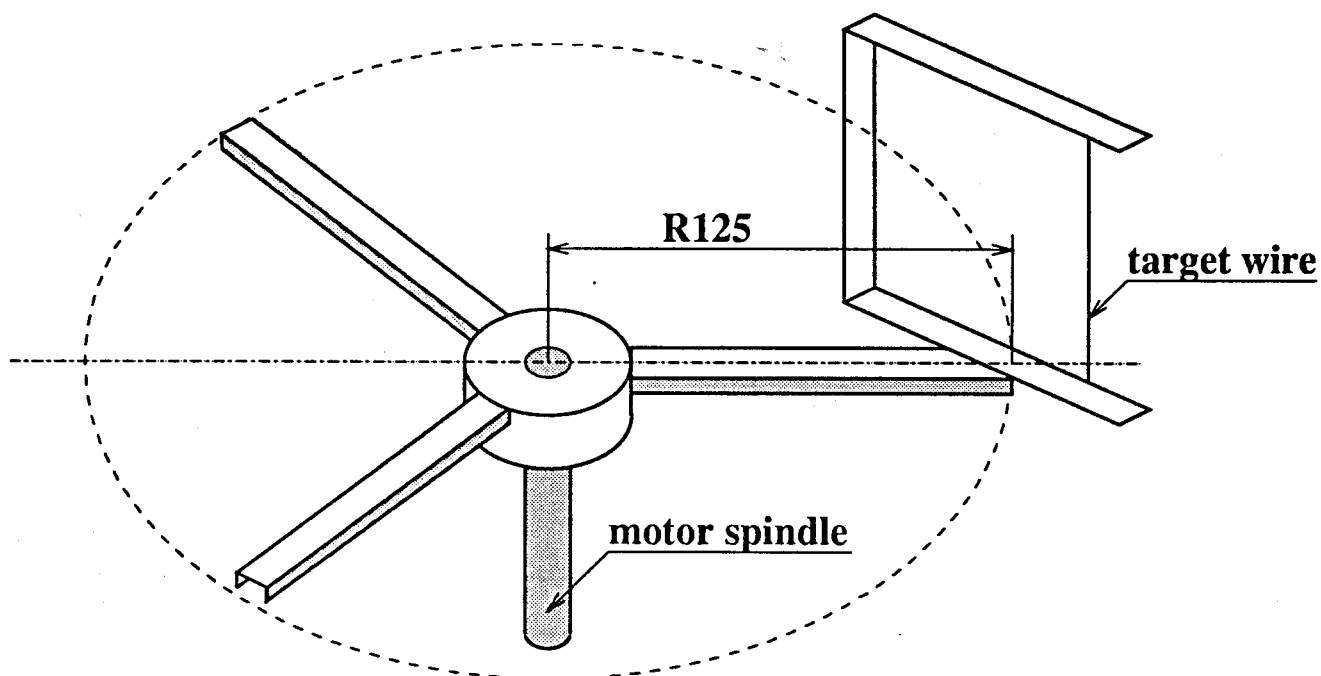
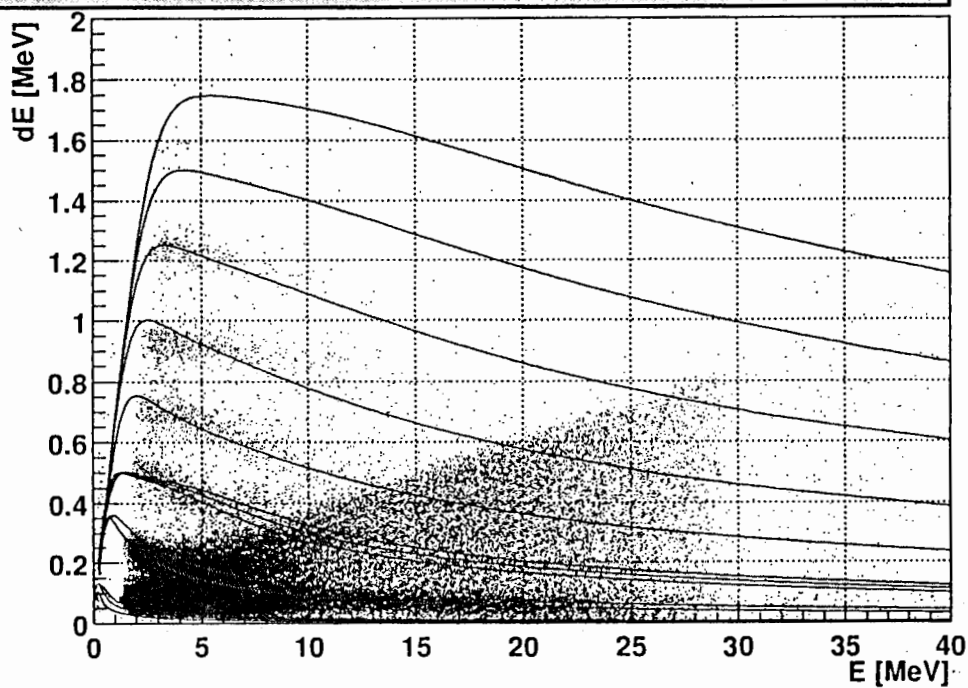


Fig. 2. Target frame holder

Fragments produced by 500 MeV d beam and Au target



Fragments produced by 1500 MeV d beam and Au target

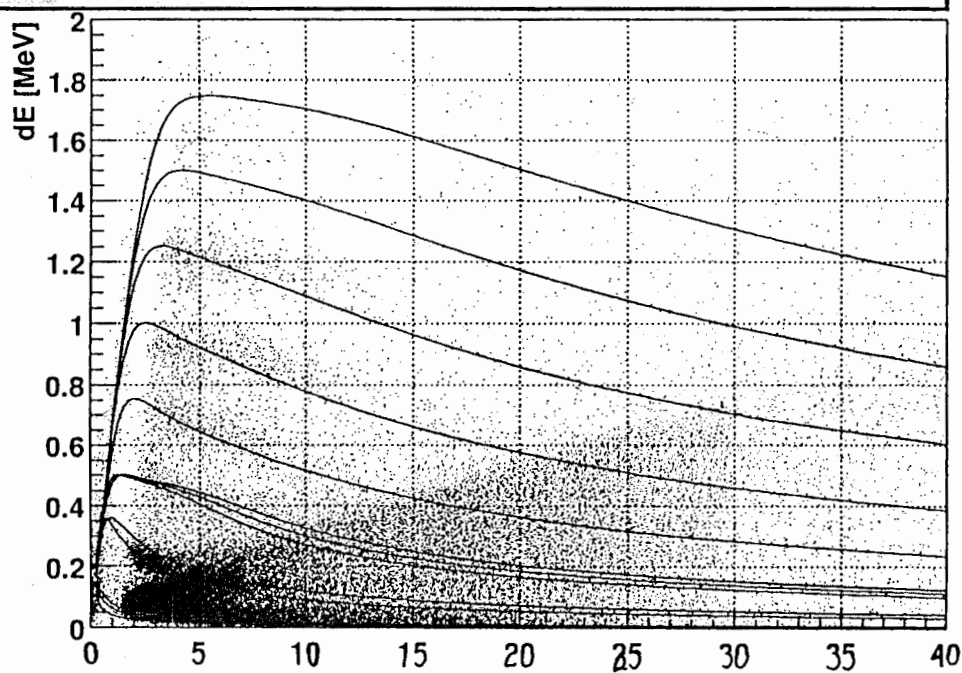


Fig. 3

Fragments separation (1044 MeV d beam on Au target)

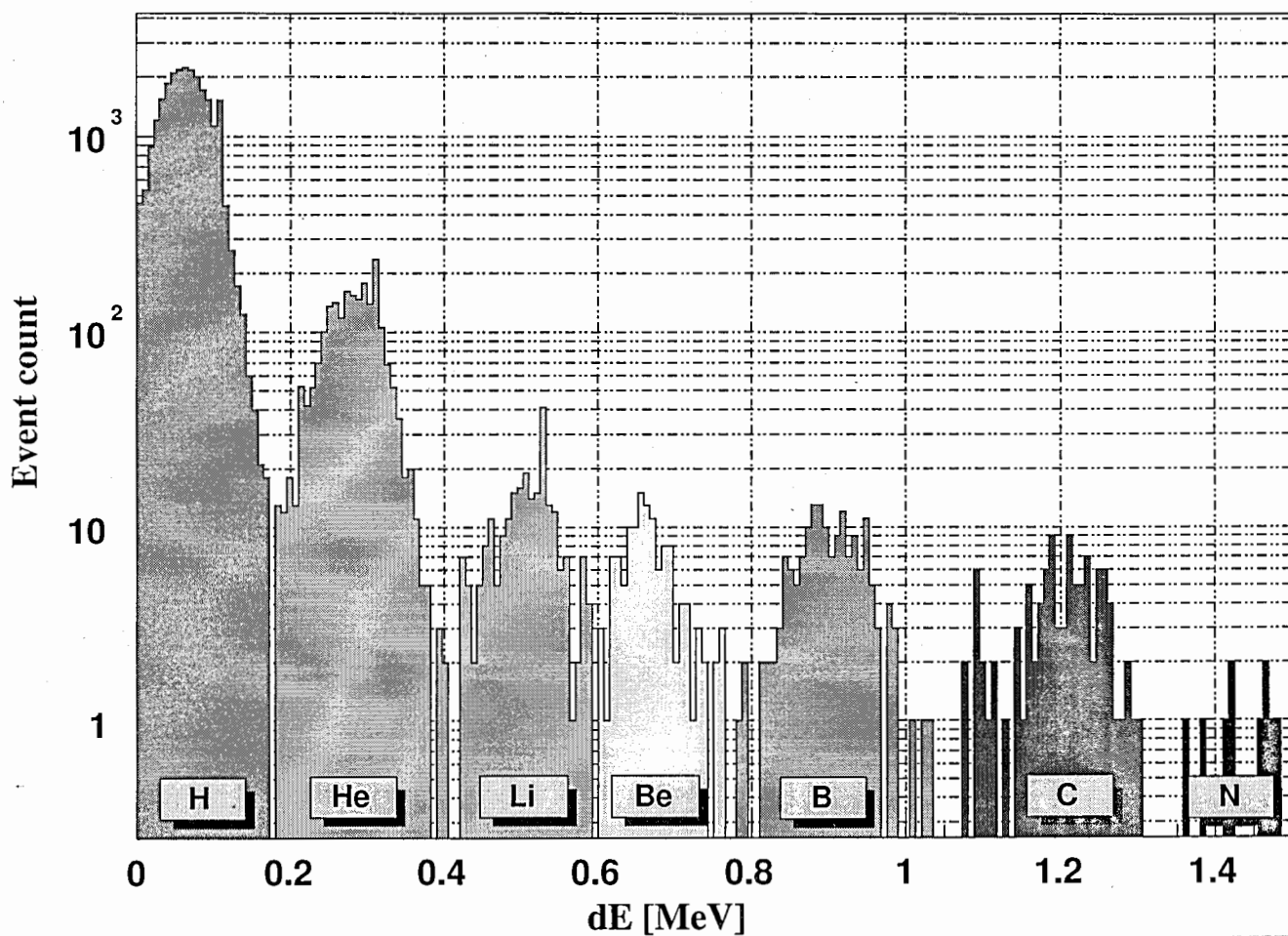


Fig. 4. Fragment separation for reaction $d + \text{Au}$ at 100° , deuteron beam energy 1044 MeV

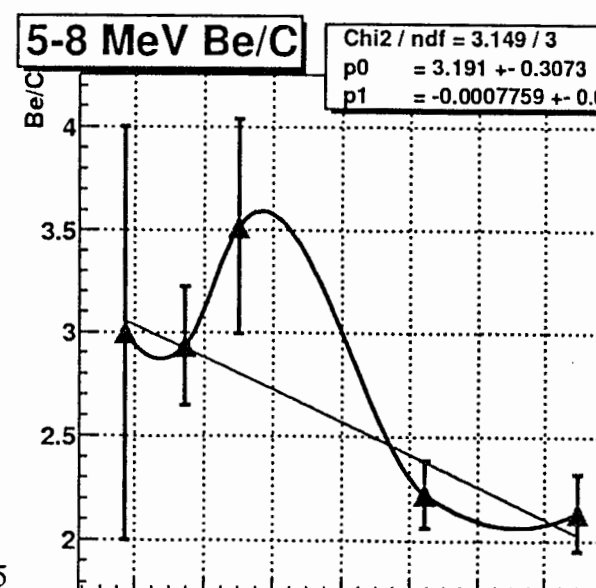
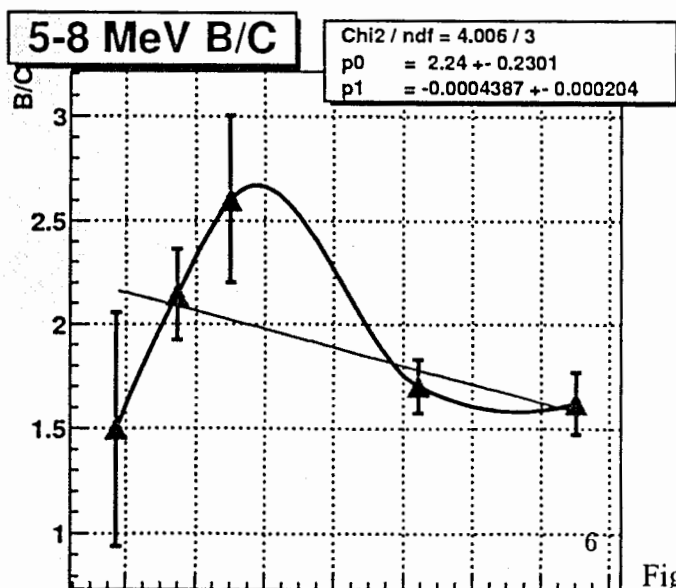
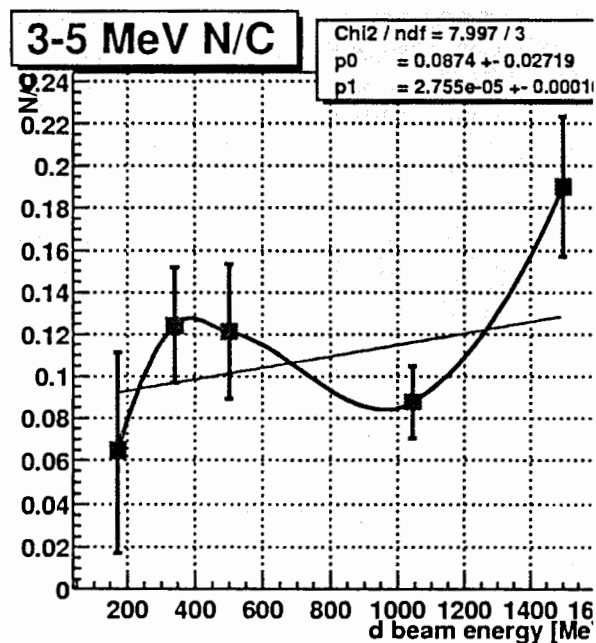
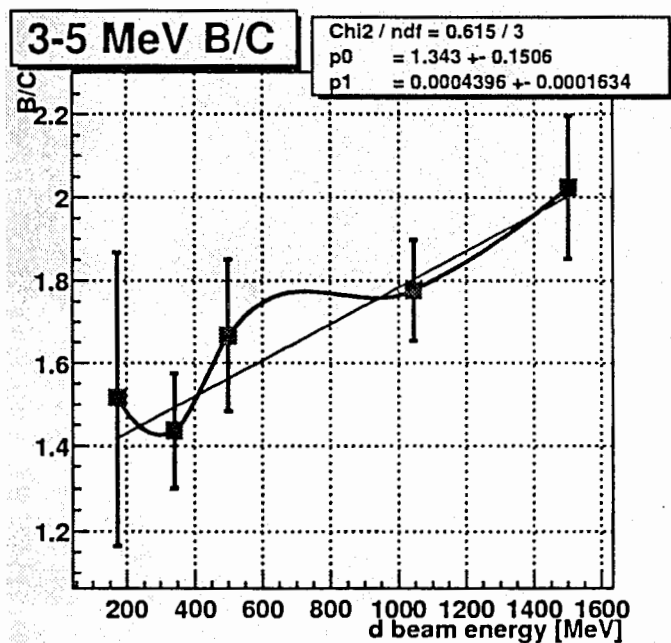
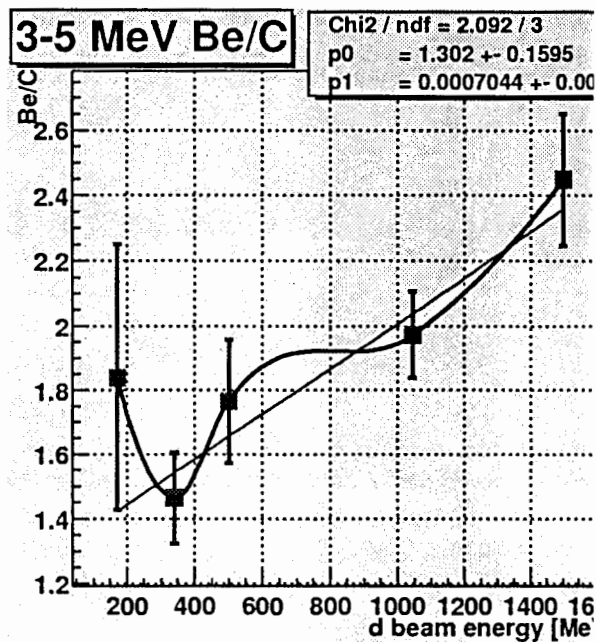
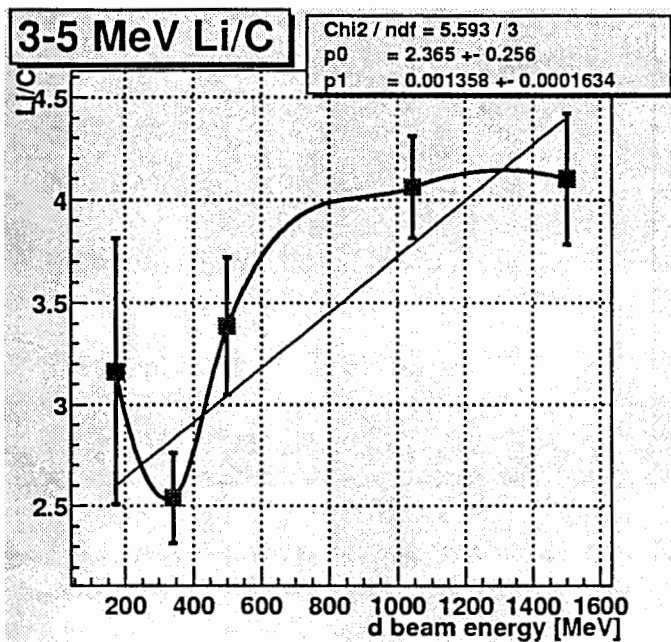


Fig. 5

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Concluding Remarks

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As we come to the end of this workshop, my first in this region of the world, I am pleased to have the opportunity to provide some brief personal remarks on some of the ideas I found interesting in what I heard this week. You must remember that, from several points of view, I am an outsider here, and so my comments and analyses are not based on broad knowledge of all the physics discussed nor of the entire program at the Nuclotron. On the other hand, you have been most hospitable, and perhaps you will find my viewpoint refreshing. My current research involves electron beams and electromagnetic physics, but for many years I did experiments at LAMPF, so I am reasonably familiar with a range of hadron physics topics, including some that might be pursued at the Nuclotron. I have no expertise in heavy ions, and so I will omit that topic entirely. Of course, we have covered a huge variety of topics here, from low energy to the LHC, and so in no sense will I attempt to summarize the results presented.

In fact, for me, the Nuclotron itself is the first highlight of the meeting. I came here this week with only a vague notion of this accelerator. I knew that my friends Charles Perdrisat and Vina Punjabi had done some experiments in Dubna, and I knew that they were hoping to arrange that the MRS, the medium resolution spectrometer that I had worked with in Los Alamos, be shipped there for experiments at a new machine called the Nuclotron. I didn't know whether this machine was still under construction, I didn't know its eventual capabilities, and I had no idea of the range of experiments that might be possible there. Here I have discovered that the Nuclotron is a working accelerator that, with a relatively small infusion of operating funds, would provide some unique opportunities for physicists around the world. With the closing of LAMPF in Los Alamos, Saturne in Saclay, and IUCF in Bloomington, the Nuclotron will be almost alone among hadron machines in the energy range up to 10 GeV. I'll return to this later.

Primary among these unique features is the wide ranging program with beams and/or targets of deuterons, particularly high energy polarized deuteron

beams. We heard here about a number of experiments and projects in this direction. It is important to relate this program to specific goals of high current interest around the world. This seems very straightforward for a program of hadron spectroscopy, as mentioned below. It is clear also for short distance phenomena. But sometimes, I think, the language and framework of some original JINR contributions might need some translation for the world community. An example is cumulative production, discussed early in the meeting. My impression, perhaps incorrect, is that this concept has not had the impact it deserves, at least in part because physicists in the West have not taken the trouble to translate this physics language into the current jargon they are used to. It can be said (and Egle Tomasi-Gustaffson said it strongly here!) that this is our fault, and, of course, that's true. But in your own interest, I think it would be better if a concept could be discussed in terms of $x_{bjorken}$, for example, instead of the b_{ij} that I heard was more or less equivalent.

Another subject clearly important for the long range program at the Nuclotron is the investigation of the meson, baryon, and dibaryon spectrum. Boris Tatischeff told us of his results that overlap nicely with long term studies by Troyon et al. here. This program is also highly complementary to the current program in Hall B at Jefferson Lab and to the proposed Hall D program that hopefully will take place not too many years from now. This was to be a major avenue of investigation for the proposed LISS accelerator, which has not received funding; it was to have elaborate spin capabilities. Some new equipment will be necessary to pursue a vigorous program in this area at the Nuclotron, and funding for such equipment can well be a contribution to the program that can appropriately be asked of visitors. I think it is unlikely that outsiders will be able to contribute directly toward the operation of the machine, but it is likely that well-motivated equipment proposals will be favorably received.

Two specific experiments discussed here must be mentioned. The one, still at the proposal stage, is a highly original search for collective effects, a Bose-Einstein condensation of pions in individual reactions discussed by Nikitin. It carries on the tradition of Russian interest in collective phenomena. At this stage, it looks highly speculative, and it will definitely be a very difficult experiment—squeezing all the pions possible out of a small region of phase space—but observation of the effect would be richly rewarding.

The other is the apparent observation of η meson nuclear bound states in the γA reaction. This is very interesting, and it should be developed further at both the Nuclotron and at Jefferson Lab.

Now I would like to return to the subject of the Nuclotron itself. Again I am very mindful of the fact that I am an outsider, one that you have made feel very welcome but one who, nevertheless, is not familiar with the situation at the Nuclotron in detail. My remarks may seem naive. In any case, the suggestions I would like to make for increasing participation from the world community of physicists are indeed only suggestions of some possibly new paths for your consideration. Of course, you are already making steps in this direction, for example, by inviting "outsiders" to this workshop, and I know from conversations here that you are interested in increasing participation from new users. Perhaps some of the following ideas, developed in discussion with Tim Hallman and Egle Tomasi-Gustafsson, may prove helpful.

First, I believe a specific invitation to participate should be distributed widely to nuclear physicists around the world. Before I came here, I (and I suspect many others like me) was not aware of your open welcome. The JINR installation appeared (almost) like a closed box, with scientists from Eastern countries within and others mostly on the outside, trying for a glimpse of the interior. This was actually true in the political sense, of course, for a long time, and now that the political situation has changed, it is good to hear that the physics box has been opened wide as well. To publicize this, I suggest a letter of welcome—not sent by e-mail!—of perhaps several pages, with a statement about the capabilities of the accelerator, the equipment available, how to make arrangements for participation, PAC procedures, and the like.

These questions should also be addressed in a highly developed Web site. I have not visited the JINR site, but I have been assured that it is quite good. Nevertheless, I am sure that, like most laboratory sites, it can be improved, especially keeping in mind the needs of outside users. So the site might expand upon the issues mentioned in the letter, including more details about the capabilities of the machine and equipment, what kind of housing is available, persons to contact, etc. In addition to the Web site, I encourage broad distribution of your useful Progress Report to major laboratories and groups around the world, which you may already do. In all of these activities, a clear statement of the goals and priorities of the Nuclotron laboratory should be included. A visitor wants to know where he might fit in, or how far outside the regular program his exciting idea might fall.

Finally, a most important, if most difficult, piece of advice. Every effort must be made to increase the running time on the accelerator. I have learned here how much of a problem this has been, and how much progress has been made recently. It is clear to me, however, that most outside participants will not be willing to invest in the Nuclotron program unless they can look forward to successful completion of their experiment in timely fashion. It is remarkable how much more running time could be made available with a small (by Western standards) increase in funds. Of course, increased overall funding of the JINR nuclear physics programs would be very helpful, but this I am sure is very difficult in these times. Even in the absence of such an overall increase, however, a recognition of the priority that the Nuclotron deserves, for its impact on nuclear physics as a whole and on the world view of nuclear physics research in the Eastern countries, should lead to a relative increase in operating funds for the Nuclotron, enough to run the program for at least eight months per year. Such a rearrangement of the budget will require imagination and more sacrifice in other areas, but I believe it is most important for long term progress.

On behalf of all the participants, let me, in closing, express our thanks to all the organizers for the invitation to this most interesting workshop. The high Tatras provided a splendid site for the meeting, and our hosts provided warm and generous hospitality and a congenial atmosphere for interactions. We are very grateful.

HIGHLIGHTS

STARA LESNA 2000

C. G.

1. THE NUCLOTRON

WITH EXTRACTED BEAM

AN ACCELERATOR NOT
WIDELY KNOWN IN THE WEST
WITH UNIQUE FEATURES

OPENS POSSIBILITIES
TO PHYSICISTS AROUND THE
WORLD.

2. DEUTERONS

WIDE-RANGING PROGRAM
WITH BEAMS AND TARGETS
OF DEUTERONS (PARTICULARLY
HIGH ENERGY $\vec{L}$)

IMPORTANT TO RELATE
THIS PROGRAM TO SPECIFIC
GOALS CURRENTLY OF INTEREST
AROUND THE WORLD. LANGUAGE
AND FRAMEWORK OF ORIGINAL
JINR CONTRIBUTIONS MAY NEED
SOME TRANSLATION FOR WEST.

3. MESON, BARYON, + DIBARYON SPECTRUM

IDEAL PROGRAM WITH LONG
HISTORY HERE AND HIGHLY
COMPLEMENTARY TO PROGRAM
IN HALL B AT JEFFERSON LAB
AND ELSEWHERE. NEW
EQUIPMENT NEEDED?

4. HIGHLY ORIGINAL PROPOSAL
FOR INVESTIGATING NEW
COLLECTIVE EFFECTS
VERY DIFFICULT, BUT
HIGHLY REWARDING IF SUCCESSFUL

5. EVIDENCE FOR OBSERVATION OF η -MESIC NUCLEI

(CLEARLY INTERESTING
TO PURSUE (PROBABLY AT
JEFFERSON LAB) HOPEFULLY
ALSO AT NUCLOTRON.

SUGGESTIONS

FOR INCREASING PARTICIPATION

FROM WORLD COMMUNITY

1. INVITATION DISTRIBUTED BROADLY

— STATEMENT OF CAPABILITIES,
EQUIPMENT AVAILABLE, HOW TO
MAKE ARRANGEMENTS, PAC.

2. PROGRESS REPORT SENT TO LABORATORIES WORLDWIDE.

3. DEVELOPMENT OF WEB SITE

4. CLEAR STATEMENT OF PHYSICS GOALS AND PRIORITIES

5. MAKE EVERY EFFORT TO INCREASE AVAILABLE RUNNING TIME ON ACCELERATOR













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