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SOME NEW RESULTS OF INVESTIGATIONS IN RELATIVISTIC NUCLEAR PHYSICS

RESEARCH PROGRAMME FOR THE LABORATORY OF HIGH ENERGIES IN 2001–2003

Report to the 89th Session
of the JINR Scientific Council
January 18–19, 2001

Dubna 2000

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1. Introduction

At present the scientific programme of the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR), is concentrated on investigations of interaction of relativistic nuclei in the energy region from a few hundred *MeV* to a few *TeV* per nucleon to search 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 the lightest nuclei. Experiments along these lines are being carried out with the beams of the Synchrophasotron - Nuclotron accelerator complex as well as of other accelerators at CERN (SPS, LHC), BNL (RHIC), GSI (SIS) and at CELSIUS storage ring in Uppsala (Sweden). During several years the LHE research programme has been carried out mostly on the Nuclotron and the Synchrophasotron is used practically only for the research with polarized deuteron beams. In the nearest future we have a plan to obtain polarized beams at the Nuclotron, too.

2. Development of the 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 the energy range up to 6 GeV/u. The general view of the facility is shown in fig.1.

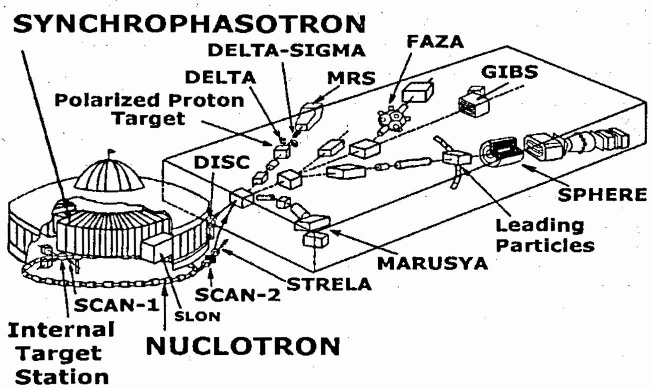
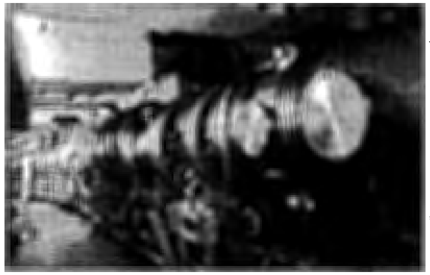


Fig.1. The accelerator complex of the Laboratory of High Energies, Joint Institute for Nuclear Research.

The Nuclotron is based on the unique technology of the superconducting magnetic system, proposed and investigated at the Laboratory [2]. Two years ago only the internal beam of the Nuclotron was used for physics experiments. In the end 1999 the external beam of the Nuclotron was obtained by means of the beam slow extraction system constructed on the base of the superconducting elements (fig.2).



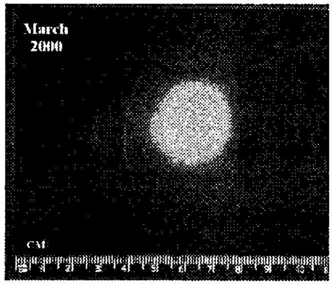


Fig.2. View of the Nuclotron beam extraction system (a) and image of the cross section of the Nuclotron extracted of deuterons beam with 4.5 *GeV/c* momentum and 10^9 d/cycle intensity (b).

Now the experiments at the Nuclotron external beams have started. Some parameters of the Synchrophasotron and Nuclotron beams are presented in table.1.

Table.1. Some beam parameters of the Synchrophasotron and Nuclotron.

Intensity (Particle per cycle)				
Beam	Synchrophasotron	Nuclotron		
		Available	have to be reached	
			Ion sources development	Booster
p	$4\cdot10^{12}$	$2\cdot10^{10}$	$1\cdot10^{11}$	$1\cdot10^{13}$
D	10^{12}	$2\cdot10^{10}$	$5\cdot10^{10}$	$1\cdot10^{13}$
^{4}He	$5\cdot10^{10}$	$8\cdot10^8$	$5\cdot10^9$	$2\cdot10^{12}$
^{7}Li	$2\cdot10^9$		$2\cdot10^{10}$	$5\cdot10^{12}$
^{12}C	10^9	10^8	$7\cdot10^9$	$2\cdot10^{12}$
^{20}Ne	10^4		10^8	$5\cdot10^9$
^{24}Mg	$5\cdot10^6$		$3\cdot10^8$	$5\cdot10^{11}$
^{32}S	10^3		10^8	10^{10}
^{40}Ar			$3\cdot10^7$	$2\cdot10^9$
^{56}Fe				10^{11}
^{84}Kr		10^3	$2\cdot10^7$	$5\cdot10^8$
^{96}Mo				10^{10}
^{131}Xe			10^7	$2\cdot10^8$
^{181}Ta				10^8
^{209}Bi			$3\cdot10^6$	10^8
^{239}U				10^8
n	10^{10}	$2\cdot10^7$	10^8	10^9
n↑	10^6	$3\cdot10^5$	10^6	$5\cdot10^7$
d↑	$2\cdot10^9$	$3\cdot10^8$	10^9	$5\cdot10^{10}$
t	10^9	$4\cdot10^5$	10^6	10^{10}
Energy	4,5 AgeV	5.2 A·GeV	6.0 A·GeV	

In 2000 the accelerated beams of protons and nuclei from the Nuclotron – a superconducting synchrotron were extracted to the experimental installations for physical research. The extracted beams of protons, deuterons and nuclei of carbon with energy up to 3 GeV per nucleon are used by ten groups of experimentalists. Simultaneously experiments on the internal beam of the Nuclotron are continued.

The main directions of the Nuclotron development for the nearest future the LHE will be the following:

- completion of transportation of the Nuclotron extracted beam in the large experimental hall to the experimental setups
- development of the injector complex including ion sources, partial reconstruction of the linac, technical design and construction activities on the Nuclotron booster
- upgrade of cryogenic supply, diagnostic, control and r.f. systems.

We have developed a programme of the first experiments at the Nuclotron external beams as well as a long-range programme. In the first runs of the Nuclotron with the extracted beam two setups (STRELA and SCAN-2) were used 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 $np \to pn$ 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*.

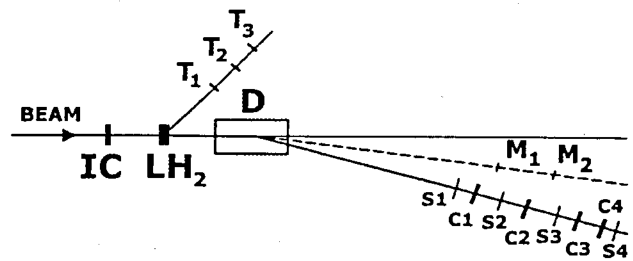


Fig.3. The Layout of the STRELA experimental setup. IC - ionization chamber, LH_2 - liquid hydrogen target, D- analyzing magnet, T1-T3 and M_1, M_2 - scintillator monitors, C1-C4 - Cherenkov counters, S1-S4 - scintillator counters.

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

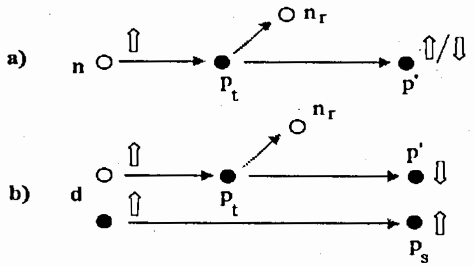


Fig.4. Elementary $np \to pn$ (a) and $dp \to (pp)n$ (b) charge exchange reactions.

A simplified version of these two processes in the framework of the Impulse Approximation is shown in fig.4: a) the $np \to pn$ charge exchange process and b) the $dp \to (pp)n$ reaction, i.e. charge exchange process 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 a 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 the $dp \to (pp)n$ reaction is determined by the spin flip part of the $np \to pn$ charge exchange process.

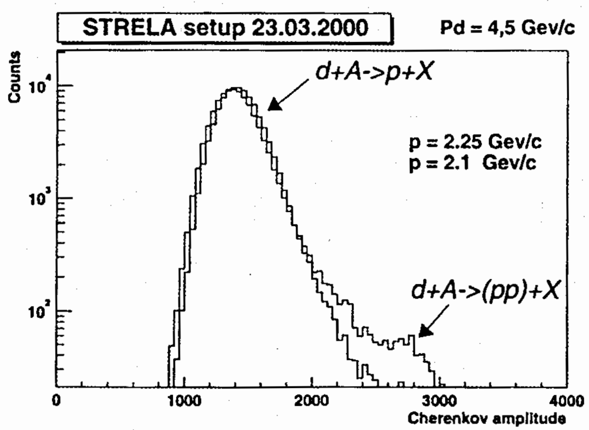


Fig.5. Preliminary results of STRELA experiment on separation of events with two protons and one proton.

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

At the end of the year, the experiments on STRELA and SCAN-2 setups were continued.

3.1.2. The Experiments at the Internal Nuclotron Beams.

The target fragmentation into two cumulative protons with the help of the **SKAN-1** setup (Spokesman S.V.Afanasiev) is investigated at the internal beam of the Nuclotron (fig.6). The goal of the experiment is measuring the transversal dimension of nucleus-nucleus interaction region. The method is the measurement correlation of cumulative protons, emitted at a small relative momentum. Correlations of protons, emitted in the angle interval between 106-112° in the laboratory system, are studied in the reactions d + C → p + p + ... and d + Cu → p + p +... ($p_d = 2\ A{\cdot}GeV$). The results of the measurements are presented in fig.6 [3].

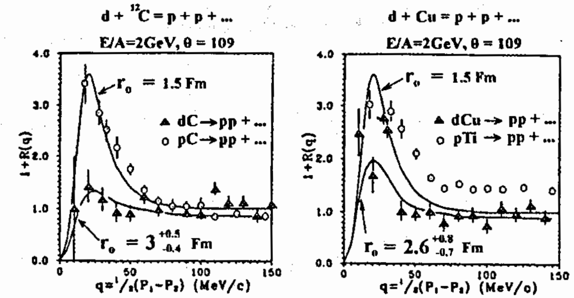


Fig.6. The correlations functions of cumulative protons emitted at small relative momentum q for dC and dCu reactions.

Approximately the same transversal radius for dC and dCu interactions: $r_{dC} = 3.0 \pm {}^{0.5}_{0.4}$ *fm* and $r_{dCu} = 2.6 \pm {}^{0.8}_{0.7}$ *fm* was obtained. These investigations will be continued for other projectiles and targets.

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

These data are in the process of analysis now and will be used to study the effect of the full destruction of the nuclei because the energies of the secondary fragments are very low.

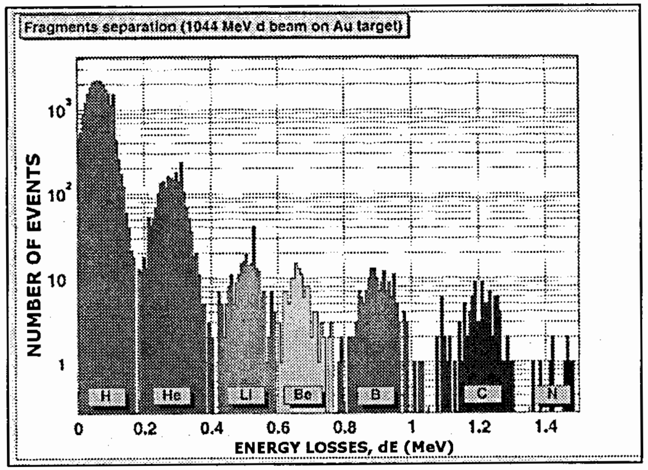


Fig.7. Separation of the secondary fragments for d + Au reaction at 1.044 GeV deuteron energy.

3.2. Long-range Experimental Programme at the Nuclotron

Now there are 12 setups at the Nuclotron for carrying out the basic research. They are: **SPHERE, GIBS, FAZA, DELTA-SIGMA, DELTA, DISC, Leading Particles, MARUSYA, SCAN-1, SCAN-2, STRELA, SLON** (fig.1). And there is also a plan to use the Medium Resolution Spectrometer (MRS) from Los Alamos, USA at the LHE Accelerator Complex. A short review of the research programme at these setups is given below.

3.2.1 Experiments with Relativistic Nuclei

SPHERE project

The main goal of the project SPHERE is to investigate fragmentation of the relativistic nuclei in the geometry close to 4π. A general layout of the spectrometer SPHERE is shown in fig.8. With forward detector of the SPHERE setup some new results were obtained 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 a 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 the hydrogen target (fig.9).

Fig.8. General layout of the SPHERE experimental facility.

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].

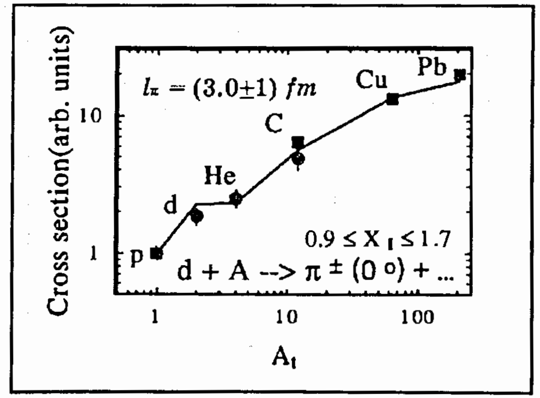


Fig.9. Cross section for production of cumulative pions as function of atomic number A of the nucleus.

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

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

GIBS project

The GIBS setup is a magnetic spectrometer on the base of the streamer chamber of 1.9 x 0.8 x 0.6 m^3 volume. Interesting results were obtained by GIBS collaboration at the Synchrophasotron. One of them is observation of the expansion of the volume from which the irradiated narrow pion pairs in Mg-Mg interaction. M.I.Podgoretsky proposed 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 the streamer chamber with a magnesium target inside, exposed to the extracted magnesium beam from the Synchrophasotron.

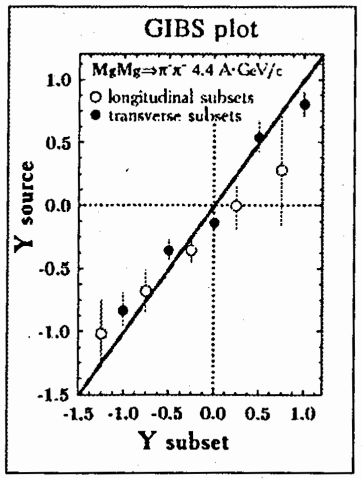


Fig.10. Rapidities Y_{source} of the pion production volume elements corresponding to different pion subset moving with different rapidities y_{subset} along and across the reaction axis in the *Mg-Mg* rest frame.

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

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 the source, moving with respect to one another with almost the highest possible velocities. For a stationary source all points must be on the horizontal axis.

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

The second experiment will study the production of hypernuclei with momentum 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 bounding energy of Λ.

FAZA project

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

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

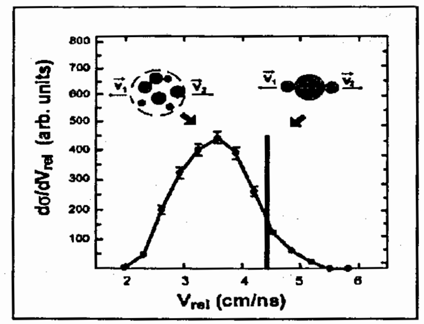


Fig.11. Distribution of relative velocities for the coincident fragments from $\alpha + Au$ collisions measured at correlation angles 150° - 180°. The vertical line shows the expected maximum position for fragments evaporation from the nucleus surface. The experimental distribution is shifted to lower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

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

The research programme 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 a more complicated one with the increasing projectile mass.

MARUSYA project

This project has a goal to investigate the transition regime (transition from nucleon to quark-gluon degrees of freedom in nuclei) on the basis of the experimental study of hadron production in relativistic nuclear collisions. A schematic view of MARUSYA setup is presented in fig.12.

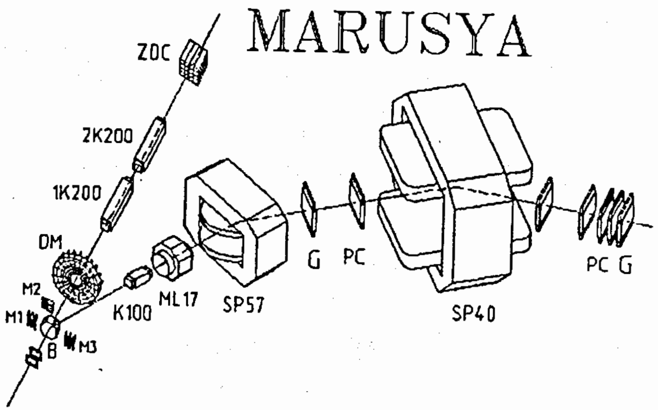


Fig.12. A schematic view of MARUSYA setup. M1-M3 - the beam monitoring system consists of three scintillation telescopes . K100, ML17 - magnetic lenses. SP57, SP40 dipole magnets. B- barrel system located around the target. PC - proportional chambers. G - scintillator hodoscopes. DM - multiplicity detector.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

Leading Particles project

The 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 $d\uparrow + {}^{12}C \rightarrow \pi^{\pm}$ (0, 135, 178 *mrad*) + ... 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 kinematical nucleon-nucleon collisions (Fig.13).

The measured values of A_{yy} are in disagreement on the 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 the polarized beam with enough intensity.

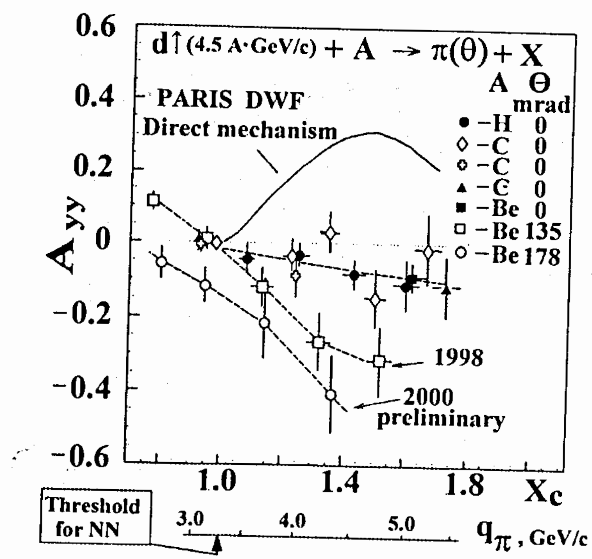


Fig.13. A_{yy} vs x_c, and q_π for the reaction $d + A \rightarrow \pi^-$ (0, 135, 178 *mrad*) + ...

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).

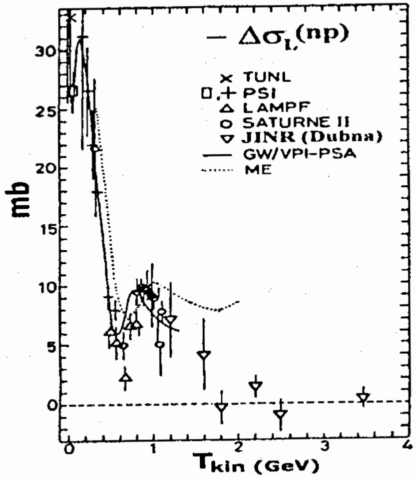


Fig.14. Energy dependence of the $\Delta\sigma_L(np)$ observables obtained with the neutron polarized beam.

A quasi-monochromatic neutron beam was produced by break-up of the accelerated and extracted vector polarized deuterons from the 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*. It is also necessary to measure the energy dependence of the $\Delta\sigma_T(np)$ with the transverse polarized beam of neutrons and target protons. These experiments are proposed to continue at the Nuclotron.

MRS project

It is proposed to use the Medium Resolution Spectrometer (LAMPF, Los Alamos, USA) at the accelerator complex. This possibility appeared after signing the agreement on the Scientific Collaboration between Los Alamos National Laboratory, the Institute for Nuclear Research of RAS and the Joint Institute for Nuclear Research. Research programme includes the 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 particles production, nuclear fragments and antinuclei in relativistic nuclear collisions in the central rapidity region ($y = 0$). The results 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 the asymptotic behaviour of production cross section of particles, nuclear fragments and antinuclei. An example of this prediction is given in fig.15 from the Nuclotron energies up to LHC [10, 11].

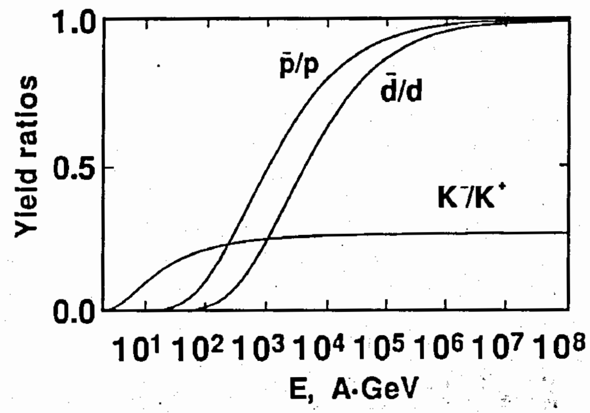


Fig.15. Predictions of the production cross section ratios for antiparticles to particles versus laboratory collision energy.

4. Applied Research

We have used Synchrophasotron for applied research and will continue these investigations at the Nuclotron with heavier ions. The following applied research is carried out at the Laboratory:

- radiobiology and space medicine (fig.16) [12]
- influence of nuclear beams on microelectronic components
- transmutation of radioactive waste products [13]
- aspects of the electronuclear method of energy generation [14]
- using carbon beam for tumor therapy and so on.

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

5. Cooperation with other Scientific Centers

Physicists of our Laboratory participate in heavy ion programme at accelerators in other centres and are involved in CERN experiments NA45 (CERES), NA49, WA98, EMU01 running in SPS nuclear beams. Essential contributions of various type detector equipment were made for these facilities.

Some results of experiments NA45, NA49 and WA98 and the results of the other experiments at SPS lead beam in CERN were interpreted as signals of quark-gluon plasma (fig.17).

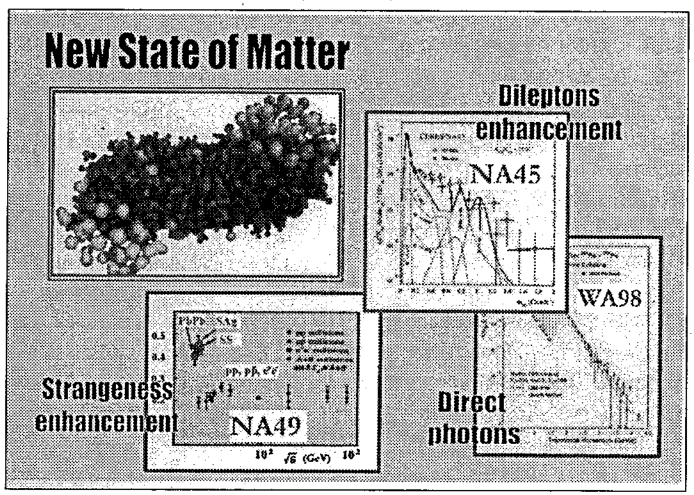


Fig.17. Signals NA45, NA49 and WA98 experiments which were interpreted as signals from quark-gluon plasma.

During 2001-2003 years we are planning to continue participation in the above-mentioned experiments except WA98 which is finished now.

NA45 (CERES) collaboration with a fully upgraded apparatus (fig.19) has a plan to continue production running with Pb beams for a high statistic ω and ϕ production measurement.

Primary items of the NA49 experimental programme are the following:

- to obtain more statistics for Pb+Pb collisions at 158 A·GeV as it is needed for rare processes
- to study Pb+Pb collisions at lower beam energies (40 A·GeV and 80 A·GeV) in order to establish the collision energy dependence of QGP signals
- to study collisions of lighter ions (C+C, Si+SI and Ag+Ag) in order to investigate how the properties of matter depend on the size of colliding objects
- to continue the investigation of proton (meson)-nucleon and nucleus reactions for ralated to nucleus-nucleus collisions

Dr. Morozov B. was elected as spokesman of WASA collaboration at the CELSIUS storage ring in Uppsala and his group active by participates in this experiment.

It is also planned to continue participation in the STAR collaboration at RHIC (BNL) which obtained the first experimental data last year (fig.18).

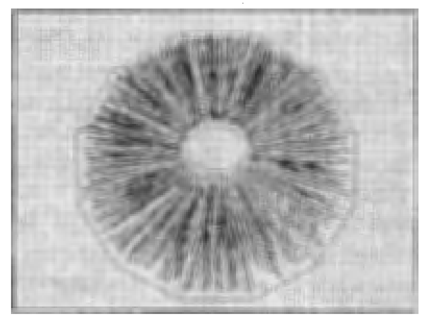


Fig.18. One of the first Au + Au events at 60 TeV registered by the STAR setup

New research prospects of relativistic nuclear physics research will be opened in the energy range of the order of few TeV per nucleon. In this respect ALICE and CMS experiments at LHC will give a new and complementary information and LHE physicists actively participate in the preparation of these experiments.

A warm dipole magnet for the muon arm spectrometer will be designed and constructed at Dubna by joint efforts of JINR and CERN for ALICE experiment (fig.19). The LHE physicists are also involved in ALICE software development and simulation.

Fig. 19. The view of the warm dipole magnet for the muon arm ALICE setup.

Current Dubna CMS Group participation in CMS heavy ion studies includes:

- contribution to a global observable chapter of a planned CMS heavy ion Physics Report
- further development of physics programme on shadowing manifestation in global observables of nucleus-nucleus collisions
- development of programme on a possible modification of a global flow of hard hadronic jets produced in a colliding nuclear matter.

Our Laboratory group is manufacturing a system of Multilayer Drift Chambers for HADES experiment at the SIS in GSI. 6 Modules of low mass drift chambers equipped with readout electronics were installed into the magnet and sucsessfully used in November, 2000 commissioning beamtime at GSI. This multilayer chambers offer a position resolution of better than 100 μm in X and Y direction at high rates and high multiplicity and are an essential part of the high resolution tracking system in large acceptance HADES spectrometer for e^+e^- pair decay studies in heavy ion collision.

The main goal of the join JINR-Japan experiment R308n(0A) is to explore the short-range ^{3}He (^{3}H) spin structure via the measurement of the angular distribution of the tensor analyzing powers A_{yy}, A_{xx} and A_{xz} in the dd $\rightarrow$ ^{3}Hen and dd $\rightarrow$ ^{3}Hp binary reactions. These polarization observables are sensitive to the spin structure of ^{3}He and ^{3}H at short distances in the framework of one nucleon exchange approximation. The LHE-RIKEN collaboration performed the measurement of the tensor A_{yy}, A_{xx} and A_{xz} and vector A_y analyzing powers using polarized deuteron beam of RIKEN cyclotron and the SMART spectrometer from the 26th of November until the 11th of December this year. These observables have been measured with the statistical errors of ±0.02 at the energies 270 and 200 MeV over full angular range for the dd $\rightarrow$ ^{3}Hp reaction. The same set of analyzing powers has been obtained for the dd $\rightarrow$ ^{3}Hen channel at 270 MeV between 0° and 120° in the center of mass. Such a high precision of the experimental data will allow to discriminate different models of the three-nucleon bound state up to nucleon internal momenta of ≈ 600 MeV/c. These investigations can be continued in future by using the polarized deuteron beam of LHE Accelerator Complex.

6. Conclusions

We have developed the programme of the first experiments at the Nuclotron external beams as well as a long-range programme.

We have developed the research programme 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.

Also, we have a long-range programme of the cooperation with other Scientific Centres.

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