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LABORATORY OF NUCLEAR PROBLEMS

REPORT ON RESEARCH ACTIVITIES IN 1999

Report to the 87th Session
of the JINR Scientific Council
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Dubna 1999

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Elementary Particle Physics

A full sample of NOMAD (WA96 experiment at CERN) data corresponding to $\sim 1\,300\,000$ ν_μ charged current (CC) interactions was reconstructed and analyzed. The upper limit (at 90% C.L.) on the probability of $\nu_\mu \to \nu_\tau$ oscillations was established to be $P(\nu_\mu \to \nu_\tau) < 4.2 \times 10^{-4}$. The corresponding limit on the oscillation amplitude is $\sin^2 2\theta < 8.4 \times 10^{-4}$ for large Δm^2 [1]. The previous limit from the E531 collaboration is improved by a factor of 6 (Fig. 1). A new limit on the probability of $\nu_e \to \nu_\tau$ oscillations was obtained (at 90% C.L.) to be $\sin^2 2\theta < 5.2 \times 10^{-2}$ for large Δm^2 [2]. This result improves the existing limit by a factor of more than 2 (Fig. 2).

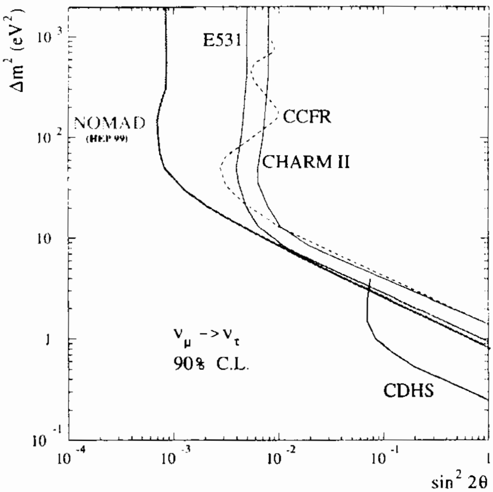

Figure 1: The Δm^2–$\sin^2 2\theta$ plane for $\nu_\mu \to \nu_\tau$ oscillations. The region excluded by NOMAD at 90% C.L. is shown together with the limits published by other experiments.

The collaboration memo of the JINR group on the study of Λ hyperon polarization in ν_μ CC interactions is accomplished and published in the NOMAD preprint database [3]. The statistics of the NOMAD Λ sample is ~ 15 times larger than the one of the previous neutrino experiments performed with bubble chambers.

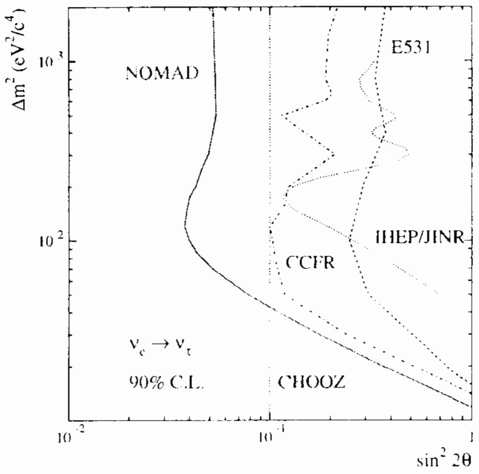

Figure 2: The Δm^2–$\sin^2 2\theta$ plane for $\nu_e \to \nu_\tau$ oscillations. The region excluded by NOMAD at 90% C.L. is shown together with the limits published by other experiments.

There is a strong collaboration between the JINR and INR (Moscow) groups within the NOMAD experiment.

DELPHI is a general-purpose detector for physics at LEP on and above the Z^0, offering three-dimensional information on curvature and energy deposition with fine spatial granularity as well as identification of leptons and hadrons over most of the solid angle.

During the 1999 data taking period LEP has been routinely operating at the collision energies of up to 202 GeV. A total integrated luminosity of about 230 pb^{-1} was recorded by the DELPHI experiment. These new data allowed the exclusion limit on the mass of the Standard Model Higgs boson of about 106 GeV (at 95% C.L.) to be set. Improvements between 3 and 6 GeV were reported on the mass limits for new particles, compared with the data obtained in 1998. The data are also being used for the high precision measurement of the W-boson mass and the tests of electroweak theory, QCD, two-photon and other physics. DELPHI results from running at Z-resonance and at LEP200 are summarized in about 250 papers. New results are regularly presented at the conferences.

The main contributions of the JINR group in hardware concern the maintenance and running of the Hadron Calorimeter and the Surround Muon Chambers of DELPHI. In the area of physics analysis the Dubna people are working on the precision tests of the Electroweak theory from Z- and W-data, τ-lepton physics, tests of QCD and studies of multi-particle production dynamics at Z and higher energies, two-photon physics etc.

The construction of the new neutrino beam with energy of 1.5 GeV at the U-70 accelerator (Protvino) was finished in 1999. The structure of the target of the IHEP-JINR Neutrino Detector was modified by removing aluminum plates.

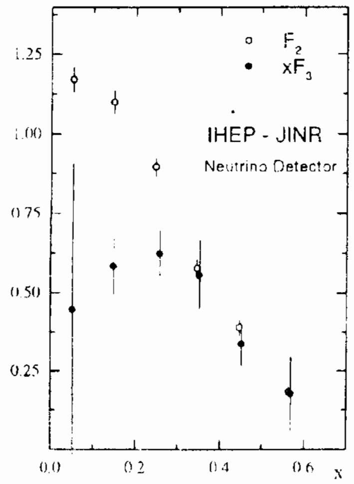

Figure 3: Structure functions $F_2(x)$ and $xF_3(x)$ measured with the Neutrino Detector.

The target part of this new setup consists only of liquid scintillator counters and drift chambers. It allows protons from elastic scattering of neutrinos on protons to be registered. During the first testing run with the new beam and the upgraded detector the on-line program was tuned and tested, performance of different detector components was checked after a long pause in operation (more than 3 years). The structure functions xF_3 and F_2 in low Q^2 were obtained on the basis of the experimental data collected in previous exposures on the Neutrino Detector (Fig. 3) [4]. Under the assumption that QCD is valid in the region of low Q^2 the analysis of xF_3 yields $\Lambda_{\overline{MS}} = (411 \pm 200)$ MeV. The corresponding value of the strong interaction constant $\alpha_S(M_Z) = 0.123^{+0.010}_{-0.013}$ agrees with the recent result of the CCFR collaboration and with the combined LEP/SLC result.

The collaboration with physicists from the Institute of High Energy Physics (IHEP) is decisive for this project.

In 1999 the DIRAC collaboration, aimed at the lifetime measurement of $\pi^+\pi^-$ atoms, achieved the following main results. The dedicated processor of the forth-level trigger was developed. The map of the spectrometer magnet field was reconstructed with the accuracy of 0.4%. The programs for determination of the setup geometric constants and for event reconstruction were developed.

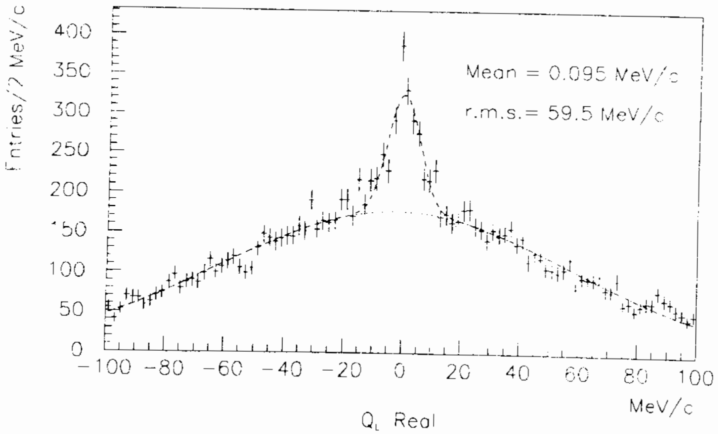

Figure 4: Distribution of $\pi^+\pi^-$ pairs over the longitudinal component of relative momentum in the c.m. frame.

Experimental data for measurement of the dimesoatom yields on the targets of Ni and Pt were obtained during a 4-month data taking at the CERN PS accelerator. Performance of the setup is demonstrated by the observation of the Coulomb enhancement in the yield of $\pi^+\pi^-$ pairs in the relative momentum range below 5 MeV/c (Fig. 4) and by observation of a peak from Λ decay in the spectrum of the detected π^-p-pairs (Fig. 5).

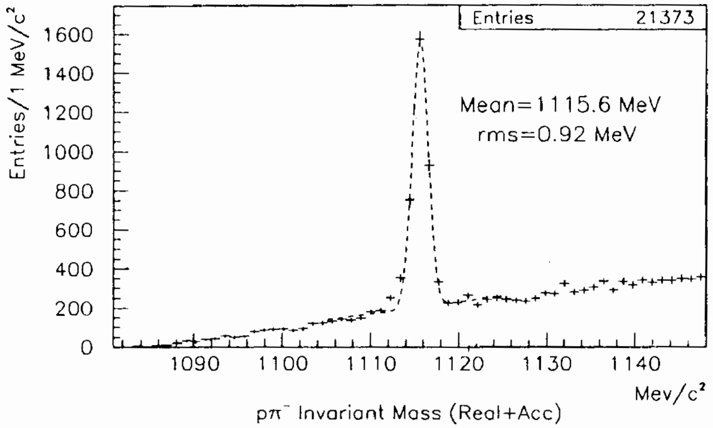

Figure 5: Effective mass distribution of π^-p pairs.

The processing of 25% of new experimental data (about 14000 events) obtained with the HYPERON setup allows new determination of the slope parameter of the vector form factor of the $K^+ \to \pi^0 e^+ \nu$ decay: $\lambda_+ = 0.0277 \pm 0.0040$ [5]. This result (Fig. 6) is in good agreement with the world average value and the accuracy of measurement is comparable with the accuracy achieved in the best experiments.

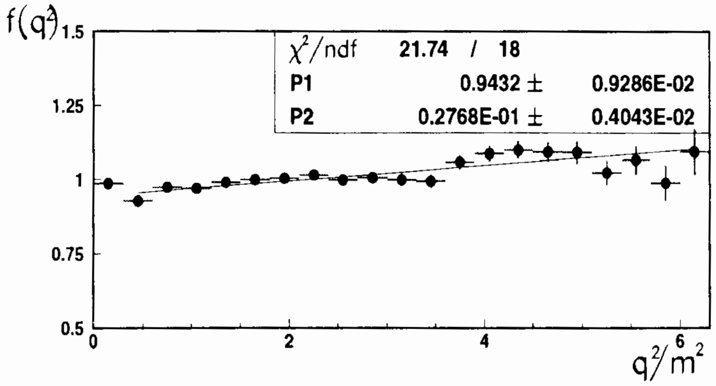

Figure 6: The dependence of the vector form factor of $K^+ \to \pi^0 e^+ \nu$ decay on q^2-momentum transferred to the lepton pair.

The experiment was carried out at IHEP (Protvino) with a valuable contributions from the scientific group of IHEP.

At the Nuclear Center of Charles University (Prague) new measurements of spin-dependent total cross-section differences $\Delta\sigma_L$ and $\Delta\sigma_T$ were performed with the transmission method. For these experiments the frozen-spin polarized target was developed, which includes a stationary cryostat with a dilution refrigerator, a movable magnetic system and electronic equipment for providing dynamic polarization and NMR signal detection (Fig. 7).

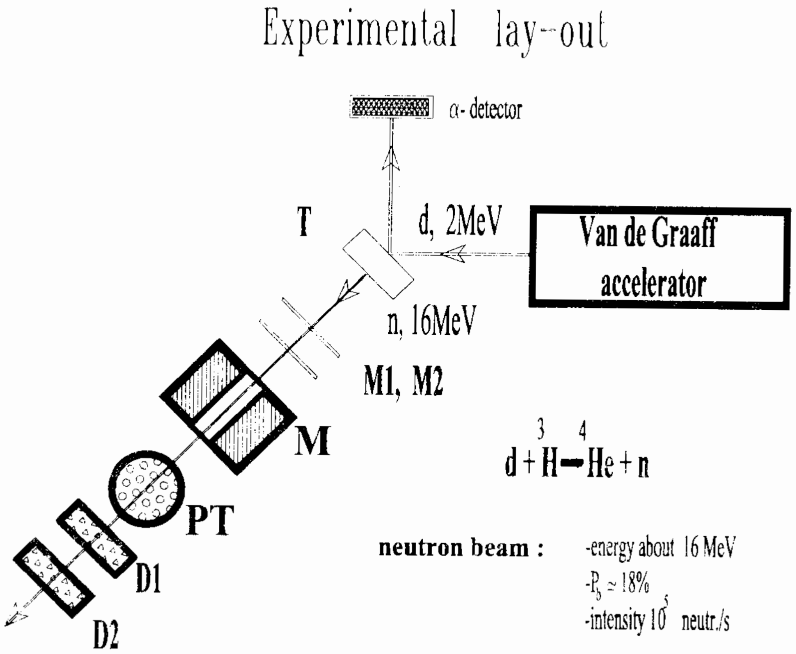

Figure 7: α-detector — the silicon detector for monitoring of the neutron beam; T — titanium-tritium target; M_1, M_2 — thin plastic scintillator detectors; M — magnet for neutron spin rotation; PT — polarized target; D_1, D_2 — liquid scintillation detectors.

A polarized neutron beam is produced with the Charles University Van de Graaf electrostatic accelerator by means of the reaction $^3H(dn)^3He$ with an initial deuteron energy 1.82 MeV.

The physics results on the measurement of $\Delta\sigma_L$ and $\Delta\sigma_T$ obtained in Prague permit a new view at the earlier data in this energy range. Earlier, some experiments (Bonn, Erlangen) supported the hypothesis of the minimal value of the $^3S_1$–$^3D_1$ mixing parameter (ϵ_1) in the range of 15 MeV. These results disprove it, which is in good accord not only with the other experimental data, but also with the model predictions [15].

In 1999 the main activities of the ATLAS TileCal-group were a) study of performance of combined calorimeter and the hadronic Tile calorimeter, b) production of modules of the Tile calorimeter, c) construction of opto-mechanical test benches for PTM and d) development of slow control.

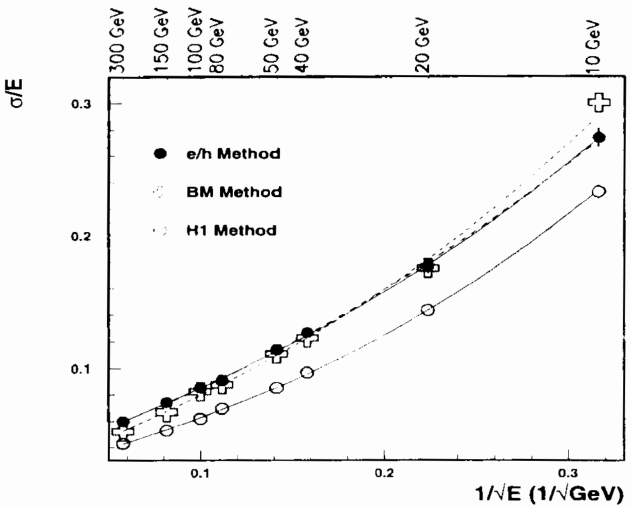

Figure 8: Energy resolutions (for 10, 20, 40, 50, 80, 100, 150 and 300 GeV pions and electrons) obtained with the e/h method (black circles), the benchmark method (crosses) and the cells weighting method (open circles).

The response to pions and electrons at an incident angle of 12° was investigated [6, 7] (Fig. 8). The response of the ATLAS calorimeter system to single charged pions was investigated via full simulation [7]. Performance was estimated for the cases when energy and rapidity dependent and independent calibration parameters were applied. The best results were obtained with the energy and rapidity dependent parameters. The lateral and longitudinal profiles of hadronic showers detected by the prototype ATLAS Iron-Scintillator Tile Hadron Calorimeter were investigated [8]. The detailed experimental information about the electron and pion responses, the electron energy resolution and the e/h ratio as a function of incident energy E, impact point Z and incidence angle Θ of the Module-0 of the tile iron-scintillator barrel hadron calorimeter is obtained [9].

The main achievement in 1999 was the successful start of mass production of the ATLAS Barrel Hadron Calorimeter Modules and submodules at JINR [10]. In Dubna 110 submodules were manufactured. Nine Modules were sent to CERN in 1999. The expected average delivery cycle is 1 Module per 2 weeks. Module assembly is controlled by a special laser hardware and software complex which was developed at JINR and which allows measurement precision of 50 μm.

LNP started the construction of seven opto-mechanical test benches to be used for the detailed study of 10300 photomultipliers. This test bench will allow one to measure 24 photomultipliers at once.

The architecture of the Tile calorimeter control system (TCS) was elaborated including detailed functionality arrangement and data flow distributions. The pilot project of final version of HV subsystem was started.

The main task of the JINR Muon ATLAS group in 1999 was to construct a site (Fig. 9) for full cycle production and test of Muon Chambers (MDT-chambers) at JINR.

To this end a lot of high-technology set-ups and tools were constructed. Their list consists of 1) two dust-free production areas with climate control; 2) full infrastructure for the production area (with cranes, compressors, vacuum pumps, gas pipes, computer network, etc.); 3) semi-automatic wiring line for mass-production of drift tube detectors (DDT); 4) full set of tools for DDT testing (with wire tension, tightness, HV-test) including X-ray set-up for wire position control inside the detector; 5) full set of tools for high-precision muon chamber assembling, which includes: large-scale high-precision granite table $(3.5 \times 2.5 \times 0.5)$ m^3, set of precision tools for high-accuracy DDT positioning, computer-controlled pneumatic sag compensation mechanism and automatic glue machine.

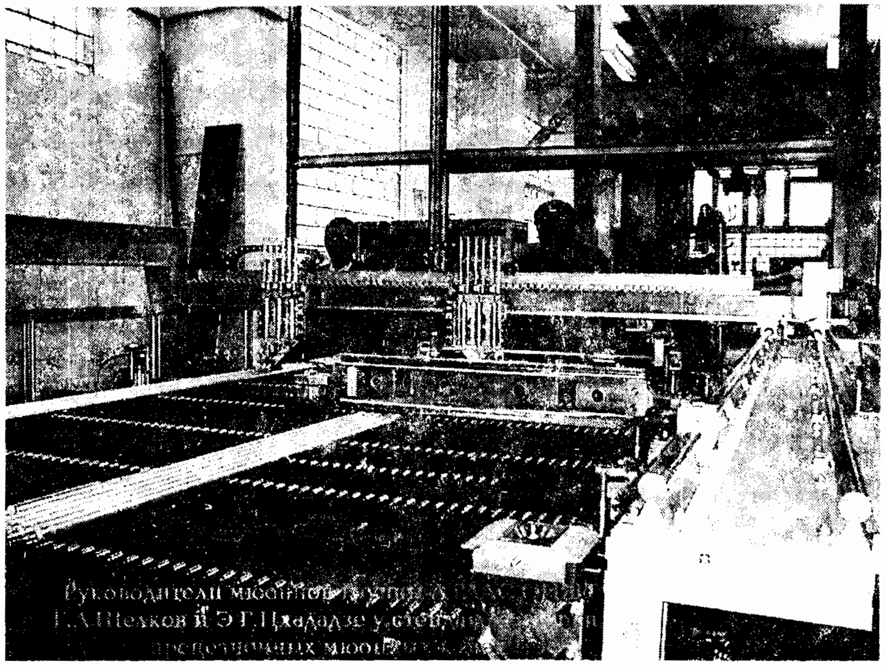

Figure 9: Site for full cycle production and test of Muon Chambers at JINR.

Search for the flavor-changing neutral-current (FCNC) decays of B-mesons was performed by the CDF Collaboration with 88 pb^{-1} of Run I data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [11]. The best limits $\mathrm{Br}(B^+ \to \mu^+\mu^-K^+) < 5.2 \times 10^{-6}$ and $\mathrm{Br}(B^0 \to \mu^+\mu^-K^{*0}) < 4.0 \times 10^{-6}$ were found at 90% C.L.

The oscillation frequency Δm_d of $B^o\bar{B}^o$ mixing was measured using the semileptonic decay $\bar{B}^o \to l\bar{\nu}D^* + X$. The value obtained is $\Delta m_d = 0.516(\mathrm{stat.}) \pm 0.099^{+0.029}_{-0.035}(\mathrm{syst.})\ ps^{-1}$ [12].

Silicon Vertex Trigger (SVT) is designed to reconstruct track parameters $P_\perp$ and ϕ with a sufficient speed and accuracy [13]. The SVT is aimed at tagging events containing secondary vertices from the b decay. The LNP group participates in the design and hardware implementation of the SVT [14]. The SVT operation time for most of events from $B \to \pi^+\pi^-$ decays in Run II was found to be between 8.6 and 10.8 μs. A new layer of silicon detector (L00) was proposed as an upgrade to CDF.

The main 1999 results of JINR cooperation with Fermilab on construction of the upgraded D0 detector (forward/backward muon system) for Run II at the Tevatron Collider are the following:

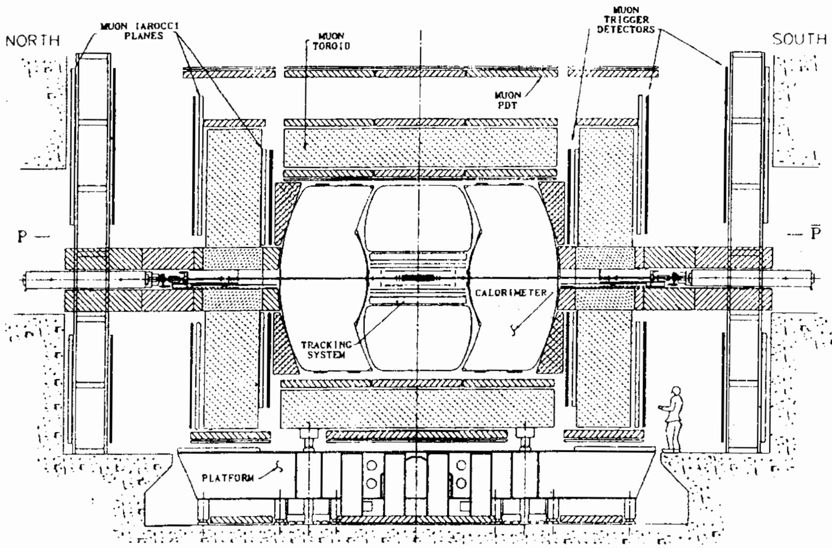

Figure 10: Shematic view of the D0 upgrade Detector

a) A new type of wire detector, called Mini-Drift Tubes (MDTs), is designed and tested. These Iarocci-type multiwire tubes with a metallic cathode run in a proportional mode and are suitable for large-surface setups, like muon systems, in particular.

b) Mass production and testing of MDTs were developed practically on the basis of the domestic (Russian) technologies. Production of all 6500 detectors is accomplished at the JINR central workshop and 2/3 of this total amount are already shipped to Fermilab.

c) ASIC chips were developed, tested and produced for the D0 muon system in cooperation with Byelorussian institutes and industries. These chips include an 8-channel amplifier (D0M Ampl-8.3) and an 8-channel discriminator (D0M Disc-8.3). A total amount of channels produced is 52736, most of them are shipped to Fermilab.

The D0 cooperation involves industries of 5 countries (Armenia, Byelorussia, Canada, Russia and USA). In Russia five enterprises, "Serp i Molot" (Moscow), "Agrisovgaz" (Maly Jaroslavets), "Savma" (Savelovo), "Himplast" (Dzerzhinsk) and "JINR workshop" (Dubna), participated in technology development and mass production.

The JINR physicists are presently participating in assembly of the D0 muon system in Fermilab and in preparation for commissioning and running the detector. They also plan to participate in data analysis.

The "Muon Wall 1" detector of the COMPASS setup is under full responsibility of JINR. Conceptual and technical design of the MW1 was agreed upon with collaboration. Proportional tubes of Iarocci-type (like in the Fermilab D0 setup) will be used as detectors. A production line was set up at JINR. The detector consists of aluminum profile with 8 cells of 10 mm width and a sensitive wire in the center. This unit is covered by a ABS plastic envelope. In total COMPASS MW1 detector will use about 4 km of these tubes (1040 pieces).

These MW1 fabricated at JINR workshop have passed inspections and tests at JINR and at CERN in a test beam run. Amplificaters and discriminators for the MW1 read-out system have been also tested. The mass production of the MW1 tubes started.

Multiwire proportional chambers (MWPCs) to be used as Large Area Trackers in the Small Angle Spectrometer of the COMPASS.

In the beginning of 1999 various prototype MWPCs configurations (new fast CF4-based gas mixtures, new front/end electronics, etc.) were tested. The final test was performed with the full-size chamber at CERN. Results obtained confirm the ability to use MWPC with the new gas mixtures and new electronics together with a sufficiently large efficiency plateau and acceptable working high voltage potential.

During the second half of 1999 the passportization of almost full set of available Omega-spectrometer chambers was completed. Chambers were checked for the gas tightness, the efficiency plateau were measured for each chamber, the leakage current was examined.

Low and Intermediate Energy Physics

Precise measurement of the probability of the pion β-decay allows a rigorous test of charged quark-lepton current universality, unitarity of the Cabbibo-Kobayashi-Maskawa mixing matrix and search for a possible manifestation of "new physics". The goal of the PIBETA experiment is to improve the accuracy from 4% to 0.5% at the first stage.

The data taking runs were successfuly performed in 1999. The general duration of these runs exceeded 4 month. Dubna specialists took part in preparation of the setup for the data taking and in the running of the setup. The new electronics for anode wires of proportional chambers was developed at LNP. This electronics provides more reliable and efficient read out of chamber information.

The μSR experiments with silicon carried out in 1999 were aimed at investigating the effect of impurities on the relaxation rate of the magnetic moment of the shallow acceptor centre.

The measurements were carried out in the temperature range 4–300 K with four silicon samples with different boron impurity ($7.4 \cdot 10^{13}$ cm^{-3}–$4.1 \cdot 10^{18}$ cm^{-3}), with two samples with gallium impurity ($1.1 \cdot 10^{15}$ cm^{-3}, $1.1 \cdot 10^{18}$ cm^{-3}) and with two samples with arsenic impurity ($8.0 \cdot 10^{15}$ cm^{-3}, $2.0 \cdot 10^{17}$ cm^{-3}). These measurements allow the constant of the hyperfine interaction of the muon magnetic moment with the electron shell in the acceptor centre (muonic atom $_{\mu}$Al) as well as the type of temperature dependence of the relaxation rate of the magnetic moment of Al acceptor centre in silicon to be found.

The values of the hyperfine interaction constant $A_{\rm hf}/2\pi$ are close to 30 MHz for different samples except two samples with the highest concentration of boron impurity. For these samples the temperature dependence of the shift of the muon spin precession frequency is not yet studied completely. This does not allow the unambiguous determination of $A_{\rm hf}$. The temperature dependencies of the relaxation rate of the magnetic moment of the acceptor centre (muonic atom) for the samples investigated are well approximated by the power function $\nu(T) = C \cdot T^q$ [16].

In 1999 the main objective of the analysis of the OBELIX data on the antiproton-proton annihilation at low energy into five pions $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ is the investigation of the 4π decay mode of the 0^+0^{++} scalar mesons $f^0(1300)$ and $f^0(1500)$, which proceeds mainly via $f^0 \to \rho\rho$ and $f^0 \to \sigma\sigma$. Due to the phase space available the two pion states in this reaction are limited by the low energy part of the $\pi\pi$ S- and P-waves. It is found that the $\pi^+\pi^-$ invariant mass and angular distributions are rather sensitive to the mass and width of the σ meson ($f^0(400 \div 1200)$ in the Review of Particle Physics), and the particularities of their behavior can be well described only with the small σ mass ($M_\sigma \approx 500$ MeV/c^2).

Measurements of the double differential cross section for subthreshold K^+-production in pC-collisions at the spectrometer ANKE wer carried out in the energy range from 2.0 GeV down to 1.0 GeV. This low value (1.0 GeV) is 580 MeV below the free NN-threshold.

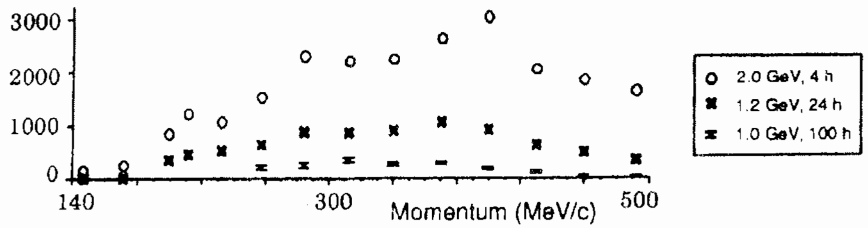

Figure 11: Preliminary results of the ANKE collaboration on the kaon spectra in the process $p + C \to K^+ + X$. The numbers in the frame denote the beam energy and time of the data taking.

The kaon spectra are obtained at an angle about 0^o [17] (Fig. 11). A software package for the ANKE data processing, developed in Dubna, provides calibration of the spectrometer momentum scale with a relative accuracy not worse than 4×10^{-3}. The gained energy dependence of the differential cross section is significantly more sensitive to mechanisms of the deep subthreshold kaon production than the total cross section dependence measured earlier in Gatchina. In the middle of 1999 a deuterium cluster target developed in Münster was installed and tested in the beam conditions. The commissioning of the target and the detector system developed in Dubna allows an experiment on cumulative deuteron break-up by protons with the energy from 0.5 GeV up to 2.5 GeV.

The collaboration DUBTO has completed the experimental apparatus for studying pion interactions with light nuclei at low energies. The experimental setup is based on the JINR streamer spectrometer STREAMER, serving both as a vertex and track detector, and is equipped with CCD telecameras for recording the images of nuclear events occurring inside the gas volume of the streamer chamber. With the exception of the streamer chamber, no available apparatus can be used for measuring energies down to ~ 1 MeV of charged secondaries, such as protons and light nuclei, produced in reactions occurring inside gas targets. A 150-hour run was performed in November 1999, and video images (over 1000) of inelastic π^+-^{4}He nuclear events were obtained; data processing is under way.

The purpose of the experiment DISTO is to measure the differential cross sections, as well as the spin observables P_Λ, P_{Σ^0}, A_Y and D_{YY}, for the reactions $pp \to pK^+\Lambda$, $pp \to pK^+\Sigma^0$, and $pp \to pK^+Y^*$ at energies between the reaction thresholds and the maximum attainable energy at Saturne (about 2.9 GeV). The correlation between these observables and the N^* and Y^* resonances will also be determined [18]. The measurement of spin observables at Saturne provides a way to investigate the relationship between the fundamental QCD approach and the boson-exchange theories.

The Dubna group has undertaken investigation of the reaction $pp \to p\pi^+\Lambda K^0$, which, in case both neutral particles decay via charged modes, requires registration of events with 6 charged particles and 2 secondary vertices. This problem is noticeably more complicated than registration of the main reaction $pp \to pK^+\Lambda$. No events involving K^0_S decays have been found yet, most likely owing to the geometry of the DISTO apparatus. The registration of events with a Λ-decay in $pp \to p\pi^+\Lambda K^0$ permits estimating the number of events of this reaction that can be obtained by registering events with all strange particles decaying via the channels with charged particles. The results obtained are not final, and studies will be continued with more profound investigation of how well the simulation program describes the experimental data for the reactions at issue.

In 1999 the measurements of the astrophysical S-factor for the *dd*-reaction at very low deuteron collision energies with the liner plasma technique were performed under project LESI. The experiment was fulfilled at the high current generator of the High-Current Electronics Institute (Tomsk, Russia). It is worth to stressing that investigation of nuclear reactions at ultralow collision energies ($\sim$ keV) with ordinary accelerators is unrealizable in practice due to a very low cross section of the processes under investigation ($\sigma \approx 10^{-43} \div 10^{-32}$ cm^2) and extremely low luminosity of beams of charged particles. The first measured values of the S-factor for the deuteron collision energies 1.8, 2.06 2.27 keV are $S_{dd} = (53 \pm 16); (64 \pm 30); (114 \pm 68)$ b$\cdot$ keV, respectively. The ultralow S-factors do not disagree within experimental uncertainties with the values of the S-factor extrapolated from larger collision energies ($7 \div 45$ keV) (Fig. 12). The corresponding *dd* cross sections described as a product of the barrier factor and the measured astrophysical S-factor are $\sigma^n_{dd} = (4.3 \pm 2.6) \times 10^{-33}$ cm^2, $\sigma^n_{dd} = (9.8 \pm 4.6) \times 10^{-33}$ cm^2, $\sigma^n_{dd} = (2.1 \pm 0.6) \times 10^{-32}$ cm^2, respectively [19].

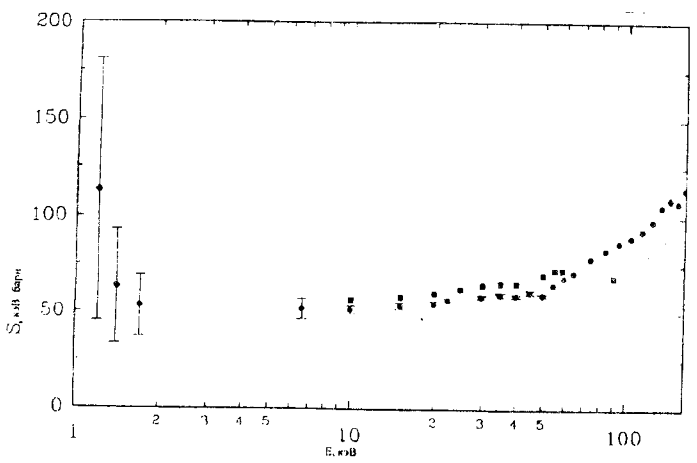

Figure 12: Dependence of the astrophysical S-factor on the energy of *dd*-interaction. Filled circles and squares — previous data, ◆ — results obtained.

The project performed in collaboration with High-Current Electronics Institute of RAN (Tomsk), Electrophysical Institute of RAN (Ekaterinburg) and Nuclear Physics Institute of Politechnical University (Tomsk).

In 1999 the research on μ-catalyzed nuclear fusion was continued to measure basic characteristics of the processes in a high-density mixture of hydrogen isotopes, including tritium. Two runs with a high-pressure hydrogen target were carried out at the JINR LNP Phasotron to investigate dependence of the cycle rate (neutron yield) on temperature (300–800K), pressure (up to 1500 atm) and concentration of isotopes in the double (H/D) and triple (H/D/T) mixture. Processing of the experimental data is under way, which will make it possible to find the rate for formation of $dt\mu$ mesomolecules on DD and DT molecules and neutron multiplicities per muon as a function of temperature (300–800K), pressure (800–1500 atm) and tritium concentration.

An additional W target (100 μm, 4 g) is installed in the mass separator unit of the ISOL complex YASNAPP-2, which allowed some five-fold increase in the yield of radioactive rare-earth isotopes. An e–γ coincidence mode of operation is provided for the "miniorange" spectrometer. A precision technique for determining γ-quantum energies is proposed on the basis of the delayed coincidence method and fiber optics. A quasi-differentiation method is introduced to eliminate Compton distribution in γ-spectra measured by SCD [20].

Monopole excitations in transition nuclei (^{152}Gd) and strongly deformed nuclei (Dy isotopes with A=156, 158, 160) were systematically searched for. A lot of E0 and E0+E2 transitions were observed [21]. A few new isomeric states are identified and studied in the ^{152}Eu and ^{156}Ho nuclei that are in the vicinity of the deformation jump (N=88) [22].

The investigation of the ^{221}Fr ($T_{1/2} = 4.9$ min) α-decay is completed [23]. Populations of ^{217}At levels by the ^{221}Fr α-decay and multipolarities of some γ-transitions are found from the quantitative analysis of α-γ coincidences. The properties of ^{217}At levels agree with their interpretation as excitations related to shell-model states $\pi h^3_{9/2}$ and $\pi h^2_{9/2} f_{7/2}$. The investigation of the ^{209}Tl ($T_{1/2} = 22$ min) β-decay is accomplished; the investigation of the ^{213}Bi(β^-, 46 min) ^{213}Po decay is under way. The probabilities for the β-decay of ^{213}Bi to ^{213}Po levels are found. Investigation of $\gamma\gamma$-coincidences confirm the decay scheme.

Cadmium KLL and KLZ Auger spectra from the ^{111}In decay are studied with an ESA-50 electrostatic spectrometer [24]. Energies and relat-

ive intensities of all nine well-resolved KLL lines are found with a high accuracy. The intensity values are in very good agreement with the calculations by the relativistic model of intermediate coupling. On the other hand, the energies, especially their absolute values, differ from the results of widely used semiempirical calculations. The investigations allow the conclusion that more accurate theoretical calculations should be carried out for the complicated mechanism of interaction between two inner-shell vacancies.

The work done under the AnCor project (*Angular Correlations with Neutrinos*) was aimed at searching for scalar interaction in β-decay and in μ-capture.

In order to search for scalar interaction in a pure Fermi β-decay of ^{18}Ne, a two-week experiment was carried out at the MP-Tandem accelerator (IPN, Orsay, France). The angular correlation between the neutrino and positron momenta was measured by means of high-precision γ-spectroscopy via the Doppler shift of γ-rays following the β-decay. The data analysis is in progress.

A similar idea was used in the four-week experiment on μ-capture at the muon beam of PSI (Villigen, Switzerland). The oxygen gas target at a pressure of 1 bar was irradiated by low-energy unpolarized muons. The 277-keV γ-line following the OMC (Ordinary Muon Capture) by ^{16}O nuclei was measured very precisely with several independent HPGe detectors. The Doppler-broadened shape of this line is very sensitive to the possible admixture of Scalar Interaction (genuine and induced). Analysis of the line shape provided the correlation coefficient value $\alpha = +0.096 \pm 0.020$ (68% C.L.), which corresponds to the presence of the scalar form factor at the level of 5–10% (depending on the nuclear model used for the NME calculation).

After few years of operation of the NEMO-2 double-beta spectrometer, many new results on the $2\beta2\nu$-decay and upper limits for the $2\beta0\nu$-decay of several isotopes have been obtained. On the basis of this experience, a new NEMO-3 spectrometer is developed in order to replace the previous one and to search for *neutrinoless* double-beta decay of ^{100}Mo at the level of $T_{1/2} \simeq 10^{25}$ years, which would correspond to the Majorana neutrino mass of 0.1 eV.

Initially, 10 kg of this enriched isotope were planned to be used as a source. Thanks to recent R&D made by our Moscow and American colleagues, several purification procedures are being applied now to ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd and ^{130}Te. All these isotopes will be measured *simultaneously*.

In 1999 the most of mechanical work on NEMO-3 was successfully finished in Dubna, now all of 20 sectors are being equipped with Geiger cells and plastic scintillators. Almost 2000 such scintillators (total mass about 7 tons) were produced by LNP JINR in 1996–1999, now this production is also finished. 3 of 20 sectors are already installed in the Frejus tunnel (LSM, Modane, France), the rest will be finished (cabling, PMTs, front-end electronics, etc.) next spring.

The 5-year experiment with NEMO-3 is planned to start after few months of tests and tuning, at the end of next year, and this plan seems to be quite realistic.

Relativistic nuclear physics

The aim of the FASA project is the investigation of nuclear multifragmentation induced by relativistic light ions in heavy targets. In the case of a proton beam, thermal multifragmentation takes place. It is governed by the statistical laws, as the excitation energy of the target spectator is entirely thermal one. It is not the case in collisions of very heavy ions, when the collective degrees of freedom are also excited, and decay of hot nuclear system is influenced by the dynamic effects related to compression (followed by expansion), rotation and shape distortion. The evolution of the reaction mechanism from thermal to more complicated one was investigated by comparing the collisions of protons, ^{4}He and ^{12}C with Au. Figure 13 shows mean multiplicities of intermediate mass fragments (IMF, $2 < Z < 20$) as a function of the beam energy.

The saturation effect is observed for energies above 5 GeV for the all projectiles. This fact cannot be rendered by the traditional approach with the intranuclear cascade (first stage of collision) followed by the statistical multifragmentation model (SMM or EES). Considering an expansion phase between two parts of calculations, the excitation energies

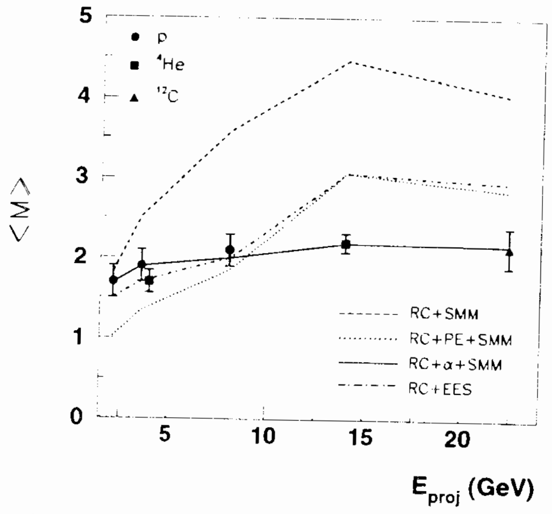

Figure 13: Mean IMF multiplicity as a function of the beam energy. The solid line is obtained with taking into account the additional energy and mass loss during the expansion of the system. Other lines are the calculations in traditional approaches (which are not adequate to the data).

and the residual masses are empirically modified to obtain agreement with the measured IMF multiplicities. The mean excitation energy is found to be (400–500) MeV for the beam energies above 5 GeV. It is believed that the expansion is driven by the thermal pressure. It is larger for He- and C-induced collisions because of higher initial temperature. Therefore the expansion flow is visible in the kinetic energy spectra of IMF, they become harder (Fig. 14). The estimation of the expansion velocity gives a value $0.1c$ (on the system surface). The analysis of the data reveals very interesting information on the fragment space distribution inside the break-up volume: heavier fragments are formed predominantly in the interior of the nucleus. This conclusion is in contrast to the predictions of the Statistical Multifragmentation Model (Copenhagen version) [25].

The FASA collaboration includes scientists from Dubna, Kurchatov Institute, Institute for Nuclear Research (Moscow), H.Niewodniczanski Institute of Nuclear Physics (Cracow), TU-Darmstadt (Darmstadt), Iowa State University.

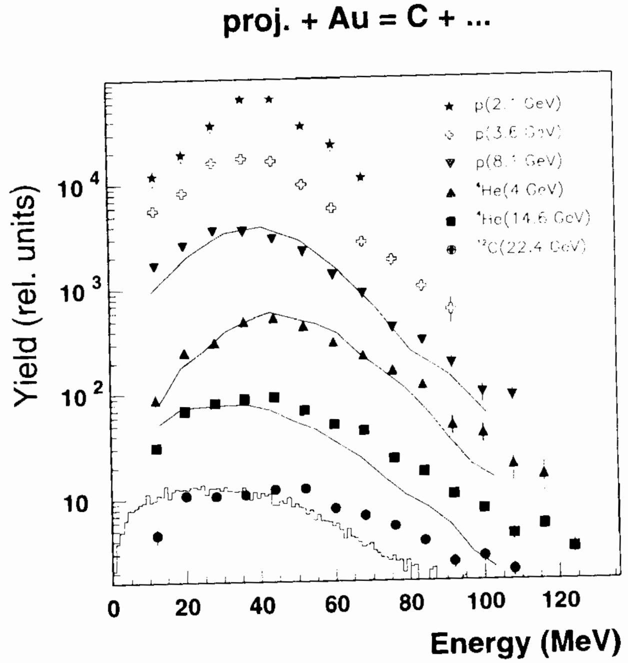

Figure 14: Energy spectra of outgoing carbon nuclei created in collisions of protons, ^{4}He and ^{12}C with the Au target. Lines show the spectra calculated in the combined model with account of the expansion stage of reaction. Calculations are made under the assumption of no flow in the system. Fitting the spectrum for proton collisions, model calculations disagree with the data obtained with He (14.6 GeV) and C (22.4 GeV) beams indicating the contribution of a collective flow.

Applied scientific research

Neutralization of the beam space charge in the electron cooling system permits one to increase the quality of an electron beam and to decrease the cooling time. In the experiments on the JINR Test Bench the influence of the ion mass composition on the electron beam stability was found. The specially method of the ion mass composition determination in the neutralized electron beam was discovered. This method showed that the number of hydrogen ions decreases with reducing cathode heating current of the electron gun. In this way the threshold of beam-drift instability increases and the electron beam becomes more stable. On the basis of the experimental data it is concluded that heavy ions are accumulated in the neutralized electron beam [26].

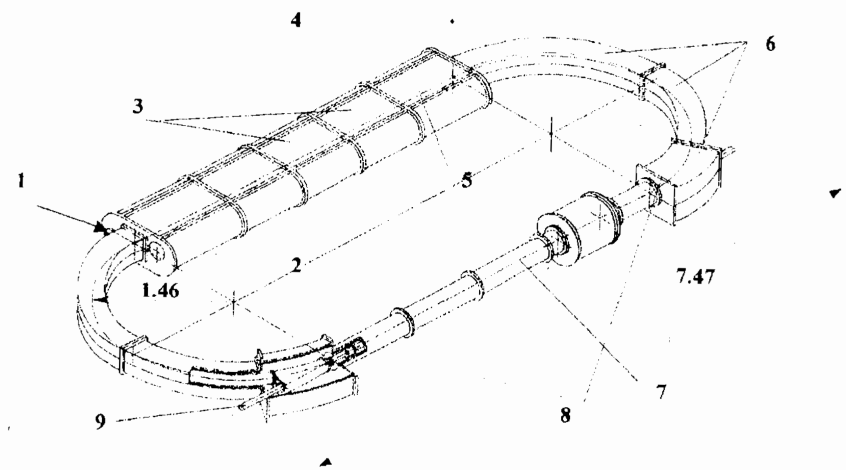

Figure 15: LEPTA Design (dimensions in meters): 1 — positron beam from injector, 2 — electron gun of the electron cooling system, 3 — septum, 4 — collector of electrons, 5 — injection kicker, 6 — toroidal solenoids, 7 — electron cooling section, 8 — pick-up stations of the diagnostic system, 9 — tubes for vacuum pumping and positronium beam extraction.

In the collaboration with the INOE2000 institute (Romania) a vacuum chamber of the LEPTA storage ring was designed and constructed (Fig. 15). The first vacuum test was performed and a vacuum pressure of 10^{-8} Torr was obtained. The vacuum chamber was transported to JINR and was reassembled in LNP. The straight section of the magnetic system was made (Fig. 15, pos.7) in 1999. The magnetic field was measured inside solenoids and a correction coil was developed. The coils allowed the quality of the magnetic field to be improved up to the necessary value $\Delta B/B < 10^{-3}$. The positron source based on the radioactive ^{22}Na source and the positron trap for storage of positrons before the injection in the LEPTA ring were designed [27].

Participants in the research under the topic "Radiation treatment with JINR Phasotron beams" are the Laboratory of Nuclear Problems, the Cancer Research Centre and the Medical Radiological Research Centre of the Russian Academy of Medical Sciences, the Institute of Atomic Energy and the Institute of Nuclear Physics (Poland), the Radiation Dosimetry Department of the Institute of Nuclear Physics and the Institute of Radiation Oncology (Czech Republic).

The main objective is to carry out medico-biological and clinical research on treatment of tumour patients on the basis of the many-room clinico-physical complex at the JINR LNP, to improve equipment and instruments, and to devise new methods for radiation treatment and diagnosis of tumour patients with medical hadron beams from the JINR Phasotron. The following results are obtained in 1999.

Clinical investigations on proton treatment of tumour patients with Phasotron beams are resumed after a long idle period. Irradiation of three patients with malignant head tumours was carried out in cooperation with radiology physicians from the MRRC (Obninsk). A new radiation treatment method was used, which required some preparation activities that resulted in highly conformal irradiation of guaranteed quality, namely,

- a beam of 150-MeV protons, uniform in the transverse section, was formed, which allowed homogeneous dose distribution inside the target volume;
- a multiplate collimator is designed and manufactured, which allows formation of a proton beam with the prescribed transverse profile matching the target profile;
- a method of calculating and manufacturing boluses (complex-shaped moderators) that allow the dose distribution maximum to be brought into coincidence with the tumour volume is devised and tested;
- treatment planning software is realized, which greatly increases the quality guarantee of the radiation treatment;
- systems of additional laser alignment and fixing of the patient in the chair are developed, manufactured and tested; they guarantee highly accurate (within 1 mm) reproducibility of the patient's position from session to session.

An important step forward in organization of clinical research on hadron therapy of tumour patients with LNP Phasotron beams is a special radiological 30-bed department opened in Medico-Sanitary Unit No 9 in Dubna. It will allow up to 150 patients per year to be treated with medical beams at JINR. The Russian Health Ministry has given an official permit for clinical research on hadron therapy of tumour patients at the JINR LNP medico-technical complex.

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