DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS

The Dzhelepov Laboratory of Nuclear Problems (DLNP) carries out experimental research in modern particle physics, investigation of nuclear structure, study of condensed matter properties; theoretical support of the experimental research; medicobiological investigations; development of new detectors and accelerators, as well as new experimental methods and facilities. The DLNP is nowadays the only laboratory at JINR where modern rare-decay experiments and *new physics researches*, like investigation of neutrino properties, are also performed. Modern important trends in experimental astroparticle and underground physics are also under close consideration in the Laboratory — new projects in the fields are also being developed.

ELEMENTARY PARTICLE PHYSICS

The **DIRAC** experiment at CERN successfully measures the lifetime of $\pi^+\pi^-$ atoms to test low-energy QCD predictions. The addendum to the DIRAC proposal «Lifetime Measurement of $\pi^+\pi^-$ and $\pi^\pm K^\mp$ Atoms to Test Low-Energy QCD» was prepared in 2004. The addendum includes plans for $\pi^+\pi^-$ atom lifetime measurement and determination of $|a_0 - a_2|$ with an accuracy better than 3%, observation of $\pi^\pm K^\mp$ atoms and estimation of $\left|a_{1/2} - a_{3/2}\right|$ with an accuracy of about 10%, observation of long-lived states of $\pi^+\pi^-$ atoms, which offer opportunities of measuring the difference ΔE_{2s-2p} and determining the new combination for $\pi\pi$-scattering length $|2a_0 + a_2|$ [1–3].

The new DIRAC Scintillating Fiber Detector (SFD) with fibers 0.27 mm in diameter and a working area 50×50 mm was tested for 20 days at CERN PS. The new electronics (developed and produced at JINR) allowed the time and amplitude for each channel measurement. The results of this test completely proved advantages of the detectors and electronics. The system of microdrift chambers (MDC) with the modified readout electronics was tested for 14 days with all DIRAC setup. About 100 million events were collected with the chambers to measure the efficiency of the detectors to double-track events.

In 2005 the collaboration plans to perform the final processing of the data collected in 2001–2003 with the Ni targets for the lifetime measurement with a statistical accuracy of about 10% and evaluation of systematic errors in the lifetime, to develop a system for identification of π, K mesons and protons, to make a modification of the electron/positron identification system, Data Acquisition System and Slow Control System.

The goal of the **NOMAD** (Neutrino Oscillation MAgnetic Detector) experiment is to search for $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\tau$ and $\nu_\mu \to \nu_e$ oscillations and to study neutrino interactions [4–7]. The NOMAD scientific programme also includes studies of Λ and $\bar{\Lambda}$ polarization in the ν_μ and $\bar{\nu}_\mu$ neutral current (NC) interactions and studies of neutral strange particles and heavy strange hyperons in ν_μ NC interactions.

In 2004 the final results of the search for $\nu_\mu \to \nu_e$ oscillations in the NOMAD experiment were obtained [4]. No evidence for oscillations was found. The 90% confidence limits obtained are $\Delta m^2 < 0.4$ eV^2 for the maximal neutrino mixing, and $\sin^2 2\theta_{\nu_\mu\nu_e} < 1.4 \cdot 10^{-3}$ for large Δm^2. This result excludes the LSND allowed region of oscillation parameters with $\Delta m^2 > 10$ eV^2.

The first measurements of $K^*(892)^\pm$ meson production and spin alignment in ν_μ CC and NC interactions have been performed [5]. For the $K^{*\pm}$ mesons produced in ν_μ CC interactions and decayed into $K^0\pi^\pm$, the most precise yields are $2.7 \pm 0.2\,(\text{stat.}) \pm 0.1\,(\text{syst.})$ and $1.5 \pm 0.1\,(\text{stat.}) \pm 0.1\,(\text{syst.})$ respectively, while for the $K^{*\pm}$ mesons produced in ν_μ NC interactions the yields are $2.3 \pm 0.3\,(\text{stat.}) \pm 0.2\,(\text{syst.})$ and $1.0 \pm 0.3\,(\text{stat.}) \pm 0.2\,(\text{syst.})$ respectively.

The preliminary results for the neutrino quasi-elastic (QEL) $\nu_\mu n \to \mu^- p$ cross section and measurement of the axial mass value (M_A) have been obtained (Fig. 1). The largest statistics of the NOMAD QEL event sample (8192 QEL candidates with about 30% background contamination) allowed the highest accuracy of these measurements. The data obtained are of great importance for neutrino physics, especially for the interpretation of the results from atmospheric neutrino experiments [6].

A narrow peak at 1530 MeV/c^2 (stable with respect to variations of the selection criteria) was observed in the analysis performed to search for an exotic baryon resonance with positive strangeness (pentaquark). The Θ^+ mass is $M = (1528.7 \pm 2.5)$ MeV/c^2. The Θ^+ width is dominated by the experimental resolution of 8.8 MeV/c^2 [7].

In 2005 the collaboration expects to finish the research on the production properties and spin alignment of K^{*+} vector mesons measured in both charged and neutral current samples of the NOMAD data, on the measurement of the neutrino quasi-elastic cross section, and on the search for an exotic baryon resonance with positive strangeness (pentaquark) in neutrino interactions.

With the aim of establishing an electromagnetic energy scale of the **ATLAS Tile Calorimeter** and understanding of performance of the calorimeter, 12% of the modules were exposed to electron beams with various energies in three possible ways (cell scan at $\theta = 20°$

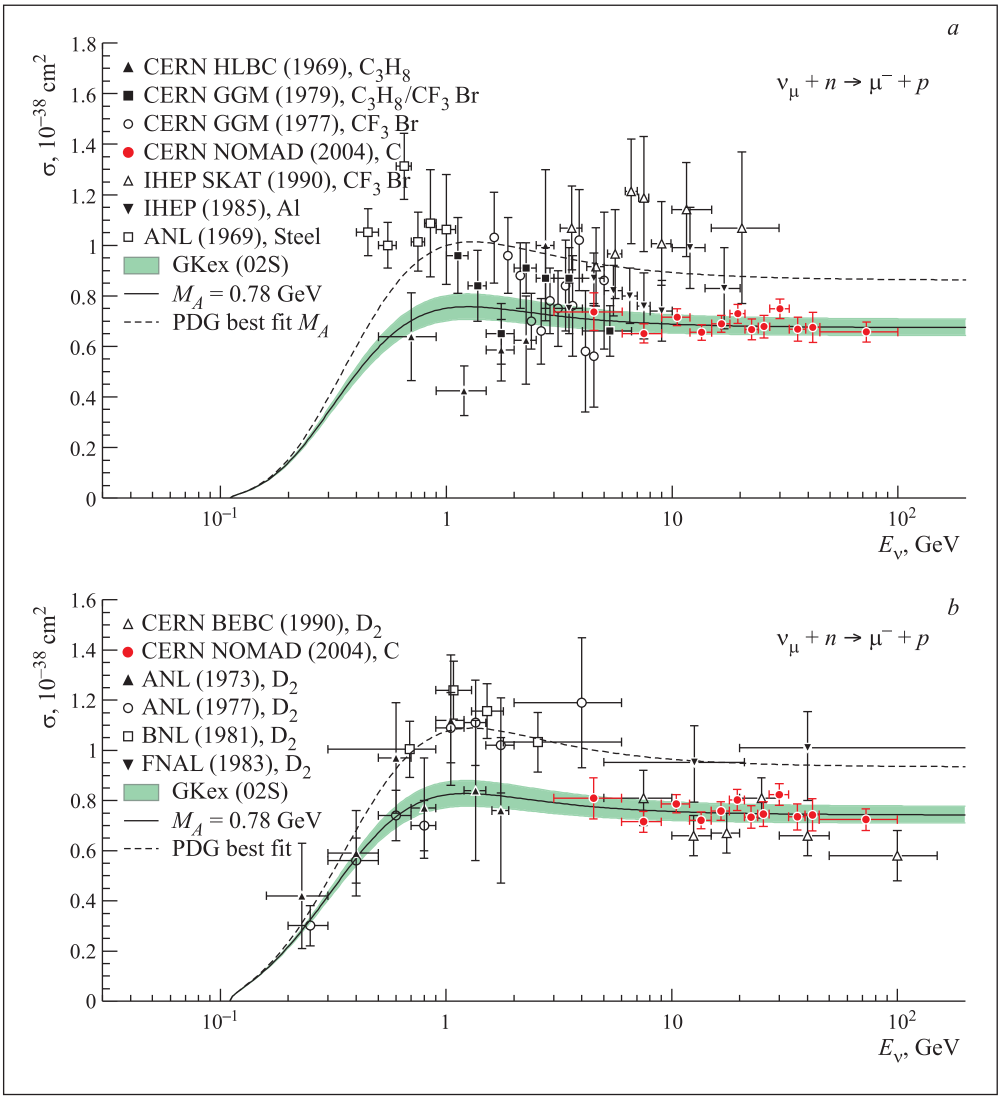

Fig. 1. Comparison of the preliminary NOMAD QEL cross section measurements with the previous experimental data obtained with a heavy liquid bubble chamber and a spark chamber (*a*) and with a deuterium-filled bubble chamber (*b*). The solid line with the error band corresponds to the M_A value obtained in the NOMAD experiment

at the centres of the front face cells, η scan and tile scan at $\theta = 90°$ for the module side cells) [8]. The average values of energy calibration constants are equal to $\langle R_e \rangle = (1.157 \pm 0.002)$ pC/GeV for the cell scan, $\langle R_e \rangle = (1.143 \pm 0.005)$ pC/GeV for the η scan and $\langle R_e \rangle = (1.196 \pm 0.005)$ pC/GeV for the tile scan. The RMS values are $(2.6 \pm 0.1)\%$ for the cell scan, $(4.2 \pm 0.3)\%$ for the η scan and $(5.7 \pm 0.3)\%$ for the tile scan. The energy linearities of the modules are within RMS = 1% at $\theta = 20°$ and 2% at $\theta = 90°$. Uniformities for the electron response are in the range of 1–2% for cells and about 4% for tile rows. The calibration constants at $\theta = 90°$ are 4% larger than at $\theta = 20°$. This is the manifestation of the transition effect. The statistical and constant terms for the electron energy resolution are determined (Fig. 2). Good agreement is observed for the linear fit Monte Carlo–based parameterization.

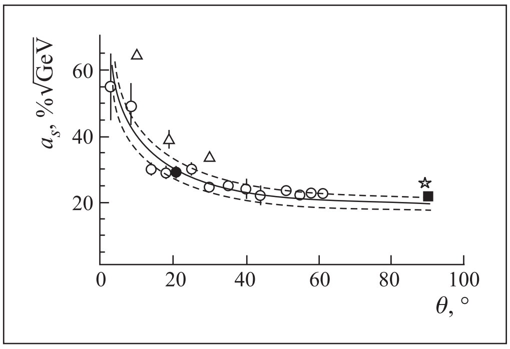

Fig. 2. Parameters a for the quadratic fit of the electron energy resolution $\sigma/E = a/\sqrt{E} \oplus b$ as a function of the angle θ: ○ — the η-scan data; ● — the $\theta = 20°$ data; ■ — the $\theta = 90°$data; △ — the prototype data; ☆ — the module-0 90° data. The solid curve is the parameterization from [9], dotted curves denote the $\pm 10\%$ error corridor

The e/h ratios of the TileCal for five values of pseudorapidity η in the range of $-0.55 \leqslant \eta \leqslant -0.15$ for the beam energy range from 10 to 300 GeV are observed. The main value is $e/h = 1.36 \pm 0.01$, which agrees within the errors with the Monte Carlo calculations $e/h_{\text{MC}} = 1.40 \pm 0.013$. The method of the pion calibration of a single module was suggested and applied. The mean pion energy deposited in a single module amounts to $(0.89 \pm 0.01)\%$ for η scan. The lateral energy leakage for one module amounts to about 10%. The good ($\pm 1\%$) energy uniformity is observed. The mean pion energy resolution for one module is equal to $(6.0 \pm 0.3)\% \sqrt{\text{GeV}}$ for 180 GeV and comparable with the value $4.8\% \sqrt{\text{GeV}}$ expected from the required overall physics performance $\sigma/E = 50\% \sqrt{\text{GeV}}/\sqrt{E} \oplus 3\%$.

In the framework of the **OPERA** project the mass production of the OPERA detector components and systems has been started. JINR's group is involved in several activities: technological and quality control of the scintillator strip production in Kharkov (Ukraine), Target Tracker (TT) modules production in Strasbourg (France), TT walls assembly in Gran Sasso (Italy), TT software development and nuclear emulsion scanning station creation in Dubna.

In Kharkov almost 70% of the total amount of the strips is already produced and delivered to Strasbourg. The strips have very high level of the light output, and their quality exceeds the analogue products used in other detectors. In Strasbourg the joint French–Russian team is working on the TT modules production in a framework of the JINR–IN2P3–OPERA cooperation protocol. The JINR experts do all the tests and calibrations of the assembled modules. So far $\sim 50\%$ of the total amount of 520 modules have been produced. First 12 TT walls have been assembled in Gran Sasso, their installation into OPERA detector started as well. The JINR physicists are taking an active part in this activity according to the JINR–INFN (FAI) cooperation protocol.

The software which allows determining efficiently the emulsion brick where the neutrino event occurred is under development. Physicists of JINR (DLNP and LIT) and IReS (Strasbourg) take part in this work. The creation of the automatic scanning station is under way as well. In 2004 a few important steps have been done: the movable stage which allows precise positioning of the emulsion sheet in X-Y coordinates and the microscope objective position in Z has been fabricated, along with the controllers for them, and commissioned. The work on creation of high-speed custom CCD camera is in progress. The JINR physicists took part in the development of the controller for the prototype of the robot which automatically replaces the emulsion sheets at the scanning station.

In 2004 the JINR/**CDF** group continued measurements of top-quark mass, data processing for the search for thermalization processes and maintaining efficient functioning of Dubna-produced hardware and software of the CDF when Tevatron was operating.

The JINR group contributed significantly to the measurement of the top mass in two decay modes. The current results are based on 193.5 pb^{-1} of the integrated luminosity for $\sqrt{s} = 1.96$ TeV of $p\bar{p}$ collisions. The method was developed for the top-mass measurement and was successfully applied to the lepton + jets topology ($p\bar{p} \to t\bar{t} \to WbW\bar{b} \to l + \text{jets}$). In a non-tagged sample of lepton + 4 jets, 39 $t\bar{t}$ events were reconstructed and fitted as superposition of the top (signal) and W + jets (background) events. The signal-constrained and unconstrained fits gave a mass $M_{\text{top}} = \big(179.1 \pm^{10.5}_{9.5} (\text{stat.}) \pm 8.5 (\text{syst.})\big)$ GeV/c^2 (Fig. 3, *a*) and $M_{\text{top}} = \big(177.5 \pm^{9.1}_{7.7} (\text{stat.}) \pm 8.5 (\text{syst.})\big)$ GeV/c^2, respectively.

New procedures for top-mass measurement in the dilepton topology ($p\bar{p} \to t\bar{t} \to WbW\bar{b} \to l + l + \text{jets}$) were developed and successfully used. A set of 13 events was reconstructed according to the $t\bar{t}$ hypothesis and fitted as superposition of a signal and a background.

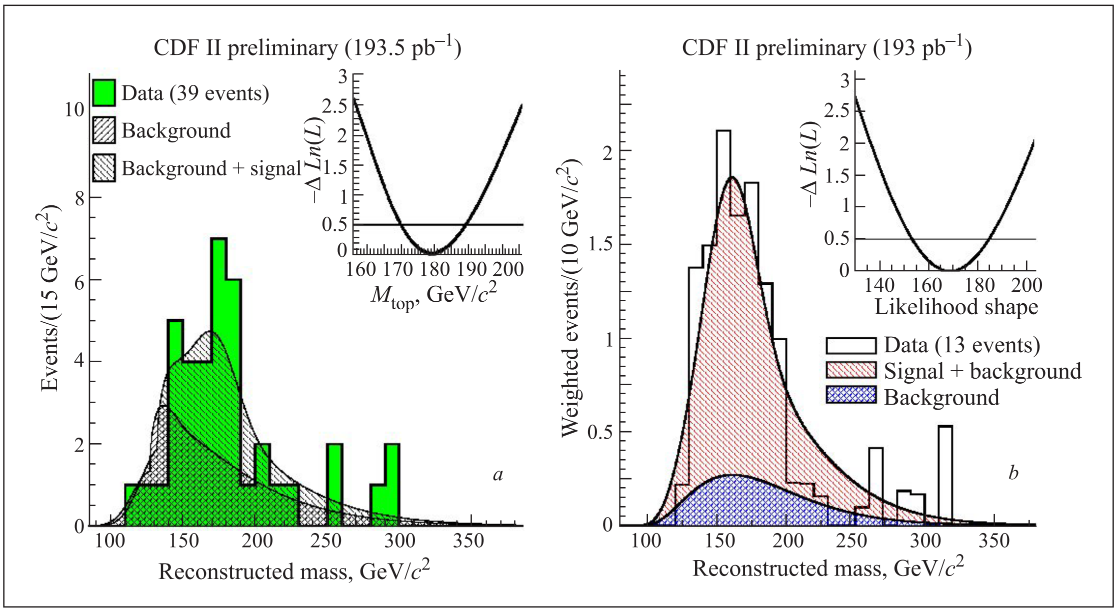

Fig. 3. *a*) $l+$jets mode; *b*) dilepton mode

By using the background constrained fit (with 2.7 ± 0.7 events expected from background), the value $M_{\rm top} = (170.0 \pm 16.6({\rm stat.}))$ GeV/c^2 was measured. The estimate of the systematic error is ± 7.4 GeV/c^2 (Fig. 3, *b*) [10–12].

In 2004 the JINR group contributed to construction of the sensitive element of the Central Calorimeter Preshower. It is now assembled and is ready for data taking at the CDF. High γ pointing and energy reconstruction precisions (essential for c-, b-, t-physics studies) are guaranteed by the light yield (up to 36 ph.e.) of the preshower.

The Dubna Muon group maintained efficient functioning of all the CDF scintillator detectors (1200 channels) and supported the iFix-based High Voltage slow control system. The group detected a 25%/y decrease in the light yield of the Scintillator Counters and proposed upgrading measures [13–15].

In 2005 the JINR/CDF group plans to obtain new limits on the Higgs mass on the basis of accumulation and processing of more top-mass measurement statistics.

The **HARP** experiment was designed to perform a systematic and precise study of hadron production with beam momenta between 1.5 and 15 GeV/c, for 12 target nuclei ranging from hydrogen to lead. HARP physics goals are the measurements of pion yields to allow a quantitative design of the proton driver of neutrino factories and more precise calculations of the atmospheric neutrino flux. HARP energy range is suitable to measure particle yields for the prediction of neutrino fluxes for the K2K and MiniBooNe experiments.

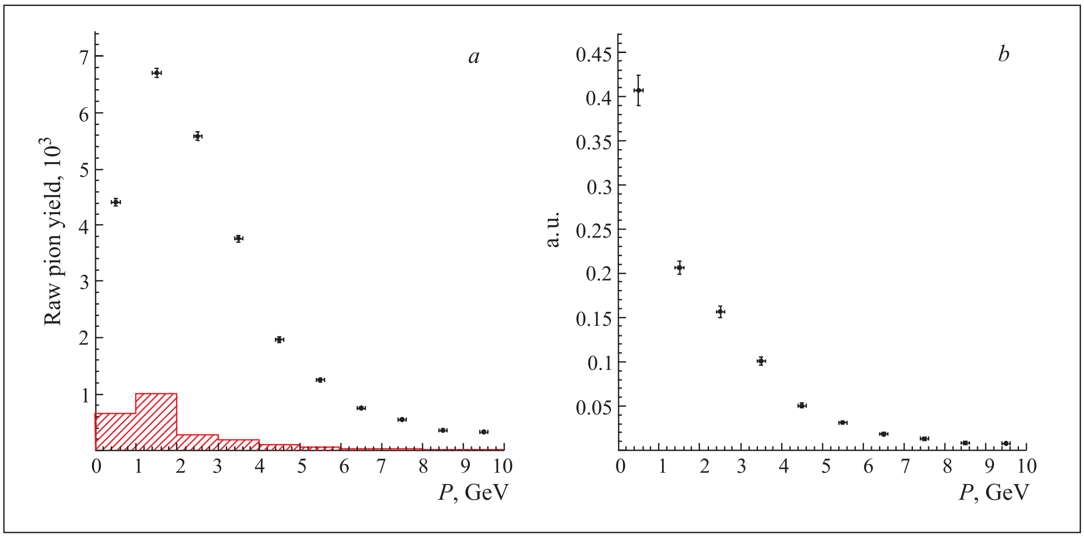

Fig. 4. *a*) Raw pion yield for the 12.9-GeV/c protons interacting in the prototype of the K2K target. The hashed area corresponds to the background from protons and electrons. *b*) The same pion yield corrected for pion identification purity, acceptance and efficiency

Tracking of forward-going particles is performed by a set of large NDC's (NOMAD drift chambers) placed upstream and downstream of the dipole magnet. In 2004 the data analysis was performed for the 12.9-GeV/c protons interacting in the prototype K2K target. The thus obtained momentum and angular distributions of secondary pions (Fig. 4) are essential for better prediction of neutrino spectra in the K2K experiment and for minimization of the systematic errors of the neutrino oscillation parameters [16–18].

The aim of the ongoing data analysis with two water targets in the TPC (Time Projection Chamber) is to shed light on the largest uncertainty in the background to the anomalous $\bar{\nu}_e$ signal observed in the LSND experiment. The HARP measurement of the π^-/π^+ ratio in the interactions of 1.5-GeV/c protons with water and measurement of the ratio e^-/e^+ from the decay of stopped muons in the water target can contribute to this issue.

In 2005 the collaboration plans to develop software for the NDC and TPC, to unify the reconstruction programmes for the analysis of the data at small and large angles, to measure the cross section of hadron production at a proton momentum of 12.9 GeV for the analysis of the K2K oscillation experiment and to finish the water data analysis.

The main goal of the **HYPERON** experiment in 2004 was to finish building of the set-up for study of meson-nuclear effects in charge exchange reactions with neutral mesons in the final state and to start data taking. The tagging system is delivered to Protvino and mounting of the counters is started. Mounting of the beam proportional chambers with new fast electronics is finished. Chamber communications were repaired and assembled. Purging with gas mixture was done. The LED monitoring system is not fully built (50%), but the part which is already made allows us to calibrate the most loaded elements of the calorimeter.

In 2005 the collaboration plans to finish mounting the tagging system and making the LED monitoring system, to perform data-taking runs in December 2004 and April 2005, to obtain preliminary results on A-dependence in the charge exchange meson-nuclear reactions by the end of the year.

Within the framework of the **TUS** experiment, together with the ENERGIA corporation, the carbon plastic module of the prototype Fresnel mirror was produced. Such a material is needed due to temperature variation in open space between -150 and $+150\,°$C. A few similar epoxy modules were produced for the Fresnel mirror of the full-scale ground TUS prototype. A special device was designed and produced for mirror surface measurements on line with a CCD camera and a PC. Two beam tests were done at the SPS accelerator of CERN within the framework of the preparation of the TUS and **NUCLEON** experiments. To know the fluorescent radiation yield of the $\sim 10^{20}$ eV EAS in the Earth's atmosphere is important for the proper interpretation of the existent and future data. For this purpose, the MACFLY experiment was conducted at the electron, muon and pion 20–80 GeV beams to measure such radiation in the air and the nitrogen gas at different pressures. Those measurements were continued at the 8–23 MeV electron beam of the JINR microtron. The NUCLEON project progressed in 2004 from phase A to phase B, assuming the launch of the NUCLEON apparatus in orbit in 2008. The prototypes of the NUCLEON silicon and scintillator detectors were successfully tested at the 150–350 GeV pion and electron beams [19, 20].

The small TUS prototype is planned to be launched as a part of the MSU TATIANA satellite in 2005. The full-scale ground TUS prototype is planned to be produced. The double-sided scintillator trigger plane is planned to be produced and tested for the basic and second options. In addition, possibilities of using the silicon photomultipliers SiPM instead of standard PMTs in the space experiments like TUS and NUCLEON will be investigated.

The **E391a** experiment is aimed to search for the rare kaon decay process $K_L \to \pi^0\nu\nu$, by using a pencil beam and a detector system having a very high performance of photon vetoing. It successfully finished data taking in June 2004 and data analysis is being done. A very rough estimate of sensitivity based on one-day analysis reaches the level of 10^{-10} without tight vetoing. Detailed study is going on, especially for optimization of vetoing and proper estimation of acceptance for the signal with a view to getting a primary result from part of the data within 2005 [21].

LOW- AND INTERMEDIATE-ENERGY PHYSICS

The **NEMO-3** detector located in the Modane Underground Laboratory (LSM, France, 4800 m.w.e.) is searching for neutrinoless double beta decay ($0\nu\beta\beta$), which would be an indication of new fundamental physics beyond the Standard Model. The study of $0\nu\beta\beta$ decay is a unique way to solve the fundamental problems of the absolute neutrino mass scale, nature of the neutrino (either Dirac or Majorana), and neutrino hi erarchy. The main goal of the NEMO project is to reach 0.1–0.3 eV sensitivity for the effective Majorana

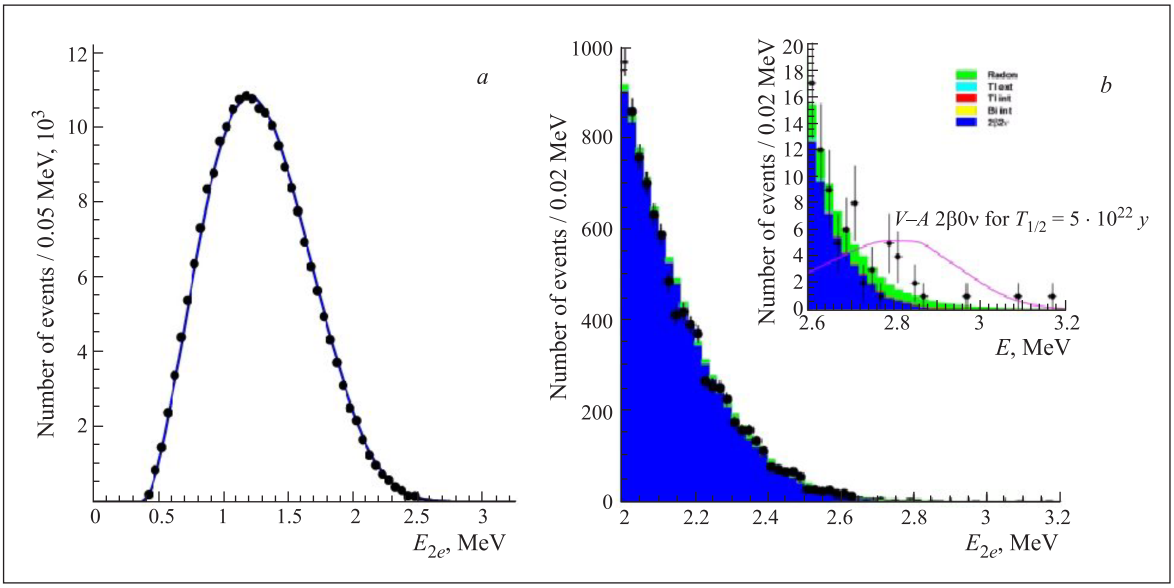

Fig. 5. Full (*a*) and tail-zoomed (*b*) spectra of the energy sum of two electrons from ^{100}Mo after 9496 h of data taking (228640 events were observed versus 5565 background events expected). Points are experimental data, solid lines and painted regions are simulations

neutrino mass $\langle m_\nu \rangle$ ($T_{1/2}^{0\nu\beta\beta}$ (^{100}Mo) up to $\sim 10^{25}$ y). The NEMO-3 registers tracks (in 20 m^3 volume with 6180 Geiger cells) and energies (1940 scintillator/PMT channels) of two electrons emitted from thin foils (30–60 mg/cm^2) of $\beta\beta$-decay sources (^{100}Mo, ^{82}Se, ^{150}Nd, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{48}Ca). This method gives unique information (single electron energy spectrum, angular distribution between electrons, etc.), which cannot be obtained by other geochemical and calorimetric methods of $\beta\beta$-decay measurements.

In 2004 the NEMO-3 detector operated in a regular mode under stable conditions, taking data 75% of time. Thorough background studies were performed. The total exposure was 450 days (February 2003 – November 2004). The components of the background were directly evaluated by analyzing different channels in NEMO-3 data. The expected numbers of events in the $0\nu\beta\beta$ energy window for ^{100}Mo (2.8–3.2 MeV) are 0.3 counts/kg/y for the $2\nu\beta\beta$ tail (e, e channel) (Fig. 5), and 0.1 counts/kg/y for ^{208}Tl impurities in the source foils (e, γ and $e, \gamma\gamma$ channels). The contributions from neutrons and high-energy γ rays (e, e events below 4 MeV), as well as from external ^{208}Tl contamination (mostly inside PMTs, e, γ events), were found to be negligible. Background activities measured by NEMO-3 are in agreement with previous HPGe measurements of NEMO-3 materials.

It was found that ^{222}Rn which diffused inside NEMO-3 from the laboratory air ($\sim$15 Bq/m^3) was the dominant $0\nu\beta\beta$ background. The level of radon inside the tracking volume of 20–30 mBq/m^3 contributes $\sim$ 1 counts/kg/y $0\nu\beta\beta$-like events in the energy region 2.8–3.2 MeV, which is too high to reach the expected NEMO-3 sensitivity. For this reason, antiradon factory (ARF) was designed, built and installed in the LSM in 2003–2004. It has been pumped purified air (125 m^3/h, $A(^{222}\mathrm{Rn}) < 1$ mBq/m^3) into the tent covering NEMO-3 since 4 October 2004. Due to this unique ARF, the level of ^{222}Rn in the air around the NEMO-3 detector was suppressed by a factor of 25 (from 16 Bq/m^3 in August down to 0.6 Bq/m^3 at the end of October), with a potential of further reduction if required. As a result, we expect elimination of the radon background in the next portions of the NEMO-3 data.

Analysis of the $2\nu\beta\beta$ mode was fulfilled. Due to huge statistics, various systematic errors for background, tracking, and simulation were studied carefully. The results obtained for different isotopes are presented in Table 1.

Table 1

Isotope	Mass, g	Exposition, days	Number of events	Signal/background	$T_{1/2}^{2\nu\beta\beta}$, y
^{82}Se	932	241.5	2385	3.3	$(10.3 \pm 0.2(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})) \cdot 10^{19}$
^{96}Zr	9.4	168.4	72	0.9	$(2.0 \pm 0.3(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})) \cdot 10^{19}$
^{100}Mo	6914	241.5	145245	45.8	$(7.72 \pm 0.02(\mathrm{stat.}) \pm 0.54(\mathrm{syst.})) \cdot 10^{18}$
^{116}Cd	405	168.4	1371	7.5	$(2.8 \pm 0.1(\mathrm{stat.}) \pm 0.3(\mathrm{syst.})) \cdot 10^{19}$
^{150}Nd	37	168.4	449	2.8	$(9.7 \pm 0.7(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})) \cdot 10^{18}$

After analysis of data collected over 265 days, no evidence for $0\nu\beta\beta$ was found either in ^{100}Mo or in ^{82}Se with the corresponding limits (90% CL):

$$T_{1/2}^{0\nu\beta\beta}(^{100}\mathrm{Mo}) \geqslant 3.5 \cdot 10^{23}\ \mathrm{y} \Rightarrow \langle m_\nu \rangle \leqslant 0.7\text{–}1.2\ \mathrm{eV},$$

$$T_{1/2}^{0\nu\beta\beta}(^{82}\mathrm{Se}) \geqslant 1.9 \cdot 10^{23}\ \mathrm{y} \Rightarrow \langle m_\nu \rangle \leqslant 1.3\text{–}3.2\ \mathrm{eV}.$$

NEMO-3 is also the best experiment to probe double beta decay with emission of a Majoron $\beta\beta\chi$. The current limit is $T_{1/2}^{\beta\beta\chi}(^{100}\mathrm{Mo}) \geqslant 1.5 \cdot 10^{22}$ y (90% CL), corresponding to a limit of $\chi < (5\text{–}8) \cdot 10^{-5}$, which is the world's best result at the moment. The analysis of the $2\nu\beta\beta$ decay to the excited states of ^{100}Mo, and the $2\nu\beta\beta$ decay in ^{48}Ca is in progress.

R&D for the next-generation SuperNEMO module started at the end of 2003. The main goal of SuperNEMO is to reach the 0.03 eV $\langle m_\nu \rangle$ sensitivity with a 100-kg $\beta\beta$ source, which is relatively small in comparison with other ambitious projects requiring tons of $\beta\beta$ sources. Successful experience with NEMO-1/2/3 and a potentially zero background to register «gold-event» give SuperNEMO strong advantages in competition with other projects (CUORE, MAJORANA, GERDA, EXO, MOON, etc.).

The main R&D directions for SuperNEMO are improvement of the energy resolution of the calorimeter up to 5–7% at 1 MeV (against 15–17% in NEMO-3), choice, production, and purification of a $\beta\beta$ source, design of the SuperNEMO module.

The Dubna NEMO group contributes essentially to NEMO-3, concentrating on detector maintenance, calibrations, SuperNEMO tests, and all stages of data analysis from software support and development to obtaining final results [22–24].

In 2005 NEMO-3 will continue to take radon-free data. The efforts of the NEMO team will be focused on improvement of data analysis with the aim to reduce systematic errors of background estimations, tracking and simulation. Cross-checking tests of analysis made by different NEMO groups will be continued in order to verify the results obtained. The SuperNEMO R&D programme will be fulfilled in parallel with the work on finding an optimal design of the whole SuperNEMO module, as well as the best PM&scintillator for the SuperNEMO calorimeter.

Within the framework of **LESI** project, the first investigations of the $p + d \rightarrow {}^3\mathrm{He} + \gamma$ (5.5 MeV) reaction in the ultralow proton-deuteron collision energy range 2.7–16.7 keV have been carried out at the pulsed high-current generator MIG ($\tau \approx 100$ ns, $U \approx 1$ MV, $I_H \approx 2.5$ MA) of the Institute of High-Current Electronics SD RAS (Tomsk). The upper boundary estimates of the astrophysical factor and the effective cross section for the pd reaction in the proton–deuteron collision energy range $2.7 \leqslant E_{pd} \leqslant 16.7$ keV are found to be $S_{pd}(E_{pd} = 10.2\ \mathrm{keV}) \leqslant 2.5 \cdot 10^7$ MeV, $\tilde{\sigma}_{pd}$ $(2.7 \leqslant E_{pd} \leqslant 16.7\ \mathrm{keV}) \leqslant 4 \cdot 10^{-33}$ cm^2, which agrees with the calculations.

In parallel with these experiments, the collaboration investigated the reaction between light nuclei by using the high-intensity plasma counterfluxes formed in the crossed $E \times H$ fields.

In 2004, work on construction of the accelerator with the ionic source started. This type of ionic source will make it possible to form high-current (~ 100 A) ballistic converging ionic beams of H^+, D^+ with an energy of 1–12 keV and a divergence of 1–5%. The use of the given accelerator is rather promising for the study of the pd, dd, d^3He reactions in the ultralow energy range [25–27].

Unique experimental investigations of the muon-catalyzed fusion process in a D/T mixture have been conducted within the framework of **CATALYSIS** pro-

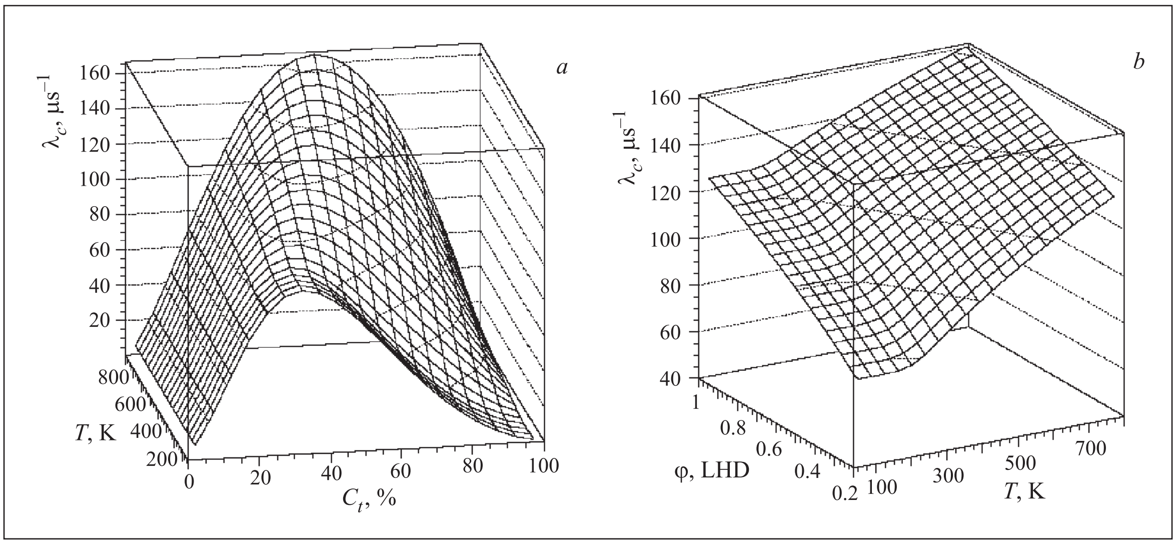

Fig. 6. Normalized cycling rate as a function of the D/T mixture conditions plotted with the optimum parameters obtained. *a*) The rate as a function of the tritium concentration and temperature for $\varphi = 0.4$ LHD. *b*) The rate as a function of the temperature and density for $C_t = 0.35$

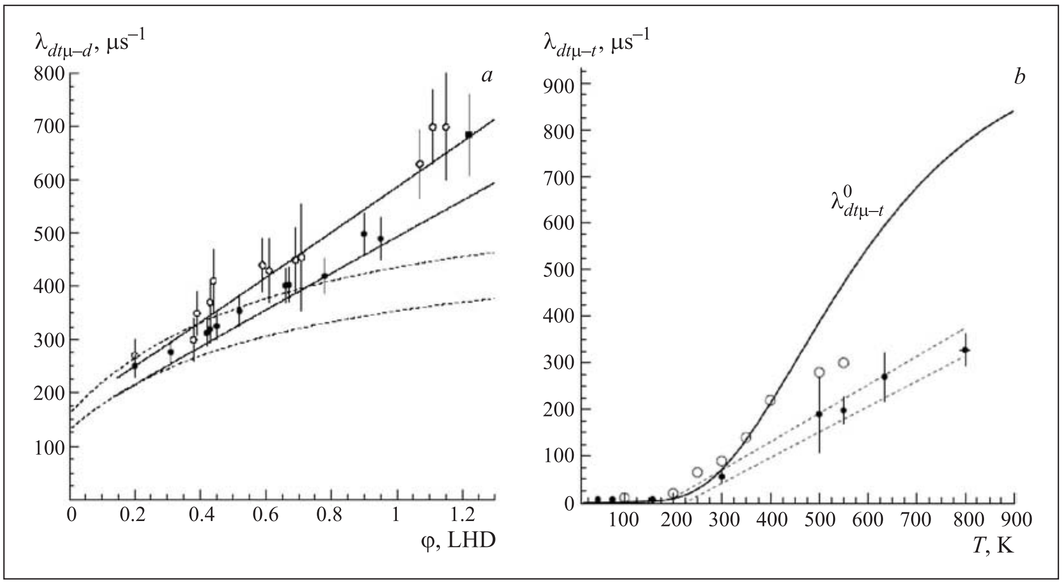

Fig. 7. *a*) $\lambda_{dt\mu-d}$ as a function of density. Solid circles are obtained for gas; open circles are the results of LAMPF; the square is the result for liquid; solid lines give the allowed values found from the common fit; dashed lines are limits for the $\lambda_{dt\mu-d}$ region obtained in PSI. *b*) $\lambda_{dt\mu-t}$ as a function of temperature. The solid line is the theoretical prediction for $\lambda_{dt\mu-t}$; dashed lines are limits of the parameterization used for $\lambda_{dt\mu-t}$

ject in collaboration with RFNC–VNIIEF by novel methods at the JINR Phasotron. Measurements were performed in a wide range of mixture parameters (density $\varphi = 0.2-1.2$ LHD, temperature $T = 20-800$ K and tritium concentration $C_t = 15-85\%$). The variety of the experimental conditions can be seen in Fig. 6, showing the cycling rate as a function of the mixture conditions.

Common analysis of the data allows determining the basic MCF parameters (temperature and density dependencies of $\lambda_{dt\mu-d}$ and $\lambda_{dt\mu-t}$). In general they are in agreement with the results obtained by other groups in the region where the experimental conditions were similar (see Fig. 7). The comparison of the experimental data with the theory confirms the efficiency of the main mechanisms considered in the MCF theory, but the full qualitative description of the process is not achieved yet. It will be very important to make measurements with a D/T mixture at the highest temperatures $T = 1000-2000$ K where the main resonances manifest themselves most effectively.

Measurements of the MCF process in liquid tritium have been carried out at the JINR Phasotron with the aim to determine the $tt\mu$-molecule formation rate, nuclear $t + t$ fusion rate, probability of muon sticking to helium and estimation of the role of $(\alpha - n)$ correlation in final state.

In 2005 the data analysis for determination of the basic MCF parameters in liquid tritium will be completed. The installation for the measurement of the yield of the radiative capture reaction in deuterium from the $dd\mu$ muonic molecule state will be mounted and tested.

With the data recorded over the period from 1999 to 2001 with a large-acceptance **PIBETA** detector and a stopped pion beam, precise measurement of the branching ratio of the rare π_β decay $\pi^+ \to \pi^0 e^+ \nu (\pi_\beta)$ was carried out. The branching ratio $\Gamma(\pi^+ \to (\pi^0 e^+ \nu)/\Gamma(\text{tot.}) = (1.036 \pm 0.004(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.003(\pi_{e2})) \cdot 10^{-8}$ (the first uncertainty is statistical, the second systematic and the third is the π_{e2} branching ratio uncertainty) was found by normalizing the number of the observed π_β decays to the number of the observed $\pi^+ \to e^+ \nu (\pi_{e2})$ events. The result agrees well with the Standard Model prediction.

The PIBETA collaboration have also studied radiative pion decays $\pi^+ \to e^+ \nu \gamma$ in three kinematic regions: a) $E_{e^+}, E_\gamma > 51.7$ MeV; b) $E_{e^+} > 20.0$ MeV, $E_\gamma > 55.6$ MeV; c) $E_{e^+} > 55.6$ MeV, $E_\gamma > 20.0$ MeV (in all the three regions the relative angle $\theta_{e^+,\gamma} > 40.0°$). The absolute $\pi^+ \to e^+ \nu \gamma$ branching ratios in the three regions were evaluated based on Dalitz distributions of 41601 events. Combined analyses of the integral and differential distributions result in the axial-to-vector weak form factor ratio of $\gamma \equiv F_A/F_V = 0.443(15)$ (or $F_A = 0.0115(4)$ with $F_V = 0.0259$). However, deviations from Standard Model predictions in high-E_γ–low-E_{e+} kinematic region (b) indicate the need for further theoretical and experimental work [28, 29].

In 2004 the PIBETA collaboration had a special run for the $\pi^+ \to e^+ \nu \gamma$ decay. About 450 Gbyte of experimental data were recorded and will be analyzed during 2005. In 2005 a revision of the PIBETA detector is also planned, to prepare it for the precise measurement of the $\pi^+ \to e^+ \nu$ decay.

DUBTO is a joint JINR–INFN project aimed at studying pion–nucleus interactions at energies below the Δ resonance. The experimental device STREAMER made use of is a self-shunted streamer chamber filled with helium at the atmospheric pressure, in a magnetic field, equipped with two CCD video cameras for recording nuclear events occurring in the fiducial volume of the chamber. This technique was developed in the 1970s at JINR's Laboratory of Nuclear Problems in collaboration with the Turin section of INFN (Italy).

In the DUBTO experiment the streamer chamber was exposed to the pion beam of the JINR Phasotron of the Laboratory of Nuclear Problems; the beam intensity amounted to $1-5 \cdot 10^4$ s^{-1} at a pion momentum of 218 MeV/c.

One of the tasks of DUBTO is to get information on the effective πNN mass at low energies, when the influence of the Δ resonance is small. This can be done by determining the invariant mass of the scattered pion and the two secondary neutrons in the three-prong breakup reaction $\pi^{\pm 4}\text{He} \to \pi^+ 2p2n$. For identification of this reaction channel, an artificial neural network (ANN) was used.

Table 2

Reaction	Pion energy, MeV	Events
π^{+4}He	100	0.12346
π^{-4}He	100	9211
π^{+4}He	70	1930
π^{-4}He	70	1430

The total number of $\pi^{\pm 4}$He events obtained during the DUBTO runs is shown in Table 2.

Certain problems in low-energy pion-nucleus physics can be resolved only if the complete kinematics of all the charged reaction products is measured.

Approximately 200 events of the reaction $\pi^{\pm 4}\text{He} \to \pi^+ 2p2n$ that satisfied rigorous selection criteria and the condition of two neutrons interacting in the final state, revealed a distribution (Fig. 8) of the effective invariant πNN mass exhibiting the same resonance behaviour as the distribution obtained in the study of the proton–proton interaction at an energy of 920 MeV at ITEP and a maximum at ~ 2.07 GeV. A similar result is obtained with negative pions.

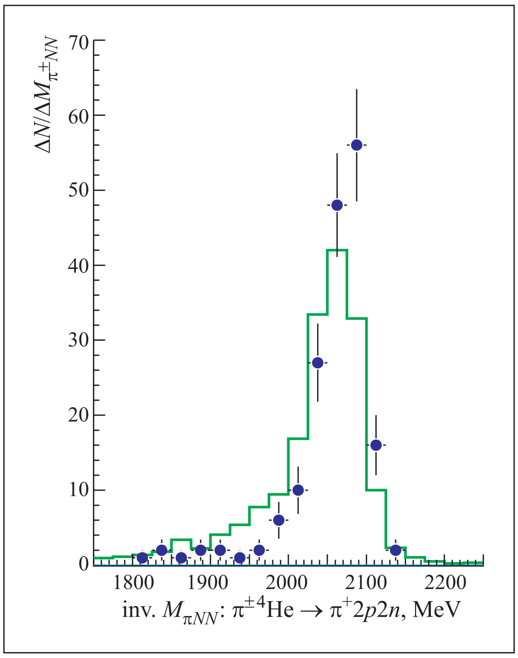

Fig. 8. $\pi^{\pm} NN$ mass distribution: histogram is the simulation, solid circles are the experiment

Another physical result obtained by the collaboration is the first observation of positive pion bremsstrahlung on helium nuclei. This was possible owing to measurement of the momenta of recoil nuclei in two-prong $\pi^{\pm 4}$He interaction events that permitted one to separate events of purely elastic scattering from events of pion bremsstrahlung on the ^{4}He nucleus.

RELATIVISTIC NUCLEAR PHYSICS

The study of the decay of very excited nuclei is one of the most challenging topics of nuclear physics, giving access to the nuclear equation of state for the temperatures below the critical temperature for the liquid–gas phase transition (T_c). The main decay mode of very excited nuclei is copious emission of intermediate-mass fragments (IMF), which are heavier than α particles, but lighter than fission fragments. The great activity in this field has been caused by the expectation that this process is related to a phase transition in nuclear media. These expectations have been realized in the **FASA** project, which is concentrated on the investigation of thermal multifragmentation induced in heavy targets by relativistic light ions.

The 4π set-up FASA is installed at the external beam of the JINR Nuclotron. It was proved that thermal multifragmentation should be considered as spinodal decomposition, which is the liquid–fog phase transition [30, 31]. It is found that the critical temperature for the liquid–gas phase transition is equal to (17 ± 2) MeV, which is significantly larger than the temperature of fragmenting system (5–6 MeV).

The inclusive experimental data on the fragment charge distribution, $Y(Z)$, and kinetic energy spectra for the target multifragmentation in $p(8.1\ \text{GeV}) + \text{Au}$ collisions are analyzed within the framework of the statistical multifragmentation model (Fig. 9). It is found from the shape of $Y(Z)$ that the partition of hot nuclei is specified after expansion of the target spectator to a volume equal to $V_t = (2.9 \pm 0.2)V_0$, with V_0 being the volume at normal density (Fig. 10). However, the freeze-out volume is found from the energy spectra to

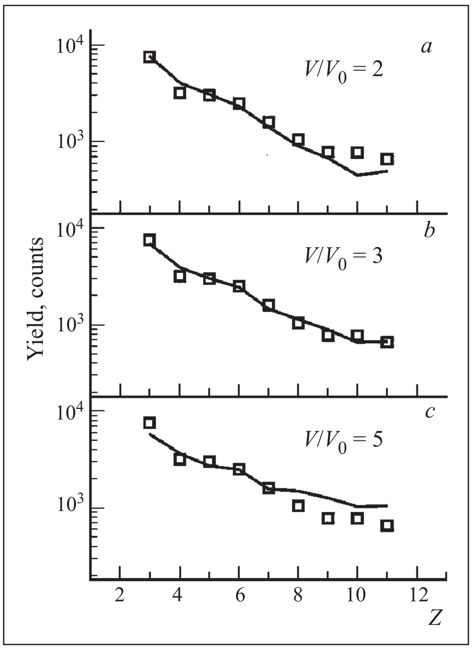

Fig. 9. Charge distributions of intermediate-mass fragments measured for $p(8.1\ \text{GeV}) + \text{Au}$ collisions (dots) and calculated with the INC + experiment + SMM prescription using different values of the system volume at the partition

be $V_f = (11 \pm 3)V_0$. At freeze-out, all the fragments are well separated and only the Coulomb force should be taken into account, while the nuclear interaction is still important at the stage of prefragment formation. Thus, thermal multifragmentation is characterized by *two* size parameters.

Existence of two different size parameters for multifragmentation has a transparent meaning. The first volume corresponds to the stage of fragment formation, when the properly extended hot target spectator transforms into a configuration consisting of specified prefragments. These prefragments are not yet fully developed, there is still the nuclear interaction between them. The final channel of disintegration is completed during the dynamical evolution of the system up to the moment of time when receding and interacting prefragments become completely separated. This is just as in ordinary fission. The saddle point resembles the final channel of fission by way of having a fairly well-defined mass asymmetry. Nuclear interaction between fission fragments ceases after descent of the system from the top of the fission barrier to the scission point. Thus, the first volume, V_t, corresponds to the configuration of the system at the top of the energy barrier for fragmentation, when charge distribution is actually specified. The other volume, V_f, corresponds to the multiscission point in terms of ordinary fission. Note that in the traditional application of the statistical models only one size parameter is used which is called «freeze-out volume».

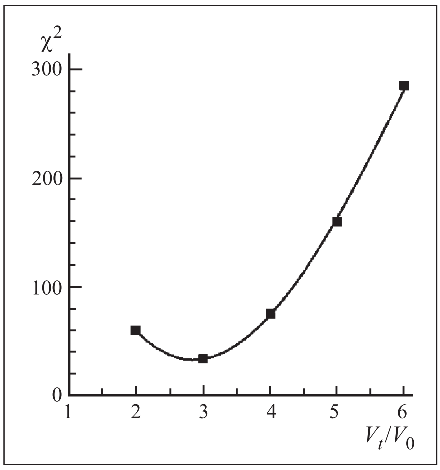

Fig. 10. Value of χ^2 as a function of V_t/V_0 for comparison of the measured and calculated IMF charge distributions. The best fit of the model to the data corresponds to $V_t = (2.9 \pm 0.2)V_0$

In 2005 the collaboration plans to upgrade the FASA device with the aim to increase the efficiency of triggering, to modernize shielding of beamline 3V to get the possibility of working with higher intensity proton beams. New experimental studies of the time-space properties of the multifragmentation induced by relativistic beams and model studies of IMF–IMF correlations triggered by the preequilibrium particles will be started.

APPLIED SCIENTIFIC RESEARCH

Numeric simulations are carried out to optimize the beam parameters of the **CYTRACK** cyclotron intended for track membrane production. For this purpose a code in MATLAB for calculation of particle dynamics by integration of differential equations and a computer model of the spiral inflector for ion bending from the axial to the median plane are developed. Space-charge effects and beam losses due to charge exchange with the residual gas are considered. Particle dynamics modeling in the buncher and the inflector is carried out. The theoretical transmission factor through the buncher and the inflector (as far as the first accelerating gap) is about

20%, which is completely supported by the experimental data.

Numeric simulation of the beam distribution on the polymer films shows that it is possible to achieve project uniformity of the pores by using a sinusoidal waveform generator for the scanning magnet, but the saw-tooth waveform decreases irradiation losses from 30 to 20%. Pore distribution uniformity also improves. The use of a saw-tooth waveform generator is recommended. The CYTRACK cyclotron design and manufacture results are published in journals [32, 33] and are nominated for 2004 JINR prizes.

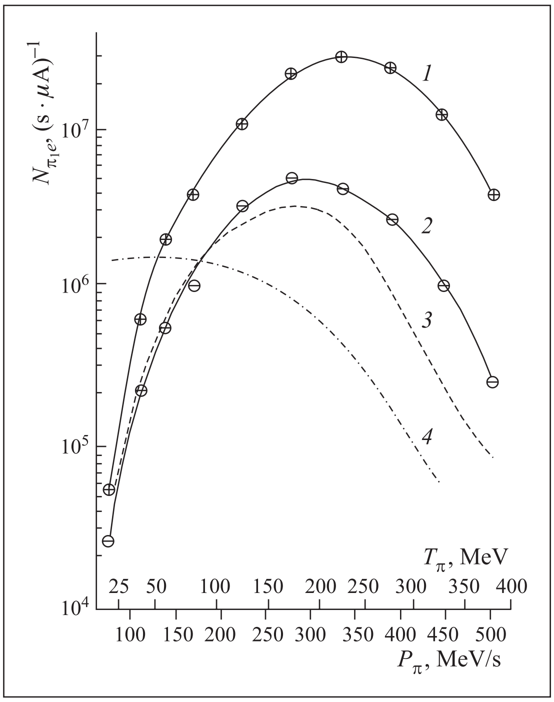

Fig. 11. Intensity of π^+ (*1*) and π^- (*2*) beams in channel 3 after modernization of the Phasotron; intensity of the π^+ (*3*) and π^- (*4*) beams before modernization

Channels 1–3 of the DLNP **Phasotron** have been modernized. The modernization was aimed to increase potentiality of experiments with meson beams. As a result, the intensity of pion beams in channel 3 increased by a factor of 3 to 40 (for the energy range 100–400 MeV) and reached $3 \cdot 10^7$ s^{-1} per 1 μA of extracted proton beam. The maximal intensity of the π^- beam in this energy range is equal to $5 \cdot 10^6$ s^{-1} per 1 μA of the extracted proton beam (Fig. 11).

Under the JINR topic **«Physics and Technology of Particle Accelerators»**, the LEPTA storage ring was commissioned. A circulating electron beam in the energy range 1.5–10 keV of beam current up to 10 mA was observed and a beam lifetime of about 2 ms was obtained. Construction of the positron injector is in progress. Solenoids and a vacuum chamber of the positron trap were manufactured. Creation of the positron source based on the ^{22}Na isotope was completed. The first measurement of the positron flux from the radioactive source was performed and positron spectrum was analyzed. A programme of in-flight experiments with positronium was developed. The positronium beam will be generated in LEPTA by applying the electron cooling to the circulating positron beam. The project of the first experiment on measurement of the para-positronium lifetime was elaborated.

In 2005 within the framework of the LEPTA project it is planned to develop a technical design project of the positron accumulator for generation of directed flux of antihydrogen atoms in an antiproton ring.

The main goal of the topic **«Further Development of Methods and Instrumentation for Radiotherapy and Associated Diagnostics with the JINR Hadron Beams»** is to carry out medicobiological and clinical investigations on cancer treatment, to improve equipment and instrumentation, and to develop new techniques for treatment of malignant tumours and for associated diagnostics with medical hadron beams of the JINR Phasotron in a seven-compartment Medicotechnical Complex (MTC) of DLNP.

In 2004 in collaboration with the Medical Radiological Research Centre (Obninsk), the Radiological Department of the Dubna hospital and medical research centres of the Czech Republic and Bulgaria, the research on proton therapy of cancer patients with the Phasotron beams in treatment room 1 of the MTC was continued. Before 1 December 2003 and 30 November 2004, a total of 95 patients (125 targets) were fractionally treated with the medical proton beam. The total number of the single proton irradiations exceeded 3000. Other 55 patients were irradiated at the ^{60}Co gamma unit Rokus-M (more than 1500 irradiations). A therapeutic proton beam with a mean energy of 225 MeV was delivered to treatment room 1 for irradiation of patients with prostate cancer. For this beam, special devises — ridge filters — were designed and elaborated. The filters allow forming a beam with a flat maximum at depth dose distributions 70 and 85 mm long depending of the size of a tumour to be irradiated (Fig. 12). All

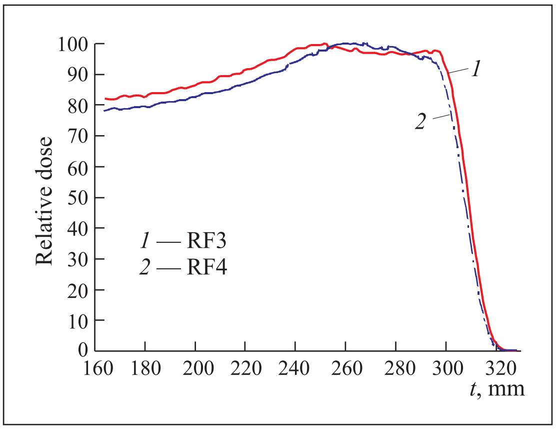

Fig. 12. Depth dose distributions of the 225-MeV proton beam with two different ridge filters

necessary dosimetric characteristics of the beam were measured and inserted into a treatment planning system for 3D conformal proton therapy.

The construction of a removable deck to the therapeutic chair for patient set-up in the supine position during proton radiotherapy in treatment room 1 has been finished. It will allow irradiation of a new class of tumours such as prostate cancer. For patient set-up in the therapeutic chair, two additional X-ray apparatus were installed in the treatment room and were put into operation. Investigations on molecular analysis of radiation-induced mutations in animal and human genes were continued [34].

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