# VEKSLER AND BALDIN LABORATORY OF HIGH ENERGIES

In 2004 the scientific programme of the Veksler and Baldin Laboratory of High Energies (VBLHE), as in the previous years, was concentrated on investigations of interactions of relativistic nuclei in the energy region between a few hundred MeV and a few TeV per nucleon to search for manifestations of quark and gluon degrees of freedom in nuclei, asymptotic laws of nuclear matter in high-energy collisions, as well as on the study of the spin structure of the lightest nuclei [1, 2].

Experiments along these lines were carried out with the beams of the VBLHE accelerator complex, as well as accelerators at CERN, BNL, GSI, and others. Today VBLHE is an accelerator centre at which a wide range of research is feasible in the energy region where the transition from the effects of nucleon structure of a nucleus to the asymptotic behaviour in nuclear interactions takes place. International scientific cooperation of the Laboratory is diverse: CERN, scientific centres in the JINR Member States, a number of research centres in the USA, Germany, Japan, India, Egypt and other countries.

This report presents some new results obtained at VBLHE in 2004.

## MAIN RESULTS OF THE DEVELOPMENT OF THE NUCLOTRON IN 2004

The Nuclotron accelerator complex at VBLHE is the basic facility of JINR. It produces proton, polarized deuteron (as well as neutron/proton) and multicharged ion beams.

Three long runs were held. Fourteen basic scientific-experimental groups worked on the $p$, $d$, He, Li, C, B and Mg beams of VBLHE's Nuclotron accelerator complex. The energy of the accelerated particles ranged from 0.5 to 3.0 GeV/nucleon for nuclei and up to 5.7 GeV for protons. The maximum working energy of deuterons in a December run was 3.685 GeV/nucleon.

In 2004, the total running time of the VBLHE accelerator complex was limited by 2304 hours. The main task of the Nuclotron development in 2004 was to accelerate deuterons to the maximum energy 6 $A \cdot$ GeV, for which purpose works were carried out during the December run of the Nuclotron.

Particle beams available now and during 2005 at the Nuclotron are shown in table [3, 4].

During 2004, construction of the new internal target station at the Nuclotron was completed [5, 6]. The Prague Vacuum plant and the Physical Institute of SAS, Bratislava, took an active part in this work.

**Parameters of the Nuclotron extracted beams**

| Beam | Intensity, particles per cycle | | |
|---|---|---|---|
| | Year 2002 | Year 2004 | Year 2005 |
| $p$ | $3 \cdot 10^{10}$ | $1 \cdot 10^{11}$ | $2 \cdot 10^{11}$ |
| $d$ | $5 \cdot 10^{10}$ | $5 \cdot 10^{10}$ | $1 \cdot 10^{11}$ |
| $^{4}$He | $8 \cdot 10^{8}$ | $3 \cdot 10^{9}$ | $2 \cdot 10^{10}$ |
| $^{7}$Li | $8 \cdot 10^{8}$ | $1 \cdot 10^{9}$ | $2 \cdot 10^{9}$ |
| $^{10}$B | $2.3 \cdot 10^{7}$ | $2 \cdot 10^{8}$ | $2 \cdot 10^{9}$ |
| $^{12}$C | $1 \cdot 10^{9}$ | $2 \cdot 10^{9}$ | $1 \cdot 10^{10}$ |
| $^{14}$N | — | $1 \cdot 10^{7}$ | $5 \cdot 10^{7}$ |
| $^{16}$O | $5 \cdot 10^{8}$ | $7 \cdot 10^{8}$ | $1 \cdot 10^{9}$ |
| $^{24}$Mg | $2 \cdot 10^{7}$ | $1 \cdot 10^{8}$ | $3 \cdot 10^{8}$ |
| $^{40}$Ar | $1 \cdot 10^{6}$ | $3 \cdot 10^{7}$ | $2 \cdot 10^{9}$ |
| $^{56}$Fe | — | $1.2 \cdot 10^{6}$ | $5 \cdot 10^{7}$ |
| $^{84}$Kr | $1 \cdot 10^{3}$ | — | $5 \cdot 10^{6}$ |
| $^{131}$Xe | — | — | $1 \cdot 10^{6}$ |

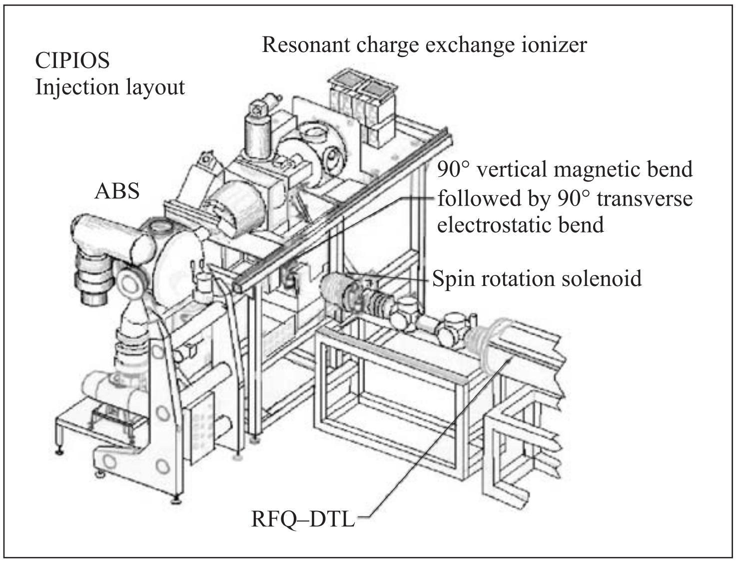


Fig. 1. The CIPIOS polarized source

A very important event in 2004 was signing an agreement between the Indiana University and JINR on handing over the CIPIOS polarized ion source to be mounted at the Nuclotron. The source parameters are: pulsed 1 to 4 Hz; 25 keV beam energy; polarized H or $d$; normal polarization $> 80\%$; 1.5 mA (peak) from source; $> 25$ mA (peak) unpolarized.

Using this source at the Nuclotron will make it possible to provide an intensity of the external beam of polarized deuterons up to $5 \cdot 10^{10}$ per cycle. Reaching such an intensity of polarized deuterons is the main task in 2005–2007. INR RAS (Troitsk) will take an active part in this work.

At present this source is ready for transportation to Dubna (Fig. 1).

The modernization of a cryostatting scheme of the Nuclotron with the jet pumps was proposed and realized. This allowed one to increase greatly the flow rate of liquid helium pumpable via the superconducting magnets of the accelerator. As a result, the reliability and the operation stability of the superconducting magnet system of the Nuclotron were increased; power consumption in the cryogenic system of the accelerator was reduced by no less than 600 kW. Preliminary measurements of additional flow rate of liquid helium in the case of cryostatting of the Nuclotron with the use of the jet pumps were made.

The Nuclotron operation opens up new possibilities for different research programmes with ion beams and polarized ion beams. The experience of its maintenance and exploitation is very helpful for design and construction of new accelerators.

## RESULTS OBTAINED AT THE VBLHE ACCELERATOR COMPLEX

In 2004, research on internal and external beams of the VBLHE accelerator complex was continued by scientific graups from various countries, and analysis of the previously obtained data was carried out. Some of the results obtained are given below.

**DELTA-2 Experiment.** We have searched for an enhancement in the excitation function of the pion yield in the $p + d$ reaction at projectile energies near 350 MeV/nucleon. The measurements were carried out on the DELTA-2 set-up at the Nuclotron internal beam with Ag, Cu, Al and C targets during two runs in March and June 2004. The layout of the DELTA-2 set-up and preliminary experimental results are presented in Fig. 2. It is seen that for heavier targets (beginning with Cu) a narrow peak appears in the region of the beam energy 350 MeV/nucleon. It means that this effect has a nuclear nature.

For interpretation, further experimental data are required. It is planned to study the effect in more detail for various targets, projectiles and pion emission angles in 2005–2006.

The first preliminary results were presented at the XVII international Baldin seminar on high energy physics problems «Relativistic Nuclear Physics and Quantum Chromodynamics», 27 September – 2 October 2004.

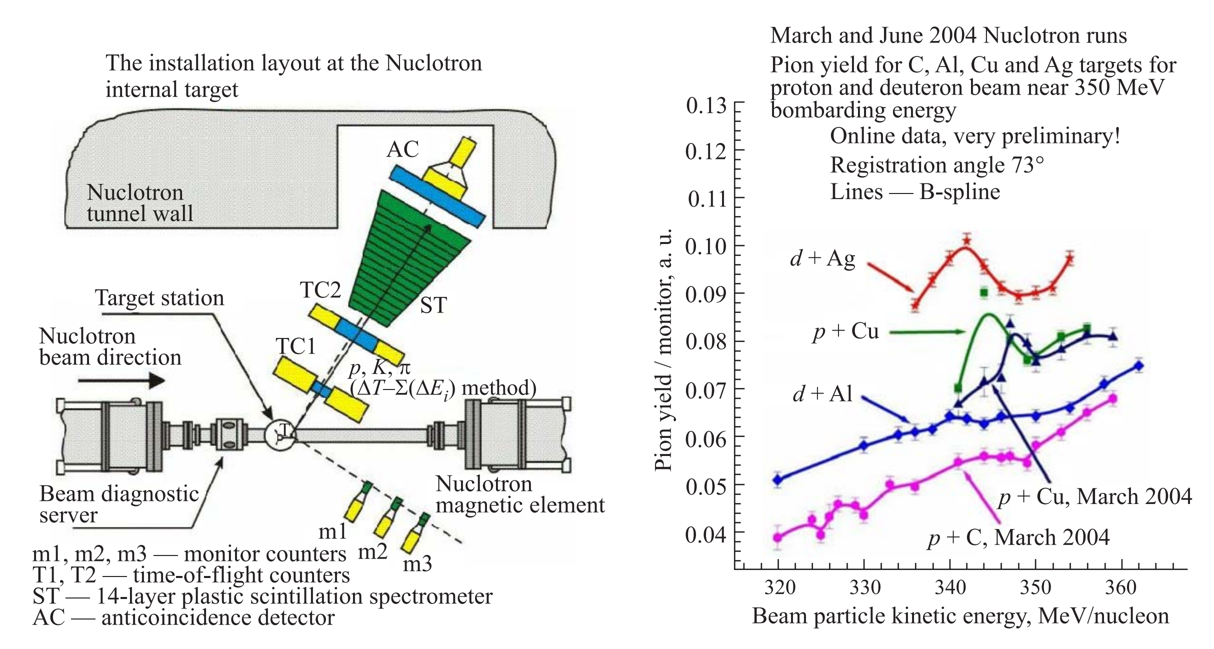


Fig. 2. *a*) Layout of the DELTA-2 set-up; *b*) preliminary normalized pion yields in $d + A$ and $p + A$ reactions as functions of beam energy

**FASA Experiment.** 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 $T_c$ — the critical temperature for the liquid–gas phase transition. The main decay mode of very excited nuclei is a copious emission of intermediate mass fragments (IMF), which are heavier than $\alpha$ 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 $4\pi$ set-up FASA is installed at the external beam of the Nuclotron. It was proved that thermal multifragmentation should be considered as a spinodal decomposition, which is the *liquid–fog* phase transition [7, 8]. Results of the refined measurements of $T_c$ are presented in [7]. $T_c$ is found to be $(17 \pm 2)$ MeV, which is significantly larger than the temperature of fragmenting system (5–6 MeV). This is a very important observation in favour of the mechanism of spinodal disintegration.

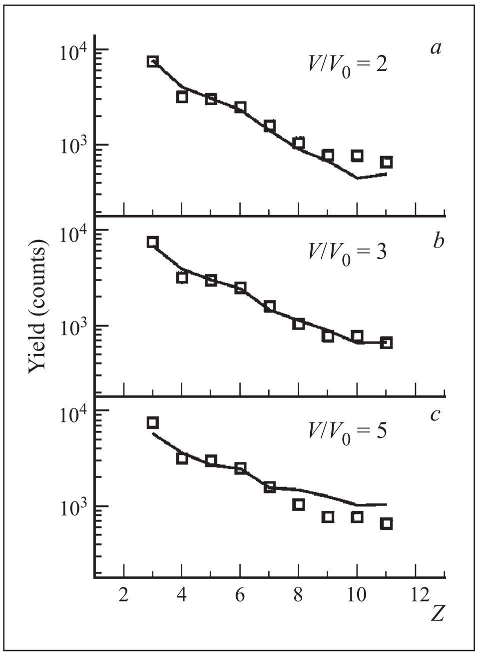


Fig. 3. Charge distributions of intermediate-mass fragments measured for $p\,(8.1\ \mathrm{GeV}) + \mathrm{Au}$ collisions (dots) and calculated with the INC + Exp. + SMM prescription using different values of the system volume at the partition moment

The space characteristics for the target multifragmentation in $p\,(8.1\ \mathrm{GeV}) + \mathrm{Au}$ collisions (Fig. 3) were experimentally determined [8]. The inclusive experimental data on the fragment charge distribution $Y(Z)$ and kinetic energy spectra are analyzed within the framework of the statistical multifragmentation model. 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 $V_0$ as the volume at normal density (Fig. 4). However, the freeze-out volume is found from the energy spectra to 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.

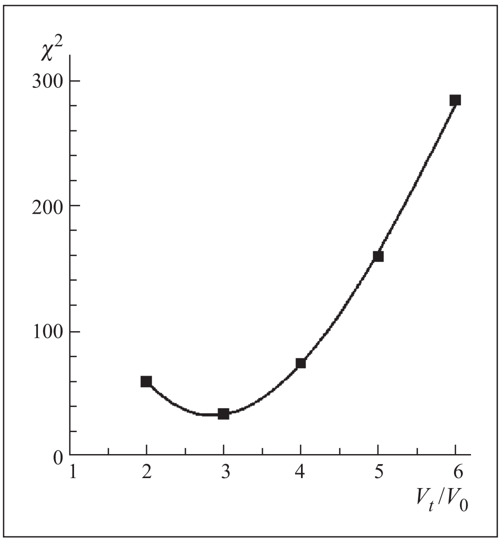


Fig. 4. Value of $\chi^2$ as a function of $V_t/V_0$ for comparison of the measured and calculated IMF charge distributions. The best fit of the model to the data corresponds to $V_t = (2.9 \pm 0.2)V_0$

Thus, thermal multifragmentation is characterized by *two* size parameters.

The 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 nuclear interaction between them. The final channel of disintegration is completed during the dynamical evolution of the system up to the moment 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». Now FASA studies have demonstrated the shortcoming of such a simplification of the model.

**DELTA–SIGMA Experiment.** New accurate results of the neutron–proton spin-dependent total cross section difference $\Delta\sigma_L(np)$ at neutron beam kinetic energies of 1.39, 1.69, 1.89 and 1.99 GeV were obtained [9]. The results are shown in Fig. 5.

The measured $\Delta\sigma_L(np)$ values are compatible with the existing $np$ results, using free neutrons. The rapid decrease of $\Delta\sigma_L(np)$ values above 1.1 GeV is confirmed and a minimum or a «shoulder» around 1.8 GeV is observed.

The $\Delta\sigma_L(I = 0)$ values obtained from the measured $\Delta\sigma_L(np)$ values and the existing $\Delta\sigma_L(np)$ data are also presented. They show a plateau or a weak maximum around 1.4 GeV, followed by a rapid drop with energy growth and by a minimum around 1.8 GeV.

The obtained results were compared with the dynamic model predictions and with the recent ED GW/VPI PSA fit. The necessity of further accurate $\Delta\sigma_L(np)$ measurements around 1.8 GeV and new $\Delta\sigma_L(np)$ data in the kinetic energy region above 1.1 GeV is emphasized.

The spin-dependent results were supplemented by the measurement of unpolarized total cross sections $\sigma_{0\mathrm{tot}}(np)$ and $\sigma_{0\mathrm{tot}}(n\mathrm{C})$.

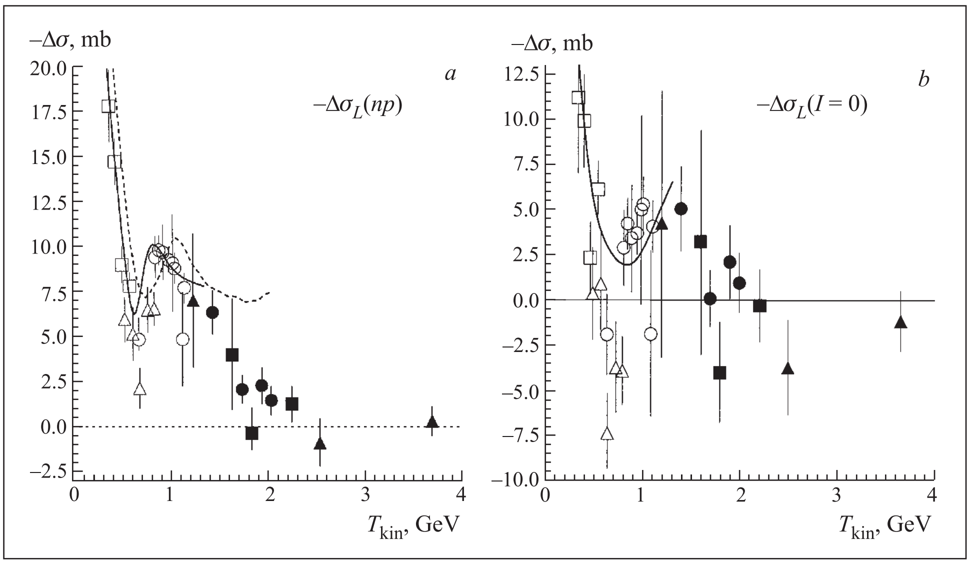


Fig. 5. Energy dependence of $-\Delta\sigma_L(np)$ (*a*) and $-\Delta\sigma_L(I = 0)$ (*b*). ● — our experimental data; ▲, ■ — our earlier data; □ — PSI data; △ — LAMPF data; ○ — SATURNE II data

**BECQUEREL** (Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation) project is oriented toward emulsion irradiation with light stable and radioactive nuclei with an energy of the order of a few GeV per nucleon in the beams of the Nuclotron.

In accordance with the BECQUEREL project, emulsion tracks were exposed to the Nuclotron beams enriched with light 1.2 $A \cdot$ GeV $^7$Be, $^8$B, $^9$Be and $^9$C nuclei.

The primary $^7$Li charge exchange reaction was chosen to form a $^7$Be beam. The total irradiation flux was 40 000 $^7$Be nuclei for about 1.5 h irradiation time. The charge beam spectrum is given in Fig. 6. At present the irradiated material is being processed. There is reason to hope that the statistics on fragmentation of this nucleus will essentially increase with the retest to early irradiation.

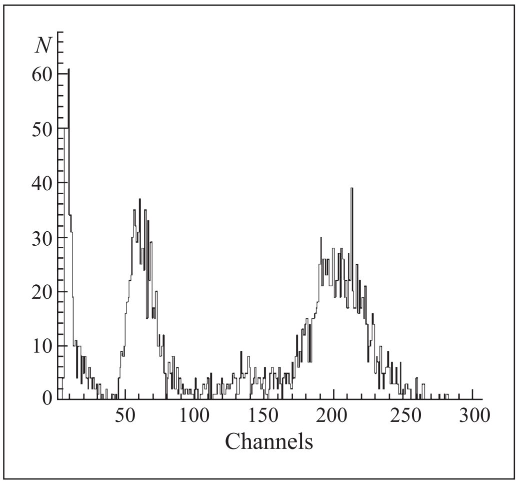


Fig. 6. The spectrum of signals from the scintillation counter monitoring the beam flux on the emulsion stack. Right to left: peaks from $^7$Be and $^3$He nuclei, as well as the background and strob-signals

The $^9$Be and $^8$B beams were formed on the basis of the primary $^{10}$B stripping reaction and the $^9$C beams — in $^{12}$C fragmentation. About 80 percent of the beam was enriched by these nuclei; the rest background was lighter nuclei with close charge-to-weight ratio.

A visual scanning of emulsions exposed to $^9$Be nuclei revealed, by the present time, about 200 interactions in which the total charge of secondary tracks in the relativistic fragmentation cone is equal to the charge of the primary one (for examples see Fig. 7). Figure 8 shows the $b_{ik}$ (squared relative four-velocity difference) distribution for two-charged fragment pairs from 31 measured events. The distribution is limited by the region which, following Baldin's definition, is typical of nuclear physics. A part of this distribution near zero is represented on an enlarged scale in Fig. 8. One can see a concentration of 8 events for $b_{ik} < 2 \cdot 10^{-4}$ which is due to the decay of an unbound $^8$Be nucleus from the ground state. The decay energy, which is determined as the difference between the invariant mass of a pair of fragments and their total mass, is $(88 \pm 10)$ keV. This result is of interest for the study both of the decays of $^8$Be nucleus itself and of its possible role in multifragmentation of heavier nuclei.

The BECQUEREL collaboration has classified the results on the charged state topology in light relativistic nucleus multifragmentation processes [10, 11]. The «white» star type events which contain only relativistic nucleus fragment tracks and contain neither charged meson no target-nucleus fragment tracks were selected. The multifragmentation topology was considered for these events. The peculiar feature of the charge topology in Ne, Mg, Si and S fragmentation is an almost total suppression of pairing splittings of nuclei into fragments with charges larger than 2. Processes with separation of individual fragments occurring at minimal excitation

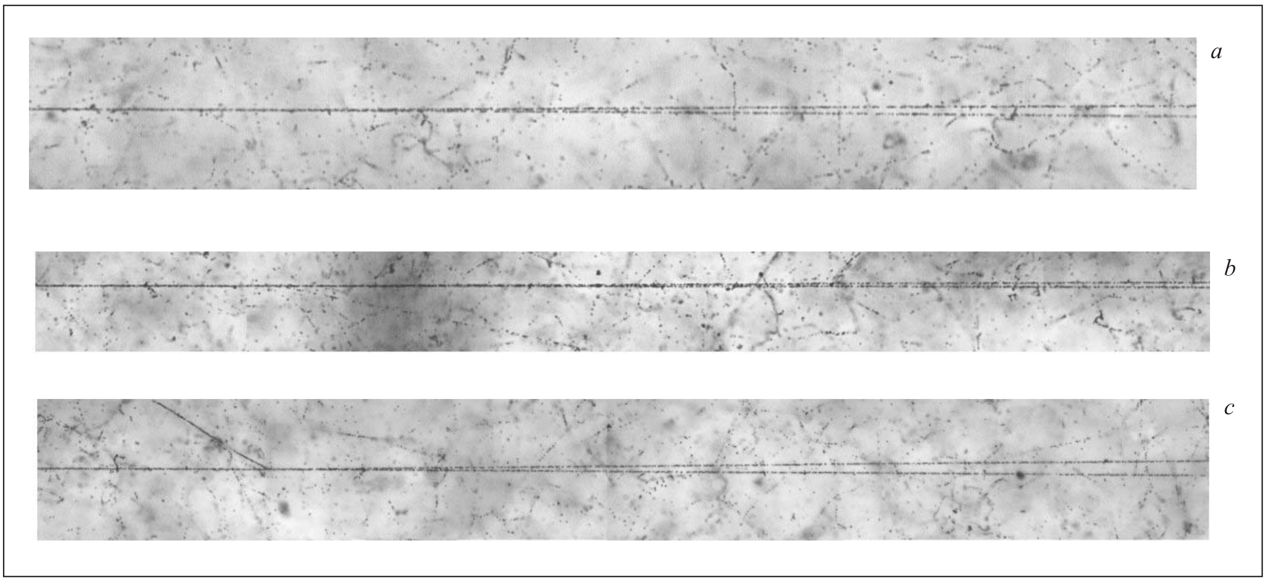


Fig. 7. Examples of the events of peripheral 1.3 $A \cdot$ GeV $^9$Be interactions in emulsion with splitting into two nuclei: without excitation of the target nucleus or the recoil nucleus (*a*), with the recoil proton (*b*) and the nuclear fragment (*c*)

energies are found to be dominant. The increase in the nuclear fragmentation degree is revealed in the fact that the multiplicity of fragments with charges 1 and 2 grows with decreasing charge in the main nonexcited part of the fragmenting nucleus.

The particular features of formation of the lightest alpha, $d$ and $t$ nuclear systems are defined in $^7$Li [12], $^{10}$B and $^{14}$N multifragmentation processes. So, nucleon clustering in the form of deuterons in $^6$Li and $^{10}$B decays and triton clustering in $^7$Li decays have been established in addition to alpha clustering. To study clustering of these types, emulsions exposed to relativistic $^{14}$N and $^{11}$B isotopes are being analyzed. Emulsions have been exposed to $^7$Be, $^8$B and $^9$C nuclei, and statistics is being accumulated for the investigation of $^3$He clustering in them.

**LNS Project.** Anomalous behaviour of the $dp$ elastic cross section is called Sagara discrepancy. This effect reflects the experimental fact that modern nucleon–nucleon potentials cannot reproduce the behaviour of the cross section in deuteron–proton elastic scattering in the vicinity of 120° in the c.m.s. (Fig. 9). Only taking into account strong contribution of the 3-nucleon forces allows one to reach an agreement with the data. The influence of the 3-nucleon forces on this effect is studied at the LNS se-tup. The LNS detectors are now in the construction and calibration stage, and the first measurements are beginning (Fig. 10).

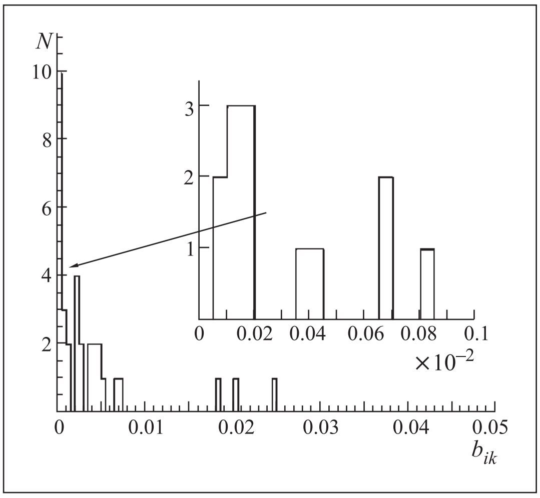


Fig. 8. The distribution with respect to the $b_{ik}$ variable (the squared 4-velocity difference) for two-charged fragment pairs in 1.2 $A \cdot$ GeV $^9$Be dissociation. The concentration of 8 events for $b_{ik} < 2 \cdot 10^{-4}$ which is due to the decay of an unbound $^8$Be nucleus from the ground state is seen

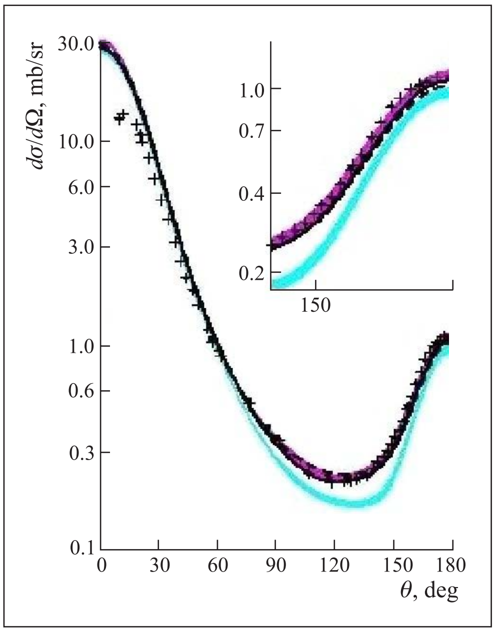


Fig. 9. Sagara discrepancy effect

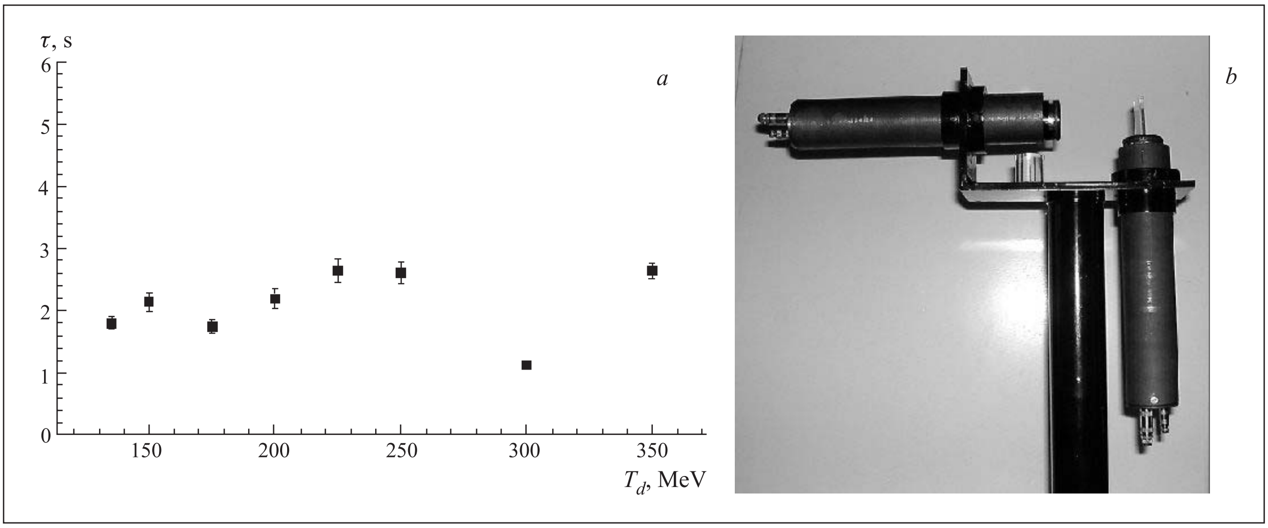


Fig. 10. $a$) Deuteron beam lifetime at the internal Nuclotron target station vs deuteron kinetic energy $T_d$; $b$) typical detectors of the LNS set-up

**PHOTON Experiment.** By using the VBLHE 90-channel lead glass Cherenkov spectrometer, the cross sections for the inclusive production of $\pi^0$ mesons in the reactions $d + \mathrm{C} \to \pi^0 + X$ and $d + \mathrm{Cu} \to \pi^0 + X$ at an incident momentum of 4.5 GeV/$c$ per nucleon are measured for the kinematical region specified by the inequalities $\theta_\pi \leqslant 16^\circ$ and $E_\pi \geqslant 2$ GeV (lab. system).

The combinatorial invariant mass spectrum of $\gamma\gamma$ combinations is shown in Fig. 11.

The following main results have been obtained:

1. The cumulative number $X_c$ and transverse momentum dependences of the exponent $n$ in the cross section parametrization $Ed^3\sigma/d^3p \sim A_T^n$ are investigated by comparing the observed cross sections for $\pi^0$ production on carbon and copper targets in the intervals $0.6 \leqslant X_c \leqslant 1.8$ and $0.04 \leqslant P_t^2 \leqslant 0.40$ (GeV/$c$)$^2$. It is found that $n = 0.39 \pm 0.02$ and $n$ is essentially independent of $X_c$ and $P_t$.

2. The probabilities $p_6$ of the formation of six-quark configurations in $^2d$, $^4$He and $^{12}$C nuclei (invoking our data for the reactions $\alpha + A_T \to \pi^0 + X$ and $\mathrm{C} + A_T \to \pi^0 + X$) are estimated: $p_6(^2d) \approx 2\%$; $p_6(^4\mathrm{He}) = 5 \div 10\%$; $p_6(^{12}\mathrm{C}) = 20 \div 40\%$.

3. The double differential invariant cross section of the reaction $d + \mathrm{C} \to \pi^0 + X$ is first measured using statistics of more than 40 000 $\pi^0$ mesons (see Fig. 11, *a*).

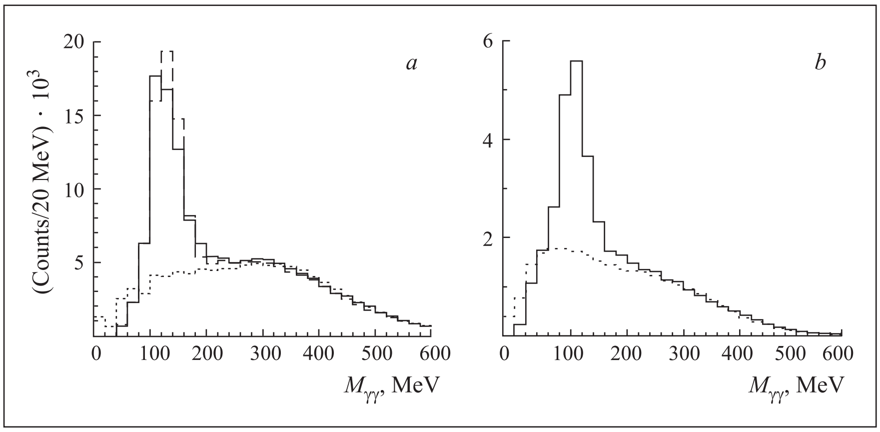


Fig. 11. Invariant mass spectra of $\gamma\gamma$ pairs for $d + \mathrm{C} \to \pi^0 + X$ (*a*) and $d + \mathrm{Cu} \to \pi^0 + X$ (*b*) reactions. The dotted histograms represent the invariant mass distributions for $\gamma\gamma$ pair combinations selected accidentally from different events. The dashed line in panel *a* indicates the invariant mass spectrum of $\gamma\gamma$ pairs from a Monte Carlo simulation

## RESULTS OBTAINED AT OTHER ACCELERATOR CENTRES

**Experiments at RHIC.** The VBLHE group participated in design and manufacturing of the aerogel detector for the PHENIX experiment. The detector system consisting of 80 aerogel counters was assembled, tested and installed at the PHENIX set-up and used for obtaining new physical information at RHIC in 2004.

At the PHENIX set-up the new data on suppression of high-$P_t$ hadrons in $d + \mathrm{Au}$ collisions were obtained in addition to the earlier data on such suppression in $\mathrm{Au} + \mathrm{Au}$ collisions (Fig. 12). As seen from this figure, significant suppression of high-$P_t$ hadrons is observed in $\mathrm{Au} + \mathrm{Au}$ interactions, while in $d+\mathrm{Au}$ interactions

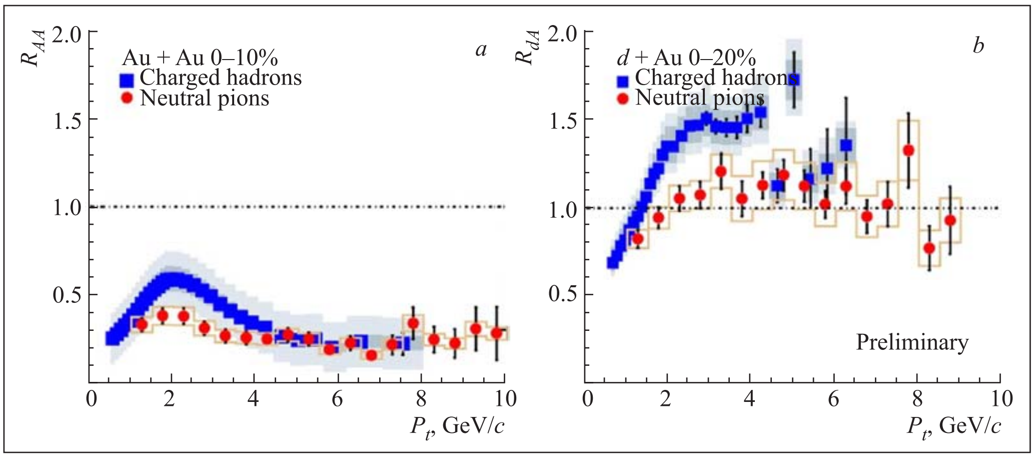


Fig. 12. High-$P_t$ hadron suppression in $\mathrm{Au} + \mathrm{Au}$ collisions (*a*) and in $d + \mathrm{Au}$ collisions (*b*) obtained in the PHENIX experiment at RHIC

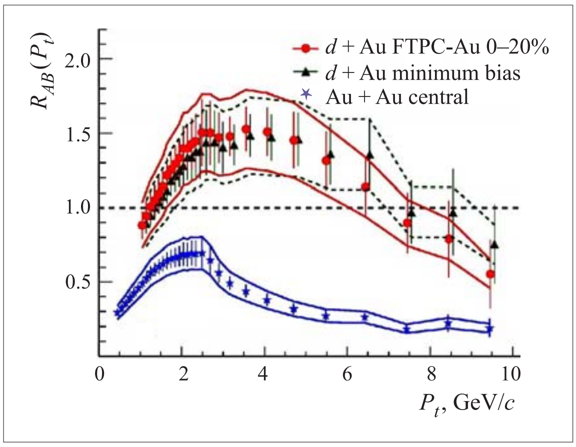


Fig. 13. High-$P_t$ hadron suppression in Au + Au collisions and in $d$ + Au collisions obtained in the STAR experiment at RHIC

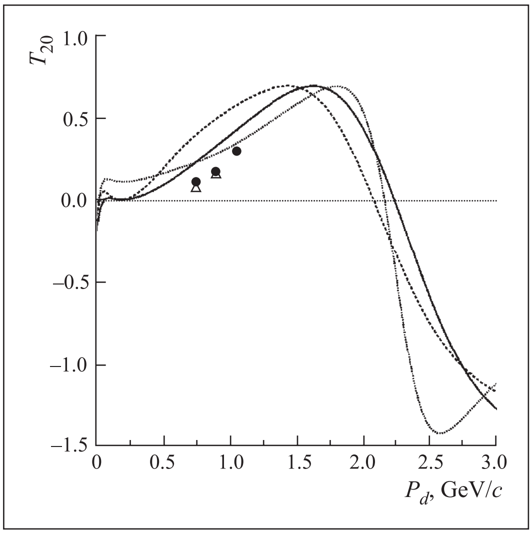


Fig. 14. Behaviour of the tensor analyzing power $T_{20}$ in the $dd \to {}^3\mathrm{He}n$ and $dd \to {}^3\mathrm{H}p$ reactions [14] shown by the black and open symbols, respectively. The curves are the predictions based on the conventional picture of the light nuclei spin structure at short internucleonic distances

such suppression is not observed [13]. High-$P_t$ hadron suppression in the Au + Au collisions is interpreted as a result of strong energy losses in quark–gluon plasma in central collisions at RHIC energies.

A similar result was obtained in the **STAR** experiment at RHIC. The VBLHE group took an active part in this work (Fig. 13).

High-$P_t$ hadron suppression in central Au + Au, but not in $d$ + Au, clearly proves the Jet Quenching Effect to be a final-state phenomenon, indicating very strong interactions of hard-scattered partons or their fragments with dense, dissipative medium.

Participation in the PHENIX and STAR experiments at RHIC will be continued in 2005–2007.

**New Detector Laboratory at VBLHE.** At VBLHE in bldg. 40 a new Detector Laboratory for development and construction of gas position-sensitive detectors has been built. It includes several clean rooms (total area $\sim$ 120 m$^2$) with a climate control, new computer-controlled winding machine and modern tools for detector construction.

The first chambers with dimensions $\sim 1 \times 1$ m for the Transition Radiation Detector of the ALICE experiment at LHC (CERN) are produced now in this new laboratory. This work is performed in collaboration with Heidelberg University, GSI (Darmstadt), Frankfurt University and NIPNE (Bucharest).

**pHe3 Project.** The aim of the collaboration between two spin groups of VBLHE and Centre for Nuclear Study of the University of Tokyo is to investigate the light nuclei spin structure at intermediate and high energies using polarized beams of the Nuclotron and RIKEN facilities.

This collaboration was started in 1999, when the joint experiment on the investigation of the ${}^3$He spin structure was approved by the PAC of RIKEN with the first priority. This experiment was performed at RIKEN's RARF in 2000.

The data on the tensor analyzing power $T_{20}$ in the $dd \to {}^3\mathrm{He}n$ and $dd \to {}^3\mathrm{H}p$ reactions [14] showed the unexpected behaviour versus the energy of the initial beam (Fig. 14). Such behaviour, being very sensitive to the $D$ wave in the ${}^3$He and ${}^3$H nuclei, is in complete disagreement with predictions based on the conventional picture of the light nuclei spin structure at short internucleonic distances. The data on the angular behaviour of the tensor analyzing powers at 27 MeV obtained in the same experiment have already been reported at different international conferences and are in preparation for publication.

In April 2002 the experiment on the measurements of the polarization observables in the $d{}^3\mathrm{He} \to p{}^4\mathrm{He}$ reaction at the Nuclotron was approved by the JINR PAC with the first priority. This experiment requires the high-intensity polarized deuteron beam of the Nuclotron and serious modification of the polarized ${}^3$He target developed by Japanese collaborators [15]. To satisfy the conditions of the experiment at the Nuclotron, it is essential to significantly increase the target length and gas density, as well as to further develop the polarization optical pumping system.

From 10 to 21 December 2004 Professor T. Uesaka and Dr K. Suda of CNS visited the Veksler and Baldin Laboratory of High Energies. The goal of their visit was to check equipment and to prepare a set-up for the polarization measurements at the internal target station of the Nuclotron. The detectors, trigger system and DAQ system based on CAMAC and VME brought from Japan were tested and prepared for the measurements in 2005.

The high-energy deuteron polarimeter will be calibrated using the beam provided by the polarized ion source POLARIS in 2005. The obtained data will be used in future to measure the polarization of the deuteron beams provided by the new modified ion source CIPIOS at the Nuclotron and also at a new facility, RIBF, at RIKEN. The high-energy polarimeter developed for the Nuclotron will be used as basic equipment for the wide spin programme at VBLHE.

**CMS Experiment.** Another VBLHE group participated in development of Heavy Ion Programme for CMS and in a test beam run of the hadronic calorimeter and electronics at CERN in 2004. Express online analysis of some data was performed. In particular, the VBLHE group obtained the ratios of the calibration coefficients for different types of particles. With these coefficients the resolution of the Hadron Endcap Calorimeter $\sigma_E/E \approx 12.5\%$ for 150-GeV pion beam was obtained (see Fig. 15).

The VBLHE group also continued the analysis of the wire-source calibration data for the Hadron Endcap Calorimeter. The semi-automatic procedure to obtain the calibration constants was developed. The effect of geometry due to the various sizes of the scintillators obtained as a ratio of the signal from the wire source to the collimated source was studied. This effect was found to be several percent, which is essential for correct calibration of the Hadron Endcap Calorimeter.

**Preparation for Future Experiments.** VBLHE participates in R&D for the new facility at GSI — FAIR (Facility for Antiproton and Ion Research) (accelerators, detectors, and physics), including:

— fast-ramped magnets (Nuclotron-type);
— SIS100/SIS300 lattice optimization;
— cryogenic magnetic system, superconductive beamlines;
— TRD detector for the CBM project;
— superconductive magnets for the CBM and PANDA projects;
— simulation (track fitter and track finder);
— physical programme.

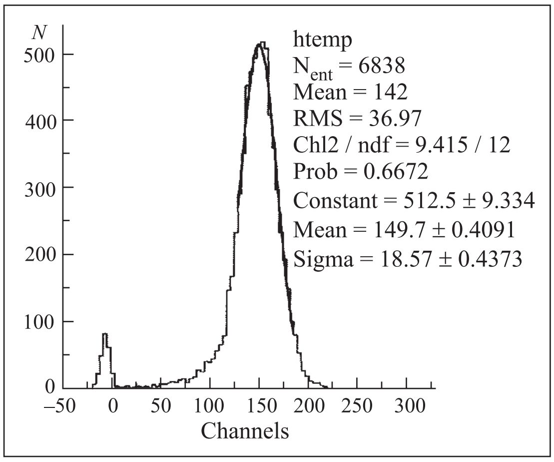


Fig. 15. Signal from 150-GeV pions in the Hadron Endcap Calorimeter

## INTERPRETATION OF THE EXPERIMENTAL DATA

The production and properties of the resonances with the strangeness $S = +1$ in the system of $nK^+$ were studied in the reaction $np \to npK^+K^-$ at the momentum of incident neutrons $P_n = (5.20\pm0.12)$ GeV/$c$. A number of peculiarities were found in the effective mass spectrum of the above-mentioned system. All these resonances have a large statistical significance. Their widths are comparable with the mass resolution. The estimation of the spins of resonances was carried out and the rotational band connecting the resonances masses and their spins was constructed [16, 17].

The study was carried out using the data obtained in an exposure of 1-m $H_2$ bubble chamber of VBLHE to a quasi-monochromatic neutron beam that was constructed in 1972 due to the acceleration of deuterons by VBLHE's Synchrophasotron.

Figure 16 shows the effective mass distribution of $nK^+$ combinations for all events from the reaction $np \to npK^+K^-$ at $P_n = (5.20\pm0.12)$ GeV/$c$. The distribution is approximated by an incoherent sum of the background curve (taken in the form of a superposition of Legendre polynomials up to the 8th power, inclusive) and by 10 resonance curves taken in the Breight–Wigner form. The part of the background is 75.8% in this distribution. The requirements to the background curve are the following: firstly, the errors of the coefficients must be no more than 50% for each term of the polynomial; secondly, the polynomial must describe the experimental distribution after «deletion» of resonance regions with $\overline{\chi^2} = 1.0$ and $\sqrt{D} = 1.4$ (the parameters of $\chi^2$ distribution with one degree of freedom). The parameters for the distribution in Fig. 16 are $\overline{\chi^2} = 0.92 \pm 0.29$ and $\sqrt{D} = 1.33 \pm 0.20$. The same parameters for the background curve normalized to 100% of events (resonance regions are included) are $\overline{\chi^2} = 1.40 \pm 0.19$ and $\sqrt{D} = 2.38 \pm 0.14$. The significance level of the resonance at $M = 1.541$ GeV/$c^2$ is 4.5 S.D.

In the same figure the distribution of effective masses is presented for $nK^+$ combinations selected under the condition $\{\cos\,\Theta_n^* < -0.85 \cup \cos\,\Theta_n^* > 0.85\}$, where $\Theta_n^*$ is the angle of secondary neutron emission in c.m.s. One can see that this distribution has no essential bumps and a deletion of such kind of events can decrease the background.

The estimation of the cross section for the resonance at the mass $M = 1.541$ GeV/$c^2$ in the $nK^+$ system from the reaction $np \to npK^+K^-$ is $\sigma = (3.5\pm0.7)\ \mu$b at $P_n = (5.20 \pm 0.12)$ GeV/$c$.

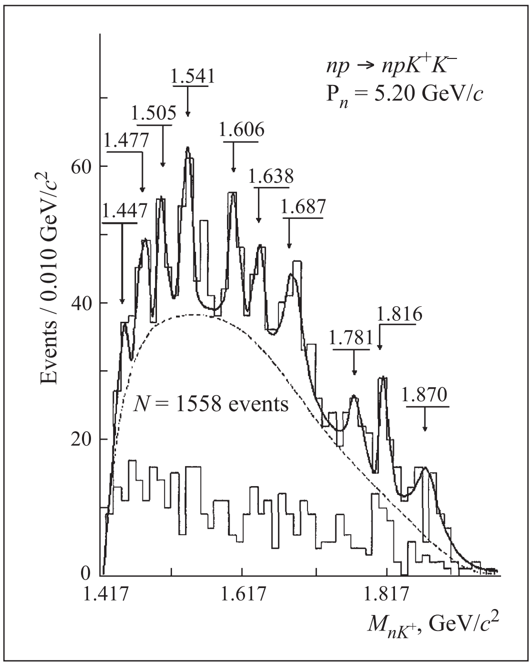


Fig. 16. The effective mass distribution of $nK^+$ combinations for all events from the reaction $np \rightarrow npK^+K^-$ at $P_n = (5.20 \pm 0.12)$ GeV/$c$. Dotted line — the background curve taken in the form of Legendre polynomial to the 8th power. Solid line — the sum of the background curve and the 10 resonance curves taken in the Breight–Wigner form. Bottom histogram — the effective mass distribution of $nK^+$ combinations selected under the condition $\{\cos\,\Theta_n^* < -0.85 \cup \cos\,\Theta_n^* > 0.85\}$

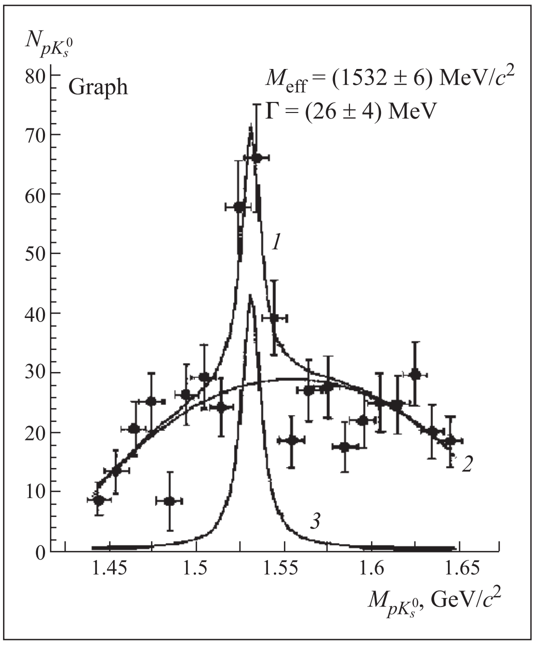


Fig. 17. The spectrum of $K_s^0p$ effective masses in $C + C_3H_8 \rightarrow K_s^0p + x$ reaction at carbon beam momenta $P_c$ = 4.2 $A \cdot$ GeV/$c$

The results on observation of pentaquarks were also obtained by another group of physicists by using the data from the VBLHE 2-m propane bubble chamber. This group studied the reaction $C + C_3H_8 \rightarrow K_s^0p + x$ at carbon beam momenta $P_c$ = 4.2 $A \cdot$ GeV/$c$. A narrow peak with $M = (1532 \pm 6)$ MeV/$c^2$ and width $\Gamma \approx (26 \pm 4)$ MeV/$c^2$ was observed in the $K_s^0p$ effective mass spectrum (Fig. 17) [18].

Physicists of the Laboratory took an active part in other research as well.

The consequences of the effect of the relativistic spin rotation for a system of two free particles with a nonzero vector of relative momentum were investigated, setting the spin states of the particles in the corresponding rest frames. In this connection, the transformations of components of the correlation tensor for a system of two spin-1/2 particles at the transition from the c.m.s. of two particles to the laboratory frame with parallel respective spatial axes were considered. In the case when the vectors of the particle velocities in the laboratory frame are not collinear, the angles of the relativistic spin rotation for two particles are different. It was shown that, taking into account this difference, the relative fractions of the singlet and triplet states in a relativistic system of two particles with spin 1/2 depend on the concrete frame in which the two-particle system is analyzed. Thus, the total spin for a system of two relativistic particles with a nonzero vector of relative velocity is not a Lorentz invariant [19, 20].

The study of spin correlations in two-particle quantum systems was continued. The general phenomenological theory of the angular correlations in the decays of any two arbitrarily polarized particles (resonances) was constructed in terms of the multipole production parameters for the system of two unstable particles and the multipole decay parameters. The angular correlations in the decays of two identical unstable particles with close momenta were investigated using the model of independent one-particle sources emitting unpolarized particles with nonzero spin. These angular correlations reflect the spin correlations conditioned by the effects of quantum statistics and final-state interaction [21].

By using the formalism of helicity amplitudes, the polarization effects are studied in the direct reaction $p + {}^3\mathrm{He} \rightarrow \pi^+ + {}^4\mathrm{He}$ and in the inverse process $\pi^+ + {}^4\mathrm{He} \rightarrow p + {}^3\mathrm{He}$. It was shown that, due to the $T$ invariance, the dependence of the effective cross section of the reaction $p + {}^3\mathrm{He} \rightarrow \pi^+ + {}^4\mathrm{He}$ upon the polarization vectors of the proton and the ${}^3\mathrm{He}$ nucleus completely determines the polarization vectors and the spin correlations of the final particles in the reaction $\pi^+ + {}^4\mathrm{He} \rightarrow p + {}^3\mathrm{He}$. It is established that in this reaction the system «proton + ${}^3\mathrm{He}$ nucleus» is always created in the nonfactorizable triplet state with the tightly correlated spins. It is shown that in the reaction $\pi^+ + {}^4\mathrm{He} \rightarrow p + {}^3\mathrm{He}$ one of the incoherence inequalities for the sum of two diagonal components of the correlation tensor, which were established earlier for the case of the incoherent mixture of factorizable two-particle states, is necessarily violated [22].

The concepts of the lifetime and path length of a virtual particle were introduced. It is shown that near the mass surface of the real particle these quantities constitute a 4-vector. The formulae for the lifetime and path length of an ultrarelativistic virtual electron in the process of bremsstrahlung in the Coulomb field of a nucleus, and also for the lifetime and path length of the virtual photon at its conversion into the electron–positron pair were obtained. The connection between the path length of the virtual particle and the coherence length (formation length) has been established [23].

## APPLIED RESEARCH

**Using $^{12}$C Beam for Cancer Therapy.** The JINR Programme Advisory Committee approved in 2004 a new project, **Med-Nuclotron**. During the first stage of this project it is planned to prepare the Nuclotron carbon beam with the parameters required for irradiation of patients. The first measurements of the Bragg peak at the $^{12}$C Nuclotron beam are presented in Fig. 18. The energy of the carbon beam was 500 $A \cdot$ MeV.

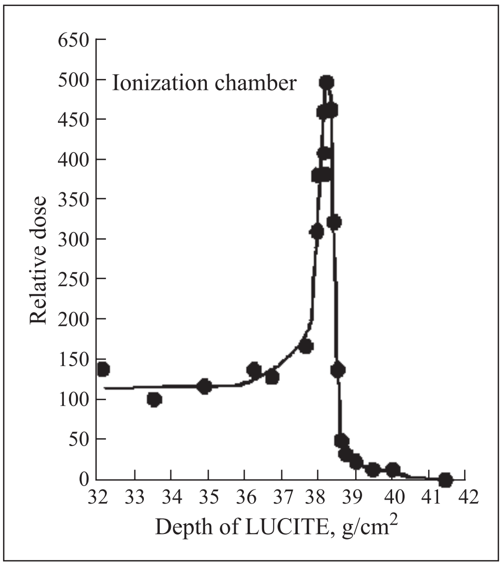


Fig. 18. The Bragg peak of 500 $A \cdot$ MeV $^{12}$C ions from the Nuclotron

During the next three years the required carbon beam and a special place for irradiation of biological samples will be prepared.

Some other results obtained at VBLHE in 2004 are published in [24–28].

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