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THE RESULTS OF 2003 AND THE RESEARCH PROGRAM OF THE VEKSLER AND BALDIN LABORATORY OF HIGH ENERGIES FOR 2004–2006

Report to the 95th Session
of the JINR Scientific Council
January 15–16, 2004

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1. Introduction

In 2003 the scientific program of Veksler and Baldin Laboratory of High Energies (VBLHE), Joint Institute for Nuclear Research (JINR), 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 center 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 behavior in nuclear interactions takes place. International scientific cooperation of the Laboratory is diverse: CERN, scientific centers in the JINR member states, a number of research centers in the USA, Germany, Japan, India, Egypt and other countries.

Termination of the Synchrophasotron in 2003 was approved by the 93rd Session of the JINR Scientific Council. Research is currently continued at the new accelerator, Nuclotron.

This report presents the new results of VBLHE obtained in 2003 and the research program for the next three years.

2. The main results of the development of Nuclotron in 2003

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 in the energy range up to 6 $A{\cdot}GeV$.

Tabl.1. Parameters of extracted beams of Nuclotron

Particle	Intensity (Particles per cycle) Year 2003	Year 2006	Particle	Intensity (Particles per cycle) Year 2003	Year 2006
p	$1{\cdot}10^{11}$	$2{\cdot}10^{11}$	^{16}O	$7{\cdot}10^{8}$	$1{\cdot}10^{9}$
d	$5{\cdot}10^{10}$	$1{\cdot}10^{11}$	^{24}Mg	$1{\cdot}10^{8}$	$3{\cdot}10^{8}$
^{4}He	$3{\cdot}10^{9}$	$2{\cdot}10^{10}$	^{40}Ar	$3{\cdot}10^{7}$	$2{\cdot}10^{8}$
^{7}Li	$1{\cdot}10^{9}$	$2{\cdot}10^{9}$	^{56}Fe	$1.2{\cdot}10^{6}$	$5{\cdot}10^{7}$
^{10}B	$2.3{\cdot}10^{7}$	$5{\cdot}10^{7}$	^{84}Kr	-	$5{\cdot}10^{6}$
^{12}C	$2{\cdot}10^{9}$	$1{\cdot}10^{10}$	^{131}Xe	-	$1{\cdot}10^{6}$
^{14}N	$1{\cdot}10^{7}$	$5{\cdot}10^{7}$	$d\uparrow$	$3{\cdot}10^{8}$	$3{\cdot}10^{9}$

The accelerator complex of VBLHE includes:

- Superconducting accelerator – Nuclotron;
- Linac LU-20;
- Electron beam source of highly charged ions;
- Laser sources of light ions;
- Polarized deuteron source;
- Slow beam extraction system;
- Nuclotron cryogenic system;
- Cryogenic facility;
- Beam lines;

Particle beams available now and during the next three years at Nuclotron are shown in Table 1 [3, 4].

Recent progress in production of intermediate ion beams, such as Ar^{16+} and Fe^{24+} , at Nuclotron results mainly from the success in the design and application of a new EBIS-type ion source "Krion-2" in "a string mode of operation" [5]. Such ion source, called ESIS (**E**lectron **S**tring **I**on **S**ource), is based on multiple longitudinal reflections of electrons in the drift space of the source. The investigation of a reflection mode of EBIS operation based on a specially designed electron gun and electron reflector resulted in the discovery and study of an electron string phenomenon and finally allowed to reconstruct the existing EBIS "Krion-2" into ESIS suitable for application at the accelerator facility.

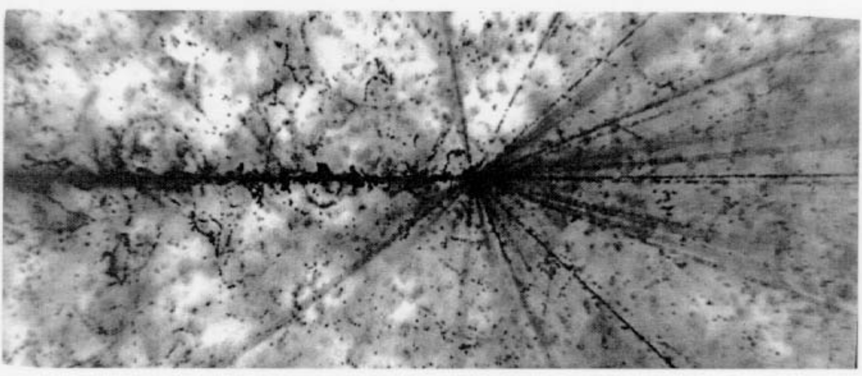

Fig.1. Interaction of ^{56}Fe ion with $E_{kin} = 1\ A{\cdot}GeV$ from Nuclotron with an emulsion nucleus.

The new source made it possible to obtain beams of N^{6+}, N^{7+}, Ar^{16+} and Fe^{24+} ions during the runs of Nuclotron in 2002 and 2003. The output ion currents of ESIS "Krion – 2" were 300 μA, 350 μA, 200 μA and 150 μA, respectively. Typical times of ion confinement in electron string were: 40 *ms* for N^{6+}, 120 *ms* for N^{7+}, 300 *ms* for Ar^{16+}

and 1100 *ms* for Fe^{24+}. The estimated effective density of electron current in a string is about 150 – 200 A/cm^2. The ion pulse duration from the source is about 8 *mks* (corresponds to a single turn injection in the Nuclotron ring). The EBIS-type ion sources used ionization of gases for ion production. Thus, the possible set of ion species was limited. A new technology of injection of molecules evaporated from solid materials into the source was developed at the Laboratory. Solid material ferrocene ($FeC_{10}H_{10}$) was used to obtain Fe-ions. The efficiency of ferrocene vapor ionization was close to 100 %, providing a long-term utilization of a small amount of the material, stored in a special container. All the important parameters of ESIS are monitored. Stabilization circuits allow keeping the source in automatic mode of operation during the run time. Stability of the ion beam intensity of the source output was about 95 %. More detailed description of the current status of ESIS Krion-2 is presented in [6]. An event of interaction of ^{56}Fe ion with the kinetic energy E_{kin} = 1 $A{\cdot}GeV$ with an emulsion nucleus is shown in Fig.1.

Substantial progress was made also in improvement of the slow beam extraction system in 2003. Feedback systems for stabilization of both the extracted beam intensity and the extracted beam time structure were put into operation. The result is exemplified in Fig. 2. Pulse duration of an extracted beam of up to 10 *s* was obtained. Intensity oscillations are suppressed by the feedback system [3].

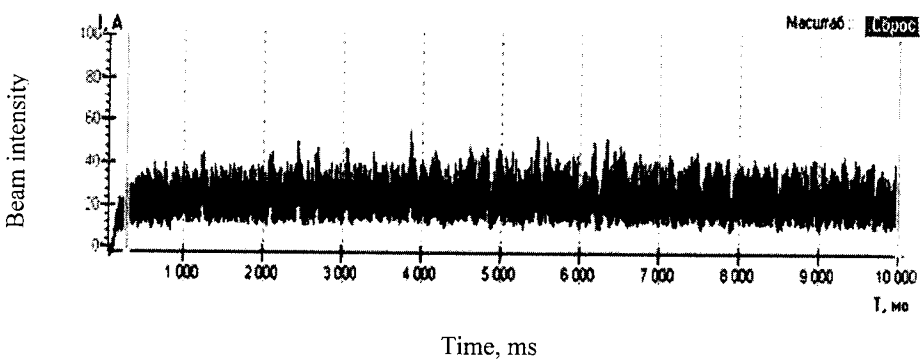

Fig.2. A Nuclotron beam spill controlled by a closed feedback loop.

3. The scientific results obtained in 2003

3.1. The results obtained at VBLHE accelerator center

Joint SMS MSU – SPHERE LHE Experiment.

Measurement of the analyzing power reduction at polarized proton scattering on intranuclear nucleons.

In 2003 the data of the joint SMS (Scintillation Magnetic Spectrometer of the Moscow State University, MSU) -- SPHERE (VBLHE) experiment, obtained in November 2002 during the run of Synchrophasotron, were analyzed. The polarized deuteron beam with the intensity $3\cdot10^9$ deuterons/cycle was used. Stripping polarized protons with the energies of 2.51 and 3.00 GeV bombarded C/Cu targets. The goal of the experiment was the measurement of analyzing power reduction at secondary polarized protons scattering on intranuclear nucleons.

The parameter R of reduction of the analyzing power $A(T)$ can be calculated as

$$R_{pN}(T) = 2\cdot A_{qe}(T) / [A_{pp}(T) + A_{pn}(T)]$$

for scattering on any intranuclear nucleon and as

$$R_{pp}(T) = A_{qe}(T) / A_{pp}(T)$$

for scattering on intranuclear proton only,
where $A_{qe}(T)$ is $A(T)$ for the quasielastic channel and T is the proton kinetic energy.

The following reactions were studied (with the detection of the quasielastic channel by magnetic analysis of the scattered particle momentum):

$$p\uparrow + {}^{12}C\ ({}^{64}Cu) \rightarrow p_L + p(n)_R + X$$

without any separation of the pp- or pn- interaction and

$$p\uparrow + {}^{12}C\ ({}^{64}Cu) \rightarrow p_L + p_R + X$$

with the detection of the recoil proton.

The indices L and R denote left and right scattering directions.

The new experimental data are presented in Fig.3 for pN (open circles) and pp (solid circles) events. It was concluded that at GeV energies reduction of the analyzing power is close for protons and neutrons.

Main results are the following:

- there is no difference between the measurements for copper and carbon target nuclei;
- anomalous analyzing power reduction was not observed.

Analyzing power reduction R(T) vs energy

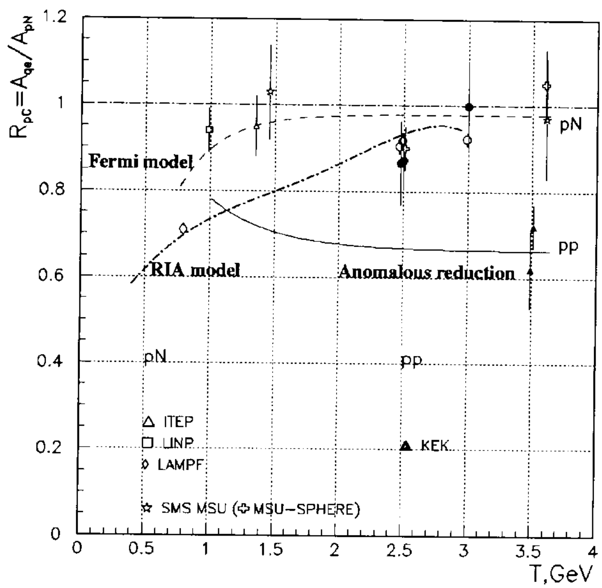

Fig.3. Analyzing power reduction R_{pC} as a function of the proton kinetic energy T.

Experiment FAZA

It was proved that a "liquid-fog" phase transition (of the first order) takes place at the temperature T_f =(5÷7) *MeV* [7, 8]. A hot nucleus expands due to thermal pressure and enters the phase-unstable spinodal region. Due to density fluctuations, a homogeneous system converts into a mixed state, consisting of liquid droplets surrounded by nuclear gas. The final state of this transition is a *nuclear fog*, which explodes due to Coulomb repulsion and is observed as multifragmentation.

It is known that the shape of the fragment charge distribution $Y(Z)$ is well approximated by the power law: $Y(Z) \sim Z^{-\tau_{app}}$. Comparison of the experimental power-law exponent (for *p*+Au at 8.1 *GeV*) and the ones predicted by the model for different assumed values of T_c is shown in Fig.4. The measured power-law exponent is shown as a band with the width determined by the statistical error. The size of symbols marking the calculated values of τ_{app} is of the order of the error bar. The critical temperature of the "liquid-gas" phase transition is found to be T_c = (17±2) *MeV* from the best fit of the data and calculations. In some papers the lower value of the critical temperature is declared. But the analysis of these works reveals that the break-up temperature T_f is actually measured there.

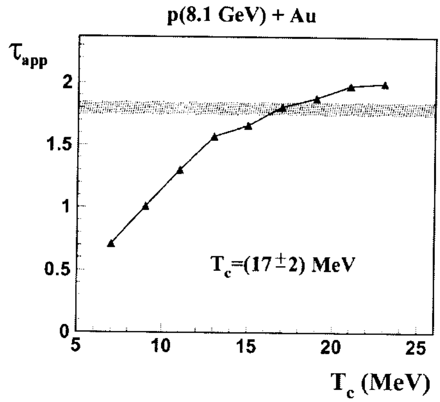

Fig. 4. Estimation of the critical temperature T_c for the nuclear "liquid-gas" phase transition from the fragment charge distribution. The latter is approximated by the power law:
$Y(Z) \sim Z^{\tau\ app}$. The measured τ_{app} value (shown by the band) is compared to the ones predicted by the model with T_c as a free parameter. It is found that T_c=(17±2) MeV.

Experiment PIKASO

Strong transverse momentum dependence of A_{yy} in the fragmentation of 9 *GeV* tensor polarized deuterons into cumulative pions was obtained as a result of data analysis of PIKASO experiment (Fig.5). The data were obtained during the last run of the Synchrophasotron. As the pion transverse momentum increases from p_t=0.4 to 0.8 *GeV/c* the tensor analyzing power A_{yy} drops from near zero to –0.4. The starting point of $A_{yy}(p_t)$ – drop corresponds to cumulative variable x_c = 1 – the beginning of the cumulative regime. $A_{yy}(p_t)$-drop is linear at the two angles of pion emission, 135 and 180 *mrad.*

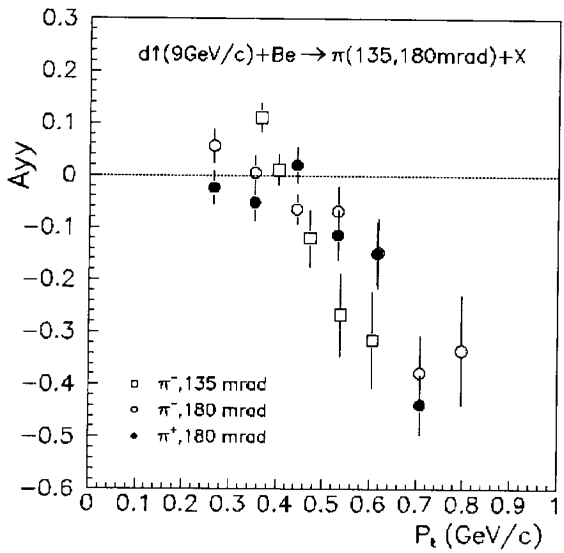

Fig. 5. Tensor analyzing power A_{yy} as a function of p_t for 9 *GeV* tensor polarized deuterons.

Experiment STRELA

The aim of experiment STRELA is the study of the spin-dependent component of nucleon scattering amplitude in the charge-exchange process $np \rightarrow pn$ using extracted deuteron beam at Nuclotron. At zero momentum transfer the differential cross section of the reaction $dp \rightarrow (pp)n$ is determined by the spin-flip section of the charge-exchange $np \rightarrow pn$ amplitude.

During the run of Nuclotron in June, 2003 the experiment using 3.5 and 4.0 *GeV/c* deuteron beams was carried out at the set-up STRELA (Fig.6a). Extracted deuteron beam hit a liquid hydrogen target T, and primary deuterons were separated from secondary particles by the analyzing magnet M. The flux of the deuteron beam was measured using the ionization chamber *IC*. The scintillation counters S_1 and S_2 were used to determine the angular (~ 0.2 *deg*) and momentum (~ 10%) acceptance and to form the trigger of event. The drift tubes DT_1 – DT_4 and the multiwire proportional chambers PC_1 – PC_2 were used to detect one or two-proton events. The Cherenkov counter $\check{C}_1$ with a quartz radiator served for pion suppression. Registration of events with two protons is illustrated schematically in Fig.6b.

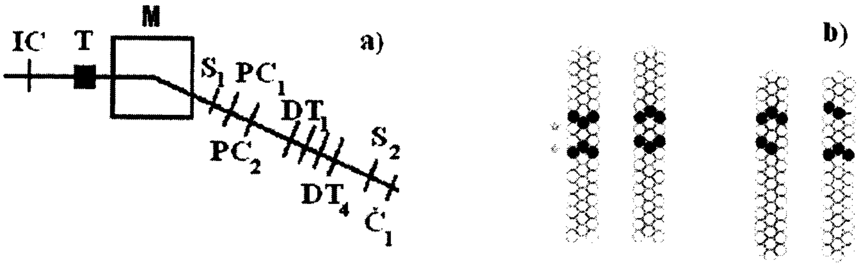

Fig. 6. (a) The scheme of the set up STRELA. (b) Samples of events with two protons in the drift tubes.

Project DELTA-2

A new proposal on search for η-nuclei was prepared in the framework of DELTA-2 project in 2003.

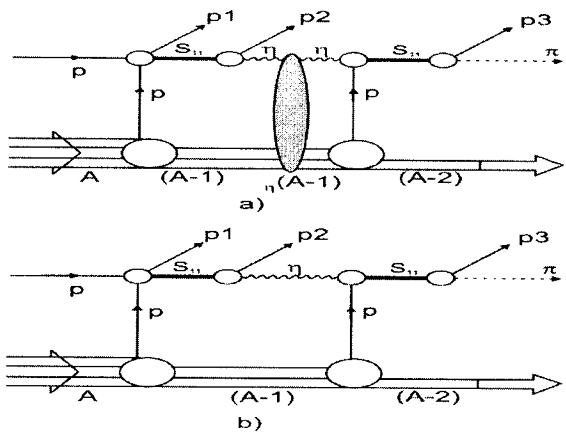

Fig. 7. Mechanism of formation and decay of the η-nuclei in pA-collisions (if $E_\eta < 70$ *MeV*) – a); mechanism of production and annihilation of η's in the nucleus (if $E_\eta > 70$ *MeV*) – b).

The experimental investigation of new objects of nuclear physics - η-mesonic nuclei, ηA, a bound system of an η - meson and a nucleus, is proposed with the internal target at Nuclotron [9]. Beams of η-mesons cannot be obtained because of a very short life-time of η-mesons (~10^{-19} *sec.*). So the study of interactions of η-mesons with nucleons in elementary processes of $\eta N \rightarrow \eta N$ or pN type is not possible. Interaction can be investigated only in the final state of an elementary process, for example $\pi N \rightarrow \eta N$, $\gamma N \rightarrow \eta N$. The η-mesonic nuclei give us a unique possibility to study ηN-interaction in nuclear matter. Let us assume production of η-nuclei in the reaction:

$p_0 + A \rightarrow p_1 + p_2 + {}_{\eta}(A\text{-}1) \rightarrow p_1 + p_2 + p_3 + \pi^- + X.$

The upper diagram in Fig.7. illustrates the process describing the stage of η-meson production in a nucleus with formation of the bound state of η-meson and the nucleus and at last the stage of η-nucleus decay. The lower diagram corresponds to the process where η-mesonic nucleus is not produced. One can assume that the kinetic energy of η-meson is rather high ($E_\eta > 70$ MeV) in this case and there is no attraction between η-meson and nucleon. This stage proceeds through single N-interactions mediated by the S_{11} (1535) nucleon resonance.

Project BECQUEREL (**Be**ryllium (Boron) **C**lustering **Que**st in **Rel**ativistic Multifragmentation) is oriented toward emulsion irradiation with light stable and radioactive nuclei with the energy of the order of a few GeV per nucleon in the beams of Nuclotron [10, 11]. Observations of the fragmentation of light relativistic nuclei open up new opportunities to explore highly excited nuclear states near multiparticle decay thresholds. The interest in such states is motivated by their predicted properties as loosely bound systems with spatial spread significantly exceeding the fragment sizes. Natural components of such states are the lightest nuclei having no excited states below particle decay thresholds, i.e. deuterons, tritons, ^3He, and ^4He nuclei. ^3He clustering manifests in decays of light neutron deficient nuclei. The aim of investigation is to clarify a role of ^3He clustering in forthcoming exposures with ^7Be ($^{4,3}He$-^3He), ^8B ($^{1,2}H$-$^{4,3}He$-^3He), ^9Be (^4He-^4He), ^9C (^3He-^3He-^3He), ^{10}C (^3He-^3He-^4He), and ^{11}C (^3He-^4He-^4He).

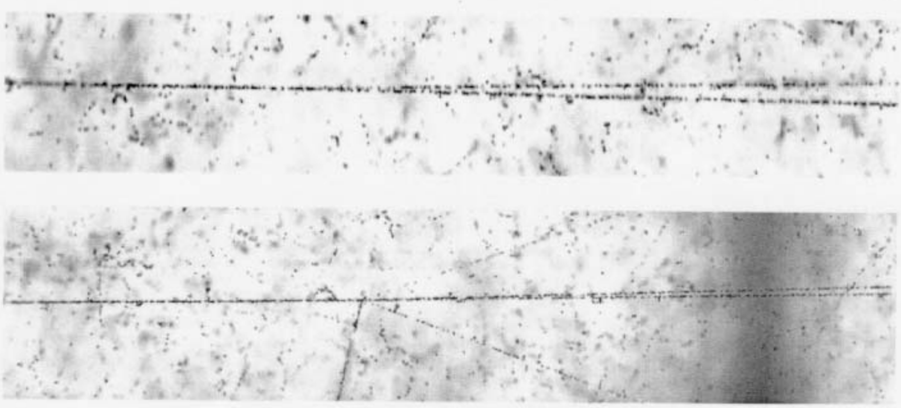

Fig.8. Examples of peripheral dissociation of $1.23A{\cdot}GeV$ ^{7}Be nuclei into pairs of He nuclei. Upper photo: dissociation without target nucleus excitation and without charged meson production. Lower photo: dissociation accompanied by production of a target fragment and a meson-like pair.

A secondary beam containing a significant fraction of $1.23A{\cdot}GeV$ ^{7}Be nuclei was formed during the run of Nuclotron in 2003 by selecting the products of charge exchange of primary ^{7}Li nuclei with the aid of a beam transport channel. Emulsion stacks were irradiated. ^{7}Be nucleus is convenient for magnet optics selection due to the maximum charge-to-weight ratio. Besides, it gives the most complete observation of final fragments. By visual scanning along tracks, 22 decays of incoming nuclei to helium fragments without other accompanying tracks were found. The examples of events are shown in Fig.8. Helium isotopes were identified via their total momentum derived from multiple scattering measurements. This makes it possible to conclude that a dominant fraction is due to a coherent dissociation $^{3}He+^{4}He$ and only 3-4 decays to $^{3}He+^{3}He+n$. Thus, one can conclude that ^{3}He clustering manifests in decays of excited relativistic ^{7}Be nuclei.

Project MARUSYA

The novelty of the proposed research is in the investigation of rare subthreshold, cumulative processes and antimatter production taking into account the polarization of colliding objects, the extraction of events by the degree of centrality and reaction plane on the basis of the additional measurement of multiplicity and identification of nuclear fragments not participating in an interaction. Investigation of such processes is possible only with magnetooptical spectrometers of high acceptance and high selectivity of secondaries. The magnetooptical spectrometer MARUSYA was put into operation in 2002.

The new experimental data on one-spin analyzing powers in production of π^{+}, p, d at interactions of 3.3 GeV/c polarized protons and of 5 GeV/c tensor polarized deuterons with carbon target obtained with the Synchrophasotron beams were analyzed and reported at International conferences. Below are the main results of these investigations (Fig. 9).

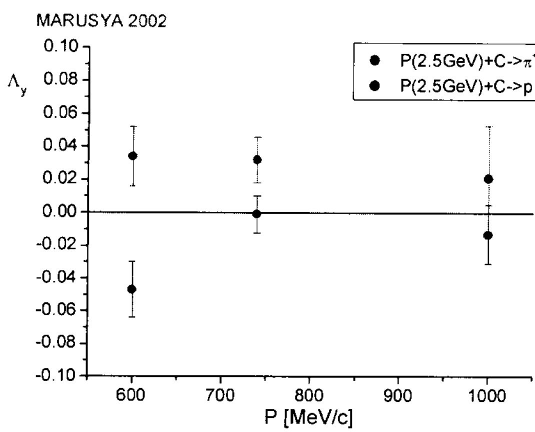

Fig. 9. Analyzing power for the vector polarized beam:

$$\Lambda_y = \frac{1}{P_z}\frac{n^+ - n^-}{n^+ + n^-}$$

- Analyzing powers in inclusive spectra of p and d at interaction of polarized proton (3.3GeV/c) and deuteron (5GeV/c) beams with carbon nuclei were measured in the momentum range of registered particles 0.6÷1.2GeV/c at the angle 26°.
- In the momentum range 0.6÷1.2GeV/c vector analyzing power for $\pi+$ tends to decrease, changing its sign, with increasing particle momentum, while vector analyzing power for p tends to increase, changing its sign, with increasing particle momentum.
- It is shown that the existing intensities of polarized beams of Nuclotron are sufficient for the planned future investigations at the set up MARUSYA.

In December, 2003 the experimental investigation of antimatter production at Nuclotron began. The first experimental data on production of antiprotons and K^- in the reactions p+Pb, p+Al were obtained.

Secondary beams produced at the magnetooptical spectrometer MARUSYA provide the experimental conditions for development and testing of new types of detectors.

3.2. The results obtained at other accelerator centers

Experiment PHENIX

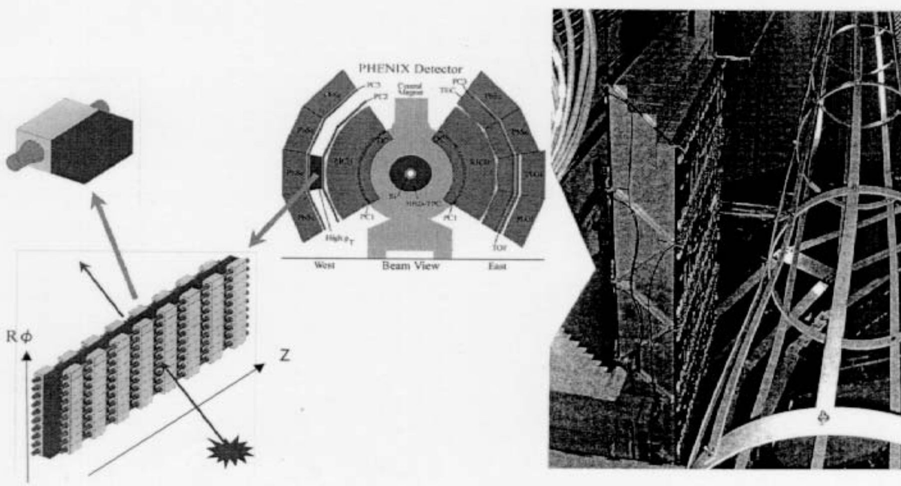

Fig.10. The layout of the aerogel subsystem (left) installed at PHENIX; the photo of the detector system (right).

One half of the aerogel detector was installed at PHENIX (RHIC) in 2003. The whole detector of the area 4 m^2 will consist of 160 individual Cherenkov counters with aerogel radiators. The JINR group participated in this project at all stages of it realization (from LOI and R&D to installation and maintenance). Two tests were performed in 2003 using Nuclotron beams. The boxes for this detector system were designed and manufactured at the JINR central workshop and delivered to Brookhaven National Laboratory. The detector system consisting of 80 aerogel counters was assembled, tested and installed at the West Arm of PHENIX in 2003 (Fig. 10).

This aerogel detector is needed to study events with high p_t in order to investigate the so called Jet Quenching Effect. It manifested as a strong suppression of high momentum tail in momentum transfer spectrum for central *Au+Au* collisions (Fig.11). This suppression is interpreted as a result of strong energy losses in quark-gluon plasma in central collisions at RHIC energies [14]. This effect has essentially different values for different kinds of particles. Installation of the aerogel detector can give additional information for clarification of the nature of this effect as well as properties of quark-gluon plasma created in collisions, if it exists. The latest results obtained by PHENIX collaboration with participation of the physicists from VBLHE are published in [12-20].

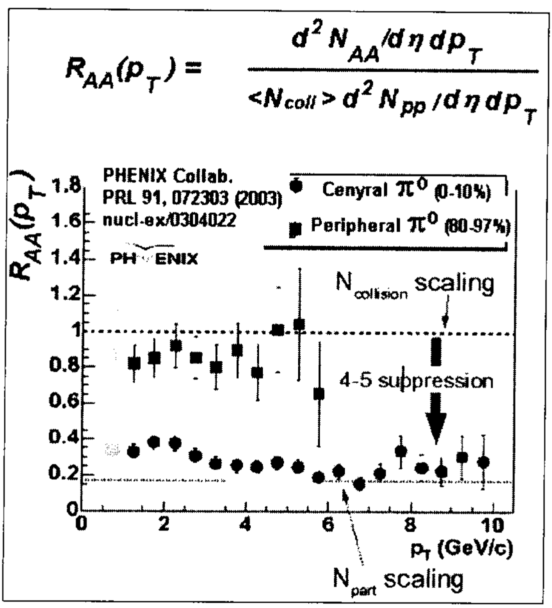

Fig. 11. The Jet Quenching Effect at PHENIX.

Experiment STAR

JINR contribution:

1. Participation in design and manufacturing of the Endcap EM Calorimeter (EEMC);
2. Simulation of the EEMC;
3. Study of the asymmetry in processes with jets, dijets, prompt g and g-jet production;

Important result: High p_t particle production is suppressed in central *Au+Au* collisions and no indication of suppression at large p_t for *d+Au* events was observed.

As it is seen in Fig.12, *p+p* and *d+Au* data show the existence of back-to-back pairs of jets. Central Au+Au data show the jet peak around the trigger particle, at 0 degrees, but no recoil jets. Such absence of recoil jet is expected in the case of strong energy loss in a dense medium.

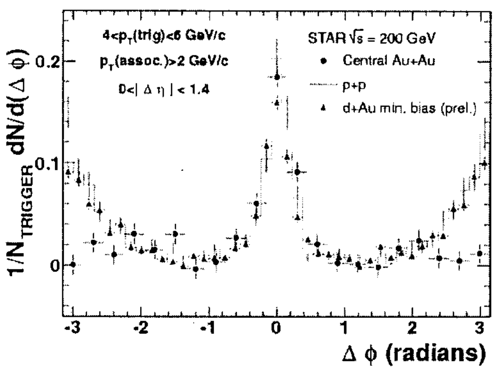

Fig. 12. The angular distribution of jets in *p+p*, *d+Au* and central *Au+Au* events at STAR.

Experiment NA49

Observation of new exotic baryonic resonances

The results of resonance search in the $\Xi^-\pi^-$, $\Xi^-\pi^+$, anti- $\Xi^+\pi^-$, anti-$\Xi^+\pi^+$ invariant mass spectra in proton-proton collisions at $\sqrt{s} = 17.2$ *GeV* are presented in [21]. Evidence is shown for the existence of a narrow $\Xi^-\pi^-$ baryonic resonance with the mass 1.862±0.002 GeV/c^2 and the width below the detector resolution of about 0.018 GeV/c^2 (Fig.13). The significance is estimated to be 4.0σ. This state is a candidate for the hypothetical exotic $\Xi^{--}(3/2)$ barion with S = - 2, I = 3/2 and quark content (*dsdsū*). At the same mass a peak is observed in the $\Xi^-\pi^+$ spectrum which is a candidate for the $\Xi^0(3/2)$ member of this isospin quartet with quark content (*dsusd̄*). The corresponding antibarion spectra also show enhancement at the same invariant mass.

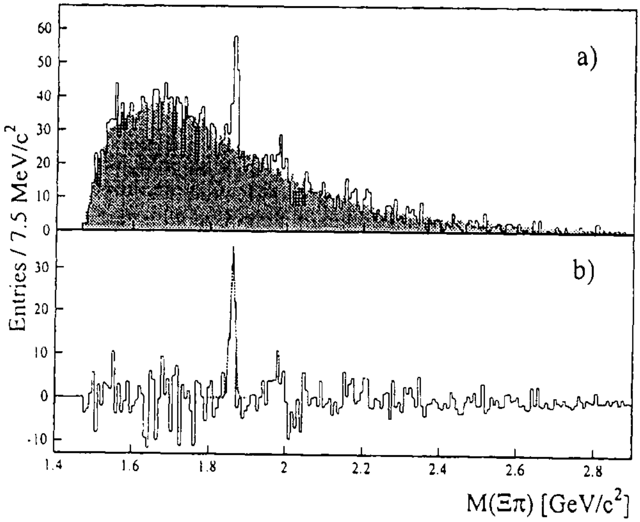

Fig.13. (a) The sum of $\Xi^- \pi^-$, $\Xi^- \pi^+$, anti- $\Xi^+ \pi^-$, anti-$\Xi^+ \pi^+$ invariant mass spectra. The shaded histogram shows the normalized mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

Observation of the deconfinement phase transition

The VBLHE group was responsible for measurement and analysis of charged kaon spectra, and spectra of protons and deuterons in *Pb+Pb* collisions at 20 and 30 *A·GeV* and completion of the energy scan program (20, 30, 40, 80 and 158 *A·GeV* beam energies).

The results of this analysis are the following:

- the number of pions produced per nucleon participating in the collision increases with energy both in *p-p* and *NN* reactions. However, the rate of increase in *NN* becomes larger within the SPS energy range and then stays constant up to the RHIC energy range (the upper plot in Fig.14);
- the most dramatic effect is seen in the energy dependence of the ratio $<K^+>/<\pi^+>$ of the average multiplicities of K^+ and π^+ produced in central *Pb+Pb* collisions (the middle plot in Fig.14);
- the third important result is that temperature of K^+ mesons in central *Pb+Pb* collisions at SPS energies is constant (the lower plot in Fig14).

These results suggest that deconfinement phase transition exists and that in *Pb+Pb* collisions it begins to manifest in the SPS energy range.

The latest results obtained by NA49 collaboration with participation of the physicists from VBLHE are published in [21-24].

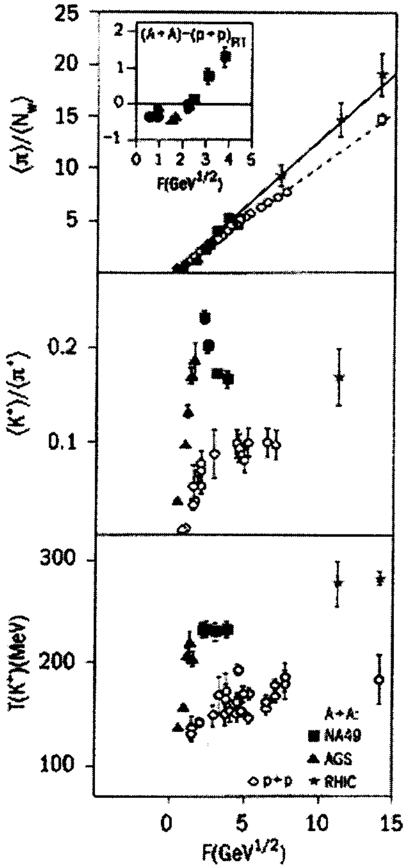

Fig.14. Collision energy dependence of the various hadron production rates measured in central *Pb+Pb* and *Au+Au* collisions (solid symbols) compared with the results from $p + p$ reactions (open circles). The changes within the SPS energy range (solid squares) suggest the onset of the deconfinement phase transition. $F = (\sqrt{S_{NN}} - 2m_0)^{3/4} / (\sqrt{S_{NN}})^{1/4} \approx S_{NN}^{1/2})$, where m_0 is the nucleon mass.

Experiment NA45

Mass data processing of 31 million *Pb+Au* events at $158A{\cdot}GeV$ was completed.

The recent back-to-back correlation analysis of the charged hadrons and high p_t pions with account of flow (v2) and HBT corrections shows the significant contribution of non-flow component possibly originating from the semi-hard processes (fig.15).

The centrality dependent HBT analysis at different energies shows that thermal pion freeze-out occurs at constant mean free path $\lambda_f \sim 1.0\,fm$ that implies a significant opaqueness of the pion source. These studies are exceptionally interesting now as RHIC has claimed the discovery of jet-quenching phenomenon in the region of pQCD applicability.

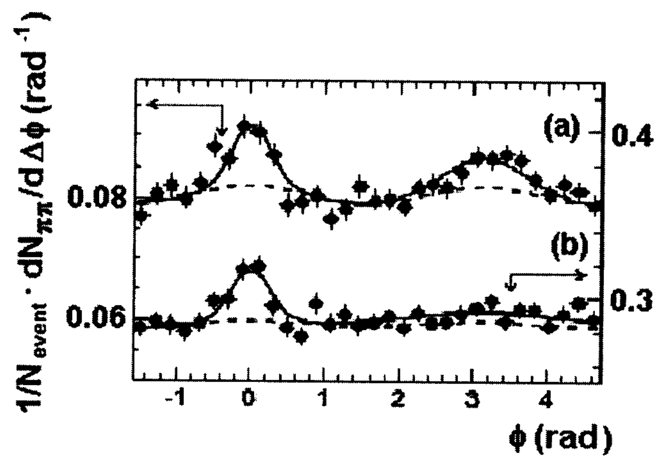

Fig. 15. Two-pion opening angle distributions for p_t > *1.2 GeV/c* (a) for the first centrality bin, (24-30%) and (b) for the fourth centrality bin, (11-15%). A cut $\Delta\Theta \geq 20$ *mrad* and corrections for close-pair efficiency losses were applied. Solid line shows Gaussian fits to semi-hard components above the flow-modulated background (dashed line).

4.1. The main directions of research at Nuclotron in 2004-2006

The research program of VBLHE for 2004-2006 was formulated in accordance with the Program of JINR Scientific Research and Development for the Years 2003-2009, which was approved by JINR Scientific Council [25]. There are the following main directions of research at Nuclotron.

Effects of nonpertubative QCD in nuclei. As the experiments at the energies of several *GeV* have shown, production of particles and nuclear fragments in nuclear collisions approaches the asymptotic regime — limiting nuclear fragmentation. This indicates a significant role of parton degrees of freedom. These investigations formed an empirical basis for the development of nuclear models at distances smaller than the nucleon size (the models of fluctons and short-lived nucleon correlations, multiquark states in nuclei and so on). It is planned to extend these studies at Nuclotron to the region of subthreshold particle production in collisions of nuclei and polarized deuterons. These investigations are of great interest for studying nonperturbative effects, vacuum structure and spin effects in nuclear matter.

Spin effects in deuteron. Investigation of deuteron structure with account of spin degrees of freedom is a high-priority direction of experimental research with polarized deuteron beams of a record energy obtained at the VBLHE accelerator complex. These energies correspond to internal momentum in a nucleus up to 1 *GeV/c*. Investigations of reactions with relativistic polarized deuterons are aimed at studying spin effects at meson production beyond the kinematic limits of one nucleon collision (cumulative mesons). This regime corresponds to fragmentation of a strongly correlated pair of nucleons. Studies in this field will yield information on spin structure of the deuteron core at small internucleon distances and will help to understand deeper the mechanisms of cumulative meson production.

Interaction of polarized nucleons. The unique beams of polarized neutrons were produced using the break-up reaction of relativistic deuterons. The existing polarized targets allow to carry out the studies in the field of the physics of intermediate energy nucleon-nucleon interactions — measurement of interaction cross sections of neutrons and protons in pure spin states at a record collision energy. Investigation of meson production in these conditions is promising for studying possible manifestations of quark structure of a nucleon.

Fundamental role of three-nucleon forces. Three-nucleon forces play a fundamental role in nuclei beginning with tritium and ^{3}He. Even the value of tritium binding energy cannot be obtained only using pair nucleon-nucleon potentials. The study of deuteron-proton elastic scattering reactions and deuteron break-up in different kinematics has also shown that the obtained experimental data cannot be described within the solution of Faddeev's equation taking into account only nucleon-nucleon interactions. Taking three-nucleon forces into consideration allows one to reproduce both the binding energies of three-nucleon bound state and the data on the reaction cross sections of deuteron-proton interactions.

Nuclear structure at relativistic energies. The study of nuclear structure at the level of nucleons and their clusters is deeply associated with astrophysics phenomena. The progress in creating relativistic nuclear beams opens up new approaches to the solution of high-priority problems of nuclear structure from the lightest to the heaviest nuclei. Radioactive nuclei and resonance nuclear states are not simply a train of wastes from star burning reactions and explosion-type processes in cosmos, they are intermediate stages ("waiting rooms") on the way to generation of the world of stable nuclei. Observations of nuclear cosmos activity and investigations of nuclear structure at accelerators, including radioactive nuclei, may prompt new solutions in the field of fusion energy production.

4.2. Scientific program of VBLHE at Nuclotron in 2004-2006

The scientific program at Nuclotron includes the following directions [25].

4.2.1. Relativistic interactions of few-nucleon systems ($A < 5$)

Studies of polarization effects in fragmentation of light nuclei will be carried out under the project **PIKASO** at the set-up SPHERE. The main aim of this project is to investigate deuteron spin structure at short internucleon distances as well as spin effects correlated with meson- and quark-exchange mechanisms. This program is directed to the use of deuteron beams with momentum up to 9 *GeV/c* which are available at the VBLHE accelerator complex.

The project **DELTA-2** (Institute for Nuclear Research, Moscow) includes experiments with the VBLHE polarized proton target using extracted beams of Nuclotron as well as experiments with internal target of Nuclotron. The set-up represents a two-arm free-magnet spectrometer used to register and measure energy of neutral (gamma-quanta and mesons) and charged (mesons, protons, deuterons) particles. It is planned to investigate in detail π^0 and η meson production in neutron-proton collisions using polarized beams of the energies 1.2–2.0 *GeV* in order to test theoretical assumptions of meson production mechanism and also the hypothesis of the presence of a spin-polarized $s\bar{s}$-component of strange quarks inside the nucleon.

In the experiment **STRELA** it is proposed to study a spin-dependent part of the nucleon scattering amplitude in the $np \to pn$ charge-exchange process using extracted deuteron beams of Nuclotron. It is planned to measure the production cross section of two protons at small momentum transfer in *dp* interactions in the region of deuteron momenta from 3.0 to 4.0 *GeV/c*.

The main objective of the project **DELTA-SIGMA** is to study nucleon-nucleon interactions using secondary beams of polarized high energy neutrons which are now available only at the VBLHE accelerator complex. It is proposed to make detailed measurements of the energy dependence of $\Delta\sigma_T(np)$ and $\Delta\sigma_L(np)$. These quantities represent the differences of the total neutron-proton cross sections for antiparallel and parallel spin orientation of beam neutrons and target protons polarized in the longitudinal (*L*) and transverse (*T*) directions.

The project **NIS** was proposed by VBLHE and the Laboratory of Particle Physics (LPP) of JINR. The project is aimed at searching for effects of polarized nucleon strangeness, including violations of the OZI rule, in vector meson production in *pp* and *np* interactions near threshold. If this hypothesis is confirmed, both the "spin crisis" problem and the seeming violation of the OZI rule will find their natural explanation. It is necessary to carry out measurements of the ratio of the production cross sections of φ and ω mesons near their production threshold in nucleon interactions, i.e. at laboratory nucleon momenta above 2.7 *GeV/c*.

The project **LNS**. In the experimental program of this project it is planned to investigate deuteron and ^{3}He structure at small distances between nucleons. The program includes study of *dp*-elastic scattering and deuteron break-up reaction in *dp* interactions using nonpolarized and polarized deuteron beams, internal target of Nuclotron and measurement of the tensor analyzing power of the reactions $d+d \to {}^3He+n$ and $d+d \to {}^3H+p$ as well as polarized RIKEN deuteron beam (Japan).

The project **pHe3**. The main objective of the joint VBLHE-RIKEN experiment is to study the structure of ^3He (^3H) at distances unachievable now with the use of electromagnetic probes, by measuring the angular dependences of the tensor analyzing powers A_{yy}, A_{xx} and A_{xz} in the reactions $d+d \to {}^3He+n$ and $d+d \to {}^3H+p$. These polarization observables are sensitive to the neutron (proton) spin distribution in ^3He (^3H) at small distances in the framework of one-nucleon exchange approach. On the other hand, both ^3He and ^3H are mirror nuclei with respect to the number of protons and neutrons, and the difference in their observed values can be interpreted in terms of charge symmetry violation.

In the project **SPIN** it is planned to measure spin effects in nucleon-nucleon and nucleon-nucleus interactions (and in nuclear decays) and to obtain the main spin observables in the reaction $np \rightarrow pp\pi^-$.

4.2.2. Manifestation of the structure and excited states of nuclei at relativistic energies

The project **SPHERE** includes the following investigations at Nuclotron in the geometry close to 4π: study of multiple cumulative particle production (special attention will be given to the study of vector meson production in the cumulative region); investigation of resonance physics and search for exotic quark states; study (with the GIBS collaboration) of dynamic correlations of secondary particles and nuclear excitations in charge-exchange reactions, investigation of hypernuclei (measurement of the lifetime of $^3H_\Lambda$, $^4H_\Lambda$, $^6He_\Lambda$ hypernuclei and the binding energy of $^3H_\Lambda$, $^6He_\Lambda$ hypernuclei) and study of their Coulomb dissociation; investigation of η-nucleus production. The set-up GIBS is a magnetic spectrometer based on a $2\,m$ streamer chamber. It is proposed to upgrade the spectrometer GIBS for further experiments at Nuclotron. The spectrometer is equipped with a new filmless information registration system from the streamer chamber and also with proportional chambers for ^3He momentum measurement. The streamer chamber will be used as a vertex detector.

The project **FAZA** is performed by the researchers of Dzhelepov Laboratory of Nuclear Problems (DLNP) of JINR and VBLHE. The scientific goal of the project is to investigate the nuclear equation of state at reduced density and at temperature below the critical T_c for the “liquid-gas” and “liquid-fog” phase transitions. The study of “thermal” multifragmentation (with beams of light relativistic ions) is adequate to this goal. This is a new, many-body type of decay of very hot nuclei (E^*=500–700 MeV) which is characterized by copious emission of intermediate mass fragments ($2<Z<20$). It was shown by the FAZA collaboration for the first time that this type of disintegration takes place after expansion of an excited nucleus due to thermal pressure.

In the project **BECQUEREL** it is planned to expose nuclear emulsions to different beams of relativistic particles. The research program is concentrated on a detailed study of relativistic fragmentation of light radioactive and stable nuclei. The expected results will allow one to answer some high-priority questions of the cluster structure of light nuclei. Due to the best space resolution, nuclear emulsions will permit unique and provable results to be obtained. The most important exposures will be performed on secondary beams of radioactive *He, Be, B, C* and *N* nuclei formed from the beams of stable nuclei at Nuclotron.

4.2.3. Study of multiple particle production in collisions of relativistic nuclei from the lightest to the heavy ones at the energies from hundreds of *MeV* to *TeV*

The project **MARUSYA** is aimed at investigation of the properties of the transition (from nucleon to quark-gluon degrees of freedom) regime in relativistic nuclear collisions. The project also implies investigations of rare subthreshold, cumulative processes and antimatter production (including polarized colliding objects) and selection of events by centrality using the measurement of multiplicity of secondary particles. The development of a multiplicity detector will allow to obtain new data on these processes .There are no such data available in the transition energy region.

The set-up **SCAN-1** is designed to study fragmentation of target nuclei into two cumulative protons. The aim of the experiment is to measure the transverse size of the region of nucleus-nucleus interactions using the method of measuring correlations of cumulative protons emitted with small relative momenta.

The project **SMS** (VBLHE and Moscow State University) is dedicated to the study of leading particles in proton-nucleus interactions. The aim is to clarify the mechanism of strong interaction of particles. The experimental set-up represents a one-arm magnetic spectrometer with variable geometry of the spectrometric part, and it is used to solve two basic problems: study of the space-time structure of hadron interaction and also measurement of the analyzing power of quasi-elastic scattering of polarized protons on nuclei. In the framework of investigation of interaction of polarized protons with nuclei, it is proposed to measure the one-spin scattering asymmetry of polarized protons on internuclear nucleons (for comparison with similar scattering on free nucleons) in the energy range of 1–4 *GeV*.

4.2.4. Applied Research Using Relativistic Nuclear Beams of Nuclotron

The applied research performed at the VBLHE accelerator complex includes the following main directions: radiobiology and space biomedicine; influence of nuclear beams on microelectronic components; radioactive waste transmutation; electronuclear method of power production; use of carbon beam for cancer treatment and so on.

5. Cooperation of VBLHE with other Scientific Centers in 2004-2006

Collaboration with CERN

We plan to continue participation in NA45 and NA49 experiments at SPS:

NA45

1. Analysis of 31M Pb+Au events at 40, 80 and 158 $A{\cdot}GeV$ and reconstruction of e^+e^- - pair effective mass spectrum with resolution compared with natural width of the φ-meson.
2. Disassembly of the CERES/NA45 setup.

NA49

1. TOF calibration, analysis and study of anti-deuteron production in central collisions and anti-proton production at various collision centralities and energies (40, 80 and 158 $A{\cdot}GeV$).
2. Preparation for the workshop on future program of the SPS fixed target experiments beyond 2005 (LoI for experiments with the NA49 Large Acceptance Hadron detector)

3. Analysis of the kaon and pion production (energy, centrality and size dependence) in view of the search for the onset of deconfinement at SPS energies.

We will participate in preparations of experiments for LHC:

ALICE

1. Production of the yoke and some subsystems for dipole magnet of the muon spectrometer;
2. Testing of PWO crystals produced in Kharkov for the photon spectrometer;
3. Production of chambers for transition radiation detector;
4. Physics simulations.

CMS

1. Participation in development of Heavy Ion program;
2. Simulations for Heavy Ion Physics;
3. Testing and calibration of Hadron Endcap Calorimeter.

Collaboration with BNL

Participation in **PHENIX** and **STAR** experiments at RHIC will be continued.

Collaboration with GSI

Continuation of participation in **HADES** experiment.
Participation in R&D for **The International Accelerator Facility for Research with Ions and Antiprotons at Darmstadt** (accelerators, physics, detectors).

The main topics of the VBLHE research program for 2004-2006 are presented in Table.2.

Miscellaneous

The other results of VBLHE in 2003 are published in [26-32]

Table 2. The main topics of the VBLHE research program for 2004-2006

Polarization Phenomena at Relativistic Energies
▪ Spin effects in the interactions of polarized nucleons and the lightest nuclei at the energies above 1 *GeV*: ***SINGLET, ALPOM, KAPPA, SMS MSU – SPHERE, DISK, SPIN, BES, SINGLET*** ▪ Spin structure of the *np* forward scattering amplitude: ***DELTA-SIGMA*** ▪ Spin-dependent part of the nucleon scattering amplitude: ***STRELA*** ▪ Search for the role of three nucleon forces: ***pHe3, LNS*** ▪ Investigation of the spin structure of the lightest nuclei at short distances: ***SPHERE-PIKASO*** Investigation of meson production and resonances in collisions of polarized nucleons and the lightest nuclei: ***DELTA-2, NIS, WASA (CELSIUS, Uppsala)***
Nuclear Beams at Relativistic Energies
Study of multiple particle production in collisions of relativistic nuclei from the lightest to the heaviest ones at the energies from hundreds of *MeV* to *TeV*
▪ Investigation of multiple particle production regularities at the Nuclotron energies in inclusive and semi-inclusive measurements and measurements in 4π- geometry: o External Beams: ***SPHERE, BECQUEREL, MARUSYA, SCAN-2, SMS MSU, DISK*** o Internal Beams: ***MARUSYA, SCAN-1, DELTA-2, LNS*** ▪ Establishment of asymptotic multiple particle production regularities at ultrarelativistic energies: ***STAR, PHENIX (BNL), ALICE, NA49, Heavy_Ions@CMS (CERN)*** • Participation in the new International Project at GSI.
Manifestation of the structure and excited states of nuclei at relativistic energies
▪ Research of clusterization in light stable and radioactive nuclei: ***BECQUEREL, SPHERE*** ▪ Investigation of multifragmentation of the medium and heavy target nuclei: ***FAZA*** ▪ Investigation of light hypernuclei: ***GIBS, SPHERE*** ▪ Investigation of lepton pairs: ***NA45 (CERN), HADES (GSI)***

Applied Research using Relativistic Nuclear Beams of Nuclotron
▪ Laboratory tests of elements of space devices ▪ Radiobiology and space biomedicine (in cooperation with DRRR) ▪ Transmutation of radioactive wastes, problems of the electronuclear energy production method: ***GAMMA2, Energy+Transmutation*** ▪ Use of carbon beam for medical purposes (in cooperation with DLNP)

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