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REVIEW OF EXPERIMENTS ON THE NUCLOTRON

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Some selected experimental and methodical results obtained in the field of relativistic nuclear physics at the Veksler and Baldin Laboratory of High Energies of the Joint Institute for Nuclear Research at Dubna during last years are presented. A detailed review of the physics research programme at the Nuclotron and the future plans for 2004 – 2009 are given.

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1 Introduction

An overview of the physics research programme at the Nuclotron and the future plans in 2004 – 2009 are given. Firstly, the present status of the Accelerator Complex and the Nuclotron development in 2004 – 2009 are briefly characterized. Then, some latest selected experimental and methodical results obtained in the experiments performed on the Synchrophasotron and Nuclotron are presented and the long-term physics research programme at the Nuclotron in 2004 – 2009 is discussed.

2 Acceleration Complex of VBLHE

The acceleration complex of the Veksler and Baldin Laboratory of High Energies (VBLHE) is the basic facility of JINR producing beams of protons, polarized deuterons (also polarized protons and neutrons) and nuclei (double- and multi- charged ions) in the energy range up to 6 GeV per nucleon. It includes the old machine — Synchrophasotron and a new superconducting accelerator – the Nuclotron [1].

Taking into account the proposals of the JINR Directorate and the recommendations of the PACs, the JINR Scientific Council on its 93rd Session held on January 16–17, 2003 endorsed the outphasing of the Synchrophasotron [2]. The Nuclotron was built during 1987–92. The accelerator is based on the unique technology of the superconducting magnetic system, developed at the VBLHE [3]. Data taking for physics started in 1994. In March 1999 the Nuclotron beam

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Tab. 1. Parameters of the Nuclotron beams.

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

had been extracted by using the superconducting system of slow extraction. Presently, the experiments with extracted Nuclotron beams function stably. Several beam parameters are listed in Table 1. During last ten years a substantial progress has been achieved in the development of the following key systems of the Nuclotron accelerator facility. The slow beam extraction system has been successfully commissioned. As a result, the Nuclotron has become one of the leading JINR experimental facilities. The cryogenic system was developed and the long-term operation runs of the Nuclotron were provided. The efficiency of the cryosystem has been improved and electric power consumption dropped down by a factor of 2. An increasing variety of the ion species (up to ^{56}Fe) is available now.

Improvement of the extracted beam parameters in 2002–2003 has been made. In December 2002 the extraction time grew up to 2 s, the extraction repetition rate — 0.2 Hz and the overall duty factor — about 0.4. The important progress was made in March 2003. The beam spill of the extracted deuterons beam with kinetic energy of 2 A GeV and intensity 1.2×10^{10} particles per spill reach up 5 seconds, the accelerator cycle 8 s and the beam duty factor 0.6.

In December 2002 the **polarized deuteron beam** was firstly accelerated and extracted from the Nuclotron with the energy of more than 2 A GeV and beam intensity of 1.8×10^8 particles per cycle. The vector polarization measured in the ring and point F3 at the energies in the range of 1–2 A GeV, was 0.57–0.60. The polarization coefficient of the extracted beam corresponded to the coefficient of the polarization of the beam injected into the Nuclotron ring.

What can we expect from the Nuclotron with the existing source of polarized deuterons and single turn injection?

At present with existing polarized deuterons source and single turn injection can be expected as follows the Nuclotron parameters: Intensity — 1 $\times10^9$ part./cycle, spill duration — up to 3–4 seconds, energy — up to 4 and 2.7 A GeV for internal and external beams, respectively. On the other side some polarized deuteron beam parameters (energy or momenta and intensity) requested in the frame of our projects are shown in Table 2.

So one can conclude that the use of the Nuclotron as an accelerator of polarized deuterons can be started and further progress depends on the financial support of the Nuclotron development programme for 2004 – 2009.

As for the **nuclear beam**, the large success was obtained during last years. In 2001 the beams

Tab. 2. Parameters of the beams of polarized deuterons requested by some of the VBLHE projects.

Project	Energy/Momentum	Intensity, part. per cycle
PIKASO, SPHERE setup	$P_d = 4.5 - 9.0$ GeV/c	$> 3 \times 10^9$
STRELA	$P_d = 2.7 - 4.0$ GeV/c	$\sim 10^7$
DELTA-SIGMA	$P_d = 4.5 - 9.0$ GeV/c	$> 3 \times 10^9$
LNS	$E_d = 0.3 - 1.0$ GeV	5×10^8
PHe3	$E_d = 1.0 - 1.75$ GeV	10^9
SMS	$P_d = 4.5 - 9.0$ GeV/c	5×10^7 $\vec{\mathrm{p}}$

of ^{12}C, ^{24}Mg and ^{10}B nuclei were accelerated with intensities of 8×10^9, 1×10^7 and 1×10^5 particles per cycle. In 2002 the intensity of the external beam of ^{24}Mg ions was increased up to 10^8 and ions of ^{40}Ar were accelerated for the first time with the intensity of 1.4×10^6 particles per cycle and the kinetic energy about 1 A GeV. In 2003 even the ions of nitrogen and iron were accelerated for the first time with the intensities and kinetic energies of external beams equal to 5×10^5 particles per cycle and 2.1 A GeV for ^{14}N nuclei and 5×10^5 particles per cycle and 1 A GeV in the case of ^{56}Fe nuclei.

Based on the results obtained in 1999 – 2002 and following the conclusion of the Technical Evaluation Committee for the Scientific Programme of the Nuclotron [4], the main three directions of the Nuclotron development are planned:

(1) The improvement of the Nuclotron Beam Extraction System and of the External Beam Lines. All of the main design parameters have been achieved. The current upgrade of the beam diagnostic equipment and electrostatic septum is required.

(2) The development of the Injector Complex, including the ion sources, the linear accelerator upgrade, and the booster construction. The main goal is to increase the intensity of polarized deuteron beam at the Nuclotron up to 10^9 particles per cycle and acceleration and extraction of the ions heavier than Fe.

(3) The development of cryogenic, diagnostic, and control systems of the Nuclotron. The main goal is to reach the peak beam energy.

3 Physics Programme of the VBLHE

The physics programme of the first experiments with internal and external Nuclotron beams has been prepared in 1999 by the VBLHE [5] and the research programme of the VBLHE in 2002 – 2006 was reported at the 91st Session of the JINR Scientific Council [6] (see also [7]). After that the long-term research programme for 2004 – 2009 [8] was prepared and also approved by the JINR Scientific Council at its 94rd session in June 2003 [9].

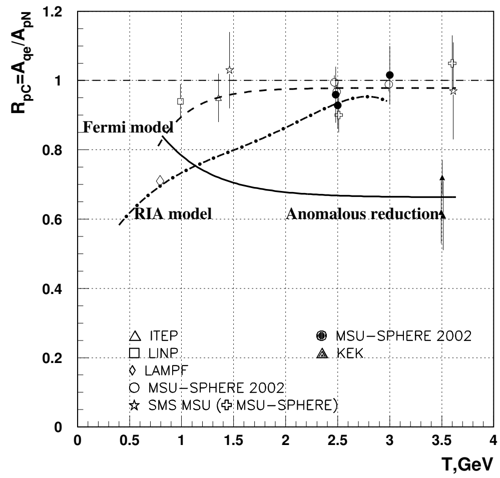

Fig. 1. The energy dependence of the analyzing power reduction R_{pC} at polarized proton scattering on intranuclear nucleons measured in SMS MSU – SPHERE VBLHE Experiment. Here, A_{qe} and A_{pN} are the vector analysing powers for the quasielastic channel and for scattering on any intranuclear nucleon, respectively.

3.1 Last Experiments on the Synchrophasotron

The last Synchrophasotron run was performed in November 2002. The joint experiment of the Moscow State University (MSU) and the VBLHE performed at the SMS MSU setup and the PIKASO experiment on the SPHERE setup were the last investigations carried out at this machine.

In the first experiment performed in the frame of the **SMS MSU/SPHERE project** the stripping polarized protons with energies of 2.51 and 3.00 GeV bombarded targets of carbon and copper.

The main subject of experimental investigation was to measure the analyzing power reduction at polarized proton scattering on intranuclear nucleons in the region of energies 1–4 GeV.

By the comparison of the value of the vector analyzing power $A(T)$ for the scattering on the free and intranuclear nucleons the parameter R of the reduction of $A(T)$ can be calculated as

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

for the scattering on any intranuclear nucleon, or

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

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

In the experiment, the first case corresponds to the measurements of the $A(T)$ in proton-nucleus scattering with the detection of the quasielastic channel by the magnetic analysis of the scattered particle momentum but without any separation of the pp- or pn- interaction,

$$\vec{\mathrm{p}} +^{12} C(^{64}Cu) \longrightarrow p_L + p(n)_R + X. \quad (1)$$

The second case corresponds to the measurement of the $A(T)$ in proton-nucleus scattering with the detection of the recoil proton,

$$\vec{\mathrm{p}} +^{12} C(^{64}Cu) \longrightarrow p_L + p_R + X. \quad (2)$$

Here, the letters p(n) denote proton (neutron), X - any other reaction products and the indices L and R denote left and right scattering directions. The aim of the experiment is to test critically the model predictions for the analyzing power reduction parameter. It is important that in the inclusive reaction (1) an arbitrary value of the pp and pn analyzing power has been measured, but simultaneously at the detection of the recoil proton the pp scattering (2) has been measured separately. So, this experiment was sensitive to the possible difference of the pp and pn analyzing power reduction. The results are given in Fig. 1.

New data were measured under the same experimental conditions. Main results of the experiment are as follows:

At GeV energies the reduction of the analyzing power is close for protons and neutrons and its behavior is approximately described in the frame of the relativistic impulse approximation. There is no difference for the measurements on the copper and carbon target nuclei. The anomalous analyzing power reduction is not observed.

In near future the investigations on the polarized beams of the VBLHE JINR Nuclotron in the frame of the SMS MSU – SPHERE VBLHE project will be continued. The measurements of the analyzing power reduction in the quasielastic scattering of the polarized deuterons on carbon at 1.27 and 1.74 GeV, the investigation of the A-dependence of the analyzing power reduction from Be to Pb nuclei and the direct measurement of the analyzing power reduction at proton-neutron scattering will be carried out.

The second experiment was performed in the frame of the **PIKASO project** which is focused on the studies of the deuteron spin structure at short internucleon distances by using hadron probes and the studies of the spin effects in hadron scattering at energies of few GeV. The deuteron beams with the highest momentum in the world up to 9 GeV/c are planned to be used in the programme.

In past, the experiments using deuteron polarized beams and unpolarized targets were done mostly in Dubna and Saclay (see review done in [10]). A large amount of spin dependent data coming from deuteron break-up experiments and from backward elastic dp scattering showed that the content of nucleons should be taken into account starting from relative momenta k of the nucleon constituents close to $k \sim$ 0.2–0.3 GeV/c in any consistent description of the nuclear structure at short distances.

This is demonstrated in Fig. 2., where the tensor analyzing power T_{20} is presented for the polarized deuteron break-up reaction $\vec{\mathrm{d}} + A \rightarrow p + X$. It is shown that T_{20} has a big value and is described by calculations based on impulse aproximation (IA) only for internal momentum $k < 0.2 - 0.3$ GeV/c. The mechanism additional to IA (rescattering, FSI - interactions in final states) allows one to describe experimental data up to $k \sim 0.5$ GeV/c. But there are no calculations based on the nucleon model describing T_{20} for the whole measured region.

The mentioned above deviations of the experimental data from the calculations can be related to the manifestation of non-nucleon degrees of freedom in the deuteron wave function (DWF)

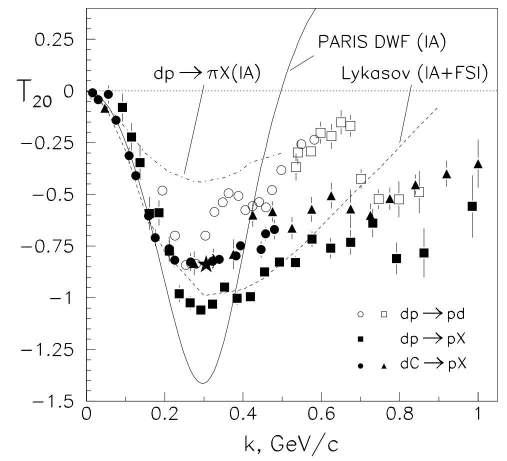

Fig. 2. Tensor analysing power T_{20} as a function of the internal nucleon momenta k in the deuteron.

for these small distances ($l < 0.4$ fm). In this case it is natural to use, as a probe, hadrons with quark contents different to those of the nucleon. This was one of the reasons to study polarization observable for the reaction of the deuteron fragmentation into cumulative (subthreshold) pions at zero angle $\vec{\mathrm{d}} + A \rightarrow \pi(0^{\circ}) + X$.

The variable A_{yy} was firstly studied in the fragmentation of 9 GeV tensor polarized deuterons into cumulative pions. The results are shown in Fig. 3. Here, the cumulative number X_c for the cumulative pion production in the reaction $A + B \longrightarrow \pi + X$ can be written as [10]:

$$X_c = (p_B p_\pi - m_\pi^2/2)/(p_A p_\pi - m_N^2 - p_A p_\pi), \tag{3}$$

where p_A, p_B are the four-momenta per nucleon for projectile and target nuclei, respectively, p_π is the four-momentum of the produced pion, m_N and m_π are the nucleon and pion masses. In other words, X_c is the minimum fragmenting mass in units on nucleon mass required to produce a pion with momentum q_π.

The sign of A_{yy} in the cumulative region ($x_c > 1$) is negative at all angles of pion emission in comparison with IA-predictions and A_{yy}-behavior in $A(d,p)$. Magnitude of A_{yy} increases with rise of Θ_π, also in contrary to $A(d,p)$. A_{yy} reaches the value of -0.4 at $x_c \sim 1.5$, where D/S-ratio in DWF is close to its maximum. Large D-state effects are revealed at fragmentation of 9 GeV tensor polarized deuterons into cumulative pions.

Strong transverse momentum dependence of A_{yy} in the fragmentation of 9 GeV tensor polarized deuterons into cumulative pions was measured (Fig. 4). As the pion transverse momentum increases from P_t=0.4 to 0.8 GeV/c the tensor analyzing power A_{yy} rises from the magnitude of near zero to -0.4. The starting point of $A_{yy}(P_t)$ - rise corresponds to $x_c = 1$ – the beginning of the cumulative regime. $A_{yy}(P_t)$-rise is linear at both angles of pion emission, 135 and 180 mrad.

In November 2002 the tensor analyzing power A_{yy} was measured in the fragmentation of 5 GeV tensor polarised deuterons into cumulative pions. New preliminary data are shown in Fig. 3. One can see that the energy dependence of A_{yy} is very significant in the 5–9 GeV range. The

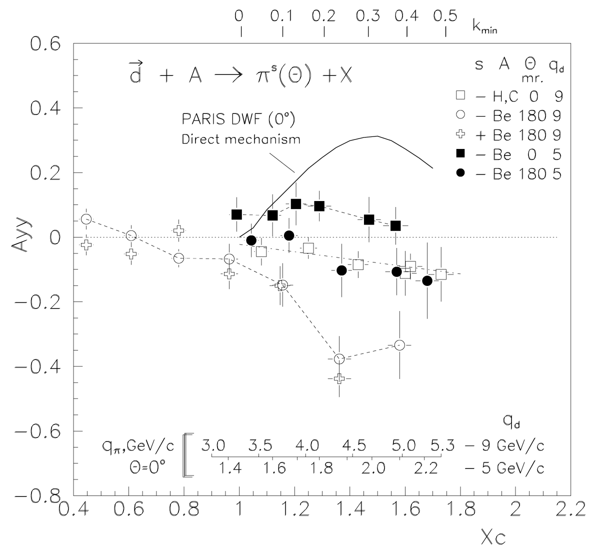

Fig. 3. Tensor analyzing power in the reaction $Be(d,\pi)X$ at deuteron momenta $q_d = 5$ and 9 GeV/c. Here, k_{min} is the minimum internal momentum k of the nucleon N_f in the deuteron required to produce a pion at corresponding X_c through the direct mechanism (in $N_f N \rightarrow NN_\pi$ process).

value A_{yy} measured at 0 degrees changes its sign when going from 5 to 9 GeV/c. On the other side the values A_{yy} measured at 180 mrad increase steeply at $x_c > 1$. This A_{yy}-rise is correlated with P_t-rise, and the linear dependence of $A_{yy}(P_t)$ is observed from $P_t = 0.4$ to 0.8 GeV/c as in the previous case of 9 GeV tensor polarized deuterons. In future it is very important to study $A_{yy}(P_t)$ at $x_c > 1.5$ and $P_t > 0.8$ GeV/c.

3.2 Experiments on the Nuclotron

There are many fields of activities on the Nuclotron. Most of our experiments are performed in the frame of fundamental research. They use nuclear and polarized beams. The VBLHE old accelerator, Synchrophasotron, was also used for applied research for many years with rather fruitful results [7]. This research is continued at the Nuclotron. Furthermore, the Nuclotron beams offer new opportunities for applied research whose spectrum will be enlarged. Later, the comments on some of them will be presented.

The major part of the on-going research projects at the Nuclotron are carried out in collaboration with scientific groups from many countries. The Nuclotron programme is tightly connected with the research programmes at CERN, BNL and other research centres. Participating in international experiments the VBLHE also contributes in the design of experimental facilities at other research centres, including NA45 and NA49 at CERN SPS, CMS and ALICE at constructed CERN LHC, HADES at GSI SIS, WASA at UPPSALA CELSIUS, STAR and PHENIX at BNL RHIC and others [7].

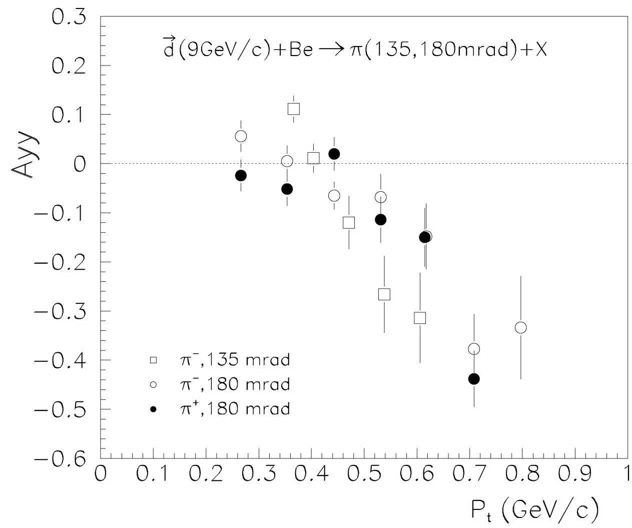

Fig. 4. Dependence of A_{yy} on P_t for 9 GeV tensor polarised deuterons.

VBLHE projects are focused on studies of interactions of relativistic nuclei in the energy region from a few hundred MeV to a few GeV per nucleon to search for preasymptotic manifestations of quark and gluon degrees of freedom in nuclei, the study of the spin structure of the lightest nuclei and to investigate the nuclear structure at relativistic energies.

A number of research facilities are beeing prepared or already operate at the VBLHE accelerator complex, including SPHERE, GIBS, FAZA, DELTA-SIGMA, DELTA-2, DISK, SMS, MARUSYA, SCAN-1, SCAN-2, STRELA, and others (Fig. 5).

Further development of the existing research facilities and the construction of new ones (SINGLET, NIS, and others) are planned.

The three core directions in the Nuclotron **fundamental research programme** are: Polarization phenomena at relativistic energies, Effects of nonperturbative QCD in nuclei and Nuclear structure at relativistic energies. This is the concluding result of the JINR interlaboratory and internal committees work during the last several months. In the opinion of these committees the energies of accelerated particles at the Nuclotron are good to investigate cumulative relativistic nuclear effects at the intermediate energies. There is a number of projects being implemented in the frames of these three topics. They are presented in the Table 3 together with the different directions of the **applied research** carried out with the Nuclotron beams. All these investigations were performed in 2003 in the frame of 9 topics of research of the first priority in the field of relativistic nuclear physics (two of them are all-Institute topics) and 3 topics of the second priority [11].

Polarization Phenomena at Relativistic Energies
Spin effects in the interactions of polarized nucleons and the lightest nuclei at energies above 1 GeV: **SINGLET, ALPOM, KAPPA, SMS MSU-SPHERE, DISK, SPIN, BES** 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)**
Nuclear Beams at Relativistic Energies
Study of multiple production processes in collisions of relativistic nuclei from the lightest to the heaviest ones at energies from hundreds of MeV to TeV
Investigation of multiple production regularities at the Nuclotron energies in inclusive and semi-inclusive measurements and measurements in 4π- geometry: a) External Beams: **SPHERE, BECQUEREL, MARUSYA, SCAN-2, SMS MSU, DISK** b) Internal Beams: **MARUSYA, SCAN-1, DELTA-2, LNS** Establishment of asymptotic multiple production regularities at ultrarelativistic energies: **STAR, PHENIX (BNL), ALICE, NA49**
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 the multifragmentation of medium and heavy target nuclei: **FAZA** Investigation of light hypernuclei: **GIBS, SPHERE** Investigation of lepton pairs: **NA45 (CERN), HADES (GSI)**
Applied Research using Nuclotron Relativistic Nuclear Beams
Provision of space apparatus elements with ground tests Radiobiology and space biomedicine (in cooperation with DRRR) Transmutation of radioactive wastes, Problems of the electronuclear energy generation method: **GAMMA2, Energy+Transmutation** Use of the carbon beam for medical purposes (in cooperation with DLNP) **Med-Nuclotron**

Tab. 3. Main topics of the Long-Term Research Programme at VBLHE.

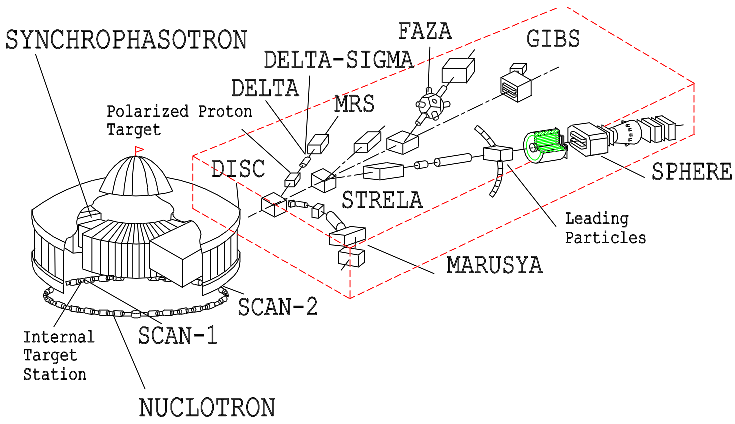

Fig. 5. The schematic view on the Nuclotron setups.

3.2.1 Polarization Phenomena at Relativistic Energies

The main aim of the **project DELTA-SIGMA** is to extend studies of the NN interaction over a new higher energy region of free polarized neutron beams, which are currently available at VBLHE accelerator only.

This project suggests the detailed measurements of energy dependence of $\Delta\sigma_L$(np) and $\Delta\sigma_T$(np), which are the differences between the total np cross sections for the antiparallel and parallel orientations of the spins of the projectile neutrons and the target protons polarized in the longitudinal (L) and the transverse (T) direction, respectively. Simultaneously with this the measurements of the spin correlation parameters A_{oonn} and A_{ookk} in np backward elastic scattering will be performed.

Next figure (Fig. 6.) shows the experimental "DELTA-SIGMA" setup (VP1 = beam line of slowly extracted polarized deuterons, 1V = beam line of polarized neutrons, BT = neutron production target, IC = ionization chamber for monitoring the deuteron beam intensity, PIC 1-3, 9-16 = multiwire proportional/ionization chambers to measure the deuteron beam profiles, CM = sweeping magnet, C1-C4 = a set of neutron beam collimators, SRM = neutron spin rotating dipole, PPT = polarized proton target, NP = neutron beam profilometer, M1, M2 = monitor neutron detector modules, T1-T3 = neutron transmission detector modules). The free polarized quasi-monochromatic neutron beam is produced by break-up of the extracted vector-polarized deuterons accelerated at the Nuclotron. Neutrons are passing through a large polarized proton target.

New results on the $\Delta\sigma_L(np)$ observable were obtained in 2002 as a result of processing and analysis of the data measured by Delta-Sigma group in 2001 at the neutron beam kinetic energies 1.4, 1.7, 1.9 and 2.0 GeV. They are presented in Fig. 7. together with previously published $\Delta\sigma_L(np)$ data for six energies from 1.2 GeV to 3.7 GeV of the polarized quasi-monochromatic neutrons beam. One can see that all the VBLHE results are smoothly connected with the existing

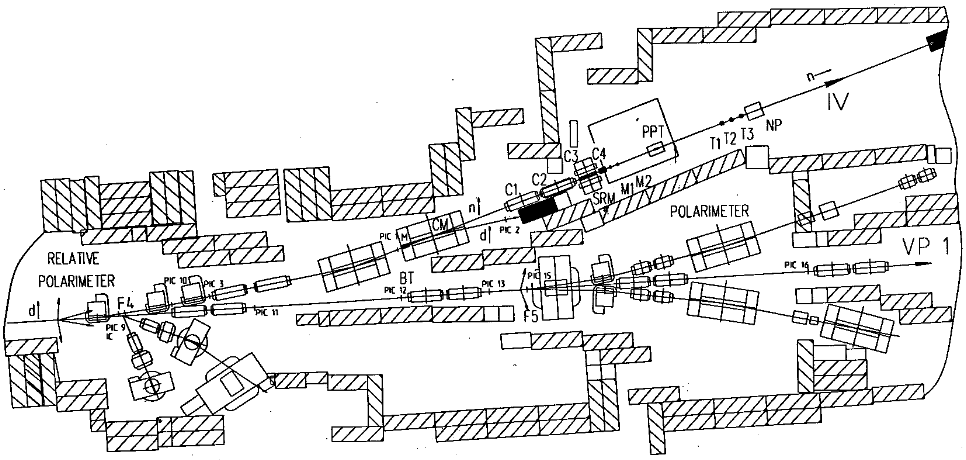

Fig. 6. Experimental "DELTA-SIGMA" setup

data measured at lower energies. The fast unexpected energy drop to zero in $\Delta\sigma_L(np)$ was observed between 1.1 and 2.0 GeV.

The data are compared with the meson-exchange model prediction (ME) and with the phase shift analysis (PSA) fit. The conventional ME theory of NN scattering agrees qualitatively with the data at low energy but one can see a disagreement with the model prediction at the high energy. The nonperturbative model of the interaction between quarks induced by strong fluctuations of vacuum gluon fields, i.e., instantons, gives only a qualitative estimation of the energy-dependent contribution to $\Delta\sigma_L(np)$.

In future, the energy dependence of $\Delta\sigma_T(np)$ with transversely polarized projectile neutrons and target protons must be also measured in experiments made at the Nuclotron together with the completion of the energy dependence of $\Delta\sigma_L(np)$.

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

In the early fifties A.B. Migdal [12] and I.Y. Pomeranchuk [13] emphasized a possibility to get additional information about the amplitude of the elementary $np \to pn$ charge exchange reaction by means of the charge exchange processes from the experiments with unpolarized deuterons. The simplifiest versions of these two processes in the framework of the Impulse Approximation (IA) are shown in Fig. 8: (a) charge-exchange process $np \to pn$ and (b) charge-exchange reaction on the simplest nucleus - deuteron $dp \to (pp)n$.

Vertical arrows stand for the nucleon spins with respect to an arbitrary axis of quantization. As one can see, in the case (a) both spin orientations are allowed, while in the second case, (b), at small scattering angle (spatial symmetry) due to the produced charged symmetry (two protons move in the very forward direction with a small relative momentum) the reaction can proceed

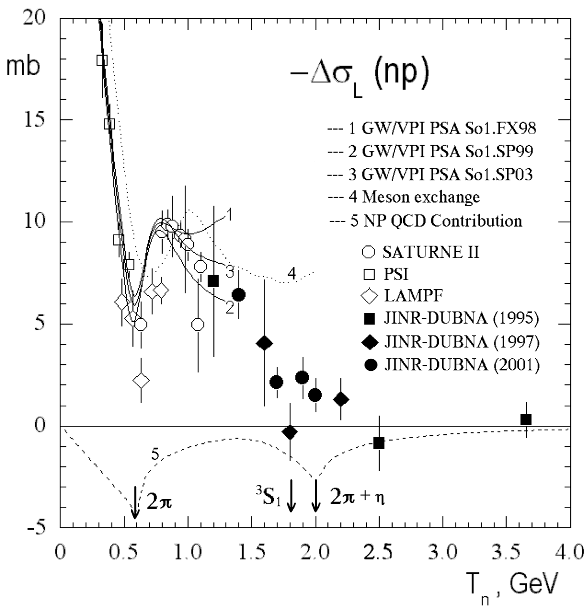

Fig. 7. The energy dependence of the total np cross section differences for parallel and antiparallel spin orientations of the beam neutrons and the target protons $\Delta\sigma_L(np)$, with particle spins oriented along the beam momentum direction.

only if the scattered proton spin flips (caused by the Pauli exclusive principle).

So, the deuteron behaves as a spin filter. It can be shown that at zero momentum transfers the differential cross section of the reaction $dp \to (pp)n$ is determined by the spin-flip section of the charge-exchange $np \to pn$ amplitude.

In the June 2003 run some period of time the STRELA setup (Fig. 9) was exposed to the beam of deuterons with momenta of 3.5 and 4.0 GeV/c. The extracted deuteron beam is incident on a liquid hydrogen target T and the analyzing magnet M separates the primary deuterons and secondary particles. The ionization chamber IC measures the flux of the deuteron beam. The scintillation counters S_1 and S_2 determine the angular ($\sim$ 0.2 deg) and momentum ($\sim$10%) acceptance and trigger of the events. The drift tubes DT_1–DT_4 and the multiwire proportional chambers PC_1–PC_2 detect one or two-proton events. The Čerenkov counter C_1 with a quartz radiator serves for the pion suppression.

In the **project ALPOM** the measurements of the analyzing power for the inclusive reaction $p + CH_2 \to one\ charged\ particle + X$, at proton momenta of 3.8, 4.5 and 5.3 GeV/c, for different thicknesses of the CH_2 target were made during two earlier beam runs at the Synchrophasotron. It was shown (Fig. 10.) that for protons of 3.8 GeV/c, the analyzing power is fairly independent of the amount of material in the analyzer, from 37 to 80 g/cm^2.

The analyzing power decreases with increasing the incident momentum, but it is still sizeable at a proton momentum of 5.3 GeV/c.

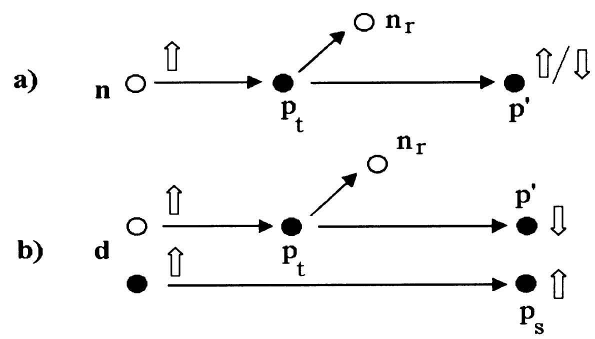

Fig. 8. $np \to pn$ charge exchange reaction in the frame if IA.

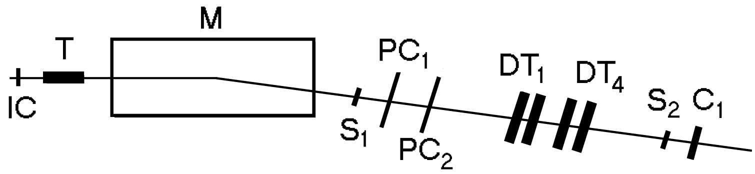

Fig. 9. The scheme of the STRELA setup which was exposed in the June 2003 Nuclotron run.

In a wide region of momentum transfers, the analyzing power both for graphite and CH_2 targets has a maximum around $p_t = p \cdot \sin\theta \sim 0.3$ GeV/c. In the momentum range investigated so far, the analyzing power is inversely proportional to the incident momentum.

The continuation of measuring the analyzing powers for the reaction p+CH_2 (C) for the incident polarized proton momenta up to 6.5 GeV/c by using the polarized deuteron beams at the Nuclotron is proposed. No such measurements have ever been reported about. This database is generally of great interest, in particular, it may support further investigations of the proton form factors to Q^2 values larger than 10 GeV^2 at Jlab ([14, 15]).

The aim of the **project KAPPA** is to extend the range of the measurements of the polarization transfer coefficient κ from deteron to proton in the reaction $^1H(\vec{\mathrm{d}}, \vec{\mathrm{p}})$ X up to internal momenta k $\sim$ 0.8 GeV/c. The motivation is connected with the fact that the data measured earlier ([16–18]) are rectricted by the value k = 0.58 GeV/c (see Fig. 11.) and the extension of the existing data set on the polarization transfer could be very important for the theoretical models.

The experimental setup is shown in Fig.12. It is assumed to use the polarimeter ALPOM to measure the polarization of secondary protons. They are produced by the fragmentation of the vector polarized deuterons (P_d = 6.6-7.0 GeV/c, I_d = 2.10^9 part. per beam spill) on the 0.2 m thick carbon target (F3). The beam transport line (from F3 up to F5) is 60 m long. The setup will be supplemented with the time-of-flight system (TOF, 40 m base between S_0 and S_2 counters) to separate secondary protons and deuterons of the same momenta. Different values of internal momenta will be set by the variation of primary deuteron beam momentum.

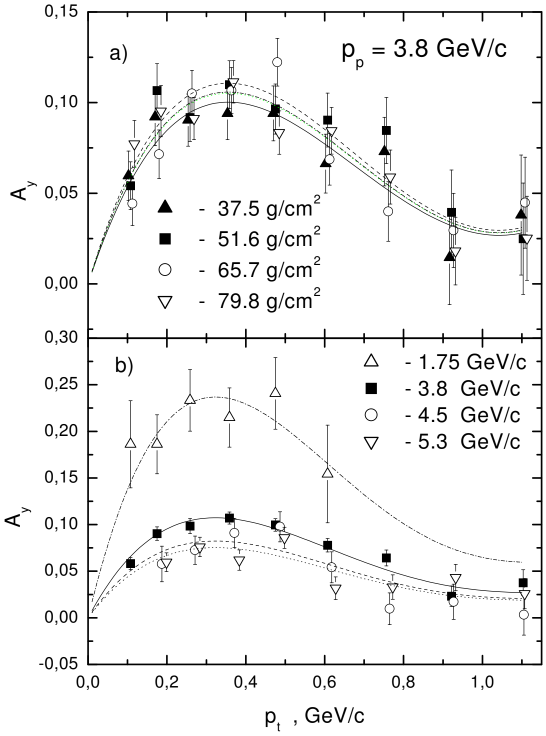

Fig. 10. Analyzing powers as a function of p_t for different target thicknesses at 3.8 GeV/c (a) and for different momenta at 51.6 g/cm^2 (b).

The **project DELTA-2** is intended for experiments on the VBLHE polarized proton target by using extracted beams of the Nuclotron as well as for experiments on the Nuclotron internal target (together with PI and INR RAS).

The setup which represents a two-arm free-magnet spectrometer used to register and measure the energy of neutral (gamma-quanta and mesons) and charged (mesons, protons, deuterons) particles is shown in Fig. 13.

In the physics programme, it is planned to investigate in detail π^0 and η meson production (in association with deuteron production in the final state inclusive) in neutron- proton collisions of the polarized beam and target nucleons at energies of 1.2–2.0 GeV in order to test theoretical assumptions of the meson production mechanism and also the hypothesis of the presence of a spin-polarized component of strange quarks inside the nucleon ([19, 20]).

The experimental investigations of new objects of nuclear physics - η-mesic nuclei, $_\eta$A, a bound system of η-meson and nucleus, is proposed to performed on the Nuclotron internal target [21]. Beams of η-mesons cannot be obtained because of a very short life-time of the η-mesons ($\sim 10^{-19}$ s). So the study of the interactions of the η-mesons with nucleons in elementary processes of $\eta N \rightarrow \eta N$ or pN type is not possible. The interaction can be investigated only in

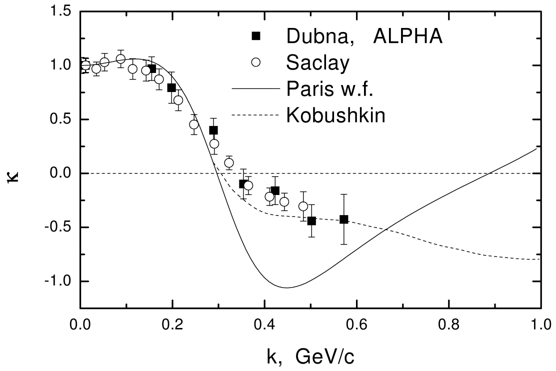

Fig. 11. The polarization transfer coefficient κ in the $p(\vec{\mathrm{d}},\vec{\mathrm{p}})X$ breakup reaction. Solid lines – Paris wave function, dashed lines – Kobushkin's calculations.

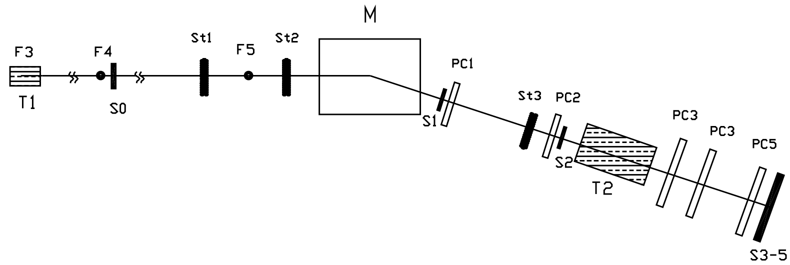

Fig. 12. The scheme of the setup. S_i– scintillation counters, PC_i – proportional chambers, St_i – straws, M – magnet, T_i – targets.

the final state of the elementary processes, for example $\pi N \to \eta N$, $\gamma N \longrightarrow \eta N$. The η-mesic nuclei give us unique possibility to study ηN-interaction in nuclear matter. Let us assume the production of the η-nuclei in the reaction:

$$p_0 + A \to p_1 + p_2 + \ _\eta(A-1) \to p_1 + p_2 + p_3 + \pi^- + X.$$

The upper diagram in Fig. 14. presents the process describing the stage of η-meson production in the nucleus with formation of the bound state of η-meson and the nucleus and at last the stage of the η-nucleus decay. The lower diagram corresponds to the process where η-mesic nucleus is not produced. One can assume that the kinetic energy of the η-meson is rather great ($E_\eta > 70$ MeV) in this case and there is no attraction between η-meson and nucleon. This stage proceeds through single N-interactions mediated by the $\mathrm{S}_{1\,1}$ (1535) nucleon resonance.

The **project NIS** has been proposed by VBLHE and LPP. The project is aimed at searching for effects of polarized nucleon strangeness, including violations of the Okubo-Zweig-Iizuka

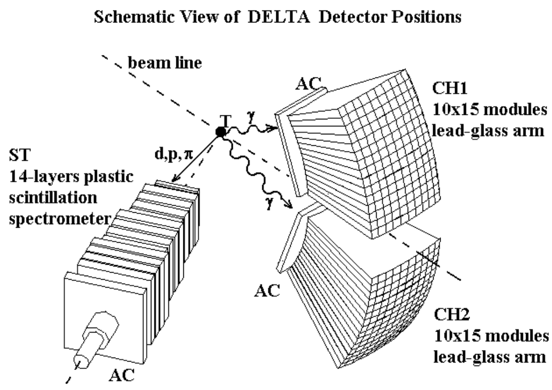

Fig. 13. A schematic view of the DELTA-2 setup. T – polarized proton target PPT: CH1, CH2 – two arms of the Čerenkov lead-glass spectrometer for two gammas after neutral meson decay measurements, ST – 14-layer fiber-optic scintillation telescope for multi-ΔE measurements of charged particles, AC – anticoincidence detectors.

(OZI) rule, in vector meson production in pp and np interactions near the 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 violation of the OZI rule in pp collisions is a critical test of the idea of hidden polarized strangeness in the nucleon. Such a violation has been observed in antiproton-proton collisions, and it is important to find it in the NN system. The NIS experiment will provide data on the OZI rule violation and its energy dependence near the φ- and ω-meson production threshold.

The NIS project will be conducted at the SPHERA setup supplemented by necessary detectors. The main parts of the NIS magnetic spectrometer (Fig. 15.) come from the completed EXCHARM experiment (2×1 m^2 multiwire proportional chambers (MWPC) with all their read-out electronics) and SPHERE installation (the analyzing magnet, DAQ and logical electronics, beam monitoring system).

The use of the deuteron beam allows one to compare the total and differential production cross sections of φ- and ω-mesons in pp and np interactions under the same kinematic conditions. It should be emphasized that in a visible future, such measurements can be made only at the Nuclotron, since the maximum energy of the other proton accelerator of such a kind in this energy region (COSY) in Germany corresponds just to the φ-meson production threshold.

The **project LNS** assumes to investigate the deuteron and ^{3}He structure at small distances. The programme includes a study of dp-elastic scattering and a deuteron break-up reaction in dp interactions by using a nonpolarized and polarized deuteron beam, an internal target of the Nuclotron and a measurement of the tensor analyzing power of the $d + d \rightarrow\ ^3He + n$ and $d + d \rightarrow\ ^3H + p$ reactions using the polarized RIKEN deuteron beam in Japan. These measurements will help to understand the spin structure of many-body systems at distances that are

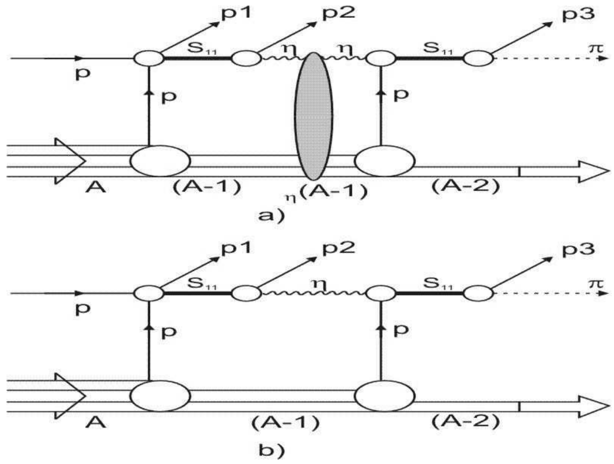

Fig. 14. Mechanism of formation and decay of the η-nuclei in pA-collisions (if $E_\eta < 70MeV$) – up. Mechanism of production and annihilation of η's in the nucleus (if $E_\eta > 70MeV$) – down.

currently unfeasible with electromagnetic probes. The main idea of the project is to extend measurements of different quantities observed in processes comprising three nucleon systems in the new energy and angular region where the Faddeev technique is still working, and, consequently, the comparison of experiment and theory can be made with a high degree of accuracy.

The experimental programme of the project LNS includes three different experiments:

(1) measurement of the cross section, vector (A_y) and tensor (A_{yy}) and (A_{xx}) analyzing powers in dp elastic scattering over the range of kinetic deuteron energies from 300 to 500 MeV;

(2) measurement of the cross section, vector A_y and tensor A_{yy} analyzing powers in the deuteron break-up reaction in dp collisions over the energy range of (300–500) MeV for different configurations (coplanar geometry, spacial star and so on);

(3) measurement of tensor analyzing powers in the reactions $d + d \rightarrow\ ^3He + n$ and $d + d \rightarrow\ ^3H + p$ with the energy of the projectile deuteron up to 270 MeV.

The first two experiments are planned to be performed by using unpolarized and polarized deuteron beams on the internal target of the Nuclotron, the third one has been performed at RIKEN facility in Japan.

The main objective of this joint VBLHE-RIKEN **R308n** experiment ([22]- [23]) was to study the ^{3}He (^{3}H) structure at distances, unachievable now with the use of electromagnetic probes, by measuring the angle dependences of the tensor analyzing powers A_{yy}, A_{xx} and A_{xz} in the $d + d \rightarrow\ ^3He + n$ and $d + d \rightarrow\ ^3H + p$ reactions. These polarization observables are sensitive to the spin neutron (proton) distribution in ^{3}He (^{3}H) at small distances in the framework of one-nucleon data exchange. On the other hand, both ^{3}He and ^{3}H are mirror nuclei relative to the number of protons and neutrons, and the difference in their observed values can be interpreted

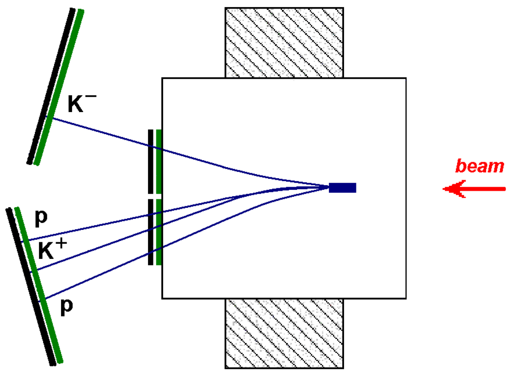

Fig. 15. Scheme view of the NIS setup.

in terms of the charge symmetry violation. The measurement of the tensor analyzing powers, which are insensitive to Coulomb corrections in the first order in the $d + d \rightarrow\ ^3He + n$ and $d + d \rightarrow\ ^3H + p$ reactions, in particular, at large internal momenta, could give additional information on the nature of the charge symmetry violation. The VBLHE-RIKEN collaboration carried out measurements of the tensor A$_{yy}$, A$_{xx}$, A$_{xz}$ and vector A$_y$ analyzing powers on the polarized deuteron beam of the RARF cyclotron (RIKEN) at the SMART set-up in the autumn of 2000. The observed data were calculated with a statistical error of ±0,02 at energies of 270 and 200 MeV over the whole angular range for the reaction $d + d \rightarrow\ ^3H + p$. The same set of analyzing powers was obtained for the mode $d + d \rightarrow\ ^3He + n$ at 270 MeV between 0 and 120 degrees in the c.m.s. Such a high accuracy of experimental data will allow one to discriminate different models of three-nucleon bound state to the internal nucleon momentum of 600 MeV/c. It is planned to continue these investigations on the polarized deuteron beams of the Nuclotron in the framework of the new pHe3 project.

The last selected results of R308n experiment are shown in Fig. 16. The results on the vector A$_y$ and tensor A$_{yy}$ analyzing powers in the $d + d \rightarrow\ ^3He + n$ and $d + d \rightarrow\ ^3H + p$ reactions at 270 MeV are obtained. The data on A$_{yy}$ have shown the sensitivity to the spin structure of ^{3}He (^{3}H) and deuteron at the forward and backward angles, respectively. However, the data are not reproduced by the current theoretical models with the use of the standard wave functions of light nuclei.

The schematic view of the polarized ^{3}He target developed in Japan, which will be used for the **PHe3** project at the Nuclotron, is shown in Fig. 17. The ^{3}He nuclei are polarized via the spin-exchange reaction with the optically-pumped Rb atoms. The circularly polarized light ($l = 794.7$ nm) emitted by diode lasers is used for the optical pumping. The target cell contains ^{3}He gas together with a small amount of N_2 gas and Rb vapor. The aim of this project is to study the polarization observables of the reaction $d +\ ^3He \rightarrow p +\ ^4He$ at Dubna energies sensitive to the short-range spin structure of the deuteron.

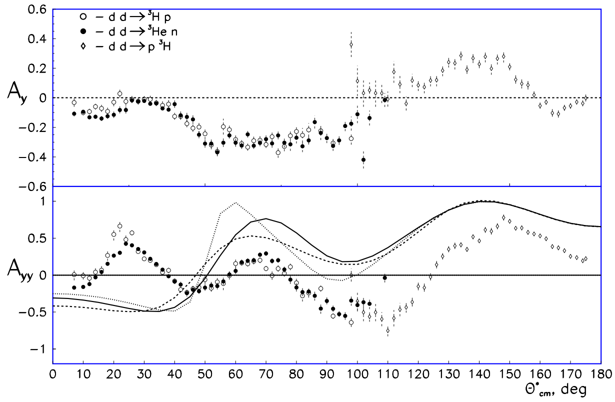

Fig. 16. The angular dependence of the vector and tensor analyzing powers in the center-of-mass frame measured at 270 MeV. The solid, dot-dashed and long-dashed curves are the results of the ONE calculations made by [22] using different ^3He wave functions.

The goal of the **project DISK** is to study the cumulative particle production and structure of the lightest nuclei in experiments with polarized and unpolarized beams.

In future the experiments on the cumulative meson production with polarized deuterons will continue. The polarization has opened a very promising field of research. The investigation of polarization phenomena in particle and relativistic nuclear physics is one of the most perspective directions of the nature study. The unique cryogenic targets and the polarized deuteron beams at the VBLHE Accelerator complex has opened a possibility to perform investigations of the vector and the tenzor analyzing powers of inclusive particles in collisions of polarized deuterons with various targets at large angles and in the cumulative region with the DISK setup. Mechanisms of the particle production in this kinematical region are not well understood but directly connected with our understanding of the internal structure of the nucleus; moreover, since the deuteron is the simplest nuclear system, questions still remain about its structure at short distances $<$ 1 fm, where nucleons are overlapped and therefore one can expect the manifestation of the non-nucleon degrees of freedom in the deuteron wave function. The polarization adds new physical parameters which can help us to make a more clear separation between the different models.

The **project SINGLET** is performed in close cooperation with the Laboratory of Particle Physics of the JINR. It is aimed at studying the energy and angular dependence of spin-spin correlation in elastic pp scattering near 90 deg in the centre of mass in the interval of kinetic energy of 2.6–3.5 GeV with the direct reconstruction of the spin-single amplitude to define its energy dependence.

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

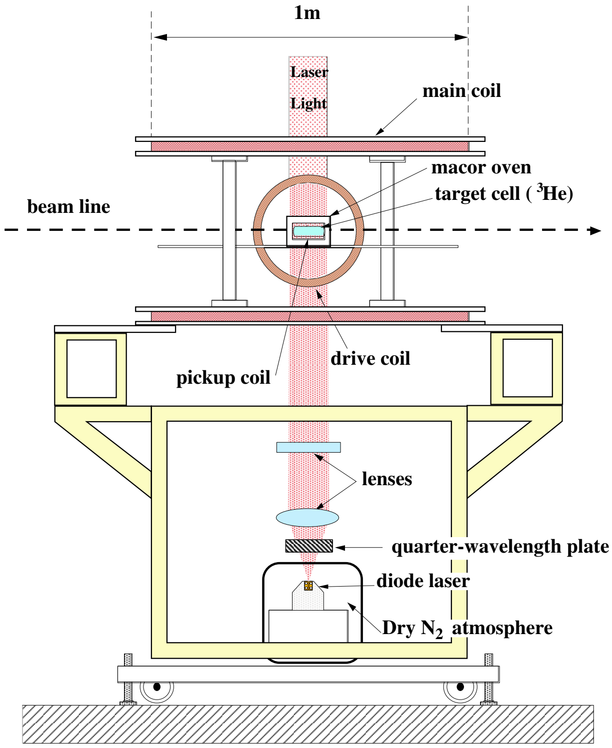

Fig. 17. Schematic view of the polarized ^{3}He target.

3.2.2 Nuclear Collisions at Relativistic Energies

The aim of the **SCAN-1 project** is to measure the transverse size of the region of nucleus-nucleus interactions by using the method for measuring the correlations of cumulative protons emitted at small relative momenta. The SCAN-1 (Spectrometer of Cumulative Hadrons at the Nuclotron) setup is designed to study the fragmentation of target nuclei into two cumulative protons and includes the following elements (Fig. 18).

The two-arm **scintillation spectrometer** which is used to register two protons in the momentum range of 0.28-0.72 GeV/c and relative difference of momentum of two protons $q_T = P_1 - P_2 < 0.2$ GeV/c. The detectors P_1, P_2 and P_3 are used to develop a trigger signal definition of time-of-flight (TOF-system), P_4 – to detect the kinetic energy of particles, and P_5 – to select high energy particles. All detectors are made of plastic scintillators. Lights are registered from two ends of plastic by means of photomultipliers. The spectrometer is installed at angle H = 106 deg concerning the axis of the beam.

The 16 channels scintillation hodoscope H_M (detecting charged particles in the angular range 15–30 deg) is used to select the impact parameter. Two triple monitors F_L and F_R (installed at the angles of 32 and 68 degrees) are used for luminosity monitoring.

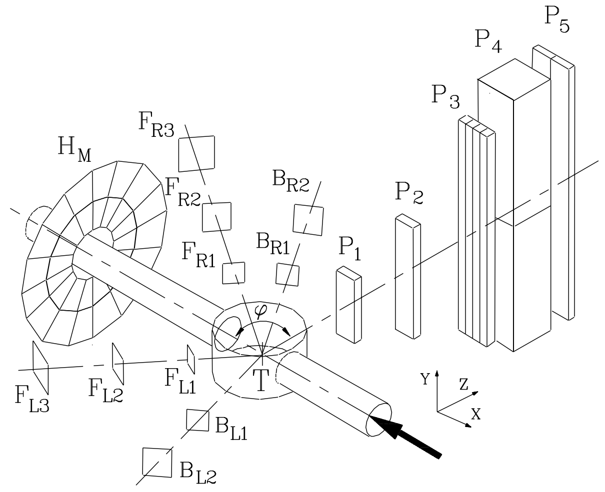

Fig. 18. Scheme of the SCAN-1 setup.

Correlation functions of cumulative protons emitted in dC and pC collisions with a small relative momentum q were measured (Fig. 19). It is shown (if the relative difference of momentum of two protons q_T is: 750 MeV/c $< q_T <$ 1200 MeV/c) that the radius of the emission zone is not sensitive to the type of primary particles and slowly increases with the measured angle (the simplex method of fitting was used).

This investigations using SCAN-1 setup will be continued with other projectiles and targets.

To measure the degree of the beam polarization, a specialized polarimeter was manufactured in the Nuclotron, which uses the inner target of the Nuclotron (the setup **PINTA** - Polarimeter on INternal TArget). The general position of the polarimeter is shown in Fig. 20. The experimental setup consists of a remote controlled target station (polyethelen and carbon targets) and four scintillation telescopes.

The basis of the apparatus consisted of two monitor telescopes F_{R1-R3} and F_{L1-L3} of the spectrometer SCAN installed at the angle of 14° to the right and to the left from the ionguide of the accelerator. To extract the recoil protons, the set-up was completed with two telescopes B_L and B_R, which were placed at the angle of $\pm$68° and had two scintillation counters each. The angles of 14° and 68° were chosen due to the kinematic parameters of the reaction of the quasi-elastic pp-scattering, when the analyzing power is maximal.

A polyethelen film, 10^{-2}m thick, 2×10^{-3} m wide, was taken as a hydrogen containing target. The second target consisted of 10 carbon threads, 8 mm diameter, placed in a row. In the December run of 2002 this assembled system was used to measure the deuteron beam polarization inside the Nuclotron chamber at several values of the energy. The measured value of the vector polarization was about 0.6 at the momentum P_d = 3–5 GeV/c. The assembled set-up has demonstrated an extremely high sensitivity. First measurements were carried out on the beam with the intensity of not more than 10^7 particles per cycle. Additionally the regime of the joint operation with the beam extraction was realized. It allowed the experimentalists to carry out mea-

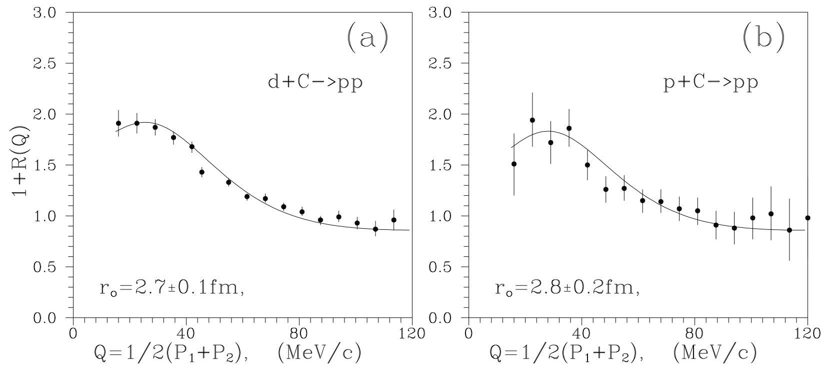

Fig. 19. The angular dependence of the parameter R.

surements simultaneously with the polarimeter installed in focus F3. The obtained values turned out to be identical. The express output of the information from the set-up to the WWW-server was also realized.

In the **project SCAN-2**, it is supposed to study the production of proton pairs with small relative momenta of $0 < q < 50$ MeV/c which are emitted in the reaction $d+p \rightarrow (pp)(180°)+n$ at the angle of 180° in the center-of-mass reference frame. The reaction cross section and the tensor analyzing power T_{20} will be measured to obtain information on the deuteron spin structure at small internuclear distances. It is planned to carry out measurements on the Nuclotron extracted beam with a momentum of P_d = 0.5–6.0 GeV/c.

A schematic view of the spectrometer is shown in Fig.21. It includes the system of beam monitoring (monitor detectors S1-S3 and the vertex coordinate system T1-T2), the analyzing dipole magnet and scintillation hodoscopes (a hodoscopic 32-channel system) for coordinate and time-of-flight measurements. Preliminary results of the cross section of the reaction $d+p \rightarrow (pp)_s + n$ were obtained in the last Nuclotron run in June 2003. They are analysed now and will be compared with the data measured on the ANKE spectrometer at COSY (Julich) and with theoretical predictions ([24, 25]).

The **project MARUSYA** is aimed at investigating the properties of the transition (from nucleon to quark-gluon degrees of freedom) regime in relativistic nuclear collisions [26]. In the project, it is also suggested to make investigations of rare subthreshold and cumulative processes (for polarized colliding objects included) and to select events by the centrality degree using the measurement of secondary particle multiplicity. It is planned to study the yield of antiprotons and negative kaons. They are interesting due to their production from "sea" quarks. At event selection according to the centrality degree, one can observe a large difference in the production cross sections of antinuclei in nucleus-nucleus interactions. Such data are absent in the transition energy region. In addition, it is planned: to continue the measurement of the production cross section of nuclear fragments from deuterium to silicon at the Nuclotron internal targets; to study experimental low-energy part of the production spectrum of nuclear fragments over the energy range of 1–150 MeV; to test and develop theoretical models to describe relativistic nuclear

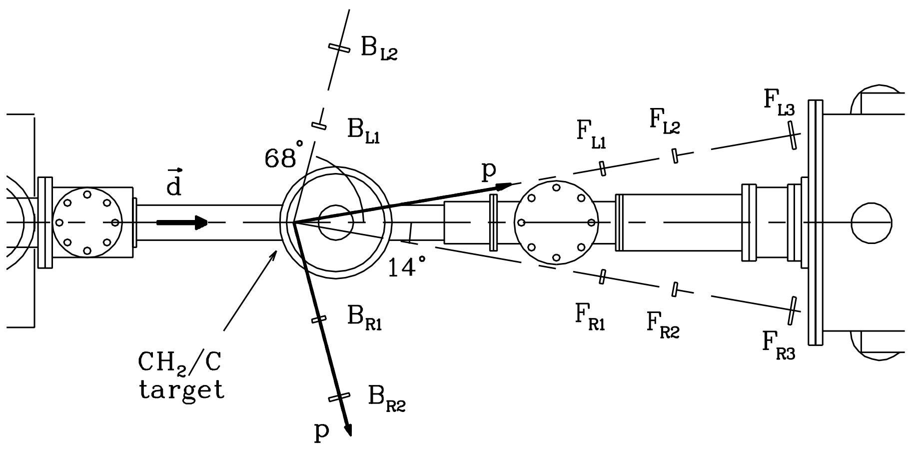

Fig. 20. The schematic view of the PINTA.

collisions by using the obtained experimental data.

The adjustment of the spectrometer was carried out during the last runs of the Synchrophasotron and the Nuclotron. The spectra of pions, protons and deuterons were received. Asymmetries in the inclusive spectra of π^+, protons and deuterons were measured at the MARUSYA setup (Fig. 22.) in the reactions of the polarized protons and deuterons with the carbon target ($\vec{\mathrm{p}}$, $\vec{\mathrm{d}} + C \rightarrow \pi^+$, p, d). Here, M1-M3 is the beam monitoring system consists of three scintillation telescopes located around the target at the angle of the 90 degree. Also the information on the extracted beam intensity will be obtained by an ionisation chamber placed on the beam axes in front of the target. The K100, ML17 are the magnetic lenses and SP57, SP40 are the dipole magnets. The B is the small size barrel system located around the target which provides the trigger from the interaction in the target. The PC are the proportional chambers, G, DM and ZDC are the scintillator hodoscopes, the multiplicity detector and the zero degree hadronic calorimeter. Some new results are shown in Fig. 23.

Analyzing powers in inclusive spectra of p and d in the interaction of the polarized proton (2.5 GeV/c) and deuteron (5 GeV/c) beams with carbon nuclei were measured in the momentum range of the registered particles 0.6–1.2 GeV/c at the angle 26°. In this momentum range the vector analyzing power tends to decrease for π^+ and to increase for protons with the increasing particle momentum. Further investigations with polarized beams of the Nuclotron are feasible.

In the MARUSYA Collaboration the research by using the internal target is also performed - experiment **ITELEF**. New experimental data on the yield of secondary nuclear fragments Li, Be, B, C, . . . of very low energies (0.5–60 MeV) in p, d, $C + Au$ reactions were obtained using thin semiconductor detector.

Good separation of secondary fragments with very low energies in the region from 2 up 25 MeV was obtained in $d + Au$ interaction at 1.044 GeV deuteron energy (Fig. 24).

In the **project BECQUEREL**, it is planned to expose nuclear emulsions to different beams of relativistic particles. The research programme is concentrated on a detailed study of relativistic

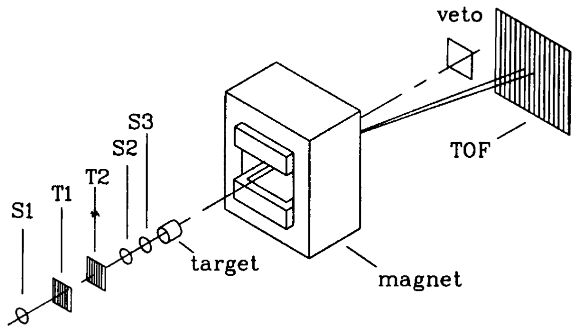

Fig. 21. The scheme of the SCAN-2 setup.

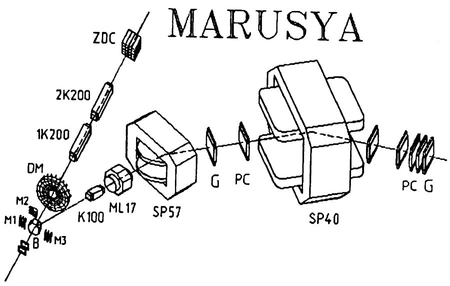

Fig. 22. The schematic view of the MARUSYA setup.

fragmentation of light radioactive and stable nuclei [27]. 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 the Nuclotron. As the first step of the research, preliminary results on charge topology for relativistic fragmentation at small energy-momentum transfers have been obtained.

Using the ^{6}Li nucleus beam extracted from the JINR Synchrophasotron at a momentum of 2.67 A GeV/c, a secondary beam was produced with a composition of 1% of ^{6}He and 99% of ^{3}H nuclei. Preliminary results on the features of nucleus-nucleus interactions of ^{6}He nuclei and charge exchange (CE) of ^{3}H nucleus have been obtained (Fig .25). A three dimensional image of the event is reconstructed as a plane projection by means of an automatic microscope of FIAN and the PAVICOM complex. Interactions of ^{6}He nucleus external neutrons with emulsion nuclei as well as a coherent stripping of ^{6}He nucleus external neutrons are observed.

Then ^{10}B nuclei were accelerated at the JINR Nuclotron, and the ^{10}B nucleus beam of the energy of 1A GeV was formed. The beam was used to irradiate stacks composed of BR-2 type

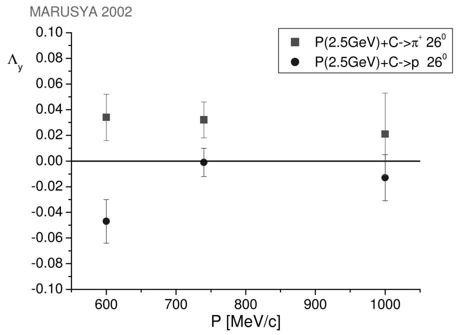

Fig. 23. The analyzing power A_y for the vector polarized beam.

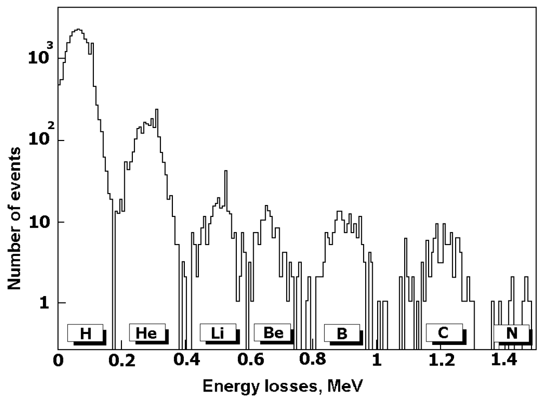

Fig. 24. Separation of the secondary fragments for $d + Au$ reaction at 1.044 GeV deuteron energy.

emulsion layers 550 micron thick and measuring 10×20 cm^2 which were sensitive to the minimum ionization of single-charged particles. During irradiation, the emulsion layers were located in parallel to the beam direction so that the beam particles could enter the butt-end of the emulsion layers.

Information about the charge composition of charged fragments and about the channels of ^{10}B nucleus fragmentation in peripheral collisions has been obtained (Table 4). To the peripheral interactions we attribute the events in which the total charge of relativistic fragments is equal to the charge of the primary ^{10}B nucleus, the production of charged mesons have not been observed, but the emission of slow nuclear fragments could occur.

In 65% of these peripheral interactions the ^{10}B nucleus is disintegrated to two double charged and one single-charged particles. A single-charged particle is the deuteron in 40% of these events. 10% of the events contain fragments with a charge equal to 3 and 2 (Li and He isotopes), and

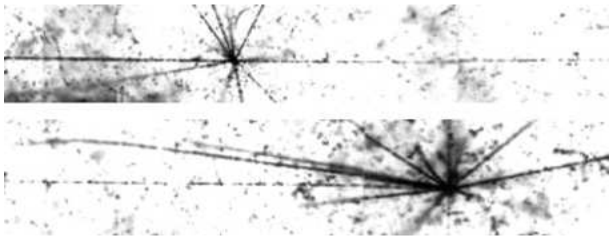

Fig. 25. Event of the ^{6}He nucleus interaction (upper shot) with fragmentation into α-particle on two consecutive sections of the track. The α-particle track is followed until the inelastic interaction (lower shot).

Tab. 4. Topology of the ^{10}B fragmentation. Charge state distribution of the number of fragments in projectile fragmentation cone (< 15 deg) in the events of "white star" formation, without an accompanying track in wide cone (> 15 deg) is given in parenthesis.

Fragment Charge					**Number of Events**
5	**4**	**3**	**2**	**1**	
	1			1	3(1)
		1	1		11(5)
			1	3	14(5)
			2	1	56(30)
1					5(0)
				5	2(0)

2% of events contain a fragment with charges equal to 4 and 1 (Be nucleus and the proton). The ^{6}Li production accompanied by an alpha particle may be considered as a correlation of the alpha particle and deuteron clusters.

The **project FAZA** is being performed by specialists from DLNP and VBLHE. The scientific goal of the project is investigating the nuclear equation of the state at the reduced densities and the temperatures below the critical one T_c (for the "liquid-gas" phase transition). Thermal multifragmentation is adequate to that [28]. This is a new multi-body decay process of the hot target spectator with the copious emission of the intermediate mass fragments (IMF, $2 < Z < 20$). It was shown by FAZA collaboration that this type of disintegration takes place after the expansion of the excited nucleus. The break-up density is $\rho_b \approx 0.3\rho_0$ and the temperature is (5–7) MeV. These findings correspond to the onset of the multifragmentation of nucleus entering the phase coexistence (spinodal) region. Due to the density fluctuations, a homogeneous system converts very fast into a mixed phase, consisting of charged droplets (IMF's) surrounded by the nuclear gas. This is a *nuclear fog*, which expands because of Coulomb repulsion. So, the thermal multifragmentation can be interpreted as the first order nuclear *liguid-fog* phase transition in the spinodal region.

The critical temperature can be estimated by analysis of the IMF charge distribution. They

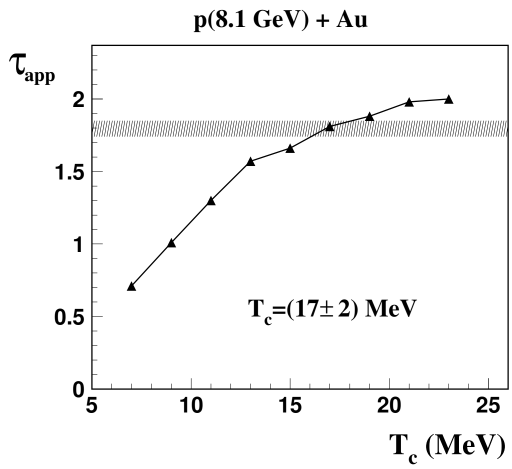

Fig. 26. Estimation of the critical temperature T_c for the nuclear liquid-gas phase transitions from the fragment charge distribution. The last is approximated by the power law: $Y(Z) \sim Z^{\tau}$. The measured τ_{app} value (show by the band) is compared to the model predicted ones with T_c as a free parameter.

analyzed the charge distribution of fragments produced in p(8.1GeV)+Au collisions using the statistical multifragmentation model (SMM) with the critical temperature T$_c$ as a free parameter. It is known that the shape of $Y(Z)$ is well approximated by the power law: $Y(Z) \sim Z^{\tau}$.

The results are shown in Fig. 26. The measured power-law exponent is given as a band with a width determined by the statistical error. The calculated values assuming different T$_c$ are given by symbols. From the best fit of the data and calculations one concludes that T$_c$ = (17 $\pm$ 2) MeV at the 90$\%$ confidence level.

These studies will be continued. The FAZA Collaboration have a well prepared programme of further investigations. It includes the study of evolution of the reaction mechanism with increasing the projectile mass (from p up to Ne), measuring the expansion time of the hot nucleus and of various fragment correlations. As result, the nature of the collective flow observed for the beams heavier than He will be established; the new information on the nuclear liquid-fog and liquid-gas phase transitions will be obtained as well as new data on the space configuration of the system at the break-up moment. This investigation of the expansion dynamics of hot nuclei driven by thermal pressure promises to get the unique information on the nuclear rigidity at the temperature 5–7 MeV. The limits of the statistical interpretation of the multifragmentation will be explored. Generally, the better understanding of the multifragmentation phenomenon will be achieved.

The modified 4π-setup FAZA installed on the Nuclotron beam, has been used. This device includes 30 telescopes dE(gas)-E(Si) and a fragment multiplicity detector, composed by 64 thin CsI(Tl) scintillators. The total number of electronic channels is 205.

The **project GIBS** is supposed to investigate charge exchange reactions together with the hypernuclear programme. The study of the reaction p(t,^{3}He) and the measurements of the produc-

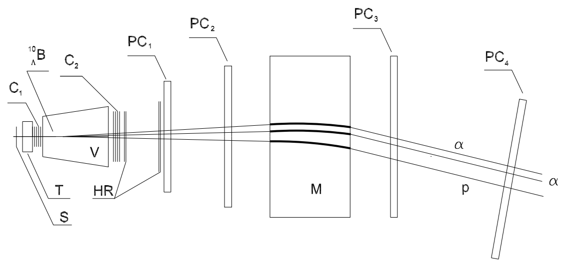

Fig. 27. SPHERE spectrometer modified to investigate the nonmesonic decay of ${}^{10}_{\Lambda}$B produced in the Nuclotron carbon beam. S – the beam control counters, T – the target, $C_{1,2}$ – the trigger Čerenkov counters, V – vacuum decay volume, HR – the high resolution detectors, M – the magnet, PC_{1-4} – the proportional chambers.

tion of pions in the 4π-geometry will be made in the frame of the charge exchange experiment. The setup GIBS, e.g., the magnetic spectrometer based on a 2 m streamer chamber, will be used.

It is proposed to upgrade the GIBS spectrometer for further experiments at the Nuclotron. The spectrometer is equipped with new filmless-data-recording system based on three CCD TV cameras. The TOF system and the proportional chambers will be used to measure the tritium and ^{3}He precise momenta. The relativistic tritium beam offered for this experiment is unique and has no analogs in the world because only at VBLHE there is experience with the tritium beam.

The hypernuclear programme is also aimed at studying production and decays of hypernuclei (measurement of the lifetime of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{6}_{\Lambda}$He hypernuclei and the binding energy of ${}^{3}_{\Lambda}$H, ${}^{6}_{\Lambda}$He hypernuclei) and their Coulomb dissociation. Moreover it is suggested to measure nonmesonic decays of hypernuclei and determine the partial width of nonmesonic ${}^{10}_{\Lambda}$B decay. The modified SPHERE spectrometer with a trigger and time-of- flight system from GIBS will be used (Fig. 27).

3.2.3 Applied Research on the Nuclotron Beams

The main regions of the applied studies at the Nuclotron are: radiobiology and space biomedicine, the impact of nuclear beams on the microelectronic components, transmutation of radioactive wastes, accelerator driven energy production, the use of the carbon beam in cancer therapy.

The **radiobiology project** is particularly important for long-term space expeditions. This research has been carried out since the time of the first space expedition. Recently, within this programme (see Table 5), irradiation of biological objects and their components (the human lymphocyte nuclei) by different beams (different linear energy transfer L_{∞}) has been carried out in collaboration with the JINR Division of Radiobiology and Radiation Research (DRRR) [30].

Investigations of the mutagenic action of low doses radiation with different LET on human blood lymphocytes were carried out at the proton, ^{12}C and ^{24}Mg beams of the VBLHE Nuclotron. The future trends of the radiobiological investigations at the Nuclotron heavy ions are promising.

The accelerator-driven methods of the transmutation of radioactive wastes have been studied

Tab. 5. Beams, their energy and linear energy transfer used in experiments performed in collaboration with DRRR during 1998-2003 .

Nuclei	P	He	C	C	Mg	Ar	Fe
Energy A GeV	1	0.5	1	0.48	0.5	1.0	1.25
$\mathbf{L}_{\infty}$ keV $\cdot \mu m^{-1}$	0.233	1.157	8.40	10.65	39.62	75.5	151.4

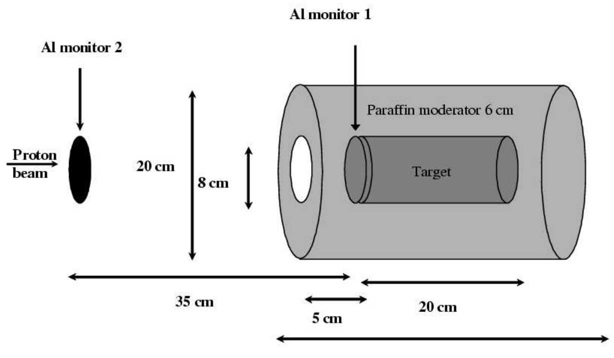

Fig. 28. The scheme of the GAMMA-2 setup.

at the VBLHE for many years. The accelerator-driven methods for more effective and safe energy production are also under study. This research at the VBLHE was initiated by K.D. Tolstov in the 1950s. The work on this programme is fulfilled at the VBLHE in the frame of the **GAMMA2** project. Their experimental setup is shown in Fig. 28.

It consists of a heavy target surrounded by a paraffin moderator of secondary neutrons. The detectors of neutrons can be installed at different positions. The samples to be transmutated are installed on the external surface of the moderator. The studies with the GAMMA2 setup are focused on measuring the neutron yield as a function of the beam energy, type of the particles in the beam, and the target material [31].

Another experiment of this type is the **Energy+Transmutation project**. The experimental setup is shown in Fig.29.

A natural uranium assembly surrounding a heavy material target is planned to be used in the experiment.The activation and tracking detectors and the samples of transmutated radioactive isotopes will be installed in the slots between uranium elements. The uranium assembly is equipped with thermometric sensors.

The first experiments with the prototype of the working set have already been carried out and first calorimetric results have been obtained [32].

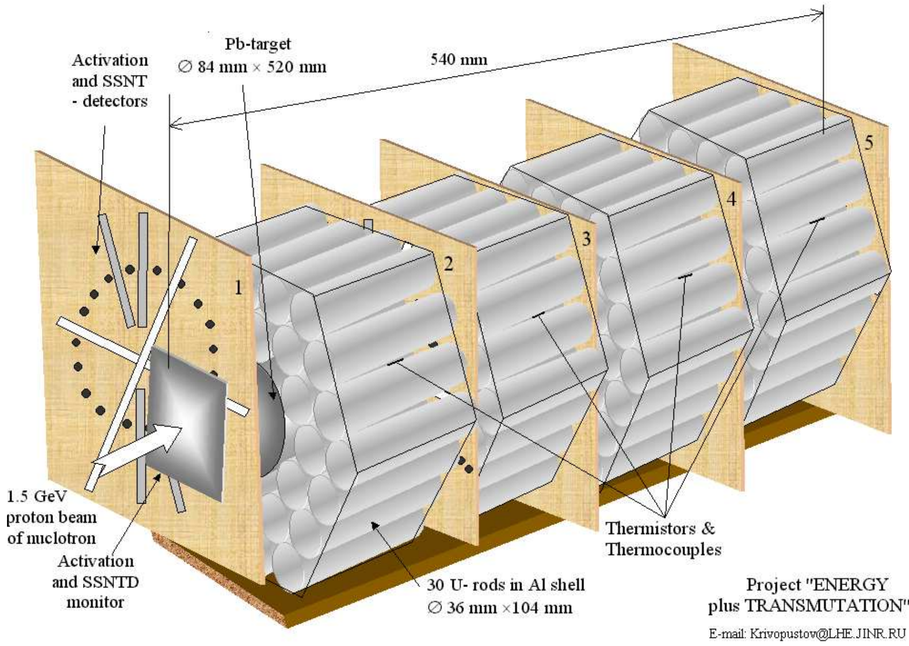

Fig. 29. The scheme view of the Energy + Transmutation setup.

4 Conclusion

A wide-reaching programme of research with relativistic ions, polarized deuterons and neutrons/protons is carried out at the VBLHE of the JINR with active participation of researchers from Russia and other countries. The extracted Nuclotron beams of particles and ions offer new promising directions in relativistic nuclear physics and applied research.

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