Synchrophasotron and Nuclotron Equipment for Investigation of Polarization Phenomena

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Abstract

The development of the unique cryogenic source of polarized deuterons, POLARIS, in the late 1970s was very fruitful and significantly enhanced JINR's instrumental base for studies of nucleon-nucleon interactions as well as interactions of lightest nuclei with heavier nuclei.

Experimental data on polarization-dependent effects, obtained at the Synchrophasotron and the Nuclotron, significantly influenced the worldwide understanding of strong interactions between hadrons as well as the structure of lightest nuclei (the deuteron, first of all) at short inter-nucleon distances.

Experiments with polarized deuteron, proton and neutron beams at intermediate (several GeV) energies resulted in creation of wide collaborations between VBLHEP of JINR and other world centers (in the USSR and Russia, France, the USA, Germany, Japan, China). Many new and unexpected experimental results were obtained by those collaborations. In particular, many new unique results were obtained for the nucleon electromagnetic formfactors of nucleons, thanks to results of works within the ALPOM/ALPOM2 project. In addition, new ways became opened for experimental investigations with polarized ^{3}He beams. In this direction, new unique results were obtained.

The necessary developments of the techniques for the spin program at the Nuclotron/NICA are discussed in the paper.

Keywords: source of polarized ions, polarimeter, deuteron, proton, spin transparency

1. Introduction

In 1970, an accelerated beam of deuterons with momenta up to 11 GeV/c was obtained by the Synchrophasotron for the first time [1]. This work was initiated by A. M. Baldin. Almost immediately after the start of experiments on relativistic deuteron beams, physicists and specialists in accelerator physics started consideration of the possibility to produce accelerated polarized deuteron beams at the Synchrophasotron. This work was successful and

resulted in the creation of the POLARIS source [2–5] of polarized deuterons, production of accelerated polarized beams and start of physical experiments with polarized deuterons using an internal target as well as a slowly extracted beam of polarized deuterons on external targets. The POLARIS source was used at the Synchrophasotron and at the Nuclotron superconducting accelerator until 2002 and in 2002–2005, respectively. The significant increasing of the deuteron beam intensity made it possible to create a unique beam of high energy polarized neutrons in 1995 used for spin correlation measurements with a polarized proton target. Nowadays the newly developed Source of Polarized Ions [6] provides polarized deuteron and proton beams for the experiments at the Nuclotron with fixed targets. Several polarimeters were developed to measure and monitor of beam polarization.

The undoubted advantage of the Synchrophasotron/Nuclotron accelerator complex was and remains a wide range of the deuteron beam energies (and, accordingly, the energies of beams of secondary neutrons and protons) from hundreds of MeV to several GeV. This feature allows studying the spin effects and polarization phenomena in hadronic reactions in the region of transition from nucleon-mesonic to the fundamental degrees of freedom.

The experimental work with polarized deuteron and secondary nucleon beams was focused on two main directions, namely: (a) on the traditional study of the nucleon-nucleon (NN) elastic scattering at intermediate energies with measurements of polarization observables [7] and (b) on the study of the lightest nuclei structure at short internuclear distances [8]. Such studies used new theoretical ideas and approaches to description of relativistic composite systems and the NN elastic scattering, which appeared at that time. In the physics devoted to the lightest nuclei structure, many experiments on the deuteron fragmentation with measurement of various polarization observables were performed after the 1980s. In that physical program, the experiments were focused both on the fragmentation reactions of polarized deuterons by protons and nuclei and on the backward (in the center of mass) elastic dp scattering. Simultaneously, new data were obtained on the neutron-proton scattering in different polarization states. Also, some new experiments on the polarimetry of high-energy protons, neutrons and deuterons were fulfilled. In particular, the results of ALPOM and ALPOM2 experiments were highly important for studies of nucleon electromagnetic formfactors at large Q^2 [9].

All these investigations were performed in close cooperation with physicists from France (Saclay), the USA (JLAB) and Japan (several centers). This collaborative work resulted in proposals and experiments on studies of the deuteron and ^{3}He (^{3}H) spin structure, on the spin effects in regions of the Delta and Roper resonance excitations, on measurements of the neutron magnetic- to-electric formfactor ratio at the accelerator centers in France, Japan and the USA, under the leadership of JINR physicists.

The spin physics program at the Nuclotron/NICA complex includes both experiments at a fixed target and with colliding beams. The scientific mission of the Spin Physics Detector (SPD) is to study the gluon spin structure of the proton and deuteron [10] and other spin effects and polarization phenomena [11] using polarized proton and deuteron beams at the luminosity up to 10^{32} cm$^{-2} \cdot$ s^{-1} and at the collision energy up to 27 GeV. The kinematical region accessible at SPD will cover the transition region between the non- perturbative and perturbative QCD. Some of the experiments proposed in [11] can be performed both in the collider and fixed-target modes. The equipment developed for the polarization phenomena studies at the Nuclotron will also be used to provide the experiments at NICA. Additionally, the systems of the proton beam polarization preservation and control based on siberian snakes and spin navigators, as well as the high-energy polarimetry at the NICA rings are required.

The review contains the historical part describing the development of the instrumental base for polarization studies at the LHEP Accelerator Complex, the major worldwide results obtained with this equipment and their impact on the physics program at other accelerator centers, the current status of the polarized ion source and polarimetry, and necessary technical developments for the spin program at the Nuclotron/NICA in the future.

2. Polarized sources at LHEP of JINR

The JINR Synchrophasotron, which had been accelerating nuclear beams up to the kinetic energies of 4.5 GeV/nucleon since 1970, was able to accelerate a wide set of nuclear beams. Since 1981, it became able to accelerate polarized deuteron beams.

The unique capabilities of the Synchrophasotron, an accelerator with weak focusing and multi-turn injection, made it possible to accelerate polarized deuteron beams without polarization loss across its full energy range, because the 1st strongly depolarizing resonance for deuterons was located much above the maximal possible energy of deuterons in this machine. This circumstance stimulated the idea to develop a source of polarized deuterons for the Synchrophasotron.

The implementation of this idea with the great and very significant contribution of its enthusiast Yu. K. Pilipenko and his team made it possible to create a long-term program of polarization research in the field of intermediate and high energy spin physics at the Laboratory of High Energies (LHE) of the Joint Institute for Nuclear Research (JINR).

As a result, a unique cryogenic source of polarized deuterons was created, which used the method of producing a polarized atomic beam with its subsequent ionization in a Penning ionizer.

In 1981, the cryogenic source of polarized deuterons POLARIS [2–5] was installed and the polarized beam of deuterons was accelerated to relativistic energies for the first time in the USSR [2]. The main components of the POLARIS source are shown in Figure 1.
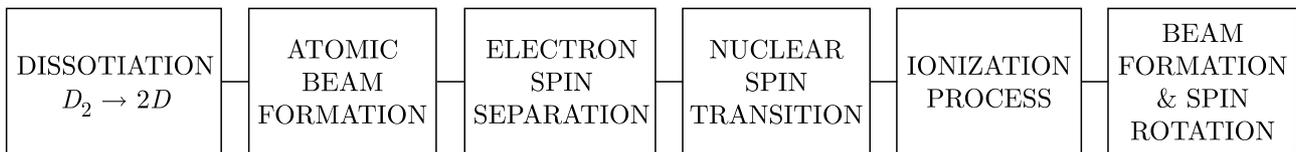
DISSOTIATION $D_2 \rightarrow 2D$	ATOMIC BEAM FORMATION	ELECTRON SPIN SEPARATION	NUCLEAR SPIN TRANSITION	IONIZATION PROCESS	BEAM FORMATION & SPIN ROTATION

Figure 1. Main components of the POLARIS source.

The POLARIS cryogenic source had the following set of the distinctive features:

- the superconducting magnets operating in the direct current (DC) mode were used to generate the magnetic fields in the source,

- the required vacuum in the source was provided by the gas condensation, because the surfaces of the cryostats were cooled up to the liquid helium temperature,

- a thermal contact with the cryostat's walls allowed cooling the dissociator, nozzle and skimmer,

- the cryogenic source was compact and required power only for the RF units and the control systems.

This was important, because the source was installed on a 750 kV terminal. Information exchange was performed by a fiber glass optic system. The layout of the POLARIS polarized deuteron source [2–5] is presented in Figure 2.
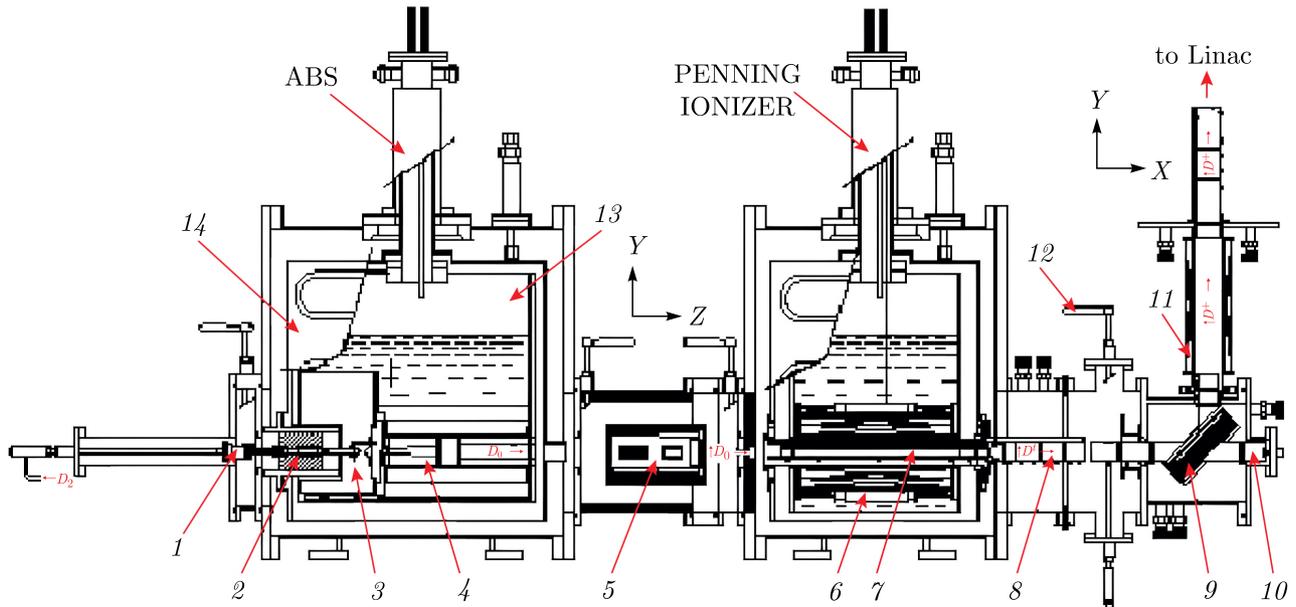

Figure 2. Layout of the POLARIS polarized deuteron source [2–5]. ABS — atomic beam source, PENNING IONIZER – atomic beam ionizer. *1* — electromagnetic gas valve, *2* — dissociator, *3* — nozzle chamber, *4* — sextupole superconducting magnet, *5* — RF cell, *6* — superconducting solenoid. *7* — electron optics, *8* — ion optics, *9* — electrostatic mirror, *10* — Faraday cup, *11* — solenoid of the spin-rotator, *12* — vacuum gate, *13* — helium cryostat, *14* — nitrogen shield.

The energy of the deuteron beam was about 3 keV at the output of the source, while the beam current was about 200 μA. The expected polarization parameters of the slowly extracted deuteron beam were the following:

$p_{z^+} = 0.54 \pm 0.01$ (82% of the theoretically expected), $p_{z^-} = -0.57 \pm 0.01$ (86% of the theoretically expected),

$p_{zz^-} = -0.82 \pm 0.01$ (82% of the theoretically expected), $p_{zz^+} = 0.80 \pm 0.02$ (80% of the theoretically expected).

The creation of the POLARIS source made it possible to perform research according to the program of polarization studies at accelerated polarized deuteron beams from the Synchrophasotron as the base facility and later from the Nuclotron at its initial stage. Many successful runs for physical experiments were conducted using the POLARIS source producing polarized beams with unique characteristics.

The creation of a new superconducting accelerator, the Nuclotron, a hard-focusing superconductive machine, with a single-turn, short-duration injection mode, stimulated development of a new source of polarized ions in order to get more intensive polarized beams with a wider set of their polarization parameters.

Further development of polarization phenomena studies demanded a substantial increase of the beam intensity from the polarized particle source. The goal was to increase the intensity of the accelerated polarized beam up to $5 \cdot 10^{10}$ particles per pulse. The theoretical estimates and the first runs with a polarized beam showed that the main depolarizing resonances for accelerated deuterons were absent within the entire energy range of the Nuclotron.

For this purpose, within the polarization research program of the NICA project at the JINR accelerator complex, equipment for polarization studies, which includes the high-intensity pulsed Source of Polarized Ions (SPI) [6], the SPI low-energy polarimeters, and polarimeters at the output of the LU-20 linear accelerator, is being developed.

The planned output current of the SPI is up to 10 mA for $\uparrow D^+(\uparrow H^+)$. The $D^+(H^+)$ polarization will be up to 90% of the maximal vector (± 1) and tensor $(+1, -2)$ polarization.

The SPI was developed by the JINR – INR RAS (Moscow, Troitsk) collaboration to provide polarized deuterons and protons for the Nuclotron and future NICA.

The SPI is an atomic beam-type polarized ion source with a charge-exchange plasma ionizer and a storage cell in the ionization region. It was developed using part of the equipment of the CIPIOS polarized ion source [12] from IUCF.

2.1. General description of the SPI

The layout of the SPI is shown in Figure 3. It consists of an atomic beam apparatus, a plasma charge-exchange ionizer, a polarized ion beam transportation system and a spin-rotator to the vertical direction.
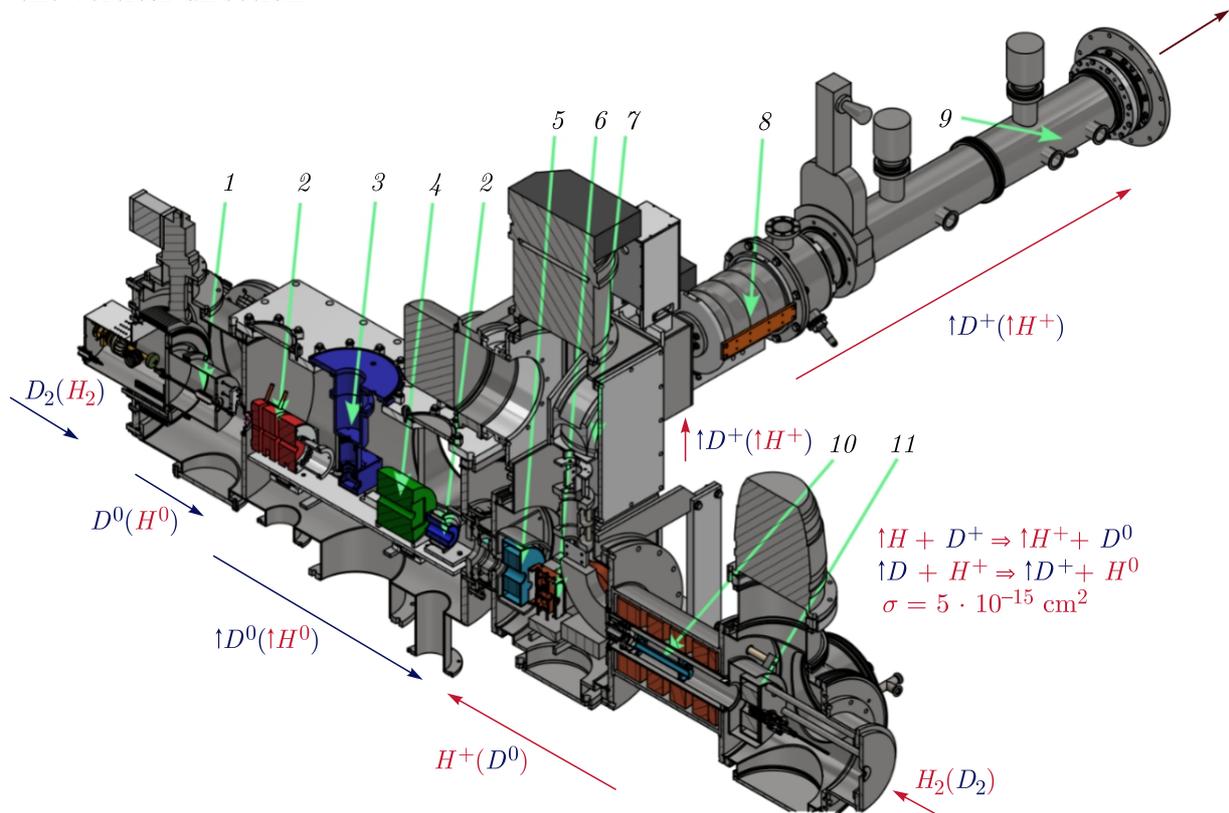

Figure 3. Layout of the SPI [6]. *1* — dissociator chamber, *2* — permanent sextupole magnets, *3* — time-of-flight mass-spectrometer, *4* — medium field RF transition unit (MFT), *5* — weak field RF transition unit (WFT), *6* — strong field RF transition unit (SFT), *7* — bending magnet and spherical mirror, *8* — spin rotator, *9* — beam transport channel, *10* — charge-exchange ionizer with a storage cell, *11* — electric arc plasma source.

2.1.1. Atomic beam apparatus

Thermal-energy polarized deuterium (or hydrogen) atoms are produced by the atomic beam apparatus consisting of a pulsed radio frequency (RF) discharge dissociator, sextupole magnet system and "High Frequency Transition" (HFT) units.

Atomic deuterium is produced by the dissociation of molecular deuterium in an RF discharge as in a conventional atomic beam type source. Molecular deuterium is injected through a pulsed electromagnetic gas valve into the dissociator tube, where a pulsed RF discharge is induced. The deuterium molecules break up into atoms in the RF discharge plasma upon collisions with plasma electrons. The atomic deuterium enters the vacuum from the dissociator tube through a 100 mm long Pyrex channel with an inner diameter of 5 mm, which ends with a sonic nozzle with a diameter of 2 mm. The channel walls are cooled to a temperature of ~ 80 K using a cryocooler (model 350 Cryodyne Refrigeration System).

The SPI magnet system consists of four permanent sextupole magnets. An atomic beam passes through the sextupole magnet system, where atoms with the spin state $m_j = 1/2$ are focused, and atoms with the spin state $m_j = -1/2$ are defocused. Thus, the atoms become polarized after passing through the sextupole magnet system.

The nuclear polarization of the deuterium atoms ionized in the strong magnetic field is increased using an HFT unit system that includes medium-field (MFT), weak-field (WFT), and strong-field (SFT) transition units. Numerous deuteron polarization states can be obtained using various combinations of HFT.

2.1.2. Charge-exchange plasma ionizer with a storage cell

The beam of polarized atomic deuterium produced by the atomic beam apparatus is injected into the storage cell installed inside the solenoid of the charge-exchange plasma ionizer. The pulse duration of the atomic beam determined by the pulse duration of the RF discharge dissociator is up to 3 ms. The polarized deuterium atoms are injected and stored in the cell during the pulse. Then, a jet of hydrogen plasma generated by a plasma arc discharge source is injected into the storage cell in the direction opposite to the momentum of the beam of deuterium atoms through a 3 mm diameter hole at the end of the storage cell. Polarized deuterons are produced in the storage cell as a result of charge exchange collisions between polarized deuterium atoms and unpolarized protons:

$$D^0 \uparrow + H^+ \rightarrow D^+ \uparrow + H^0 \tag{1}$$

The following reaction is used to produce polarized protons:

$$H^0 \uparrow + D^+ \rightarrow H^+ \uparrow + D^0 \tag{2}$$

In this case, the atomic beam apparatus produces a polarized beam of atomic hydrogen, and the plasma source generates deuterium plasma.

The cross-sections of the charge-exchange reactions (1) and (2) increase with a decrease of the colliding particles' relative energy and reaches $5 \cdot 10^{-15}$ cm^2 with an energy of incident particles of ~ 10 eV (typical for gas discharge plasma).

The radial holding of low-energy polarized ions formed in the charge exchange region is provided by the magnetic field of the ionizer solenoid.

Then, the polarized ions slowly move under the influence of weak electric fields in the plasma in the direction of the extraction electrode system, where they are accelerated to an energy of up to 25 keV along with the unpolarized plasma ions. A three-electrode Pierce system is used to extract and form the ion beam.

2.1.3. Beam transport and spin rotator system

The extracted ion beam with an energy of 25 keV passes through a 90° bending magnet, where the polarized ion beam is separated from the unpolarized ions. The current of the

unpolarized ion beam is recorded using an ion beam collector located downstream the bending magnet. The polarized beam exits the magnet in the vertical direction, passes through an electrostatic Einzel lens and is then deflected by a 90° electrostatic deflector into the horizontal plane to the x direction. The ion spin direction remains unchanged when passing through the deflector. At the source exit, the polarized ion beam passes through a solenoid, which is used to rotate the spin of a deuteron or proton into an optimal orientation: thus, the maximum polarization of deuterons and protons in the Nuclotron ring can be ensured.

2.1.4. Commissioning of the SPI

The SPI was installed into the Linac hall and commissioned in May 2016. It was used in the Nuclotron runs in November – December 2016 and in February – March 2017. In these runs, the SPI operated with polarized and unpolarized deuterons for 900 hours and 600 hours, respectively. A short 40-hour test run with polarized protons was also performed.

Measurements of the deuteron beam polarization carried out using a Nuclotron internal beam polarimeter (described in Subsection 3.4) showed that the polarization of deuterons was $0.6-0.88$ of the theoretically maximum values. The tensor polarization of deuterons, equal to 0.88 ± 0.049; $–1.47 \pm 0.03$ (theoretically maximum +1, –2), was measured by additional tuning of the HFTs using the internal beam polarimeter. The measurements showed long-term stability of the beam polarization. This demonstrated the absence of depolarization in the storage cell of the plasma ionizer, which was first used for a source of polarized ions operating in long accelerator runs.

2.2. Low-energy polarimeters

An important aspect is monitoring the degree of beam polarization during the operation of the SPI source in runs with polarized beams at the JINR accelerator complex. Polarimeters designed to measure the polarization of proton and deuteron beams at the output of the SPI are currently being developed. The polarimeter is intended to operate with beams in the energy range up to 150 keV. It will allow for the optimal tuning of the SPI nuclear polarization units and for determining the influence of the facility's disturbing elements on the polarization of the beams.

2.2.1. Nuclear reaction polarimeter for low-energy deuterons

A polarimeter for the complete measurement of tensor and vector polarization of deuteron beams in the energy range of 20–90 keV has been developed. The polarimeter is based on the $d(d,p)^3\mathrm{H}$ reaction, detected at various angles using a set of surface-barrier silicon detectors. The main group of four detectors is arranged symmetrically in the horizontal and vertical planes at an angle of 10°, enabling accurate measurement of the beam tensor polarization. An additional pair of detectors is installed symmetrically at an angle of 110° for measuring the vector polarization, where the analyzing power A_y reaches values of 0.19–0.22 in the operating energy range.

The polarimeter demonstrates high efficiency and reliability in operation. At a beam current of 1.6 μA, the counting rate is 19 counts per second for the detectors at 10°, allowing the tensor polarization to be measured with a relative error of 5% in just 14 minutes. The device provides clean spectra with clear identification of reaction products and minimal background. The use of thin-film deuterated targets of various types ensures flexibility in experimental conditions.

The large values of the analyzing power A_{zz} (ranging from –0.59 to –0.85 in the operating energy range) for tensor measurements and significant values of A_y for vector measurements, combined with smooth energy and angular dependencies, make this polarimeter a universal tool

for the complete determination of beam polarization parameters. The device is successfully used for measuring tensor and vector polarization in reactions involving deuterons and for the SPI [13].

2.2.2. Nuclear reaction polarimeter for low-energy protons

A proton polarimeter has been developed for measuring the vector polarization of proton beams in the energy range up to 150 keV. The polarimeter is based on the ^{6}Li$(p, ^3$He$)^4$He reaction [14], detected at backward angles of 110° and 130° using four silicon surface-barrier detectors. The targets are tantalum sheets coated with ^{6}Li, which allows operation with high beam currents up to 10 mA.

The polarimeter demonstrates good performance for measurements. The analyzing power of the reaction reaches a value of 0.21 at an energy of 300 keV for the 130° angle. The ^{3}He and ^{4}He nuclei spectra are well separated, ensuring signal purity. The setup allows achieving a relative polarization measurement error of 2% in 220 seconds at an energy of 200 keV and a beam diameter of 10 mm.

The device was housed in a vacuum chamber with a pressure of up to $10-6$ mbar and includes a target cassette with 5 targets, a Faraday cup for measuring beam intensity, and a collimator. The design is optimized for operation in an accelerator complex and can be used for real-time beam polarization monitoring.

2.2.3. Low-Energy ^{3}He Polarimeter

A universal polarimeter has been developed for measuring the vector and tensor polarization values of proton and deuteron beams in the energy range of 4–12 MeV. A unified gaseous ^{3}He target is used as a polarization analyzer, where the elastic scattering reaction ^{3}He$(p, p)^3$He for protons and the ^{3}He$(d, p)^4$He reaction for deuterons take place [15].

For protons, the scattered particles are detected by surface-barrier silicon detectors, positioned symmetrically to the left and right of the beam over a range of laboratory angles from 20° to 150° [16]. For deuterons, the reaction products are detected in the horizontal plane at a laboratory angle of 27°, which corresponds to the center-of-mass angles of $\theta_{\rm c.m.} = 32°$ for protons and $\theta_{\rm c.m.} = 132°$ for recoil alpha particles [17].

The polarimeter demonstrates high measurement accuracy. For protons, the accuracy of ± 0.005 or better has been achieved for the analyzing power A_{y0} [15]. For deuterons, the polarimeter provides measurements with an accuracy of 2% in the 5–10 MeV range and about 4% at 10–12 MeV [16]. The proton beam polarization has been maintained at a level of 0.85 with a determination accuracy of 1–2%.

A ^{3}He gas cell operating at pressures up to 3 bar is used as a target. The angular resolution of the system is $\pm 0.38°$ when using 1 mm wide slits [16]. The versatile design allows for the measurement of both vector and tensor polarization for various beam types on a single experimental setup.

2.3. NICA Absolute Polarimeter

The Absolute Polarimeter (APol), with the jet-polarized hydrogen and deuterium targets, is being developed to measure the polarization of proton and deuteron beams in the rings of the NICA.

This polarimeter will allow monitoring of the beam polarization and optimal adjustment of the polarization control systems of the NICA, as well as determining the influence of the
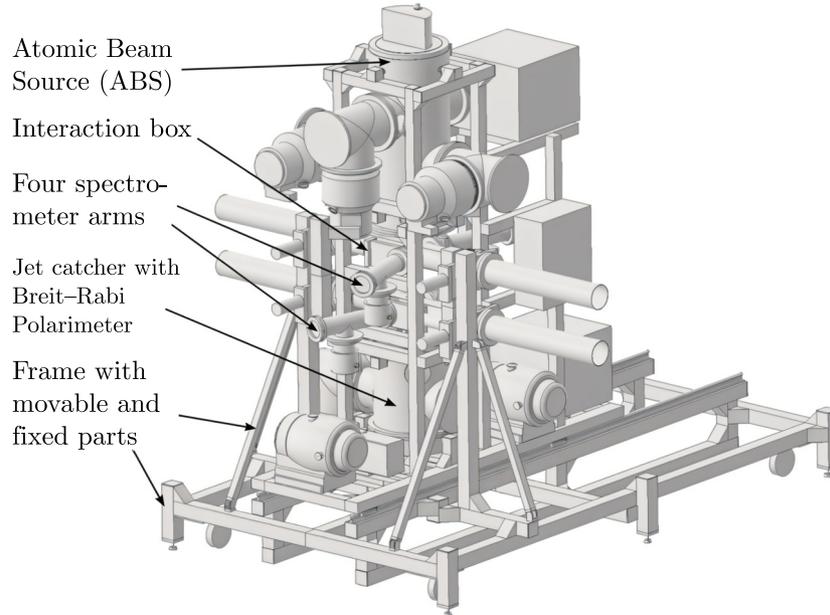
Figure 4. Layout of the NICA Absolute Polarimeter [18].

collider's disturbing devices on the beam polarization. Another important aspect is the monitoring of the beam polarization degree during the operation of the collider in polarized beam runs at the accelerator complex.

It is proposed to install the polarimeter in the "warm" gap of the ring arc of the collider. The polarized jet will intersect both accelerated beams. The jet target is based on the classical principle of an atomic beam source. The expected thickness of the target jet in the interaction regions is 10^{12} atoms/cm^2.

The polarization of the atomic hydrogen/deuterium jet will be measured by a Breit-Rabi polarimeter located under the collider ring in the volume of the jet catcher. Elastic scattering reactions of identical nuclei (protons or deuterons) will be used in APol.

The APol polarimeter allows quick (within a few minutes) measurements of the absolute values of polarization and its signs for protons and deuterons beams accelerated at the maximum collision energy. Measurements will be carried out simultaneously on both NICA beams using a single polarized jet target [18].

2.4. Equipment for creation of polarized beams at the JINR accelerator facility: future prospects

2.4.1. SPI source upgrade

The use of transverse injection into a T-shaped storage cell in a charge-exchange plasma ionizer makes it possible to reduce the emittance of polarized ion beams by transitioning to a single-aperture ion-optical system and reducing the emission surface radius in the plasma electrode of the ion-optical system.

It is possible to increase the magnetic field in the storage cell up to ~ 250 mT, which should result in higher polarization of the generated beams of polarized protons and deuterons due to suppressing the depolarization from collisional and spin-exchange relaxation.

The increase of the polarized ion beam intensity is possible, which should result from raising the accelerated beam energy in the ion-optical system up to 45 keV.

The resulting increase in the beam quality factor from the source: $QF = I \cdot P^2/\varepsilon^2$, where I is the intensity, P is the polarization, and ε is the transverse emittance of the polarized ion

beam, by (approximately) an order of magnitude is of substantial importance for achieving the design luminosity of polarized proton and deuteron beams in the NICA collider [19].

2.4.2. Polarized $^3He^{++}$ ion source

In the polarized $^3He^{++}$ ion source concept, ^{3}He atoms will be polarized by the Method of Optical Pumping (MEOP) in a glass cell at a pressure of 1–10 mbar within a 5.0 T magnetic field inside an EBIS solenoid, and after that directed into an EBIS drift tube for ionization and accumulation [20]. A high (90%) nuclear polarization of ^{3}He has been achieved in a strong 3–5 T magnetic field during the MEOP process [21]. In the EBIS, $^3He^{++}$ ions can be produced and accumulated in the EBIS trap region with an effective length of 100 cm and a total charge of about 10^{12} (for an electron beam current of 10 A). It is proposed to develop a new source (based on the BNL EBIS prototype) with a direct current of 5 A and electron beam current recovery. The magnetic compression of the electron beam by a MIEG (Magneto Immersed Electron Gun) allows the creation of an ion trap for the EBIS with a capacity of 10^{12} elementary charges [20–22].

2.4.3. Polarized beams in the NICA accelerator complex

2.4.3.1. Requirements for polarized particle beams in the collider

It is planned to perform experiments with beams of polarized protons, deuterons, and ^{3}He to study spin-dependent effects and polarization phenomena in various processes at NICA. The polarization control scheme must meet the following basic requirements [23]:

- to achieve longitudinal and transverse polarization on SPD/MPD with a degree of polarization of at least 70% and a sufficiently long lifetime of polarization (not shorter than the lifetime of the beam);

- to provide luminosity of $\sim 10^{30}-10^{32}$ cm$^{-2} \cdot$ s^{-1} in the proton momentum range from 2 to 13.5 GeV/c;

- to ensure operation in the asymmetric beam momentum mode;

- to ensure simultaneous spin flipping in all beam bunches during the experiment.

2.4.3.2. Spin Transparency mode

A new method for controlling the polarization of light nuclei — the spin transparency (ST) mode — has been developed for NICA by MIPT (Dolgoprudny) in collaboration with JINR (Dubna) [24]. This method provides effective control of ion polarization, particularly for deuterons, during experiments, using quasi-stationary weak fields.

In order to operate in the ST mode at any energy, two solenoidal snakes will be introduced into opposite straight sections of the collider. These snakes will compensate for the spin effect of the arc dipoles per particle revolution. In the ST mode, there is no dedicated direction of the stable polarization. Stabilization of the required polarization direction (the n-axis) will be achieved by using spin navigators (SN) — special magnetic inserts, based on "weak" magnetic fields [25]. The effect of the navigator on the spins (navigator strength) must significantly exceed the depolarizing influence, caused by magnetic element alignment and manufacturing errors, as well as the impact of the beam betatron and synchrotron oscillations.

The field integral of the spin navigators, required to control the spin direction, is smaller by orders of magnitude than that of the spin rotators. The "weak" navigator fields "indicate" the polarization direction at the detector. The further kinematics of the polarization along the
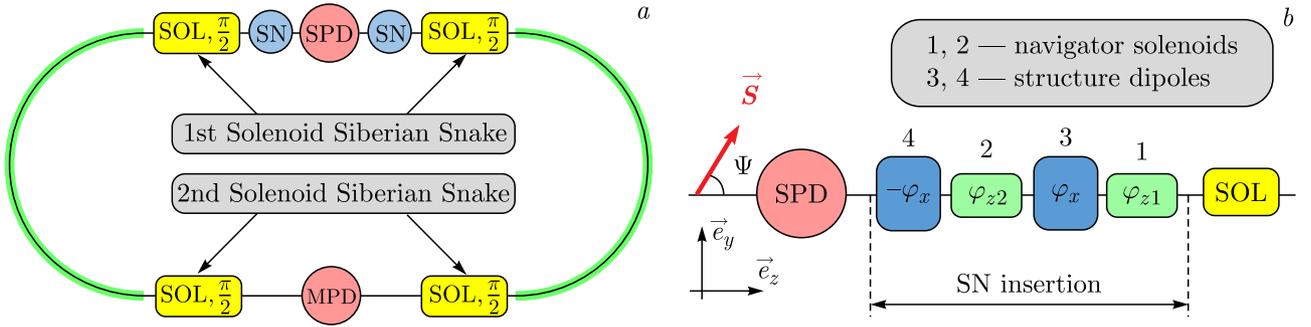
Figure 5. ST mode in NICA: (*a*) location of the solenoidal snakes, (*b*) location of the weak solenoids in the spin navigator.

collider ring is determined by the "strong" magnetic fields of the structural elements (solenoidal snakes and arc magnets) [26].

Figure 5, *a* shows the layout of the solenoid snakes in NICA. Each snake is split into two parts (50%-snakes), symmetrically positioned around MPD and SPD [27]. The details of the SN are shown in Figure 5, *b*. It consists of two "weak" solenoids separated by a dipole with a radial field, which provides beam focusing at the interaction point in the detector. The SN allows for achieving any spin direction in the detector's vertical plane or any spin direction in the collider's plane within its arcs.

The longitudinal field integral per one 50%-snake for operation across the entire momentum range up to 13.5 GeV/c is 25 T·m for protons and 80 T·m for deuterons. Field integrals of 0.6 T·m in the navigator solenoids are sufficient to control the polarization of protons and deuterons over the entire energy range.

At the first stage, it is planned to install four one-meter 6 T solenoids, which will allow operation with protons up to 3.5 GeV/c and deuterons up to 1 GeV/c. For the rest of the energy range, operation is planned at discrete energies corresponding to integer spin resonances (ST mode at integer resonances), which occur with a step of 523 MeV for protons [28]. For deuterons in NICA, there is only one integer depolarizing resonance at a momentum of 13 GeV/c. In this case, solenoid snakes are not required, as the spins complete an integer number of revolutions in the collider arcs per particle revolution.

At subsequent stages, it will be necessary to extend the s momentum range for the ST mode by increasing the longitudinal field integral of the introduced solenoids. A relevant task is the development of snakes for protons based on transverse fields, whose field integral, unlike solenoid snakes, is practically independent of energy.

It is important to note that, compared to the ST mode at integer resonances, the ST mode with two snakes significantly alters the spin dynamics: the spin tune is zero at any energy point. Unlike the ST mode at integer resonances, it becomes possible to form bunches with a large number of particles and a high degree of polarization at low energy, with subsequent preservation of polarization when accelerated to the energy of the experiment. The effect of synchrotron energy modulation and higher-order spin resonances on beam polarization is eliminated, which significantly increases the polarization lifetime.

2.4.3.3. The Spin Flipping (SF) system

It is based on quasi-stationary fields and is naturally implemented in the ST collider mode [29]. As already noted, a pair of "weak" navigator solenoids allows for simultaneous control of both the direction of polarization and the spin setting. This allows maintaining a constant value of the spin tuning during a polarization flip, thereby avoiding the intersection of

both a zero spin resonance and higher-order resonances. As a result, with a slow change of the "weak" solenoid fields, the degree of polarization will be maintained with exponential accuracy.

The SF system in the ST mode changes the methodology of polarized beam experiments, elevating them to a new level of precision. When operating with the SF system, simultaneous spin flipping occurs in all bunches of one ring. Consequently, the same pairs of bunches, whose polarization direction can be alternately changed, will collide in the detector. This makes it possible to compare collisions between bunches not only with inverted polarization, but also with any desired directions: vertical-longitudinal, vertical-radial, radial-longitudinal, etc.

2.4.3.4. Compensation of structure imperfection

Spin navigators can also be used to compensate for the depolarizing influence of alignment and manufacturing errors of the structure's magnetic elements [30]. As a result, a real synchrotron with structural imperfections becomes equivalent to a synchrotron with a perfectly aligned magnetic structure.

2.4.3.5. Online polarization monitoring

When the collider is operating in the ST mode, there is a unique opportunity for online polarization monitoring. Since the time of field change in "weak" navigator solenoids ($t_{\text{change}} \sim 1$ s) is significantly longer than the time of the spin revolution around the induced spin field ($t_{\text{rev}} \sim 10^{-4}$ s), any manipulations with the spin direction at a fixed value of the spin setting will be performed adiabatically. The degree of polarization will be maintained with exponential accuracy during the experiment. The direction of the beam polarization will depend on the fields of the navigator solenoids. It can be controlled by measuring the field values in the weak control solenoids.

2.4.3.6. Preservation of proton polarization in the Nuclotron ring

Polarized protons or deuterons from the SPI are first accelerated in the LU-20 linear accelerator, then injected into the Nuclotron, followed by transfer of the beam to the collider. During the beam transfers between the complex's rings, it is necessary to match the polarization directions at the injection points.

Polarization loss during beam acceleration in the Nuclotron is associated with crossing spin resonances. The problem of resonant depolarization is practically absent for deuterons. The only integer resonance for deuterons at a beam momentum of 13 GeV/c is not achievable in the Nuclotron. In contrast, for protons resonant depolarization leads to a significant loss of polarization.

In order to preserve proton polarization in the Nuclotron, the most effective approach is to use a partial solenoidal snake. Two options are considered.

In the first option, a weak 5% snake with a longitudinal field integral of 0.65 T·m can be used [31]. It allows preservation of proton polarization up to a momentum of 3.4 GeV/c, which corresponds to the first intrinsic resonance. This option is suitable when the collider operates in the ST mode with two snakes, and the beam is injected from the Nuclotron at low energy with subsequent acceleration in the collider to the experiment's energy. This option is necessary for obtaining beams with a high luminosity and polarization degree by utilizing electron cooling at low energies.

In the second option, a sufficiently strong 50% snake with a longitudinal field integral of 25 T·m can be used [32]. It allows preservation of proton polarization across the entire energy range. This option is suitable when the collider operates in the ST mode at integer resonances, and the beam is injected from the Nuclotron into the collider at the discrete energy value of the

experiment. This opens the possibility to conduct experiments with polarized protons, either independently or in parallel with experiments in the heavy-ion mode of the NICA collider, on both external and internal targets in the Nuclotron. These experiments will significantly expand the program of fundamental research on spin physics at the NICA complex.

The implementation of spin flipping, structure imperfection compensation, and online polarization control within the spin-transparent mode will enable to perform unique polarized beam experiments at JINR.

3. Beam polarimetry at LHEP of JINR

3.1. Polarimetry of the extracted deuteron beam at the Synchrophasotron

The first task, which had to be solved simultaneously with the task of creation of a polarized deuteron source, was the task to measure the polarization parameters of the accelerated deuteron beam, extracted from the Synchrophasotron. This problem was solved by arranging the ALPHA polarimeter [33] at the external (slowly extracted) deuteron beam in experimental hall 205 at the LHE accelerator complex.

Later on, several polarimeters (on the extracted beam as well as on the internal beams of the Synchrophasotron and the Nuclotron) were arranged (see Figure 6 and the descriptions below).
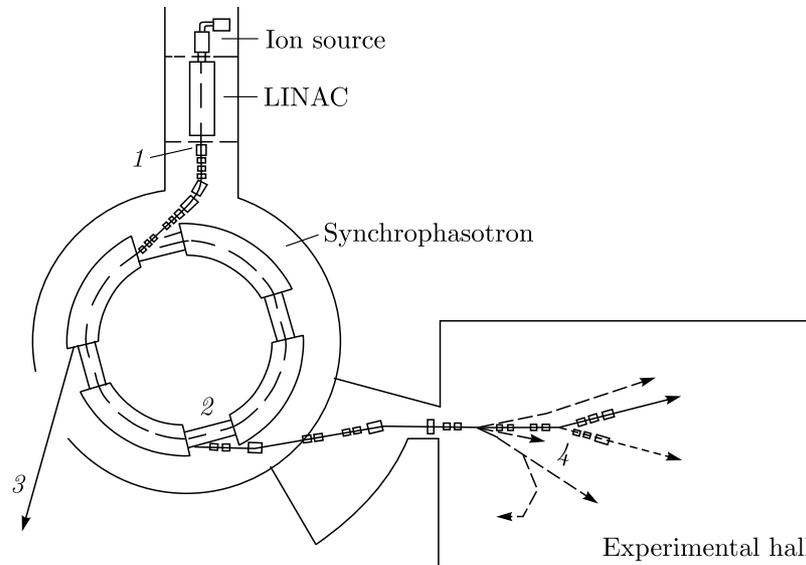

Figure 6. Schematic view of accelerator components and beamlines of the Dubna Synchrophasotron. The numbers indicate the positions where the beam polarization was measured: *1* — low-energy polarimeter; *2* — internal beam vector polarimeter; *3* — fast beam extraction and the beamline into the hydrogen bubble chamber; *4* — high-energy polarimeter at the slow extraction beamline.

The efficient and precise polarimetry of the deuteron and proton beams at the Nuclotron (and at the future NICA collider) plays quite an important role in obtaining the high-quality data on study of the spin-dependent effects in dp, pp and dd collisions.

With the help of the ALPHA polarimeter (Figure 7), the vector and tensor polarizations of the deuteron beam, accelerated and extracted from the Synchrophasotron, were measured, the stability in time of the extracted beam polarization parameters was checked and some important parameters of the accelerator were tuned in order to get the optimal intensity and polarizations of the extracted beam for the experiments (see Figures below).
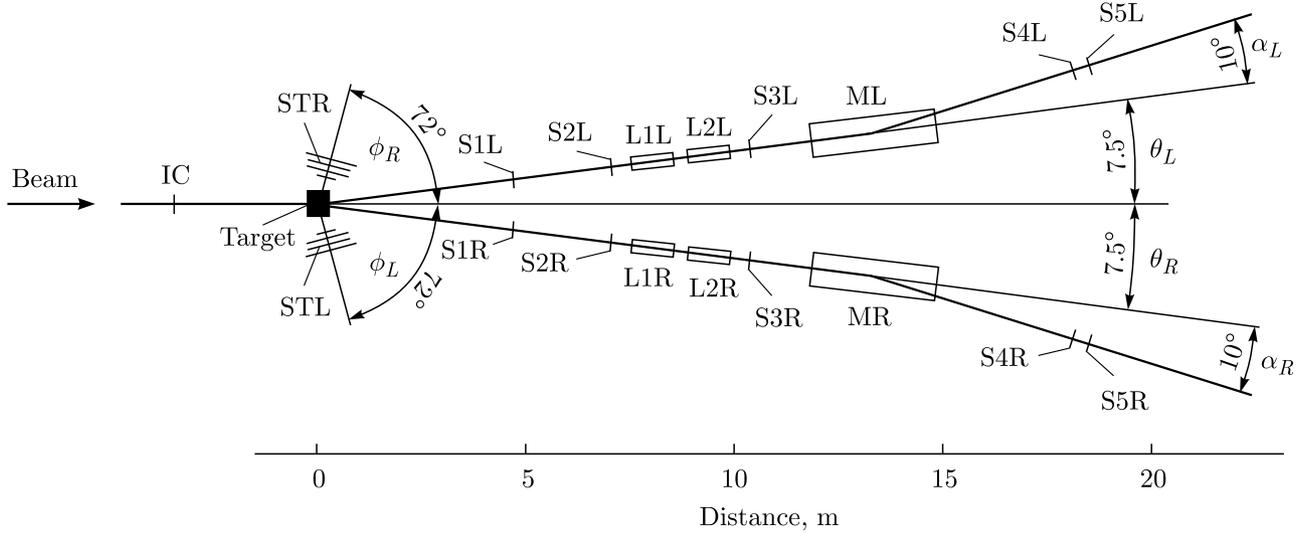
Figure 7. High-energy ALPHA polarimeter [33]. Here, IC — beam intensity monitor ionization chamber; STL, STR — scintillation counter telescopes for detection of slow recoil protons; S — scintillation counters for detection of scattered deuteron; L1, L2 — quadrupole lenses; M — analyzing magnet; Target — the liquid hydrogen target, located in F5 focus of the beam transportation line.

Finally, the t-dependence of the analyzing powers A_y and A_{yy} of elastic dp scattering was measured at a beam momentum of 3 GeV/c by varying the scattering angles using the described polarimeter. Also, similar measurements were done at a fixed scattering angle but with the changed beam momentum (3.0, 4.0 and 4.5 GeV/c). The results obtained using such different methodological procedures are in good agreement with each other (see ref. [33]).

Later on, other polarimeters were constructed to measure and monitor polarizations of extracted deuteron and proton beams at the Synchrophasotron (see Figure 10, a and ref. [34]).

The polarimeter consisted of a symmetrical left-right detection system to measure elastic dp scattering in the range of $-t = 0.1-0.5$ GeV/c at 3 to 4 GeV/c. The polarization values could be determined with a statistical accuracy of better than 10% during measurement periods of about 15 min. with a beam intensity of $\sim 5 \cdot 10^8$ deuterons per spill directed at a 20 cm long liquid hydrogen target. As a rule, values of vector and tensor polarizations exceeding 60% of the expected theoretical values were obtained.

The axis of spin quantization had to be correctly oriented relative to the direction of the accelerator's magnetic field in order to preserve beam polarization during acceleration. The spin rotation (angle φ) depends on the magnetic field strength of the spin rotator magnet (solenoid) at the outlet of the ion source (see Figures 2 and 6). The changes in the measured vector p_z and tensor p_{zz} polarizations as a function of the field strength of this solenoid are shown in Figure 8.

It is known that depolarization effects can occur during the acceleration of polarized particles. This was proved by comparing vector polarizations for two different acceleration modes: (i) the deuteron beam was extracted when it reached a momentum of 3 GeV/c; (ii) the beam was accelerated up to 9 GeV/c, then decelerated to 3 GeV/c and extracted.

The ratio of the p_z values obtained in these modes was constant within 4%. In other words, there were no noticeable depolarization effects during the acceleration (at least in the momentum range available at the Synchrophasotron).
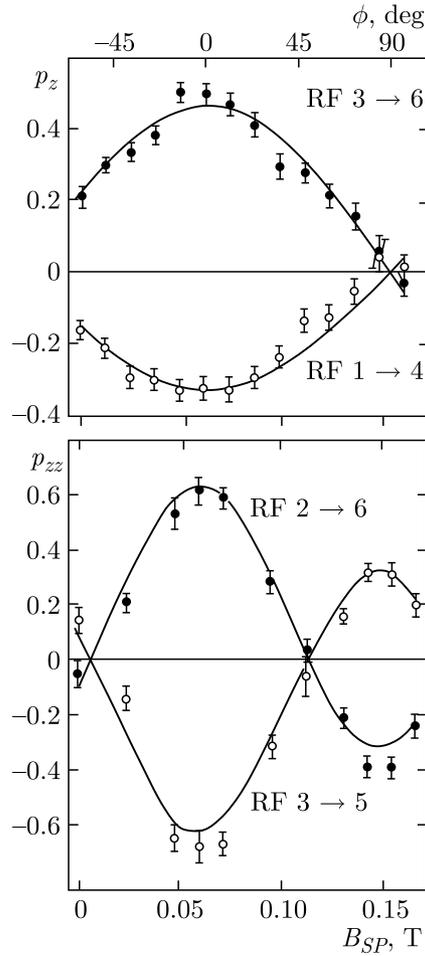
Figure 8. Polarizations p_z and p_{zz} as the functions of the magnetic field B_{SP} strength of the spin rotator solenoid for the four transition modes available at the ion source. The rotation angle φ (the angle between the direction of the accelerator's magnetic field and the axis of spin quantization) is also presented. The solid lines are explained in ref. [33].
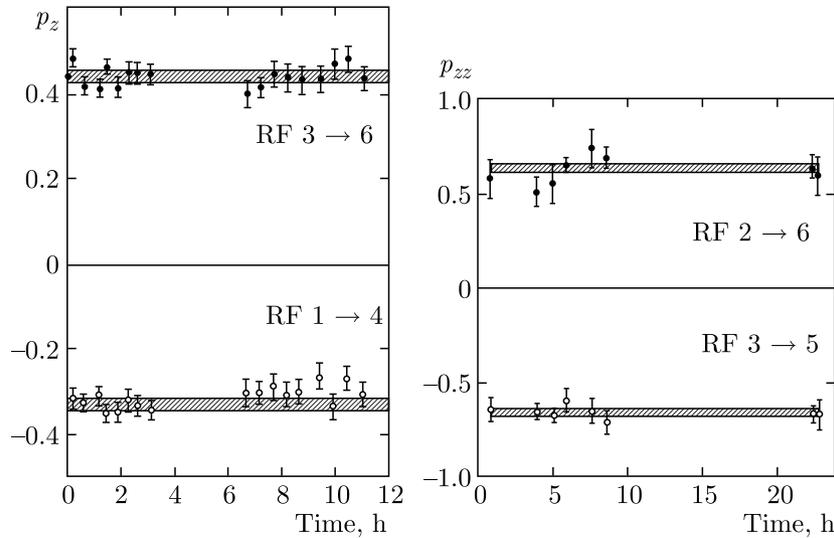

Figure 9. Left: Vector polarization of the deuteron beam depending on the operating time of the accelerator with average values of $p_z(+) = 0.440 \pm 0.006$ and $p_z(-) = -0.328 \pm 0.008$. Right: The same dependence for the tensor polarization of the deuteron beam with average values of $p_{zz}(+) = 0.634 \pm 0.024$ and $p_{zz}(-) = -0.658 \pm 0.018$.

The operational stability of the polarized deuteron source, as well as the experimental beam extraction systems, is shown for the vector and tensor polarizations in the left and right panels of Figure 9, respectively.

3.2. Monitoring polarimeter at the extracted beam from the Synchrophasotron and the Nuclotron

In order to control and monitor polarization of the extracted deuteron beam, a special monitoring polarimeter was built. It was located at beam focus point F4 first, but later it was modernized for work at focus F3. This polarimeter was a relative polarimeter and its operating principle was based on the following factors: (1) the polarimeter should record the left-right asymmetry of quasi-elastic *pp* scattering of a proton from a deuteron on a hydrogen-containing (CH$_2$) target; (2) the well established factor of high analyzing power of elastic *pp* scattering was exploited, as well as (3) a large elastic *pp* scattering cross section and (4) maintaining the direction of the polarization vector of nucleons, formed during deuteron fragmentation, at zero angle relative to the direction of the spin quantization axis of polarized deuterons.

The polarimeter [34, 35] was first installed on the extracted polarized deuteron beam of the JINR Synchrophasotron and consisted of eight scintillation counters recording both scattered and recoil protons arising from the beam's interaction with the hydrogen-containing (CH$_2$) target, see Figure 10 (left). The beam polarization vector was oriented along the normal to the scattering plane. The left-right scattering asymmetry was determined using quadruple coincidence counters. The polarimeter arms were oriented at angles corresponding to the elastic scattering kinematics and the maximum analyzing power. Later on, the new version of the beam polarimeter was installed at focal point F3, and had 12 scintillation counters.
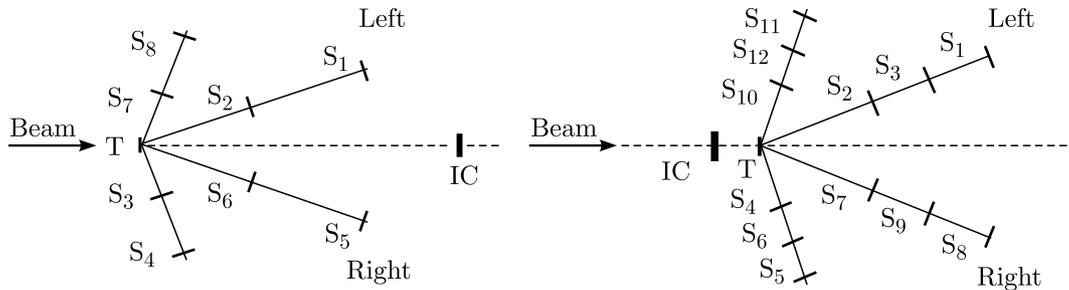

Figure 10. Left: Layout of the *pp* polarimeter [34, 35, 37] at focal point F4. S1–S8 are the scintillation counters. Right: New version of the beam polarimeter [38] at focal point F3. S1–S12 are the scintillation counters. On the both figures, IC is the ionization chamber, T is the target.

The magnitude of the asymmetry characterizes the product of the polarization value of the deuteron beam (or deuteron nucleons) and the vector analyzing power of the quasi-elastic *pp* reaction; the stability of this value is responsible for the reliability of physical measurements (see Figure 13 in [36]). In works [37, 38], some methodological aspects of the use of the described polarimeters were discussed.

3.3. Polarimetry of secondary beams of protons and neutrons

Double scattering experiments are time-consuming. Therefore, meticulous optimization of the polarimeter's performance is essential. This requires careful selection and study of the analyzing reaction, which should have a high yield and high analyzing power; optimization of the analyzer target material and thickness; and selection of detectors to ensure 2π geometry of the polarimeter.

The ALPOM2 [36] is an upgraded version of the ALPOM polarimeter [39], which, in turn, is based on the POMME polarimeter used at SATURNE. The main improvement was the replacement of the proportional chambers with the drift chambers and the addition of a hadron calorimeter. A schematic view of the ALPOM2 geometry is shown in Figure 11. The mean momentum direction of the incoming proton/neutron beam determines the direction of the Z-axis.
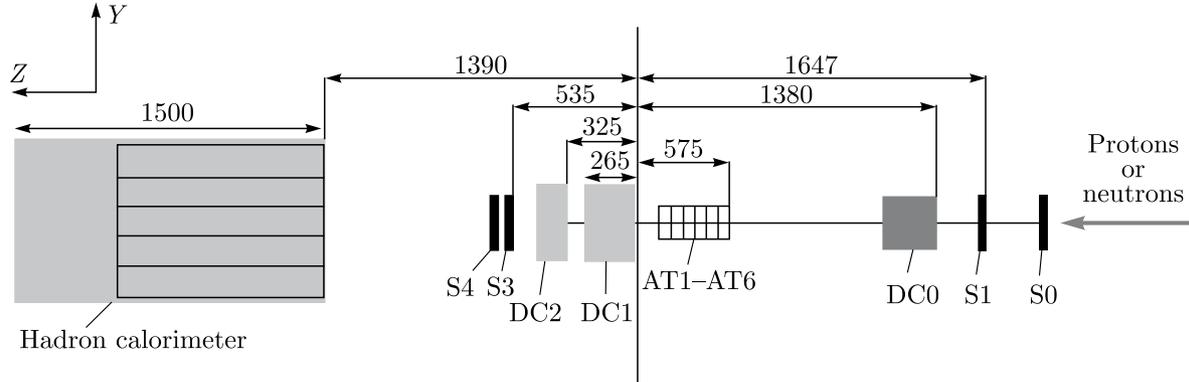

Figure 11. Layout (side view) of the ALPOM2 setup [36] located at the secondary proton/neutron beam line, including the scintillation counters (S0, S1, S3, S4); drift chambers (DC0, DC1, DC2); the hadron calorimeter. The analyzing targets were located between DC0 and DC1. Here a CH (AT1–AT6) active target is shown as an example. Sizes are given in mm, relative to the origin of the Z coordinate axis.

The main components of the ALPOM2 setup are:

— fast plastic-scintillator counters (S0, S1, S3, S4 and optionally AT1-AT6) for triggering purposes;

— the drift chambers (DC0, DC1, DC2) for tracking of charged particles;

— the segmented hadron calorimeter for measuring the energy and position of outgoing particles;

— different analyzing targets (C, CH, CH_2, Cu) for polarimetry.

In the first stage, the analyzing power A_y was measured for the inclusive reaction $p + CH_2 \rightarrow$ one charged particle $+X$ at proton momenta of 1.75, 3.8, 4.5, and 5.3 GeV/c.

The measurement results revealed the following interesting features:

- For protons at 3.8 GeV/c, A_y is virtually independent of the amount of material in the analyzer, from 37 to 80 g/cm^2 (see Figure 12).

- The target thickness above the nuclear collision length and polarimeter acceptance above $p_t > 0.7$ GeV/c do not improve the polarimeter's performance, i. e. the "Figure of merit": FOM $\sim A_y^2$ (normalized fraction of useful events).

- A_y decreases with increasing incident momentum, but remains significant at a proton momentum of 5.3 GeV/c; in the measured range, A_y is inversely proportional to the incident momentum.

- The CH_2 target exhibits a higher A_y than the carbon target.
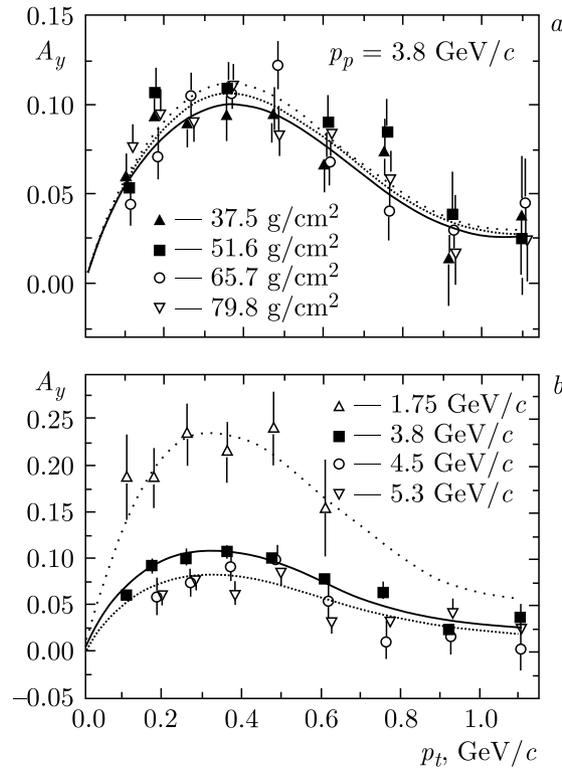
Figure 12. Analyzing powers depending on p_t: (a) for different target thicknesses at a proton momentum of 3.8 GeV/c; (b) for different momenta and $L = 51.6$ g/cm^2.

The preliminary results of the Dubna measurements were immediately reviewed at Jefferson Laboratory: PAC 20 (17–20 July of 2001) approved the proposal E-01-109 of the experiment "Measurement of G_{Ep}/G_{Mp} up to $Q^2 = 9$ (GeV/$c)^2$ by Measuring Recoil Proton Polarization", stating that: "The sensitivity of the experiment depends on the analyzing power of the polarimeter (2×60 cm CH$_2$), which is significantly different from zero in the relevant momentum range. At the time of writing of the proposal, no analyzing power data were available that would support the extrapolations made in preparing the new experiment. The collaboration has carried out measurements of this analyzing power at Dubna, and the Committee is pleased to note, that the preliminary results, obtained this summer, are in reasonable agreement with the extrapolations, made in the proposal". The result of the G_{Ep} measurements (black points) [40] and [41] is shown in Figure 13.

The significance of the "Polarization method of measurements of the ratio G_{Ep}/G_{Mp}" is extremally important, and results, obtained with the ALPOM/ALPOM2 experiment, were crucial for the successful realization of that method. In that method, the information about the ratio $R = \mu G_E/G_M$ of the electric (G_E) to magnetic (G_M) formfactors of a nucleon was extracted from the data on the polarization of recoil nucleons from the elastic $eN \to eN$ scattering of longitudinally polarized electrons. As A. I. Akhiezer and M. P. Rekalo showed, this ratio R was proportional to the ratio of the longitudinal (relative to the recoil nucleon momentum direction) to the transverse (relative to the same direction) polarizations of the recoil nucleon. Therefore, such measurements are of the double-scattering type.

A series of such experiments was done at Jefferson National Laboratiory (USA) and made very significant contribution to the study of that ratio R for protons. Importance of those results is well recognized; for example, well-known theorist N. M. Nikolaev said (private com-
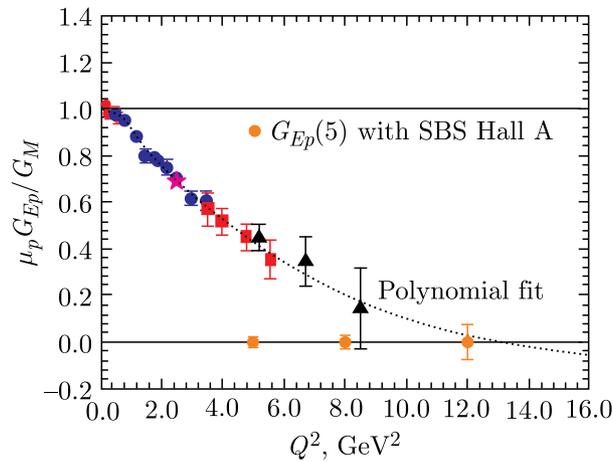
Figure 13. Predictions of experimental uncertainties for the JLab experiment E12-07-109 (filled orange circles). The previous JLab G_{Ep}/G_{Mp} data for G_{Ep} (blue), G_{Ep} (red), G_{Ep} (black) are also shown for comparison. The dotted line is a polynomial fit. (See also [41] and references therein).

munication): "The similarity between the magnetic and charge form factors of the proton, which followed from Rosenbluth's analysis of half a century of experimental data on electron-proton scattering, became one of the most persistent ***misconceptions*** in high-energy physics. Textbooks are already being rewritten, and Figure 13 will forever be included in them. This is a completely new chapter in the question of nucleon structure. A. I. Akhiezer and M. P. Rekalo, with their method for transferring the longitudinal polarization of electrons to recoil protons, will rightfully be included among the new classics of theoretical physics. It was the measurement of two components of proton polarization in the scattering plane that made possible the first direct determination of the GE/GM ratio at Jefferson Laboratory. The transition from isolating a quadratically small signal to a linear one significantly increased the sensitivity of the experiment to the contribution of the charge form factor and led to a revolution in understanding the charge structure of the proton... Therefore, this polarimetry work, carried out by the team at LHE JINR, and then at LHEP JINR, has also guaranteed a place in textbooks."

During the second stage of the study in Dubna, measurements of the analyzing powers using polarized proton and neutron beams were performed at the momenta from 3 to 4.2 GeV/c [36]. For the first time, a hadron calorimeter was used to measure the energy of particles emitted from the target, and a charge-exchange reaction was used as the analyzing reaction for neutrons in these measurements.

The inclusion of the hadron calorimeter is determined by the fact that, already at 7 GeV/c, only about 30% of reactions in the analyzer are elastic, i.e., without the formation of secondary particles (mesons). Thus, with increasing energy, the probability of detecting all particles in the final state increases; this depends on the detector's features such as angular resolution, the ability to select the leading particle, the ability to reconstruct multiparticle events, and so on. It could be expected that the greatest analyzing capability will be achieved when the selected particle has the smallest scattering angle and the highest energy; then this particle is more likely to be a scattered incident particle.

The dependence of A_y on the target material, shown in Figure 14, is very weak; there is no significant difference between the data for C, CH, CH$_2$, and Cu targets. It can be concluded that the charge-exchange reaction is the same for both free protons and protons in nuclei.
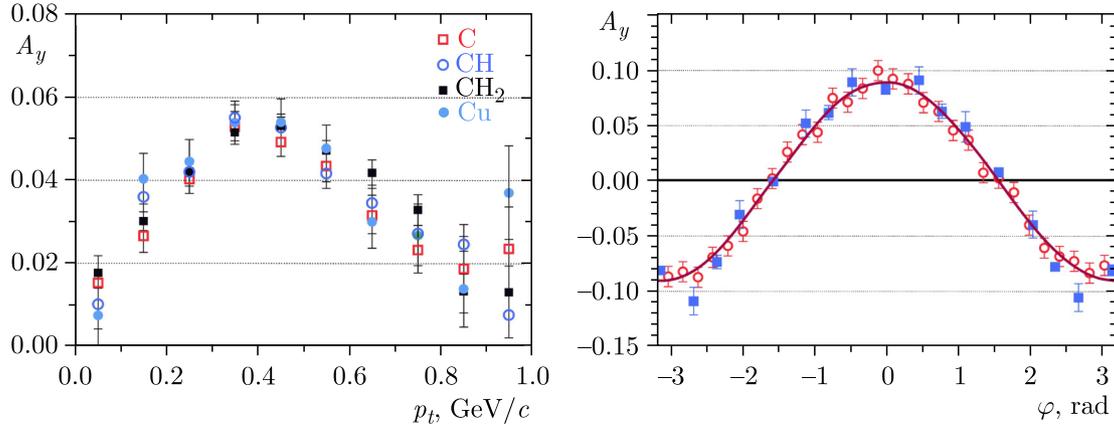
Figure 14. Left: Dependence of the analyzing power A_y on p_t for scattering of 3.75 GeV/c neutrons on carbon (red), a scintillator (blue), polyethylene (black) and copper (full blue). Right: Azimuthal dependence of A_y for $p + CH_2$ scattering at 3.0 GeV/c, obtained using activated modules of the hadron calorimeter (blue squares) and tracking information from the drift chambers (red circles).

The asymmetry of the scattered particles can be obtained independently: both with the help of drift chamber tracks and with the help of the activated modules of the hadron calorimeter. The results on the analyzing power for the $p + CH_2$ reaction at a momentum of about 3.0 GeV/c are shown in Figure 14 (filled squares). The excellent agreement between both measurements of asymmetry allows the use of a calorimeter for proton polarimetry both with and without tracking detectors.

For the first time, data on the analyzing powers were obtained using 3.75 GeV/c polarized protons and neutrons incident on a copper target, upon detection of a single charged particle flying in forward direction, and at different values of the energy thresholds of the hadron calorimeter. After selecting events with an energy deposition exceeding 1.76 GeV, A_y for $n + Cu$ and $p + Cu$ increases by ~ 2 times and ~ 1.3 times, respectively. This increases the FOM for the $n + Cu$ charge-exchange reaction by almost 40%. For a 4 cm thick copper target, the FOM value is $8.0 \cdot 10^{-5}$, and when events are selected using a calorimeter, the FOM value increases to $1.1 \cdot 10^{-4}$.

Three new approaches to the development of polarimetry, namely: *a*) using a calorimeter to select high-energy nucleons in the final state, *b*) using a charge exchange reaction, and *c*) replacing a light target rich in hydrogen with heavier nuclei, open the way to simpler and more efficient measurements of the polarization of nucleons in the GeV energy region. Experiments at Jefferson Laboratory requiring recoil nucleon polarimetry have already incorporated these concepts into the approved experiments E12-07-109 and E12-17-004, which have obtained data and are in progress now.

3.4. Polarimetry of internal beams of the Nuclotron

The efficient and precise polarimetry of deuteron and proton beams at the Nuclotron (and NICA) plays quite an important role for obtaining the high-quality data on the spin effects in dp, pp and dd collisions.

The deuteron beam polarimeter, based on the use of the asymmetry measurements in dp elastic scattering at large angles ($\Theta_{cms} > 60°$) at 270 MeV [42, 43] and installed at the Internal Target Station (ITS) at the Nuclotron [44], allows obtaining both vector and tensor components of the deuteron beam with high precision. The measurement of proton beam polarization in the energy range of the Nuclotron requires new developments.

The deuteron and proton polarimeter operated using ITS at the Nuclotron with up to 6 different targets. This setup was also well suited for studying the energy dependence of the cross section and the analyzing power of deuteron-proton and proton-proton elastic scattering at large angles in the reaction center of mass (cms). A 10 μm thick CH_2-target was used for these measurements. The carbon yield from the CH_2 target was estimated during separate measurements using several twisted 8 μm carbon wires. The intensity was controlled by recording the *pp* quasi-elastic scattering at 90° in the cms using scintillation counters located in a horizontal plane. The $CH_2 - C$ subtraction procedure was used to obtain the effect on hydrogen.

The existing setup has been significantly upgraded. A new control and data acquisition system [45] was used to perform beam polarization measurements at ITS. The SPI was used to obtain a polarized deuteron beam [46, 47]. The spin modes with maximal ideal values $(P_z, P_{zz}) = (0, 0)$, $(+1/3, +1)$ and $(+1/3, -1)$ were used in experiments with a deuteron beam. The polarization of the deuteron beam was measured at 270 MeV [42], where precise data on the analyzing powers A_y, A_{yy}, A_{xx}, and A_{xz} were available [48, 49].

The scintillation detectors were located in the horizontal and vertical planes in accordance with the *dp* elastic scattering kinematics for the deuteron initial energy of 270 MeV. The use of a large amount of scintillation counters made it possible to cover a wide angular range in the horizontal and vertical planes. The measurements were performed using the CH_2 target. The carbon target was used only once to estimate the background which was found negligible. The *dp* elastic scattering events were selected using time-of-flight difference and the correlation of the energy losses for deuteron and proton detectors. The normalized numbers of the *dp* elastic scattering events at 270 MeV for each spin mode were used to calculate the values of the tensor and vector components of the deuteron beam. The beam polarization values for different spin states were obtained as weighted averages for several scattering angles. The typical values of the vector and tensor components of the beam polarization were ~ 65–75% of the ideal values [50].

The *pp* quasi-elastic scattering reaction was studied using beams of polarized deuterons and protons. The data were taken using the same detection system as for the *dp* elastic scattering experiment. The detectors used were placed only in the horizontal plane in accordance with the kinematics of *pp* elastic scattering. The selection of useful events was performed using the difference in flight time and the correlation of the energy losses for coupled detectors, similar to the selection of *dp* elastic scattering events. The normalized numbers of the quasi-elastic *pp* scattering events for each spin mode were used to calculate the values of either the analyzing power A_y or the vector component of the deuteron (proton) beam polarization.

The analyzing power A_y in the quasi-elastic *pp* scattering was obtained at energies of 200, 500, 550 and 650 MeV/nucleon using a polarized deuteron beam in the test experiment [51]. The taken data were in a fairly good agreement with the world data obtained at close energies, as well as with the results of the SP07 solution of the SAID partial wave analysis [52].

The values of the deuteron beam vector and tensor polarization were measured several times during the runs in 2016–2017. These values had small systematic errors. They were fairly stable during each part of the experiment, as well as during more than 200 hours of the SPI operation [50]. Moreover, the SPI demonstrated a good correspondence of polarization values for different data sets collected over fairly long time intervals. It was also found that the magnitude of the β-angle (which is (according to the Madison convention, reference [53]) the angle between the direction of the spin quantization axis in space and the direction of the beam momentum) was about –90°, i.e. it was perpendicular to the Nuclotron orbit plane. Vector polarimetry for deuteron and proton beams can be implemented using either elastic *dp* scattering at an energy of 270 MeV or quasi-elastic *pp* scattering over a wide range of energies,
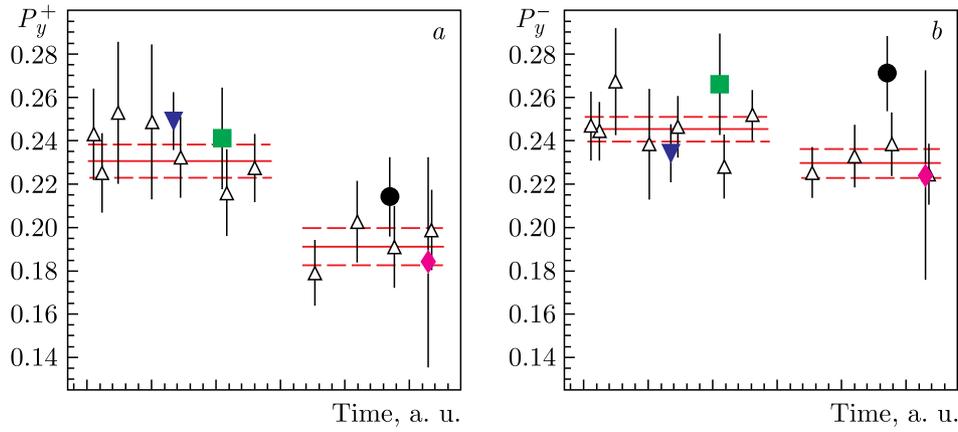
Figure 15. Vector polarization of the deuteron beam, measured by two different methods for two spin modes as a function of time. The open symbols are the results, obtained using elastic *dp* scattering at 270 MeV [50]. The solid triangles, squares, circles, and rhombuses represent the data, obtained using quasi-elastic *pp* scattering at 500, 650, 550 and 200 MeV/nucleon, respectively.

respectively. The results on the vector polarization of the deuteron beam for the spin modes (+1/3, +1) and (+1/3, –1) measured by these various methods are shown in Figure 15, (*a*) and (*b*), respectively; they are in good agreement with each other [43]. Thus, it was proved that quasi-elastic *pp* scattering at large scattering angles can be used to measure the polarization of a deuteron/proton beam, at least up to kinetic energies from 200 to 650 MeV/nucleon, using the existing equipment at the Nuclotron.

The beams of polarized and unpolarized protons produced by the SPI were accelerated to 500 MeV. The typical values of the beam intensity were $(2–3) \cdot 10^7$ ppp and $1.5 \cdot 10^8$ ppp for polarized and unpolarized cases, respectively. The SPI provided polarization of the proton beam using a "Weak Field Transition" (WFT) $1 \rightarrow 3$ with an ideal polarization value of +1. The polarization of the proton beam was obtained using data from 12 pairs of detectors located in kinematic coincidences on the left and right. The analyzing power values for elastic *pp* scattering were taken from the partial wave analysis SAID mentioned above. The average value of the proton beam polarization was 0.368 ± 0.023. The results of the proton beam polarization for a polarized proton beam at different angles in the cms are shown in the left panel of Figure 16, (*a*). The result for the false asymmetry (polarization) of an unpolarized proton beam, shown in the right panel in Figure 16, (*b*), is consistent with zero: 0.038 ± 0.023.
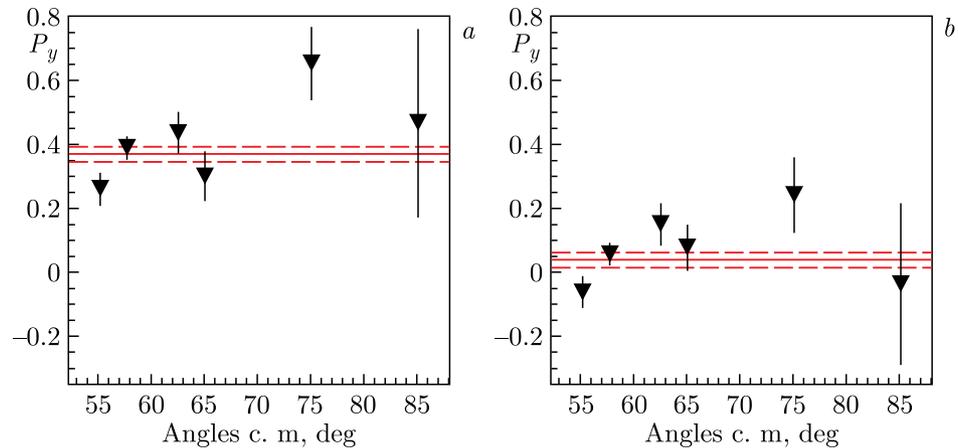

Figure 16. Proton beam polarization at 500 MeV as the function of the scattering angle in the cms. (*a*) and (*b*) corresponding to the polarized (WFT $1 \rightarrow 3$) and unpolarized proton beams, respectively.

22

A new proton polarimeter, which will use both *pp* and *pd* elastic scattering at 100–1000 MeV, is being developed. The Monte-Carlo simulation of this polarimeter has been performed in order to maximize the Figure of merit [54].

4. Investigations with polarized beams (protons, deuterons, ^{3}He)

4.1. Experiments on the study of the lightest nuclei structure

Studies of the lightest nuclei structure were started by experiments on fragmentation of (unpolarized) deuterons, ^{3}He and ^{4}He nuclei on protons or nuclei, with registration of fragments emitted in the "forward" direction. When the fragment was a proton, it had momentum values from p_{beam}/A up to the maximal possible proton momentum, corresponding to the kinematics of backward (in the center-of-mass system of reference) elastic projectile-proton scattering. In the reactions with helium-3 or helium-4 nuclei, where more complicated fragments were detected, their momenta were also in a similar region (from $A_{\text{fragment}} \cdot (p_{\text{beam}}/A)$ up to the maximal possible value). After successful acceleration of polarized deuterons, such experiments were continued with measurements of the polarization observables in the $p(d, p(0°))X$ reaction.

As an example, the data on the invariant cross sections for unpolarized deuteron fragmentation on carbon and hydrogen are demonstated in the left and right panels of Figure 17. The data were obtained at several energies, at the emission angle $0°$ (in the lab. system). The data are shown in dependence on the "light cone variable" $k_{||}$, defined as follows:

$$\alpha = (p_{\text{frag}} + E_{\text{frag}})/(p_d + E_d), \quad k_{||} = (\alpha - 1/2) * (m_p^2/(\alpha(1-\alpha)))^{1/2}, \tag{3}$$
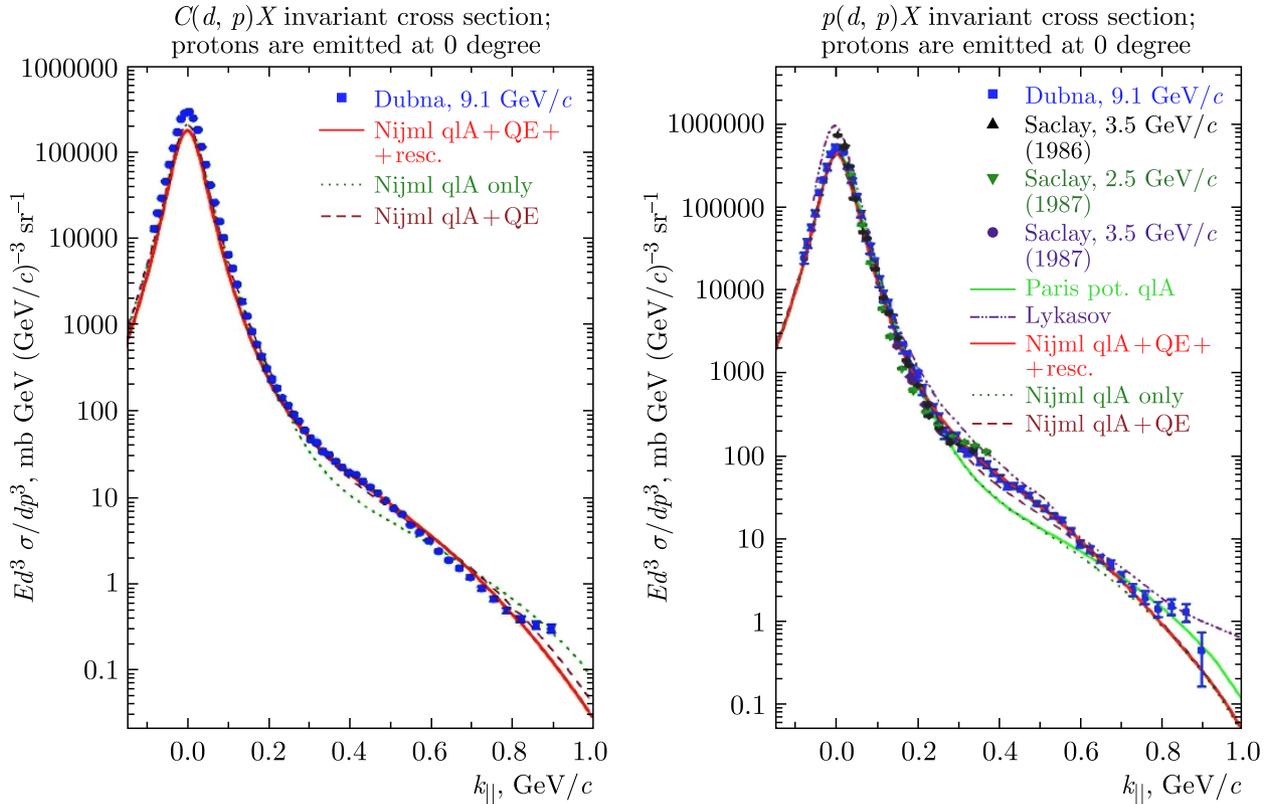

Figure 17. The data points are from Dubna and Saclay experiments (see refs. [55–65]). Lines: model calculations with various deuteron wave functions.

where p_{frag} is the module of the proton-fragment's 3-momentum, E_{frag} is its energy (all quantities are taken in the lab. system), the index d indicates that the corresponding quantities are for the projectile deuteron, m_p is the value of the proton mass.

After polarized deuteron beams appeared at the Synchrophasotron, such investigations were extended for processes of polarized deuteron fragmentation (including the deuteron breakup without production of mesons), for backward elastic dp scattering of polarized deuterons, as well as for elastic dp scattering at large angles (in the center-of-mass system). Examples of some obtained results are given below and can be also found in other papers (see the references in the corresponding list).

A compilation of the data on the polarization observables for the deuteron fragmentation at protons and carbon nuclei is presented in Figure 18. The data include the tensor analyzing power T_{20} (left panel) and the polarization transfer coefficient κ_0 (right panel), which is defined as the ratio of the polarization of the emitted proton to the vector polarization of the incident deuteron, when that deuteron does not have the tensor polarization (i. e. it has only pure vector polarization).

In the Synchrophasotron experiments on the investigation of deuteron fragmentation, performed with unpolarized and polarized deuteron beams, the measurements of the tensor analyzing power T_{20} were performed also in the region, where the system X of the reaction $p(d,p)X$ consisted of 2 nucleons only (the mesonless breakup) [62].

Finally, it should be mentioned that the same teams performed collaborative experiments on measurements of polarization observables (T_{20} and A_{yy}) for inelastic $A(d,d')X$ forward scattering of deuterons on nuclei in the region of excitations of the Δ and Roper resonances in nuclei (see refs. [66–69]). The data on the tensor A_{yy} and vector A_y analyzing powers were also obtained for the inclusive $A(d,d')X$ reaction in the vicinity of baryonic resonances [70, 71] at the SPHERE spectrometer.
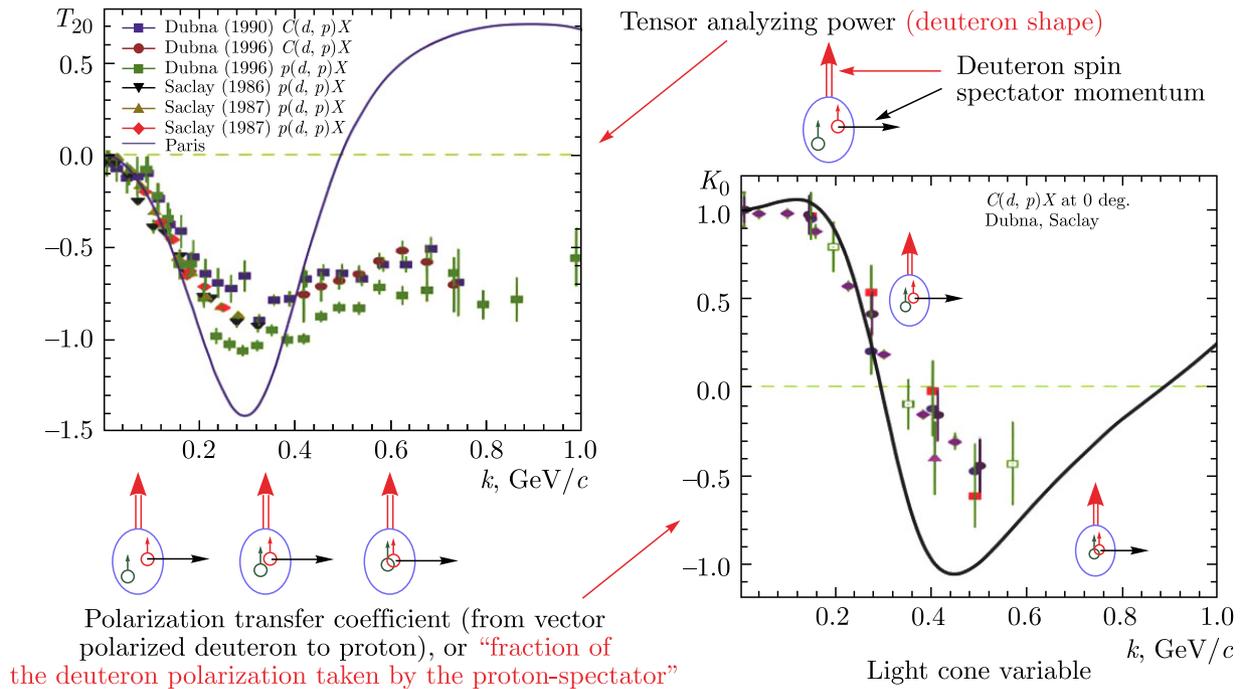

Figure 18. The data points are from Dubna and Saclay experiments (see ref. [55–65]). Lines: calculation within the "Impulse Approximation" (IA) with the deuteron wave function based on the Paris NN potential (G. I. Lykasov, see in ref. [64] and in the capture to the next Figure).
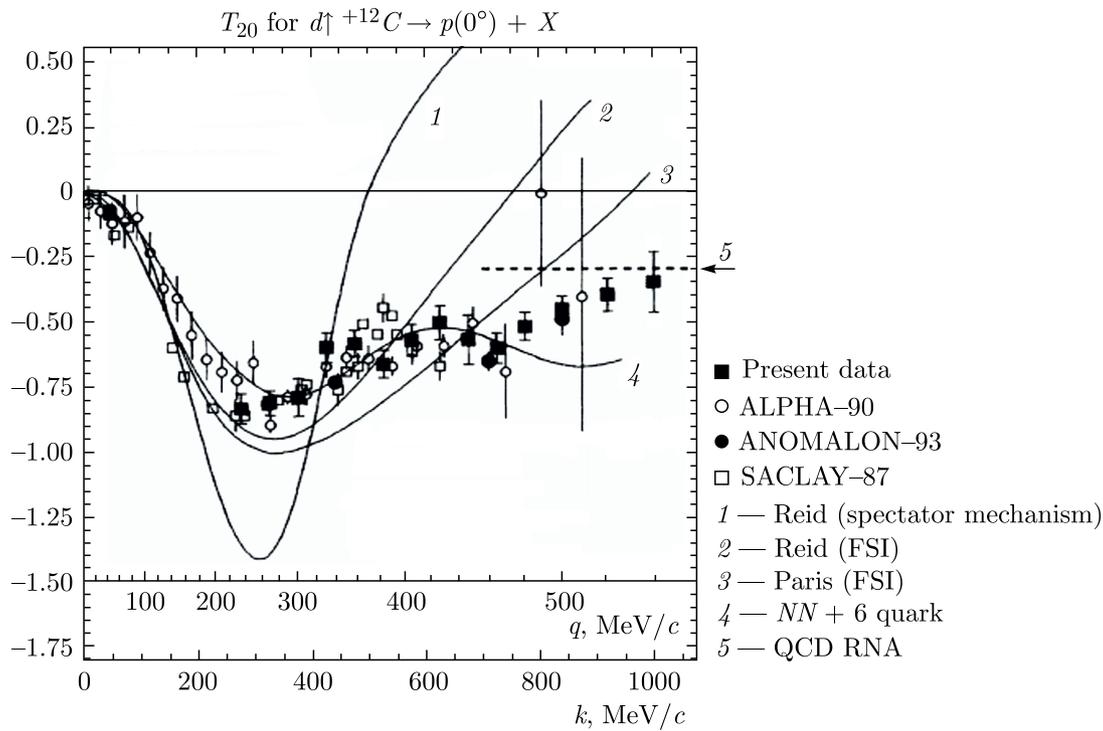
Figure 19. T_{20} data from the paper by T. Aono et al, (ref. [64], 1995) together with previous Dubna and Saclay data. Lines (G. I. Lykasov, 1993, see in refs. [55–64]): *1* — calculation within the "Impulse Approximation" (IA) with the deuteron wave function based on the Reid NN potential, *2, 3* — results of his more elaborated calculations with the "Reid" (line 2) and "Paris" (line 3) deuteron wave functions, *4* — calculations with allowance for the composite $6q$-component in the deuteron wave function, *5* — QCD motivated asymptotic prediction (A. P. Kobushkin, see ref. [65]).

Also, with the SPHERE spectrometer, experimental investigations of polarization-dependent effects were done for cumulative pion production processes, as well as for processes of the deuteron inclusive breakup with registration of cumulative protons emitted with large transverse momenta. In particular, data on the tensor analyzing power T_{20} in cumulative meson production (see refs. [72, 73]), as well as data on the tensor analyzing power A_{yy} at large transverse momenta of pions [74] were obtained. For processes of the deuteron breakup with emission of cumulative protons, the data on the tensor analyzing power A_{yy} were obtained at different initial deuteron energies and large transverse momenta of the emitted protons (see refs. [75–78]).

A vectorially polarized deuteron beam at 1 GeV/nucleon and the hydrogen bubble chamber were used to obtain the polarization data on the mesonless breakup [79] and dp elastic scattering [80].

4.2. Experiments at external nucleon beams

A very important part of experiments with polarized nucleons, performed using polarized deuteron beams from the Synchrophasotron and the Nuclotron, was measurements of the energy dependence of the $\Delta\sigma_L$ value for np scattering, when both participants were polarized along the beam direction (refs. [81–83]). Such investigations were performed by an international collaboration with the use of a Movable Polarized proton Target (MPT) (see refs. [84, 85]; the beam of polarized neutrons was obtained by breakup of the vectorially polarized deuterons.

Quasi-monoenergetic beams of polarized protons or neutrons can be produced by breakup of accelerated polarized deuterons. That was used for a new generation of the JINR experiments to investigate NN interactions at the intermediate and high energy, when both participants were polarized. In order to get full benefit of this opportunity, experiments with polarized beams must be performed in conjunction with polarized proton or deuteron targets. Many tests of the fundamental laws and particle productions in such interactions, which could be dependent on the spin orientations of the beams or target nucleons, became possible.

A polarized proton target (PPT, 20 cm long and 3 cm in diameter), used previously at Fermilab, became available for experiments at JINR. A collaboration of scientists from 9 countries was set up in order to reconstruct this PPT as a Movable Polarized Target (MPT), which could be easily transported from one beamline to another and to get this unit operating outside of Russia. The main goal of the reconstruction was to set all the target elements on two decks, which could be moved as blocks, to set the apparatus "in" and "out" of the beam for easy maintenance.

1.2-propanediol with a paramagnetic Cr(5) impurity having a spin concentration of 1.5×10^{20} cm^{-3} was used as the target material. The maximum values of proton polarization obtained were 80 and 85% for positive and negative polarizations respectively [84, 85]. In order to measure $\Delta\sigma_L(np)$ using a polarized neutron beam from deuteron fragmentation scattered at a polarized proton target, a new setup was constructed.

The results on $-\Delta\sigma_L(np)$, obtained in transmission experiments [81–83], complete mainly the measurements of the energy dependence in the range of the Dubna Synchrophasotron (Figure 20). The measured values $-\Delta\sigma_L(np)$ are in agreement with the existing data at lower energies. The energy dependence of $-\Delta\sigma_L(np)$ shows a rapid decrease to zero above 1.1 GeV
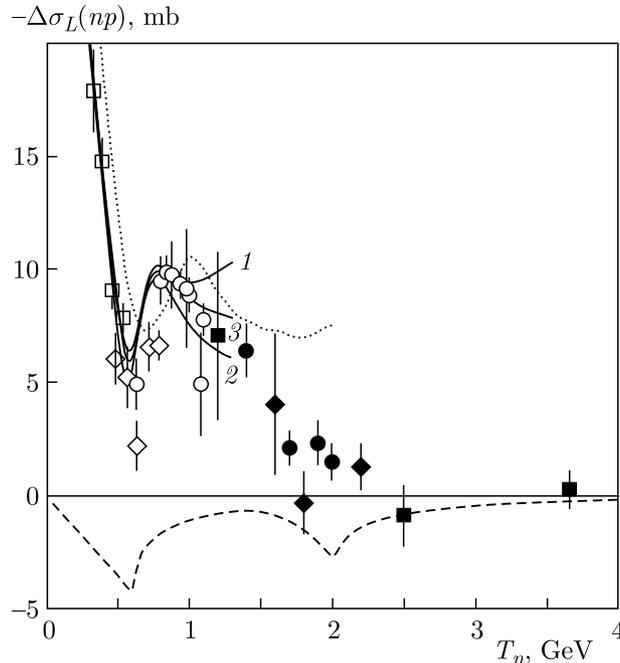

Figure 20. Energy dependence of $-\Delta\sigma_L(np)$. The solid and open points were measured at JINR and at PSI, LAMPF, Saturne II, respectively. Solid curves *1*, *2*, and *3* — FA85, SP99, and SP03 ED GW/VPI PSA solutions, respectively. The dotted and dashed curves are the prediction of meson-exchange model and contribution from nonperturbative QCD interaction induced by instantons, respectively. The data tables with a compilation of all experimental data can be found in the book [86], see Tabs. B17–B25 in that book.

and a possible structure around 1.8 GeV. The data obtained are compared with the predictions of partial wave analysis and different theoretical models.

4.3. Experiments at internal beams of the Nuclotron

Apart from experiments at extracted beams of the Synchrophasotron and the Nuclotron, physicists conducted experiments at internal beams of these machines. In particular, many new experimental data were obtained for the reaction of elastic dp scattering in a rather wide interval of the scattering angles around 90° in the reaction cms. Such studies were performed within the Deuteron Spin Structure (DSS) experiment at ITS working at the internal beams of the Nuclotron.

The DSS experiment was focused on studying the spin-dependent parts of the $2N$ and $3N$ correlations by measuring the deuteron analyzing powers in dp elastic scattering at Nuclotron energies [87, 88]. The first results on the vector A_y and tensor A_{yy} and A_{xx} analyzing powers of elastic dp elastic scattering in a wide range of the scattering angles around 90° in the cms were obtained at ITS of the Nuclotron at kinetic energies of deuterons T_d of 880 MeV (Figure 21 and ref. [89]) and 2000 MeV [90]]. Systematic data on the cross section [91] were obtained at large angles in the cms.
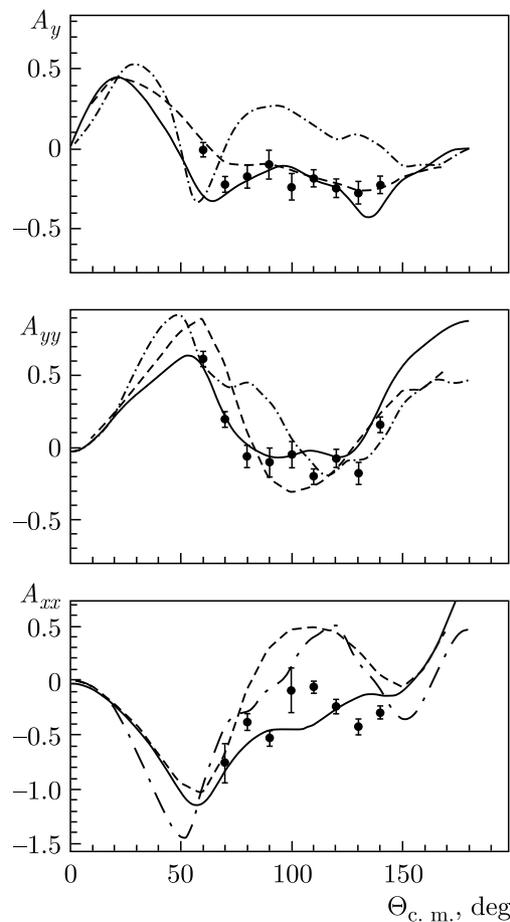

Figure 21. The data on the vector (A_y) and tensor $(A_{yy}$ and $A_{xx})$ analyzing powers in elastic dp scattering obtained at the Nuclotron at $T_d = 880$ MeV [89]. The lines represent results of theoretical calculations, based on different approaches.

The data on the angular dependence of vector A_y and tensor A_{yy} and A_{xx} analyzing powers in elastic dp scattering were obtained at several energies from 400 to 1800 MeV using a polarized deuteron beam. The data on A_y and A_{yy} at large scattering angles in the cms show positive and negative asymptotic values, respectively.

4.4. Collaborative work at polarized beams at other facilities

Among the results of experiments at the Synchrophasotron and the Nuclotron was establishment of quite fruitful collaboration with physicists worked at Saturne-II in Saclay. Quite a bright example of such cooperative work was the joint Dubna–Saclay–Virginia experiment on studies of the tensor analyzing power T_{20} and polarization transfer coefficient κ_0 for dp backward elastic scattering [58]. It was done at SATURNE-II using a polarized deuteron beam of high intensity and the POMME proton focal plane polarimeter [92]. Also, there were done measurements of the analyzing powers (A_y and A_{yy}) in $p(d, d')X$ scattering in the region of the Δ and Roper resonances' excitations [70]. That was done by the JINR-France-PNPI Collaboration, which used a polarized deuteron beam and the SPES4 π spectrometer at SATURNE-II. The studies were the natural continuation of the program of the study of the "nuclear Delta-excitations", started at the Synchrophasotron with the use of ^{3}He beams. The tensor analyzing power T_{20} in inclusive forward scattering of deuterons on hydrogen and carbon, $A(d, d')X$, in the region of the resonance excitations was measured at the Synchrophasotron.

Apart from the experiments with unpolarized and polarized deuterons, reactions with other beams of the lightest nuclei were performed at the Synchrophasotron and other accelerators. In particular, experiments with unpolarized ^{3}He as well as with polarized ^{3}He beams were done at several facilities. In those experiments, the invariant cross sections of the unpolarized ^{3}He projectile fragmentation into deuterons and protons at small transverse momenta were measured at the Synchrophasotron. The idea of the experiments on measurements of the spin observables in ^{3}He inclusive breakup fragmentation into deuterons [93] was proposed at JINR. For those purposes, the new focal plane high-energy deuteron polarimeter HYPOM [94] was developed and calibrated. It had a unique three-cell liquid hydrogen target with plane geometry [95]. In particular, for the first time in the world, in the collaborative experiment [96] at SATURNE-II (Saclay), data were obtained for the tensor polarization ρ_{20} of the deuteron fragment, emitted "forward" in the fragmentation of the polarized ^{3}He projectile.

The studies of the ^{3}He (and ^{3}H) spin structure with the active role of JINR physicists were continued at RIKEN and RCNP facilities in Japan. For the first time in the world, the spin correlation coefficient C_{yy} was measured in backward elastic scattering ^{3}He$(p, {}^3$He$)p$, with a polarized proton beam and a polarized ^{3}He target, as well as the corresponding differential cross sections. The GRAND RAIDEN spectrometer (at RCNP) was used in those measurements [97]. The vector (A_y) and the tensor (A_{yy}, A_{xx} and A_{xz}) analyzing powers in the $dd \to {}^3$He n and $dd \to {}^3$H p [98–100] were measured at RIKEN using the SMART spectrometer.

5. Conclusions

The development of the unique cryogenic source of polarized deuterons POLARIS and the beam polarimetry was very fruitful and significantly enhanced the instrumental base for studies of polarization phenomena at the Synchrophasotron and the Nuclotron. The commissioning of the SPI in 2016–2017 opened new opportunities for continuation of such studies at the Nuclotron/NICA complex.

The obtained experimental data significantly influenced the worldwide understanding of spin-dependent effects in nucleon-nucleon and nucleon–nuclei interactions at high energies,

the deuteron spin structure at short internuclear distances. These results were successfully published and awarded with many JINR prizes. The results obtained at the LHEP Accelerator Complex were used to measure the electromagnetic formfactors of the proton and neutron, and as a motivation to perform experimental investigations of the ^{3}He spin structure at short distances at other facilities within wide international collaborations.

Further development of the instrumental base, namely, the systems of proton beam polarization preservation and control based on solenoindal siberian snakes and spin navigators, as well as the high energy polarimetry at NICA is necessary to fulfill the experimental program proposed for SPD.

Acknowledgments

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