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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

# Vector Analyzing Power in Quasi-Elastic Proton-Proton Scattering at an Energy of 500 MeV/nucleon

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**Abstract**—The values of the analyzing power in quasi-elastic proton-proton (*pp*) scattering are obtained at the Nuclotron Internal Target Station using a polarized deuteron beam at an energy of 500 MeV/nucleon and the polyethylene target. The selection of useful events has been performed using the time and amplitude information from scintillation counters. Asymmetry by protons has been obtained by the subtraction of the carbon background from the data accumulated on polyethylene. The analyzing power values are compared with predictions of SAID partial-wave analysis and the data of other experiments.

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## 1. INTRODUCTION

Experiments to study proton-proton (*pp*) elastic scattering are fundamental for understanding nucleon-nucleon interactions [1]. For energies below 1 GeV, a large database of cross sections and polarization observables was obtained in various ranges of scattering angles. These data are well described by the solutions obtained using partial wave analysis [2–11].

Modern phenomenological potential models provide a good description of the data up to the threshold of the pion production. However, the extension of the meson exchange model to high energies requires the inclusion of contributions from inelastic channels due to the excitation of baryon resonances.

On the other hand, elastic *pp* scattering is well suited for studying the short-range part of nucleon-nucleon interactions. Accurate values of the analyzing power at energies above the pion production threshold make it possible to clarify the contribution of the spin-orbit forces that are sensitive to the exchange of heavy mesons.

In the course of the work, we obtained the values of the vector analyzing power of the reaction of interaction between deuterons and protons in the kinematics of *pp* elastic scattering at an energy of 500 MeV/nucleon.

Section 2 illustrates the general layout of the experiment. The procedure for selecting useful events on polyethylene and carbon is described in Section 3. The details of the process of subtracting carbon background from polyethylene data are explained in Section 4. Beam shift modeling was used to correct detector adjustment angles. The corresponding results are given in Section 5. Section 6 describes the acquisition of the values of analyzing power. Section 7 describes finding the polarization values of a deuteron beam. The values of analyzing power and beam polarization are presented in Section 8, and the conclusion is formulated in Section 9.

## 2. EXPERIMENTAL LAYOUT

The experiment was carried out at the internal target station [12, 13] of the Nuclotron—a superconducting synchrotron located at the Laboratory of High Energy Physics at JINR.

The experiment was carried out as follows: a beam of polarized deuterons was generated by a source of polarized ions [14, 15]; the polarization of deuterium nuclei was performed using radiofrequency transitions of the hyperfine structure and polarized deuterons were accelerated by a linac, and then injected into the Nuclotron ring for further acceleration. Upon reaching a given energy, the disk with targets rotated, put-

**Table 1.** Average polarization values obtained using dp elastic scattering at an energy of 135 MeV/nucleon [16] for spin modes 2-6 and 3-5

| Spin mode | $p_y$ | $\Delta p_y$ |
|---|---|---|
| 2-6 | 0.231 | 0.008 |
| 3-5 | 0.245 | 0.006 |

ting the desired target onto the beam trajectory. Particles obtained from the interaction of the beam with the target were recorded by scintillation detectors.

The experiment used an ion source developed for the Nuclotron and the NICA collider. It is an atomic source of beam-type polarized ions with a charge-exchange plasma ionizer and a storage cell. Atomic deuterium was obtained from molecular deuterium using a radio frequency plasma dissociator. Atomic deuterium then passed through a cooling channel, the walls of which were cooled to 80 K. The atoms then passed through a sextupole magnet, which focused atoms with atomic polarization 1/2 and defocused the rest. Nuclear polarization of deuterium atoms was achieved using a complex system of magnetic fields of varying strengths. The polarized deuterium then entered an accumulation cell located inside the solenoid. The ionization of atoms was achieved by injecting protons in the direction opposite to the movement of deuterium. Thus, a charge exchange reaction between deuterium and protons was occurring. As a result, deuterons were produced at the exit from the cell.

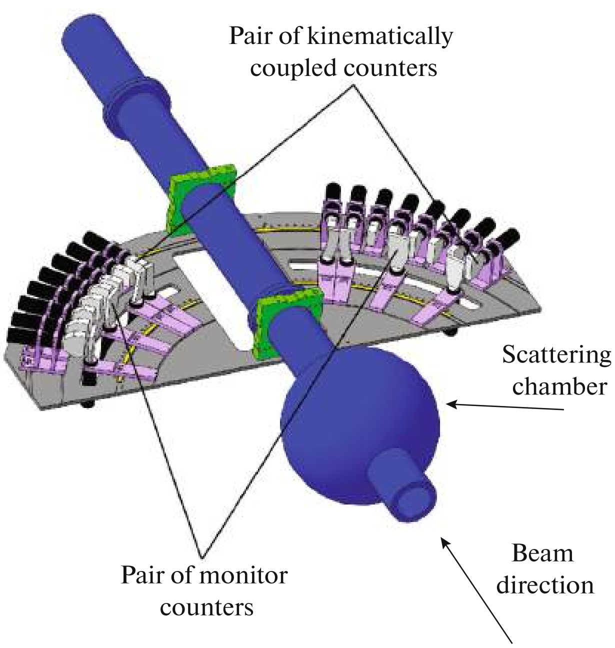


**Fig. 1.** Layout of detectors for an experiment to study the analyzing power $A_y$ in *pp* quasi-elastic scattering at the Nuclotron internal target station. The detectors were installed in accordance with kinematics of the *pp* elastic scattering.

The polarization of the deuteron beam was achieved through the radio-frequency transitions in hyperfine structure. Three spin modes of a source of polarized ions were used in the experiment: unpolarized, 2-6 and 3-5, with maximum theoretical values $(p_y, p_{yy}) = (0,0)$, $(+1/3,+1)$, and $(+1/3,-1)$, respectively. The spin modes of the source were changing alternately from cycle to cycle. The polarization quantization axis was located perpendicular to the plane of the Nuclotron ring.

Beam polarization was measured using deuteron-proton (dp) elastic scattering at a beam energy of 135 MeV/nucleon [16]. This procedure was performed regularly during the experiment, alternating with sets at other energies. When carrying out calculations, the beam was assumed to have the same degree of polarization at higher energies. The values of the vector component of polarization are shown in Table 1.

The internal target station is a spherical vacuum chamber with a target changing system [12]. The chamber is fixed to the accelerator ion tube using a flange connection. A disk with various targets ($CH_2$ (polyethylene), C, W, Cu, etc.) is fixed inside the chamber on the axis of the stepper motor. The targets were installed inside slots in the disk. During beam acceleration, the disk is turned with an empty slot and, upon reaching the required energy, the disk rotates, introducing the desired target into the ion tube [13]. For the experiment, polyethylene film with a thickness of 10 μm was used. To evaluate the background from carbon contained in polyethylene, a target consisting of ten twisted carbon filaments, each 8 μm in thickness, was used.

Particles obtained during the interaction of the beam with the target were recorded by scintillation counters located around the scattering chamber in the direction of the beam (Fig. 1). The counters were mounted in such a way as to record the reaction products of pp quasi-elastic scattering. The experiment used 22 detectors to record protons scattered to the left and right. They were located at the same angles symmetrically relative to the ion tube axis. To use the largest scintillator area to compensate for the kinematic scattering angles of a pair of particles, detectors of different sizes were used. Two additional detectors were located symmetrically relative to the beam direction at 90° in the center-of-mass system (CMS), which ensured their insensitivity to the vector polarization of the beam. They were also called monitor counters.

In the experiment, part of the detectors of a deuteron polarimeter was used. The latter uses the asymmetry of *dp* elastic scattering at an energy of 135 MeV/nucleon [17]. Scintillator parameters, as well as detector installation angles in the laboratory system and in the CMS for a beam energy of 500 MeV/nucleon are listed in Table 2. The installation

**Table 2.** Dimensions and installation angles of detector scintillators in the laboratory system and CMS used in the polarimeter to measure the analyzing power at a deuteron beam energy of 500 MeV/nucleon. The detectors were installed symmetrically to the right and left relative to the center of the ion tube

| Setting angles °, CMS | Lab. Setting angles,° | Width, mm | Height, mm | Thickness, mm | Distance to the point of interaction, mm |
|---|---|---|---|---|---|
| 55 | 24.8 | 20 | 40 | 20 | 580 |
| 58 | 26 | 24 | 40 | 10 | 555 |
| 62 | 28.4 | 24 | 40 | 10 | 555 |
| 65 | 29.5 | 20 | 40 | 20 | 580 |
| 75 | 34.3 | 20 | 40 | 20 | 580 |
| 85 | 39.2 | 20 | 40 | 20 | 580 |
| 90 | 41.6 | 50 | 60 | 10 | 555 |
| 95 | 44.1 | 20 | 60 | 20 | 580 |
| 105 | 49.2 | 20 | 60 | 20 | 580 |
| 115 | 54.4 | 20 | 60 | 20 | 580 |
| 120 | 57.0 | 50 | 40 | 10 | 555 |
| 125 | 59.6 | 20 | 60 | 20 | 580 |

angles in the CMS are the ideal values corresponding to the passage of the primary beam through the center of the ion tube. The software part of the data acquisition system is described in more detail in [18].

## 3. SELECTION OF USEFUL EVENTS

To select events in the experiment, pairs of detectors were used, installed in accordance with the kinematics of pp elastic scattering (see Table 2). Useful events were allocated using criteria for the difference in signal arrival times and the correlation of energy losses in kinematically coupled scintillation detectors, as well as taking into account the position of the interaction point.

The target position was recorded for each event during the experiment. Therefore, it is possible to discard events that are far from the point where the maximum number of events were observed [19]. The dependence of the number of events on the position of the target at the moment of interaction with the beam is shown in Fig. 2. Dashed lines are the criteria that were used to discard events located far from the point of interaction between the beam and the target.

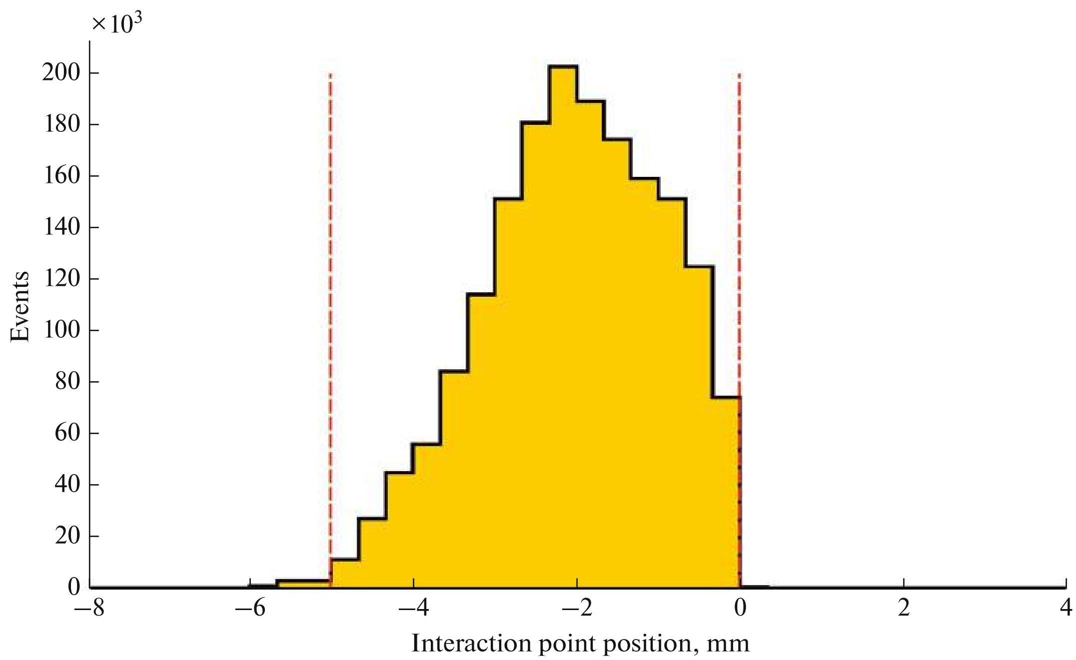


**Fig. 2.** Number of events depending on the position of the target at the moment of interaction with the beam relative to the center of the ion tube. Dashed lines show the criterion for selecting events.

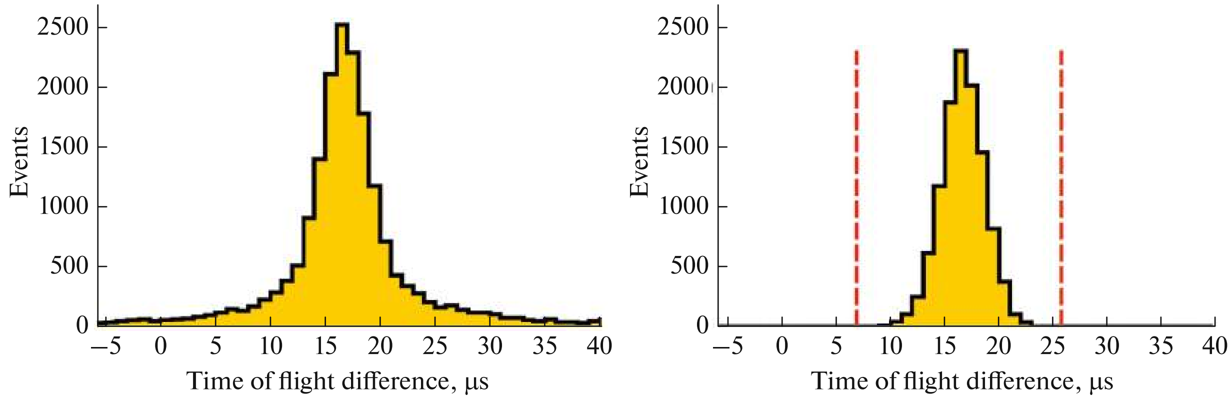


**Fig. 3.** Criterion for selecting events based on the difference in the arrival time of signals from two kinematically coupled detectors for an angle of 65° in the CMS. Left: dependence of the difference in arrival time on the number of events before setting the criteria. Right: dependence of the difference in arrival time on the number of events after applying the criterion for the difference in arrival time, the correlation of energy losses, and the target position. Dashed lines are the criterion for selecting events.

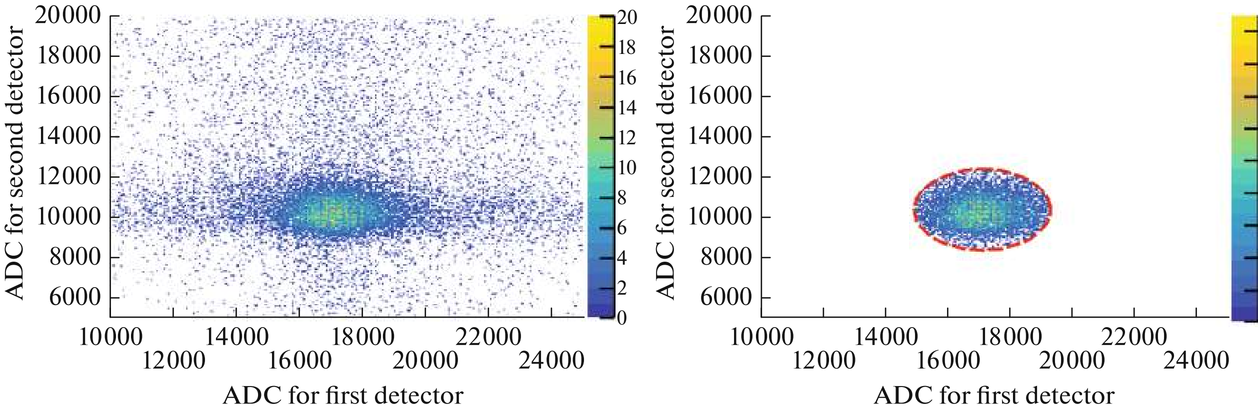


**Fig. 4.** Selection criterion for correlation of energy losses in two kinematically coupled detectors for an angle of 65° in the CMS. Left: correlation of energy losses without applying criteria. Right: correlation of energy losses after setting the criterion for the correlation of energy losses and the difference in arrival time. The dashed line is the event selection criterion.

The time of flight difference shows the difference between the arrival time of signals from two kinematically coupled counters (Fig. 3). Only events with a relatively small time difference are taken into account in the final calculations.

The correlation histogram of energy losses of kinematically connected counters is shown in Fig. 4. One can clearly distinguish a spot on this hystogram, which relates to pp elastic events. Only events located inside the selected area are accounted for. The criteria for the difference in signal arrival times and for the correlation of energy losses were optimized to improve the selection of useful events.

## 4. CARBON BACKGROUND SUBTRACTION

Since the deuteron beam interacted with the polyethylene target, a background inevitably appeared in the data. The number of events from interaction with carbon in the $CH_2$ target was estimated from measurements using a carbon target consisting of several threads.

The shape of the carbon spectrum was assumed to be the same when scattered by polyethylene and carbon targets (Fig. 5). The procedure for subtracting the carbon background consisted of finding the coefficient by which it is necessary to multiply the data obtained on the carbon target to approximate the background in the data obtained on the polyethylene target. The following formulas were used to carry out the subtraction procedure:

$$N_{\mathrm{p}} = N_{\mathrm{CH_2}} - kN_{\mathrm{C}}, \tag{1}$$

$$\delta N_{\mathrm{p}} = \sqrt{N_{\mathrm{CH_2}} + \delta k^2 N_{\mathrm{C}}^2 + k^2 N_{\mathrm{C}}}, \tag{2}$$

where $N_{\mathrm{p}}$ is the total number of events on protons, $\delta N_{\mathrm{p}}$ is the error in calculating the number of events on

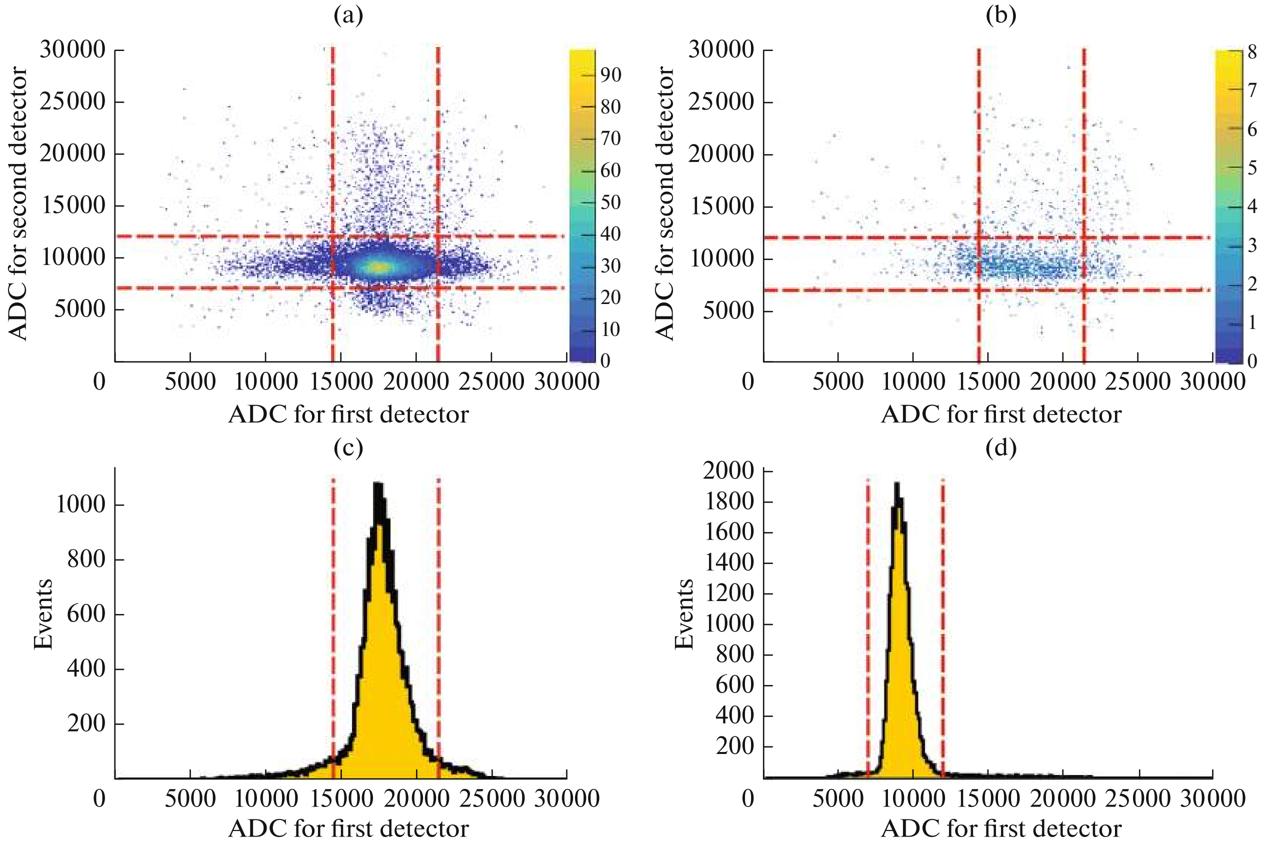


**Fig. 5.** Process of setting criteria for the CH–C subtraction procedure for an angle of 55° in the CMS: (a) correlation of ionization losses for a polyethylene target, (b) correlation for a carbon target, (c) projection of the correlation of ionization losses for polyethylene on the $X$ axis, and (d) correlation projection for polyethylene on the $Y$ axis. The dotted lines show the criteria for the background subtraction procedure.

protons, $N_{CH_2}$ is the total number of events on polyethylene, $N_C$ is the total number of events on carbon, $k$ is the required coefficient, and $\delta k$ is the error in calculating the coefficient.

Coefficient $k$ can be found in several ways: using the least squares method, the spectral summation method, and the spectral approximation method. The least squares method assumes that in the data on the correlation of the amplitude of ionization losses from kinematically coupled counters (Fig. 4), obtained from scattering on a polyethylene target, a region of useful events corresponding to pp elastic scattering was identified. This area is shown by dashed lines in Fig. 5. This criterion was also taken into account for the carbon target in the data on the correlation of ionization losses. The spectrum obtained on carbon was approximated to the spectrum obtained on polyethylene using the least squares method, taking into account events located outside the selected region. As a result, the required coefficient $k$ was obtained.

The spectral summation method used the same criteria as the least squares method. The coefficient $k$ was determined by finding the ratio of the number of events outside the criteria in the polyethylene data to the number of events outside the criteria in the carbon data.

The method of approximating the spectrum with analytical functions used a different approach. First, the spectrum with data obtained on carbon was approximated by the sum of two Gaussians. Then the spectrum on polyethylene was approximated by the sum of the Gaussian and the function obtained after approximating the data on carbon, multiplied by coefficient $k$. A single Gaussian described the proton data.

The $N_p$ and $\delta N_p$ values were calculated separately for each mode of the source of polarized ions. To obtain the final result, the coefficient found using the least squares method was used. The remaining methods were used to estimate the systematic error associated with the carbon background subtraction procedure. Table 3 represents the number of events for an angle of 85° in the CMS obtained using various methods for the carbon background subtracting. The results agree within 10%.

**Table 3.** Number of events for an angle of 85°CMS obtained using various methods of subtracting the carbon background, as well as taking into account criteria for the target position and the difference in the time of arrival of the signal and the correlation of energy losses. Data are presented for the unpolarized mode of the ion source

| Method for finding the coefficient | $k$ | $\Delta k$ | $N_p$ | $\delta N_p$ |
|---|---|---|---|---|
| Least squares method | 3.29 | 0.03 | 6531 | 96 |
| Integral | 4.90 | 0.30 | 5950 | 162 |
| Approximation | 4.57 | 0.12 | 6352 | 199 |

Figure 6 shows the result of subtracting the carbon background from the data obtained on the polyethylene target. A good coincidence is seen between the data obtained on the carbon target, multiplied by the factor $k$, and the background in the data obtained on polyethylene. The coefficient $k$ here was obtained using the least squares method. The figure shows data for the unpolarized mode of the ion source. The dashed line is the horizontal semiaxis of the elliptical criterion for selecting useful events, shown in Fig. 4.

The resulting number of proton events was obtained by bin-by-bin subtraction of the carbon data from the polyethylene histogram. To calculate the number of events, data were used taking the criteria for the position of the target into account, the difference in arrival times of signals, and the correlation of energy losses. The number of proton events is necessary to determine the asymmetry of particle scattering. Asymmetry, in turn, is needed to calculate the beam polarization or the analyzing power of the reaction.

## 5. BEAM POSITION SIMULATION

While the detectors were positioned symmetrically relative to the center of the ion tube, the resulting events were recorded with a shift, which can be seen in Fig. 2. However, the installation angles of the detectors can be corrected using data on the position of the target at the moment of interaction with the beam in order to eliminate the appearance of false asymmetry.

For this procedure, $pp$ elastic events were generated using the Pluto generator for an energy of 500 MeV. It represents a set of libraries for the ROOT

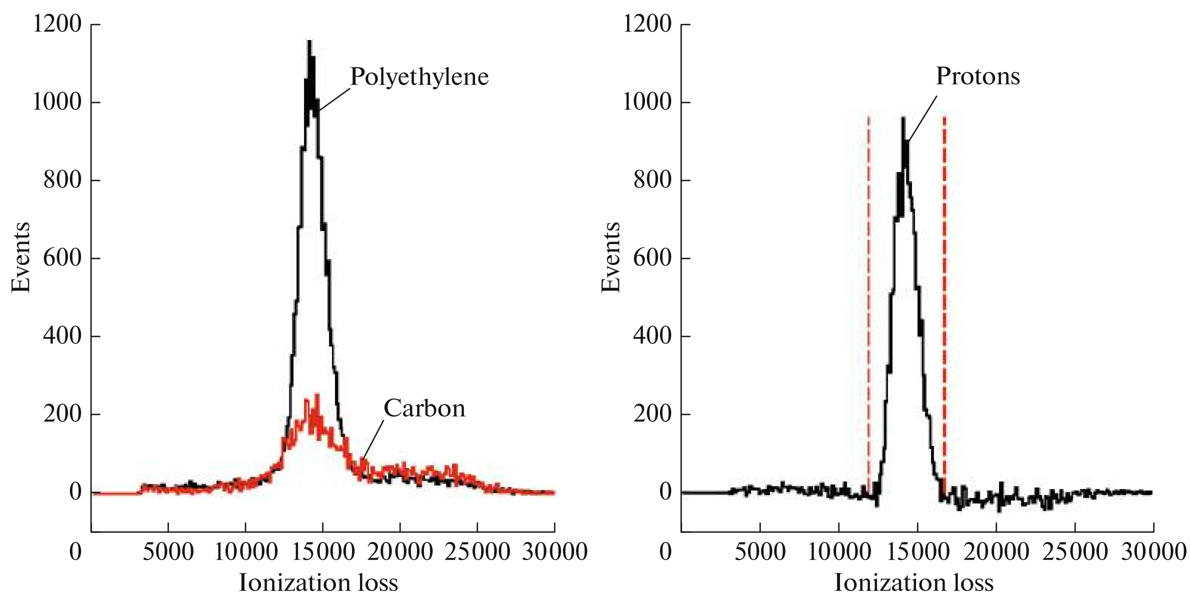


**Fig. 6.** Result of the carbon background subtraction procedure at a scattering angle of 85° in the CMS for the unpolarized mode of the ion source. Left: ionization loss histograms for data obtained on polyethylene and carbon targets. The data on carbon were previously multiplied by the factor $k$. Right: histogram after subtracting the carbon background from the histogram on polyethylene. The dashed line is the horizontal semiaxis of the elliptical event selection criterion shown in Fig. 4.

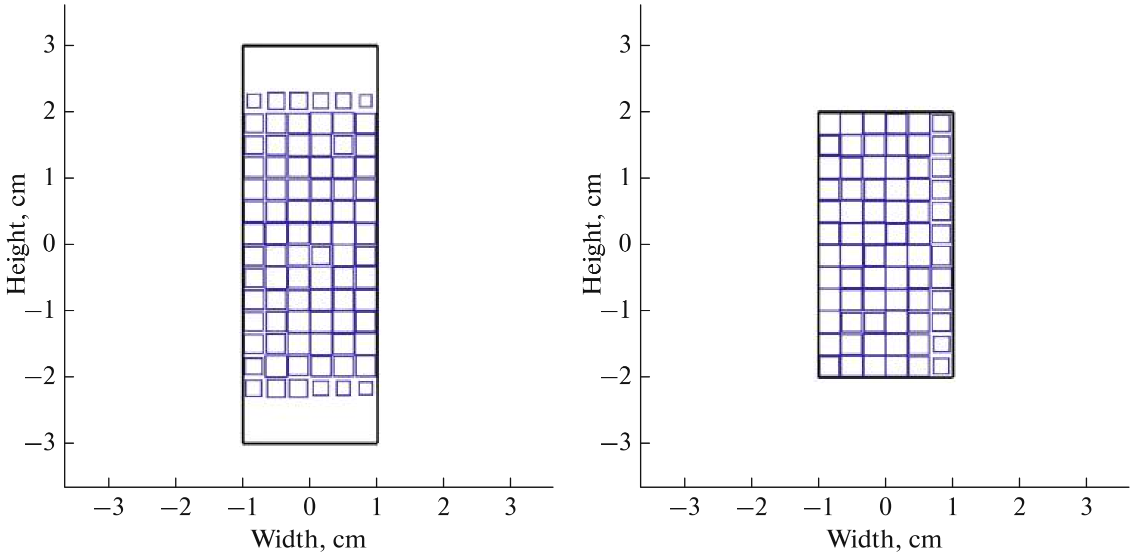


**Fig. 7.** Example of the output data on detector striking by particles as a result of modeling the behavior of the beam for an angle of 85 in the CMS. The figures show the striking in the pair of kinematically coupled detectors with allowance for their coincidence. The left detector is given on the left and the right detector is given on the right (relative to the beam direction). Solid lines show the boundaries of the detectors.

software package. The angular dependence of *pp* elastic scattering was taken from the SAID SP07 solution.

The scattering profile of the incident proton in the horizontal plane for the simulation was generated based on the shape of the distribution presented on the histogram in Fig. 2. Next, using the angles for the two scattered particles in the event, it was checked whether the particles hit the kinematically coupled detectors.

The installation angle of the detector in CMS was determined by averaging the angles of all particles that hit the detector.

An example of the output of information on striking the detector by particles is presented in Fig. 7. This information was used to monitor the accuracy of the simulation process.

## 6. CALCULATION OF ANALYZING POWER

The pp quasi-elastic scattering analyzing power values were calculated using data obtained by subtracting the carbon background from the polyethylene target data. For this purpose, equations were used that were obtained using formulas from [20] for the case described in this article:

$$\frac{N_{\rm L}}{M} = \frac{N_{\rm L}^0}{M^0}(1 + P_y A_y), \quad (3)$$

$$\frac{N_{\rm R}}{M} = \frac{N_{\rm R}^0}{M^0}(1 - P_y A_y), \quad (4)$$

where $N_{\rm L}$ and $N_{\rm R}$ are the numbers of events when scattering to the left and to the right, $M$ is the number of events of monitor counter, $P_y$ is the vector polarization value, and $A_y$ is the vector analyzing power of scattering.

To determine the vector analyzing power $A_y$ of the pp quasi-elastic scattering, 13 different pairs of counters were used: 6 pairs for scattering to the left, 6 pairs for scattering to the right, and 1 pair for scattering at 90° in CMS The results obtained for scattering to the left and to the right were then averaged using the weighted average rules for each angle in the CMS. The following formulas were used to calculate the analyzing power:

$$A_{y\rm L} = \frac{\dfrac{N_{\rm L}^+ M^0}{N_{\rm L}^0 M^+} + \dfrac{N_{\rm L}^- M^0}{N_{\rm L}^0 M^-} - 2}{P_y^+ + P_y^-}, \quad (5)$$

$$A_{y\rm R} = -\frac{\dfrac{N_{\rm R}^+ M^0}{N_{\rm R}^0 M^+} + \dfrac{N_{\rm R}^- M^0}{N_{\rm R}^0 M^-} - 2}{P_y^+ + P_y^-}, \quad (6)$$

where $A_{y\rm L}$ and $A_{y\rm R}$ is the vector analyzing powers for scattering of pairs to the left and right, respectively. $N_{\rm L}^+$, $N_{\rm L}^-$, and $N_{\rm L}^0$ are the numbers of events in a particular pair when scattering to the left and right for polarized ion source modes 2-6, 3-5, and the unpolarized mode, respectively. $N_{\rm R}^+$, $N_{\rm R}^-$ and $N_{\rm R}^0$ are the numbers of events in a particular pair when scattering to the right for modes 2-6, 3-5, and the unpolarized mode, respectively. $M^+$, $M^-$, and $M^0$ are the numbers of events in monitor counters for the corresponding spin

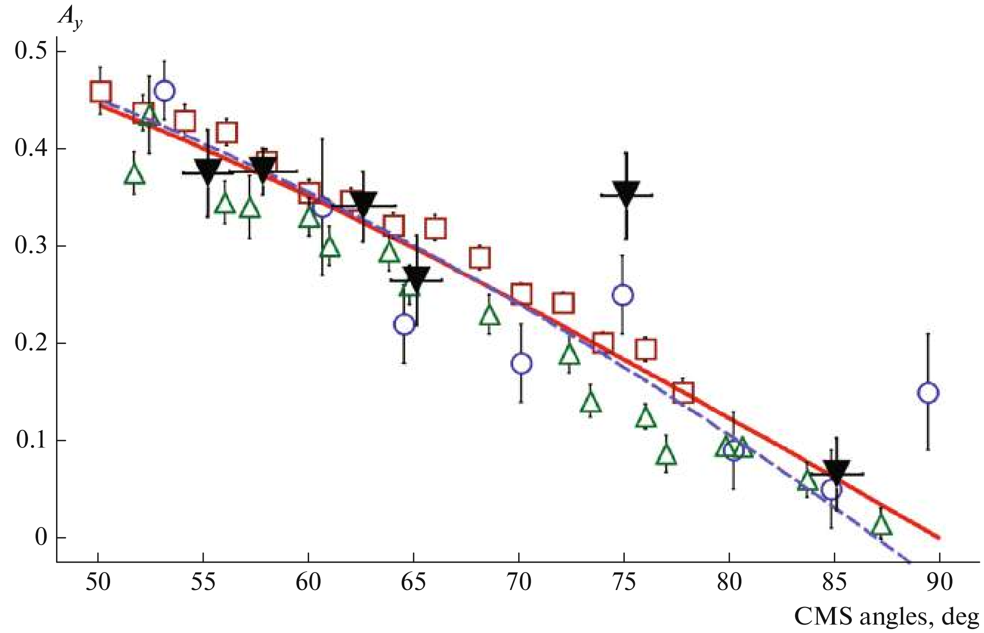


**Fig. 8.** Comparison of the analyzing power in the pp quasi-elastic scattering reaction at 500 MeV/n with global data and the results of the SAID SP07 partial wave analysis. Filled symbols are the results of this experiment. Unfilled symbols are data obtained in other experiments: circles [21], squares [22], and triangles [23]. Solid line indicates predictions by SAID SP07 [10]. Dashed line indicates approximation of data from other experiments by a second-degree polynomial.

modes. $P_y^+$ and $P_y^-$ are the values of the vector polarization of the beam for polarized ion source modes 2-6 and 3-5 , respectively, shown in Table 1.

## 7. POLARIZATION CALCULATION

Using data on the asymmetry of pp scattering, one can find not only analyzing powers, but also the polarizations of the beam. For this purpose, the same yields of the pp quasi-elastic scattering reaction were used as in the calculation of the analyzing power. To calculate the polarization, the following expressions also obtained from (3) and (4), were used:

$$P_y^+ = \frac{\dfrac{N_L^+ M^0}{N_L^0 M^+} - \dfrac{N_R^+ M^0}{N_R^0 M^+}}{2A_y}, \quad (7)$$

$$P_y^- = \frac{\dfrac{N_L^- M^0}{N_L^0 M^-} - \dfrac{N_R^- M^0}{N_R^0 M^-}}{2A_y}, \quad (8)$$

where $P_y^+$ and $P_y^-$ are the values of the vector polarization of the beam for modes 2-6 and 3-5 of the source of polarized ions, respectively. $N_L^+$ and $N_R^+$ are the numbers of events for polarized mode 2-6 when scattering to the left and right, respectively. $N_L^-$ and $N_R^-$ are the numbers of events for polarized mode 3-5 when scattering to the left and right, respectively. $N_L^0$ and $N_R^0$ are the numbers of events for unpolarized mode when scattering to the left and right, respectively. $M^+$, $M^-$, and $M^0$ are the numbers of events in monitor counters for the corrresponding spin modes, and $A_y$ is the vector analyzing power of reaction.

Polarization values were calculated for each angle in CMS separately (in fact, for each pair) and then averaged using the weighted average rules to obtain the current energy values.

## 8. RESULTS AND DISCUSSION

The resulting angular dependence of the vector analyzing power $A_y$ in pp quasi-elastic scattering at a beam energy of 500 MeV/n is presented in Fig. 8. Filled symbols show the results obtained in this experiment. Unfilled symbols are data obtained in other experiments with the same or similar energy: circles [21], squares [22], and triangles [23].

Figure 8 shows only statistical errors. The systematic error associated with the accuracy of measuring beam polarization is 3.7%. The systematic error due to the carbon background subtraction procedure varies from 5 to 50% depending on the scattering angle. The mean angles and their spread, indicated by the horizontal lines in Fig. 8, were obtained from the simulations described in Section 5.

**Table 4.** Analyzing power $A_y$ obtained from the approximation of global data by a polynomial (see formula (9)) and from the SAID SP07 partial wave analysis. These data were used for comparison with the data obtained in this work, as well as to calculate the deuteron beam polarization

| CMS angle, ° | Polinomial | SAID SP07 |
|---|---|---|
| | $A_y$ | $A_y$ |
| 55.2 | 0.405 | 0.399 |
| 57.8 | 0.380 | 0.373 |
| 62.6 | 0.329 | 0.324 |
| 65.1 | 0.301 | 0.297 |
| 75.1 | 0.177 | 0.183 |
| 85.1 | 0.033 | 0.061 |

**Table 5.** Polarization values obtained using *pp* quasi-elastic scattering at an energy of 500 MeV/nucleon by two methods: using the analyzing power obtained by approximating global data [21–23] by a polynomial of the second degree (see formula (9)) and using the analyzing power from SAID SP07 solutions [10]

| Spin mode | Polynomial | | SAID SP07 | |
|---|---|---|---|---|
| | $p_y$ | $\Delta p_y$ | $p_y$ | $\Delta p_y$ |
| 2-6 | 0.245 | 0.013 | 0.249 | 0.013 |
| 3-5 | 0.231 | 0.013 | 0.234 | 0.013 |

The analyzing power values were also compared with the SAID SP07 partial wave analysis [10], represented by the solid line. The dashed line is a result of the approximation of world data [21–23] by a second-degree polynomial of the form:

$$A_y = 0.636 + 0.067\theta - 0.3184\theta^2, \quad (9)$$

where θ is the angle (in radians) in CMS.

Since $A_y$ is antisymmetric relative to the angle 90°(in CMS), the data on analyzing power are presented only for the angular range of 0°–90° when scattering in forward direction (in CMS). There is good agreement between the experimental data and the data of other experiments [21–23], as well as with the results of partial wave analysis SAID [10]

The values of the angle-averaged vector polarization of the deuteron beam at an energy of 500 MeV/nucleon are presented in Table 5. Polarization was calculated using the analyzing power from the SAID SP07 solution [10]. In addition, we used the values obtained by approximating the data of other experiments by a second-degree polynomial (see formula (9) at angles indicated in Table 4). The table shows only statistical errors.

When calculating polarization, asymmetry values were used taking into account criteria for the position of the target at the moment of interaction of the beam with the target, the difference in the arrival times of signals, and the correlation of ionization losses. When subtracting the carbon background, the coefficient obtained using the least squares method was used.

The beam polarization values are shown on the left and right panels in Fig. 9, respectively. They were obtained at an energy of 500 MeV/nucleon using the analyzing power calculated by formula (9), at different angles for spin modes 2-6 and 3-5.

Figure 10 compares the angle averaged beam polarization values with the results obtained at an energy of 135 MeV/nucleon using dp elastic scattering [16]. Only statistical errorrs are shown. The systematic error associated with the subtraction of the carbon background is ~6%. The contribution of the uncertainty of the analyzing power is ~1.3%. One can note good agreement between the results obtained by different methods.

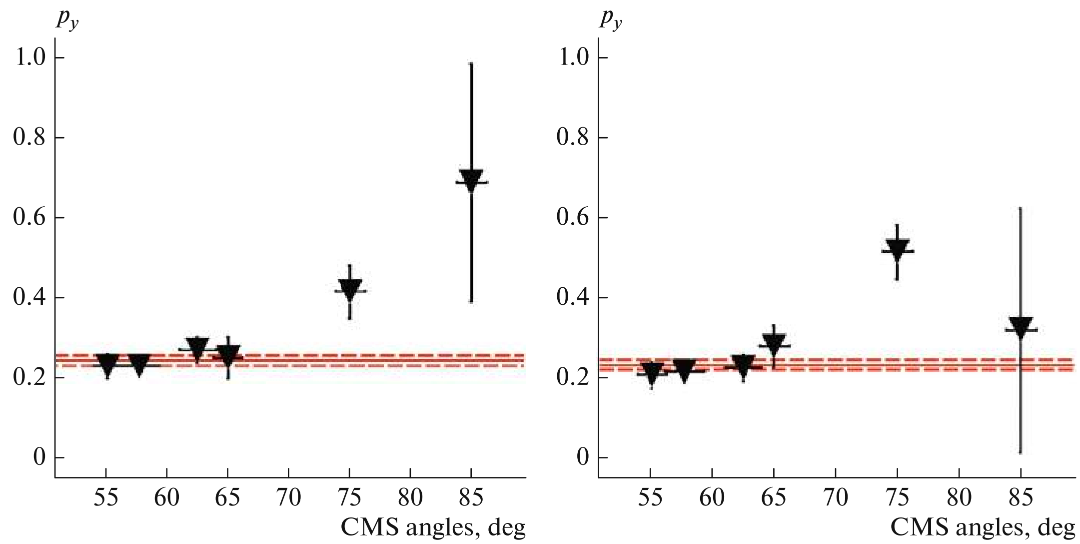


**Fig. 9.** Angular dependence of the vector polarization of the deuteron beam for various modes of the source of polarized ions at an energy of 500 MeV/nucleon: (left) for 2-6 and (right) for 3-5. The analyzing power that was calculated by formula (9) was used. The solid line is the weighted mean of the obtained data. The dotted lines correspond to the error of the weighted average.

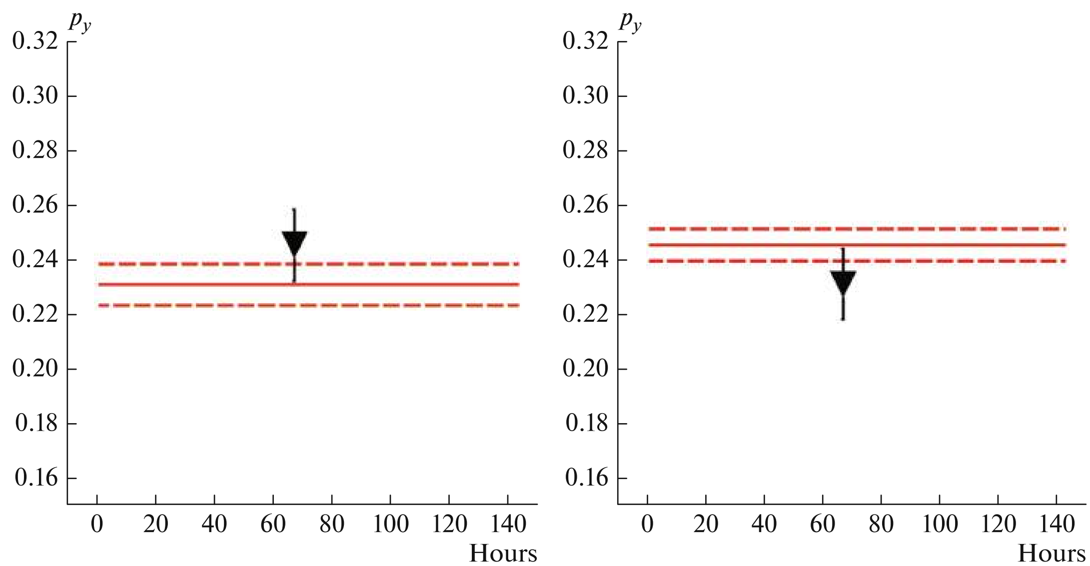


**Fig. 10.** Comparison of vector polarizations of the deuteron beam obtained using the analyzing powers calculated by formula (9) for various modes of the source of polarized ions at an energy of 500 MeV ((left) for 2-6 and (right) for 3-5) with polarization values obtained at deuteron-proton scattering at an energy of 135 MeV/nucleon [16] (the horizontal line shows the data fit). The dotted lines correspond to deviations $\pm\sigma$ from the fitted data.

## 9. CONCLUSIONS

We obtained the vector analyzing power $A_y$ of the pp quasi-elastic scattering reaction using a polarized deuteron beam with an energy of 500 MeV/nucleon. At a given energy and at large CMS angles, the analyzing power of *pp* quasi-elastic scattering was obtained for the first time.

The analyzing power values were compared with data obtained in other experiments [21–23], as well as with the SAID SP07 solution of the partial wave analysis [10]. The results of this work are consistent with world data and SAID results within the obtained accuracy. This indicates that the effects of proton binding in the deuteron and possible rescattering effects are small.

Using the same data on asymmetry, the vector polarization values of the deuteron beam were obtained. The results are in agreement with measurements performed using asymmetry of the dp elastic scattering [16].

The experiment was carried out on the internal target of the JINR Nuclotron in 2016. The rather large statistical uncertainty of the measurements was a consequence of the fact that the experiment was carried out in test mode. In future studies with polarized beams of protons and deuterons, it is planned to improve the accuracy of measurements of analyzing power and polarization by increasing the angular range of measurements and acquisition time of statistics [24].

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## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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