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MEASUREMENT OF THE EXTRACTED DEUTERON BEAM VECTOR POLARIZATION AT THE NUCLOTRON

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The results of the vector polarization measurements of the extracted deuteron beam at the Nuclotron are presented. The intensity of the polarized deuteron beam during the measurements was $\sim 2.5 \cdot 10^7$ particles/spill. The measurements were made at the initial deuteron momenta of 5 and 3.5 GeV/c. The averaged polarizations of the beam were 0.606 ± 0.014 and 0.540 ± 0.019, respectively.

Приведены результаты измерений векторной поляризации пучка дейтронов, выведенного из нуклотрона. Интенсивность пучка поляризованных дейтронов во время измерений составляла $\sim 2{,}5 \cdot 10^7$ частиц/импульс. Измерения выполнены при начальных импульсах дейтронов 5 и 3,5 ГэВ/c. Усредненные значения поляризации пучка составили $0{,}606 \pm 0{,}014$ и $0{,}540 \pm 0{,}019$ соответственно.

INTRODUCTION

The experimental spin program proposed for the Nuclotron (LHE, JINR) requires a good knowledge of the polarization of the primary deuteron beam and/or a continuous monitoring of the vector polarization stability during the experiment. Such experiments are, for example, A_{yy} [1], PIKASO [2], PHe3 [3], DELTA–SIGMA [4], SMS–MGU [5], STRELA, and others, which are planned to be performed at the Nuclotron.

For these purposes the new version of the polarimeter [8, 9] based on the measurement of the asymmetry of quasi-elasic pp scattering on hydrogen in CH_2 target has been installed at the focal point $F3$ in the LHE experimental hall.

The aim of this paper is to present the results of the vector polarization measurements during first extraction of the polarized deuteron beam from the Nuclotron in December 2002.

A brief description of the new version of on-line beam polarimeter is given in Sec. 1. The results of the deuteron beam vector polarization measurements are given in Sec. 2. The effect of the trigger is discussed in Sec. 3. The conclusions are drawn in the last section.

1. POLARIMETER

The measurement of the left-right asymmetry of quasi-elastic pp scattering is the classical method to obtain the value of nucleon beam polarization at intermediate energies. It has been used earlier at SATURNE II [6]. The comparison of the elastic and quasi-elastic pp analyzing powers shows no difference between these quantities in a very large energy range [7]. Using this property, the LHE polarimeter [8, 9] measures $\mathbf{P}_B(d)$ of deuterons provided by the ion source POLARIS [10]. The polarizations of protons and neutrons produced by the deuteron breakup reaction in the forward direction are equal to each other; they are related to the vector polarization of the deuteron beam.

The polarimeter for the measurement of the deuteron beam vector polarization was installed close to the focal point $F3$ of the extraction beam line of the Nuclotron at LHE, JINR. The details of the polarimeter were discussed in Refs. [8, 9]. Here we refer briefly the main changes made for the new version of the polarimeter.

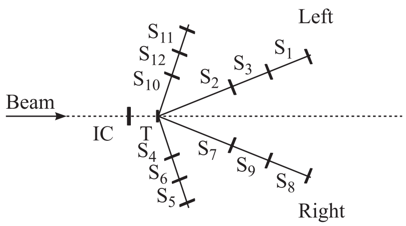

Fig. 1. New version of the beam polarimeter at focal point $F3$. IC is the ionization chamber, T is the CH_2 (or C) target, S_1–S_{12} are the scintillation counters

The layout of the polarimeter is given in Fig. 1. Here S_{1-12} are the scintillation counters, IC is an ionization chamber, T is the target.

The polarimeter measures the left-right (L–R) asymmetry of pp quasi-elastic scattering, detecting both scattered and recoil particles in coincidence. It consists of two pairs of arms in the horizontal plane installed at the angles corresponding to pp-elastic scattering kinematics. Each arm is equipped with three scintillation counters. The six-fold (instead of four-fold in the previous version [8, 9]) coincidence of counter signals from each pair of conjugated arms S_1 to S_6 and S_7 to S_{12} defines L or R scattering events, respectively. The increase in the level of coincidence reduces significantly the number of random coincidences. Also, the ionization chamber IC used as beam intensity monitor is installed just in front of the polarimeter target T.

Table 1. **Dimensions of plastic scintillators ($x \times y \times z$), where x and y are the sizes in the horizontal and vertical planes, respectively, and z is the thickness, and their distance from the target center**

Arm	Counter	Dimensions, mm	Distance from the target, mm
Forward	S_1, S_8	$40 \times 40 \times 5$	1720
	S_3, S_9	$40 \times 40 \times 5$	1260
	S_2, S_7	$35 \times 35 \times 5$	835
Recoil	S_5, S_{11}	$50 \times 160 \times 8$	940
	S_6, S_{12}	$45 \times 145 \times 8$	690
	S_4, S_{10}	$40 \times 130 \times 8$	460

The sizes of plastic scintillators and the distance of the counters S_1–S_{12} from the target point are given in Table 1. The solid angles of the forward and recoil arms are defined by the sizes and positions of the S_1, S_8 and S_5, S_{11} counters, respectively. The solid angle for pp elastic scattering is defined by the acceptances of the forward arms, while the recoil arms have larger acceptance. The size of the forward arms determining counters (S_1 and S_8) is 40×40 mm and their distance from the target center is 1720 mm. Therefore, the scattering angle acceptance and solid angle subtended by the L or R counters are $\Delta\theta = \pm 0.67^\circ$ and

$\Delta\Omega = 5.4 \cdot 10^{-4}$ sr, respectively. The solid angle for the recoil particles is $\Delta\Omega_{\rm rec} = 9 \cdot 10^{-3}$ sr. Such an angle allows one to detect the recoil protons from pp elastic scattering without losses of the statistics and with insignificant magnification of the admixture of the quasi-elastic events from the carbon content of CH_2 target.

Coincidence counts of the polarimeter arms and monitor informations were recorded for each beam polarization direction and stored by a PC data acquisition system after the end of each beam spill.

The polarization of the extracted beam was oriented along the vertical axis (perpendicularly to the beam momentum direction) and flipped every accelerator spill.

The method of the vector polarization measurement is based on the detection of the particles scattered leftwards and rightwards. The left-right asymmetry for a certain sign of the beam polarization ($\pm$) can be calculated from the relation

$$\epsilon^{\pm} = \frac{n_L^{\pm}/n_R^{\pm} - n_L^0/n_R^0}{n_L^{\pm}/n_R^{\pm} + n_L^0/n_R^0}, \tag{1}$$

where $n_L^{\pm,0}$ and $n_R^{\pm,0}$ are the respective numbers of events scattered leftwards and rightwards for different spin states of polarization source normalized to the beam intensity.

If an effective analyzing power of the polarimeter A is known, the beam polarization $P^{\pm}$ can be calculated according to

$$P^{\pm} = \epsilon^{\pm}/A. \tag{2}$$

2. MEASUREMENTS OF THE BEAM POLARIZATION

The polarized deuterons were produced by the ion source POLARIS [10]. The extraction of the polarized deuteron beam from the Nuclotron has been performed at 5.0 and 3.5 GeV/c. The typical beam sizes on the target during the experiment were 25 and 45 mm (2σ) in the horizontal and vertical directions, respectively. The intensity of the beam was measured by the ionization chamber IC placed in front of the polarimeter. The results of the intensity measurements versus time are shown in Fig. 2.

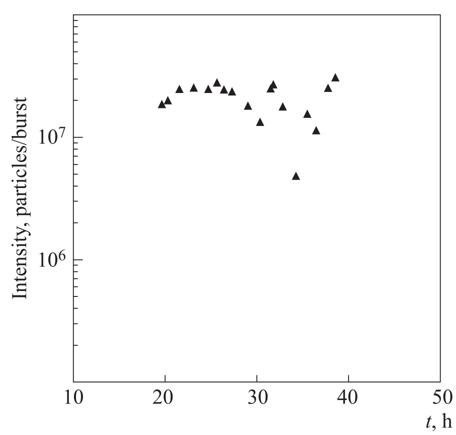

Fig. 2. Intensity of the extracted polarized deuteron beam at the Nuclotron in the December 2002 run versus time

The averaged beam intensity was only $\sim 2{-}3 \cdot 10^7$ particles per burst. Therefore, to have a reasonable counting rate for both left and right arms of the polarimeter, the CH_2 target thickness was increased up to 5 cm, and the level of coincidences was decreased from 6 to 4 (or 3). The signals from counters 8–11 and 1, 3, 5 were used to organize the coincidences for the right and left detectors, respectively. By doing this, the effective solid angles of the right and left detectors were increased, which gave the increase in the counting rate by a factor of ~ 4.

The results of the asymmetry measurements for both signs of the beam polarization are shown in Fig. 3. The measurements were made at the initial deuteron momenta of 5.0 and 3.5 GeV/c (last three points in Fig. 3). The forward scattering angle was set 14° for both momenta, while the angle for the recoil proton was set in accordance with the kinematics of elastic pp scattering. At higher momentum the absolute value of the asymmetry is lower due to a fall in effective analyzing power of the polarimeter versus energy [8, 9].

Since the polarimeter was not calibrated at both these deuteron momenta, the values of the effective analyzing power $A(\mathrm{CH_2})$ were taken from the parametrization. The results of the linear and quadratic proton momentum dependences of the analyzing power $A(\mathrm{CH_2})$ are presented in Fig. 4 by the dashed and solid lines, respectively.

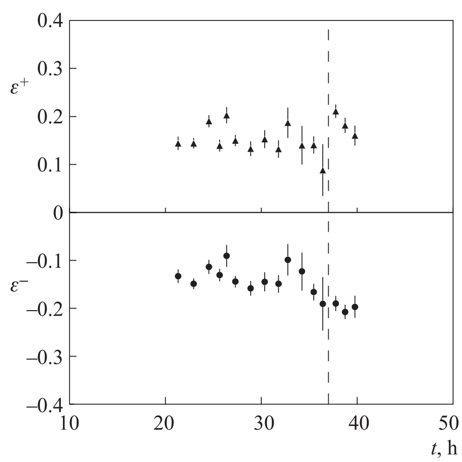

Fig. 3. Asymmetry of the extracted polarized deuteron beam at the Nuclotron in the December 2002 run at 5.0 and 3.5 GeV/c (last three points) versus time

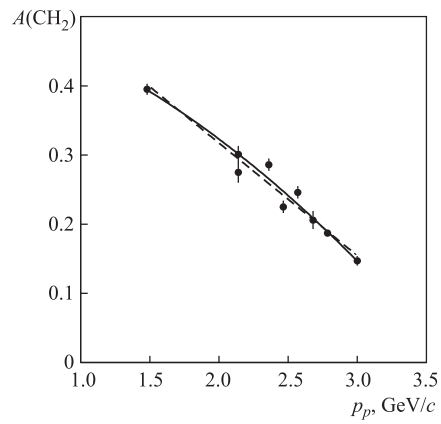

Fig. 4. The fit of the momentum dependence of the effective analyzing power $A(\mathrm{CH_2})$ at 14° [9, 11]. The dashed and solid lines are the results of the parametrization by the linear and quadratic dependences on the proton momentum, respectively

The linear dependence of the analyzing power on the proton momenta has the following form [11]:

$$A(\mathrm{CH_2})(p_p) = (0.6429 \pm 0.0157) - (0.1628 \pm 0.0061)p_p, \tag{3}$$

while the quadratic dependence is given as

$$A(\mathrm{CH_2})(p_p) = (0.5190 \pm 0.0198) - (0.0456 \pm 0.0162)p_p - (0.0262 \pm 0.0038)p_p^2. \tag{4}$$

The values of the effective analyzing power $A(\mathrm{CH_2})$ at proton momenta of 1.75 and 2.5 GeV/c were taken according to relation (4) as 0.359 and 0.241, respectively. Note that the values of the analyzing power $A(\mathrm{CH_2})$ at 1.75 GeV/c obtained from expressions (3) and (4) agree with a precision better than 0.5%.

The values of the deuteron beam vector polarization at both deuteron momenta are presented in Table 2. The polarization values averaged over spin states are 0.540 ± 0.019 and

0.606 ± 0.014 at 3.5 and 5.0 GeV/c, respectively. Some difference in the polarization values at these momenta can be due to uncertainty in the values of the effective analyzing power $A(\mathrm{CH}_2)$ used.

Table 2. **Vector polarization of the extracted deuteron beam at incident momenta of 3.5 and 5.0 GeV/c**

P_d, GeV/c	$P^+ \pm \Delta P^+$	$P^- \pm \Delta P^-$	$P \pm \Delta P$
3.5	0.531 ± 0.026	-0.548 ± 0.027	0.540 ± 0.019
5.0	0.633 ± 0.019	-0.578 ± 0.020	0.606 ± 0.014

3. TRIGGER EFFECT

The level of coincidences of scintillation counter signal was reduced because of a low intensity of the beam during polarization measurements. In this case the effective solid angle of the polarimeter changes due to finite size of the beam and target. Therefore, the effective analyzing power of the polarimeter could also change due to possible different yield from the carbon content of the target.

Special study to test such an effect was performed using unpolarized deuteron beam with a momentum of 3.5 GeV/c at the Nuclotron in the June 2003 run.

The idea of these studies is based on the following assumption. Let us suppose that an effective analyzing power of the polarimeter A may be represented as

$$A = (1-k)A_{pp} + kA_{p\mathrm{C}}, \tag{5}$$

where A_{pp} and $A_{p\mathrm{C}}$ are the analyzing powers of pp elastic scattering and $p\mathrm{C} \to ppX$ reaction, respectively, and k is a coefficient proportional to the carbon content of CH_2 target. If the effective solid angle changes, the fraction of events from carbon also may change, and new value of an effective analyzing power $\bar{A}$ can be written as

$$\bar{A} = (1-\bar{k})A_{pp} + \bar{k}A_{p\mathrm{C}}, \tag{6}$$

where $\bar{k}$ is some new coefficient. If $A_{pp},\ A$, k and $\bar{k}$ are known, a corrected value of the effective analyzing power $\bar{A}$ may be found from

$$\bar{A} = \frac{\bar{k}}{k}A + \left(1 - \frac{\bar{k}}{k}\right) A_{pp}. \tag{7}$$

The value of $A_{pp} = 0.418$ is known from the fit to the world pp data for the scattering at an angle of 14° (see Fig. 5), $A = 0.359$ can be taken from the previous calibration of polarimeter at a deuteron momentum of 3.5 GeV/c, and k and $\bar{k}$ have been obtained from direct measurements in a special run at the Nuclotron in June 2003.

The results of these measurements are presented in Fig. 6 for two configurations of the polarimeter trigger: Trigger 1 is six-fold coincidences, while Trigger 2 is four(three)-fold coincidences. The counting rates normalized for the beam intensity and target thickness for CH_2 (open symbols) and carbon (filled symbols) are shown versus recoil particle scattering angle. The solid lines are the results of the fit of the CH_2 and carbon yield.

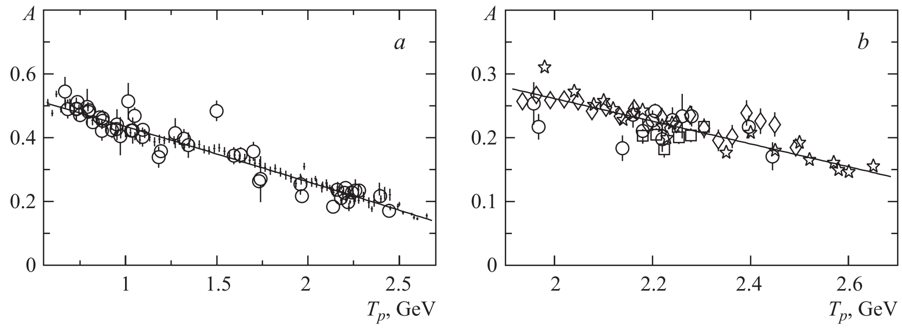

Fig. 5. The fit of the energy dependence of the A_{pp} analyzing power at 14° [11]

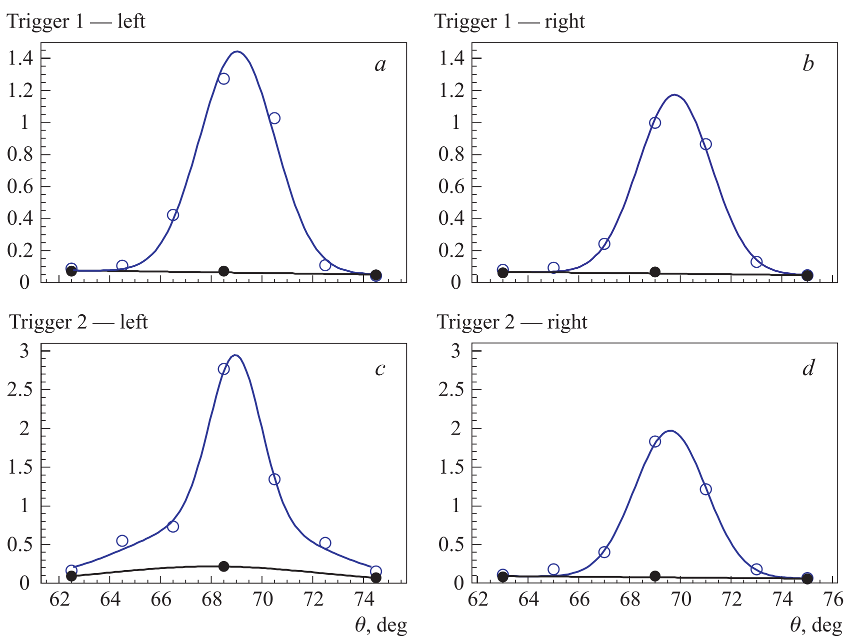

Fig. 6. The normalized counting rate for the CH_2 (open symbols) and carbon (filled symbols) targets for different configurations of the trigger versus recoil particle scattering angle. Panels *a* and *b* correspond to the six-fold coincidences for the left and right arms, while panels *c* and *d* correspond to the four(three)-fold coincidences, respectively

Since the carbon content, in general, can be different for the left and right arms, both of them were considered as the separate polarimeters with their own effective analyzing powers. The polarization of the beam was calculated for the left and right arms of the polarimeter and weighted averaged for each sign of the polarized ion source.

Two methods to estimate possible trigger effect were used. The first method (Method 1) is based on the subtraction of the direct measurements of the event rates from the CH_2 and carbon targets normalized to the beam intensity and number of nuclei in the targets. The second one (Method 2) uses the values obtained from the parameters of the fit for CH_2 and carbon. The results are given in Table 3. The first line contain the polarization values obtained without corrections, while the second and the third ones give the values obtained with the corrections using Method 1 and Method 2, respectively. It is seen that the values of polarization corrected with our methods agree in the limits of error bars with those obtained initially.

Table 3. **The beam polarization for both spin states of the polarized ion source without and with the correction for the trigger effect**

Method	$P^+ \pm \Delta P^+$	$P^- \pm \Delta P^-$	$P \pm \Delta P$
Without corrections	0.531 ± 0.026	-0.552 ± 0.027	0.541 ± 0.019
Method 1	0.540 ± 0.027	-0.552 ± 0.027	0.546 ± 0.019
Method 2	0.563 ± 0.028	-0.564 ± 0.028	0.563 ± 0.020

Figure 7 demonstrates the normalized yield of the events from the hydrogen content of the CH_2 target obtained by the CH_2–C subtraction. The cleanness of the subtraction, especially for the six-fold coincidences, allows one to obtain the values of the polarization by using the

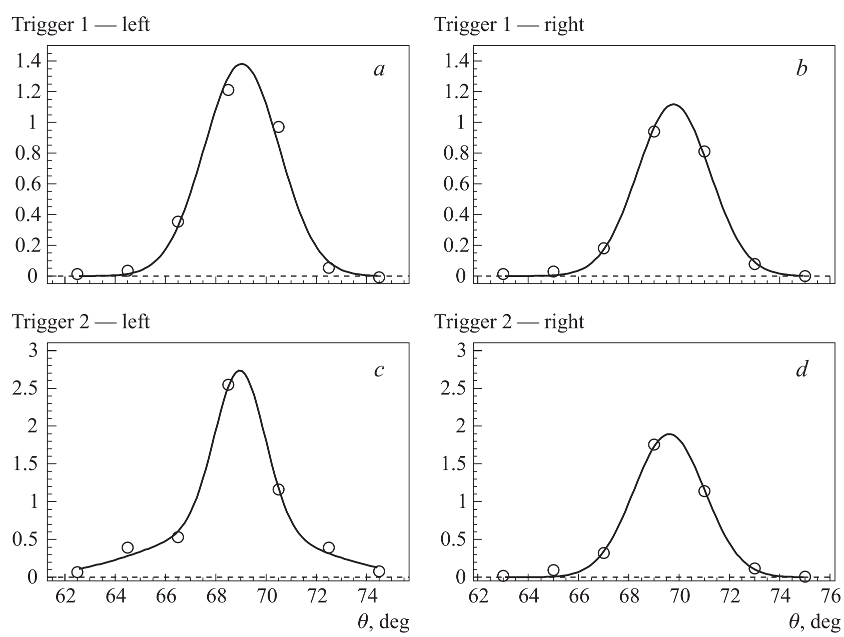

Fig. 7. The normalized counting rate for the hydrogen content of the CH_2 target for different configurations of the trigger versus recoil particle scattering angle. Panels *a* and *b* correspond to the six-fold coincidences for the left and right arms, while panels *c* and *d* correspond to the four(three)-fold coincidences, respectively

data on the analyzing power of pp elastic scattering only, as proposed in Ref. [11]. Such a procedure can be applied in future to polarized deuteron beam at the Nuclotron.

CONCLUSIONS

The results of this work can be summarized as follows.

The intensity of the firstly extracted polarized deuteron beam at the Nuclotron during the measurements was $\sim 2.5 \cdot 10^7$ particles/spill.

The polarimeter placed at the focal point $F3$ measured significant asymmetry at 5 and 3.5 GeV/c for the vector polarized deuteron beam. The polarization of the extracted deuteron beam averaged over the spin states was 0.606 ± 0.014 and 0.540 ± 0.019 at 5 and 3.5 GeV/c, respectively.

Special study was performed to estimate the possible systematics due to trigger effect using unpolarized deuteron beam. It was shown that the modification of the polarization values at 3.5 GeV/c due to this effect is small and does not exceed the statistical and systematic errors.

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