УДК 539.1.07

ON AN ABSOLUTE CALIBRATION OF DEUTERON BEAM POLARIZATION AT LHE

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The method of an absolute calibration of both vector and tensor polarizations of a deuteron beam at the Laboratory of High Energies is proposed. It is shown that such a method can be applied using a reasonable beam time.

The investigation has been performed at the Laboratory of High Energies, JINR.

Об абсолютной калибровке поляризации пучка дейтронов в ЛВЭ

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Предложен метод абсолютной калибровки векторной и тензорной поляризаций дейтронного пучка в Лаборатории высоких энергий. Показано, что применение данного метода возможно при использовании разумного пучкового времени.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. INTRODUCTION

A wide experimental programme on the study of spin effects has been performed at the Laboratory of High Energies, JINR [2]— [13] beginning from putting into operation the ion source of polarized deuterons POLARIS [1]. All the above experiments required the knowledge of beam polarization with a good precision.

In order to measure the beam polarization behind the linac, the polarimeters based on ^{4}He$(d,d)^4$He [14] and ^{3}He$(d,p)^4$He [15] reactions have been developed. Such reactions have large vector [16] and tensor [17] analyzing powers known to a good precision. However, these polarimeters are not in operation now because of a low counting rate during the measurements of the polarization.

To measure the polarization of a slow extracted beam, the 2-arm polarimeter ALPHA [18] was installed in the experimental hall. This polarimeter is based on dp-elastic scattering at 3 GeV/c and 7.5°. The analyzing powers A_y and A_{yy} of this reaction are quite large [19–21]. Note that most of the LHE experiments [2]— [13] used the values of polarizations

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obtained from the polarimeter ALPHA [18]. However, the values of A_y and A_{yy} obtained at SATURNE-2 might be $\sim 6-9\%$ and $\sim 14\%$ lower than the published ones [19,21] due to sizeable dead-time corrections [22] of the results of polarization measurements by the low energy polarimeter [23].

A new on-line beam polarimeter used to measure the vector admixture of deuteron polarization has recently been installed at focus F4 of the beam line VP1 [24]. The main principle of the polarimeter is based on the measurement of the left-right asymmetry of pp-quasi-elastic scattering by detecting scattered and recoil particles in coincidence. The polarimeter consists of 2 arms installed at the angles corresponding to pp-elastic scattering kinematics. Since a polyethylene target (CH_2) is used instead of a hydrogen one, this polarimeter needs to be calibrated. The vector polarization of the deuteron obtained from the measurement by this polarimeter [24] (after a correction for the carbon content in the CH_2 target) is approximately 10% higher than the value obtained using the ALPHA polarimeter [18]. Apart from this, the data on the analyzing power of pp-elastic scattering at high energies are scarce, and therefore the systematic error is large. For instance, the systematic error of such a method is found to be as $\sim 6\%$ and $\sim 9\%$ at deuteron momenta of 6 and 9 GeV/c [25], respectively.

The tensor polarization of a beam can be measured using deuteron inclusive breakup on nuclear targets at a zero proton emission angle, $d+A \to p(0^\circ)+X$ as an analyzing reaction [26]. This reaction has a large tensor analyzing power T_{20} [2,27] which is only weakly dependent on the atomic number of target. The $|T_{20}|$ has a maximum value of about 0.8 at proton momentum $P_p \approx \frac{2}{3}P_d$ independently of an initial momentum of the deuteron beam between 2.5 and 9.0 GeV/c [2,27]. The systematic error of the method is estimated to be $\sim 5\%$ [26]. However, the T_{20} data obtained at SATURNE [27] seem to have a normalization problem due to a dead-time correction for the low energy polarimeter [22]. In principle, the Dubna data should be also corrected because of different values of A_y and A_{yy} in dp-elastic scattering used for polarimetry at LHE till 1993 and published in [21], as well as possible distortions of T_{20} due to a large dead-time of the set-up [28].

Therefore, the problem of absolute calibration of the deuteron polarization exists, apart from the problem of relative normalization of different high-energy polarimeters at LHE [18,24,26]. One of the possible ways is to restore low-energy polarimeters [14,15] with well-known ($\sim 1-2\%$) analyzing powers [16,17] and to recalibrate in future the high-energy polarimeters available to LHE. In principle, one can use another reaction to determine the degrees of deuteron polarization. For example, it can be dp-elastic scattering at an initial energy of 270 MeV and a scattering angle between 60° and 140° in the centre of mass, where the analyzing powers A_y, A_{yy}, A_{xx} and A_{xz} are measured with good statistics and systematics [29]. But in any case, such a method gives a systematic error in determining polarization values no better than a few per cent because it is based on the results of measurements from other experiments with their own statistical and systematic errors.

The aim of this paper is to describe the possibility of **absolute** calibration of vector and tensor polarizations of relativistic deuterons at the Laboratory of High Energies, JINR.

2. CALIBRATION OF A VECTOR POLARIZED BEAM

The idea of absolute calibration of a vector polarized deuteron beam is based on the consequences of T-invariance for elastic scattering processes. If T-invariance holds, the polarization of secondary particle P is equal to the analyzing power A of the elastic reaction:

$$A \equiv P. \tag{1}$$

Therefore, the measurements of the analyzing power A and the polarization of secondary particle P of elastic scattering reactions (for instance, $pp \to pp$ or $dp \to dp$) with good statistics and using of relation (1) can provide the determination of the polarization degree in different states.

Since the typical intensity of the polarized deuteron beam is $\sim 1 \div 2 \cdot 10^9$ per spill, in principle, one can use either a *pp*- or *dp*- elastic scattering reaction for the absolute calibration of vector polarization.

The main difficulty of such a method is to provide a small statistical error in measuring secondary particle polarization P. For this purpose, it is necessary to use such a focal plane vector polarimeter as POMME [30–33] based on the measurements of the azimuthal asymmetry of the semi-inclusive reactions:

$$p + C \to one \quad charged + X, \tag{2}$$
$$d + C \to one \quad charged + X. \tag{3}$$

The performance of a polarimeter is expressed in terms of the figure of merit, $\mathcal{F}$. The $\mathcal{F}$ is the function of efficiency ϵ and analyzing power A. It is defined as

$$\mathcal{F}^2 = \int \epsilon(\theta) A^2(\theta) d\theta, \tag{4}$$

where θ is the polar angle and integration is over the angular domain of the polarimeter. The figure of merit allows one to evaluate the counting rate N_{inc} necessary to obtain the desired precision of polarization ΔP:

$$\Delta P \approx \frac{\sqrt{2}}{\mathcal{F}\sqrt{N_{inc}}}. \tag{5}$$

The figures of merit of such a polarimeter at a proton and deuteron momentum of ~ 3 GeV/c are $\sim 4\%$ [31] and $\sim 4.5\%$ [33], respectively. An error ~ 0.015 in measuring polarization P can be obtained for a 1-day beam time using the SPHERE set-up [12, 13] with an averaged dead-time of $\sim 50\%$. Such a fraction of dead-time allows one to extract correctly the «true» value of asymmetry [28]. Such a precision in measuring the polarization only provides a relative error of $\sim 5 - 6\%$ in its determination.

However, the measurements at lower proton momenta, for instance, at ~ 1.5 GeV/c, where the figure of merit is ~ 0.1 [31], provide an error of ~ 0.01 in measuring polarization P for 10 hours of the beam time. This accounts for $\sim 2\%$ of the relative error in determining the beam polarization.

The scenario of the measurements is the following.

1. First of all, it is necessary to calibrate the polarimeter using a primary polarized proton beam. Protons with a momentum of ~ 1.5 GeV/c are obtained from the breakup of 3 GeV/c vector polarized deuterons on a hydrogen or nuclear target. The polarization of the proton is the same as that of the deuteron [3, 4]. The polarimeter consists of a system of incident

particles identification, a carbon (or polyethylene) target and a system for measuring the scattered particle angle (see Fig.1.). The standard equipment of the SPHERE set-up [12, 13] is used for incident particle identification. The polarimeter is placed behind the SPHERE set-up. The polar, θ, and azimuthal, ϕ, angles of the secondary particle are measured using scintillation counter hodoscopes. To reduce the counting rate from unscattered events with a zero analyzing power, an additional veto counter is needed behind the hodoscopic system. Such a polarimeter with a standard SPHERE set-up data acquisition system is quite fast. It allows one to store $\sim$ 600 events per burst with a $\sim$ 50% dead-time.

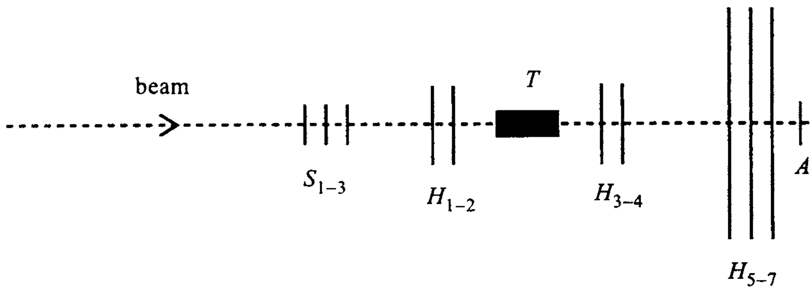

Fig. 1. A schematic view of the set-up used to measure the proton polarization. S_{1-3} — scintillation counters, H_{1-7} — hodoscopes of the scintillation counters , A — veto counter and T — carbon or polyethylene target

The angular distribution of scattered events in different polarization states can be written as

$$N^{\pm}(\theta,\phi) = N_0(\theta)\cdot(1+\epsilon_c^{\pm}(\theta)\cdot\cos\phi) = N_0(\theta)\cdot(1+p_z^{\pm}\cdot A_c(\theta)\cdot\cos\phi), \qquad (6)$$

where $p_z^{\pm}$ are the polarization values in different polarization states, $\epsilon_c^{\pm}(\theta)$ are the asymmetries at given polar angle θ and $A_c(\theta)$ is the analyzing power of pC- (or pCH_2) semi-inclusive reaction (2). The calibration of the polarimeter requires about 12 hours of the beam time.

2. We measure the analyzing power of the *pp*-quasi-elastic scattering reaction at 1.6 GeV/c/nucleon and a scattering angle of $\sim$ 14°. Note that the initial momentum of the deuteron in this measurement is slightly higher than during the calibration of the polarimeter to provide the same momentum of the proton from *pp*-quasi-elastic scattering. This part of the measurements requires to detect both protons. The proton scattered at an angle of $\sim$ 14° is detected by the SPHERE set-up; the second proton emitted at $\sim$ 70° is detected by the scintillation counter telescope (see Fig.2.). The number of events stored in different polarization states is written as

$$n^{\pm} = n_0\cdot(1+\epsilon^{\pm}) = n_0\cdot(1+p_z^{\pm}\cdot A), \qquad (7)$$

where $\epsilon^{\pm}$ are asymmetries in different polarization states, A is the analyzing power of the *pp*-quasi-elastic reaction. This measurement requires about 2 hours to provide errors of 0.005 in the determination of $\epsilon^{\pm}$.

At the same time, the polarimeter placed at F4 [24] can be calibrated. The comparison of the results on the asymmetry measurements for the polarimeter at F4 [24] and the SPHERE set-up will allow one to obtain the empirical coefficient taking into account the carbon content of the CH_2 target.

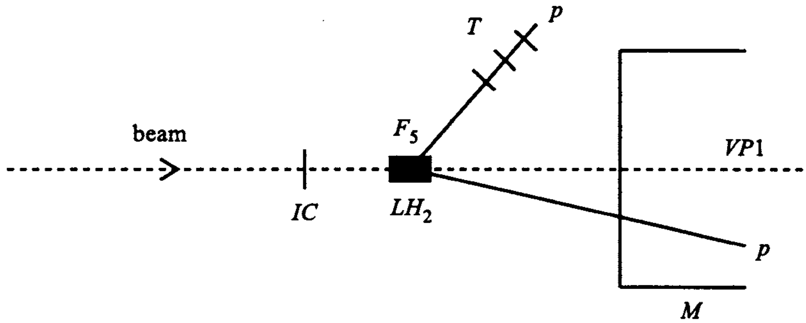

Fig. 2. A scheme of event selection from *pp*-quasi-elastic scattering. LH_2 — liquid hydrogen target, T — telescope of the scintillation counters, IC — ionization chamber, M — magnet and F_5 — focus of the beam line $VP1$

3. The polarization of the proton P in *pp*-quasi-elastic scattering at $\sim 14°$ is measured using the calibrated polarimeter. The second proton is detected using the scintillation counter telescope. The unpolarized deuteron beam with a momentum of $\sim$ 1.6 GeV/c/nucleon is used for such measurements. The angular distribution of scattered events is written as

$$m(\theta, \phi) = m_0(\theta) \cdot (1 + \epsilon_0(\theta) \cdot \cos\phi) = m_0(\theta) \cdot (1 + P \cdot A_c(\theta) \cdot \cos\phi), \tag{8}$$

where $\epsilon_0(\theta)$ is the asymmetry at given θ. Such measurements require $\sim 10 - 12$ hours of the beam time.

The use of the fitting procedure of $N^{\pm}(\theta, \phi)$ and $m(\theta, \phi)$ over $\cos(\phi)$ allows one to obtain $\epsilon^{\pm}(\theta)$ and $\epsilon_0(\theta)$ at each given θ, respectively. In principle, the ratios $\epsilon^{\pm}(\theta)/\epsilon_0(\theta)$ are independent of polar angle θ and are equal to

$$R_c^{\pm}(\theta) = \epsilon_c^{\pm}(\theta)/\epsilon_0(\theta) = p_z^{\pm}/P. \tag{9}$$

Using the results on the measurements of analyzing power (7), one can obtain:

$$R^{\pm}(\theta) = R_c(\theta) \cdot \epsilon^{\pm} = (p_z^{\pm})^2 \cdot \frac{A}{P}. \tag{10}$$

The weighted average of $R^{\pm}(\theta)$ gives the squared polarization of beam $p_z^{\pm}$ by using relation (1). The error in determining the beam polarization using this method is about 2%.

3. CALIBRATION OF A TENSOR POLARIZED BEAM

The application of the above-discussed method for the absolute calibration of tensor beam polarization is more difficult because the corresponding figures of merit (F_{20}, F_{21}, and F_{22}) of existing polarimeters are much smaller than the figure of merit of vector polarimeters. For instance, the figure of merit F_{22} of the POMME polarimeter at $\sim$ 600 MeV is equal to ~ 0.03 [30]. Therefore, the beam time necessary to carry out such measurements is about 10 days.

One of the opportunities to calibrate the tensor polarization of the deuteron beam is to exploit the reaction with a maximum tensor analyzing power due to a particular spin structure. For example, the reaction $^4He(d,d)He^4$ at 35.7 MeV and a deuteron scattering angle of $\theta^d_{cm} = 150°$ is proposed as a polarization standard because the tensor analyzing power $A_{yy} \equiv 1$ in this kinematics [34]. Such measurements can be made using a tensor polarized beam accelerated by the Nuclotron up to 35.7 MeV and the low energy polarimeter [14] placed in the storage ring. At lower energies (below 12 MeV), the absolute calibration can be performed using particular angle/energy combinations [35]. For example, the maximum values of tensor analyzing power $A_{yy} \equiv 1$ are expected at 4.3, 4.57 and 11.88 MeV.

The reaction

$$d + d \to ^4\text{He} + \eta \qquad (11)$$

can be used as a polarization standard at relativistic energies. At threshold and in collinear geometry, this reaction is described by the only amplitude $\mathcal{F}$ [36]:

$$\mathcal{M} = \frac{1}{(2\pi)^3}\sqrt{4m_\alpha\, m_d}(i\mathcal{F}\cdot\vec{\xi}_d\times\vec{\xi}'_d\cdot\hat{k}_d), \qquad (12)$$

where $\vec{\xi}_d$ and $\vec{\xi}'_d$ are the deuteron polarization vectors, $\hat{p}_d$ is the operator of deuteron momentum in the center of mass. Using expression (12), one can obtain the value of tensor analyzing power T_{20} as $1/\sqrt{2}$ independently of initial energy. Therefore, the polarized cross sections $\sigma^\pm$ can be written as

$$\sigma^\pm = \sigma_0(1 - \frac{p^\pm_{zz}}{2\sqrt{2}}\cdot T_{20}) = \sigma_0(1 - \frac{p^\pm_{zz}}{4}), \qquad (13)$$

where σ_0 is the unpolarized cross section. The beam polarizations in different states can be obtained as

$$p^\pm_{zz} = 4\cdot\frac{\sigma_0 - \sigma^\pm}{\sigma_0}. \qquad (14)$$

The cross section of reaction (11) is measured near threshold between η-meson momenta of 10 and 90 MeV in the center of mass p^*_η at SATURNE [37,38]. Since α particles at threshold go in the forward direction within a narrow cone, all the products from this reaction (11) can be measured using a usual spectrometer having a solid angle of $\sim 10^{-3}$ *sr*. The number of events from reaction (11) is equal to ~ 20 per burst with a typical beam intensity $\sim 2\cdot 10^9$ and a liquid deuterium target 10 cm in length. Therefore, an error of $2-3\%$ in measuring tensor polarization $p^\pm_{zz}$ (14) can be provided for 16 hours.

Using the known values of (14), one can obtain value of A_{yy} in *dp*-elastic scattering [18] to have the renormalization constant for the previous experiments. Then, one can measure T_{20} in deuteron inclusive breakup to have a tensor polarimetry standard at LHE.

4. CONCLUSIONS

The results of the present work can be summarized as follows.

- The methods of deuteron beam vector and tensor polarizations measurements [18,24,26] used at LHE can have a sizeable systematic error. Therefore, it is very desirable to perform the absolute calibration of deuteron beam polarizations.

- The absolute calibration of vector polarization can be done by measuring the analyzing power and polarization of the proton from quasi-elastic pp scattering. The use of a high efficiency proton focal plane polarimeter can provide an error of $\sim 2\%$ in the determining beam polarization.
- The absolute calibration of a tensor beam can be done using the $d + d \to {}^4\text{He} + \eta$ reaction near threshold. Since this reaction is described by the only amplitude, the tensor analyzing power T_{20} has a fixed value of $\equiv 1/\sqrt{2}$. It is shown that one can obtain an error of $\sim 2\%$ in determining tensor polarization for 16 hours of the beam time.

5. ACKNOWLEDGEMENTS

The author thanks Professor L.S. Azhgirey, N.B. Ladygina and A.A. Yershov for fruitful discussions.

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Received on April 29, 1999.