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PROPOSAL ON THE MEASUREMENTS OF d–p ELASTIC SCATTERING ANALYZING POWERS AT 0.3–2.0 GeV AT INTERNAL TARGET STATION OF THE NUCLOTRON

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A new high-energy beam polarimeter is proposed for the Nuclotron using the Internal Target Station (ITS). This polarimeter based on the measurement of the asymmetry for the d–p elastic scattering will allow one to measure both vector and tensor components of the deuteron beam polarization simultaneously. For that purpose the measurement of analyzing powers for the d–p elastic scattering at energies $T_d = 0.88-2$ GeV is proposed. The precise measurements of the deuteron analyzing powers over the energy range $T_d = 300-2000$ MeV can give an irreplaceable clue to the study of spin-dependence of three-nucleon forces.

Предложен новый поляриметр для пучка высоких энергий на станции внутренней мишени нуклотрона. Данный поляриметр, основанный на измерении асимметрии упругого рассеяния d–p, позволит одновременно измерять как векторную, так и тензорную компоненты пучка дейтронов. Для этой цели предложено измерение анализирующих способностей упругого рассеяния d–p при энергиях $T_d = 0,88-2$ ГэВ. Точные измерения дейтронных анализирующих способностей в энергетическом диапазоне $T_d = 300-2000$ МэВ могут стать незаменимым ключом к изучению спиновой зависимости трехнуклонных сил.

1. MOTIVATION

Spin physics programs with ~GeV-energy polarized deuteron beams are proposed at JINR in Russia and RIBF in Japan. In the investigations, an established measurement of deuteron polarization is required to deduce values of polarization observables reliably. Especially,

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according to the installation plan of the atomic-beam type polarized ion source, CIPIOS, to the LHE accelerator complex, it is crucial to establish a polarimetry suited for a vector-tensor mixed polarized beam.

Among possible candidates of deuteron polarimetries, the d–p elastic scattering at forward angles [1], the d–p quasi-elastic scattering [2] and the deuteron inclusive breakup [3] have been used as polarimetries in GeV energy region. The latter two polarimetries do not fit the requirement of vector-tensor mixed polarimetry, because the d–p quasi-elastic scattering has no tensor analyzing power while the deuteron inclusive breakup at zero degree has no vector analyzing power. On the other hand, the d–p elastic scattering at forward angles requires a two-arm spectrometer to identify the deuteron scattered at $7.5°$ off hydrogen from deuterons from other reaction channels or other particles [1].

The proposed polarimetry, the d–p elastic scattering at backward angles ($\theta_{\rm cm} > 70°$) at energies 0.88–2.0 GeV, has several advantages as a beam-line polarimetry over the others. Firstly, both vector and tensor analyzing powers for the reaction can have large values. Secondly, a kinematical coincidence measurement of deuteron and proton with simple plastic scintillation counters suffices for event identification. This is mainly due to a small background event rate, compared with the forward angles. The use of this reaction as a deuteron polarimetry at 140–270 MeV at large angles is established at RIKEN [4–6].

At intermediate energies, intensive studies on three-nucleon force effects are proceeded via the deuteron–proton and deuteron–neutron elastic scattering and breakup reactions. At energies $T_d \leqslant 300$ MeV, Faddeev calculations can provide good description of cross-section data, by introducing a three-nucleon force, over the whole angular range. However, their reproduction of polarization observables is not as good as that for cross-section data, which may be regarded as an insufficiency of our knowledge of spin-dependence of three-nucleon force. To clarify the situation of the spin-dependence, it is undoubtedly promising to perform systematic study of polarization observables in the region of the so-called «cross-section minimum» which spans $\theta_{\rm cm} = 90{-}130°$. At higher energies, for example $T_d = 500$ MeV, the Faddeev calculation deviates from the cross-section data at backward angles. This may be due to relativistic effects and/or new three-nucleon force other than Fujita–Miyazawa type. Subthreshold pion production may play a role. Measurement of energy dependences of polarization observables in the region of cross-section minimum can give an irreplaceable clue to the problem. The measurement of the deuteron analyzing powers A_y, A_{yy} and A_{xx} at $T_d = 300{-}500$ MeV in the vicinity of cross-section minimum using the Internal Target Station (ITS) at the Nuclotron has been proposed within the LNS project [7, 8].

The ITS setup is well suited for study of energy dependence of polarization observables for the deuteron–proton elastic scattering. Most of the studies so far are conducted at cyclotron facilities, RIKEN [4, 6, 9, 10], RCNP [11], KVI [12–14], and IUCF. At the facilities, measurement of energy dependence is very expensive because a change of beam energy in a cyclotron takes much time (typically more than one day). The Nuclotron can accelerate a polarized deuteron beam from several tens of MeV to higher than 1 GeV and can provide us a good opportunity to measure the energy dependence.

2. *d*–*p* ELASTIC SCATTERING AT GeV ENERGIES

Data of vector and tensor analyzing powers at the energies of interest are very scarce except for the very forward angles. The existing vector and tensor analyzing powers data at backward angles and high energies are those obtained at 1.2, 1.6, and 2.0 GeV at Argonne National Laboratory (ANL) [15–17] and at 1.6 GeV at Saturne [18].

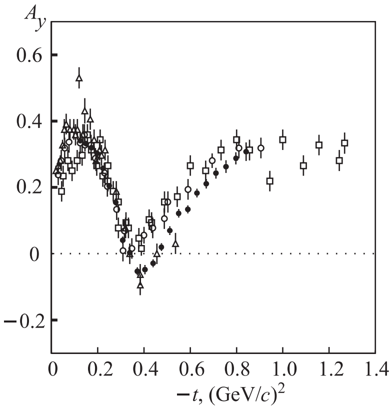

Fig. 1. Vector analyzing power A_y versus $-t$ for the d–p elastic scattering at T_d = 1.2 GeV (△), 1.6 GeV (○) and 2.0 GeV (□) by ANL group [17] and at 1.6 GeV (•) by Saturne group [18]

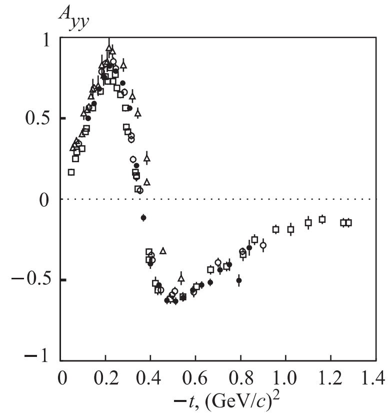

Fig. 2. Tensor analyzing power A_{yy} for the d–p elastic scattering at T_d = 1.2, 1.6, and 2.0 GeV [17, 18]. The symbols are the same as in Fig. 1

The data on vector analyzing power A_y and tensor analyzing powers A_{yy} and A_{xx} [17, 18] are shown in Figs. 1–3, respectively. The open triangles, circles and squares correspond to the data obtained at ANL [17] at the energies of deuteron 1.2, 1.6 and 2.0 GeV, respectively. The full circles are the Saturne data [18] obtained at 1.6 GeV. One can see an approximate t scaling of the analyzing powers. Therefore, one can expect the large values of analyzing powers at energies of 0.88–1.2 GeV.

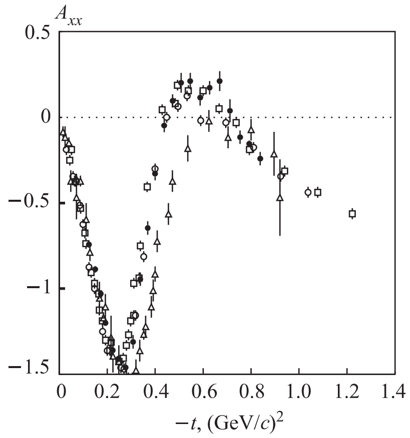

Fig. 3. Tensor analyzing power A_{xx} for the d–p elastic scattering at T_d = 1.2, 1.6, and 2.0 GeV [17, 18]. The symbols are the same as in Fig. 1

Note that the value of the tensor analyzing power A_{xz} at 1.6 GeV equals zero [18]. Therefore, the full set of data on analyzing powers exists at this energy up to $t \sim -1$ (GeV/c)^2.

As is shown in Figs. 1 and 2, both vector A_y and tensor A_{yy} analyzing powers have modest values of $A_y = +0.3- + 0.4$ and $A_{yy} = -0.4- - 0.3$ in the region of $-t = 0.7-0.9$ (GeV/c)^2. They are almost stable over the t range. Tensor analyzing power A_{xx} is almost zero at $-t = 0.4$–0.7 (GeV/c)^2. But its absolute value increases linearly at larger $-t$ and can be used for polarimetry.

The cross section of d–p elastic scattering has been measured at 270 [4], 850 [19], 1060 [20], 1600 [21] and 2000 MeV [22]. The value of the cross section at $\sim 70°$ in the

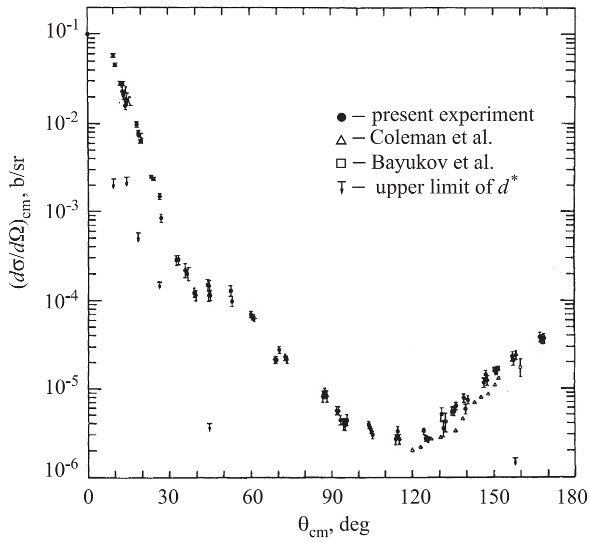

Fig. 4. Differential cross section for the d–p elastic scattering at $T_d = 2.0$ GeV [22]

center of mass changes from ~ 500 μb/sr at 270 MeV up to ~ 20 μb/sr at 2000 MeV. The data on differential cross section for the d–p elastic scattering at $T_d = 2.0$ GeV [22] are shown in Fig. 4.

3. PROPOSED EXPERIMENT

The proposed experiment comprises three groups of measurements. All of them are based on asymmetry measurement of deuteron–proton elastic scattering at ITS.

1) Measurement of deuteron beam polarization at $T_d = 270$ MeV;

2) Calibration measurement of the polarimeter at $T_d = 0.88-2.0$ GeV;

3) Measurement of polarization observables for the d–p elastic scattering at $T_d = 300-800$ MeV.

In the following, an experimental setup and details of measurements are presented together with some results of a test experiment conducted in March 2005.

3.1. Internal Target Station. The measurement will be carried out at the ITS. The sketch of a new ITS is shown in Fig. 5.

This target is composed of spherical hull, ion tube and the cylinder where the target holder carrying up to six different targets is located. For the present experiment only two targets (polyethylene 10 μm sheet and carbon wire) will be used. The details on the new ITS can be found in Ref. [23].

A detector support to install proton and deuteron detectors is placed down-stream of the ITS as shown in Fig. 6.

3.2. Polarization Measurement at $T_d = 270$ MeV. The polarization of the deuteron beam will be measured with the standard detection system of the LNS project [24] at 270 MeV. The detection of the elastic events will be done by four pairs of detectors, each of them detects

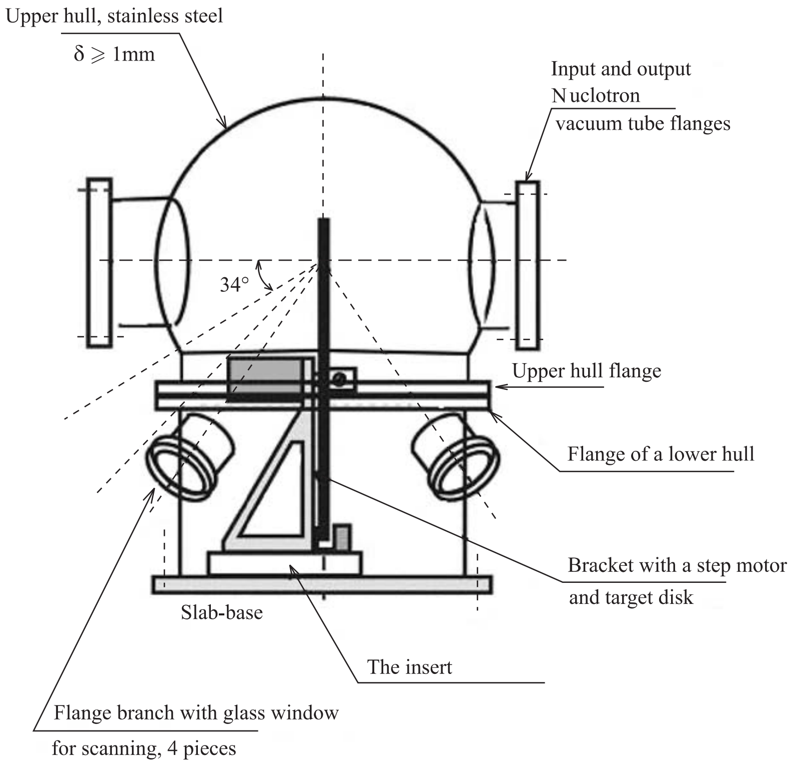

Fig. 5. The sketch of a new Nuclotron Internal Target Station

proton and deuteron in coincidence. The four pairs of detectors will be placed symmetrically in the directions of azimuthal angles to left, right, up, and down. The detectors will be placed at the angles corresponding to $\theta_{\rm cm} = 86.5°$, where absolute calibration of analyzing powers of *d–p* elastic scattering at 270 MeV has been performed at RIKEN [5].

Each detector consists of two scintillation counters. The plastic scintillators with thicknesses of 0.5 and 2 cm are coupled to FEU-85 photomultiplier tubes (see Fig. 7). A lead block can be placed in front of the thick scintillator to degrade the kinetic energy of the scattered particles such that their energy loss in the plastic scintillator will be maximized. Two particles from the *d–p* elastic scattering will be clearly distinguished by their energy losses in the thick plastic scintillators and the differences between their time of flight from the target. The background from carbon content of CH_2 target was estimated as $\sim 1\%$ at 270 MeV [9]. Such a technique was successfully adopted previously at RIKEN [9] and tested in March 2005 at the Nuclotron. Figure 8 demonstrates the selection of the *d–p* elastic scattering at 270 MeV. Panels *a* and *b* are the correlation for the energy losses in plastic scintillators for protons and deuterons, and time-of-flight difference between protons and deuterons, respectively. The achieved timing resolution of ~ 0.5 ns allows one to clearly separate true *d–p* coincidences. The carbon contribution has been found negligibly small.

The measurement of the polarization will be done by low-energy polarimeters [3], by this setup at 270 MeV, where high-precision data of analyzing powers from RIKEN exist [9, 5, 6].

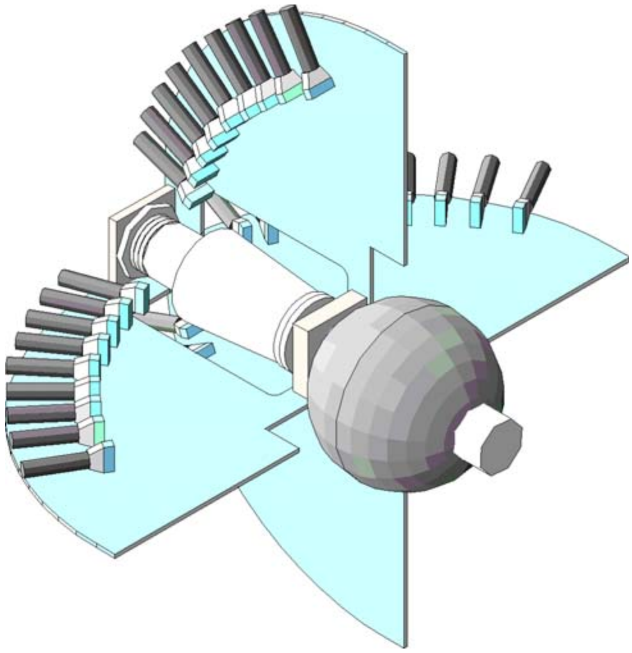

Fig. 6. Schematic view of the detector setup

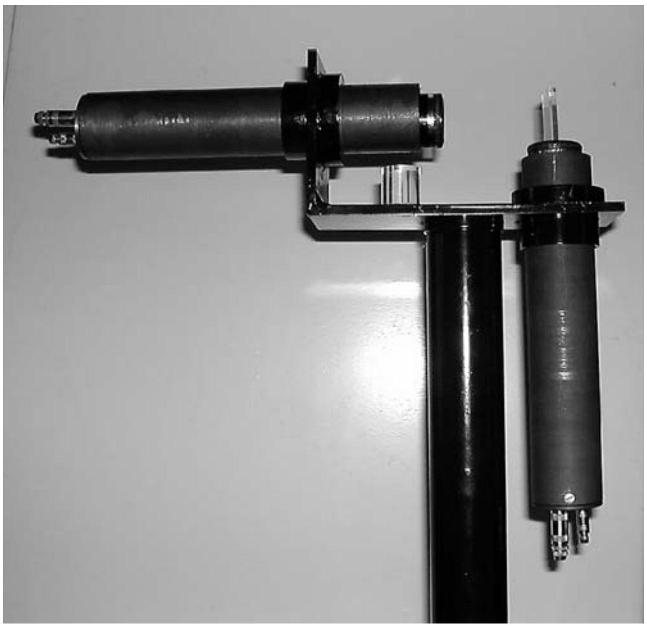

Fig. 7. Detector to register the protons and deuterons at 270 MeV

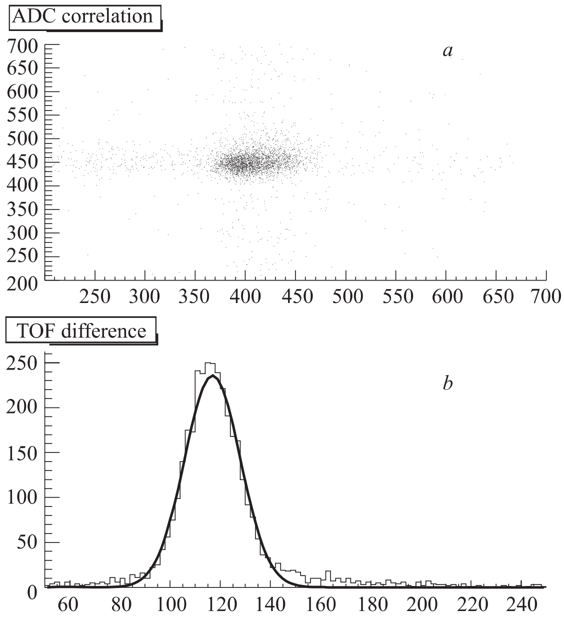

Fig. 8. Selection of the d–p elastic scattering at 270 MeV. a) Corellation for the energy losses in plastic scintillators for protons and deuterons; b) time-of-flight difference between protons and deuterons

The measurements of the vector admixture of the beam polarization can be done using polarimeter located at the focal point F3 [2]. The systematic error due to measurement of the polarization is expected to be $4-5\%$.

3.3. Calibration Measurement at $T_d = 0.88-2.0$ GeV. The calibration of the deuteron beam polarimeter will be performed at seven energies: 0.88, 1.0, 1.25, 1.5, 1.6, 1.75, and 2.0 GeV. The lowest energy corresponds to the maximal energy of polarized deuteron beam of RIBF. The calibration at higher energies is necessary for the PHe3 project at the LHE (JINR) [25]. Particular attention will be paid to the measurements at an energy of 1.6 GeV, where the data on the full set of analyzing powers exist [18].

The detectors will be also placed symmetrically in the directions of azimuthal angles to left, right, up, and down. This will allow one to measure vector A_y, tensor A_{yy} and A_{xx} analyzing powers. The scattering angles of proton and deuteron correspond to $70-130°$ in the center of momentum system.

The feasibility study of the d–p elastic scattering measurements at high energies was performed in the test experiment in March 2005 at ITS. Figures 9 and 10 present results of test measurement at $T_d = 1.6$ GeV. In the time difference spectra between the proton and deuteron detectors (Fig. 9), a distinct peak due to true coincidence is observed at 0 ns. Ratio of the true coincidence rate to the accidental one is about 2.5 for a beam intensity of $1.0 \cdot 10^9$ per spill. Figure 10 shows ADC spectra of proton detector. A peak corresponding to d–p elastic scattering appears at ~ 600 channels on a broad bump. A part of the bump is due to the accidental coincidence and can be subtracted by use of TDC information in Fig. 9.

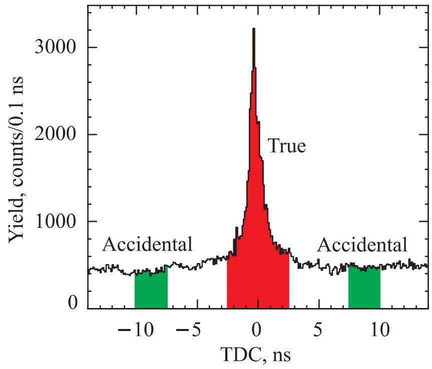

Fig. 9. TDC difference of deuteron and proton detectors. The shadowed peak at 0 ns is used to estimate «true + accidental» events, while the shadowed regions at ±10 ns show the number of «accidental» events

The remaining background originates from carbon in polyethylene target and can be subtracted by use of spectra for carbon target. The resulting spectrum is shown in Fig. 10, *c*. It is experimentally confirmed that the *d–p* elastic scattering events by polyethylene target can be clearly extracted by subtracting accidental coincidence events and carbon events. It should be noted that, at the higher energies, carbon contribution, mainly quasifree *d–p* scattering, can have a large analyzing power as free *d–p* elastic scattering and may be used for the purpose of polarization analysis. The proposed experiment measures the analyzing powers for the carbon target to clarify the usefulness of the quasifree *d–p* scattering as polarimetry.

In the proposed experiment the detectors are plastic scintillation counters of $20 \times 60 \times 20$ mm (width $\times$ height $\times$ thickness) in size. At forward angles, smaller scintillation counters of $20\times40\times20$ mm (width $\times$ height $\times$ thickness) in size are used. Each scintillation counter is attached to a photomultiplier tube (HAMAMATSU H7416) through lightguide. Angular span of one detector

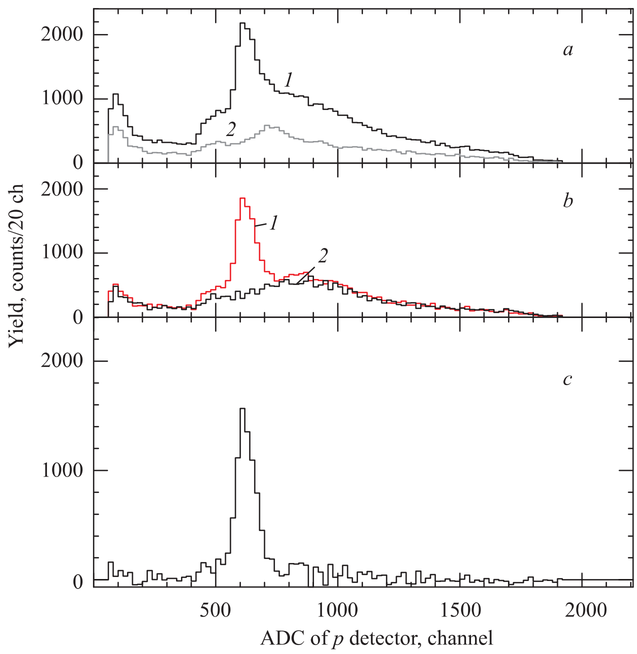

Fig. 10. ADC spectra for deuteron detector at 1.6 GeV. *a*) «True + accidental» (*1*) and «accidental» (*2*) spectra for CH_2 target. *b*) CH_2 (*1*) and carbon (*2*) spectra after subtraction of «accidental» events. *c*) Spectra for hydrogen target obtained by subtraction of carbon contribution in polyethylene

is 2° in the laboratory frame, which corresponds to 4° in the center of momentum frame. Detection solid angles of the detectors are 3.3 and 2.2 msr for large and small detectors, respectively.

3.4. Measurement of Polarization Observables at $T_d = 300-800$ MeV. Monte-Carlo simulation [26] performed for the LNS project [7, 8] shows the possibility to measure the d–p elastic scattering in the region of cross-section minimum up to $T_d = 500$ MeV.

The detailed investigation of the singles rates of detectors, true/accidental coincidence rates, carbon contribution and test of luminosity monitor based on p–p quasi-elastic scattering performed in March 2005 test run at ITS allowed one to evaluate the values of the cross section for the d–p elastic scattering at intermediate energies. The filled symbols in Fig. 11 show the result of cross-section measurement in March 2005. The relative angular dependence of the Nuclotron data is in good agreement with RCNP data [11] indicated by open circles.

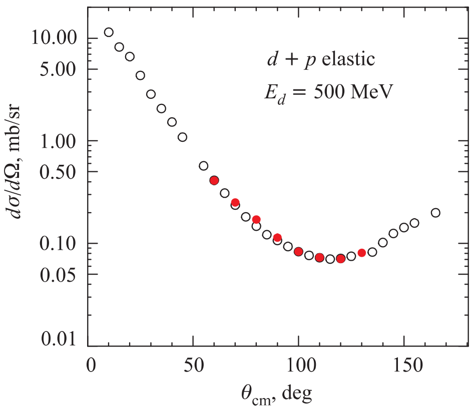

Fig. 11. Differential cross section for the $d-p$ elastic scattering measured at ITS (•) and at RCNP, Japan (○). Data at ITS are normalized by a factor of 0.22

The increasing of the number of detectors makes it possible to extend energy range for the measurements of the vector and tensor analyzing powers in the region of $\theta_{\rm cm} = 60$–$130°$ to the higher energies than it was initially proposed by the LNS project [7, 8]. In the proposed experiment new polarization data will be obtained at energies of 300–800 MeV with an interval of 50 MeV.

4. YIELD ESTIMATION AND BEAM REQUEST

The yield is estimated on the basis of the results of test run in March 2005. In the test measurement at $T_d = 500$ MeV, a counting rate for 1.1 msr detector was ~ 1 cps at an angle of $\theta_{\rm cm} = 120°$, where cross section takes its minimum value, for a beam intensity of 10^9 per spill.

The intensity of polarized beam is expected to be of $\sim 10^8$ per spill. On the other hand, effective target thickness will be enhanced by a factor of 10, by changing target sweep direction from that used in the test run. Additionally, solid angle of each detector will be increased to 2.2 msr. Thus, a counting rate for each counter is expected to be 2 cps. For determination of tensor analyzing power with a statistical uncertainty of $\Delta A = 0.02$, one needs 10^4 counts for one detector. It takes 4.5 h for three polarization modes. For vector analyzing power measurement, yield of $2.5 \cdot 10^3$ counts is enough to achieve the same precision, which leads to 1 h measurement for three polarization modes.

Energy dependence of the expected yield is discussed here. The cross section decreases with a beam energy by a factor of 20 from 270 MeV to 2.0 GeV. This decrease is compensated by an increase of luminosity due to a small energy loss of higher energy particle and by an increase of repetition rate of the Nuclotron. Consequently, expected yield is almost independent of the beam energy.

In total, the beam request is 15 days, which includes the time for the setup tuning, beam polarization measurements and data taking.

CONCLUSIONS

The aim of the present proposal is to calibrate new high-energy deuteron polarimeter located at ITS of the Nuclotron. This polarimeter will be able to measure both vector and tensor components of the deuteron beam polarization.

The calibration at an energy of 0.88 GeV is necessary for the development of the deuteron polarized beam at the new facility RIBF (Japan).

The calibration at the energies 1.0–2.0 GeV will be done to fulfill the PHe3 project at the Nuclotron.

The deuteron beam polarization measurements will be performed at 270 MeV using the data on the analyzing powers of d–p elastic scattering measured at RIKEN [4, 6]. For this purpose a moderate-energy polarimeter will be installed at ITS. Such a procedure will allow one to have the same polarization standard at two facilities: RIBF and the Nuclotron.

The ITS polarimeter setup is also suited for the measurement of the energy dependence of the d–p elastic scattering deuteron analyzing powers. New data obtained at $T_d = 300-800$ MeV can have a great impact on theories of three-nucleon force.

The present experiment is proposed under the agreement on academic exchange between the Joint Institute for Nuclear Research and Graduate School of Science, the University of Tokyo.

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