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EXPERIMENTAL RESEARCH OF THE *NN* SCATTERING WITH POLARIZED PARTICLES AT THE VdG ACCELERATOR OF CHARLES UNIVERSITY. PROJECT «*NN* INTERACTIONS»

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The purpose of the project is to study three-nucleon interactions using 14–16 MeV polarized neutron beam in conjunction with polarized deuteron target. Spin-dependent total cross-section differences $\Delta\sigma_L$ and $\Delta\sigma_T$ will be measured in the energy range, where there are no experimental data, with sufficient accuracy to check the contribution of the three-nucleon forces. In the test run, the obtained deuteron vector polarizations were $P_- = (-39.5 \pm 2)\%$ and $P_+ = (32.9 \pm 2)\%$. The proposed experiment is the continuation of the preceding measurements of the same quantities in the np scattering at the Van de Graaff accelerator of Charles University.

Целью проекта является изучение трехнуклонных взаимодействий с использованием поляризованного нейтронного пучка с энергией 14–16 МэВ совместно с поляризованной дейтронной мишенью. Спинзависящие разности полных поперечных сечений $\Delta\sigma_L$ и $\Delta\sigma_T$ будут измерены в области энергий, где нет экспериментальных данных, с точностью, достаточной для проверки вклада трехнуклонных сил. В методическом сеансе были достигнуты значения векторной поляризации дейтронов $P_- = (-39,5 \pm 2)\%$ и $P_+ = (32,9 \pm 2)\%$. Предлагаемый эксперимент продолжает предшествующие измерения тех же самых величин в np-рассеянии на ускорителе Ван-де-Граафа Карлова университета.

INTRODUCTION

It has now become possible to carry out exact experiments and perform numerical calculations of the Faddeev equation for neutron–deuteron scattering using present-day NN forces [1]. There are theoretical predictions of the Bochum–Cracow group concerning 3N system [2]. It is proposed to measure spin-dependent total neutron–deuteron cross-section differences with both neutron and deuteron polarized ($\Delta\sigma_T$ and $\Delta\sigma_L$) at incoming neutron

energies smaller than ≈ 20 MeV. In [2] $\Delta\sigma_T$ and $\Delta\sigma_L$ were calculated with four recent NN potentials: AV18, CD Bonn, Nijm I, and Nijm II. As the 3NF, the 2π-exchange Tucson–Melbourn (TM) model [8] was adjusted to the triton binding energy. It was shown that the 3NF change the magnitudes of the longitudinal and transversal asymmetries of the total **nd** cross sections, and the value of the effect is large enough to be measured. The results of such measurements will form the data basis to test the present 3NF models.

The total cross-section difference ($\Delta\sigma_L$) between parallel and antiparallel configurations of neutron and deuteron spins was measured at TUNL [3] for incident neutron energies of 5.0, 6.9, 8.9, and 12.3 MeV. The data were compared to the theoretical predictions based on the CD Bonn NN potential calculations, with and without the inclusion of the TM–3NF. The authors found that the data were greater by a factor of ~ 1.5, and noted that, «given reasonable agreement with other nd observables, a sizable discrepancy between experimental and calculational values would be a large surprise». The origin of this discrepancy with the calculations remains unknown.

The experiment on the **d**p elastic scattering has been carried out at $E_{\mathrm{lab}} = 270$ MeV in RIKEN [4]. A discrepancy with Faddeev calculations using recent NN forces was found. This discrepancy can be completely removed for the cross-section data and for A_y^d, by including the TM–3NF in the calculation. In contrast, the inclusion of the 3NF does not lead to a better description of the A_{ij} data, in comparison with the predictions using NN forces only. These facts clearly indicate deficiencies in the TM–3NF spin-dependence calculations. At RCNP the cross-sections and polarization parameters have been measured for **p**d scattering at 250 MeV [5].

It is important to note that the nd scattering is interesting in view of the 3NF effects, as there is no Coulomb interaction, and a direct comparison with a Faddeev type calculation is possible. Such experiment on the backward **n**d scattering at $E_{\mathrm{lab}}(n) = 250$ MeV was carried out at RCNP [6]. The review of the present situation is contained in paper [7].

The aim of the Project is to study 3N interactions in the final state, using the 14–16 MeV polarized neutron beam in conjunction with the polarized deuteron target (PDT).

We propose to measure $\Delta\sigma_L$ and $\Delta\sigma_T$ in the nd transmission experiment at neutron energies up to 16.2 MeV, where no experimental data exist. The proposed experiment is the continuation of the previous measurements of the same quantities in neutron-proton transmission [9, 10].

1. EXPERIMENTAL EQUIPMENT

An apparatus measuring the spin-dependent total cross-section differences has been constructed in Charles University. The set-up used in this experiment includes a tritium target for the polarized neutron production, a collimator, a background protection system, a magnet rotating neutron spins, a polarized deuteron target with the frozen nuclear polarization, and data acquisition equipment.

1.1. Polarized Target. The authors of the Project propose to use the existing frozen-spin target [11] for nd spin-dependent experiments used earlier for the np experiment (Fig. 1).

The target includes a stationary cryostat with a dilution refrigerator, a movable magnetic system including a superconducting magnet with a large aperture, a superconducting solenoid,
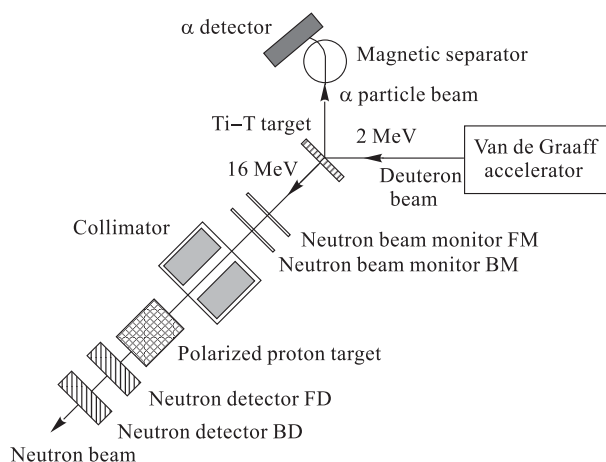
Fig. 1. The layout of experiment

a high-frequency generator providing the dynamic polarization and a NMR-signal detection array.

As target material, 1,2-propanediol $C_3H_8O_2$ (volume 20 cm^3) with a paramagnetic Cr(V) impurity was used. The maximum obtained polarization was 93 and 98 % for positive and negative values, respectively. The target was maintained at a temperature of ~ 20 mK in the holding magnetic field of 0.37 T. Under these conditions, the spin relaxation time was approximately 1000 h for positive polarization and 300 h for negative polarization.

The polarization direction is defined by the orientation of the holding field. The experiments with longitudinal polarization are performed with the superconducting solenoid. For the experiments with vertical polarization the superconducting dipole is used.

The target polarization measurement is carried out using a Q-meter of Liverpool type with operating frequency of about 17 MHz. An ATT diode generator with output power of ~ 200 mW at a frequency of ~ 75 GHz is used for the dynamic build-up of polarization.

The polarized target was upgraded in order to use deuterated propanediol $C_3D_8O_2$. This target material, in the form of small balls ≈ 2 mm in diameter, is placed in a teflon container, 2 cm in diameter and 6 cm long.

The test run was carried out in 2001. The following deuteron vector polarizations were obtained: $P_- = (-39.5 \pm 2)$ % and $P_+ = (32.9 \pm 2)$ % (Fig. 2).

As the nuclear magnetic resonance (NMR) signal from deuterons is much weaker than from protons, it is necessary to accumulate the signals and to use a PC for registration. The
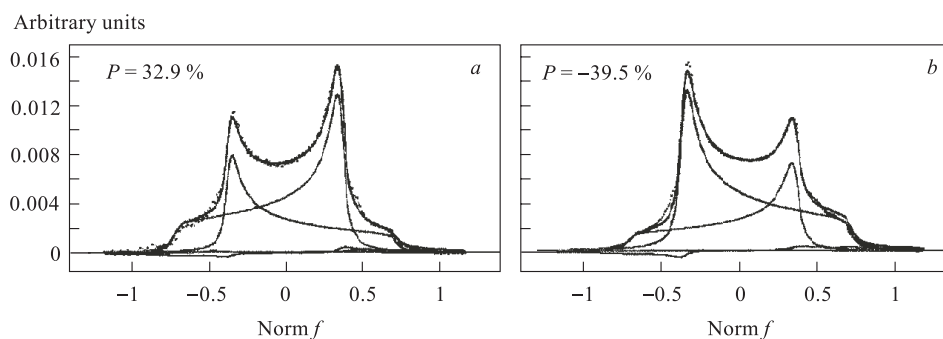

Fig. 2. Deuteron NMR spectra for a positive polarization (*a*) and a negative one (*b*)

upgraded polarization measurement system permits one to measure $\Delta\sigma_T$ and $\Delta\sigma_L$ for the nd scattering and to increase the sensibility for other experiments.

1.2. Polarized Neutron Beam and Detection System. As in the previous $\Delta\sigma_{L,T}(np)$ experiments, the exoenergetic two-body reaction $T(d,\mathbf{n})^4\text{He}$ should be used for the neutron production [12]. Unpolarized incident particles provide the transversally polarized outgoing neutrons. Their polarization value P_n depends on kinematic conditions of the reaction.

The Van de Graaff accelerator HV-2500 AN produces the deuteron beam ~ 1 mm in diameter, with the maximum current of 30 μA at the energy of (1.820 ± 0.005) MeV. The beam strikes the production target, where tritium was absorbed on Ti, under $45°$. The neutrons emitted at the angle $\theta_{\text{lab}} = (62.0 \pm 0.7)°$ have the kinetic energy $E_n = (16.2 \pm 0.1)$ MeV and $P_n = (-13.5 \pm 1.4)\,\%$.

Neutrons, together with γ rays, incident on the polarized target, are monitored by two neutron detectors. Two other counters behind the target are used as neutron transmission detectors.

The conjugate α particles, emitted with the energy $E_\alpha = 3.2$ MeV at $\theta_{\text{lab}} = -90°$, together with deuterons elastically scattered at the same angle, pass through the magnetic separator with a field of 0.5 T. They are registered by a silicon surface-barrier detector (8×5 mm). The α detector was adjusted to the position corresponding to the desired α-particle curvature in the separator magnetic field. It detected only a small amount of scattered deuterons. The tagging of neutrons is obtained by the coincidence of α-detector signals with signals from any neutron detector. In addition, for the background reduction, the time-of-flight (TOF) method, with a time resolution better than 2.5 ns, is used. Typically, $2 \cdot 10^4$ neutrons/s in a well collimated beam were obtained.

For the $\Delta\sigma_L$ experiments, the transversal neutron beam polarization is rotated into the longitudinal direction by the permanent magnet, having a field of 1.8 T at the length of 26 cm.

In order to increase the number of events and improve the effect/background ratio, the neutron detectors were upgraded to discriminate against γ counts more efficiently. Several liquid scintillator containers with high reflective ability and a reliable atmosphere insulation have been designed and manufactured.

To increase the light collection factor, a method was developed consisting of pure aluminium covering of the container inner surface, with high vacuum evaporation technology. An aging test was carried out of the counter equipped with the new-type container. Good n/γ discrimination parameters were observed still after one year of storage. A new movable support was used for the flat liquid scintillation counters, filled with NE-213 scintillator. The neutron beam incident on the polarized target is monitored by two beam detectors. Two other detectors are placed behind the target.

For the signal processing and the data acquisition the CAMAC system was used. This system includes the fast-slow coincidence circuits and the pulse-shape discriminator (PSD). The PCD module was constructed in order to suppress the unwanted γ background. This method reduces the background 40 times and enables us to set the neutron signal threshold quite low and to reach a maximum detection efficiency.

1.3. Minimum Statistics and Estimated Data Taking Time. For the purpose of this subsection, we treat the simplified case of $\Delta\sigma_{L,T}$ measurement using the vector polarized deuteron target, the beam and target polarizations in one parallel and one antiparallel directions. We set the neutron beam diameter to be smaller than the target diameter. The transmission method for the total cross-section differences needs relative measurements only,

and the knowledge of unique absolute value, i. e., the number of polarizable deuteron per unit of the target cross section.

For $\Delta\sigma_{L,T}$ we find

$$\Delta\sigma_{L,T} = \frac{\ln\left(\xi(\text{parallel})\right) - \ln\left(\xi(\text{antiparallel})\right)}{\omega P_b P_t}, \tag{1}$$

where ω is the number of deuterons per unit area of the target; P_b and P_t are the beam and target polarizations, respectively; and $\xi = N_d/N_{\text{mon}}$, where N_d and N_{mon} are net counts in the detector and monitor.

The statistical error of $\Delta\sigma$ is

$$\delta_{\text{stat}}(\Delta\sigma) = \frac{\sqrt{2}}{\omega P_b P_t}\sqrt{\frac{1}{\bar{N}_{\text{mon}}} + \frac{1}{\bar{N}_d}}, \tag{2}$$

where $\bar{N}_{\text{mon}} = (N_{\text{mon}}(\text{parallel}) + N_{\text{mon}}(\text{antiparallel}))/2$; $\bar{N}_d = (N_d(\text{parallel}) + N_d(\text{antiparallel}))/2$. For $E_n = 16.2$ MeV and D-propanediol $\omega = 3\cdot 10^{-4}$ mb^{-1}, $P_b = 13.5$ %, $P_t = 36$ %, we have $1/\omega P_b P_t = 6.9\cdot 10^4$ mb.

Demanded values for $E_n = 16.2$ MeV are: for $\Delta\sigma_L\delta = \pm 10$ mb, for $\Delta\sigma_T\delta = \pm 30$ mb.

To get the statistical errors of such values, with $N_{\text{mon}} \simeq N_d = 100$ events/s (considering that the accelerator functions 18 hours/day $\simeq 65000$ s), it is necessary to have a run of 30 days for measuring $\Delta\sigma_L$ and a run of 4 days for $\Delta\sigma_T$.

For a systematic error of $\Delta\sigma$:

$$\delta^2_{\text{syst}}(\Delta\sigma) = \delta^2_{P_b} + \delta^2_{P_t} + \delta^2_{\omega} + \delta^2_{\text{geom}}, \tag{3}$$

or

$$\delta^2_{\text{syst}}(\Delta\sigma) = (0.104)^2 + (0.05)^2 + (0.03)^2 + (0.01)^2 = (0.12)^2. \tag{4}$$

2. PROPOSED POLARIZED NEUTRON SOURCE

It is known that $T(\mathbf{d}, \mathbf{n})^4\text{He}$ is a good source of polarized neutrons for deuteron energies of less than 1 MeV [18]. The notations are taken from paper [18] (Fig. 3). Below approximately 0.5 MeV, the reaction is almost completely described by S wave $J = \frac{3}{2}$ resonance. At scattering angle of $0°$, the outgoing n polarization for a deuteron beam polarized along the y axis is given by

$$p_{y'}(\mathbf{n}) = \frac{\frac{3}{2}p_y K_y^{y'}}{1 + \frac{1}{2}p_{yy}A_{yy}}. \tag{5}$$

For pure $J = \frac{3}{2}^+$ interaction, the analyzing power A_{yy} tends to $\frac{1}{2}$ and the polarization transfer coefficient $K_y^{y'}$ tends to $\frac{2}{3}$. If tensor polarization p_{yy} equals zero, $p_{y'}$ tends to p_y.
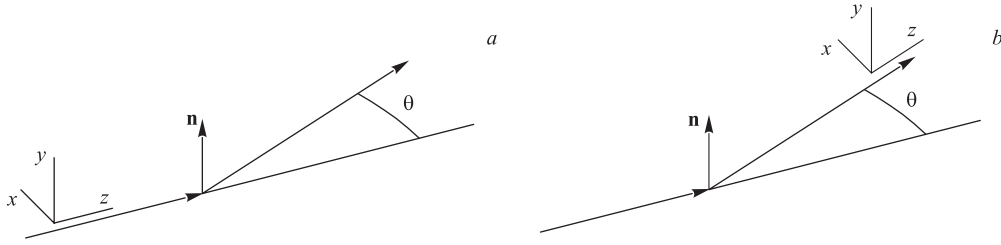
Fig. 3. *a*) Projectile helicity frame; *b*) outgoing reactant helicity frame

If the incident beam is polarized along the z direction,

$$p_{x\prime} \rightarrow \frac{p_z \sin\theta}{1 - \frac{1}{4}(3\cos^2\theta - 1)p_{zz}}, \tag{6}$$

$$p_{z\prime} \rightarrow \frac{\frac{1}{2}p_z \cos\theta}{1 - \frac{1}{4}(3\cos^2\theta - 1)p_{zz}}, \tag{7}$$

$$p_{y\prime} \rightarrow 0. \tag{8}$$

There are severe difficulties in mounting the polarized ion source at the Van de Graaff accelerator. These difficulties are connected with the shortage of space and energy at the high voltage terminal. But it is possible to test the early proposal made by Zavoiskii [13] on the ion polarization, using the capture of polarized ferromagnetic electrons in a thin foil. The first such experiment was carried out by Kaminsky in 1969 [14, 15]. His results were confirmed by Feldman et al. [16].

The success of the experiments made by Kaminsky is related to the use of the channeling through a single crystal foil. The technique investigated here is to direct the incident deuterons in one of the channeling direction of a monocrystalline nickel foil magnetized to saturation.

After passing the weak magnetic field region, the tensor polarization of the well-channeled deuterium atoms (now polarized in electron spin and nuclear spin) can be determined by measuring the angular distribution of the α particles emitted in the reaction $T(d,n)^4$He.

In Kaminsky's experiments the direction of magnetization was parallel to the axes of easy magnetization in the plane of the Ni foil. Saturation is reached at fields of approximately 30 G.

The measured value of P_{33} was -0.32 ± 0.01, which corresponds to a fractional population of $m_I = 0$, $N_0 = 0.440 \pm 0.003$. A beam of 0.5 μA/cm^2 of channeled deuterium atoms was obtained with nuclear spin polarization (without significant lattice damage for ≈ 25 h of operating time).

It is possible to produce a relatively cheap polarized neutron source at the Van de Graaff accelerator at Charles University [17] (Fig. 4). The nickel foil should be mounted in the
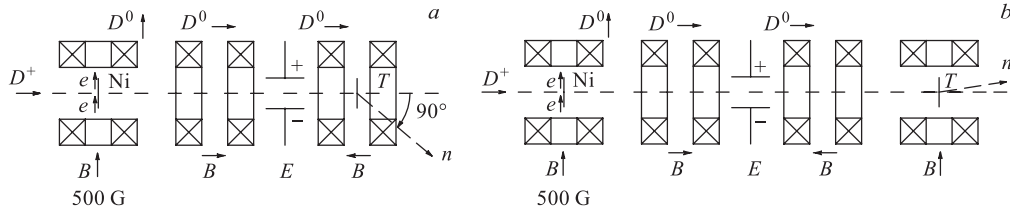
Fig. 4. Polarized neutron production: *a*) transversal horizontal polarization; *b*) transversal vertical polarization

transversal magnetic field of ≈ 500 G in the plane of the foil. Deuterium atoms with polarized electrons are directed into the longitudinal magnetic field of the same value. The calculations show that the electron polarization adiabatically follows the magnetic field direction. At the length of 50–70 cm, the reversal of the magnetic field takes place (Sona transition method [19]), and the electron polarization is transferred to the deuterons. In the ideal case, the vector polarization should be $p_z = -2/3$ and the tensor polarization $p_{zz} = 0$, where the z axis is in the direction of the magnetic field of the second magnet (e. g., along the beam direction). If the Titanium–Tritium target is mounted in a strong magnetic field, the neutrons produced at the angle of $90°$ (CM) have the same value of vector polarization, but are transversal in the horizontal plane, in the same way as the primary beam.

It it also possible to rotate the longitudinal vector polarization adiabatically into the vertical direction by the magnetic field of an additional magnet. Then, the neutrons produced at $0°$ will have, ideally, the vertical polarization equal in value to the deuteron polarization $P_n \approx 2/3$.

As shown in paper [20], the transversal vector polarization of deuterons at an energy of ≈ 200 keV can be measured using $^2\mathrm{H}(\mathbf{d}, p)^3\mathrm{H}$ reaction. The vector analyzing power of this reaction with 200 keV deuterons at $120°$ lab angle of 0.224 ± 0.017 was measured in paper [21].

Numerical calculations have been carried out using Schrödinger equation for six-component wave function, describing the state of the atom as a superposition of the six states at a high magnetic field, which have a definite nuclear spin.

With the use of data known from the cited papers and the results of calculations, it is possible to expect that the polarized deuteron current may reach 0.5 μA with an energy of < 200 keV and the vector polarization P_3 reaching 2/3 and $P_{33} = 0$. These values, if reached, will allow one to upgrade considerably the parameters of the current polarized neutron beam.

The polarization of the neutron beam will be measured using $^4\mathrm{He}(n, n)^4\mathrm{He}$ scattering, where $A_y(\theta)$ reaches the theoretical maximum ($= 1$) (near $\theta = 110°$ and around $E_n = 12$ MeV) and varies slowly with the energy and angle [22].

CONCLUSION

The Van de Graaff accelerator at Charles University, Prague provides the 16.2 MeV polarized neutron beam. In conjunction with the polarized deuteron target it is possible to measure, for the first time, the observables $\Delta\sigma_{L,T}(nd)$ at this energy.

It is of particular interest to compare the experimental results with the recent phenomeno-logic predictions for the same quantities, calculated in the neutron kinetic energy interval up to 20 MeV. Such a comparison checks a contribution of the three nucleon forces (3NF) in the final state.

It is proposed to use equipment considerably upgraded with respect to that used in previous $\Delta\sigma_{L,T}(np)$ measurements.

It is planned to reduce the relative errors of measurements from 12 to 5 %, which should help to determine a possible 3NF contribution.

It is proposed to extract polarized deuterons for the production of the neutron beam with an energy of about 14 MeV and to increase its polarization.

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