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TENSOR POLARIZATION OF DEUTERONS FROM *p-d* ELASTIC SCATTERING

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The elastic scattering of nucleons by deuterons provides a useful method for studying the fundamentally important three-nucleon system. In the present experiment, the second-rank tensor polarization moments of the recoil deuterons from *p-d* elastic scattering have been determined at several proton energies in the range between 4 and 8.7 MeV.

Satisfactory fits to *n-d* and *p-d* angular distribution data, based on the "resonating group" method, have been obtained by using velocity-independent central forces only and by assuming that the deuteron is not distorted in the interaction.[1] Such forces, however, result in predictions of zero polarization for both the nucleon and the recoil deuteron, whereas published data[2,3] appear to indicate the presence of small but nonzero values of the nucleon polarization at energies below 10 MeV and increasingly large values at higher energies. In addition, the present measurements indicate some small but nonzero values of the deuteron polarization tensors.

It would be desirable if numerical calculations were performed in which both a spin-orbit and a tensor term in the nucleon-nucleon interaction were included. Either of these terms could lead to nucleon and deuteron polarization. A resonating-group formalism in which tensor (but not spin-orbit) forces are included has been published, but numerical results have not yet appeared in the literature.[4] The problem has also been formulated with a spin-orbit (but not tensor) force, but again no numerical results have appeared.[5] A more approximate calculation, in which the exchange of the two like nucleons is not taken into account, has been published.[6] This calculation does take into account, to some extent, the distortion of the deuteron in the scattering and includes a tensor force. However, the model is a simple one and is expected to give only qualitative results.[7]

In the present experiment, the tensor polarization of deuterons from *p-d* scattering was determined for proton energies of 4.06, 5.06, and 5.84 MeV at a laboratory scattering angle of 30°, and for proton energies of 6.10, 7.59, and 8.69 MeV at a laboratory scattering angle of 45°. To make the measurements, a deuterated polyethylene target was bombarded with a proton beam, and the recoiling deuterons, after being slowed to about 800 keV, were used to initiate the reaction $He^3(d,p)He^4$.[8] From the observed angular distribution of the resulting protons, the second-rank spin moments[9] $\langle T_{20}\rangle$, $\langle T_{21}\rangle$, and $\langle T_{22}\rangle$ of the recoil deuterons were determined from the expression[10]

$$\sigma(\theta,\varphi)=\sigma_0[1-\tfrac{1}{4}\sqrt{2}\langle T_{20}\rangle(3\cos^2\theta-1) -\sqrt{3}\langle T_{21}\rangle\sin\theta\cos\theta\cos\varphi -\tfrac{1}{2}\sqrt{3}\langle T_{22}\rangle\sin^2\theta\cos2\varphi], \qquad (1)$$

where σ_0 is the cross section for scattering of unpolarized deuterons. The experimental techniques used were similar to those described by Seiler et al.[11]

The geometrical arrangement employed for the measurements is shown in Fig. 1. A proton beam from the Australian National University tandem electrostatic accelerator was collimated by a 2.4-mm tantalum aperture and allowed to strike a 1.6-mg/cm^2 deuterated polyethylene[12] target foil. The target was positioned such that the normal to its surface was at an angle of 30° with respect to the proton beam. To permit the use of beams of sufficiently high intensity, it was necessary to rotate the target during bombardment. With the target rotating at about 100 rpm and with a rotation diameter of 1.9 cm, it was found that no serious deterioration occurred with beam currents below about 0.25 μA at proton energies above 4 MeV. For some of the later points, we were able to further increase the allowable beam to about 0.8 μA by evaporating a thin film of aluminum on each side of the foil. With the conditions actually employed, counting rates for the various points obtained varied from about 100 to 300 counts per hour.

The recoil deuterons left the 13-cm-diameter scattering chamber through a 6-μm Havar[13] foil. After penetrating about 8 mm of air and the required (Mylar) slowing foils, the deuterons entered a He^3 cell through a second 6-μm Havar foil. The He^3 cell consisted of a 2.5-cm-diameter hemisphere pressed from 100-μm aluminum foil. At the operating pressure of 5.5 atm this was sufficiently large to stop 900-keV deuterons. Rectangular slits having an angular acceptance of either ±2.7° or ±1.4° were located immediately in front of the He^3 cell. The larger slits were used for all measurements except the two higher energy points taken at 45°.

Protons from the reaction $He^3(d,p)He^4$, after penetrating the aluminum hemisphere and about 9 cm of air, were detected with four CsI scintillation crystals. An annular detector having a mean polar angle of 16.9° was centered about the position $\theta_2 = 0°$, $\varphi_2 = 0°$, and three square detectors were located in the positions $\theta_2 = 52.55°$, $\varphi_2 = 0°$, $-90°$, and $-180°$ (see Fig. 1). The annular geometry for the first detector was used to avoid detecting direct protons coming through the He^3 cell from the target. The square counters subtended an angle of ±5.5°, and the annulus subtended a polar angle of ±1.5° with respect to the center of the He^3 cell.

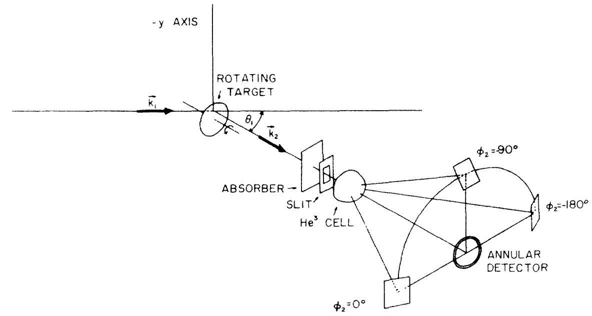

FIG. 1. A schematic diagram showing the experimental arrangement used. The parts of the apparatus beyond and including the slowing foil are not in vacuum.

Pulses from the four counters were routed into 100 channel blocks of a 400-channel pulse-height analyzer. The background counting rate was never worse than one or two counts per hour and no correction was made.

The deuteron energy variation with scattering angle is quite severe and is enhanced by the use of slowing foils. This energy spread results in lower proton yields and introduces a spurious asymmetry in the yields. To partially offset this effect, an additional Mylar slowing foil of appropriate thickness was placed on the small-angle half of the He^3 cell. This effect was, however, fully taken into account in the calculation of the polarization tensors from the data.

Equation (1) can be correctly used to determine polarizations only if the incident deuterons are s wave; this would appear to be a good approximation up to at least 800 keV.[11,14] Accordingly, the deuteron bombarding energy was adjusted so that not more than 10% of the proton yield arose from deuterons having energy greater than 800 keV. It was not possible, because of the rapid variation of deuteron energy with angle, to maintain acceptable counting rates without allowing some of the deuteron energies to exceed 800 keV. Although the possible anisotropy of σ_0 above 800 keV was not taken into account in the calculation of the parameters $\langle T_{qk} \rangle$, estimates show that even the effect of an anisotropy much more severe than that indicated by the angular distribution data[14] would be completely negligible.

The deuteron energy was set by comparing experimental curves of yield versus proton bombarding energy to theoretical yield curves which

Table I. Measured values of the tensor polarization of deuterons from p-d elastic scattering in a coordinate system with z axis parallel to $\vec{k}_2$.

E_p (MeV)	θ_d (deg)	$\langle T_{20}\rangle$	$\langle T_{21}\rangle$	$\langle T_{22}\rangle$
4.06	30	$+0.018\pm0.043$	$+0.029\pm0.027$	-0.063 ± 0.033
5.06	30	-0.001 ± 0.046	$+0.001\pm0.029$	-0.101 ± 0.034
5.84	30	$+0.044\pm0.046$	$+0.050\pm0.029$	-0.055 ± 0.035
6.10	45	-0.115 ± 0.049	-0.004 ± 0.028	-0.014 ± 0.034
7.59	45	-0.135 ± 0.049	-0.008 ± 0.028	-0.029 ± 0.035
8.69	45	-0.069 ± 0.049	$+0.009\pm0.029$	-0.043 ± 0.035

were calculated for each experimental arrangement. The calculations were performed with a CDC-3600 computer. These numerical integrations took into account the finite size of the He^3 cell and CsI detectors, variation in energy with scattering angle, variation of the p-d and $He^3(d,p)He^4$ cross sections with energy and angle, energy spread from first target thickness, the exact shape of the He^3 cell, the increased energy spreads from the slowing foils, and center-of-mass to laboratory conversion. This procedure resulted in setting the bombarding energy at a point where about 50% of the maximum yield was obtained.

To eliminate as many uncertainties as possible, the proton angular distributions were determined from a ratio at each angle of the yields resulting from (1) proton bombardment of a deuterated polyethylene target and (2) Coulomb scattering of 5.35-MeV deuterons from a 4.5-mg/cm^2 gold target. This technique cancels, to first order, factors such as detector geometry. Remaining second-order effects were taken into account in the procedure for the determination of final values of the parameters $\langle T_{qk}\rangle$.

An iterative method was used to determine the final values of the $\langle T_{qk}\rangle$. Specifically, the $\langle T_{qk}\rangle$ were first calculated directly from the observed angular distribution, using Eq. (1). The yields were then calculated using these values in a numerical integration over the experimental geometry in which all the factors already mentioned were taken into account. The $\langle T_{qk}\rangle$ were then varied until the experimental data were reproduced. However, the $\langle T_{qk}\rangle$ values obtained in this way differed from the first-order values by an amount not exceeding 50% of the statistical errors quoted in Table I. Thus we conclude that the geometry and experimental techniques used for the present measurements were highly satisfactory.

The final results are shown in Fig. 2 and listed in Tables I and II along with the statistical errors. The tensor polarizations are quoted in the coordinate system with its z axis parallel to $\vec{k}_2$ (Table I) as well as in the system with its z axis parallel to $\vec{k}_1$ (Table II).[15] For both coordinate systems the y axis is taken to be in the direction $\vec{k}_1\times\vec{k}_2$.

As may be seen from Tables I and II and Fig. 2, several points would appear to be significantly different from zero. It would appear that the present data lead to the same qualitative conclusion as do the nucleon polarization data; namely, the inclusion of spin-orbit or tensor

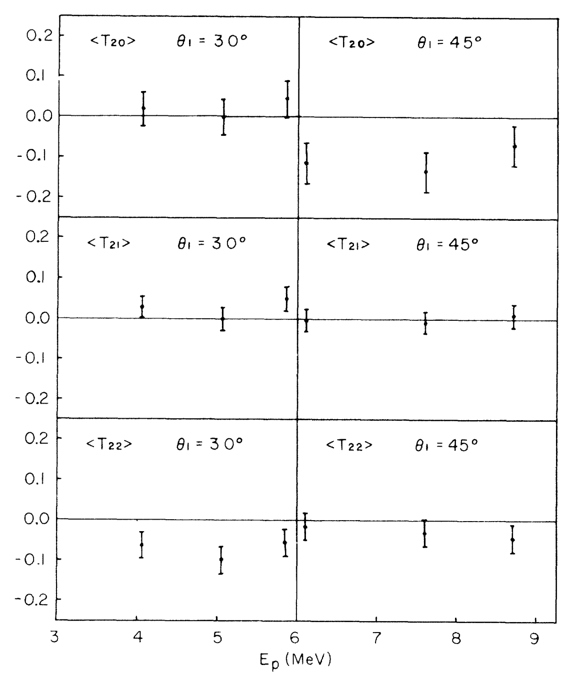

FIG. 2. Summary of the experimental data. The tensors are measured in a coordinate system whose z axis is parallel to the laboratory deuteron direction.

Table II. Measured values of the tensor polarization of deuterons from p-d elastic scattering in a coordinate system with z axis parallel to $\vec{k}_1$.

E_p (MeV)	θ_d (deg)	$\langle T_{20}\rangle$	$\langle T_{21}\rangle$	$\langle T_{22}\rangle$
4.06	30	+0.023±0.041	−0.022±0.030	−0.065±0.032
5.06	30	−0.030±0.043	−0.043±0.032	−0.089±0.033
5.84	30	+0.064±0.043	−0.022±0.032	−0.063±0.034
6.10	45	−0.042±0.042	+0.063±0.034	−0.044±0.033
7.59	45	−0.061±0.042	+0.068±0.035	−0.059±0.033
8.69	45	−0.033±0.043	+0.021±0.035	−0.058±0.034

forces is necessary to describe low-energy nucleon-deuteron scattering, but the effects of such forces are relatively small.

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