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The measurement and interpretation of the polarization in the scattering of low-energy nucleons by deuterons should have an important bearing on the understanding of nucleon-nucleon interactions in nuclear matter. Even though the two-body interaction may not be completely known, one would hope to predict the results of nucleon-deuteron scattering in terms of measured nucleon-nucleon scattering parameters, and to determine whether or not any specifically three-body interaction would be required to explain the results. Unfortunately, at low energies, where the results are of greatest interest with respect to their bearing on nuclear structure, the interactions among the three particles during the scattering are roughly equally strong and thus the three-body analytic solution of the problem becomes difficult. The maximum polarization is known to be small in p-p scattering ($\lesssim 1\%$)[1,2] and in n-p scattering ($\lesssim 5\%$)[3,4] near 20 MeV bombarding energy. On the other hand, the polarization in the scattering of protons from complex nuclei reaches values of up to 100% at energies as low as 6 MeV. In scattering from the lightest nuclei, in particular, the maximum polarization is approximately 100% in p-He^4 scattering at 6 to 14.5 MeV[5,6] and 55% in p-H^3 and p-He^3 scattering at 14.5 MeV.[6] The former is understandable in terms of the splitting of the $j = \ell + 1/2$ and $j = \ell - 1/2$ phase shifts due to the strong spin-orbit forces acting in the p-He^4 (Li^5) system. Such an explanation might be considered for the p-H^3 and p-He^3 results, treating the

target as a spin-zero nucleus and thereby ignoring any tensor interaction. However, an extension of this argument to the p-d system does not seem warranted, since measurements of the polarization in p-d scattering have been consistent with zero or very small values at energies below 17 MeV.[7] Thus, determinations of polarization in p-d or n-d scattering at energies below 50 MeV could provide information useful to the understanding of this remarkable difference between the polarization induced in nucleon-nucleon scattering and that resulting from the scattering of the nucleon from a few-nucleon system.

A general theory of nucleon-deuteron scattering, including tensor forces but neglecting the distortion of the deuteron, has been developed,[8] but calculations based on this formalism are not presently available. An approximate calculation has been made which includes, also, the effect of deuteron distortion in n-d scattering below 3.5 MeV,[9] and this calculation predicted a rapid variation with energy of the neutron polarization at 90°c.m., reaching a maximum of 12% near 1 MeV. Experimental results to date are not in agreement with respect to confirmation of this prediction.[10] Previous calculations[11] carried out for central forces alone had compared well with differential cross section data up to 10 MeV but could not result in any nucleon polarization. At higher energies calculations employing the impulse approximation have had some success in fitting p-d polarization results at 150 MeV, and these calculations have been extended to energies as low as 40 MeV.[12]

We have measured in a double scattering experiment the proton polarization produced in the elastic scattering of 22 MeV protons by deuterons. Polarized protons were produced as recoil protons (at 130°c.m.) in the scattering of 45 MeV alpha particles in hydrogen using the alpha particle beam from the 60-inch Crocker cyclotron. The protons produced in this manner are approximately 100%

polarized. The polarized proton beam entered a second scattering chamber containing deuterium at approximately 165 lbs/in^2. A scattered proton or recoil deuteron produced by scattering in the second chamber was detected by one of two counter telescopes placed symmetrically on opposite sides of the polarized beam. The dE/dx of a particle was determined by the pulse height produced in a thin (0.006" - 0.023") plastic scintillator and the energy (E) was determined from the pulse obtained by stopping the particle in a CsI crystal. A coincidence between dE/dx and E pulses was required to gate a multi-channel analyzer which recorded and stored the spectrum of E pulses.

The primary alpha particle beam intensity ranged up to about 2-1/2 μa. The energy of the polarized proton beam was 22 ± 1 MeV with principal contributions to the spread arising from the energy spread in the primary beam and by the angular acceptance of the collimating system defining the first scattering. The intensity of the polarized proton beam was about 6×10^6 particles/second. The angular resolution of the counters observing the second scattering was ± 4° at half maximum with a roughly triangular resolution function. The counting rate after the second scattering was of the order of one count per second (in the elastic-scattering peak) in the forward hemisphere. A sample of data taken at a forward angle is shown in Figure 1. Background under the elastic-scattering peak, in this case less than 1% of the number in the peak, has been subtracted. The spectrum consists of a main peak of elastically scattered protons and a continuum of protons at lower energies arising from the break-up of a deuteron by an incident proton. At some angles a peak of elastically recoiling deuterons is seen superimposed on the continuum.

At proton scattering angles greater than 106° c.m. it became easier to measure the associated forward-recoiling deuterons than the backward-scattered protons because of the low energies of protons scattered at large angles.

For this measurement, in order to enhance the separation of deuteron pulses from proton pulses, the CsI scintillator was made just thick enough to stop the deuterons while the higher energy scattered protons at the same angle passed through the scintillator losing only a fraction of their energy.

The method of analysis of the data is partially indicated in Figure 1. The three-body break-up continuum was extrapolated to its calculated endpoint and subtracted from the elastic scattering peak. A statistical error was computed based on the number of counts in the peak, the subtraction of background, and an estimate of the error involved in the extrapolation and subtraction of the continuum spectrum. The right and left counters were interchanged for about half of the time spent in determining each point in order to minimize systematic errors and to correct for differences in counter efficiency and geometry. The zero of the angular scale and corrections for the misalignment of the principal collimators in the counters were determined by passing the counters through the polarized beam at reduced beam intensity. This procedure corrects to first order for angular errors arising from misalignment of the beam in the second scattering chamber.

The polarization was determined from the right-left asymmetry in the second scattering. The sign of the polarization is given according to the Basle convention (positive polarization in the direction $\vec{k}_{inc} \times \vec{k}_{scat}$). For elastic scattering the asymmetry is given by $P_1 P_2(\theta)$, where P_1 is the fractional polarization of the proton beam and $P_2(\theta)$ is the proton polarization that would be induced in the scattering of unpolarized protons by deuterons. We have assumed P_1 to be 1.0 and thus $P_2(\theta)$ to be equal to the asymmetry.[2]

The results are presented in Figure 2 and Table I. The error associated with each point is only the statistical error mentioned above. Most systematic errors would merely shift the zero of the polarization scale and it is believed that effect of all systematic errors is less than ± 2%. The results show a

substantial polarization in p-d scattering at 22 MeV. The large values reached by the polarization suggest that it may be difficult to explain the results in terms of nucleon-nucleon scattering parameters even with maximum constructive interference in the scattering of the incident proton from the two particles of the deuteron.

Also shown in Figure 2 are the somewhat smaller back-angle values of $P(\theta)$ in n-d scattering, determined recently at 23.7 MeV.[13] That experiment utilized, from the $T(d,n)He^4$ reaction, a beam of neutrons whose polarization was taken to be $P_1 = 0.60$, the value of the proton polarization from the mirror reaction $He^3(d,p)He^4$.[14] Values for the neutron polarization, which range from 0.46[3] to 0.64[15], are less precise because of uncertainties in the analyzing power of the helium analyzer used. Thus, if a smaller value of P_1 had been taken, larger values of $P(\theta)$ in n-d scattering would have resulted. More precise data on both systems will be required before any significant back-angle difference between the p-d and n-d results could be claimed.

Table I. Measured polarization, $P(\theta)$, at various center-of-mass scattering angles in the elastic scattering of 22 MeV protons by deuterons.

$\theta_{c.m.}$ (degrees)	$P(\theta)$
31.4	+ 0.030 ± 0.007
37.2	+ 0.033 ± 0.010
44.5	+ 0.042 ± 0.011
58.8	+ 0.039 ± 0.007
64.4	+ 0.037 ± 0.013
72.5	- 0.012 ± 0.010
79.2	- 0.027 ± 0.016
85.7	- 0.076 ± 0.021
92.0	- 0.088 ± 0.010
98.0	- 0.096 ± 0.021
106.2	- 0.157 ± 0.021
122.0	+ 0.023 ± 0.022
128.0	+ 0.271 ± 0.023
136.0	+ 0.253 ± 0.025

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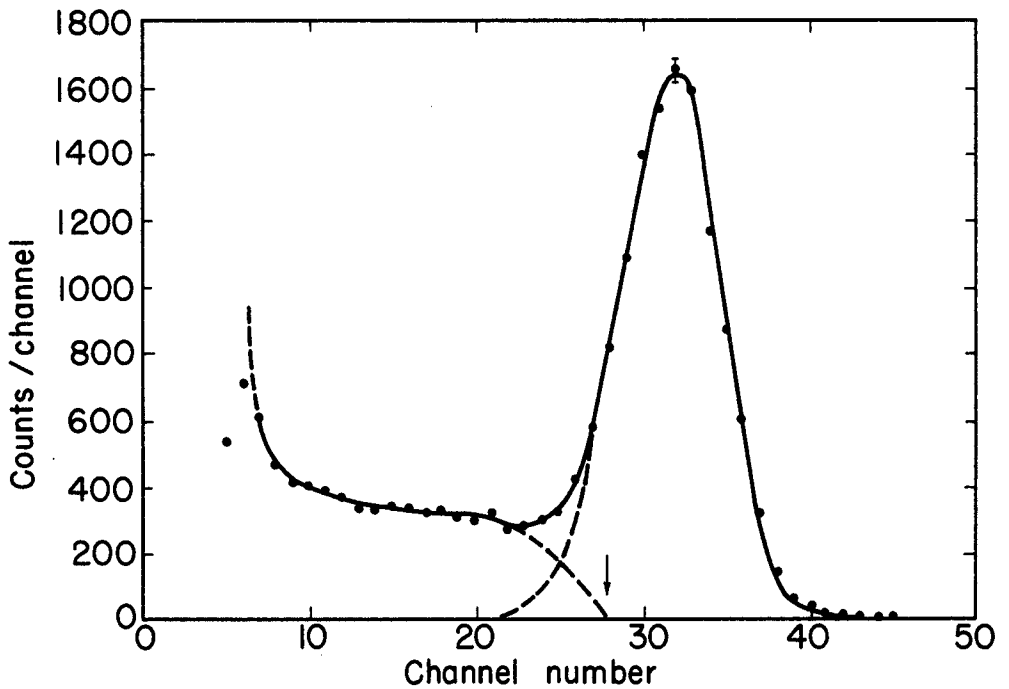

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Figure 1. Pulse-height spectrum obtained from a counter telescope placed at an angle of 40° (left) from the beam direction. The spectrum consists of a peak of 17.3 MeV elastically scattered protons and a continuum at lower energies. The arrow indicates the calculated end point of the continuum.

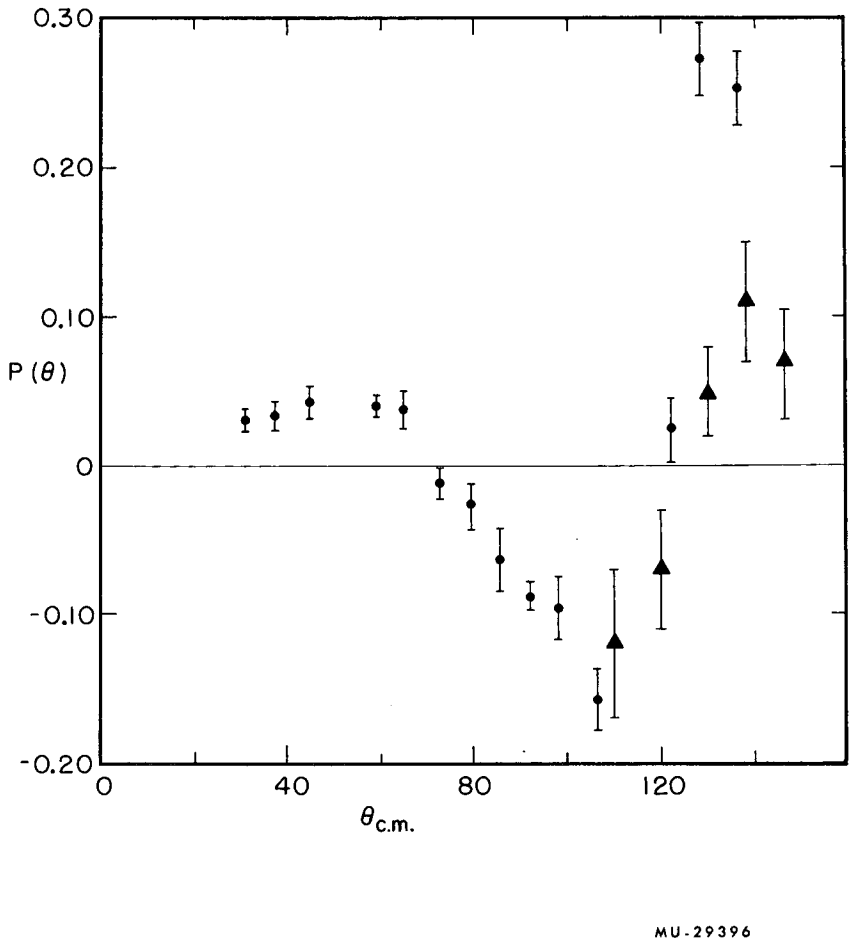

Figure 2. Polarization, P (θ), as a function of center-of-mass angle, $\theta_{c.m.}$

● Our p-d data at 22 MeV

▲ n - d data of 23.7 MeV (reference 13) .

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