orbiting [expressed by Eq. (16)]. This is satisfied if the radii of the real and absorptive potentials are equal, as one would expect for nuclei that are not easily deformed. If the absorptive potential has a larger range than the real potential, then a partial wave will be absorbed before orbiting can occur.

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APPENDIX: CLASSICAL MODEL OF ANGULAR-MOMENTUM MATCHING

Let each nonelastic channel α consist of two uniform spheres with mass, charge, and radius (m_1, q_1, r_1) and (m_2, q_2, r_2). When they are touching, their moment of inertia about the center of mass is

$$\mathcal{I}=\mathcal{I}_1+\mathcal{I}_2+\mu R^2, \tag{A1}$$

where

$$\mathcal{I}_1=\tfrac{2}{5}m_1r_1^2, \quad \text{and} \quad \mathcal{I}_2=\tfrac{2}{5}m_2r_2^2,$$

$$R=r_1+r_2, \qquad \mu=m_1m_2/(m_1+m_2).$$

In the c.m. system, the separation velocity v of the two spheres is given by

$$\tfrac{1}{2}\mu v^2\approx E+Q-q_1q_2/R, \tag{A2}$$

where $-Q$ is the threshold energy of channel α and E is the available (c.m.) energy of the incoming beam. Semiclassically, the maximum angular momentum that the channel α can carry away is

$$\hbar L_c'(\alpha)\approx\mathcal{I}v/R,$$

i.e., the classical angular momentum when the vector $\mathbf{R}$ is perpendicular to the vector $\mathbf{v}$. Finally,

$$L_c'(\alpha)\approx(1/\hbar R)\mathcal{I}[(2/\mu)(E+Q-q_1q_2/R)]^{1/2}. \tag{A3}$$

Then the cutoff L_c for absorption into any nonelastic channel is

$$L_c'=\max L_c'(\alpha). \tag{A4}$$

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Polarization in n-d Scattering at 7.8 MeV*

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Asymmetries produced in the scattering of 7.8-MeV polarized neutrons have been measured to an accuracy better than ±0.020 for 12 angles ranging from 58° to 165° (c.m.). The ^{9}Be(α, n_0) reaction was employed as a neutron source with a polarization of 0.539 ± 0.012. The measured asymmetries agree with the 8-MeV data for the charge-symmetric p-d scattering, indicating that the Coulomb effects are indeed small at this energy. The data also follow the trend of the 9-MeV calculation of Purrington and Gammel.

I. INTRODUCTION

As the two-nucleon problem becomes better understood, more interest is being directed to the three-nucleon problem, both experimentally as well as theoretically. The complexity in describing the three-nucleon problem accurately is much larger because the experiments use the deuteron, a particle with spin 1 and with a ground state having around 4% D-state admixture. Thus, many parameters, e.g., phase shifts and mixing coefficients, are involved in the representation of nucleon-deuteron scattering. Also, if one is looking for possibly weak effects, such as the three-nucleon force or charge-dependent interactions, one needs a wealth of data from a variety of polarization experiments. Work along these lines is now proceeding for the p-d interaction. The most straightforward polarization experiment, the scattering of polarized protons from deuterons, has been performed recently at many energies above 4 MeV with the high accuracy attainable with a charged-particle polarized-ion source.[1–6] In contrast, no major experimental contribution to the neutron-deuteron polarization problem has been made for energies below 20 MeV since the survey reported six years ago by Walter and Kelsey who presented polarization angular distributions at five energies.[7]

Theoretical calculations of the polarization phe-

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‡ Woodrow Wilson Fellow.

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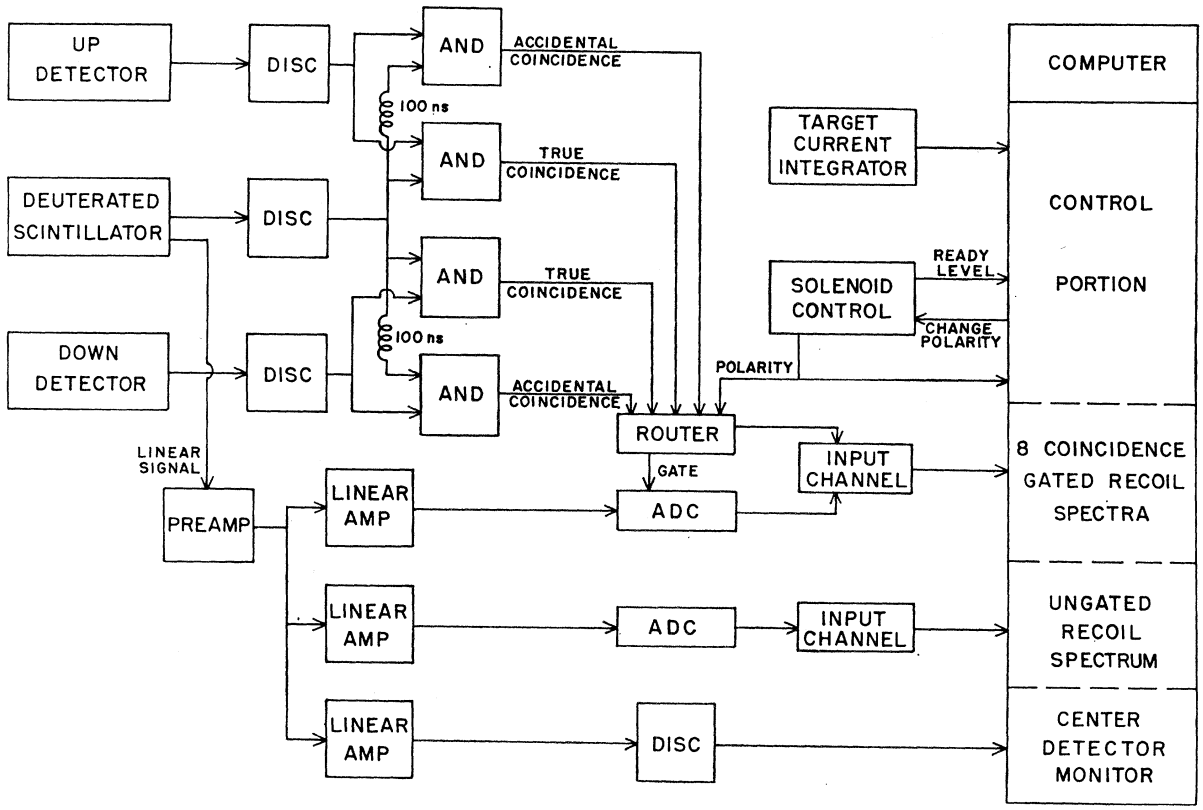

FIG. 1. Electronics diagram showing the fast-coincidence circuitry and the linear-signal analysis.

nomena in the three-nucleon problem have been lagging. Until recently, no reported calculation was able to describe the polarization even though the angular distribution of the polarization function is relatively simple. Last year, Purrington and Gammel showed the results of a Born-approximation computation at 9 MeV for *n-d* scattering in which the tensor interaction and the deuteron *D* state were included.[8] Searching on polarization and differential cross-section data at 9 MeV, Purrington and Gammel made a five-parameter fit (two phase shifts and three mixing parameters) to the data. The agreement was quite satisfying, although the most recent and most accurate *p-d* polarization data were not included in the fit.

Stimulated by the renewed theoretical activity in the three-nucleon problem and encouraged by the accuracy now possible in neutron polarization experiments, we undertook a measurement of the polarization function at 8 MeV with much greater accuracy and over a wider angular region than Walter and Kelsey reported. Polarized neutrons produced in the ^{9}Be(α, n) reaction were scattered from a deuterated liquid scintillator. Asymmetries in the scattered flux were measured over an angular range from 58° (c.m.) to 164° (c.m.). The experiment was performed in two stages, the results of the first part having been presented earlier in a preliminary form.[9]

II. EXPERIMENTAL PROCEDURE

The reaction ^{9}Be(α, n)^{12}C (g.s.) at a mean α energy of 2.55 MeV and a reaction angle of $\theta_1 = 45°$ (lab) served as a source of polarized neutrons. The neutron beam had a mean energy of 7.8 MeV and a polarization[10] of 0.539 ± 0.012. Targets of natural beryllium were prepared by evaporating the metal onto tantalum endcaps to a thickness corresponding to approximately 300-keV energy loss in the incident beam.

A deuterated scintillator, located about 1 m from the Be target, was used as a central scatterer in a polarimeter similar to the one shown schematically in Fig. 1 of Ref. 11. Two side detectors were placed above and below the deuterated scintillator at equal scattering angles θ_2. A solenoid was used to precess the neutron spins through 90° either clockwise or counterclockwise, allowing the roles of the two side detectors to be interchanged. The deuterated scintillator was a cylinder 2.5 cm long and 1.8 cm in diameter and was aligned

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with its symmetry axis along the normal to the second scattering plane. The ratio of the deuterium content to hydrogen content was greater than 2:1.

Two sets of side detectors for the polarimeter were used during the course of the measurements. For scattering angles θ_2 greater than 70° (lab), plastic scintillators which were 2.5 cm×5 cm×10 cm were placed 17 cm (center-to-center) from the deuterated scintillator. For the data points from 40° (lab) to 70° (lab), an expanded geometry was used in order to improve the time-of-flight discrimination and thus reduce the coincidence background. Liquid organic scintillators 5 cm×15 cm×8.7 cm were placed 45 cm (center-to-center) from the deuterated scintillator for these angles. All scintillators were connected by Lucite light pipes to RCA-6810A phototubes.

The recoil deuteron pulses were recorded in coincidence with pulses from the side detectors. Figure 1 shows a simplified diagram of the electronics used. A slow signal from the eleventh dynode of the center detector was analyzed by an analog-to-digital converter (ADC) yielding a measurement of the recoil energy. Fast signals from the anodes of the phototubes triggered fast discriminators to produce logic signals which were in turn fed into the appropriate "And" units with resolving times of less than 10 nsec. The resultant coincidence gate was encoded by a router and combined into one word with the corresponding pulse-height measurement from the ADC. This word was sent through an input channel to the computer which stored the event in one of eight 128-channel spectra corresponding to its combination of side detector, spin precession, and "true" or "accidental" coincidence.

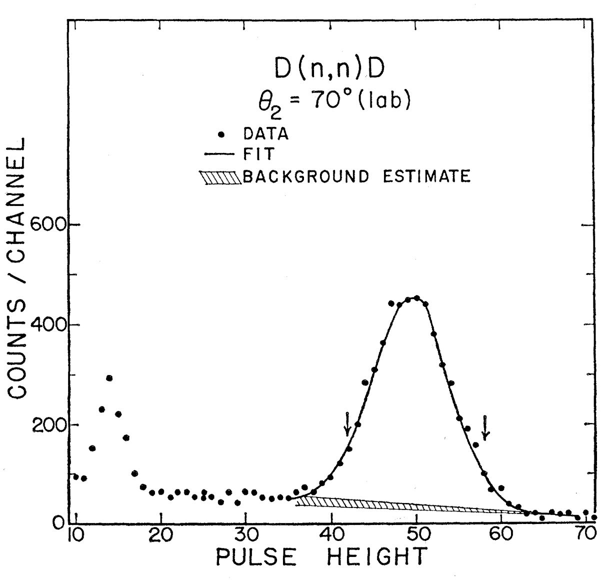

FIG. 2. Summed coincidence recoil spectrum at 70° (lab). The summed spectrum consists of the sum of the four spectra minus accidental coincidences. The solid line denotes the fit to the data with the background estimate taken at the center of the hatched area.

The computer code handling the data storage will be discussed more fully below.

Bias levels for the side-detector pulses were set low for the data points with θ_2 greater than 70° (lab) in order to have a high efficiency. However, for angles of 70° (lab) and less, the background under the peak of interest was so large that runs with high biases (about 2-MeV recoil-proton energy) were required. In this case, for each point reported, several measurements were taken at $\theta_1=45°$ (lab) alternately on each side of the α-beam axis so that instrumental asymmetries associated with reversing the solenoid current would cancel.

Simultaneous accumulation of accidental coincidences along with the true coincidences enabled accurate accidental-coincidence background subtraction, but care had to be taken that the pulse lengths of the direct and delayed signals at the inputs of the "And" units were identical. The 100-nsec delays were sufficient to guarantee that any coincidence between the delayed center signal and a side detector signal was completely accidental.

A multipurpose computer code was written to handle the experiment using the Triangle Universities Nuclear Laboratory computer system.[12] Its purposes included storage and analysis of the data, control and monitoring tasks during the data acquisition, and numerous other jobs pertinent to the data handling. The coincidence data in the eight arrays were made available to the analysis section of the program at the end of each measurement. The control software cycled the data acquisition through a sequence of short runs of equal accumulated charge. The solenoid sequence was cw, ccw, ccw, cw, where cw stands for clockwise neutron spin precession and ccw for counterclockwise. At the end of each cw or ccw run, the computer changed the solenoid polarity if necessary and typed the number of coincidence counts from each side detector. The spectra were dumped onto magnetic tape at the end of each sequence and the asymmetry and the ratio of side-detector efficiencies in the neutron peak were calculated and typed out. These calculations after each short run and after each sequence enabled the experimenter to keep a close watch on the measurement and to spot easily any detector irregularities or target deterioration. In addition, the computer continually monitored the beam current, causing an alarm to sound and the data acquisition to halt if the current wandered outside of preset limits.

III. ANALYSIS

Typical coincidence spectra are shown in Figs. 2–4. The points in each figure represent the "summed" spectrum which consists of the sum of the four true coincidence spectra minus the sum of the four accidental

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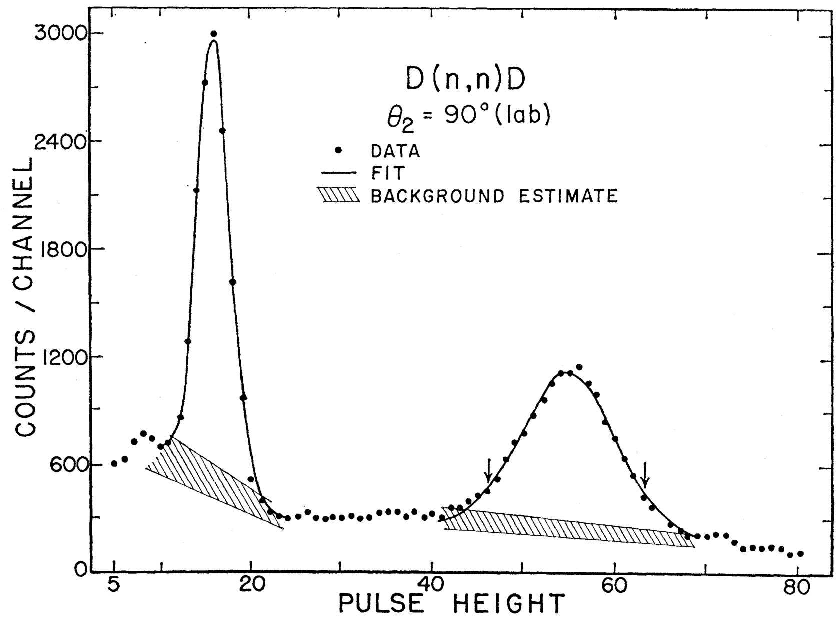

FIG. 3. Summed coincidence spectrum at 90° (lab). See caption of Fig. 2.

coincidence spectra. The high-energy deuteron-recoil peak in each figure corresponds to coincidence events with 7.8-MeV neutrons from the ^{9}Be(α, n_0) reaction, while the low-energy peak corresponds to events with 3.4 MeV from the ^{9}Be(α, n_1) reaction. Our aim was to measure the polarization at 7.8 MeV, and so the experimental conditions were set to optimize the corresponding information. Such conditions decreased the lower-energy peak relative to the background. At the forward angles, in fact, the side-detector biases were set such that most of the coincidence counts of the lower peak were eliminated, as can be seen in Fig. 2. For these reasons, the asymmetry data for the 3.4-MeV group was not obtained with sufficient accuracy to be reported.

The background under the recoil-deuteron peaks corresponding to the 7.8-MeV neutrons was never entirely eliminated. Recoil protons from *n-p* scattering did not contribute to the background because for all angles, either the recoil energy was too high, the scattered neutron energy was below the side detector bias level, or the event was outside the time window of the coincidence circuit. Of course, *n-p* scattering is kinematically forbidden for angles greater than 90° (lab). Phase-space calculations indicated that deuteron-breakup contributions were also small in the region of interest. The background probably resulted from γ interactions or from neutrons scattered from the surroundings. Such backgrounds are essentially un-

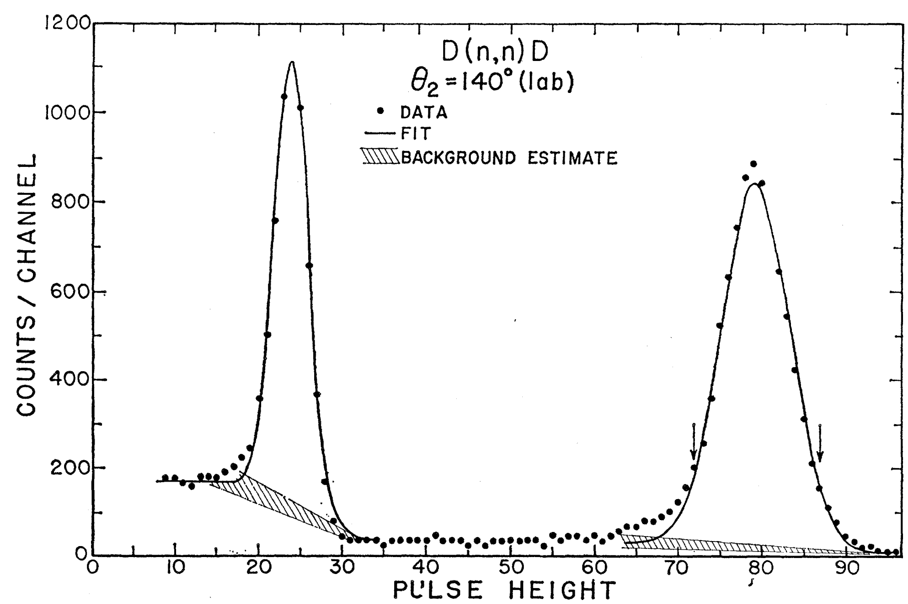

FIG. 4. Summed coincidence spectrum at 140°(lab). See caption of Fig. 2.

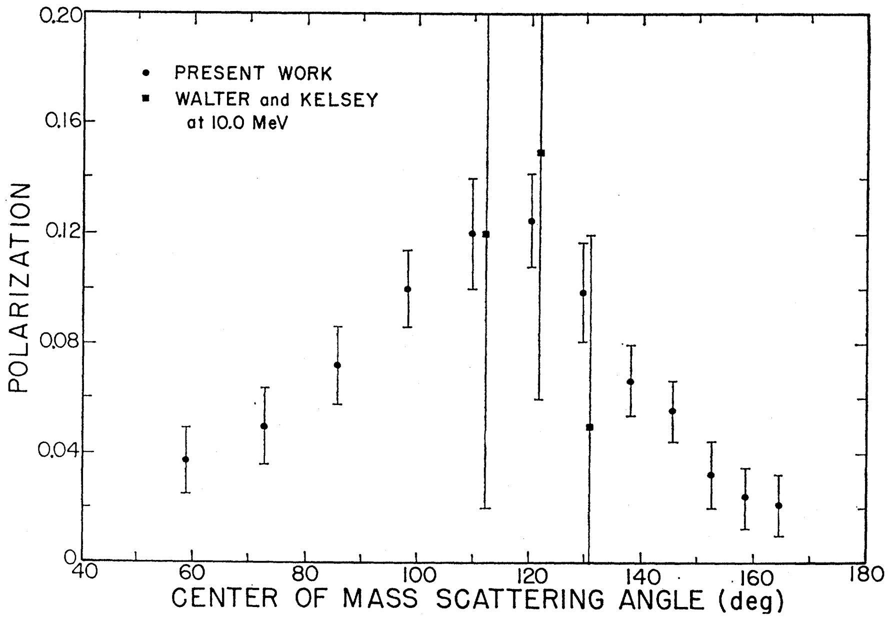

FIG. 5 Polarization of neutrons elastically scattered from deuterium at 7.8 MeV compared to the earlier data of Walter and Kelsey (Ref. 7) at 10.0 MeV.

polarized and this was assumed to be the case in the data analysis here. This assumption appears to be valid, since the asymmetry in the regions above and below the peaks in the recoil spectra was found to be consistent with zero. For simplicity, the background was assumed to be linear with recoil energy underneath both peaks in each spectrum. The magnitudes of these linear backgrounds were adjusted by a fitting program which represented the data by a sum of Gaussian peaks and the linear backgrounds. The "best" fit, shown by the solid lines, appears to represent the data very well with the exception of a small bulge which was noticeable for the large-angle measurements on the low-energy side of each recoil peak (see Fig. 4). This bulge could have been caused by inefficient light collection in the region adjacent to the small expansion chamber of the deuterated scintillator. Each of the linear backgrounds was assigned a liberal error ranging from ± 20 to 50% in the calculation of the asymmetry uncertainty to be discussed below. The asymmetry values quoted later are calculated for linear background levels at the center of the cross-hatched areas shown in Figs. 2–4. The envelopes of these areas represent the assigned uncertainties.

The asymmetry of each peak was calculated from the region between the channels indicated by the arrows in the figures. It was corrected for the unpolarized background discussed previously and for finite geometry effects by a Monte Carlo scattering program of a type described by Sawers *et al.*[11] This program was also used to determine that multiple scattering produced negligible effects. This corrected asymmetry was then divided by 0.539, the incident neutron polarization, to yield the polarization P for n-d scattering.

TABLE I. Polarization of neutrons for n-d elastic scattering at 7.8 MeV.

θ (lab) (deg)	θ (c.m.) (deg)	$P\pm\Delta P$
40	58.8	0.037 ± 0.012
50	72.6	0.050 ± 0.014
60	85.7	0.072 ± 0.014
70	98.1	0.100 ± 0.014
80	109.6	0.120 ± 0.020
90	120.1	0.125 ± 0.017
100	129.6	0.099 ± 0.018
110	138.1	0.067 ± 0.013
120	145.7	0.056 ± 0.010
130	152.6	0.033 ± 0.012
140	158.8	0.025 ± 0.011
150	164.5	0.022 ± 0.011

IV. RESULTS AND COMPARISON WITH EARLY DATA

The results are listed in Table I, where the polarization sign is given in accordance with the Basel convention. The uncertainty ΔP that is quoted contains estimates for all known uncertainties including the statistical error. In Fig. 5, we compare the present results to the only other existing data between 6 and 16 MeV, namely, that for the three points at 10 MeV obtained by Walter and Kelsey.[7] This earlier measurement indicated that the polarization was probably nonzero although each point was within 2 standard deviations from zero. Our data are consistent with the 10-MeV data but clearly show the angular dependence of the polarization.

In Fig. 6, we compare our data to the p-d polarization

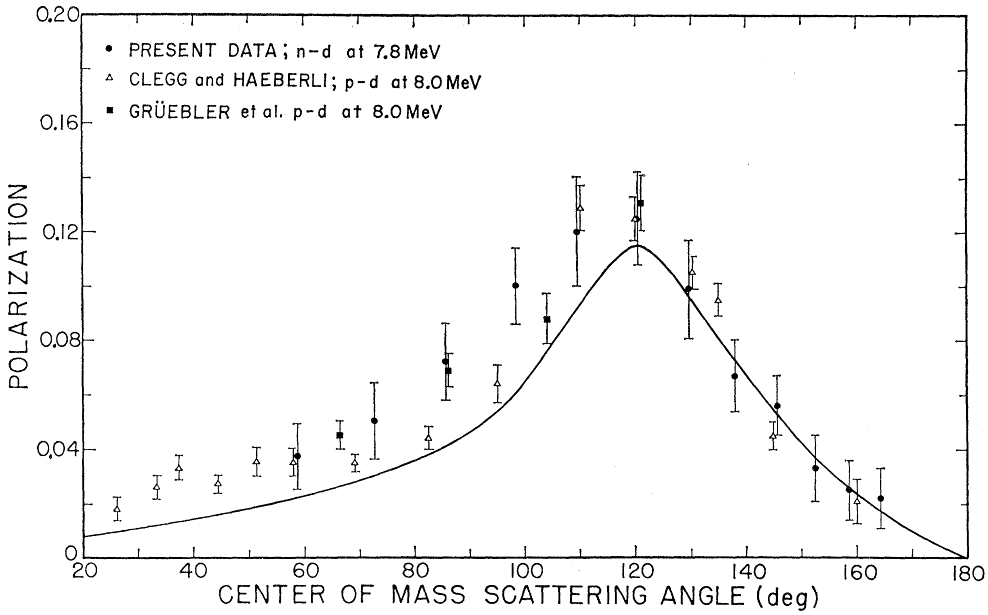

FIG. 6. Comparison of measured polarizations in *n-d* and *p-d* elastic scattering (Refs. 1 and 2). The solid curve shows the results of a Born-approximation calculation of Purrington and Gammel (Ref. 8) for 9-MeV neutron scattering.

data of Grüebler, Haeberli, and Extermann[1] and to the more recent data of Clegg and Haeberli.[2] The agreement of the data for the two charge-symmetric reactions shows that charge effects are indeed small for the region studied. Note that the *p-d* data obtained with a polarized-ion source have appreciably smaller errors than the *n-d* data which represent the present limit of the accuracy in neutron polarization measurements. We point out further that the effort involved in obtaining and analyzing the latter set of data was very sizable compared to the effort for one *p-d* angular distribution. That is, it is still very difficult to make a meaningful contribution to polarization studies using neutron beams.

Also included in Fig. 6 is the *n-d* calculation of Purrington and Gammel[8] which was a five-parameter fit to the *n-d* cross-section data of Bonner *et al.*[13] and the polarization data of Walter and Kelsey,[7] Grüebler *et al.*,[1] and McKee *et al.*[5] The calculation was done using the Born approximation and included tensor forces and the deuteron *D* state. Further adjustment of the parameters should bring the curve into closer agreement with the data shown in Fig. 6. No other nucleon-deuteron predictions are available for comparison with our data.

In summary, the measured polarization for *n-d* scattering at 8 MeV nearly agrees with the 8-MeV *p-d* data. The relatively small differences are within statistics and, hence, probably negligible. The calculation of Purrington and Gammel is encouragingly close and finer adjustment of the parameters might resolve the difference between experiment and theory.

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