solution they obtained a set of phase-shifts having a χ^2 of 136. This was later reduced to 44, compared with an expected value of 38, by omitting six differential cross-section points lying more than three standard deviations away from a smooth curve drawn through the data. At the present time a faster minimization routine is being tested, and it is hoped to investigate the uniqueness of the 48-MeV solution and perform a more comprehensive analysis of the p-He^4 phase-shifts between 10 and 50 MeV in the near future.[30]

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ACKNOWLEDGMENTS

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Neutron-Deuteron Polarization at 22.7 MeV*

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A measurement of the neutron-deuteron polarization function has been made at $E_N = 22.7$ MeV over the angular range 44.5° to 158.8° c.m. Neutrons with polarization approximately 0.5 were obtained from the $T(d,n)^4He$ reaction at a deuteron energy of 6.6 MeV and a lab angle of 30°. Comparison is made to existing neutron data at 23.7 MeV and to proton data at 22 MeV. Agreement with the latter is good except near 130° c.m. where the value given here falls low. Theoretical comparisons do not exist in the energy range of this experiment.

I. INTRODUCTION

THE existing data at 22 MeV on p-d polarization measured by Conzett, Igo, and Knox[1] display considerable structure. These data show a positive hump in the forward hemisphere, a negative region in the range $70° \leq \theta_{c.m.} \leq 120°$, where the polarization attains the value -0.16, and a positive peak at angles between 128° and 136° c.m. where $P \approx +0.26$. Charge symmetry of nuclear forces would imply that the polarization in n-d and p-d scattering should be similar, especially at back angles. The neutron data of Walter and Kelsey,[2] at the energy, $E_N = 23.7$ MeV, gave appreciably lower values than the p-d data of Ref. 1 at back angles. The motivation for the present experiment resides in the attempt to improve the back-angle neutron data and to extend the angular range of the measurements.

It may be noted that heretofore the work of Walter and Kelsey[2] provided the only existing neutron-polarization data above 6 MeV. Measurements of n-d differential cross sections in this energy range exist at 14 MeV,[3,4] while p-d cross sections[5,6,7] have been measured at 20, 32, and 40 MeV. The measurements on n-d polarization at low energy have been discussed by Elwyn, Lane, and Langsdorf,[8] with particular emphasis on energies below 2 MeV.

Recently the p-d polarization has been measured at 40 MeV by Conzett *et al.*[9] and at 30 MeV by Hall *et al.*[10] and Johnston *et al.*[10] The shape of the polarization function at the higher energies remains similar to that at 22 MeV. The magnitude of the negative peak near 115° c.m. shows a monotonic increase as a function of energy, reaching the value of -0.39 at 40 MeV.[9] The recent p-d data[10] at 30 MeV indicates that the maximum polarization in the positive peak at 140° c.m. has decreased to the value of $+0.21$, relative to the data[1] at 22 MeV. At 40 MeV, however, one datum point at 141.5° c.m. gives a value of $+0.49 \pm 0.20$ for the

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polarization. Further measurements at 50 MeV[10] may clarify the energy dependence of the back angle polarization peak.

Theoretical predictions for the nucleon-deuteron polarization function do not exist at 20 MeV. Kottler and Kowalski[11] have recently published an account of a refined impulse approximation calculation at 40 and 150 MeV. At the higher energy they obtain a fair fit to the cross section and a qualitative fit to the polarization. At 40 MeV, computed values of cross section are in agreement with experiment up to 120°; the theory fails, however, when confronted with the polarization. These authors comment that as the impulse approximation is refined, the agreement with the experiment seems to worsen, particularly in regard to the 40 MeV polarization data.

Aaron, Amado, and Yam[12] have recently published calculations on the *n-d* system at low energies by a method which takes three-body effects directly into account. The effects of spin are included in the calculation but central forces only are employed. The results to date appear very encouraging. The future inclusion of tensor forces may well provide a new standard of comparison between theory and experiment.

II. EXPERIMENT

A plan view of the experimental geometry is given in Fig. 1. The basic features of the apparatus and techniques have been described elsewhere[13] and will be discussed here only briefly. The incident 6.61 MeV deuteron beam-bombarded tritium contained in a 3-cm-long gas cell at a pressure of about 4.8 atm absolute. Partially polarized neutrons of 22.68±0.16 MeV were produced by the $T(d,n)^4He$ reaction at a laboratory angle of 30°. A 4.4-cm-high by 4.4-cm-diam

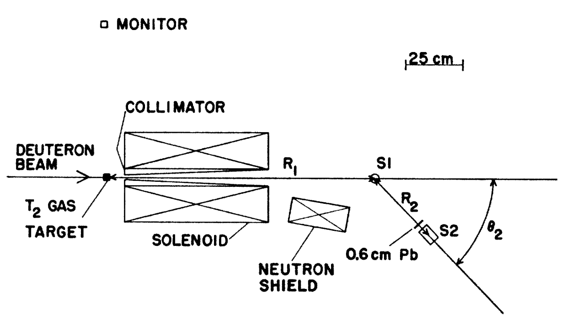

FIG. 1. The experimental geometry, as seen from the normal to the *n-d* scattering plane. *S*1 is the CD scintillator, while *S*2 is the final neutron detector. The plane in which θ_1 is measured is vertical, consequently θ_1 does not appear in this projection.

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TABLE I. Summary of experimental parameters.

$\theta_2\pm\Delta\theta_2$ (deg c.m.)	$\theta_2\pm\Delta\theta_2$[a] (deg lab)	R_2 (cm)	S_2 bias (MeV)	Rel. acc.[b]	$e_T\pm\Delta e_T$[c]
44.5±3.0	30.0±2.1	51	8.2	0.09	···
58.8±4.2	40.0±3.0	36	11.5	0.02	···
85.7±3.8	60.0±3.0	36	d	0.02	−0.02±0.02
109.5±4.5	80.0±4.1	25	6.2	0.02	+0.00±0.02
120.0±3.0	90.0±3.0	36	3.0	0.12	−0.02±0.03
129.5±2.9	100.0±3.0	36	e	0.24	+0.02±0.02
138.0±2.4	110.0±3.0	36	2.3	0.23	−0.01±0.03
145.6±2.2	120.0±3.0	36	2.3	0.16	−0.00±0.04
152.5±2.0	130.0±3.0	36	2.3	0.18	+0.04±0.06
158.8±1.8	140.0±3.0	36	2.3	0.14	+0.03±0.08

[a] The angular spread $\Delta\theta_2$ (lab) was obtained by mean-square addition of geometrical angles in the scattering plane.
[b] Rel. acc. represents the fraction of accidental counts under the elastic peak in the spectrum of *S*1.
[c] e_T is the asymmetry in the tail region of the *S*1 spectrum below the elastic peak. Δe_T is a standard deviation.
[d] Three 60° runs—*S*2 biases: 6.2, 6.5, and 9.5 MeV.
[e] Two 100° runs—*S*2 biases: 2.3 and 3.0 MeV.

deuterium-enriched liquid scintillator[14] was used as a deuteron scatterer *S*1 at a distance $R_1 = 118$ cm from the neutron source. A plastic scintillator *S*2, 5.1 cm wide, 10.2 cm high, and 7.6 cm deep, was placed at the angle θ_2 to detect the neutrons scattered by *S*1. The distance R_2 between the scintillators was varied with angle to optimize time separation of gamma rays from neutrons. The values for R_2 and the associated angular resolution are given in Table I. Also given in Table I are approximate values of the lower bias levels set on *S*2; these values are accurate to approximately ±0.5 MeV.

The longitudinal magnetic field of the solenoid was used to precess the neutron polarization ±90° so as to be parallel or anti-parallel to the normal to the *n-d* scattering plane for the asymmetry measurements. The polarization function for the scattering, $P_2(\theta)$, is defined in terms of the asymmetry

$$e = P_1P_2(\theta) = (I_+ - I_-)/(I_+ + I_-)$$

where P_1 is the polarization of the incident neutron beam, and I_+, I_- are the net scattered intensities for P_1 parallel or anti-parallel, respectively, to the normal to the *n-d* scattering plane. The direction of the normal was defined to be along the vector $\mathbf{k}_{in}\times\mathbf{k}_{out}$ which is in agreement with the Basel convention.[15] The false asymmetry in each detector associated with the reversal of the magnetic field of the solenoid was determined using a ^{60}Co gamma-ray source and was found to be consistent with zero to ±0.001. A plastic scintillation counter placed at 90° to the deuteron beam at a distance of 1.0 m from the neutron source served as a monitor for normalization of the asymmetry runs.

The electronic detection circuits utilized a fast-slow coincidence system. Fast timing was accomplished by a time-to-pulse-height converter (TPC) fed from the anodes of *S*1 and *S*2. Examples of these TPC spectra

[14] Supplied by Nuclear Enterprises in May, 1962. Gross chemical formula CD, atomic ratio $H/D \leq 0.02$.
[15] Helv. Phys. Acta, Suppl. **VI**, 436 (1961).

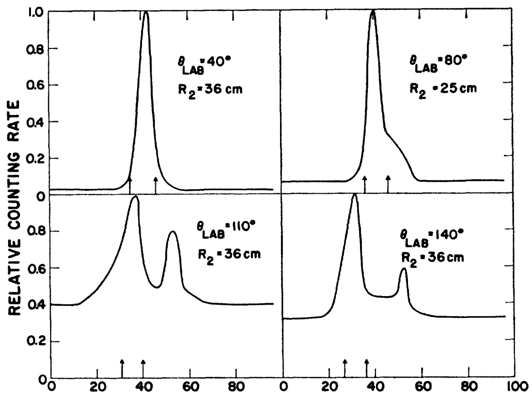

FIG. 2. Typical time to pulse-height spectra. The scale is approximately 0.6 nsec per channel. The pulse-height bounds used during the actual data runs are indicated by the vertical arrows. The smaller peak is due to events in which a gamma ray is detected in $S2$. The horizontal level of accidental background corresponds to events which occur over the entire $S1$ pulse-height spectrum.

for four different angles are shown in Fig. 2. These spectra were taken under bias conditions on $S1$ and $S2$ identical to those in actual data runs. The resolving time of the neutron peak is about 6 nsec, full width at half-maximum (FWHM). The pulse height bounds imposed on the TPC spectra during data runs are indicated in Fig. 2 by the vertical arrows. The horizontal background level corresponds to the accidental rate over the entire $S1$ energy spectra. Most of these background counts are associated with low energy pulses in $S1$. Thus the accidental contribution under the $S1$ elastic scattering peak is considerably lower, as given in Table I. Events in $S1$ associated with gamma ray detection in $S2$ were discriminated against at larger angles such as 110° and 140°, but not for very forward angles such as 40°. However, the relative importance of such events diminishes at forward angles because of the increased differential cross section.[5] The simultaneous selection of both in-phase and accidental events was accomplished by applying two separate pulse-height windows of equal width to the TPC spectra of Fig. 2. The associated $S1$ spectra were then routed to separate sections of the pulse-height-analyzer memory. Several typical deuteron recoil pulse-height spectra from $S1$ are shown in Fig. 3. Accidental events have been subtracted from these spectra.

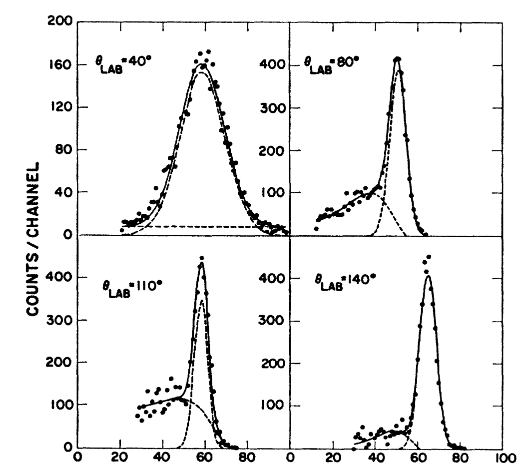

FIG. 3. Typical deuteron recoil pulse-height spectra in $S1$ taken in coincidence with $S2$. The horizontal scale is arbitrary. Accidental events have been subtracted. The solid curve is the total computer fit to the data. The dashed curves are the calculated contributions due to the elastic peak and the background tail.

III. RESULTS AND DISCUSSION

A. Data Processing

It is apparent from Fig. 3 that at most angles there is an appreciable low pulse-height background spreading into the region of the peak of the elastically scattered deuterons. This background could not be measured separately and thereby subtracted. We shall discuss later the possible sources of this background. The discussion here will be limited to the data-processing technique employed to estimate the background contribution under the peak by extrapolation, and thereby determine the corrected asymmetries.

Our approach has been basically an empirical one. A least-squares computer code was available which allowed the data to be fitted by the function[16]

$$Y=A(2\pi\sigma^2)^{-1/2}\exp[-\zeta^2/(2\sigma^2)] +B[\exp(-D\eta)][1-\exp(-\eta^2G^2/2)]. \quad (1)$$

Here $\zeta=X-E_1$ and $\eta=X-E_2$, where X is the energy variable. The second term is set equal to zero for $\eta\geq 0$. The first term of the function is simply a Gaussian function of amplitude A and width σ centered at $X=E_1$. The second term is an exponential function in $D\eta$ of magnitude B. This exponential function exists over the range from $X=0$ to $X=E_2$ where it is terminated smoothly by the factor $[1-\exp(-\eta^2G^2/2)]$. The parameters A, B, E_1, E_2, σ, and D may all be adjusted within the code in order to achieve the best fit. The width $1/G$ of the cutoff function was chosen to be approximately three times the width σ of the Gaussian.

Independent fits were made for each scattering angle and both directions of the polarization of the incident neutrons. At each angle the values thus obtained for E_1, E_2, and σ were the same within their uncertainties. These quantities were then set equal and fixed for both polarizations and fits were again made allowing only A, B, and D to be adjusted by the code. Representative results of these computer fits are displayed in Fig. 3. The solid curve is the total fit to the data, while the dashed curves are the calculated contributions due to

[16] We are indebted to H. T. Motz and E. T. Jurney for making this code available to us.

the peak and due to the tail. The choice of a Gaussian function for the elastic scattering peak is seen to be a good approximation. In fact the total fit to the entire spectrum, as expressed by the relative chi square, was satisfactory. For example, the relative χ^2 for the fits displayed in Fig. 3 are 1.10, 0.97, 1.02, and 1.84 for 40°, 80°, 110°, and 140°, respectively. These fits provide estimates of the background contribution under the peak. As will be pointed out later, the background outside the peak region is consistent with zero polarization. It is not surprising then that the background contribution under the peak, as estimated by the computer fits, was also found to be consistent with zero polarization.

Let a quantity f be defined to be the ratio of background associated events to elastic-scattering events under the elastic-scattering peak. This ratio is the average over both spin directions. Then the asymmetry e of the elastic-scattering process is

$$e=(1+f)e_M-fe_B, \qquad (2)$$

where e_M is the measured asymmetry and e_B is the asymmetry associated with the background process. The error associated with the asymmetry of the elastic-scattering process is

$$(\Delta e)^2=[(1+f)\Delta e_M]^2+[(e_M-e_B)\Delta f]^2+[f\Delta e_B]^2. \qquad (3)$$

The first, second, and third terms are, respectively, contributions due to statistical fluctuations, the uncertainty associated with the knowledge of the magnitude of the background under the elastic peak, and the uncertainty in the asymmetry associated with the background process. Although all indications are that the background under the peak possesses no polarization, any reasonable estimate based entirely on the statistics associated with the background events under the peak would produce a large error, Δe_B. In fact at certain angles this error would dominate and reduce the statistical weight of the measurement toward zero. In addition, if these large errors had any physical basis,

TABLE II. Polarization results in n-d scattering at $E_N=22.7$ MeV.

$\theta_2\pm\Delta\theta_2$ (deg c.m.)	$e_M\pm\Delta e_M$ [a,e]	f [b]	$e\pm\Delta e$ [c,e]	$P_2\pm\Delta P_2$ [d,e]
44.5 ±3.0	+0.024 ±0.009	0.12	+0.027 ±0.010	+0.058 ±0.021
58.8 ±4.2	+0.011 ±0.011	0.12	+0.013 ±0.012	+0.027 ±0.025
85.7 ±3.8	−0.031 ±0.007	0.23	−0.038 ±0.009	−0.084 ±0.019
109.5 ±4.5	−0.073 ±0.011	0.14	−0.083 ±0.014	−0.181 ±0.030
120.0 ±3.0	−0.024 ±0.019	0.65	−0.039 ±0.033	−0.086 ±0.072
129.5 ±2.9	+0.038 ±0.015	0.52	+0.058 ±0.024	+0.125 ±0.052
138.0 ±2.4	+0.059 ±0.014	0.34	+0.079 ±0.019	+0.172 ±0.042
145.6 ±2.2	+0.088 ±0.012	0.05	+0.093 ±0.013	+0.201 ±0.027
152.5 ±2.0	+0.043 ±0.012	0.02	+0.044 ±0.013	+0.095 ±0.028
158.8 ±1.8	+0.034 ±0.012	0.03	+0.035 ±0.012	+0.076 ±0.027

[a] e_M is the measured asymmetry.
[b] f is the ratio of background to elastic scattering in the peak region.
[c] e is the corrected asymmetry, $e=(1+f)e_M$.
[d] P_2 is the polarization in n-d scattering, $P_2=e/P_1$, where P_1 is taken to be 0.46.
[e] Δe and ΔP are errors expressed as standard deviations. The error ΔP_2 does not include a contribution due to the uncertainty in the beam polarization, P_1.

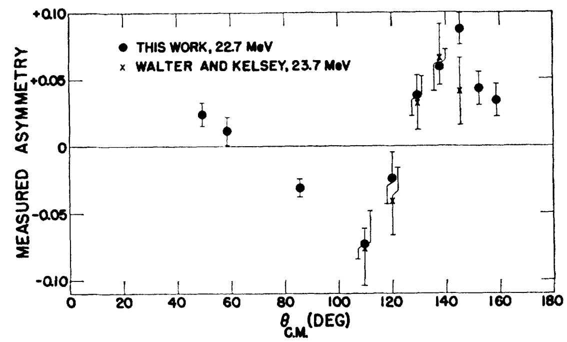

FIG. 4. Comparison of the measured neutron-deuteron asymmetries with those of Walter and Kelsey. Only accidental backgrounds have been subtracted.

the measured asymmetries would be expected to fluctuate with amplitudes comparable with these errors. This is not the case. Furthermore, as will be discussed later, the physical processes contributing to the background are expected to display a very small polarization. It has been assumed therefore, that the asymmetry associated with the background is identically zero, i.e., $e_B=0$, and $\Delta e_B=0$. The magnitude of the error due to the uncertainty in the number of background counts under the peak is dependent on the validity of the computer fits which approximate the true background distribution. We believe that these computer fits are accurate to within a factor of two, i.e., the uncertainty in the number of background events under the peak is taken to be ± one-third the number of such events.

B. Asymmetry Results

The experimentally measured asymmetries e_M and their associated errors due to counting statistics are given in the second column of Table II. The ratio f of background to elastic scattering events in the peak region, and the background corrected asymmetries e are listed in the third and fourth columns of Table II. The background corrections are largest in the vicinity of the minimum of the differential cross section. This is the region spanned by the earlier measurements of Walter and Kelsey.[2] Since no background corrections were applied to their data and because of improved electronic techniques, we regard the present measurements as superseding the earlier ones[2] at this energy. In Fig. 4 our measured asymmetries e_M are compared with those of Walter and Kelsey. With the exception of one point the agreement is good over the angular range common to both measurements.

C. Discussion of Background Contributions

As an example of a process which could generate a twofold coincidence background, consider the $^{12}C(n,n'\gamma)^{12}C$ reaction which takes place in $S1$. The gamma ray may be detected in $S1$ in coincidence with the inelastically scattered neutron in $S2$. This process should be effective only at forward angles, being eliminated at backward angles by the fast timing requirements and pulse-height bounds. The $^{12}C(n,p)^{12}B$ reaction will also take place in $S1$, followed by the high-energy beta decay of ^{12}B. These beta rays are attenuated by 0.6 cm of lead and are further reduced by timing requirements and pulse-height selection at large angles. We do not consider that either of these sources of background are important.

A more likely source of the background is the deuteron breakup reaction $D(n,2n)H$, where the proton is detected in $S1$ in coincidence with one of the neutrons in $S2$. The kinematics of this reaction are such that the maximum allowed proton energy in $S1$ is determined by the lowest energy neutron capable of detection by $S2$. The approximate bias levels set on $S2$ are given in Table I. Despite the strong dependence on the $S2$ neutron bias, the breakup process is not discriminated against except at the largest angles. The breakup cross section[17] is known to be a significant part of the total deuteron cross section.[18] The energy spectrum of the breakup protons has been observed at laboratory angles between 4° and 45° by Ilakovac *et al.*[19] for a neutron energy of 14.4 MeV. Calculations by Koehler[20] have been successful in fitting the most forward angle proton energy distributions. Although the fit deteriorates as the angle increases, the calculations at least provide an estimate of the shape of the breakup proton differential cross section at 14.4 MeV. If it is assumed that the differential cross section of each of the breakup neutrons is equal to that of the breakup proton, then estimates of the contribution due to this breakup process can be made. Such calculations for the ratio of breakup events to elastically scattered events have yielded values of the same size as the measured ratio of background tail to peak counts. These estimates have led us to believe that the breakup process provides the major contribution to the background at all angles. Furthermore, it is reasonable to assume that the breakup process is unpolarized, consequently it affects the data as a pure dilution of the measured asymmetries.

In the following paragraphs we examine the question of multiple scattering. While corrections have not been made for such effects, it will be shown that the method of data analysis will naturally correct for the main results of this process. Multiple scattering will be assumed to comprise events in which the neutron interacts twice with the nuclei of $S1$ before being detected in $S2$. A portion of such events can bear the signature of a bona fide twofold coincidence. The volume of $S1$ can be represented as a sphere of radius 2.5 cm. Over the energy range $10 \leq E_N \leq 22$ MeV the probability for an interaction of any kind in traversing 2.5 cm is ≈ 0.2. It must be assumed, therefore, that multiple scattering is playing a role for the conditions of this experiment. Furthermore, it is to be expected that double-scattered events will be most conspicuous near 130° c.m., which is the minimum of the differential cross section.

Multiple scattering affects polarization data, to first approximation, by diluting it with an unpolarized spectrum of events. In addition, the second-scattered events may retain a polarization asymmetry from the initial scattering. Consider first the unpolarized dilution. We expect that the energy spectrum of recoils in $S1$ will in general constitute a broad smear under the elastic peak. Such will certainly be the case at intermediate angles such as 130° c.m. The bias on $S2$ will place an upper bound on the $S1$ double-scattered spectrum. The method of data analysis described in Sec. III A fits the exposed tail spectrum and extrapolates it under the peak, whether the tail consists of doubly scattered events, deuteron breakup, or whatever. This procedure corrects therefore, for multiple scattering dilution, as well as for other types of unpolarized background.

In Sec. III A the asymmetry of the background tail was assumed to be identically zero. This assumption implies our opinion that polarization asymmetries induced in multiple scattering involving carbon are negligible compared to other sources of error. There is some justification for this assumption, as follows: The tail asymmetries have been measured for angles $\theta_{\rm lab} \geq 60°$ from that part of the $S1$ pulse-height spectra lying below the elastic peak. These measured tail asymmetries are given in the last column of Table I, together with errors. It may be noted that this set of values gives an average $e_T = -0.004 \pm 0.010$ and that χ^2 is 2.8 for the assumption that $e_T = 0$, which infers 90% probability for χ^2 being larger. The residual asymmetries of doubly scattered carbon polarization do not show up in these data to an extent comparable with the quoted errors. If the measured tail asymmetries given in Table I were assumed to represent the carbon doubly-scattered asymmetry effect, we could calculate the change in e that would result from Eq. (2). At 130° c.m. a reduction of 14% would be obtained, which is relatively small compared to the assigned error. At other angles the change would likewise be relatively small.

Further insight into the problem is gained by considering the shape of the nucleon-carbon polarization function[21,22] near 20 MeV. It will be assumed that p-C

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scattering is equivalent to n-C scattering, for our purposes. The proton-carbon polarization[22] is negative in the range $20° \leq \theta_{c.m.} \leq 55°$ where it attains a value of -0.32 ± 0.05 at 45° c.m. Beyond 55° c.m. it appears to remain positive with values ranging from +0.4 at 80°, zero at 110°, to +0.55 at 134° c.m. The neutron-carbon differential cross section[21] falls rapidly at small angles, while showing a tendency to level out, or oscillate at larger angles. However, the cross-section ratio for angles of negative and positive polarization mentioned above is not excessively large, for example $\sigma(45°)/\sigma(80°) \approx 3.5$. It appears unlikely, therefore, that at back angles the carbon asymmetry would supply a negative contribution to the measured asymmetry. If carbon multiple scattering were to contribute a positive asymmetry to the tail under the elastic peak, the corresponding correction would increase the discrepancy with the 22 MeV p-d data as described in the following section.

D. Polarization Results

The polarization of the incident beam P_1 is a required parameter for the determination of the polarization in n-d scattering. Most measurements of neutron polarization in this energy range are somewhat unreliable because of the uncertainties in the analyzing power of the helium polarization analyzer. Walter and Kelsey[2] chose the neutron polarization to be $P_1 = +0.60$ at $E_N = 23.7$ MeV, and $\theta_1 = 30°$. We use the recent results of Perkins and Glashausser[23] who give $P_1 = +0.49 \pm 0.06$ at $E_d = 7.0$ MeV and 30° lab from the $T(d,n)^4He$ reaction. The results of the $^3He(d,p)^4He$ polarization measurements of Brown and Haeberli[24] were then used as an extrapolation function to determine the polarization at $E_d = 6.6$ MeV corresponding to $E_N = 22.7$ MeV. The difference in the Q values of these two reactions was taken into account in performing this extrapolation. The beam polarization at 22.7 MeV was then found to be $+0.46 \pm 0.06$, the uncertainty due mainly to the error quoted in Ref. 23. The polarization errors listed in Table II do not include this uncertainty in P_1. Had it been included it would have increased the relative errors by at most 5%.

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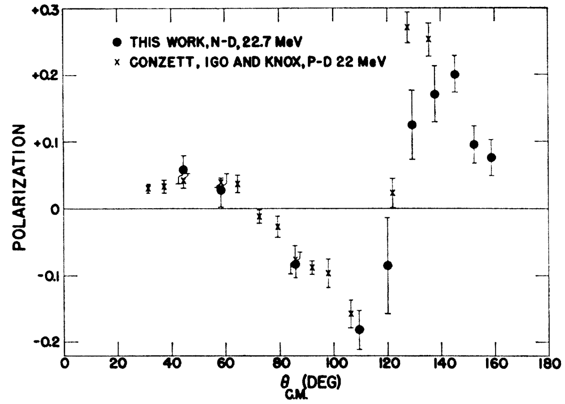

FIG. 5. Comparison between proton-deuteron polarization measurements of Conzett, Igo, and Knox and the neutron-deuteron results of the present experiment.

In Table II we list our values for the n-d polarization function and in Fig. 5 these results are compared with the p-d polarization measurements of Conzett, Igo, and Knox.[1] The agreement is good over most of the angular range. Both sets of data indicate that the polarization changes sign at 70° and 120° c.m. The previously reported differences between the neutron and proton data have been reduced. At 130° c.m., however, our final polarization result lies significantly below the p-d result. This is the location of the minimum of the elastic differential cross section and the relative error on our point is large; nevertheless the probability of our point lying 2.8 standard deviations below the p-d value is small. We do not believe that this discrepancy could be explained in terms of a background process which is polarized. If the entire background contribution at 130° c.m., represented by $f = 0.52$, were polarized, it would have to possess a polarization of -0.26 in order to bridge the gap. Such a polarized process should have exhibited an asymmetry in the background which would have been 4 times the observed errors on the tail asymmetry in this region. Although multiple scattering is a process which could produce a polarized background, in our preceding discussion we gave qualitative arguments for expecting the sign of such an effect to be positive at back angles, a circumstance which would only serve to aggravate the size of the discrepancy.