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Scattering of Polarized 3-MeV Neutrons from ^{3}He

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Partially polarized 3-MeV neutrons have been scattered from ^{3}He contained in a high-pressure gas scintillation cell. The resulting asymmetry in the elastic scattering was determined for seven scattering angles from 40 to 120° (lab). Time-of-flight techniques and neutron–γ-ray discrimination in the side detectors were used for background reduction. The measured asymmetry is small for angles less than 60° (lab) and reaches a maximum value at approximately 110° (c.m.). The maximum asymmetry determined from the present experiment corresponds to a polarization of +0.50. The differential polarization can be fitted within experimental uncertainties by assuming that D-wave effects are negligible. The principal features of the data are qualitatively reproduced by Dodder's reaction-matrix calculations which use the Werntz-Meyerhof level parameters for ^{4}He.

I. INTRODUCTION

Among the many ways of obtaining information on the unbound energy levels of ^{4}He is the study of interactions in the $p+$T and $n+{}^3$He channels for which ^{4}He is the compound system. Previous measurements by many experimenters of the cross sections and neutron polarizations for the T(p,n)-^{3}He reaction and recent experiments at Los Alamos with polarized tritons have provided considerable information on excited states of ^{4}He in the region between 20 MeV and the $d+$D threshold at 23.8 MeV in ^{4}He. The data are more sparse for reactions initiated by neutrons.

Differential cross sections for n-^{3}He scattering have been measured by Seagrave, Cranberg, and Simmons[1] and by Sayers, Jones, and Wu,[2] but few polarization measurements exist. Seagrave, Cranberg, and Simmons have reported polarization measurements at 94 and 121° (c.m.) for 1.1-MeV neutrons and at 137° for 2.15-MeV neutrons. Behof, Hevezi, and Spalek[3] performed polarization measurements for the scattering of 3.3-MeV neutrons in the angular range from 109 to 167° (c.m.). Angular distributions of polarizations for higher incident neutron energies have been reported by both Behof, Hevezi, and Spalek and Busser *et al.*[4] The polarization data for n-^{3}He scattering have been reviewed by Barshall[5] and, more recently, by Seagrave.[6]

Since no complete angular distribution of neutron polarization in n-^{3}He scattering exists for neutron energies below 7.9 MeV, asymmetry measurements have been made in this experiment for the scattering of partially polarized 3-MeV neutrons from ^{3}He.

II. EXPERIMENTAL PROCEDURE

After momentum analysis 510-keV deuterons from a Cockcroft-Walton accelerator were used to produce 2.96-MeV neutrons by the reaction D$(d,n)^3$He in a thick heavy-ice target. Figure 1 is a schematic diagram of the experimental apparatus. The ^{3}He scatterer was contained in a gas scintillation cell 3.18 cm in diameter and 6.35 cm high. The cell walls were coated with magnesium oxide which served as a diffuse reflector. A wave shifter (p-p' diphenylstilbene) was evaporated over this layer, and also upon the inside surface of the viewing window. Cryogenic pumping was used to fill the scintillator with a ^{3}He-xenon mixture to a total pressure of approximately 80 atm. Scattered neutrons were detected in stilbene crystals 2.54 cm in diameter and 1.27 cm thick oriented with the detector axis normal to the line joining the scatterer and detector, as shown in Fig. 1. The stilbene detectors were positioned 14.2 cm from the gas scintillator for laboratory angles of 90° or greater; this distance was increased to 19 cm for smaller scattering angles. Type-56 AVP photomultiplier tubes were used to view scintillations from both the helium scintillator and the side detectors. The pulse-height resolution for ^{3}He recoils as determined during the course of the polarization measurements was approximately 30%.

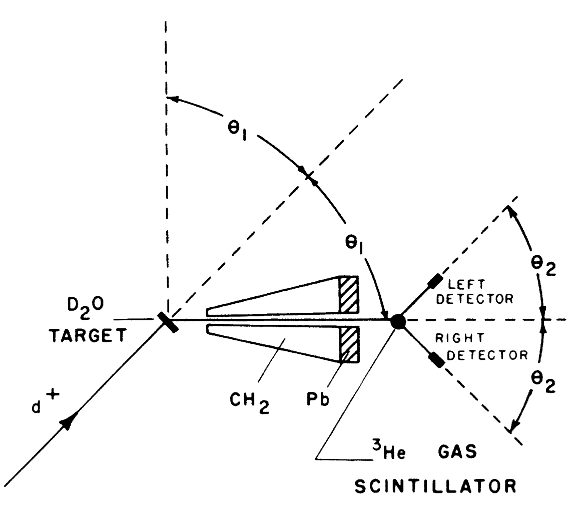

FIG. 1. Schematic diagram of the experimental geometry. Diagram not to scale.

The gas scintillator, stilbene counters, and detector shields were mounted on a table constrained to rotate about a point directly underneath the heavy-ice target. The entire assembly was rotated about the neutron source to alternately select neutrons emitted at +45 and at −45° relative to the incident deuteron direction. With this procedure the scattering asymmetry is given simply by the geometric mean of the asymmetries measured at the +45 and −45° positions, the relative efficiency between the two detectors being thereby eliminated. In order to verify that no other instrumental asymmetries were present, a preliminary polarization measurement was carried out with a scatterer of known analyzing power, namely, the measurement of $P(120°$ lab) for n-^{4}He elastic scattering. The result obtained in this measurement is in statistical agreement with the value predicted by the analysis of Hoop and Barshall.[7]

One difficulty in performing measurements with a ^{3}He scintillator at low recoil energies is the large ^{3}He(n,p)T cross section for thermal neutrons. Since this reaction is exoergic ($Q=0.764$ MeV), the recoil peak corresponding to elastic scattering of neutrons is superimposed on the thermal peak from the reaction ^{3}He(n,p)T for some part of the angular range, dependent on the incident neutron energy and pulse-height resolution in the scintillator. To minimize background contributions from the thermal peak, fast-timing techniques are required.

Figure 2 is a block diagram of the electronics used to process and record the data. A single time-of-flight (TOF) and pulse-shape discrimination system was common to each side channel as shown in the diagram. The combined TOF spectra were applied to both halves of a dual analog-to-digital converter (ADC) interfaced to a PDP-8 computer; the ADC's were gated by the outputs of two triple-coincidence circuits. The three requirements imposed were pulse height in the helium cell and both pulse height and pulse shape in either side detector. The pulse-shape signals contained a built-in fast-coincidence requirement, as indicated in Fig. 2, which further helped to reduce the random coincidence rate in the slower circuits. Gated ^{3}He-recoil pulses were routed and stored in a 256-channel analyzer.

Figure 3 shows time spectra obtained for $\theta_1 = +45°$ and the scattering angles $\theta_2 = 90°$, which correspond approximately to the minimum in the n-^{3}He scattering cross section for 3-MeV neutrons, and $\theta_2 = 50°$. The ^{3}He recoils from neutron elastic scattering through 50° have approximately the same energy as recoils from the ^{3}He(n,p)T reaction initiated by thermal neutrons. Thus, these spectra are not typical, but represent data taken under the worst conditions with respect to the signal and background counting rates.

The integral counts contained under the peaks in these time spectra do not constitute a scattering ratio or asymmetry determination but instead are the cumulative sums of many separate runs. Asymmetries were determined on the basis of 10-min runs, and the results of all such runs were weighted and averaged to obtain a final value for each scattering angle.

Corrections to the measured polarization for finite angular resolution are negligible, since relatively large scatterer-to-detector distances were used to obtain good TOF resolution. Similarly, multiple-scattering corrections are also negligible if only those scattering events within the gaseous scintillation medium are considered. However, the interaction between the helium gas and the cell is important. This may be estimated by considering only double scattering (one event of which involves a helium collision, as experimentally required for detection) and assuming no polarization asymmetry in either scattering event. The correction was carried out numerically by subdividing each volume into convenient elements and summing

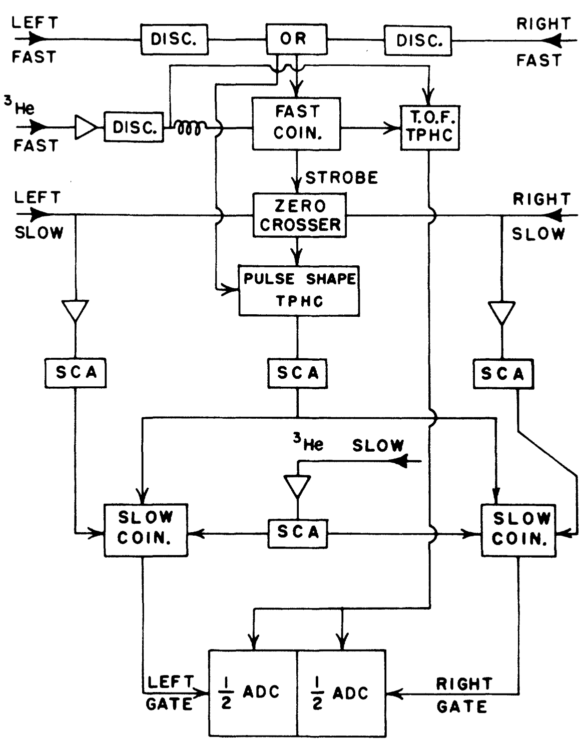

FIG. 2. Block diagram of electronics. The abbreviations used above are as follows: SCA, single-channel analyzer; TPHC, time-to-pulse-height converter; DISC., fast discriminator.

to approximate the integral describing this process. The results yielded corrections which varied from 1 to 11%. In the region where the asymmetry is greatest, the corrections were as follows: 75°, 7.4%; 90°, 11%; 105°, 8.3%; 120°, 6.4%. All corrections increased the magnitude of the measured asymmetry.

III. RESULTS AND DISCUSSION

The experimental results are presented in Table I. The errors shown are statistical counting errors only. To obtain polarizations for n-^{3}He scattering, the source polarization was assumed to be −0.16, the average value of recent measurements by Behof, May, and McGarry[8] between deuteron energies of 300 and 400 keV. In the latter experiment it was found that the polarization does not vary rapidly with energy in this region, and, furthermore, the results obtained with thick, heavy-ice targets were in good agreement with previous thin-target measurements in the same energy region. Since the differential polarization, $P_1(\theta)\sigma_1(\theta)$, of the source reaction at these energies varies approximately in the c.m. system as $\sin(2\theta_{\text{c.m.}})$, the polarization $P_1(\theta_{\text{lab}})$ is maximum and slowly varying in the laboratory system for $\theta \approx 45°$ lab. Therefore the small differences in angle and angular resolution used in the present experiment and that of Ref. 8 need not be considered. Any estimate of the uncertainty in P_1 must await future measurements; much of the earlier D(d, n) polarization data has been shown to be in error, and it is unreasonable to suppose that further revision of these data is not likely. The polarizations P_2 obtained with the assumed value of −0.16 for P_1 are given in Table I.

The present measurements, when combined with cross sections interpolated from the measurements of Sayers, Jones, and Wu[2] and Seagrave, Cranberg, and Simmons,[1] yield a differential polarization which can be fitted within experimental

TABLE I. Experimental results.

θ_2 (lab) (deg)	θ_2' (c.m.) (deg)	$P_1(\theta_1)P_2(\theta_2)$ [a]	$P_2(\theta_2)$
40	52.3	−0.003 ± 0.009	+0.02 ± 0.06
50	64.8	+0.006 ± 0.013	−0.04 ± 0.08
60	76.8	−0.016 ± 0.013	+0.09 ± 0.08
75	93.8	−0.039 ± 0.009	+0.25 ± 0.06
90	109.5	−0.080 ± 0.008	+0.50 ± 0.05
105	123.8	−0.052 ± 0.009	+0.33 ± 0.06
120	136.8	−0.033 ± 0.009	+0.20 ± 0.06

[a] The energy averaged value of P_1 for a thick heavy-ice target is assumed to be −0.16 for $\theta = 45°$ lab and E_d = 510 keV.

uncertainties assuming that D-wave effects are negligible. This is consistent with the results of an analysis of the T(p, p)T and ^{3}He(n, n)^{3}He polarization by Werntz and Meyerhof, who find that D-wave effects are small below 5 MeV (c.m.).[9]

The principal characteristics of the angular distribution, the positive values and the occurrence of a maximum near 110° c.m., are very similar to those found by Veeser *et al.*[10] for the scattering of polarized tritons from protons. Werntz's analysis[11] indicates that the triton and neutron polarizations should be similar for excitations in ^{4}He near that reached in the present experiment (approximately 22.8 MeV). The proton polarization in p + T scattering in the neighborhood of 3-MeV proton energy has been measured by Drigo *et al.*[12] and by Skakun, Strashinskii, and Klyucharev.[13] The angular distributions obtained in these measurements are qualitatively similar to the triton results of Veeser *et al.*

Dodder[14] has developed a very general reaction-matrix code which can be used to treat all reactions, including polarizations, in the n + ^{3}He and p + T channels and has performed preliminary calculations to fit the available data for these channels. Figure 4 compares the present results to Dodder's calculation. The main features of the data are well described by this calculation, which used matrix elements inferred from the ^{4}He level parameters assigned by Werntz and Meyerhof.[15] The main characteristics of the polarized triton data presented in Ref. 10 were also well described by these calculations.

The present results are in disagreement with those reported by Behof, Hevezi, and Spalek for a neighboring neutron energy of 3.33 MeV. Whereas our data indicate that the neutron polarization is a maximum near 110° c.m., the polarizations observed in the latter experiment tend toward zero in this angular region. Barit and Sergeyev[16] have performed a charge-independent phase-shift analysis of the T(p, p)T, T(p, n)^{3}He, and ^{3}He(n, n)-^{3}He differential cross sections and of the neutron polarization in the T(p, n)^{3}He reaction. Their results agree with the analysis of Werntz and Meyerhof and yield phase shifts which give satisfactory agreement with the existing polarization data (Refs. 10, 12, 13, and the present work), except for 3.33-MeV data of Behof, Hevezi, and Spalek.

In conjunction with the data of Veeser *et al.* the

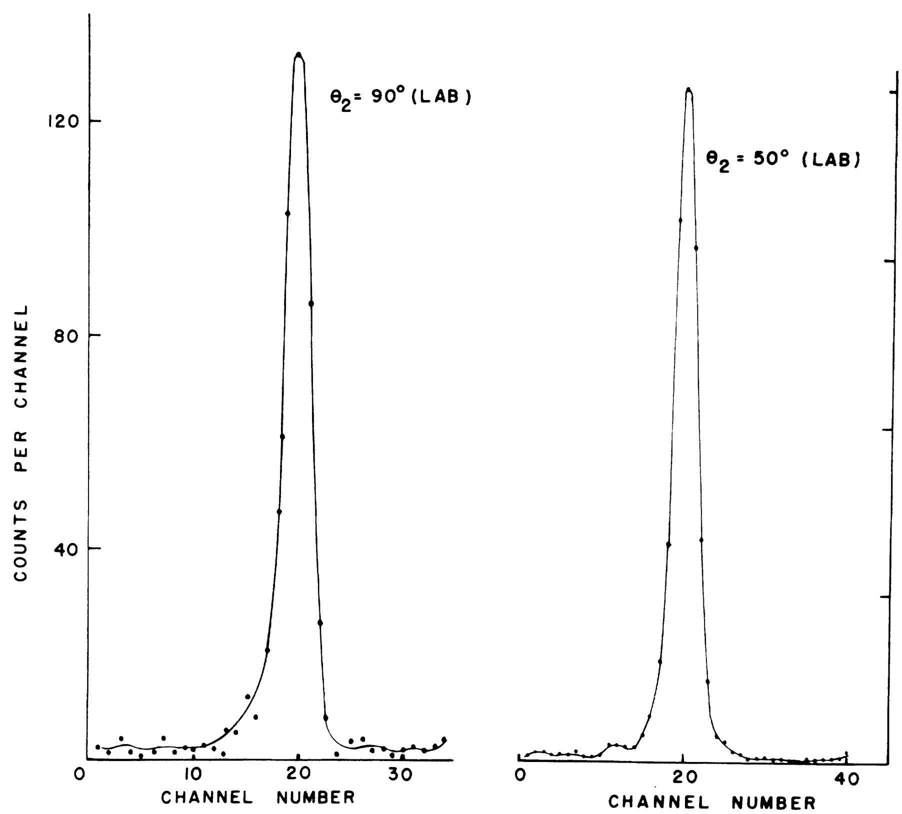

FIG. 3. Neutron time-of-flight spectrum for the laboratory scattering angles $\theta = 50$ and 90°. The time per channel is approximately 1.25 nsec.

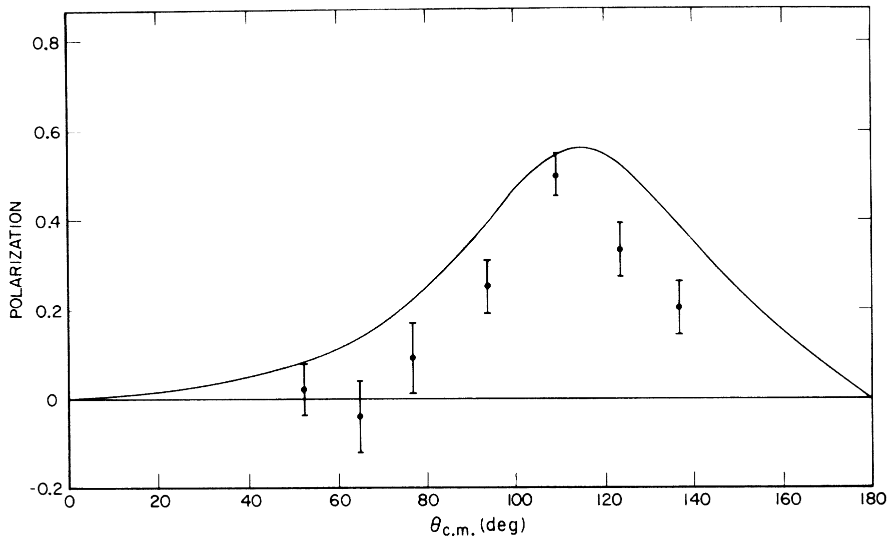

FIG. 4. Polarization of neutrons elastically scattered from ^{3}He at 2.96 MeV. The solid curve gives the results of Dodder's reaction-matrix analysis of p+T and $n+^{3}$He data using the Werntz-Meyerhof level parameters for ^{4}He.

present results indicate that some adjustment of the parameters of the $T=0$ levels near 22 MeV in ^{4}He is required. These parameters were determined by Werntz and Meyerhof by fitting the existing cross-section and neutron-polarization data for the T(p, n) reaction. Recently, Cramer and Cranberg[17] have presented new measurements of the neutron polarization in the T(p, n)^{3}He reaction which also indicate that some adjustment of these parameters is required. However, Veeser *et al.*, on the basis of their study conclude that no improvement in the Werntz-Meyerhof assignments is probable without additional experimental data. It is hoped that the present data will be useful in future studies of the level structure of ^{4}He.

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