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Measurement of the Neutron Polarization for the $^{12}C(^3He, n)^{14}O$ Reaction Between 4.1 and 5.9 MeV

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Angular distributions of the neutron polarization for the $^{12}C(^3He, n)^{14}O$ reaction have been measured at eight bombarding energies between 4.1 and 5.9 MeV. Large polarizations, both positive and negative valued, are observed over the whole energy range, with maximum values of $+0.70 \pm 0.06$ at 5.7 MeV (90°) and -0.82 ± 0.04 at 4.5 MeV (75°). As $E(^3He)$ increases, the shapes of the polarization angular distributions shift continuously and smoothly toward forward angles. A similar energy dependence is noted by Marr *et al.* for the proton-polarization measurements for the analog reaction $^{12}C(^3He, p_1)^{14}N^*$(2.31-MeV state). The data for these two reactions bear much resemblance despite the difference of the Q values and possible Coulomb distortions in the proton exit channel. Although energy dependence in polarization angular distributions is not considered a usual characteristic of a direct-reaction mechanism, the smooth and continuous nature of the variation does suggest that this mechanism may be of some importance here. Exploratory two-nucleon-transfer distorted-wave calculations show that this theory can predict an energy dependence of the polarization using reasonable optical-model parameters for this energy and mass range. However, the trend of the calculations is contrary to the data, and little agreement with the data is found.

I. INTRODUCTION

As two-nucleon-transfer reactions can produce nuclei that are two nucleons removed from stable targets, the investigation of these reactions provides a direct way of obtaining spectroscopic information on neutron- or proton-rich nuclei that are not easily studied by other techniques. Although a formalism[1-5] to describe these reactions has been developed within the framework of distorted-wave Born-approximation (DWBA) theory, the complications associated with the transfer of two particles have forced most applications of the theory into adopting simplifying assumptions.[1,6-9] For instance, it is usually assumed that the two nucleons are transferred as a pair and that each nucleon shares half the binding energy of the pair.[5,9,10] In addition, spin-dependent interactions are frequently ignored in order to remove the coherence between participating L values in the calculation of the cross section. Both of these assumptions have been questioned in recent papers.[9-12] As the extraction of reliable spectroscopic information using these reactions requires that the reaction mechanism be better understood, investigations relating to some of the assumptions should be further explored. Although little detailed information on spin-dependent interactions is presently known for reactions of this type, the sizable polarizations observed in the few experiments reported to date testify to the importance of these interactions. Since studies of polarization phenomena should provide the best insight into such interactions, a program to measure polarizations in two-nucleon-transfer reactions initiated by ^3He particles was undertaken several years ago at this laboratory.

Of the various two-nucleon-transfer reactions, the (^3He, n) and the (t, p) reactions (and their inverse) are the most interesting. Assuming that the two identical nucleons are transferred simultaneously and hence are coupled to $\vec{S} = 0$, the transferred pair can have only a single value of $\vec{L}$ for a given $\vec{J}$ transfer and hence the question of coherence does not arise. The measurement of polarization phenomena in these reactions generally requires the use of double-scattering techniques. Although yields in (^{3}He, n) reactions are generally low, the development of efficient, high-resolution polarization spectrometers[13] now permits practical measurements for those few cases where the separation of states in the final nucleus is adequate without resorting to pulsed-beam time-of-flight spectrometry.

Investigations of polarization in (^{3}He, n) reactions reported to date include the work at Duke[14,15] for ^{12}C and ^{13}C targets (2.2–3.7 MeV); the work at Ohio State[16–19] for ^{12}C, ^{13}C, and ^{24}Mg targets (4–6 MeV); the work at Berlin[20] for ^{13}C targets (5.5 MeV; and the work at Notre Dame[21] for ^{3}H targets (<4 MeV). The proton polarization for the ^{12}C-(^{3}He, p_0) and ^{12}C(^{3}He, p_1) reactions has also been measured at Ohio State[22,23] for the 2–6-MeV energy range. Other two-nucleon-transfer polarization studies include the ^{6}Li(^{3}He, p_1) and ^{10}B(^{3}He, p_1) work at Maryland[24] (<3 MeV), and the ^{12}C(t,p) work at Los Alamos[25] (16 MeV). In addition, measurements of the analyzing powers for (p, t) and (p, ^{3}He) reactions initiated by polarized protons have recently been reported for ^{12}C, ^{16}O, and ^{28}Si targets at Oxford[11] (49.5 MeV) and for ^{15}N and ^{16}O targets at Berkeley[26] (43.8 MeV). In several of the above works, DWBA calculations carried out[14,19,21–23,25,26] to compare with the data met with only limited success.

In the present work, measurements of the neutron polarization for the ^{12}C(^{3}He, n) reaction for the 4–6-MeV energy interval are reported. In this reaction, the differential cross sections exhibit an $L = 0$ stripping pattern at energies as low as 3.5 MeV, and $\sigma(\theta)$ has been qualitatively described[10,27] by DWBA. Although the excitation curves[28,29] at forward angles show much resonant-like structure up to 10 MeV, the structure appears to exert little influence on the shape of $\sigma(\theta)$. Some DWBA calculations[30] for the 2–6-MeV interval, in fact, have accounted for much of the observed structure in the excitation curves. Furthermore, as ^{3}He projectiles should be strongly absorbed at the nuclear surface, compound-nucleus effects which take place inside the nucleus are expected to be small[4] above projectile energies of a few MeV. Schaller *et al.*[14] reported polarization measurements at $E(^3\text{He}) \leq 3.7$ MeV for this reaction, and in their subsequent DWBA calculations at 3.7 MeV they showed that a qualitative description of the $\sigma(\theta)$ and $P(\theta)$ data could be achieved. Because the direct-reaction mode is generally expected to increase in importance as the incident energy increases, and because more definite conclusions regarding the reaction mode should be possible from a study[31] of the energy and angular dependence of the polarization, measurements at higher energies seemed particularly worthwhile towards furthering an understanding of the reaction mode involved. Consequently, polarization measurements were made at eight energies up to 5.9 MeV for the $10° \leq \theta_1(\text{lab}) \leq 135°$ angular range. These data are compared with the proton polarization measurements[22,23] also made at this laboratory for the ^{12}C(^{3}He, p_1) reaction. Because the data in these reactions could plausibly be explained with a direct-reaction model, DWBA calculations were carried out as discussed briefly below.

II. EXPERIMENTAL PROCEDURE

Neutrons were produced by bombarding a self-supporting natural carbon foil with a 5- to 8-μA ^{3}He beam from the Ohio State University 6-MeV Van de Graaff accelerator. The foils, made from an alcohol-Dag colloidal solution, had an average thickness of 250-keV to 5-MeV ^{3}He ions. This thickness was determined from a measurement of the shift induced in the ^{7}Li(p, n) threshold when the foil was inserted in front of the Li target. For the polarization measurements, the C foil was mounted 4 cm in front of a gold-clad-copper beam stop which helped minimize extraneous neutron production. To minimize target deterioration from the beam, the target was rotated continuously during bombardment.

The neutron polarimeter shown schematically in Fig. 1 consisted of a neutron spin precession solenoid and a high-pressure helium gas scintillator operated in fast coincidence with two plastic neutron detectors. The polarization of the neutrons produced in the reaction at a laboratory angle θ_1 was determined from a measurement of the asymmetry in the scattering from helium. The helium was contained at 167 atm (95% He, 5% Xe) in a scintillator which had an energy resolution (full width at half maximum) of about 10% for 5-MeV neutrons.[13,31] This scintillator located 85 cm from the target subtended a half angle of 1.5° with the neutron source as defined by a brass collimator inserted in the bore of the solenoid. Neutrons scattered from helium through an angle θ_2 were detected in fast coincidence ($2\tau = 12$ nsec) by one of two Pilot-B plastic scintillators located in the top or bottom positions, as illustrated in Fig. 1. Prior to scattering from the helium, the neutron spins were precessed through $\pm\frac{1}{2}\pi$ about the neutron momentum direction by a solenoid magnet which is described elsewhere.[32,33] The plastic scintillators mounted on RCA 6810A photomultiplier tubes were located at an average separation of 17.5 cm from the helium cell and subtended 7.6 cm in the scattering plane ($\Delta\theta$), 15.2 cm in the azimuthal direction ($\Delta\phi$), and 5.1 cm in depth. The analyzing angle θ_2 defined by the position of the neutron detectors varied between 112 and 123° (lab) in these measurements. A linear signal from the helium scintillator was routed into one of four preselected quadrants of a multichannel analyzer, depending on whether the scattering was into the top or bottom detector and on whether the neutron spins were precessed through $+\frac{1}{2}\pi$ or $-\frac{1}{2}\pi$. The sense of the magnetic field was reversed in approximately 10-min intervals during the measurements to counteract possible electronic drifts. Further details on the apparatus are given by DeMartini, Soltesz, and Donoghue.[32]

Background contributions to the pulse-height spectra can arise from several sources, for which corrections must be made. Events due to accidental coincidences were determined by delaying the anode signal from the helium cell by an additional 50 nsec, a duration sufficient to exclude all real coincidence events. A second source of background due to real coincidences produced by neutrons not coming directly from the target was measured by inserting a brass shadow bar of negligible transmission to the neutrons in the bore of the solenoid. These backgrounds, measured at alternate reaction angles, were each typically about 5% of the true coincidence events. Contributions to the helium recoil spectrum due to incident γ rays were also investigated using time-of-flight techniques and found to be small, affecting the determined polarizations to less than 0.005.

The two gated helium recoil spectra shown in Fig. 2 illustrate two extreme situations. The dots represent the spectra with measured backgrounds subtracted, and the dashed lines indicate the total measured background. The latter was statistically consistent with zero polarization and was assumed to be such in the data reduction. Some of the spectra exhibited a nonsubtracting background which was apparent near the low-energy edge of the peaks (e.g., see the 5.9-MeV spectrum in Fig. 2). This background which varied with angle and energy could possibly arise from excited-state transitions in the $^{13}C(^3He, n)$ reaction resulting from the natural abundance of ^{13}C in the targets. However, in most cases where it appeared, this background was estimated to influence the measured polarization by less than 0.05 of the measured values. Because of the uncertain origin and contribution of this background, no correction to the data was made.

The counts in the peak in the gated helium recoil spectrum corresponding to neutrons scattered through θ_2 were summed for each of the four quadrants, corresponding to scattering into the top (T) or bottom (B) detectors for both clockwise (cw) and counterclockwise (ccw) spin precessions. To eliminate known sources of instrumental asymmetries, the ratio r of the neutrons was calculated as the geometric mean of the individual detector ratios by the expression

$$r=\left(\frac{T_{\rm cw}}{T_{\rm ccw}}\times\frac{B_{\rm ccw}}{B_{\rm cw}}\right)^{1/2}.$$

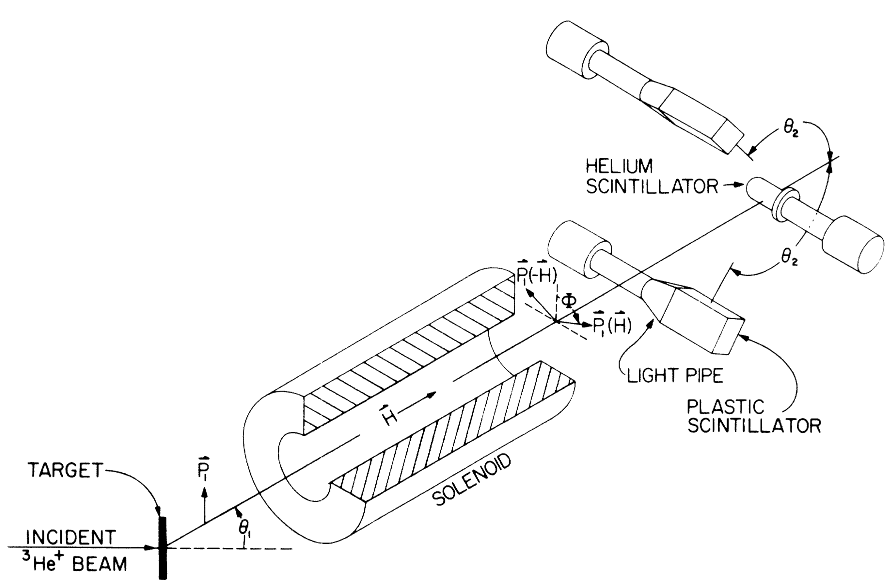

FIG. 1. Schematic view of the neutron polarimeter. The vectors $\vec{P}_1$ represent the neutron polarization before and after precession by the solenoid through the angle $\pm\Phi$, where $|\Phi|\leq 90°$.

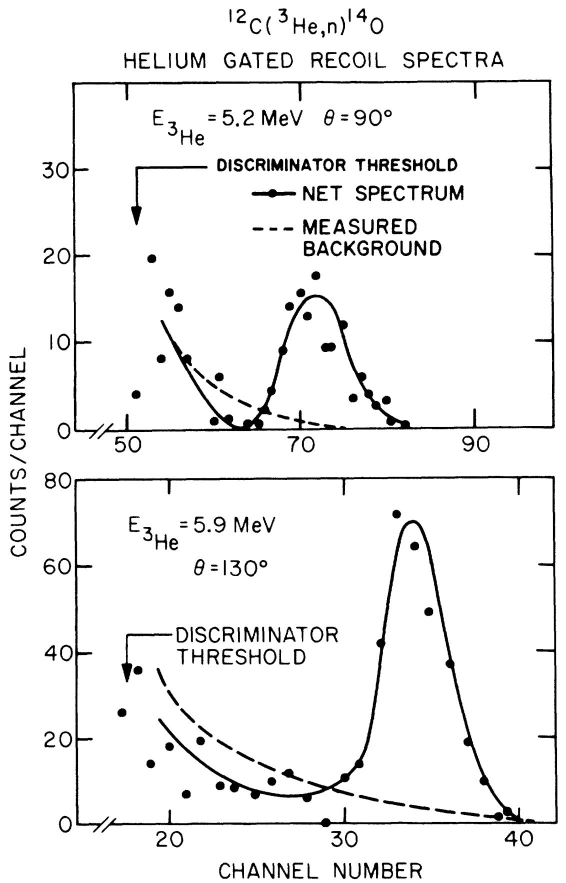

FIG. 2. Two typical gated helium recoil spectra. The dots represent the spectra with the backgrounds subtracted and the dashed lines indicate the total measured background.

The asymmetry e of the neutrons is related to r by

$$e = (r-1)/(r+1).$$

A division of the asymmetry by $\langle P_2 \rangle$, the average n-α analyzing power, then yields the polarization function for the reaction. The analyzing power was calculated using the phase shifts of Hoop and Barschall[34] and was averaged over the experimental geometry via numerical integration techniques.[32] The average values of the analyzing power ranged between 0.63 and 0.93 for these measurements. The Basel convention[35] has been used throughout this work.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Angular distributions of the neutron polarization for the $^{12}C(^{3}He, n)$ reaction were measured at nine reaction angles ($10° \leq \theta_{lab} \leq 135°$) at eight ^{3}He energies between 4.1 and 5.9 MeV. The results measured to a statistical accuracy of between 0.02 to 0.06 in the asymmetry are listed in Table I at the mean laboratory projectile energies. The quoted uncertainties arise principally from statistical considerations. Large values of the polarization are observed at all energies, with extrema ranging from −0.82 at 4.5 MeV (75°) to +0.70 at 5.7 MeV (90°). The data are presented graphically in Fig. 3, where a smooth curve has been sketched through the data points. The polarization function exhibits an energy dependence which is both smooth and regular. Noting that the 4.1-MeV distribution is characterized both by large positive- and negative-valued maxima and by a sharp cross-over angle, the trend of the polarization function with increasing energy is such that these characteristics shift slowly toward forward angles, with the positive maximum at forward angles disappearing at 5.5 MeV. In some sense, the over-all trend of the shift is reminiscent of a traveling wave coming into a fixed support. The resonant-like structure observed[28] in $\sigma(0°)$ (see Fig. 5) is ordinarily expected to produce similar fluctuations in the polarization. As there appears to be no evidence of this here, the assumption that a direct-reaction mode is responsible for the polarization is plausible, even though the observed energy de-

TABLE I. $^{12}C(^{3}He, n)^{14}O$ polarization data.

Lab angle (deg) \ $E_{^3He}$ (MeV)	4.1	4.5	4.75	5.2	5.35	5.5	5.7	5.9
15	+0.30 ± 0.03	+0.28 ± 0.02	+0.23 ± 0.04	+0.16 ± 0.04	+0.06 ± 0.05	−0.16 ± 0.06	−0.16 ± 0.03	−0.16 ± 0.04
30	+0.48 ± 0.05	+0.48 ± 0.03	+0.40 ± 0.04	+0.26 ± 0.06	+0.07 ± 0.06	−0.33 ± 0.05	−0.46 ± 0.03	−0.48 ± 0.07
45	+0.04 ± 0.09	+0.23 ± 0.04	+0.10 ± 0.04	−0.14 ± 0.05	−0.14 ± 0.05	−0.32 ± 0.08	−0.34 ± 0.06	−0.30 ± 0.07
60	−0.23 ± 0.08	−0.56 ± 0.04	−0.63 ± 0.03	−0.20 ± 0.07	+0.26 ± 0.07	+0.29 ± 0.06	+0.30 ± 0.05	+0.30 ± 0.06
75	−0.69 ± 0.07	−0.82 ± 0.04	−0.60 ± 0.05	+0.32 ± 0.06	+0.52 ± 0.05	+0.47 ± 0.04	+0.49 ± 0.06	+0.55 ± 0.07
90	−0.58 ± 0.10	−0.32 ± 0.05	−0.11 ± 0.05	+0.51 ± 0.06	+0.67 ± 0.04	+0.65 ± 0.06	+0.70 ± 0.06	+0.61 ± 0.07
105	+0.04 ± 0.11	+0.25 ± 0.06	+0.31 ± 0.06	+0.65 ± 0.05	+0.58 ± 0.05	+0.62 ± 0.04	+0.53 ± 0.06	+0.23 ± 0.07
120	+0.45 ± 0.09	+0.37 ± 0.10	+0.48 ± 0.07	+0.67 ± 0.09	+0.36 ± 0.06	+0.43 ± 0.08	+0.13 ± 0.08	−0.26 ± 0.08
130	+0.38 ± 0.09	+0.31 ± 0.07		+0.43 ± 0.09	+0.23 ± 0.08	+0.18 ± 0.09	−0.30 ± 0.10	−0.60 ± 0.07

pendence of $P(\theta)$ is contrary to expectations for such a mechanism.

A comparison of the neutron-polarization results with the proton-polarization data of Marr and Donoghue[22] for the analog reaction $^{12}C(^{3}He,p_1)$ is shown in Fig. 4, where the proton data are indicated by the crosshatched curves, the extrema of which reflect the uncertainties in the proton measurements. The final state in this proton reaction and the ground state of ^{14}O are members of the same isospin triplet. The proton data were measured with a comparable energy resolution, but sometimes at slightly different energies. The comparison is therefore made for the closest energy measurements. As noted, the general features of the angular variations and the energy dependence of the polarization function are quite similar except in the transition region around 5.2 MeV. Differ-

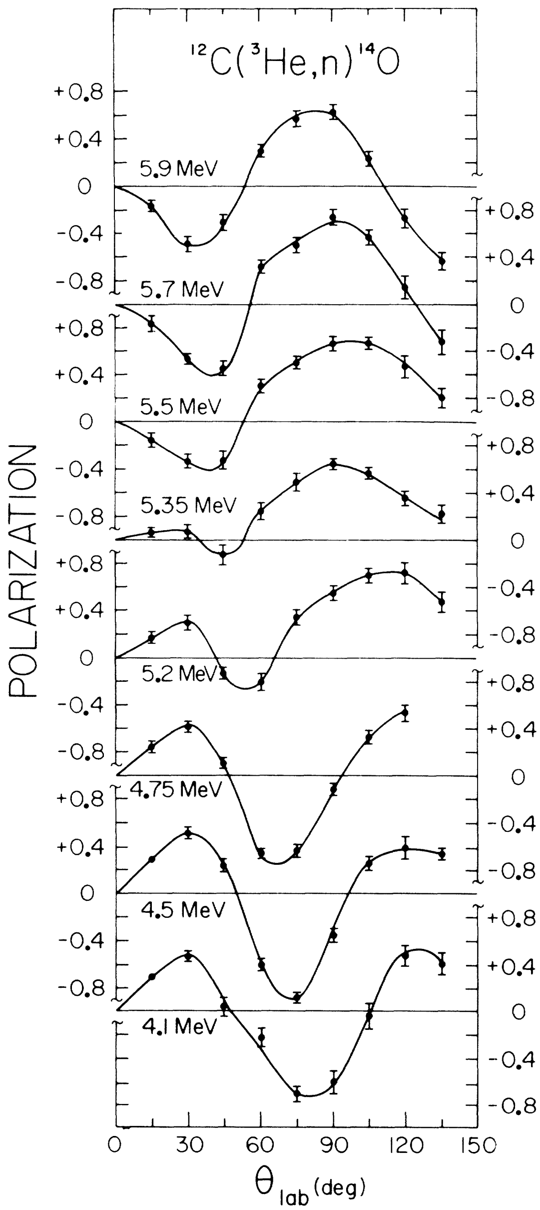

FIG. 3. Neutron-polarization angular distributions plotted as a function of the laboratory emission angle. The solid lines are smooth lines drawn through the data. The error bars represent the statistical uncertainties only.

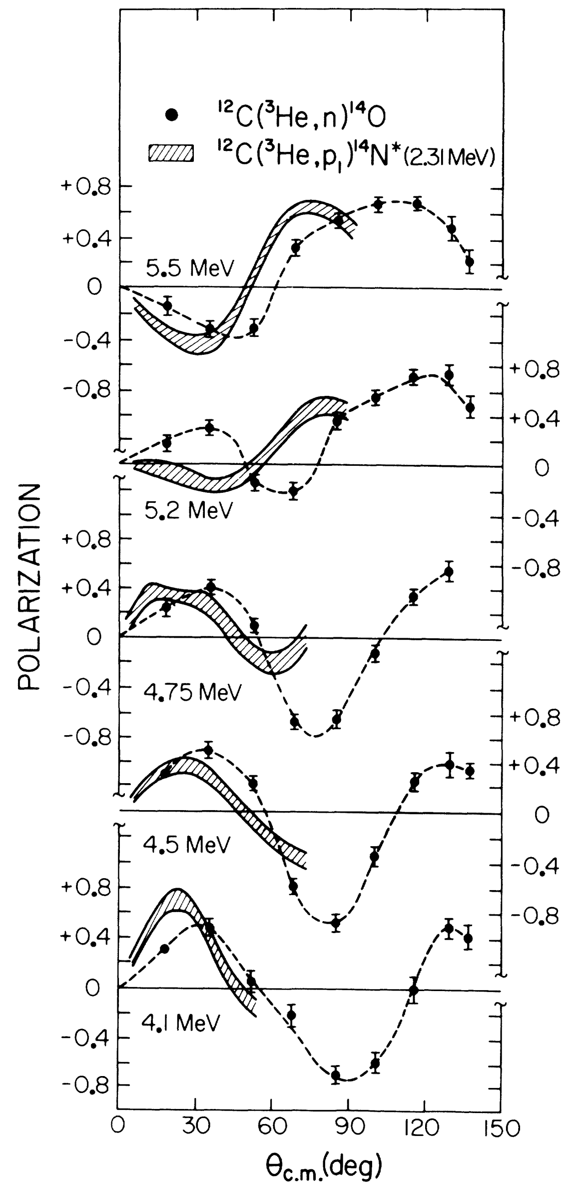

FIG. 4. Comparison of the present neutron-polarization data and proton-polarization data for the $^{12}C(^{3}He,p_1)$-$^{14}N^*$(2.47-MeV) reaction measured by Marr, and Donoghue. The dots represent the neutron-polarization data and the crosshatched curves represent the proton-polarization data and its uncertainty.

ences noted could be the result of differences in Coulomb effects in the exit channels. In general, however, the similarity of the data in the two exit channels qualitatively supports the observations of Fulbright *et al.*[27] who noted that both Coulomb and Q-value difference effects (~3 MeV here) were negligible in their comparison of cross-section data for these two reactions. The same mechanism is, however, clearly responsible for the polarization in both channels.

A contour plot of the polarization for the ^{12}C(^{3}He, n) reaction was constructed from 144 data points of the present and previous[14] investigations and is shown in Fig. 5. The 0° yield curve sketched above this plot was taken from Towle and Macefield[28] and illustrates the broad structure in the cross section discussed above. Several closed regions in the polarization contours are correlated with the structure in the excitation curve, such as at 4.6 and 5.4 MeV. This is sometimes an indication of compound-nucleus formation.[31] However, because these fluctuations can apparently be explained[30,36] also via a direct-reaction picture, such conclusions are premature until substantiated via model calculations.

Earlier calculations on the $^{12}C + {}^{3}He$ interaction carried out by many authors[10,14,22,23,27–30,37–46] show that compound-nucleus formation dominates the 2–3-MeV region in that successful fits to $\sigma(\theta)$ data[37] and to $\sigma(\theta)$ and $P(\theta)$ data simultaneously[22] can be obtained assuming that five known levels contribute to the reaction in this energy region. However, above 3 MeV, the data is very poorly described[22] via this mechanism. Furthermore, $\sigma(\theta)$ becomes strongly peaked at 0° above 3 MeV, and qualitative descriptions of the data have been obtained via DWBA calculations.[10,14,40] Some work,[44–46] however, suggests that both mechanisms may be operating to some degree in this energy range. Although compound-nucleus formation cannot be excluded as a contributing reaction mode, the stripping mode does appear to dominate above 4 MeV and it seemed worthwhile to explore via DWBA calculations the extent to which the polarization data could be explained in this simple picture.

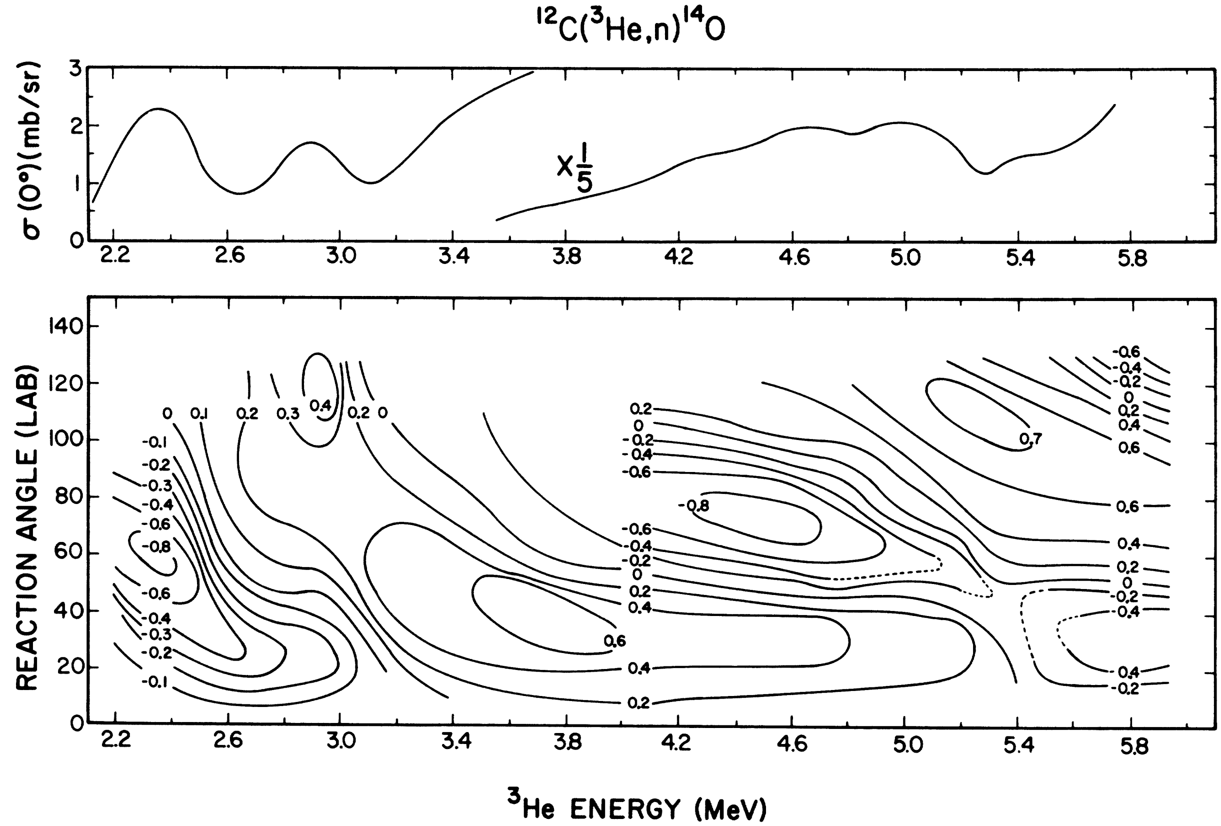

FIG. 5. Contour plot of the neutron-polarization data including the work of Schaller *et al.*, below 3.7 MeV. Above the contour plot is a $\sigma(0°)$ excitation curve from the work of Towle and Macefield. The lines represent constant values of the polarization as a function of energy and angle and are shown in intervals of 0.1 of $P(\theta)$. Dashed lines have been used when the data available was insufficient to determine the trend of contour uniquely.

Accordingly, DWBA calculations were made in the zero-range approximation using the Oak Ridge National Laboratory distorted-wave code[47] JULIE with the two-particle-transfer option.[48] The two captured protons were described by Woods-Saxon single-particle wave functions where the well depth was adjusted to produce an eigenstate of energy equal to half the difference in the binding energy between ^{12}C and ^{14}O. The two transferred protons were described by pure $(p_{1/2})^2$ shell-model configurations.[49] At the time the calculations were made,[16] the information on ^3He optical-model parameters was sparse and consisted of the parameters of Schaller *et al.* and those communicated by Park.[50] As elastic scattering data define only the asymptotic part of the wave function,[11,51] the optical-model potentials derived from an analysis of these data may describe the wave function poorly in the vicinity of the nuclear surface where the transfer reaction takes place. In this case, it is justifiable to use potential sets which are slight perturbations on these derived sets, particularly in the entrance channel where the systematics of optical potentials are essentially unknown. In the past year or two, much work on ^3He optical-model analyses of the $^{12}C + {}^3He$ scattering has been published[10,42-44,52,53] for the energy range below 20 MeV. Because our earlier venture produced encouraging results, but little agreement, further calculations were recently made using these latest parameter sets. Although optical-model parameters with a real well depth $V_0 \simeq 50A$ (A is the nucleon number of the projectile) are usually favored,[54] some of the published sets reported had shallow depths. For completeness, these were also tried but generally produced very poor descriptions of the data. The ^3He spin-orbit potential was varied between 0 and 6 MeV as recommended,[55-57] but this parameter had little noticeable effect on the calculations, as noted also by Schaller *et al.* and Marr and Donoghue.[22] Neutron parameters were originally taken from Perey,[58] but in the recent calculations the slightly different set of Becchetti and Greenlees[59] was used.

For the most part, the calculations using published ^3He parameters produced little agreement with the data although several sets resulted in calculated curves similar to those of Schaller *et al.* and hence provided a qualitative description of the polarization up to ~4.5 MeV. Two sets[42,43] did produce an energy dependence in the polarization, but this showed up more like oscillations in a standing wave pattern than as the traveling wave trend of the data. One set proposed by Marr[23] did exhibit an energy dependence in the polarization of the traveling wave variety and this is shown in Fig. 6. However, the energy dependence of the polarization pattern is contrary to the trend of the experimental data in that the distribution shifts toward the backward angles rather than the forward angles, and the shift occurs over a considerably broader energy interval than the data. These calculations are shown only to indicate that an energy dependence of the type observed experimentally is predicted using a two-nucleon stripping model. The parameters used in these calculations are cited in the figure caption, using the notation given elsewhere.[60,61] However, although these parameters are reasonable for this energy and mass range, they do not adequately describe the data and hence should not be used further.

The failure to describe the data can be attributed to a variety of causes, such as: inadequate optical-model parameters, neglect of D-state contributions in the mass-3 wave function, the use of the zero-range approximation, or the assumption of a single-step transfer mechanism. However, more

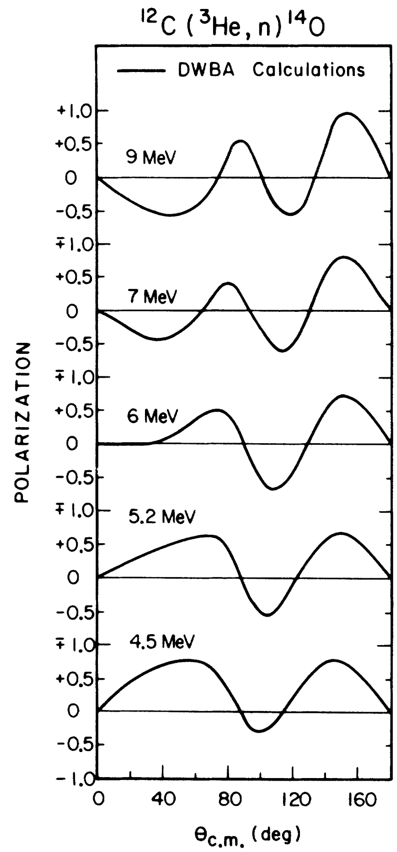

FIG. 6. The DWBA calculations carried out using the optical-model parameters of Marr, Kuenhold, and Donoghue, which are for ^3He: $V_0 = 165$ MeV, $W = 4.43$ MeV, $r_0 = 0.93$ fm, $r_c = 1.4$ fm, $a = 0.81$, $V_{so} = 6$ MeV, $W_{so} = 0$, $r' = 2.05$ fm, $b = 0.65$; and for neutrons: $V_0 = 43.5$ MeV, $W' = 11.6$ MeV, $r_0 = 1.29$ fm, $r_c = 1.25$ fm, $a = 0.73$, $V_{so} = 6$ MeV, $W_{so} = 0$, $r' = 1.26$ fm, $a' = 0.53$.

successful calculations have recently been carried out for the $^{13}C(^3He, n)$ reaction, as will be reported in a forthcoming publication.[60] The major difference in the latter case is that the excitation energy in the compound system is almost 10 MeV greater than for the $^{12}C(^3He, n)$ reaction and hence contributions from individual compound states are expected to be considerably less there than in the present case. The neutron energy in the latter case is also considerably higher and the published neutron optical-model parameters may therefore be more applicable.

IV. CONCLUSIONS

The neutron polarization measured as a function of energy and angle shows a distribution that shifts towards forward angles as the bombarding energy increases. An attempt made to describe these data via DWBA calculations has shown that with reasonable optical-model parameters, an energy dependence of the polarization is possible. However, no suitable description of the data was obtained. Therefore the earlier qualitative success in applying DWBA to this reaction by Schaller *et al.* must be regarded as fortuitious.

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Study of F^{20} Using the $O^{18}(t, n\gamma)$ Reaction*

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Some of the low-lying excited states of F^{20} were studied using the $O^{18}(t, n\gamma)F^{20}$ reaction at a bombarding energy of $E_t = 2.7$ MeV. The methods of n-γ and γ-γ angular correlations were used to obtain information concerning the spins of the 823- and 656-keV states and the multipole mixing ratios of the subsequent electromagnetic deexcitations of these states. The mean lifetime of the 823-keV state was measured with the recoil-distance technique to be 79± 6 psec. The results of the experiment are discussed in terms of current nuclear models.

INTRODUCTION

The nucleus F^{20} is an odd-odd nucleus situated in a region of mass number where large nuclear (prolate) deformations have been observed. The coupling of the odd neutron and odd proton to the deformed core results in a possibility of two rotational bands at low excitations.[1] These are the $K = 1$ and 2 bands formed in the antiparallel and parallel coupling of the last neutron ($\Omega = \frac{3}{2}$) and proton ($\Omega = \frac{1}{2}$). Of these two possible bands it is expected[2] that the $K = 2$ band would be at a lower excitation and form the ground-state rotational band. The Oak Ridge shell-model group[3-6] has made calculations for F^{20} using realistic interactions and predicts a rotational-like set of states with a spin sequence of $J^\pi = 2^+, 3^+, 4^+, 5^+$ commencing with the ground state. The ground state is known[7] to be $J^\pi = 2^+$ and the first excited state has recently been shown[8] to have a spin and parity of 3^+. It would appear that these two states are the anticipated members predicted by both models. Of vital importance, of course, is the location and confirmation of these and higher-spin members in order to further test the validity of the application of the above models to nuclei in this mass region. A state at 823 keV is known[7] to be $J^\pi = 2^+$, 4^+ and consequently is a very good candidate for a low-lying $J^\pi = 4^+$ state whose predicted position is at about 1.0 MeV.[6]

Despite the efforts of a large number of experimental investigations into the structure of F^{20}, the