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Neutron Polarization in the $^{24}Mg(^3He, n)^{26}Si$ Reaction at 5.0 and 5.8 MeV†

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Angular distributions of the neutron polarization have been measured for the $^{24}Mg(^3He, n)^{26}Si$ reaction at $E(^3He) = 5.0$ and 5.8 MeV. The measurements were made using a neutron polarimeter consisting of a high-pressure helium gas scintillator and a spin-precession solenoid. The two angular distributions are similar in shape and have values approaching 0.7 at the backward angles. An attempt was made to describe $\sigma(\theta)$ and $P(\theta)$ data with direct reaction calculations made using the multinucleon transfer distorted-wave Born-approximation (DWBA) code JULIE.

I. INTRODUCTION

Two-nucleon transfer reactions are utilized with increasing frequency to obtain spectroscopic information for nuclei that are several nucleons removed from the line of stability. The mechanism of transferring two nucleons to the core is more complex that that of single-nucleon transfer processes and the formalism used in computing the relevant quantities to compare with experimental data quickly becomes unwieldy unless simplifying assumptions are made. Frequently, spin-dependent interactions are ignored, justified partly by lack of knowledge of these interactions in two-nucleon transfer processes. These interactions are however of some importance, as witnessed by the large values of the measured polarizations in these processes. It has been our desire to provide more information on these processes by investigating polarization phenomena[1-3] in $(^3He, n)$ and $(^3He, p)$ reactions. Although several investigations of $P(\theta)$ for these types of reactions have been reported (see Ref. 1 for a recent summary), they have generally been for $1p$-shell target nuclei and, except for the most recent work,[1-3] for projectile energies below 4 MeV. Neither of these conditions are expected to be amenable to a purely direct reaction mechanism.

In the present paper, we report the investigation of the $^{24}Mg(^3He, n)^{26}Si$ reaction in the 5- to 6-MeV energy interval. This reaction is a particularly attractive one to study because (1) it is the first two-nucleon transfer reaction for which polarization measurements have been reported for a target nucleus in the $2s$-$1d$ shell, (2) the reaction cross sections show evidence of a sizable direct reaction amplitude, and (3) it offers particular advantages over previously studied two-nucleon transfer reactions from the viewpoint of a distorted-wave Born-approximation (DWBA) analysis. In particular the differential cross section measurements of McMurray *et al.*[4] and Ajzenberg-Selove and Dunning[5] for this reaction at incident energies between 4.9 and 5.6 MeV show a large 0° peak and the shape of the angular distribution changes little over the limited energy range studied, suggesting a large two-nucleon stripping contribution to the reaction mechanism. For a DWBA analysis, this reaction is attractive in that the optical-model potentials for distorted-wave calculations become more justifiable as the number of target nucleons is increased.[6] Furthermore, the elastic scattering of ^3He from targets in the medium mass range has been investigated at low energies and suitable optical-model parameters for DWBA calculations can be determined from an analysis of this data.

From an experimental point of view, the $^{24}Mg(^3He, n_0)^{26}Si$ reaction is a difficult one to study. Although its Q value (+0.06 MeV) and the separation between the ground state and first excited state of its residual nucleus make it one of the few two-nucleon transfer reactions involving a medium A target in which the polarization of the ground-state neutrons can be measured with present polarimeters, the low cross section (0.1 to 2.0 mb/sr) necessitates the use of thick targets and large detectors to obtain data in a reasonable amount of time. Because of this difficulty, the measurements reported here were limited to only two angular distributions of polarization at incident energies of 5.0 and 5.8 MeV taken with 400-keV-thick targets.

II. EXPERIMENTAL

The polarization measurements were made using the Ohio State neutron polarimeter,[7,8] which consists of a high-pressure helium-gas scintillator and a spin-precession solenoid. This scintillator is operated in fast coincidence ($2\tau \simeq 12$ nsec) with two large Pilot-B detectors (5 cm × 7.6 cm × 15 cm) located at a neutron scattering angle of 121° with respect to the helium scintillator. The fast electronics was aligned using neutrons of comparable energy of those studied here from the $^9Be(\alpha, n_1)^{12}C$ reaction[7] because of the prohibitively low reaction yields encountered in the $^{24}Mg(^3He, n)$ reaction.

The scintillator was pressurized with 153 atm of helium and 13 atm with xenon for these measurements. The apparatus, the data taking and the data reduction procedures are presented in complete detail elsewhere.[7,8]

The magnesium targets were self-supporting foils isotopically enriched to 99.96% in ^{24}Mg. These foils were determined by weighing techniques to be 400 keV thick to a 5-MeV ^{3}He beam. Beams of ^{3}He particles from the Ohio State CN electrostatic accelerator were limited to 1.5 μA to avoid foil destruction. Because of the possibility of carbon buildup, the Mg foils were changed several times during the course of the experiment. Although the neutrons from the ^{12}C(^{3}He, n) reaction do not contribute to the recoil spectrum in the region of the ground-state neutron peak, significant carbon buildup would decrease the mean reaction energy. However, the Q values of the ^{12}C(^{3}He, n) and the ^{24}Mg(^{3}He, n_1)^{26}Si* (1.79-MeV state) reactions differ by $\simeq$0.6 MeV. The detection system is not capable to separating the contributions from these two reactions and consequently no attempt was made to extract polarizations for the first-excited-state neutron group, lest the carbon buildup be a problem.

A gated helium-recoil spectrum recorded in the usual fashion[7] is shown in Fig. 1 and illustrates clearly the separation of the ground-state and first-excited-state neutron groups. Backgrounds measured in the usual way were determined to be small ($\leq$1%) and are sketched as a dashed line in the figure.

Angular distributions of the polarization were measured for angles back to 135° (lab) at E(^{3}He) = 5 MeV (9 angles) and 5.8 MeV (10 angles). The data are presented in Fig. 2 where a smooth solid curve has been sketched through the data points. The angular region between 20 and 50° in the 5-MeV distribution illustrates well the impossibilities of (^{3}He, n) polarization measurements, in that accelerator beam times of 96 h spread over two attempts yielded little insight into what the polarization might be because of the extremely low reaction yields here. On the average, 16 h of beam time were required to obtain each datum point with statistical uncertainties in $P(\theta)$ ranging from 0.06 to 0.14. The latter is the overriding uncertainty. A tabulation of the data is given by De Martini.[9] The Basel Convention[10] was used in computing the sign of the polarization. The Hoop-Barschall n-α phase shifts[11] were used in computing the helium analyzing power.

III. DISTORTED-WAVE ANALYSIS

The cross-section angular-distribution data of McMurray *et al.*[4] and of Ajzenberg-Selove and Dunning[5] exhibit pronounced $L=0$ stripping patterns, and additionally have little variation with energy. As the polarization data also show little energy dependence, it seemed reasonable to attempt to describe both data sets via distorted-wave theory, under the assumption that this is the only

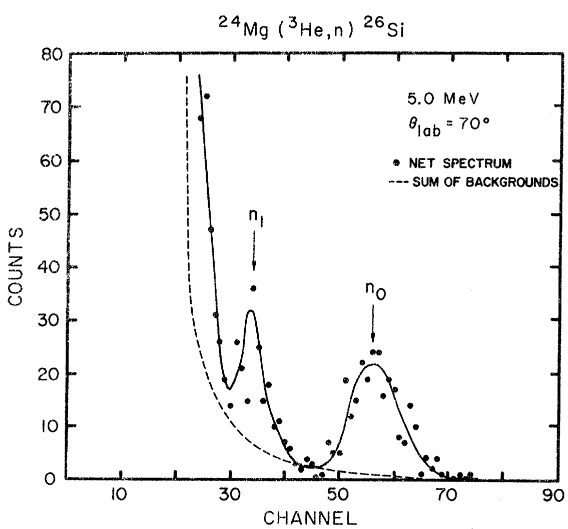

FIG. 1. A gated helium-recoil pulse-height spectrum. The net count spectrum is shown, with the measured background (which has been subtracted) indicated by the dashed line. The separation of the n_0 and n_1 groups is easily seen. The possibility of contamination of the n_1 group by neutrons from the ^{12}C(^{3}He, n_0) reaction prevented the extraction of polarizations for this group.

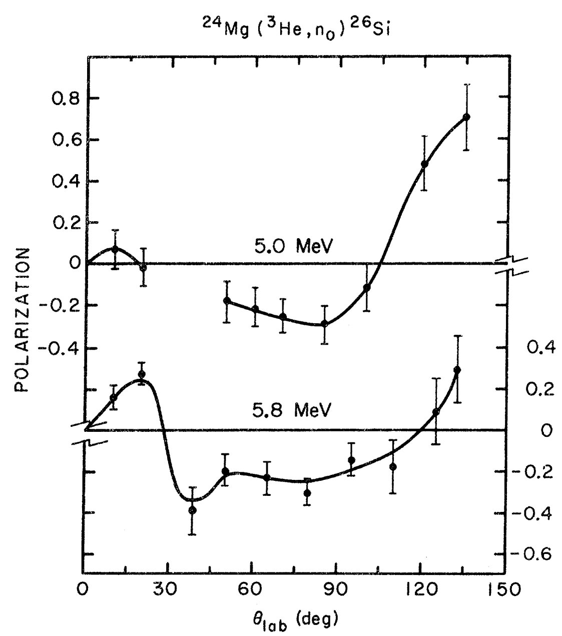

FIG. 2. The two angular distributions of the polarizations are shown. A solid line has been sketched through the data points as an aid to the eye.

reaction mechanism operating here. The calculations were made in the zero-range approximation using the multinucleon transfer version of Oak Ridge National Laboratory distorted-wave code JULIE.[12] The transferred protons were assumed to be captured as a pair into either $1d_{5/2}$ or $2s_{1/2}$ shell-model states and the depth of the potential was adjusted to yield an eigenstate equal to the binding energy of each nucleon in the transferred pair to the target nucleus in the usual way.[13]

The entrance channel optical-model parameters were obtained by fitting the ^3He elastic scattering data at 5.5 and 7.0 MeV of Bray *et al.*[14] for an ^{27}Al target. The optical-model code[15] ABACUS-2 was used, with $V_{so}(^3He)$ set equal to zero. It is generally accepted[16] that the depth of the real potential should be 3 times the single-nucleon well depth. Three potential sets roughly meeting this criterion were obtained in the fitting procedures and these are listed in Table I. The DWBA calculations were made using all of these sets. The $V_{so}(^3He)$ potential assumed the range of values listed in the table, though it was frequently fixed at 2.5 MeV except where noted. Later on, more recently published ^3He optical-model parameters were also tried, even though they were generally derived for higher-energy data analyses. These included those of: Kattenborn *et al.*[17] (^{24}Mg; 18–20 MeV); Zurmuhle and Fou[18] ($^{24,26}Mg$, 15 MeV); Baugh[19] (Mg, 29 MeV); Griffiths[20] (^{24}Mg, 29 MeV); and Luetzelschwab and Hafele[21] (^{27}Al, 29.6 MeV). The neutron parameters were taken from Perey[22] (labeled N-1 in Table I), although later on parameters from Becchetti and Greenlees[23] were also

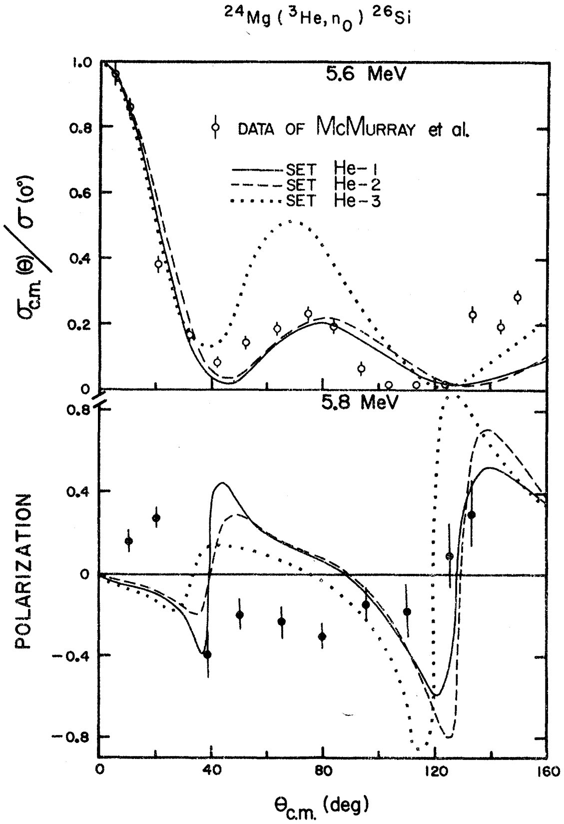

FIG. 3. DWBA calculations made using the three ^3He optical-model sets of parameters listed in Table I are shown. Neutron parameter set N-1 was used. The cross section data are taken from McMurray *et al.*

TABLE I. Optical-model parameters used in $^{24}Mg(^3He, n_0)^{26}Si$ calculations. The form of the optical-model potential used in the calculations is

$$U(r) = V_c(r) - Vf(r) - i\left(W - W'a'\frac{d}{dr}\right)g(r) + V_{so}\left(\frac{\hbar}{m_\pi c}\right)^2 \vec{l}\cdot\vec{\sigma}\frac{1}{r}\frac{d}{dr}f(r),$$

where

$$f(r) = \left[1 + \exp\left(\frac{r - R_0}{a}\right)\right]^{-1}, \quad g(r) = \left[1 + \exp\left(\frac{r - R_0'}{a'}\right)\right]^{-1},$$

and

$$R_0 = r_0 A^{1/3}.$$

Set label	V (MeV)	r_0 (fm)	a (fm)	r_c (fm)	W (MeV)	r_0' (fm)	a' (fm)	W' (MeV)	V_{so} (MeV)
He-1	179.6	1.142	0.700	1.40	20.19	1.549	0.734	0	0–5
He-2	156.9	1.068	0.776	1.40	20.02	1.614	0.638	0	0–5
He-3	112.2	1.242	0.675	1.40	18.29	1.664	0.865	0	0–5
N-1	49.9–50.4	1.25	0.65	1.25	0	1.25	0.47	54.0	2–11
N-2	56.3–56.6	1.25	0.75	1.25	0	1.26	0.58	49.9–50.8	2–11

used (labeled N-2). In comparing the calculations with the experimental cross sections, an arbitrary normalization at 0° was used to get around the difficulty that the multinucleon codes[24] have in calculating an absolute reaction cross section.

The distorted-wave calculations are compared with the only complete polarization angular-distribution data recorded, namely, that at 5.8 MeV. The calculations made using the three ^{3}He optical-model sets of parameters in the table are shown in Fig. 3. Neutron parameter set N-1 was used here, but similar calculations using set N-2 differ little from these. As seen here, the shape of $\sigma(\theta)$ is qualitatively reproduced, but the polarization angular distribution is poorly described. Consequently, other parameter variations were explored to see if the descriptions of the data could be improved. These explorations, which yielded little or no qualitative change in the shape of the calculated distributions, included using the $(2s_{1/2})^2$ form factor, and varying the $V_{so}(^3\text{He})$ potential from 0 to 5 MeV. The insensitivity of the calculations to the latter parameter has been pointed out earlier[1, 25] and is confirmed here. The use of the other ^{3}He optical-model parameters did produce worse descriptions of $\sigma(\theta)$ and/or $P(\theta)$, but none yielded a better description of the data. The use of the Becchetti and Greenlees[23] neutron optical-model parameters produced little qualitative change in the calculations. As might be expected, the variation of the V_{so} (neutron) potential between 2 and 11 MeV produced the largest effect on the $P(\theta)$ calculation, but its main effect was to reduce the magnitude of the polarization as the well depth was decreased. There was little qualitative change in the zero crossings of the calculated polarizations. The cross sections were insensitive to this parameter. Our final endeavor included a crude simulation of finite-range effects by introducing a lower cutoff in the calculations, i.e., excluding regions of the interior from contributing to the integrals. Lower cutoff radii of 3.2, 5.2, and 7.2 fm did change the shapes of $\sigma(\theta)$ and $P(\theta)$, but with little qualitative change from those shown in Fig. 3.

Thus, our present efforts to describe this $(^3\text{He}, n)$ reaction by distorted-wave theory have not been very successful. This was a little surprising in the light of our success in describing polarizations in the $^{13}\text{C}(^3\text{He}, n)$ reaction. The failure may be due to weaknesses in the current formulation of the distorted-wave code for multinucleon processes, or it may reflect the low projectile energy involved here. That is, although a direct reaction appears to qualitatively contribute at this energy (which is above the Coulomb barrier), compound-nucleus contributions, however minor, may affect the experimental polarizations.

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