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Investigation of the Reaction ^{26}Mg(p, t)^{24}Mg near E_p = 26 MeV*

J. R. Shepard, J. J. Kraushaar, and H. W. Baer†
Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado 80302
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Experimental cross sections for the first eight triton groups in the reaction ^{26}Mg(p,t)^{24}Mg have been measured over an angular range 10–168° (lab) at two incident proton energies, 25.4 and 26.8 MeV. Distorted-wave Born-approximation (DWBA) calculations were able to describe general trends in the angular distributions for low-lying states. However, higher-lying states showed dramatic rearward enhancement relative to the DWBA cross sections. Excitation functions of all eight triton groups have been measured at four angles over a beam energy range 24.96 to 27.20 MeV. The excitation functions are nearly flat for all states; further, the angular distributions show no large changes with energy. These data indicate that compound-nucleus effects are not dominant. Thus the results suggest that the population of the unnatural-parity 3$^+$ state at 5.22-MeV excitation is primarily through a direct-reaction mechanism, possibly a multistep process such as those shown to be important in (p,t) reactions by Ascuitto and Glendenning. The roles of spin transfer and multistep effects in the transition to the 5.22-MeV 3$^+$ state in ^{24}Mg were investigated, the latter being the more probable mode of excitation.

I. INTRODUCTION

There has been much recent interest in two-step or multistep contributions to the (p, t) reaction in mass-energy regions where this reaction is thought to be direct.[1-4] Calculations incorporating multistep contributions to the single-step direct process have been quite successful and suggest that such contributions are substantial.[1] It is of interest therefore to examine a particular transition in the (p, t) reaction which cannot proceed via the simple single-step direct process, but must go exclusively through multistep mechanisms. Such a transition would provide a useful test for multistep reaction theories. The (p, t) transition to the 5.22-MeV $J^\pi = 3^+$ state in ^{24}Mg appears to be a suitable candidate for such investigation. Selection rules based on the assumption that the two neutrons in the triton are in a space-symmetric ^1S state of relative motion[5] forbid the excitation of this state through a single-step direct (p, t) process, inasmuch as they require the transferred angular momentum J and parity change $\Delta\pi$ to satisfy $\Delta\pi = (-1)^J$. Thus, the mechanism populating the 3$^+$ state would seem to be either a direct multistep or possibly a compound-nuclear process. Another possible mechansim is that a small $S = 1$ component of relative motion in the two-neutron wave function could couple orbital angular momentum transfers of 2 or 4 to the $J^\pi = 3^+$ state [$J^\pi = 0^+$ for the ground state (g.s.) of ^{26}Mg]. The likelihood of this spin-transfer phenomenon will be discussed below.

Transitions to this 3$^+$ state, again forbidden by the selection rules imposed by the assumption of a simple one-step direct process, have previously been observed in the case of (α, α') scattering.[6-8] Tamura[9] has had considerable success in describing the cross section for the (α, α') excitation of this state using a coupled-channels approach. The (p, t) excitation of the state was observed by Rickey *et al.*,[10] but the data are limited to only a few angles. Recent work by Peterson *et al.*[11] has indicated that the 3$^+$ state is also excited to some extent by the two-neutron-transfer reaction ^{26}Mg(α, ^{6}He)^{24}Mg at a bombarding energy of 35 MeV.

Here it was found that the cross sections for the transition to the first two states in ^{24}Mg exhibited strong dependence on bombarding energy. This was interpreted as evidence for some processes other than a direct reaction, thus precluding an analysis using multistep reaction calculations. Motivated by these developments, we sought to achieve two ends: (1) to determine, by measuring excitation functions for several states excited in the reaction ^{26}Mg$(p, t)^{24}$Mg near $E_p = 27$ MeV, whether or not substantial nondirect processes contribute; and (2) to measure differential cross sections over a wide angular range, including extreme backward angles, for several transitions including the excitation of the 5.22-MeV 3^+ state.

II. EXPERIMENTAL TECHNIQUES

The experiment employed a proton beam from the University of Colorado 1.3-m sector-focused cyclotron incident upon a self-supporting (99.22% enriched) ^{26}Mg foil of 0.500-mg/cm^2 thickness. Proton energy spread in the beam due to target thickness was less than 60 keV. Beam energies were measured using NMR determinations of the magnetic field of an analyzing magnet, and relative beam energies are accurate to within ±20 keV. Triton energy spectra were recorded with a conventional ΔE-E counter telescope with an over-all energy resolution of about 100 keV full width at half maximum (FWHM). A typical triton energy spectrum is shown in Fig. 1, while the angular distributions and excitation functions appear in Figs. 2 and 3, respectively. The error bars shown with these data points reflect only errors arising from extraction of peak areas. These errors include an estimate of the adverse effect of high background levels.

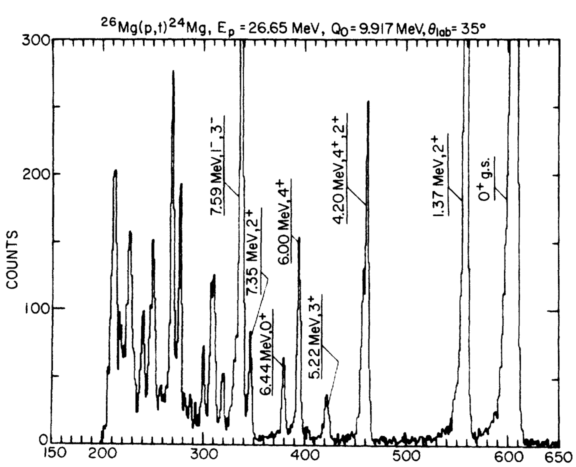

FIG. 1. Typical triton energy spectrum for the reaction ^{26}Mg$(p,t)^{24}$Mg at a proton energy of 26.65 MeV. The excitation energies, total angular momentum, and parity for the final ^{24}Mg state corresponding to each group are indicated. These values are from other work and are well documented.

III. DWBA CALCULATIONS

Several representative distorted-wave Born-approximation (DWBA) calculations are shown with the experimental angular distributions in Fig. 2. They are presented merely to illustrate the general trends with angle predicted by the type of DWBA analysis of the (p, t) reaction generally found in the literature.[12] Here, as in most studies, both the nuclear wave functions and the proton-neutron interaction are greatly simplified. Specifically, the neutron wave functions are taken to be single shell-model configurations, and the proton-neutron interaction is taken to be of zero range between the proton coordinate and the center-of-mass coordinate of the neutron pair in an S state of relative motion.[13] It is worth noting that for our purposes, the assumption of a simple, single-configuration neutron wave function, namely $1d_{5/2}$, has some justification. Our interest in the DWBA calculations lay only in the shapes of the calculated angular distributions. Calculations performed for the $L=0$ g.s. transition with $(1d_{5/2})^2$, $(1d_{3/2})^2$, and $(2s_{1/2})^2$ neutron configurations revealed only slight modification of the shapes of the DWBA curves due to the resultant differences in the form factors.

The actual numerical calculations were carried out using a recent version of the code DWUCK.[14] The optical-model potentials employed in these calculations were chosen so that the radii of the real potential wells for protons and tritons corresponded closely with those of potentials selected by Baer *et al.*[15] in a study of the (p, t) reaction on the even Ti isotopes at $E_p = 27$ MeV. These potentials along with the potential which generates the bound-state neutron wave functions are given in Table I. Note that the depth of the neutron well was adjusted to give a single neutron binding energy of $0.5(|S_n| + E_x)$, where S_n is the g.s. two-neutron separation energy and E_x is the excitation energy of the residual nucleus.

IV. DISCUSSION OF RESULTS

Examination of the angular distributions displayed in Fig. 2 reveals immediately that the transitions to the 0^+ g.s. and the 1.37-MeV 2^+ state possess the familiar diffractionlike pattern suggestive of the usual direct-reaction process. This diffraction-type structure becomes much less pronounced for transitions to higher-lying states: With the exception of the 6.44-MeV 0^+ state, the angular distributions for these excited states are indeed relatively flat and featureless. Furthermore, in contrast to known systematics of (p, t) angular distributions for direct single-step processes involving a given L transfer,[15,16] the shapes of the angular distributions for the 6.44-MeV 0^+ and 7.35-MeV 2^+ transitions bear little resemblance to their lower-lying counterparts, the 0^+ g.s. and 1.37-MeV 2^+ transitions, respectively. Both these higher-lying transitions show pronounced backward-angle peaking. This rearward enhancement becomes more dramatic when the angular distributions are compared with the distorted-wave calculations (Fig. 2). Whereas the DWBA calculations reproduce the general trend of the cross sections in moving from forward to backward angles for the first two (0^+ g.s. and 1.37-MeV 2^+) transitions, they drastically underestimate the backward-angle cross sections for the 6.44- and 7.35-MeV states. The magnitudes of these backward-angle enhancement effects for all the transitions can be ascertained by examining Table II where the total cross sections, as well as the cross sections integrated over the forward and backward hemispheres individually, are listed and compared with that of the ground-state transition. The table shows that while for the ground-state and first-excited-state transitions, the integrated cross sections drop by factors of 5 to 10 in going to the backward hemisphere, the drop for higher-lying transitions is reduced to factors of 2 or less. This enhancement in the backward hemisphere strongly suggests that perhaps mechanisms other than single-step DWBA processes account for appreciable contributions to the higher-lying transitions.

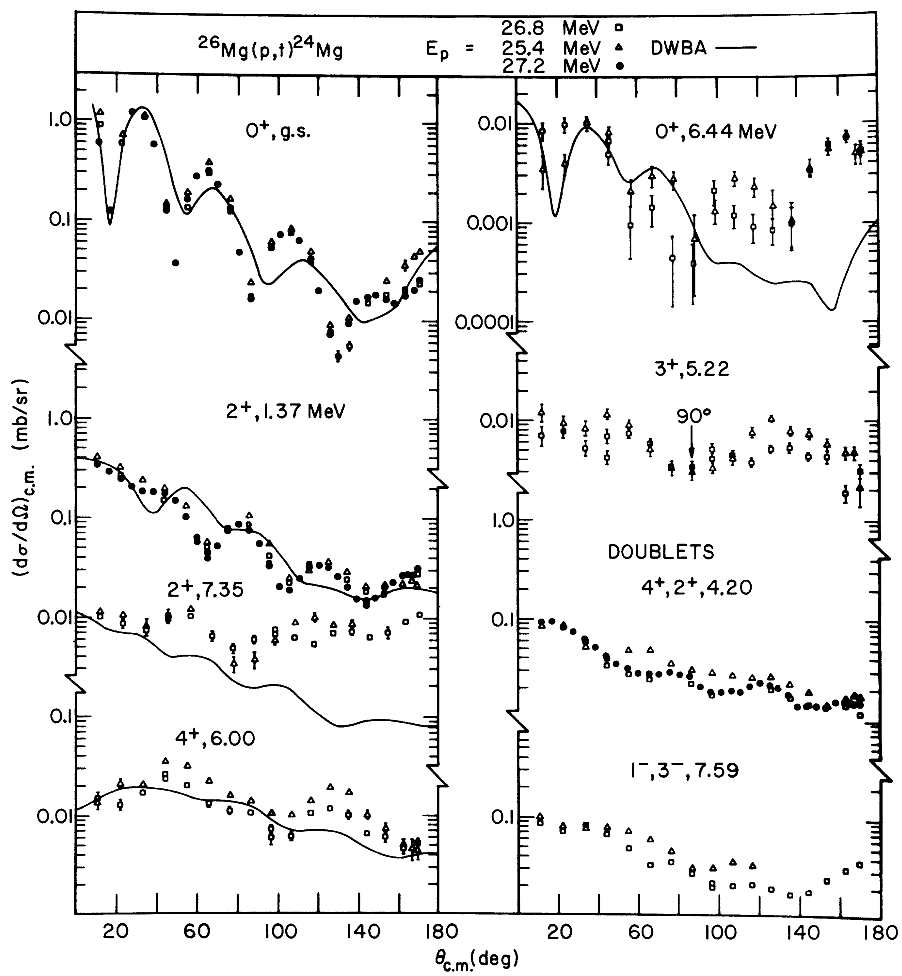

FIG. 2. Angular distributions at two (in some cases, three) incident proton energies for the first eight triton groups in the reaction ^{26}Mg$(p,t)^{24}$Mg. The solid curves indicate the renormalized results of DWBA calculations made for a proton energy of 26.8 MeV. The parameters used in the DWBA calculations appear in Table I.

If compound-nuclear effects are present and if the statistical theory of the compound nucleus[17] can be applied to this reaction, then the fluctuations in the excitation functions are expected to occur with widths (FWHM) of ~250 keV. This prediction is based on the analysis given by Ericson and Meyer-Kuckuk[17] and applied to ^{27}Al at ~35-MeV excitation. Inspection of the measured excitation functions in Fig. 3 shows that as a group the curves exhibit a smooth energy dependence. Certainly a greater percentage of the excitation curves would exhibit a discontinuous energy dependence if the data were sampling excitation curves with sharp resonances having FWHM of ~250 keV and amplitudes much larger than 25% of the mean cross section. Relating this amplitude to a ratio of direct-to-compound-nuclear cross sections is an uncertain procedure,[17] but it does suggest that such a process as falls under the purview of the statistical theory of the compound nucleus contributes significantly less to the transitions than does a direct mechanism.

In this discussion of compound-nucleus effects it should be noted that the excitation functions do, in some cases (e.g., the 1.37-MeV 2^+), exhibit slight fluctuations with a width of about 1.5 MeV, much larger than that predicted by a statistical model. These fluctuations generally have an amplitude of less than 30% of the average cross section. The width of these fluctuations remains unexplained and again, interpretation of the amplitudes in terms of the relative strengths of compound-nuclear and direct processes is quite difficult. It is worth noting that the amplitude of these fluctuations is no greater for the transition to the 5.22-MeV 3^+ state than for any of the other transitions, although the simple single-step direct process is forbidden, and hence alternative processes, including compound nuclear, are expected to have their greatest relative strength. This can be in-

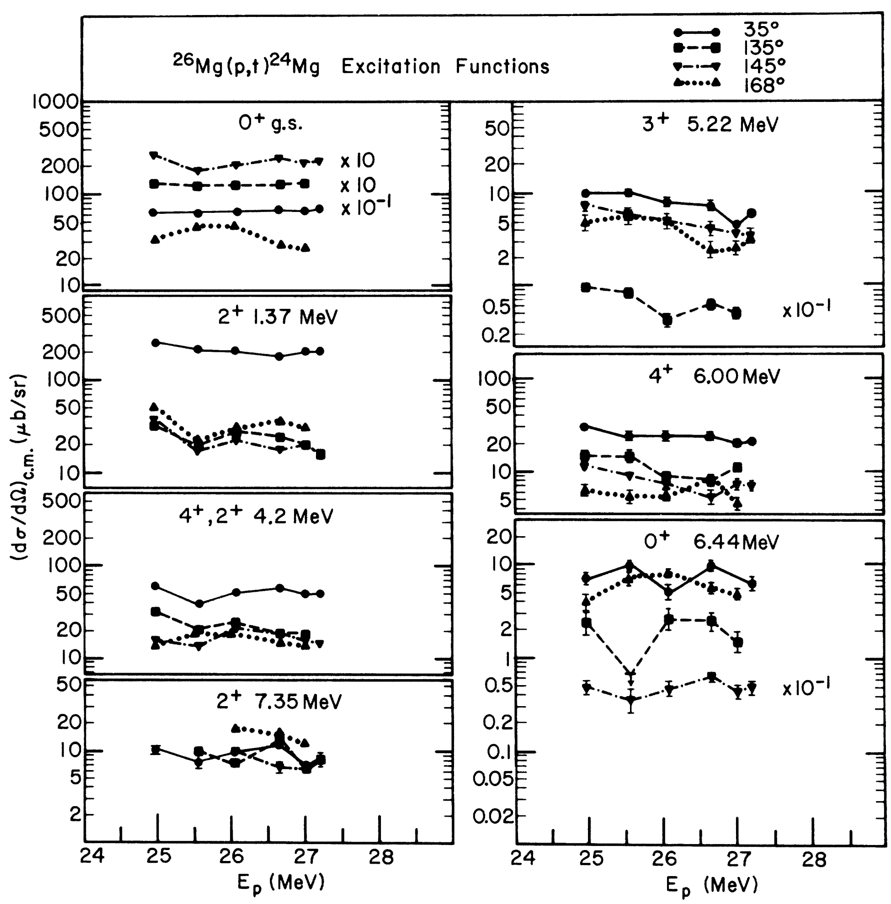

FIG. 3. Excitation functions for the first seven triton groups in the reaction ^{26}Mg(p,t)^{24}Mg as measured at several angles. The relatively large drop in the $\theta_{c.m.} = 135°$ cross section for the transition to the 6.44-MeV 0^+ state in ^{24}Mg is probably due to the steep angular dependence of this cross section in this region and its consequent sensitivity to kinematic shifts in the cross section.

TABLE I. Optical-model potentials used in calculations. The analytic form of these potentials is:

$$U(r) = -V\frac{1}{e^{X}+1} - i\left(W - 4W_D\frac{d}{dx}\right)\frac{1}{e^{X}+1} + \frac{\hbar}{(m_\pi c^2)^2}V_{so}\vec{\sigma}\cdot\vec{l}\,\frac{1}{r}\frac{d}{dr}\frac{1}{e^{X_{so}}+1} + V_e\,,$$

$$V(r) = -V\frac{1}{e^{X}+1} + \left(\frac{\lambda}{45.2}\right)V\frac{1}{r}\,\vec{l}\cdot\vec{s}\,\frac{d}{dr}\frac{1}{e^{X}+1} + V_C\,,$$

where

$$\chi = (r - r_0A^{1/3})/a_0,\quad \chi = (r - rA^{1/3})/a,\quad \chi_{so} = (r - r_{so}A^{1/3})/a_{so}\,.$$

	V	r_0	a_0	W	W_D	r^1	a^1	V_{so}	r_{so}	a_{so}
$U(r)$ proton [a]	−50.2	1.121	0.674	−4.28	3.42	1.326	0.546	−6.56	0.899	0.665
$U(r)$ triton [b]	−164.0	1.14	0.690	−14.7	...	1.600	1.08	...	...	
$U(r)$ bound state	−50.03	1.25	0.650	...	...	...	...	...	...	

[a] G. R. Satchler, Nucl. Phys. A92, 273 (1967).
[b] R. W. Zurmühle and C. M. Fou, Nucl. Phys. A129, 502 (1969).

terpreted as indicating that compound-nuclear processes are not predominating in these reactions, but that some other non-single-step process is significant.

Change in the shapes of angular distributions with relatively small changes in bombarding energies is another sensitive indicator of compound-nuclear processes.[17] In Fig. 2 angular distributions taken at two (in some cases, three) different beam energies are overlayed with no renormalization between runs. The changes of shape due to change in beam energy is seen to be relatively minor except possibly in two cases. The angular distributions for the 4.20- and 7.59-MeV doublets appear to change phase in the region 40–120° in in going from 26.8- to 25.4-MeV beam energies. These facts seem to warrant little emphasis because these phases are barely discernible in what are basically quite featureless shapes. The second exception is the drop in magnitude by a factor of ~5 of the first two points in the 6.44-MeV 0^+ angular distribution seen in going from the higher to the lower incident energy. This effect is due to

TABLE II. The experimental cross sections for the first eight triton groups in the reaction $^{26}Mg(p,t)^{24}Mg$ at $E_p = 26.8$ MeV have been integrated over 0–90, 90–180, and 0–180°. The results appear below. The units of σ are μb.

State (MeV)	$\sigma_{0-90°}$	$\sigma_{90-180°}$	$\sigma_{T(0-180°)}$
g.s. 0^+	1864.0	218.0	2083.0
1.37 2^+	765.0	177.0	942.0
4.2 4^+, 2^+	244.0	108.0	352.0
5.22 3^+	32.9	28.5	61.4
6.00 4^+	97.4	49.6	147.0
6.44 0^+	22.0	13.5	35.5
7.35 2^+	46.5	42.1	88.6
7.59 1^-, 3^-	326.0	141.0	467.0

the presence of a deep local minimum at about 17° (c.m.). Distorted-wave calculations have shown that this minimum is sufficiently kinematically sensitive to cause the observed fluctuation in the cross section.

The excitation of the 5.22-MeV 3^+ state requires the presence of processes other than those described by the usual DWBA calculation. As indicated earlier, a direct transition to the 5.22-MeV 3^+ state could be explained in the DWBA formalism by spin transfer in the actual pickup of the two neutrons due to an $S=1$ dineutron component in the triton. The spin-transfer process can be treated straightforwardly by DWBA techniques; it is of course a major factor in the $(p, {}^3He)$ reaction mechanism. With the usual form for spin-orbit forces,[18] the two possible L components of the reaction add incoherently. Thus, if the 3^+ level were excited by an $S=1$ dineutron transfer, the shape of the resultant angular distribution would be the straight sum of an $L=2$ shape and an $L=4$ shape. Our own DWBA calculations show that the shape of the angular distributions for a given L transfer are insensitive to the values of S or J. Given this fact and the assumption that there is some constancy of shape for given L transfers,[15] we anticipated that by combining experimentally determined $L=2$ and $L=4$ shapes, using relative strengths determined by DWBA calculations, we might reproduce the $J=3$ shape. Alternatively, upon seeing that the actual shape of the 3^+ angular distribution differed from such a prediction, we might conclude that such a spin-transfer process cannot be the dominant reaction mode.

Initially, DWBA calculations gave hope that such an approach might be fruitful. They suggested that the $L=2$ component of the transition to the 3^+ state should be 15 to 20 times as great as the $L=4$ component, thus predicting that the angular distribution for the 5.22-MeV 3^+ transition should have an $L=2$ shape if spin transfer were the dominant reaction mode. The computed ratio of $L=2$ to $L=4$ strength for this reaction mechanism is of course dependent on the neutron single-particle configurations used in computing the form factors. Here a simple $(1d_{5/2})^2$ confuguration was assumed. However, it seems unlikely that employing more-detailed wave functions in the form-factor calculation could alter the basic conclusion of a predominantly $L=2$ shape. Of course the reaching of any conclusions using this procedure depended upon being able to distinguish between $L=2$ and $L=4$ shapes as given by the data. Figure 2 shows that the $L=2$ and $L=4$ angular distributions nearest in excitation energy to the 3^+ state, namely the 7.35-MeV 2^+ and the 6.00-MeV 4^+, have almost identical shapes. Further, these shapes are very much like that of the 3^+ angular distribution. Thus this line of reasoning does not lead to a concrete conclusion about the likelihood of a spin-transfer mechanism being the dominant reaction mode exciting the 5.22-MeV 3^+ state.

However, arguments based on the magnitude of the cross section for the transition to the 5.22-MeV 3^+ state do suggest that spin transfer is not the mechanism operating here, since what little experimental information exists concerning the absolute magnitude of this process shows that the effect is probably too small to account for the large 3^+ cross section. The experimentally measured magnitude of this cross section is 30–50% of that for the nearby 6.00-MeV 4^+ transition and 5–10% of that for the 0^+ g.s. transition. Recent work by Peterson and Rudolph[19] has given some estimate of the magnitude of spin-transfer effects for a transition in the reaction ^{57}Fe$(p,t)^{55}$Fe at $E_p=27$ MeV from a $\frac{1}{2}^-$ state to a $\frac{1}{2}^-$ state. They estimated that the spin-flip contribution to the cross section was less than 5% of the total. Although interpretation of this number, not to mention extrapolation down to the mass region of $A=24$, is questionable, their results seem to indicate that spin transfer alone cannot account for the excitation of the 5.22-MeV 3^+ state.

On the other hand such magnitude arguments as are mentioned above in no way preclude the interpretation that the excitation of the 5.22-MeV 3^+ state proceeds largely through multistep direct processes. Ascuitto, Glendenning, and Sorensen[1] have shown that multistep processes have a large effect on both the shapes and magnitudes of angular distributions resulting from the (p,t) reaction at 20 MeV on the highly deformed nucleus ^{176}Yb. Using the same approach Ascuitto and Glendenning[2] have predicted that even for the moderately collective nucleus ^{62}Ni multistep effects can enhance the cross sections by a factor of 2 or more over standard DWBA predictions. It is interesting that work by Penny[20] shows that the expected increase in cross section for the (p,d) reaction on nuclei in the Ni region is only 10% or so, down by an order of magnitude for the effect predicted for the (p,t) reaction. An investigation of the reaction ^{24}Mg$(d,p)^{25}$Mg by Braunschweig, Tamura, and Udugawa[21] concluded that in that reaction multistep effects enhanced the cross section by a factor of 2, an increase of an order of magnitude compared with the Ni region. These facts taken together suggest that multistep effects may enhance cross sections very strongly for the reaction ^{26}Mg$(p,t)^{24}$Mg. Perhaps these effects are strong enough to account for the moderately strong transition to the 5.22-MeV 3^+ state.

V. CONCLUSION

The results presented here comprise a comprehensive study of the reaction ^{26}Mg$(p,t)^{24}$Mg in the 25- to 27-MeV energy range. The DWBA formalism is seen to predict the general features of the experimental angular distributions only for those transitions leading to states of low excitation energies. Strong backward-angle enhancement of the differential cross sections is observed for transition to higher-lying (>5-MeV) states. The failure of the standard DWBA theory to describe this enhancement phenomenon, as well as the "forbidden" excitation of an unnatural-parity state, implies that non-DWBA processes are important in this reaction.

An attempt has been made to determine from the data which reaction mode, from among compound-nuclear, spin-transfer, or multistep direct processes, plays the dominant role in the reaction. Interpretation of the excitation functions and the energy dependence of the shapes of the angular distributions is somewhat ambiguous, but suggests that while some compound-nuclear effects may be present, they do not dominate the reaction; certainly they do not have the importance here that they must have in the similar two-neutron-pickup reaction ^{26}Mg$(\alpha, ^6$He$)^{24}$Mg at $E_\alpha=35$ MeV.[11] Recent work[22] has shown that at $E_p=35$ MeV unnatural-parity states are strongly excited in the reaction ^{30}Si$(p,t)^{28}$Si. Of interest is that at this higher energy the relative strengths of the unnatural-parity transitions are comparable to the relative strength of the 3^+ transition observed here for ^{24}Mg at 27 MeV. Furthermore, the angular distributions for the strong 3^+ transition in both nuclei have the same featureless shapes at the two bombarding energies. Interpretation of the data under the assumption of a spin-transfer mechanism, especially as they might account for the excitation of the 5.22-MeV 3^+ state, is likewise somewhat ambiguous. However, arguments have been presented which make this reaction mode an unlikely possibility because of the relatively large magnitude of the cross section for the 3^+ transition.

At present multistep processes appear to us to be the most likely explanation for the excitation of the 3^+ state. The large magnitude of these effects even for nuclei which are much less collective than Mg suggests that the strength of the 3^+ transition may be explained within this framework. It will be of interest to see if multistep processes can accurately describe other features of the reaction leading to this state, especially the shape of the angular distribution. Perhaps a multistep formalism will also be able to account for the backward-angle enhancement of the transitions leading to the higher-lying states of ^{24}Mg.

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