(He^4,t) Reaction on Medium-Weight Nuclei*

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A 26.7-MeV beam of He^4 ions from the Los Alamos variable-energy cyclotron was used to study the (He^4,t) reaction on Cr^{52}, Fe^{54}, Fe^{56}, Fe^{58}, Co^{59}, Ni^{60}, Ni^{62}, and Ni^{64}. Angular distributions of tritons from the more strongly excited states of the residual nuclei were obtained over the angular range of $11° \lesssim \theta_{c.m.} \lesssim 48°$. There are marked differences between distributions from $\frac{3}{2}^-$ states and $\frac{1}{2}^-$ states, and between distributions from $\frac{7}{2}^-$ states and $\frac{5}{2}^-$ states. The behavior of the distributions also appears to depend strongly upon the Q of the reaction. The experimental results are compared to the predictions of a spin-independent distorted-wave calculation. Although such a calculation cannot reproduce the j-dependent behavior of the distributions, the extracted spectroscopic factors are usually in acceptable agreement with those obtained from recent (He^3,d) reaction studies on these nuclides, and thus a meaningful comparison of the results from the (He^4,t) and (He^3,d) reaction studies can be made. This provides evidence that under the conditions of the studies, core-excitation mechanisms are relatively unimportant.

I. INTRODUCTION

NO extensive experimental study of the (He^4,t) reaction has been reported in the literature. The information[1–5] that does exist is restricted primarily to the region of light nuclei. Although the mechanism of the reaction is not well understood, the interpretation of the related (He^3,He^4) reaction has usually been in terms of the direct-interaction stripping mechanism, at least for incident energies above 10 MeV. It is of interest to examine the behavior of the (He^4,t) reaction more thoroughly, particularly in the medium-mass region where the application of the distorted-wave (DW) theory has met with general success for stripping reactions. Initially, it seems useful to investigate the reaction for cases which previously have been studied by means of the (d,n) or (He^3,d) reactions, since it is then possible to make direct comparisons to those results. By means of these comparisons, one may be able to gain information concerning the nature of the (He^4,t) reaction mechanism, and consequently assess the utility of the reaction as a spectroscopic tool.

In the present paper we report the results of an experimental investigation of the (He^4,t) reaction on Cr^{52}, Fe^{54}, Fe^{56}, Fe^{58}, Co^{59}, Ni^{60}, Ni^{62}, and Ni^{64}. These same nuclides recently have been the subjects of (He^3,d) reaction studies.[6–9] We have focused our attention on transitions to some of the low-lying (usually the most strongly excited) states of the residual nuclei. The triton angular distributions from these states were compared to the predictions of the DW programs T-SALLY[10] and JULIE,[11] and the resulting spectroscopic information was compared to similar information obtained by means of the (He^3,d) reaction.

II. EXPERIMENTAL PROCEDURE

The experimental arrangement has been discussed previously.[8] Briefly, a 26.7-MeV α-particle beam from the Los Alamos variable energy cyclotron was momentum analyzed, passed through the thin targets and stopped in a Faraday cup. The charged reaction products were detected in a ΔE-E semiconductor detector assembly, and the preamplified pulses were fed into a mass-identification system. Parallel circuitry provided amplification and coherent addition of the ΔE and E pulses; the summed pulses were then fed into a 400-channel pulse-height analyzer gated by the output of the mass-identification system. The resulting spectra were analyzed by a least-squares computer program[12] which fits a skewed Gaussian distribution plus an exponential tail to each peak in a pulse-height spectrum and computes the area of the peak.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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[2] N. A. Vlasov, S. P. Kalinin, A. A. Ogloblin, and V. I. Chvev, Zh. Eksperim. i Teor. Fiz. **39**, 1468 (1960) [English transl.: Soviet Phys.—JETP **12**, 1020 (1961)].

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[9] A. G. Blair and E. R. Flynn, Bull. Am. Phys. Soc. **10**, 495 (1965).

[10] We are indebted to R. M. Drisko and R. H. Bassel for providing us with this code.

[11] We are indebted to R. H. Bassel for providing us with the predictions of the DW calculation using the code JULIE.

[12] P. T. McWilliams, W. S. Hall, and H. E. Wegner, Rev. Sci. Instr. **33**, 70 (1962); W. S. Hall (private communication).

The targets were prepared from isotopically enriched material.[13] The thin (200 to 400 $\mu g/cm^2$) nickel and chromium foils were prepared by vacuum evaporation and the thick (1 to 1.5 mg/cm^2) iron foils by electroplating. The isotopic purity of the target material was 99.9% for Cr^{52}, 99.9% for Fe^{56}, 91.7% for Fe^{58}, 99.8% for Ni^{60}, 98.7% for Ni^{62} and 98.6% for Ni^{64}. The over-all energy resolution of the triton particle spectra was a function of the detector geometry and target thickness and varied between 70 and 90 keV for the thin targets and 100 and 120 keV for the thick targets.

III. RESULTS

A typical energy spectrum is shown in Fig. 1. The angular distributions of the states studied in the present experiment are shown in Figs. 2 and 3. Known spins and parities[14–16] are indicated, while the values shown in parentheses are, with one exception, those indicated by recent experimental studies.[6–8] The exception is the assignment to the 2.69-MeV state of Mn^{53}, discussed later in this report.

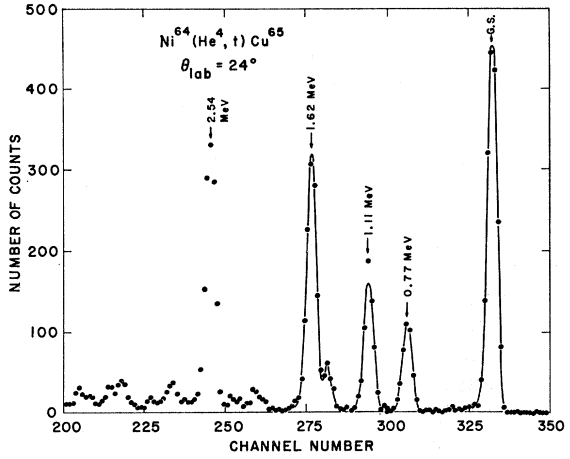

FIG. 1. Pulse-height spectrum of the tritons from the Ni^{64}-$(He^4,t)Cu^{65}$ reaction. The solid line drawn through the points is the result of a least-squares computer routine which fits a skewed Gaussian distribution with an exponential tail to specified peaks in the pulse-height spectrum.

In the previously reported (He^3,d) reaction studies,[6–8] it was established that there were no significant differences in the forward-angle regions between the shapes of the distributions for $p_{3/2}$ and $p_{1/2}$ proton transfers. Only at angles larger than approximately 50° did the observed angular distributions of $p_{3/2}$ transitions differ from those of $p_{1/2}$ transitions. In contrast to this behavior, the (He^4,t) reaction yields rather striking forward-angle differences between transitions to $\frac{3}{2}^-$ states and $\frac{1}{2}^-$ states, as can be seen in Fig. 2. Furthermore, as one proceeds from case to case, the behavior of these distributions varies considerably.

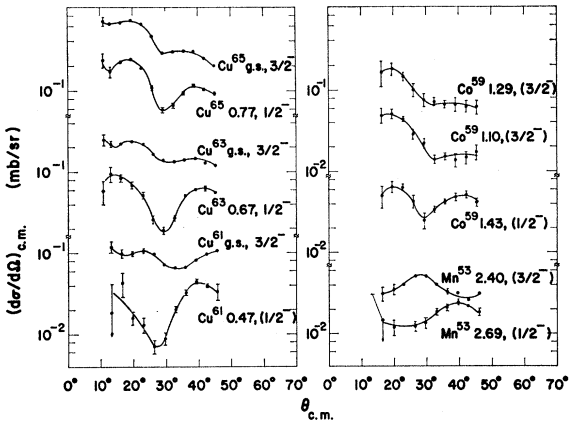

FIG. 2. Summary of the angular distributions corresponding to probably $\frac{3}{2}^-$ and $\frac{1}{2}^-$ transitions. The final state is indicated at the right of each curve. The cross-section scale appropriate for each distribution is the one adjacent to its most forward-angle data points. The lines drawn through the data points are intended as visual guides.

For transitions to $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states, the (He^3,d) reaction yielded some differences in the forward-angle distributions. These differences were most noticeable in the (He^3,d) reaction on Ni^{62} and Ni^{64}, where the final states in Cu^{63} and Cu^{65} lie at nearly the same excitation energy. In the scattering angle region of 30°–40°, the $\frac{7}{2}^-$ distributions peaked out farther in angle than the $\frac{5}{2}^-$ distributions. Some differences were also noted at more forward angles, but there the statistical errors, particularly for the $\frac{7}{2}^-$ distributions, were too large to

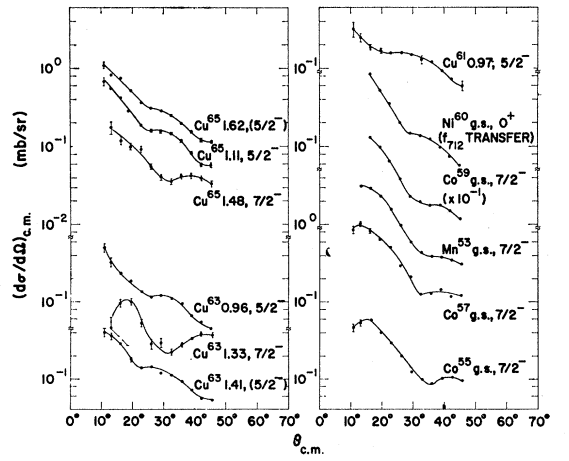

FIG. 3. Summary of the angular distributions corresponding to probably $\frac{7}{2}^-$ and $\frac{5}{2}^-$ transitions. The final state is indicated at the right of each curve. The cross-section scale appropriate for each distribution is the one adjacent to its most forward-angle data points. The lines drawn through the data points are intended as visual guides.

[13] The target material was obtained from Oak Ridge National Laboratory, Isotopes Division, Oak Ridge, Tennessee.

[14] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1961), NCR 60-4-27.

[15] B. Elbek, H. E. Gove, and B. Herskind, Kgl. Danske Videnskab. Selskab, Mat Fys. Medd. **34**, No. 8 (1964).

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TABLE I. Display of the apparent Q dependence and j dependence of the positions of the relative maxima and minima in the experimental distributions.

Assumed J^π transfer	Final state	(MeV)	Q (MeV)	θ_{max1}	θ_{min}	θ_{max2}
$\frac{1}{2}^-$	Cu^{65}	0.77	−13.12	17°	30°	40°
	Co^{59}	1.43	−13.83	20°	30°	41°
	Cu^{63}	0.67	−14.35	14°	29°	41°
	Cu^{61}	0.47	−15.51	...	27°	40°
	Mn^{53}	2.69	−15.90	...	25°	40°
$\frac{3}{2}^-$	Cu^{65}	g.s.	−12.35	(18°)	30°	36°
	Co^{59}	1.10	−13.50	19°	32°	(40°)
	Cu^{63}	g.s.	−13.68	20°	32°	39°
	Co^{59}	1.29	−13.69	20°	(32°)	(39°)
	Cu^{61}	g.s.	−15.04	23°	34°	(46°)
	Mn^{53}	2.40	−15.46	28°	42°	>46°
$\frac{5}{2}^-$	Cu^{65}	1.11	−13.46	<11°	(24°)	(28°)
	Cu^{65}	1.62	−13.97	<11°	(24°)	(27°)
	Cu^{63}	0.96	−14.64	<11°	(26°)	(29°)
	Cu^{63}	1.41	−15.09	<11°	23°	26°
	Cu^{61}	0.97	−16.01	<11°	23°	26°
$\frac{7}{2}^-$	Ni^{60}	g.s.	−10.27	<16°	(29°)	(31°)
	Co^{59}	g.s.	−12.40	<16°	(35°)	(30°)
	Mn^{53}	g.s.	−13.24	14°	(36°)	(39°)
	Cu^{65}	1.48	−13.83	(14°)	32°	39°
	Co^{57}	g.s.	−13.84	<16°	33°	39°
	Co^{55}	g.s.	−14.76	15°	36°	42°
	Cu^{63}	1.33	−15.01	18°	32°	44°

permit meaningful comparisons. In the present (He^4,t) reaction studies, there are more obvious differences between the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ distributions for these two nuclides (see Fig. 3). In every case the $\frac{5}{2}^-$ distributions are shifted inward relative to the $\frac{7}{2}^-$ distributions.

In order to determine any systematics of the behavior of the angular distributions shown in Figs. 2 and 3, we have examined them as a function of Q. In Table I, transitions are grouped according to spin and parity transfer, then within each spin and parity group according to increasingly negative Q's. Table I also lists approximate positions of observed maxima and minima as obtained from Fig. 2. Reference to Figs. 2 and 3 shows that there is obvious difficulty in locating these positions, and in some instances (e.g., $\frac{7}{2}^-$ transitions) as one follows a maximum or minimum from case to case it becomes only a point of inflection. For these cases, and for others in which the maxima and minima are especially poorly defined, the estimated positions are shown in parentheses. Some regularities and trends appear in the table. For example, there are three $\frac{3}{2}^-$ transitions (in two nuclei) with $Q \approx -13.6$ MeV, and the positions of the maxima and minima are nearly the same in each distribution. For the $\frac{3}{2}^-$ transitions as a group, however, there appears to be a shift toward larger angles as the Q becomes more negative. The same tendencies appear in the $\frac{7}{2}^-$ group. Here there are two cases (in two nuclei) for which we have $Q \approx -13.8$ MeV, and the minimum and the second maximum are in approximately the same position. Within the entire $\frac{7}{2}^-$ group, there also seems to be a shift toward larger angles with increasingly negative Q.

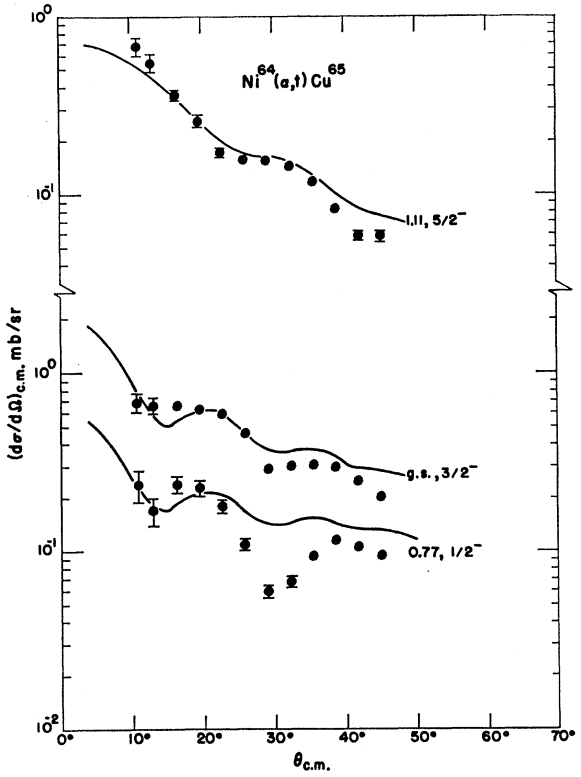

FIG. 4. Comparison for the Ni^{64}(He^4,t)Cu^{65} reaction of the results of the T-SALLY DW calculation (see text) to typical angular distributions corresponding to $\frac{5}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$ transitions.

Within the $\frac{1}{2}^-$ and the $\frac{5}{2}^-$ groups, the distribution shifts with change in Q are less apparent, but there seems to be a tendency for the patterns to shift toward smaller angles as the Q becomes more negative.

Although the evidence in Table I is meager, the positions of the minima and maxima do not appear to depend strongly upon the mass of the nucleus. Examination of the $\frac{3}{2}^-$ and $\frac{7}{2}^-$ distributions discussed above indicates, however, that for a given Q the average slope of a distribution is quite dependent upon the mass, becoming less steep as the mass increases.

The results of the Cr^{52}(He^3,d)Mn^{53} reaction study[6] showed clearly that both the 2.69 and 2.40 MeV states in Mn^{53} were $l=1$ in character. The sum rules that were applied indicated that the assumption of a spin and parity of $\frac{3}{2}^-$ for each state was reasonable, but they did not exclude a $\frac{1}{2}^-$ assignment to the 2.69-MeV state. The present study yields angular distributions of tritons from these states which are out of phase in the forward-angle region by nearly a half-cycle (see Fig. 2.) The systematics of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ distributions in the present study suggest that the spin and parity of the 2.40- and 2.69-MeV states are $\frac{3}{2}^-$ and $\frac{1}{2}^-$, respectively.

Figures 4 and 5 show comparisons of some of the experimentally determined distributions to the results of a T-SALLY DW calculation.[10] The spin-independent

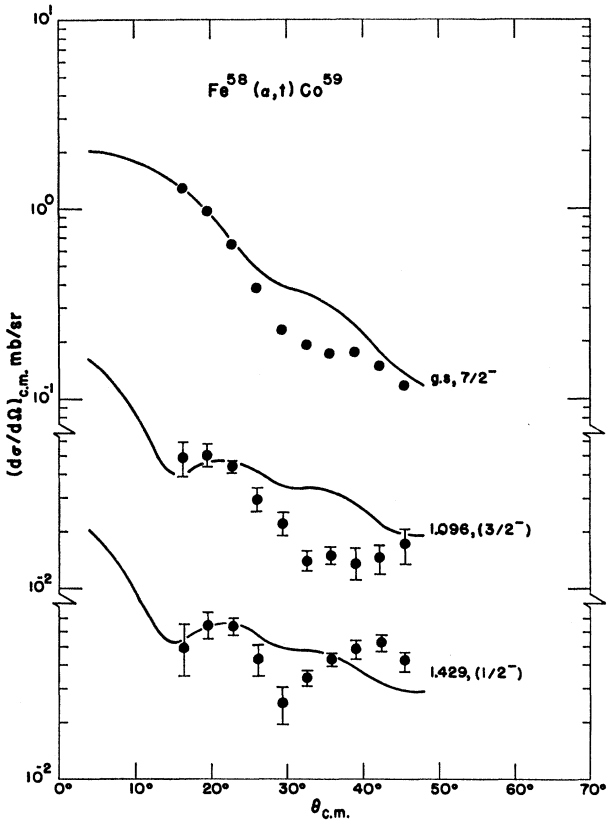

FIG. 5. Comparison for the Fe^{58}(He^4,t)Co^{59} reaction of the results of the T-SALLY DW calculation (see text) to typical angular distributions corresponding to $\frac{7}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$ transitions.

calculation was for a zero range of interaction,[17] and for a binding energy of the captured proton equal to its separation energy. These are the same assumptions that were made in the (He^3,d) reaction studies.[6–8,18] The optical-model parameters used in the calculation for the comparisons in Figs. 4 and 5 are given in Table II. The He^4 parameters are those of McFadden and Satchler[19]; identical geometry is assumed for the Woods-Saxon wells used for the real and imaginary potentials. The triton parameters are based on elastic scattering of 15- and 20-MeV tritons[20] from Cr^{52} and Ni^{62}.

TABLE II. Values of the optical-model parameters and the formula for the potential well that was used in the DW calculation.[a]

Particle	V_0 (MeV)	W (MeV)	r_0 (F)	a (F)	r_0' (F)	a' (F)	r_c (F)
Triton	127	22.4	1.15	0.794	1.51	0.790	1.40
He^4 ion	198.6	19.9	1.458	0.502	1.458	0.502	1.30

[a] $V(V_0,w,x,x') = V_0 f(x) - iWf(x')$, where $x = (r - r_0 A^{1/3})/a$ and $f(x) = (1+e^x)^{-1}$ is the Woods-Saxon form factor.

[17] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240 (unpublished).
[18] A. G. Blair and D. D. Armstrong, Phys. Rev. Letters **16**, 57 (1965).
[19] L. McFadden and G. R. Satchler, Nucl. Phys. **84**, 177 (1966).
[20] A. G. Blair, J. C. Hafele, and D. D. Armstrong, Bull. Am. Phys. Soc. **11**, 98 (1966).

TABLE III. Values of C^2S from the present study of the (He^4,t) reaction and their comparison to the values previously obtained from a study of the (He^3,d) reaction.

Residual nucleus	Excitation energy (MeV)	J^π	C^2S (He^4,t)	C^2S (He^3,d)
Cu^{65}	g.s.	$\frac{3}{2}^-$	0.79	0.79
	0.77	$\frac{1}{2}^-$	1.00	0.75
	1.11	$\frac{5}{2}^-$	0.38	0.26
	1.48	$\frac{7}{2}^-$	0.07	0.05
	1.62	$(\frac{5}{2}^-)$	0.91	0.57
	2.54	$(\frac{9}{2}^+)$	0.35	0.29
Cu^{63}	g.s.	$\frac{3}{2}^-$	0.56	0.66
	0.67	$\frac{1}{2}^-$	0.76	0.70
	0.96	$\frac{5}{2}^-$	0.40	0.33
	1.33	$\frac{7}{2}^-$	0.10	0.06
	1.41	$(\frac{5}{2}^-)$	0.68	0.45
	2.51	$(\frac{9}{2}^+)$	0.28	0.31
Cu^{61}	g.s.	$\frac{3}{2}^-$	0.59	0.72
	0.47	$(\frac{1}{2}^-)$	0.99	0.80
	0.97	$\frac{5}{2}^-$	0.86	0.83
Ni^{60}	g.s.	0^+	4.7	4.7
Co^{59}	g.s.	$\frac{7}{2}^-$	0.19	0.17
	1.10	$(\frac{3}{2}^-)$	0.08	0.11
	1.29	$(\frac{3}{2}^-)$	0.26	0.34
	1.43	$(\frac{1}{2}^-)$	0.29	0.37
Co^{57}	g.s.	$\frac{7}{2}^-$	0.17	...
Co^{55}	g.s.	$\frac{7}{2}^-$	0.21	0.22
Mn^{53}	g.s.	$\frac{7}{2}^-$	0.47	0.47
	2.40	$(\frac{3}{2}^-)$	0.19	0.45
	2.69	$(\frac{1}{2}^-)$	0.24	0.22

A cutoff radius of 5.1 F was used for all of the nuclides. For the heavier elements, a variation of this radius from 4.3 to 5.6 F did not appreciably affect the amplitude and shape of the distributions. For Mn^{53}, however, a small change in this radius changed the distribution materially. For example, a change from 4.3 to 4.5 F changed the amplitude by approximately 25%.

Figure 4, showing the results of the DW calculation compared to the Ni^{64}(He^4,t)Cu^{65} reaction distributions, exemplifies the best agreement between the calculation and the experimental data; Fig. 5 exemplifies the worst. Several families of both He^4-ion and triton parameters were also tried with no qualitative difference in the shapes of the predicted distributions. Of course, there is nothing in the present calculation that will produce a j dependence for the angular distributions. One might expect that the introduction of spin-orbit interactions into the calculation would yield such a dependence. In addition, one might consider that a choice of bound-state wave functions different for a $j=l+\frac{1}{2}$ state than for a $j=l-\frac{1}{2}$ state would yield different shapes for the respective angular distributions. To test this latter assumption, the radius of the bound-state well for f protons, and also for p protons, in Cu^{65} was changed in accord with the Pinkston-Satchler formalism[21]; the resulting angular distributions were essentially unaltered.

Because the T-SALLY DW angular distributions do

[21] E. G. Pinkston and G. R. Satchler, Nucl. Phys. **72**, 643 (1965).

not represent the experimental data very well, large uncertainties must be associated with the extraction of spectroscopic factors. Table III shows the results obtained, compared to the values previously obtained from studies of the (He^3,d) reaction. The method used to extract the spectroscopic factors is essentially identical to that discussed in Ref. 6. In general, the present values were obtained from a comparison between the DW predictions and the experimental distributions in the region of the most forward-angle maximum. However, the correspondence of the predicted distributions to the experimental distributions was so poor for some of the $\frac{1}{2}^-$ states that a visual "best-fit" comparison was used. As can be seen from Figs. 4 and 5 such a procedure is a highly subjective one.

The relationship between the cross section σ predicted by the spin-independent DW calculation and the experimental cross section $d\sigma/d\Omega$ is given by

$$\frac{d\sigma}{d\Omega}=N\frac{2J_f+1}{2J_0+1}C^2S\sigma,$$

where N is a normalization factor that includes the overlap for the dissociation of the He^4 particle into a triton and a proton, J_0 and J_f are the spins of the initial and final states, respectively, C is the isobaric-spin Clebsch-Gordan coupling coefficient, and S is the nuclear overlap factor. To simulate the effect of including a spin-orbit potential for the captured proton calculation, the normalization factor was multiplied or divided by 1.10 for $p_{3/2}$ or $p_{1/2}$ transitions, respectively.[22] For l transfer values greater than 1, this number was increased in the ratio of $2l+1$.[6–8] The value of N used in the present study was obtained empirically by normalizing the ground state of Cu^{65} to the value $C^2S=0.79$, the value obtained from the (He^3,d) reaction study for this state.[8] This procedure resulted in a value of 38.4 for N, a value which was used throughout the analysis.

The comparisons in Table III of the values of C^2S from the (He^4,t) reaction studies to those from the (He^3,d) reaction studies show, within the uncertainties of the analysis, what we believe to be reasonable agreement.

The JULIE program was used[11] for the $Ni^{62}(He^4,t)Cu^{63}$ reaction in order to determine the effect of introducing a spin-orbit interaction into the triton optical well and into the bound-state well. The calculation was performed using a Thomas-type spin-orbit well based on the parameters of the real well. The triton parameters were He^3-ion parameters[6–8] with the real well depth corrected for the isobaric spin difference between the triton and the He^3 ion. The He^4 parameters were obtained from optical-model fits to experimental elastic scattering angular distributions, but were somewhat different than those given in Table II. The effect on the predicted distributions was in the direction to improve the agreement with the experimental data as the spin-orbit depths for the triton were increased up to 20 MeV (pion mass units), but the magnitude of the effect was insufficient.

[22] G. R. Satchler (private communication).

IV. DISCUSSION

The substantial forward-angle differences between $\frac{1}{2}^-$ and $\frac{3}{2}^-$ distributions, and between $\frac{5}{2}^-$ and $\frac{7}{2}^-$ distributions, and the strong dependence of the distributions upon the Q of the reaction are effects which have not been observed in the (He^3,d) reaction on the same nuclides. Furthermore, these effects are not noticed in (He^3,d) reaction studies at other energies, as for example, in the $Fe^{54}(He^3,d)Co^{55}$ reaction at 16.5 MeV[23] and the $Ca^{48}(He^3,d)Sc^{49}$ reaction at 12.0 MeV.[24] In general, the spin-independent DW calculation for the (He^3,d) reaction yields angular distributions which compare favorably with the experimental distributions in the forward-angle region. We have seen, however, that this is not the case for the (He^4,t) reaction.

These observations suggest the possibility that under the conditions of the present study the (He^4,t) reaction may not proceed via a simple stripping mechanism. The most probable alternative seems to be that mechanism which excites excited-core configurations.[25,26] In the excited-core nuclear model[27,28] one assumes that certain of the low-lying states in a nucleus can be described as having large components of configurations in which an odd particle is coupled to an excited core. For example, in the case of Cu^{63} we can think of coupling a $p_{3/2}$ proton to the Ni^{62} core excited to its one-phonon 2^+ state to form states with spin and parity of $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$, respectively. We shall symbolize such configurations by $|J_c^\pi,j^\pi;J^\pi\rangle$, where J_c^π refers to the core, j^π to the proton orbital, and J^π to the final state. The reaction calculation yields angular distributions for the reaction mechanism which excites these configurations through inelastic effects in the entrance[28] or the exit[25] channel. Calculations for this mechanism (which we shall call "inelastic" or "core-excitation") have been performed for specific cases, such as the $Ni^{62}(He^3,d)Cu^{63}$ reaction.[25,26] For this case, the calculations indicate that the shape of the distribution is similar to the shape obtained for the direct transition. In general, however, the direct mechanism and the inelastic mechanism need not produce similar distribution shapes.[26]

Kozlowski and de-Shalit[25] have indicated that it is possible to obtain cross sections through the inelastic

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[24] J. R. Erskine, A. Marinov, and J. P. Schiffer, Phys. Rev. **142**, 633 (1966).
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[26] S. K. Penny and G. R. Satchler, Nucl. Phys. **53**, 145 (1964); S. K. Penny, Oak Ridge National Laboratory Report No. ORNL-TM-1414 (unpublished).
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mechanism which are comparable to those observed experimentally. On the other hand, in the work of Penny and Satchler[26] the inelastic mechanism yields effects which are small and which contribute importantly to the cross section only for the first $\frac{7}{2}^-$ state in Cu^{63}. In the absence of any $f_{7/2}$ proton hole in the Ni^{62} ground-state wave function, this particular state can be excited only by a secondary, e.g., inelastic, reaction process. As in the (He^3,d) reaction, the present (He^4,t) reaction yields a relatively small cross section to this state in Cu^{63} and Cu^{65}. Even for this favorable case, however, it is possible that the most important contribution to the cross section is made by the direct reaction process. Wang and Winhold,[29] in an investigation of the $Zn^{64}(n,d)Cu^{63}$ reaction, concluded that this state contains a large amount of $(f_{7/2})^{-1}$ proton configuration. If this is so, the state can be excited in the (He^3,d) and (He^4,t) reactions by the normal stripping mechanism, provided the $f_{7/2}$ proton shell in Ni^{62} is not closed. Evidence that this shell is not closed in the Ni nuclides comes from the $Ni^{58}(n,d)Co^{57}$ reaction study[29] and the (t,He^4) reaction study[30] on the even Ni nuclides.

In the present experiment, the angular distributions from this $\frac{7}{2}^-$ state in Cu^{63} and Cu^{65}, while different from the neighboring $\frac{5}{2}^-$ distributions in these nuclides, are similar to $\frac{7}{2}^-$ ground-state distributions for which the reaction Q is approximately the same. The best indication of this similarity is to be found in the comparison of the distributions from the Cu^{65} 1.48-MeV state and the Co^{57} ground state, for which the reaction Q's are nearly identical.

Thus, on the basis of cross section or angular distribution shape for the $\frac{7}{2}^-$ state in Cu^{63} and Cu^{65}, there is no requirement that the secondary mechanism we have just considered is very important in the (He^4,t) reaction. On the other hand, the small cross section to this state does not necessarily prove the unimportance of the inelastic mechanism, for interference between inelastic mechanism amplitudes in entrance and exit channels and between amplitudes from direct and inelastic mechanisms could yield a small cross section.

The experimental result for the inelastic excitation of states containing excited-core configurations should be different in the (He^4,t) reaction than in the (He^3,d) reaction. First, the use of different particles and different energies in the two reactions would yield different cross sections for production of the excited core, and second, the dynamics of proton transfer are quite different in the two reactions. It is difficult to estimate the total magnitude of the expected difference, but simple considerations show that the latter effect is dominant. An approximation to the magnitude of the latter effect can be obtained from the results of the direct-stripping DW calculation. For example, for transitions at approximately 1 MeV of excitation in Cu^{63} this calculation yields a ratio of $l=1$ to $l=3$ cross sections in the forward-angle region which is smaller by about a factor of 10 for the (He^4,t) reaction than for the (He^3,d) reaction. Thus, e.g., if in a nucleus there is one $\frac{5}{2}^-$ state whose dominant configuration is $|0^+,\frac{5}{2}^-;\frac{5}{2}^-\rangle$ (a single-particle $f_{5/2}$ proton) and another nearby $\frac{5}{2}^-$ state whose dominant configuration is $|2^+,\frac{3}{2}^-;\frac{5}{2}^-\rangle$ (a $p_{3/2}$ proton coupled to the 2^+ core), the ratio of cross sections to the two states should be quite different for the two reactions if either or both of the reactions proceeds substantially by means of the core-excitation mechanism. If one extracted spectroscopic factors for these states on the basis of the direct-stripping DW calculation, the values should be different for the two reactions. However, if both the (He^3,d) and (He^4,t) reactions proceed entirely by the direct mechanism, the spectroscopic factors will be approximately the same for either reaction.

The application of these concepts to the present experimental data is hindered by the relatively poor agreement between the shapes of the experimental angular distributions and those predicted by the present DW calculation. One notes, however, that except for the transition to the $g_{9/2}$ state at approximately 2.5 MeV there are no strong transitions in either Cu^{63} or Cu^{65} above the fourth excited state (see Fig. 1). Thus, unless there is an unusually large fragmentation of the $f_{5/2}$ single-particle state, most of its strength must appear in the second and fourth excited states in these nuclides. Also, a large fraction of the $p_{1/2}$ single-particle strength must appear in the first excited state, although an estimate of its value is more difficult to make because of the smaller $l=1$ cross sections inherent in the (He^4,t) reaction.

Within the limits of the experimental data from the (He^4,t) reaction, the second and fourth excited states have approximately the same shape in Cu^{63} and also in Cu^{65}. By our method of normalization, the spectroscopic factors for these transitions are somewhat higher than those obtained from the (He^3,d) reaction. Ratios of the spectroscopic factors for these transitions will be more meaningful, however, although they are still somewhat dependent upon details of the DW calculation such as the optical-model parameters employed and the lower limit used for the radial integration. The ratio of the spectroscopic factors of these two states in Cu^{63} is 0.59 in the present experiment, in good agreement with the value of 0.73 from the (He^3,d) reaction study. For Cu^{65}, the ratio from the present experiment is 0.42, which is also in good agreement with the value of 0.46 from the (He^3,d) reaction.

For any given strengths of direct-excitation mechanism and inelastic mechanism in the (He^3,d) reaction and, again, in the (He^4,t) reaction, it may be possible to find wave functions for these two states in Cu^{63} which yield the observed ratio of 0.66 ± 0.07 for both reactions. Similarly, for any given strengths of each of these two

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mechanisms in each of the two reactions, it may be possible to find wave functions for these two states in Cu^{65} which yield the observed ratio of 0.44 ± 0.02 for both reactions. There may even be one or more sets of strengths of the two mechanisms in the two reactions for which one simultaneously can find wave functions for these four states which yield the observed ratios. A more attractive assumption, however, is that both reactions proceed only by the direct mechanism, for then it is a simple matter to write down wave functions which yield the observed ratios.

The predicted wave functions of these states depend, of course, on the nuclear model. According to the simple excited-core model, the second excited state would be described adequately by the $|2^+,\frac{3}{2}^-;\frac{5}{2}^-\rangle$ configuration, while the fourth excited state, if it has spin and parity of $\frac{5}{2}^-$, could not be a core-excited state. The calculation of Beres[31] shows the first $\frac{5}{2}^-$ state of Cu^{63} to be predominantly the $|0^+,\frac{5}{2}^-;\frac{5}{2}^-\rangle$ configuration, while the second $\frac{5}{2}^-$ state is predominantly the $|2^+,\frac{3}{2}^-;\frac{5}{2}^-\rangle$ configuration. The calculations of Thankappan and True[32] (in which the determination of the parameters are partially guided by the (He^3,d) experimental results) yield approximately the same amount of the $|0^+,\frac{5}{2}^-;\frac{5}{2}^-\rangle$ configuration in each of the two Cu^{63} states, with the remainder (60%) of the wave functions made up of the $|2^+,\frac{3}{2}^-;\frac{5}{2}^-\rangle$ configuration and smaller amounts of $|2^+,\frac{1}{2}^-;\frac{5}{2}^-\rangle$ and $|2^+,\frac{5}{2}^-;\frac{5}{2}^-\rangle$ configurations.

Our results show that neither of the first two nuclear models describes these two states adequately. Because of the nature of the wave functions of the $\frac{5}{2}^-$ states in these two models, and because we observe approximately the same spectroscopic factor ratio in the two experiments, by our previous argument only the direct reaction mechanism is important in the two reactions. If this is the case, however, the two models then predict spectroscopic factors vastly different from those observed in the two experiments. The first model predicts a vanishing direct-excitation spectroscopic factor for the first $\frac{5}{2}^-$ state, while the second model predicts direct-excitation spectroscopic factors of 0.81 and 0.05 for the first and second $\frac{5}{2}^-$ states, respectively. From the model of Thankappan and True, on the other hand, because the wave functions of the two states are similar to each other we can draw no conclusion regarding the reaction mechanism and the accuracy of the model.

Thus, there is no evidence in the present study that the excited-core reaction mechanism plays an important role in the (He^4,t) or (He^3,d) reactions. On the contrary, the results presented here indicate that in these experiments the direct mechanism is the only important reaction mechanism.

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[32] V. K. Thankappan and W. W. True, Phys. Rev. **137**, 793 (1965).

We have recently observed the (t,He^4) reaction on the even Ni isotopes at a beam energy of 15 MeV,[30] and the $Zr^{90}(t,He^4)Y^{89}$ reaction at beam energies of 11, 15, and 20 MeV.[33] The results from the $Ni(t,He^4)Co$ reaction indicate a small and regularly behaved Q dependence for $\frac{3}{2}^-$, $\frac{7}{2}^-$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$ distributions. The study of the $Zr^{90}(t,He^4)Y^{89}$ reaction shows that the angular distribution shapes are strong functions of the bombarding energy, particularly in the case of the strongly excited $\frac{1}{2}^-$ ground state and the $\frac{3}{2}^-$ 1.51-MeV state. These results combined with the results of the present experiment suggest that the strong apparent Q dependence observed in the present experiment is more accurately described as a dependence on the energy of the triton channel, rather than a dependence on the actual linear momentum transfer.

V. CONCLUSIONS

We conclude that the results of the present experiment together with those of the (He^3,d) experiment[6–8] indicate that the (He^4,t) and the (He^3,d) reactions on the nuclides considered proceed overwhelmingly by the direct mechanism. It is somewhat surprising, therefore, that the DW calculation, including spin-orbit effects, does not predict the j dependence of the experimental distributions. For the (He^4,p) reaction[34] and the (p,He^4) reaction,[35] the DW calculations predict a substantial spin-orbit effect. This ineffectiveness of the calculation in predicting the present experimental curves may be caused by a lack of knowledge of the correct parameters to be used for the triton in the spin-orbit interaction, whereas for the proton these parameters are quite well known.

The evaluation of the (He^4,t) reaction as a general spectroscopic tool must, therefore, await the development of a calculation which more nearly predicts the experimental distributions than do the present calculations. The inclusion of a finite-range interaction into the stripping calculations with the subsequent deletion of the radial cutoff procedure may be important.

Despite the poor agreement of the predicted distributions with the experimental distributions, it appears that the (He^4,t) reaction can be useful in determining j values when l values are known as, for example, in the case of the 2.40 and 2.69-MeV states in Mn^{53}.

Further results, both experimental and theoretical, on the (He^4,t) reaction on other nuclides would be useful.

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