J Dependence in the (He^3,α) Reaction*

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(Received 14 February 1966)

The reactions $Fe^{56}(He^3,\alpha)Fe^{55}$ and $Ni^{60}(He^3,\alpha)Ni^{59}$ have been studied with particular attention to the dependence of the angular distribution on the total angular-momentum transfer. Distinct differences in phase were observed in the angular distributions corresponding to $l=3$ neutron pickup to states of different spins. Less pronounced differences were observed for $l=1$ transitions. All angular distributions showed oscillations about an exponential decrease in cross section with increasing angle. This lack of distinct character in the angular distributions may limit the usefulness of the (He^3,α) reaction as a spectroscopic tool.

INTRODUCTION

A NUMBER of recent experimental results have provided considerable evidence that angular distributions from a wide variety of direct nuclear reactions show marked dependence on the total angular-momentum transfer in addition to the well-known dependence on orbital-angular-momentum transfer.[1–4] In general these effects are not understood, although some success has been achieved with a distorted-wave Born approximation (DWBA) approach to the (α,p) reaction in which a spin-orbit term was used in the outgoing proton channel.[5] This success was facilitated by the fact that the zero spin of the alpha particle simplified the analysis considerably.

In this paper we report the results of an investigation of J dependence in the (He^3,α) reaction.[6] This reaction is thought to proceed (at least in medium-weight nuclei) primarily by a direct reaction in which a single neutron is picked up from the target. Since the outgoing alpha has spin zero, spin-dependent effects can occur only in the He^3 entrance channel and in the bound-state wave function of the captured neutron. One might therefore hope that a DWBA analysis might achieve a success similar to that with the (α,p) reaction.[5] Effects similar to those reported here have been observed by Brussel *et al.*[7] at 25 MeV and by Glashausser[8] at 30 and 40 MeV.

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

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EXPERIMENT

The 17.5-MeV beam of doubly ionized He^3 from the Argonne tandem Van de Graaff generator was used to bombard thin foil targets of natural iron (91.7% Fe^{56}) and enriched Ni^{60}(>99% Ni^{60}). Reaction alpha particles were observed simultaneously in four surface-barrier Si detectors set at 20° intervals about the target. The counters could be moved as a group for measurements over the angular ranges indicated below. Bias voltages on the counters were set so that only alpha particles were observed in the energy range of interest. Measurements were made at 5° intervals in the angular range $20° \leqslant \theta \leqslant 120°$ for the reaction $Fe^{56}(He^3,\alpha)Fe^{55}$ and $25° \leqslant \theta \leqslant 80°$ for $Ni^{60}(He^3,\alpha)Ni^{59}$. Since we wished to concern ourselves only with relative shapes of angular distributions, no attempt was made to obtain absolute cross-section measurements.

Strong transitions were observed in both reactions to the low-lying states for which strong $l=1$ and $l=3$ (p,d) pickup has been reported.[9] Angular distributions were obtained for those states listed in Table I. The listed values of l and spin are those suggested by Refs. 8 and 9; they are based on angular correlation results, on relative (d,p) and (p,d) cross sections, and on nuclear systematics. Although not all are definite, they are probably correct. It should be noted that the state listed at 1.38 MeV excitation in Fe^{55} is actually an unresolved doublet, both components of which[8,9] are probably $\frac{7}{2}^-$. A sample alpha-particle spectrum from the reaction $Fe^{56}(He^3,\alpha)Fe^{55}$ is shown in Fig. 1. Angular distributions for weak transitions were not analyzed,

TABLE I. Spins of states in Fe^{55} and Ni^{59} studied in the present experiment.[a]

Fe^{55}			Ne^{59}		
E_x (MeV)	l	J^π	E_x (MeV)	l	J^π
0	1	$\frac{3}{2}^-$	0	1	$\frac{3}{2}^-$
0.41	1	$\frac{1}{2}^-$	0.34	3	$\frac{5}{2}^-$
0.93	3	$\frac{5}{2}^-$	1.97	3	$\frac{7}{2}^-$
1.38	3	$\frac{7}{2}^-$	2.64	3	$\frac{7}{2}^-$
2.9	3	$(\frac{7}{2}^-)$			

[a] Results from Refs. 8 and 9 as discussed in the text.

[9] J. C. Legg and E. Rost, Phys. Rev. **134**, B752 (1964).

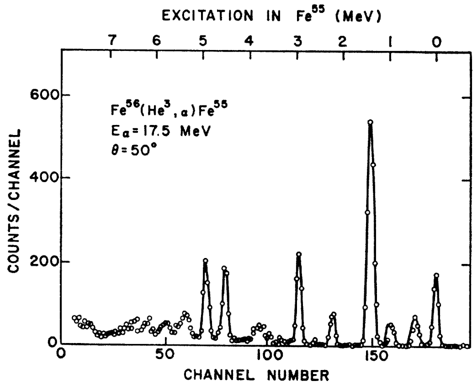

FIG. 1. Spectrum of high-energy alpha particles at 50° from bombardment of a natural iron foil with 17.5-MeV He^3. The zero of the pulse-height analyzer has been displaced so as to accept only particles having energies greater than the elastically scattered He^3, and the counter bias was selected so that high-energy protons lose only part of their energy in the counter. Corresponding excitation in the residual nucleus Fe^{55} is shown at the top of the figure.

since significant J dependence is not expected for reactions to states showing weak neutron pickup.[1]

RESULTS

Measured angular distributions for transitions for which strong $l=1$ pickup was observed are shown in Fig. 2. It is evident that there are some differences between the $J=\frac{1}{2}$ and $J=\frac{3}{2}$ angular distributions. They are particularly evident in the region $55° \leqslant \theta \leqslant 85°$ where the $J=\frac{3}{2}$ angular distributions exhibit much more oscillatory structure than does that for $J=\frac{1}{2}$. These differences, while very subtle, are qualitatively consistent with those observed by Brussel *et al.*[7] but are probably too light to be useful in nuclear spectroscopy. Indeed, Brussel *et al.* were unable to use this effect to ascertain the spin of an $l=1$ state they reported at 1.08 MeV excitation in Ni^{57}.

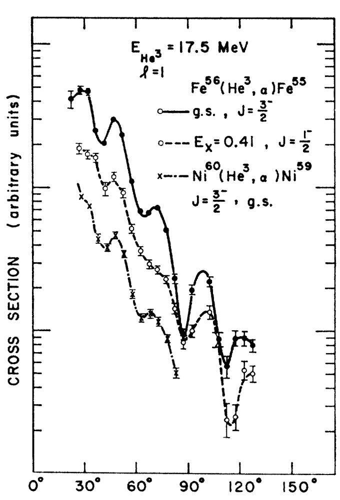

FIG. 2. Angular distributions for alpha-particle groups corresponding to known $l=1$ transitions to states in the residual nuclei Fe^{55} and Ni^{59}. The final states and their spins are as indicated on the figure. The curves are drawn roughly through the points and do *not* represent theoretical fits. The curves are arbitrarily displaced vertically for ease of comparison. (g.s. = ground state.)

Results for $l=3$ transitions to states of known spin in Fe^{55} are shown in Fig. 3. It is clear that, while the angular distributions oscillate about an almost exponential decrease in cross section with increasing angle, there is a definite systematic difference for different J values, particularly for the states at lower excitation. The phase of the oscillations about the exponential decrease is characteristic of the value of J, and the phases for different J tend to be completely different over the entire range of angle covered. The angular distribution for the 2.9-MeV state, while fluctuating less about the exponential decrease is seen, on careful examination, to most strongly resemble that for the 1.4-MeV group. This observation supports the spin assignment of $\frac{7}{2}^-$ suggested from comparisons of relative cross sections.

This J dependence for $l=3$ transitions is substantiated by our results for transitions to states in Ni^{59}. These results are shown in Fig. 4 along with smooth curves

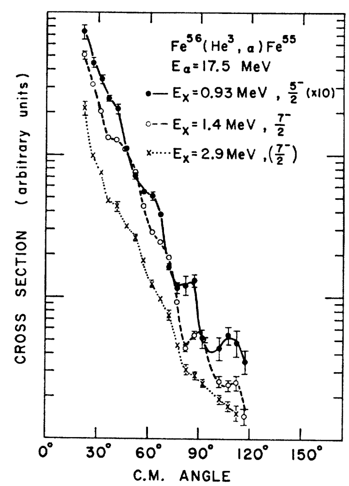

FIG. 3. Angular distributions from the reaction $Fe^{56}(He^3,\alpha)Fe^{55}$ for $l=3$ transitions to states of known final-state spin. Excitation energies and spins are as indicated. The curves are drawn roughly through the points and do *not* represent theoretical fits. Note that it is necessary to superimpose the distribution of the 2.9-MeV state on the others to observe the similarity to that of the 1.4-MeV state which is cited in the text.

corresponding to the lines drawn through the points for two of the states in Fig. 3. The relative cross sections are displaced arbitrarily for clarity of display. One notes that the Ni^{59} data display exactly the same systematic difference between J values as is observed for Fe^{55}.

Since the angular distributions are so close to an exponential decrease with increasing angle, one can display the J dependence in a more quantitative manner by comparing the observed angular distributions with this simple exponential angular distribution. Figure 5 shows one form of this comparison for the most prominent transitions for each J. Here the ratio of the measured differential cross section to an exponential decrease with angle is plotted as a function of angle. It is apparent that the measured cross sections have regular oscillations about the exponential decrease and that there is almost a complete $\frac{1}{2}\pi$ phase difference between the oscillations for the two different final-state spins.

DISCUSSION

It is clear from the above results that a systematic *J* dependence probably exists in (He^3,α) angular distributions for $l=3$ transitions in the Fe–Ni region. There is also indication of *J* dependence in $l=1$ transitions but it is neither so systematic nor so well established. All of the angular distributions exhibit oscillations about an exponential decrease with increasing angle; the $l=1$ transitions have much stronger oscillations than the $l=3$.

As noted in the introduction, it had been hoped that DWBA calculations including spin might successfully describe the behavior of the angular distributions. Such calculations were performed[10] by use of the code JULIE and parameters chosen from fits to elastic-scattering experiments. While some qualitative differences were predicted, the calculations were not able to produce the phase differences observed for the $l=3$ transitions. Changes in the shape of the angular distribution as large as the observed *J* dependence sometimes resulted merely from a change in the choice of cutoff radius. Perhaps some special spin dependence in the form factor for the transferred neutron, as suggested by Pinkston and Satchler[11] and by the Princeton-Boulder group[12] might provide a satisfactory explanation of our results. No such attempt has been made in the present work.

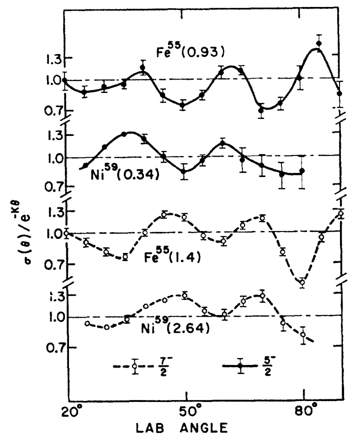

FIG. 5. Plots of the ratios of the measured differential cross sections to an exponential decrease of cross section with increasing angle. Data points are for the $l=3$ transitions between states of the indicated excitation and spin. The same exponential was used for comparison in all four cases.

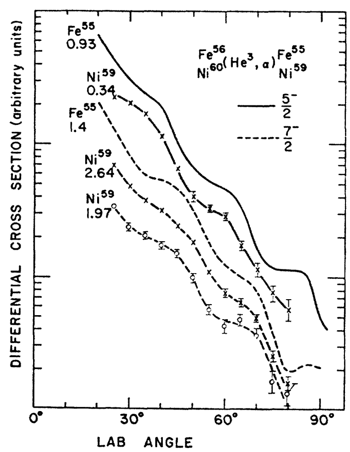

FIG. 4. Alpha-particle angular distributions for five of the $l=3$ transitions studied. The data points are shown for the reaction Ni^{60}(He,α)Ni^{59}, and smooth curves from Fig. 3 are included for the Fe^{55} states. The curves are arbitrarily displaced vertically for ease of comparison. As in Figs. 2 and 3, the curves are drawn roughly through the points and do *not* represent theoretical fits.

The near-exponential nature of the observed angular distributions and the weakness of the oscillatory structure casts some doubt on the usefulness of the (He^3,α) reaction as a general tool for nuclear spectroscopy. One should note, for instance, that even the differences between the observed angular distributions for $l=1$ and $l=3$ neutron pickup are not pronounced and distinct as they are for the (*p*,*d*) reaction.[8,9] This is probably due to the large momentum transfer inherent in the (He^3,α) reaction. It is doubtful that one could easily distinguish between adjacent *l* values in nuclei in which both values might be expected in the same region of excitation. Difficulties of this sort have already been experienced by Fou and Zurmühle[13] who, in spite of detailed DWBA calculations, are unable to identify any $l=2$ transitions in a study of the reaction Ni^{58}(He^3,α)Ni^{57}. It appears that, although more difficult experimentally, the (*p*,*d*) and (*d*,*t*) reactions remain the most useful means of studying neutron pickup.

ACKNOWLEDGMENTS

The authors are indebted to Dr. J. P. Schiffer for several helpful discussions and to Dr. M. K. Brussel, Dr. M. E. Rickey, and Dr. C. M. Glashausser for providing us with their results prior to publication. We also would like to thank Dr. R. H. Bassel for performing the DWBA calculations cited and J. McShane for his help in the data acquisition and reduction.

[10] The authors are indebted to Dr. R. H. Bassel of Oak Ridge National Laboratory for performing these calculations.

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