DEPENDENCE OF THE ANGULAR DISTRIBUTION IN THE (α,p) REACTION ON THE TOTAL ANGULAR-MOMENTUM TRANSFER*

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It has been observed recently that the angular distribution in (d,p) reactions depends on the total angular-momentum transfer.[1] Similar effects have been observed in (d,t),[2] (p,d),[3] and $(^3\mathrm{He},d)$ reactions.[4] Distorted-wave Born-approximation calculations have not been particularly successful in reproducing the experimentally observed effects, although some qualitative features appear. We have chosen to study the (α,p) reaction on spin-zero targets because here the spin-dependent interaction is confined to the proton channel.[5] The spin-orbit interaction of a proton with a nucleus has been studied extensively, in contrast to reactions involving deuterons, ^{3}He, or ^{3}H, for which little is known about the spin dependence of the potentials.

We have measured the (α,p) reaction on ^{58}Ni and ^{60}Ni using the 18-MeV alpha-particle beam of the Argonne National Laboratory tandem Van de Graaff accelerator. With the negatively charged He$^-$ beam from the Duoplasmatron source, beam currents of $(20\text{-}40)\times10^{-9}$ A of He^{++} were obtained at the target. The angular distributions of protons to the $\frac{3}{2}^-$ ground states and $\frac{1}{2}^-$ first excited states of ^{61}Cu and ^{63}Cu are shown in Fig. 1. There is a very clear difference between these two $l=1$ transitions: The $\frac{1}{2}^-$ angular distribution oscillates sharply in angle, while that for the $\frac{3}{2}^-$ state is relatively smooth. Similar effects are apparent for $l=2$ (α,p) transitions at 22 MeV in the results of Yamazaki, Londo, and Yamabe,[6] which are also shown in Fig. 1. The $\frac{3}{2}^+$ angular distributions oscillate sharply, the $\frac{5}{2}^+$ ones are smooth, except that for $^{27}\mathrm{Al}(\alpha,p)^{30}\mathrm{Si}$ there are small oscillations which, however, are still much less pronounced than for the $\frac{3}{2}^+$ states. It is evident then that the (α,p) reaction depends strongly on J; more detailed investigations should be carried out with accelerators with higher beam currents.

Calculations using the zero-range distorted-wave Born approximation were carried out. The parameters for the distorting potentials were taken from Fulmer et al.[7] for the alpha particles, and the parameters found by Perey[8] were used for protons. These are listed in Table I. Two models for the transferred triton were used. The first consists of the product of single-nucleon orbitals,[9] which for computational simplicity are taken as oscillator functions. The resultant form factor falls off too rapidly at large radii. In the second form factor investigated the triton cluster is assumed to move in the average field of the remaining nucleons and is an eigenfunction of the Schrödinger equation with the separation energy. This function has the correct asymptotic behavior.

The shapes of the angular distributions for $2p$ proton transfers, shown in Fig. 1, are relatively insensitive to the parameters of the distorting potentials and the choice of triton form factor, but the oscillatory structure for the $2p_{1/2}$ transition is only produced with a radial cutoff on the matrix element. The use of such a cutoff is plausible if the nucleon orbitals and the distorted waves are regarded as eigenfunctions of a nonlocal well[10] and finite-range effects are considered. For the $1d$ proton transfers, the results are somewhat more dependent on the optical parameters and the shape of the triton function. Indeed, it is possible to find angular distributions very similar to experiment with somewhat arbitrary parameters. However, the curves shown in Fig. 1 make use of optical parameters that fit scattering in this range of energies and masses, and of reasonable oscillator wave functions. Comparison of theory and experiment show qualitative agreement for $2p$ proton transfers. For $1d$ transitions the agreement is not good, although our calculations using the product triton form factor show more pronounced oscillatory structure for $d_{3/2}$ transitions than for $d_{5/2}$.

We conclude that the usual distorted-wave

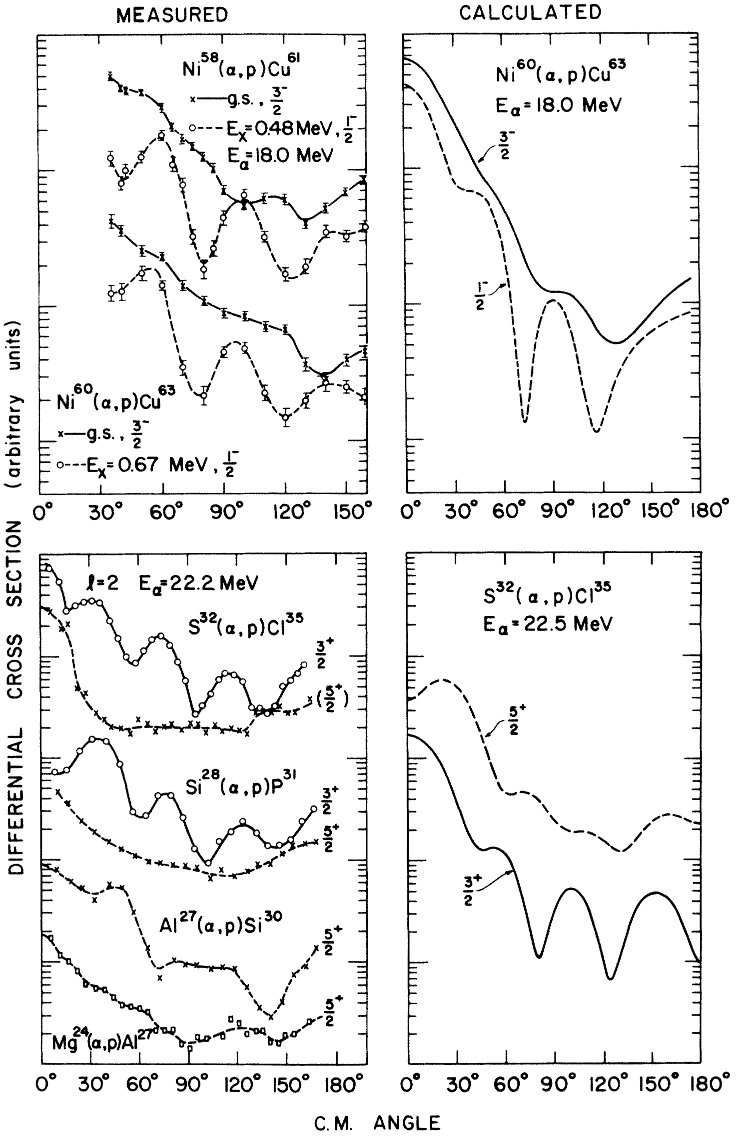

FIG. 1. Observed and calculated angular distributions for the (α,p) reaction for proton transitions in the $2p$ and the $1d$ orbitals. The experimental data on the lower left are those of reference 6. The theoretical curves on the right are calculated with the parameters in Table I and with product wave functions for the transferred tritons.

theory is able to produce J-dependent effects of the same qualitative nature and the right order of magnitude when spin-orbit coupling is included in the distorting potentials, although uncertainties in the application of the theory prevent detailed agreement with experiment.

Figure 2 shows predictions for $1f$ and $2d$ proton transfers, where again the qualitative results are insensitive to the assumptions. For $1f$ proton transfers the distorted-wave calculations do not predict striking differences at large angles but do show differences at small angles. The forward-angle rise in the $f_{7/2}$ transition has been seen by Ball, Fulmer, and Goodman[11] in the (p,α) reaction, but it remains for experiment to prove whether the flatness of the $f_{5/2}$ distribution is real or merely an artifact of the calculations. The predictions for $2d$ transitions show strong oscillations for both $d_{3/2}$ and $d_{5/2}$ at wide angles but with a difference in phase. In addition, at medium angles the angular distributions for $d_{5/2}$ transitions show

Table I. Optical parameters.

Reaction	Particle	J^π	V (MeV)	r_R (F)	r_c (F)	a (F)	W (MeV)	W_D (MeV)	r_0' (F)	a' (F)	V_{SO} (MeV)
^{32}S$(\alpha,p)^{35}$Cl, $E_\alpha = 22.5$ MeV	α		52.5	1.634	1.4	0.555	8.6	0	1.634	0.555	...
	proton	$\frac{5}{2}^+$	46.3	1.25	1.25	0.65	0	9	1.25	0.47	8.5
	proton	$\frac{3}{2}^+$	45.7	1.25	1.25	0.65	0	9	1.25	0.47	8.5
^{56}Fe$(\alpha,p)^{59}$Co, $E_\alpha = 18$ MeV	α		67.4	1.586	1.4	0.521	12.8	...	1.586	0.409	...
	proton	$\frac{7}{2}^-$	50.8	1.25	1.25	0.65	...	12.5	1.25	0.47	7.5
	proton	$\frac{5}{2}^-$	51.3	1.25	1.25	0.65	...	12.5	1.25	0.47	7.5
^{60}Ni$(\alpha,p)^{63}$Cu, $E_\alpha = 18$ MeV	α		67.4	1.586	1.4	0.521	12.8	...	1.586	0.409	...
	proton	$\frac{3}{2}^-$	51.1	1.25	1.25	0.65	...	12.5	1.25	0.47	7.5
	proton	$\frac{1}{2}^-$	51.5	1.25	1.25	0.65	...	12.5	1.25	0.47	7.5
^{116}Sn$(\alpha,p)^{119}$Sb, $E_\alpha = 18$ MeV	α		50	1.45	1.4	0.58	10	...	1.45	0.58	...
	proton	$\frac{5}{2}^+$	55.4	1.25	1.25	0.65	...	17.25	1.25	0.47	7.5
	proton	$\frac{3}{2}^+$	55.8	1.25	1.25	0.65	...	17.25	1.25	0.47	7.5

a shoulder which is not present in the $d_{3/2}$ calculation.

In recent work Glashausser, Nolen, and Rickey[12] have found very similar effects in (p,α) reactions. It seems reasonable to expect that empirically established rules on the J dependence of (α,p) and (p,α) angular distributions will be of considerable use in nuclear spectroscopy; this J dependence appears to be more unambiguous than the dependence of the angular distributions on orbital angular momentum.

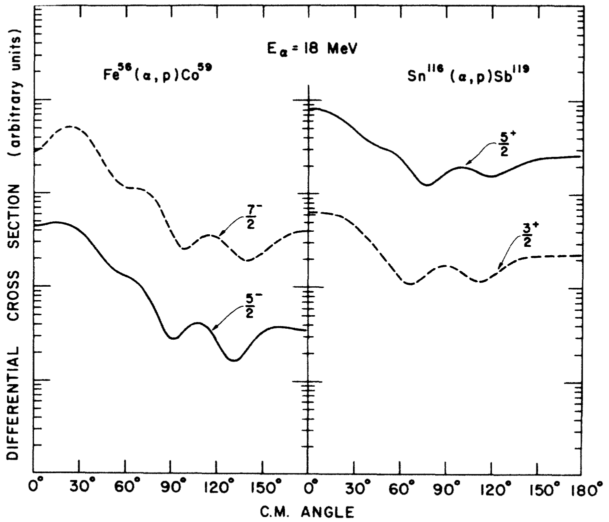

FIG. 2. Calculated angular distributions for the (α, p) reaction for proton transition in the $1f$ and $2d$ orbitals. The optical-model parameters in Table I were used with product wave functions for the transferred tritons.

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