Final-State l and j Determination by Forward-Angle Measurements of the Reaction $^{62}Ni(^{7}Li, ^{6}He)^{63}Cu$†

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In a study of the reaction $^{62}Ni(^{7}Li, ^{6}He)^{63}Cu$ at 34.0 MeV, the angular distributions of the three low-lying states have been observed to exhibit not only an L dependence but also l and j dependences at angles forward of 15°. The l and j dependences of the shapes can be understood in terms of the angular-momentum selection rules. Finite-range distorted-wave Born approximation calculations, including recoil exactly, reproduce the data. Relative spectroscopic factors are in good agreement with those from the reaction $^{62}Ni(^{3}He, d)^{63}Cu$.

Single-particle transfer reactions with heavy projectiles ($A > 4$) were thought, until recently, to be of uncertain value as spectroscopic tools since the majority of one-particle transfer-reaction data have been taken around the semiclassical grazing angle which produces the L-independent "bell-shaped" angular distributions. However, theoretical calculations[1] have recently shown the existence of strong oscillations in the forward-angle cross sections when weakly absorbing optical potentials are used. The existence of this structure has been confirmed in the forward-angle data of the reaction[2] $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$. The $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$ measurement also suggested that the forward-angle structure is L dependent. This Letter will show there is not only an L dependence but also l and j dependences (where l is the orbital angular momentum and j the total angular momentum of the transferred proton in the residual nucleus) in the shape of the forward-angle data in the reaction $^{62}Ni(^{7}Li, ^{6}He)^{63}Cu$. The j dependence noted here, which occurs at angles less than 5°, differs from that observed by Lee and Schiffer,[3] which is dependent on the spin-orbit interaction, and also differs from that described by Kovar *et al.*,[4] which is an intensity effect.

The $^{62}Ni(^{7}Li, ^{6}He)^{63}Cu$ experiment was performed using a 34-MeV ^{7}Li beam, from the Florida State University FN tandem Van de Graaff accelerator, to bombard a 100-$\mu g/cm^2$ target of ^{62}Ni enriched to 98% deposited on a thin carbon backing. Reaction products were detected with a Si surface-barrier counter telescope (ΔE thickness of 98 μm) placed in the detector chamber of a quadrupole spectrometer (QD0).[5] The use of the QD0 allowed focusing of only the momentum range of interest onto the detectors; it was thus possible to take data at 1° lab. Data were also taken in 2.5° steps from 2.5 to 20°. The data were taken, via a CAMAC link, by an EMR-6130 computer. At the end of each run the events were displayed (ΔE vs E) on a storage scope, gates were drawn around each particle type of interest, and the data were sorted on line into particle spectra. The consistency of the data at different angles was ensured by using a stationary monitor counter in the scattering chamber of the QD0 for the relative normalization. α-particle scattering at 6 MeV (which was determined to be of the Rutherford type for $\theta_{lab} \leq 40°$) was done with the same target and detector geometry as in the $(^{7}Li, ^{6}He)$ reaction. With this determination of the product of the target thickness and solid angle, the absolute cross sections were calculated for the $(^{7}Li, ^{6}He)$ reaction.

From $(^{3}He, d)$ studies on ^{62}Ni, it has been found that the first three states of ^{63}Cu are predominantly single-particle states of $2p_{3/2}$ (0.0 MeV), $2p_{1/2}$ (0.67 MeV), and $1f_{5/2}$ (0.96 MeV) configurations.[6] This conclusion is supported by the l and j dependence seen in the present $(^{7}Li, ^{6}He)$ work. In Fig. 1, the p states can be seen to peak at about 8°, while the f state peaks at about 13°. This l dependence in the shape of the angular distributions is caused by the predominance of the "normal" L transfer over the "nonnormal" L values. At very forward angles ($\leq 5°$), there is a major difference between the angular distributions of the two p states. In Fig. 2, the data for the p states are shown alone to emphasize the l-dependent and j-dependent regions of the angular distributions. Since the spectroscopic factors for the two p states are close to unity, the $\frac{1}{2}^-$ state is multiplied by a factor of 2 to cancel the remaining $2J_f + 1$ factor. The cross sections are identical in shape at scattering angles greater than 5° but are totally dissimilar in the

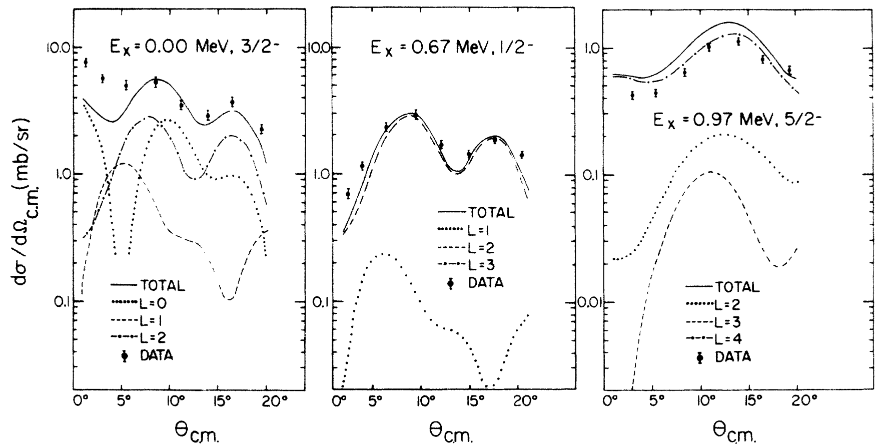

FIG. 1. $^{62}Ni(^{7}Li,^{6}He)$ angular distributions to the 0.0-, 0.67-, and 0.98-MeV states in ^{63}Cu with $E(^{7}Li) = 34$ MeV. Finite-range DWBA calculations and contributions to the cross section for the possible L transfers are also shown.

extreme forward region.

The angular-momentum selection rules governing the transferred angular momentum L are

$$|l_1 - l| \leq L \leq l_1 + l,$$
$$|j_1 - j| \leq L \leq j_1 + j, \quad (1)$$

where l_1 and j_1 are the orbital and total angular momentum quantum numbers of the transferred particle in the projectile. In ^{7}Li, the proton is in the $1p_{3/2}$ orbit and, therefore, the transfer is from an $l_1 = 1$ to an $l = 1$ orbit when stripping to a p state in ^{63}Cu. Applying Eq. (1) to this case, we find that for the $\frac{1}{2}^-$ state, only $L = 1$ and 2 are allowed, but for the $\frac{3}{2}^-$ state, $L = 0$, 1, and 2 are all allowed. Thus for the $\frac{3}{2}^-$ state there is the additional $L = 0$ transfer. If the $L = 0$ contribution is appreciable, determined by the angular-momentum matching (which in this case is good), its effect should be seen close to 0° where its contribution to the cross section would be expected to peak, making the ground-state cross section rise.

To check these arguments theoretically, preliminary finite-range distorted-wave Born approximation (DWBA) calculations were performed with the computer code MERCURY,[7] which includes recoil exactly. The optical parameters used were the shallow potentials ($V \sim 30$ MeV) from $^{40}Ca(^{7}Li, ^{7}Li)^{40}Ca$ at $E(^{7}Li) = 20$ MeV.[8] The same parameters were used for both the entrance and exit channels. Normalization of the calculations requires the use of $(C^2S)_{^7Li}$ and $(C^2S)_{^{63}Cu}$, where the S's are spectroscopic factors and the C's are the relevant isospin Clebsch-Gordon coefficients. The spectroscopic factor for the ^{7}Li system was taken from Cohen and Kurath[9] and those for ^{63}Cu from (^{3}He, d) measurements.[6] One additional normalization by a factor of 2 is required to match the calculations to the data.

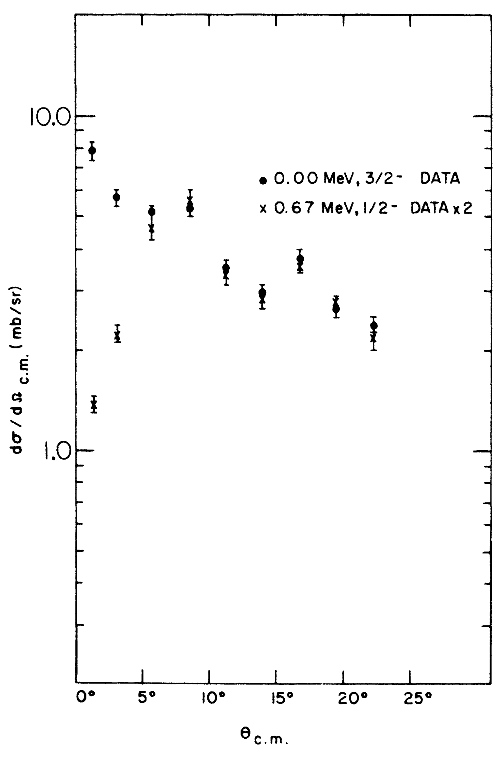

FIG. 2. Experimental data for the $^{62}Ni(^{7}Li, ^{6}He)$ transitions to the 0.0- and 0.67-MeV states multiplied by 2 to make the comparison of the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ transitions more convenient.

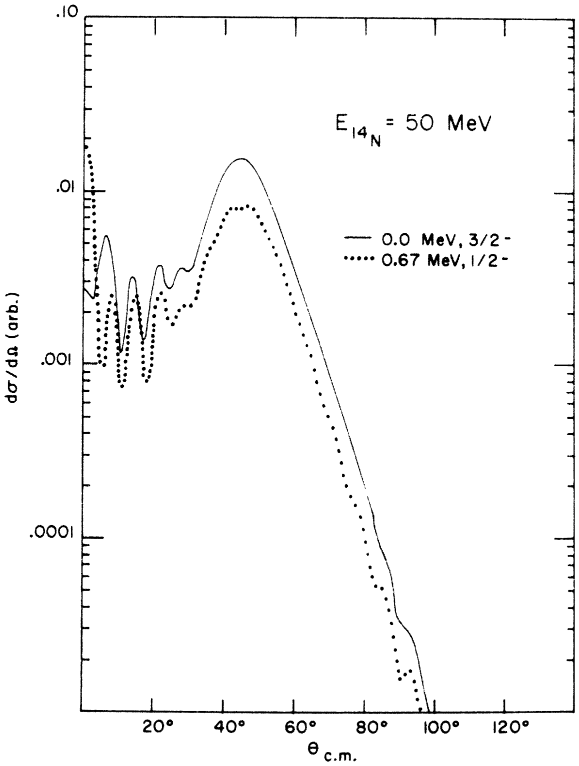

FIG. 3. Theoretical calculations for the $^{62}Ni(^{14}N, {}^{13}C)$ transitions to the 0.0- and 0.67-MeV states in ^{63}Cu. The $L = 0$ contribution to the 0.67-MeV states is apparent for angles less than 5°.

It can be shown in the DWBA formalism that

$$d\sigma/d\Omega \propto \sum_L (d\sigma/d\Omega)_L,$$

and therefore the contribution of each L transfer to the total cross section may be examined. The results of the calculations are shown in Fig. 1 for each L value, as well as the total differential cross section. It can be clearly seen that the reason for the difference in the extreme forward-angle shapes of the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states is solely the result of the addition of the $L = 0$ contribution in the $\frac{3}{2}^-$ angular distribution.

As another test of this j dependence at small angles, experimental work is under way on the reaction $^{62}Ni(^{14}N, {}^{13}C)^{63}Cu$. In this case, the transferred proton is in a $1p_{1/2}$ orbit in ^{14}N, and therefore the selection rules give us $L = 1, 2$ for the $\frac{3}{2}^-$ state and $L = 0, 1$ for the $\frac{1}{2}^-$ state. By this argument then, at small angles, the $\frac{1}{2}^-$ state should rise rather than the $\frac{3}{2}^-$ state as in the $(^7Li, {}^6He)$ reaction. Finite-range DWBA calculations were performed with the optical potentials of Ref. 2 and these calculations are shown in Fig. 3. Again the simple picture seems to be borne out by the calculations.

In conclusion, it has been shown that the shapes of the angular distributions for the $(^7Li, {}^6He)$ reaction can be l dependent and that for p states a determination of the j value may be made from the shapes for $\theta_{c.m.} \leq 5°$. This j-dependent effect has been shown to come from the additional $L = 0$ transfer allowed for the ground-state transition, which can be appreciable when the angular-momentum matching is good. In the fp shell, this technique may be a very useful experimental tool. Again assuming good angular-momentum matching, this idea can be extended to determine any l and j combination, given that a projectile could be used which would transfer a particle from an orbit with the same l value. It has been shown that finite-range DWBA can reproduce the forward-angle structure evident in the data and gives relative normalization in good agreement with previous work.

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