# ANOMALOUS $L=1$ SHAPES OF ANGULAR DISTRIBUTIONS FOR ($^3$He,$t$) TRANSITIONS TO $0^+$ ANTIANALOG STATES IN $^{64,66}$Ga AND $^{40}$K†

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The ($^3$He,$t$) reaction on $^{64,66}$Zn and $^{40}$Ar to the $0^+$ analog and antianalog states has been studied at 35 MeV. The angular distributions for the $T_<$ $0^+$ states show an $L=1$ shape, implying a need for modifications in the conventional description of ($^3$He,$t$) reactions.

The ($^3$He,$t$) reaction on light- and medium-weight nuclei has recently been the subject of many studies with the extraction of significant spectroscopic information.[1] Such charge-exchange reactions can populate both $T_>$ (analog) and orthogonal $T_<$ states (states of isospin one less than the target nucleus) that have the same spin and configuration as the analog state (antianalog states). If spin-0 states for both the initial and final nucleus are selected, then the interaction responsible for the transition, in usual microscopic terminology, is only the pure charge-exchange operator $V_\tau(\vec{t}\cdot\vec{\tau}_i)g(r)$, summed over the target nucleons $i$. If one assumes that the radial integrals (form factors) for all of the active nucleons that contribute to this sum are the same, then the excitation of $0^+$ states other than the analog state is a measure of the amount of the analog-state wave function in those states, the cross section for exciting such states being 0 in the case of no isospin mixing. However, as French and MacFarlane[2] have pointed out, if there is a neutron excess in the target nucleus that spans more than one subshell, then $T_<$ $0^+$ states can be excited if the radial integrals of the contributing neutron orbitals are different.

To see this we separate the isospin operator $V_\tau\vec{t}\cdot\vec{\tau}$ into a part for each subshell (assuming two orbitals 1 and 2 with separate isospins $T_1$ and $T_2$). The matrix element for monopole transitions (with $T_i=T_1+T_2$ being the isospin of the initial state and $T_f$ that of the final state) is then[2]

$$\langle\mathcal{H}\rangle^2(T_f=T_i-1)=(T_1T_2/2T_i)[V_1(r)-V_2(r)]^2,$$

$$\langle\mathcal{H}\rangle^2(T_f=T_i)=(1/2T_i)[V_1(r)T_1+V_2(r)T_2]^2.$$

$V_j(r)$ is the radial integral of the form $\int u_j^2(r)g(r,R)r^2dr$, where $u_j$ is the radial wave function of the nucleon in orbital $j$ and $g(r,R)$ is the radial part of the effective projectile-nucleon interaction. From these expressions it is seen that a transition to the $0^+$ $T_<$ state can proceed only if the radial integral for each subshell is different, and so a measure of the population of such $0^+$ states can provide a measure of the dependence of the interaction on the orbits involved.

Investigations of such transitions have been reported by Goodman and Roos for $^{88}$Sr [3] and $^{56}$Fe [4] targets. They conclude in the first case that they see the effect of the inequality of the radial integrals in $^{88}$Y in the large excitation of a low-lying $0^+$ state. For the $^{56}$Fe case an $L=1$ angular distribution is observed for a state at 1.453 MeV. Belote, Dorenbusch, and Rapaport[5] have assigned a $0^+$ state at this energy from the reaction $^{54}$Fe($^3$He,$p$), while Ohnuma, Hashimoto, and Tomita[6] suggest a $1^-$ state at 1.451 MeV. Goodman and Roos conclude that it is likely that both a $0^+$ and $1^-$ state occur within a few keV of each other and that the latter is excited in their ($^3$He,$t$) studies.

To study the population of $0^+$ antianalog states, we selected the nuclei $^{64}$Zn, $^{66}$Zn, and $^{40}$Ar since the positions of the $0^+$ $T_<$ states are reasonably well established in the residual nuclei. In the $^{64,66}$Ga isotopes, these states are the ground states. The $0^+$ assignment for $^{66}$Ga has been established for some time,[7] while $\beta$-$\gamma$ correlation measurements[8] strongly suggest a $0^+$ assignment for the $^{64}$Ga ground state, a spin-1 assignment being possible only with the inclusion of a very large Coulomb matrix element. (These locations are consistent with the isospin splitting relationship, $\Delta E_{T\to T-1}=\alpha T$, where $\alpha$ is found to be between 1 and 2 MeV; the analogs of the $^{64,66}$Zn ground states in $^{64,66}$Ga are at 2.05 and 3.84 MeV, respectively.) For the case of $^{40}$K, the state at 1.644 MeV is most likely a $0^+$ state. Recent $^{40}$Ar($p,n$) angular distributions at 5.5 MeV[9] indicate that this state has spin 0; a negative-parity assignment is unlikely because of the requirement of a large $M3$ enhancement factor. Also, recent $^{42}$Ca($p$,$^3$He) studies by Kolata, Shapiro, and August[10] have shown a characteristic $L=0$ shape for this transition and have confirmed the $0^+$ assignment. This contradicts earlier $^{39}$K($d,p$) work[11] which required an $L=1$ angular momentum transfer for a very weakly excited state at $1.639\pm0.013$ MeV. A ($^3$He,$t$) study by Wesolowski, Hansen, and Stelts[12] at

17.9 MeV found an $L=1$ shape for the angular distribution for the 1.65-MeV state which they felt was consistent with the $^{39}$K$(d,p)$ results. In the light of the more recent $0^+$ assignments for this state, it was of interest to investigate this ($^3$He,$t$) reaction at a higher bombarding energy.

($^3$He,$t$) angular distributions between 10° and 35° were taken with 35-MeV $^3$He ions from the Michigan State University sector-focused cyclotron. For $^{40}$Ar a detector telescope for particle identification was used to detect the outgoing tritons while for the Zn isotopes an Enge split-pole spectrograph with position-sensitive detectors was used. The resolution obtained in these latter measurements was 25 keV, adequate to separate the ground states from the first excited states at 160 and 44 keV in $^{64}$Ga and $^{66}$Ga, respectively.

The angular distributions for these three reactions to the $0^+$ $T_>$ and $T_<$ states are shown in Fig. 1. The fits shown are distorted-wave Born-approximation (DWBA) calculations for a macroscopic model using the code JULIE. A surface-peaked form factor with geometrical parameters equal to those of the imaginary optical well was used; the distorted waves for both the entrance and exit channels were calculated with optical-model parameters as determined by Gibson[13] for $^3$He elastic scattering on $^{58}$Ni and $^{40}$Ca at 37.7 MeV. For transitions to the analog state, the fits in all three cases are good. However, the fits for the $0^+$ $T_<$ states with an $L=0$ transfer are significantly out of phase with the experimental angular distributions for all three isotopes studied. Such $0^+$ to $0^+$ transitions should proceed by an $L=0$ transfer but an $L=1$ calculation, as shown, provides a very good fit to the data. These results for $^{40}$Ar are consistent with the lower-energy data. They are also similar to those seen in $^{56}$Fe if the state excited at 1.453 MeV has a $0^+$ spin.

Microscopic calculations for the transition $^{40}$Ar($^3$He,$t$)$^{40}$K(1.65 MeV) were carried out using a simple $(f_{7/2})^2$-$(d_{3/2})^2$ configuration for the state. Woods-Saxon wave functions were used for the radial wave functions and a Yukawa form was taken for the interaction. To try to fit the data for this transition, the spatial dependence

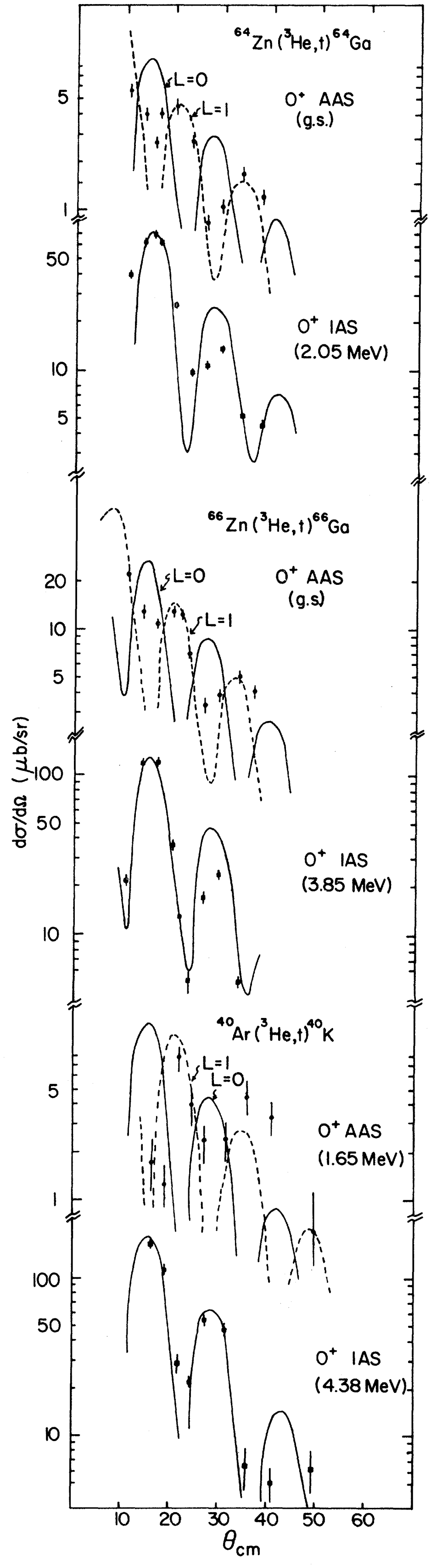


FIG. 1. Angular distributions for ($^3$He,$t$) reactions at 35 MeV on $^{64}$Zn, $^{66}$Zn, and $^{40}$Ar proceeding to the $0^+$ analog and antianalog states. The lines shown are DWBA calculations using a surface-peaked form factor with $L=0$ or $L=1$ angular momentum transfers.

of each excess neutron orbital was varied over a wide range by changing the geometrical well parameters $r_0$ and $a$, but a maximum in the angular distribution remained at 15°. (Variations in the range of the Yukawa interaction between 0.7 and 1.4 F also did not yield the desired changes.) For all cases, changes in the optical-model parameters did not alter the shape at forward angles. The ratios of the $0^+$ analog to antianalog integrated cross sections were 11 for $^{64}$Ga, 4 for $^{66}$Ga, and 16 for $^{40}$K.

The two-body effective interaction currently used in charge exchange is[14]

$$V_{\text{eff}} = \vec{t}\cdot\vec{\tau}_i\{(V_\tau + V_{\sigma\tau}\vec{\sigma}_0\cdot\vec{\sigma}_i)g(r) + V_{\text{tensor}}S_{0i}h(r)\},$$

where $V_\tau$, $V_{\sigma\tau}$, $V_{\text{tensor}}$ are the strengths of the charge-exchange, spin-flip, and tensor interactions. With this interaction only the $V_\tau$ term contributes for $0^+$ to $0^+$ transitions so that an $L=1$ transfer is not allowed. Yet the experimental evidence shows that in the three cases discussed, the antianalog $0^+$ states show an $L=1$ transfer. Since the configurations of the three nuclei differ widely, it would appear that this effect is not configuration dependent, but rather that it is due to other terms in $V_{\text{eff}}$ or to other modifications in the conventional description of the ($^3$He, $t$) reaction.

We wish to acknowledge interesting discussions with R. Schaeffer on the possible interpretations of our results. Recent discussions with P. G. Roos and C. D. Goodman revealed that they have independently come to the same conclusions as ours (based on their work on $^{56}$Fe and $^{88}$Sr).

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