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# Anomaly in the Angular Distributions for ($He^3$, $t$) Reactions*

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A systematic angular shift is noted between distorted-wave calculations and measured angular distributions for ($He^3$, $t$) reactions on even-even targets. The shift is apparent for final states whose isospin is one unit lower than that of the target state.

A recent article[1] presented evidence that ($He^3$, $t$) angular distributions for $J^\pi = 0^+$ anti-analog states could not be fitted well with $L = 0$ distorted-wave (DW) calculations but that $L = 1$ calculations were in good agreement with the data. We present evidence here that the inability to fit ($He^3$, $t$) angular distributions for certain low-lying states may be a general deficiency in the current distorted-wave treatment of the reaction mechanism. A persistent angular shift is noted between DW calculations and the measured angular distributions to $T_<$ final states from even-even targets. The shift cannot be removed by realistic adjustment of the parameters of the standard DW calculations.

The purpose of the present note is to summarize this feature which is evident in a number of experiments performed with the $He^3$ beam of the Argonne tandem Van de Graaff accelerator. They encompass the reactions $Ca^{48}(He^3, t)Sc^{48}$,[2] $Sr^{88}(He^3, t)Y^{88}$,[3] $Zr^{90}(He^3, t)Nb^{90}$,[4] and $Zr^{96}(He^3, t)Nb^{96}$.[5] Bombarding energies were 23 MeV for the $Ca^{48}$ and $Sr^{88}$ targets and 21 MeV for the Zr targets. The tritons from the reactions on $Ca^{48}$, $Sr^{88}$, and $Zr^{96}$ were detected on photographic plates placed in the focal plane of an Enge split-pole spectrograph; a position-sensitive detector was used for the reactions on $Zr^{90}$.

Experimental angular distributions for $J^\pi = 4^+$ and $6^+$ states are compared with DW calculations in Fig. 1. Since the $6^+$ state in $Y^{88}$ is apparently unresolved from a $7^+$ state, the angular distribution for a $5^-$ state has been shown instead. An angular shift of 2-7° between the curve and the data is seen in every case. Although not shown, the shift is also present for $2^+$ and $8^+$ states.

The states of $Sc^{48}$ are believed to be members of the $(f_{7/2})^2$ multiplet, the even-parity states of $Y^{88}$ and $Nb^{90}$ belong to the $(g_{9/2})^2$ multiplet, the $5^-$ state arises from the $(p_{1/2}g_{9/2})^{-1}$ configuration, and the states of $Nb^{96}$ are members of the $(g_{9/2}d_{5/2})^{-1}$ multiplet. The data thus span cases in which a neutron is replaced by a proton in the same orbit, in which the neutron and proton orbits have different spins but the same parity, and in which the two orbits differ in both spin

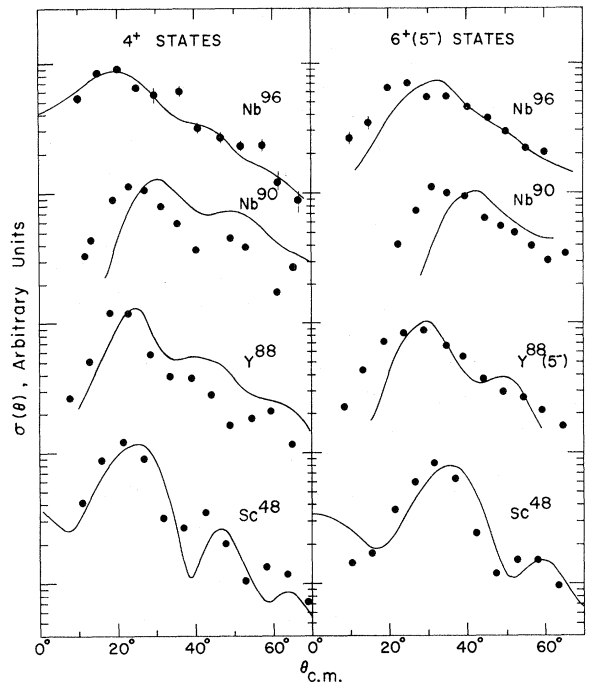


FIG. 1. Angular distributions from ($He^3$, $t$) reactions to natural-parity states in $Sc^{48}$ [g.s. ($6^+$) and 0.25-MeV state ($4^+$)], $Y^{88}$ [0.23-MeV ($5^-$) and 0.99-MeV ($4^+$) states], $Nb^{90}$ [0.12-MeV ($6^+$) and 0.33-MeV ($4^+$) states], and $Nb^{96}$ [g.s. ($6^+$) and 0.15-MeV state ($4^+$)].

and parity. The shift is present in all cases.

The distorted-wave calculations were done by use of the computer code DWUCK.[6] Special attention was given to those aspects that might produce angular shifts. The calculations included microscopic form factors which were treated according to standard methods.[7,8]

The optical potentials included real and imaginary Woods-Saxon terms with no spin-orbit coupling. Several different potentials were investigated, all of which represented variations of the "universal" $He^3$ optical potential of Gibson *et al.*[9] In general, the same potential set was used for both the $He^3$ and $t$ channels. An isospin term corresponding to a few MeV change in the real well depth and the inclusion of a small imaginary surface term in the manner of Drisko *et al.*[10] was also investigated. The effects were found to be entirely negligible. While the choice of optical potentials strongly affected the cross sections, it did not significantly affect the shapes and produced no angular shifts. Even sizable and arbitrary changes in most of the optical-model parameters, one by one, did not produce angular shifts, though large increases in the imaginary radius parameter did.

The shapes of the angular distributions were even less affected by changes in the parameters of the Woods-Saxon potentials used in calculating the microscopic form factors. The binding energies of the neutron and proton were taken from the $Q$ values for the $(\gamma, n)$ and $(p, \gamma)$ reactions to appropriate neutron single-hole and proton single-particle states. Changes of a few MeV in binding energies did not noticeably affect the calculated results.

The microscopic interaction included a Yukawa radial dependence. A reciprocal range parameter $\alpha = 1.0\ F^{-1}$ was used for most of the calculations, but $1.4\ F^{-1}$ was found to give the best results for the reaction $Ca^{48}(He^3, t)Sc^{48}$. In the work of Kossanyi-Demay *et al.* (Ref. 8, Fig. 2), it was found that an angular shift can be produced for the $4^+$ state of $Sc^{48}$ by increasing the range $\alpha^{-1}$. The calculations for our data reproduced the effect but also showed that it was not nearly so pronounced for other states. In $Y^{88}$, for example, an angular shift of at most 1° could be obtained even with $\alpha = 0.5\ F^{-1}$.

Since a simple diffraction picture will predict a shift in the angular pattern with changing radius, it was of interest to explore the effects of a cutoff radius in the DW calculations. Forcing the contribution to the distorted-wave Born approximation (DWBA) integral to come from increasingly large radii should qualitatively cause the whole oscillatory pattern to shift to smaller angles. However, no significant shift was observed until a cutoff of 10 F was used and a cutoff of 12 F was needed to obtain shifts of about the right amount. This is illustrated in Fig. 2. Such a large cutoff, which reduces the peak cross section by a factor of ~200, is, of course, totally unphysical. An increase in the imaginary radius of the distorting potentials can also accomplish the same thing. To reproduce the observed angular shift, the imaginary radius must be about twice the real-well radius. Such potentials will not fit the elastic-scattering data.

It seems clear from these cutoff calculations that the problems in fitting the data do not arise from details of the form factors used in microscopic calculations since these will all be similar at radii well beyond the nuclear surface. Thus the observed difficulties should be nearly independent of the details of configurations. It is interesting to note that a sizable angular shift results from changing the $Q$ value of the reaction. In Fig. 1, the angular distributions for the $Nb^{96}$ states peak at more forward angles than do those

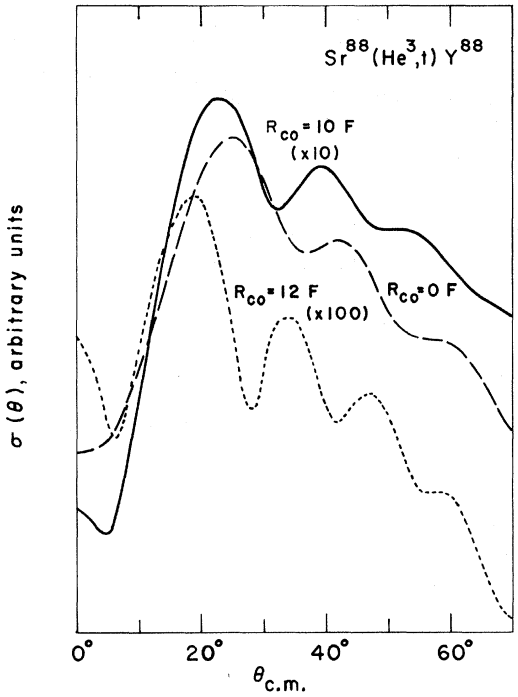


FIG. 2. Distorted-wave calculations for a $(He^3,t)$ transition to the $J^\pi = 4^+$ member of the $(g_{9/2})^2$ multiplet in $Y^{88}$. The curves show the effects of a lower cutoff on the radial integrals. The nuclear radius is about 5.3 F.

for the $Nb^{90}$ states. This is a direct result of the 6-MeV difference in $Q$ values for these reactions. The DW calculations correctly reproduce this dependence, but fail to match the data.

The effect described here is not present for all natural-parity states. Quasielastic transitions to analogs of the target ground states do not exhibit[1] shifts in the angular-distribution patterns. Indeed, our DW calculations matched the data for the $0^+$ analog state in $Sc^{48}$ very well. The results for excited analog states are not so clear.[11-15]

Similar angular shifts may also be identified for transitions to unnatural-parity states. However, since two values of $L$ are involved for these transitions and the effective charge-exchange interaction may include tensor terms, the discussion of the shift is much more complex. If the experimental data for a $5^+$ final state, for example, are compared with calculated DW curves for $L=4$ and $L=6$, the experimental pattern appears to fall about midway between the two curves. However, the measured pattern closely resembles that for a $6^+$ state, so the comparison with the calculated $L=6$ curve yields a shift very close to that of a $6^+$ state.

This resemblance between the angular distributions for unnatural parity states and those of states with the next higher $J$ is completely inconsistent with DW calculations with central interactions. The introduction of a tensor force in the effective interaction by Rost and Kunz[7] seemed to explain this anomaly quite successfully. This experimental pattern is disrupted by the measured angular distribution for a transition to the $4^-$ ground state of $Y^{88}$ in the reaction[3] $Sr^{88}(He^3, t)Y^{88}$. This angular distribution is definitely not fitted with a tensor interaction but is fitted (except for an angular shift) by a DW calculation with a central interaction. It is clearly not sensible to require a tensor force only for some final states and not for others. A solution to this difficulty may perhaps bear some relation to the cause for the angular shifts that have been discussed here.

In summary, our data for $(He^3, t)$ reactions to states of lower isospin than the target show an angular shift between observed and calculated data. Where a careful comparison can be made, this is consistent with other experimental results. This shift is not present for the quasielastic transitions to analogs of ground states. At present, no simple mechanism seems capable of explaining the effect. Refinements in DW calculations, such as $D$-state admixtures,[16] spin-orbit coherence, exchange effects, and second-order processes need to be explored. It is hoped that a simple explanation might be found for such a general effect.

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# Evidence for Intermediate Structure Near an Isobaric Analog Resonance*

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A particular $J=\frac{1}{2}^+$ analog resonance in $^{71}$As, observed in elastic and inelastic scattering of protons on $^{70}$Ge, and corresponding to a *single* $l=0$ state at 2.22-MeV excitation in $^{71}$Ge, is found to contain significant substructure encompassing many ultimate fine-structure levels.

In this Letter, we present strong evidence that structure exists *below* the rank of isobaric-analog gross structure, but *above* the level of the ultimate fine structure.[1]

This work is the by-product of blocking lifetime measurements in single germanium crystals.[2,3] We examined the elastic and inelastic proton scattering from enriched isotopes of $^{70}$Ge and $^{72}$Ge. We focus on one particular $J=\frac{1}{2}^+$ analog resonance in $^{71}$As at about 9.6-MeV excitation energy (5-MeV proton bombarding energy on $^{70}$Ge).[4] Self-supporting thin targets of $^{70}GeO_2$ were studied with protons between 2.7 and 7.4 MeV, and detectors at 90, 125, and 165 deg. These excitation curves, measured in steps between 3 and 10 keV, lead to definite $l$ values for the observed resonances. The energy resolution (beam spread plus target thickness) was about 3 keV. Figure 1 shows the correspondence between the parent nucleus $^{71}$Ge and the analog nucleus $^{71}$As. Only $l=0$ and $l=2$ resonances were observed. The information on $^{71}$Ge comes from the $(d,p)$ data.[5,6] The special analog "state" is the one corresponding to the $l=0$, and hence $J=\frac{1}{2}^+$, state at 2.22-MeV excitation in $^{71}$Ge. An enlarged view of that region is shown in Fig. 2(a); the gross structure exhibits the appropriate signature shapes of an $l=0$ resonance at all three angles. Closer examination reveals a number of narrower structures *within* the resonance, exhibiting typical $l=0$ shapes in their own right. The inelastic-scatter-

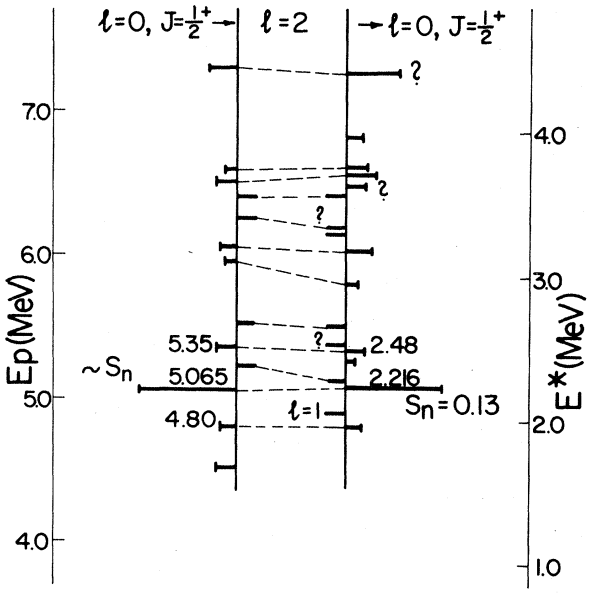


FIG. 1. Correspondence between parent states in $^{71}$Ge (right) as obtained from the $(d,p)$ reaction (cf. Refs. 5 and 6) and their analogs in $^{71}$As (left) as obtained in this work. $l=0$, $J=\frac{1}{2}^+$ states are shown with their approximate spectroscopic factors as line segments *away* from the central band, while $l=2$ states are shown *into* the central band. The analog spectroscopic factors are only qualitative as obtained from inspection of the excitation curves. Dashed lines connect analogs. Left-hand scale gives the proton bombarding energy; right-hand scale gives the excitation energy above the ground state in $^{71}$Ge.