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Collective and Higher-Order Effects Shown by the (p, t) Reaction on the Deformed Nucleus ^{159}Tb

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The reaction ^{159}Tb$(p,t)^{157}$Tb at 30 MeV strongly populates collective states in the residual nucleus. Angular distributions of β and γ vibrational and ground-state rotational band members are presented and compared with distorted-wave Born-approximation predictions. We also include evidence supporting the importance of indirect multiple-step processes accompanying the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

The (p,t) reaction on ^{159}Tb continues a general study of the characteristics of the (p,t) reaction on odd-mass rare-earth elements. From a previously completed investigation[1] of the (p,t) reaction on the closed-shell nucleus ^{141}Pr, it was found that this reaction proceeds predominantly through a direct mechanism at the bombarding energies used in this study, and that large cross sections exist for the population of collective vibrational states within the residual nucleus ^{139}Pr. However, unlike the previous study, the present investigation involves permanently deformed target and residual nuclei. These provide a very suitable system for studying and further testing the collective characteristics previously associated with the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

In this study an ≈ 300-μg/cm^2 metallic target of ^{159}Tb was bombarded with 30-MeV protons accelerated by the Michigan State University sector-focused cyclotron. The scattered tritons were analyzed with an Enge split-pole magnetic spectrometer and collected on photographic plates. Spectra were taken between 10° and 75° at 5° intervals in the lab system with an overall energy resolution of 15–20 keV, although higher-resolution spectra (10 keV full width at half-maximum) have also been obtained at some angles.

From previous radioactivity studies,[2,3] rotational bands built upon the ground state and a β vibrational excitation of the ground state have been identified in the ^{157}Tb nucleus. In addition, the presence of a $K=\frac{1}{2}$ band based at 598 keV of excitation was also indicated. There are two possibilities for the origin of such a $K=\frac{1}{2}$ band in this nucleus. It can be explained as a rotational band superimposed either on the $\frac{1}{2}^+[411]$ single proton state expected in this region, or on a γ vibrational state based on the $\frac{3}{2}^+[411]$ ground state. The vibrational origin of these states is strongly suggested both from systematics and from the very small decoupling parameter associated with this band. The empirical value of this decoupling parameter is $\approx\frac{1}{20}$ of the calculated value[2] for a $\frac{1}{2}^+[411]$ band based on a nuclear deformation of $\eta = 5$, and it is of opposite sign. However, experimentally determined K-conversion coefficients imply significant $M1$ admixtures in transitions de-exciting this band to the ground band; these should be formally forbidden for states having a vibrational origin, although band mixing could easily account for this phenomenon.

The ^{159}Tb(p,t) triton spectrum taken at the lab scattering angle of 20° appears in Fig. 1. The most striking feature of this spectrum is the strong population of the ground-state rotational band, with members certainly up to $\frac{13}{2}^+$ and possibly as high as $\frac{17}{2}^+$ being excited. At 598 keV one finds three states that, within experimental uncertainty, correspond to the first three members of the previously discussed $K^\pi=\frac{1}{2}^+$ rotational band. In addition, if one generates the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ members of this band by parametrizing the simple rotational energy relationship, one finds two additional states populated by this reaction which appear to be the next two members of this (γ vibrational) band. In light of the established tendency of the (p,t) reaction to populate collec-

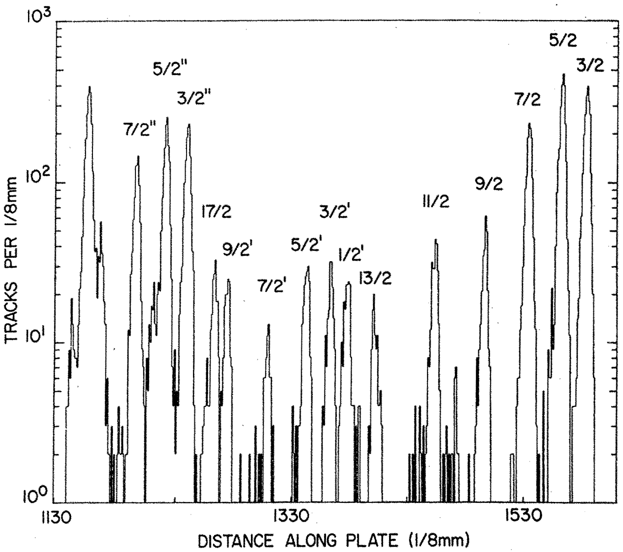

FIG. 1. Portion of ^{159}Tb(p,t) spectrum taken at the lab scattering angle of 20°. Members of the ground, γ, and β vibrational bands are labeled with unprimed, primed, and doubly primed spins, respectively. (For more complete spectra, cf. Ref. 5.)

TABLE I. States populated through the reaction ^{159}Tb(p,t).

Energy (keV)			
Present Work	Ref. 2	Theory[a]	Assignment[b] J^π
G S	G S	c	$3/2^+$
61±3	60.8	c	$5/2^+$
144±3	143.8	c	$7/2^+$
254±3	---	252	$9/2^+$
325±10	---	---	---
379±3	---	384	$11/2^+$
527±3	---	539	$13/2^+$
598±3	597.5	c	$1/2'^+$
640±3	637.5	c	$3/2'^+$
699±3	697.4	c	$5/2'^+$
795±3	---	797	$7/2'^+$
896±3	---	898	$9/2'^+$
927±3	---	923	$17/2^+$
947±10	---	---	---
994±3	992.6	c	$3/2''^+$
1048±3	1044.5	c	$5/2''^+$
1080±10	---	-----	---
1120±3	---	1124	$7/2''^+$
1207±10	---	---	---
1238±5	---	1241	$(9/2''^+)$[d]

[a] Theoretical values calculated empirically using the first-order rotational-energy expression.

[b] I, member of ground-state rotational band; I', member of $K=K_0-2\,\gamma$ vibrational band; I'', member of $K=K_0\ \beta$ vibrational band.

[c] State used to parameterize the first-order rotational-energy expression.

[d] The 1238-keV peak could possibly have a small component due to the presence of the $\frac{9}{2}^+$ member of the β vibrational band.

tive states at the beam energy used in this study, the presence of these $K=\frac{1}{2}$ states in our triton spectra strongly suggests the collective origin of this band. This assignment has since been corroborated by the recent identification, via the ^{156}Gd(τ,d) experiment,[4] of a rotational band based on the $K^\pi=\frac{1}{2}^+[411]$ single proton state located at 923 keV.

The three states based at 994 keV possess relative intensity characteristics which are remarkably similar to those exhibited by the first three members of the ground-state rotational band. Furthermore, the spacings of these states are consistent with a band-head spin of $\frac{3}{2}$ if the simple first-order rotational model is assumed. Thus, in addition to the two previously known members of the β-vibrational band, a third has been observed to be populated through this reaction. The results obtained from this spectrum are summarized in Table I and are compared with the calculated energies for the members of the various rotational bands, using the simple first-order rotational-energy expression.

The experimental angular distributions of states below 2.3 MeV populated through the reaction ^{159}Tb(p,t) appear in Fig. 2 along with distorted-wave predictions. Distorted-wave Born-approximation (DWBA) predictions for various l-value transfers were calculated using a zero-range, cluster-transfer approach as well as a more rigorous finite-range, two-nucleon pickup formalism; these are denoted by dashed and solid curves, respectively. The optical-potential and bound-state parameters used in these analyses are given by Goles.[5] The $h_{9/2}$ spherical shell-model orbit was used in calculating the bound-state wave functions of the transferred neutrons, since the least-bound pair of neutrons in the ^{159}Tb nucleus occupies a Nilsson orbit derived from this spherical state. As in the previous study of the (p,t) reaction on the spherical ^{141}Pr nucleus, the (p,t) ground-state transition proceeds through a strong dominant $l=0$ transfer. The theoretical $l=0$ curves predict the positions of the relative maxima and minima quite well but clearly underestimate the strength of the experimentally observed diffraction pattern. This phenomenon was also observed in the recently reported ^{141}Pr(p,t) experiment. Again, the finite-range, two-neutron pickup calculation does a much better job of fitting the lower-angle data

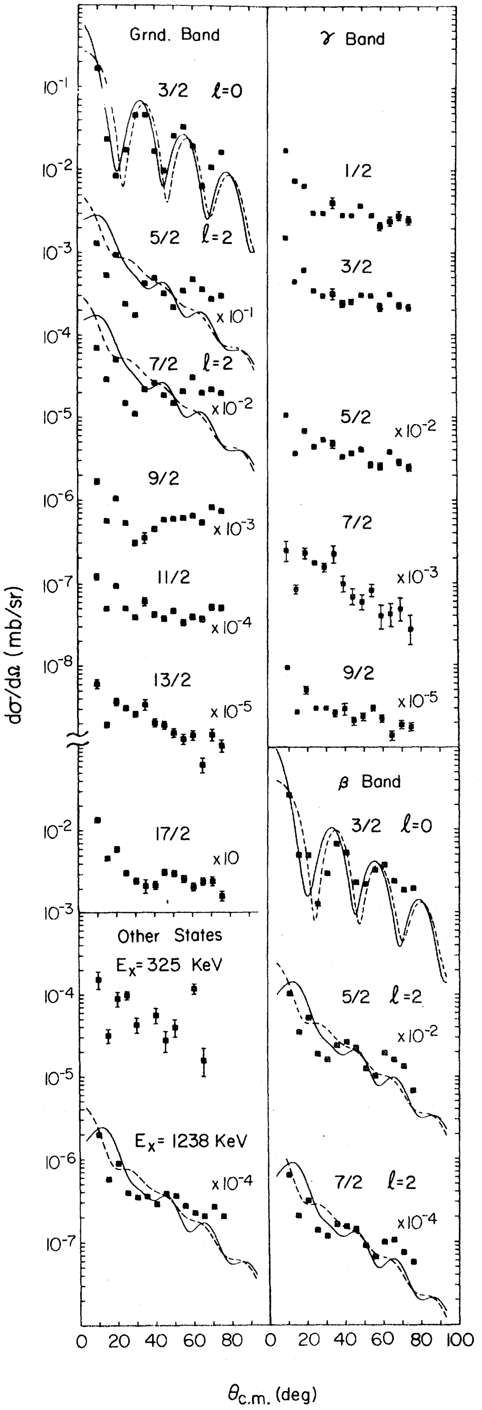

FIG. 2. Angular distributions of some states populated through the ^{159}Tb(p,t) reaction at 30 MeV. Theoretical two-neutron pickup and cluster-transfer calculations are represented by solid and dashed curves, respectively. Relative cross sections have been normalized to reflect measured absolute values. Cross-section errors are indicated when they exceed the width of the experimental points.

than does the cluster-transfer prediction, although both approaches do a respectable job of reproducing the experimental $l=0$ angular shape. The $\frac{5}{2}$ and $\frac{7}{2}$ members of the ground-state rotational band have very similar angular shapes. The positions of the relative maxima occuring in these curves are reminiscent of $l=2$ angular shapes; however, the deep minimum occuring at 30°, along with the unusual strength of the observed diffraction pattern, makes the simple $l=2$ assignments for these states extremely uncertain if indeed one is at all justified in describing this deformed system with spherical DWBA. The remaining members of the ground-state rotational band exhibit angular distributions which cannot be explained in terms of any single dominant angular-momentum transfer.

The angular shapes exhibited by the first three members of the γ vibrational band are identical within statistical uncertainty, implying a complete absence of $l=0$ strength in the transition to the $\frac{3}{2}$ member of this band. Moreover, the angular shapes exhibited by these three states, as well as the remaining two members of this band, indicate that these states are populated by a complex mixture of several allowed l values rather than through a single dominant angular-momentum transfer. Possibly this phenomenon can be understood and explained in terms of band mixing, which from previous arguments certainly must be occurring in this "γ vibrational band." Qualitatively, one would not expect complex mixed states to be populated through simple, pure angular-momentum transfers, and perhaps this is just the underlying reason behind the complex shapes.

Unlike the γ vibrational states, the members of the "β vibrational" band appear to be populated through a single dominant angular-momentum transfer. As in the ground-state rotational band, the $\frac{3}{2}^+$ band head appears to be populated by an $l=0$ wave; however, the positions of the experimental maxima and minima appear to be systematically shifted from the values they assumed in the experimental ground-state distribution—an effect that has been observed experimentally for (p,t) reactions on even-even rare-earth[6] and actinide nuclei.[7] Nevertheless, the overall shape and underlying strength of this experimental curve undoubtedly express its dominant $l=0$ character. The angular distributions of the remaining two members of this band exhibit a characteristic $l=2$ angular shape. The positions of the relative maxima of these curves are predicted quite well by the theory, although their relative strengths are once again underestimated.

Angular distributions for two additional states are included in Fig. 2, but little can be deduced about these states. The 325-keV state *might* be the 326.4-keV $\frac{5}{2}^-[523]$ proton state,[2] and the 1238-keV state (above the pairing gap) appears to have an $l=2$ shape; however, more work is needed to make any meaningful assignments for them.

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Emission of the ^{5}He in the Spontaneous Fission of ^{252}Cf

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The emission of ^{5}He ($T_{1/2}=8\times10^{-22}$ sec for decay into $\alpha+n$) in spontaneous fission of ^{252}Cf is established from a correlation measurement involving the direction and the kinetic energies of the neutrons and the long-range α particles. Approximately 11% of these α's are products of ^{5}He breakup. The initial energy of the fragments and of the ^{5}He at scission are calculated from the properties of the ^{5}He decay. They are 31 ± 11 and 3.2 ± 0.9 MeV, respectively.

The emission of a wide variety of light charged particles which accompany the process of fission has been studied extensively.[1] Among these particles ^{4}He is the most abundant with a rate of 3×10^{-3} per fission, while other particles are emitted at a lower rate, i.e., ^{1}H (1.8), ^{2}H (0.7), ^{3}H ($<5\times10^{-3}$), ^{6}He (2.6), ^{8}He (0.1), and $^{6-9}$Li (0.13). (The number in parentheses shows the yield of the particle relative to 100 α particles.) Although some of these light particles are unstable with respect to β decay, all of the particles which have been discovered so far were stable with respect to particle emission. The purpose of this Letter is to present evidence for emission of the particle-unstable ^{5}He. The ground state of ^{5}He is well known from the scattering of neutrons by ^{4}He to have a width $\Gamma=0.58$ MeV and consequently $T_{1/2}=8\times10^{-22}$ sec for the decay into a neutron and ^{4}He. The Q value of this decay is 0.957 MeV.[2] The positive identification of ^{5}He in fission is based upon the observation of a correlation between neutrons and α particles emitted in spontaneous fission of ^{252}Cf. Already in 1965 Nefedov *et al.*[3] found more neutrons [$(27\pm5)\%$] emitted in the direction of emission of the α particles than in the opposite direction; however, they did not interpret this fact as emission of ^{5}He. Halpern[1] noted that on the basis of the correlation between the "average energy costs" for production of various light particles in fission and their yields, ^{5}He should be emitted with about a 5% rate relative to ^{4}He and suggested that this emission can explain the results of Nefedov *et al.*

We have performed correlation measurements of neutrons and charged particles emitted from a thin 5×10^6-fissions/min ^{252}Cf source. Two surface barrier detectors with a 400-μm depletion layer were placed on both sides of the source to detect the long-range α particles. They were covered with an 18-mg/cm^2 gold foil, which