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

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Abstract:

The ^{159}Tb$(p,t)^{157}$Tb reaction 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 DWBA predictions. Evidence supporting the importance of indirect multiple step processes accompanying the (p,t) reaction is also included. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher lying rotational band members in odd-mass deformed nuclei.

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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 a $\approx$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 laboratory system with an overall energy resolution of 15-20 keV, although higher resolution spectra (10 keV FWHM) 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=1/2 band based at 598 keV of excitation was also indicated. There are two possibilities for the origin of such a K=1/2 band in this nucleus. It can be explained as a rotational band superimposed either on the $1/2^+[411]$ single proton state expected in this region or on a γ vibrational state based on the $3/2^+[411]$

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 ≈1/20 of the calculated value[2] for a $1/2^+[411]$ 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 deexciting 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 laboratory 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 $13/2^+$ and possibly as high as $17/2^+$ being excited. At 598 keV one finds three states that, within experimental uncertainty, correspond to the first three members of the previously discussed $K^\pi=1/2^+$ rotational band. In addition, if one generates the $7/2^+$ and $9/2^+$ members of this band by parameterizing 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 collective states at the beam energy used in this study, the presence of these $K=1/2$ 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 $K^\pi=1/2^+[411]$ 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 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 ^{159}Tb(p,t) reaction appear in Fig. 2 along with distorted-wave predictions. 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 pick-up formalism; these are denoted by broken and continuous curves, respectively. Optical potential and bound-state parameters used in these analyses are given in Ref. 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 $\ell=0$ transfer. The theoretical $\ell=0$ 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.[1] Again, the finite-range, two-neutron pick-up calculation does a much better job of fitting the lower angle data than does the cluster transfer prediction, although both approaches do a respectable job of reproducing the experimental ℓ=0 angular shape. The 5/2 and 7/2 members of the ground-state rotational band have very similar angular shapes. The positions of the relative maxima occurring in these curves are reminiscent of ℓ=2 angular shapes; however, the deep minimum occurring 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 discribing 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 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 $3/2^+$ 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 $\ell=0$ character. The angular distributions of the remaining two members of this band exhibit a characteristic $\ell=2$ 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 of two additional states were also determined in this study and appear in Fig. 2 under the heading: "Other States". The 325-keV state appearing in ^{159}Tb(p,t) spectra is a relatively low intensity peak which exhibits no apparent relationship to any other peaks in this energy region and exhibits an angular dependence which is in no way related to any single dominant angular momentum transfer. Although the energy uncertainty for the 325-keV state is rather large because of the low statistics associated with it, this state probably corresponds to the 326.4-keV $5/2^-[523]$ proton excitation. Since this negative parity state cannot be Coriolis coupled with the $K^\pi=3/2^+$ ground-state band, its cross section is most certainly a measure of the strength of indirect, multiple-step processes accompanying the (p,t) reaction in the present system. This subject will be dealt with in more detail in another report.

The 1238-keV peak, on the other hand, is a highly intense, strongly populated peak which might have a composite nature. The angular distribution of this peak appears to have a dominating $\ell=2$ angular shape. However, since this peak occurs at or above the pairing gap in this nucleus, nothing really can be said about its origin based on these data alone.

References

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Figure Captions

Figure 1. ^{159}Tb(p,t) spectrum taken at the laboratory scattering angle of 20°. Members of the ground, γ and β vibrational bands are labeled with unprimed, primed, and doubly primed spins, respectively.

Figure 2. Angular distributions of some states populated through the ^{159}Tb(p,t) reaction at 30 MeV. Theoretical two-neutron pick-up and cluster-transfer calculations are represented by continuous and broken 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.

Table I. States Populated Through the ^{159}Tb(p,t) Reaction

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]
1276±10	---	---	---
1318±10	---	---	---
1352±10	---	---	---
1417±5	---	---	---
1454±10	---	---	---
1487±5	---	---	---
1535±10	---	---	---
1578±10	---	---	---
1602±10	---	---	---
1631±10	---	---	---
1659±10	---	---	---
1695±10	---	---	---
1749±10	---	---	---

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

[b] I = member of ground-state rotational band; I' = member of $K=K_o-2$ γ vibrational band. I'' = member of $K=K_o$ β vibrational band.

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

[d] 1238 keV peak could possibly have a small component due to the presence of the $9/2^+$ member of the β vibrational band.

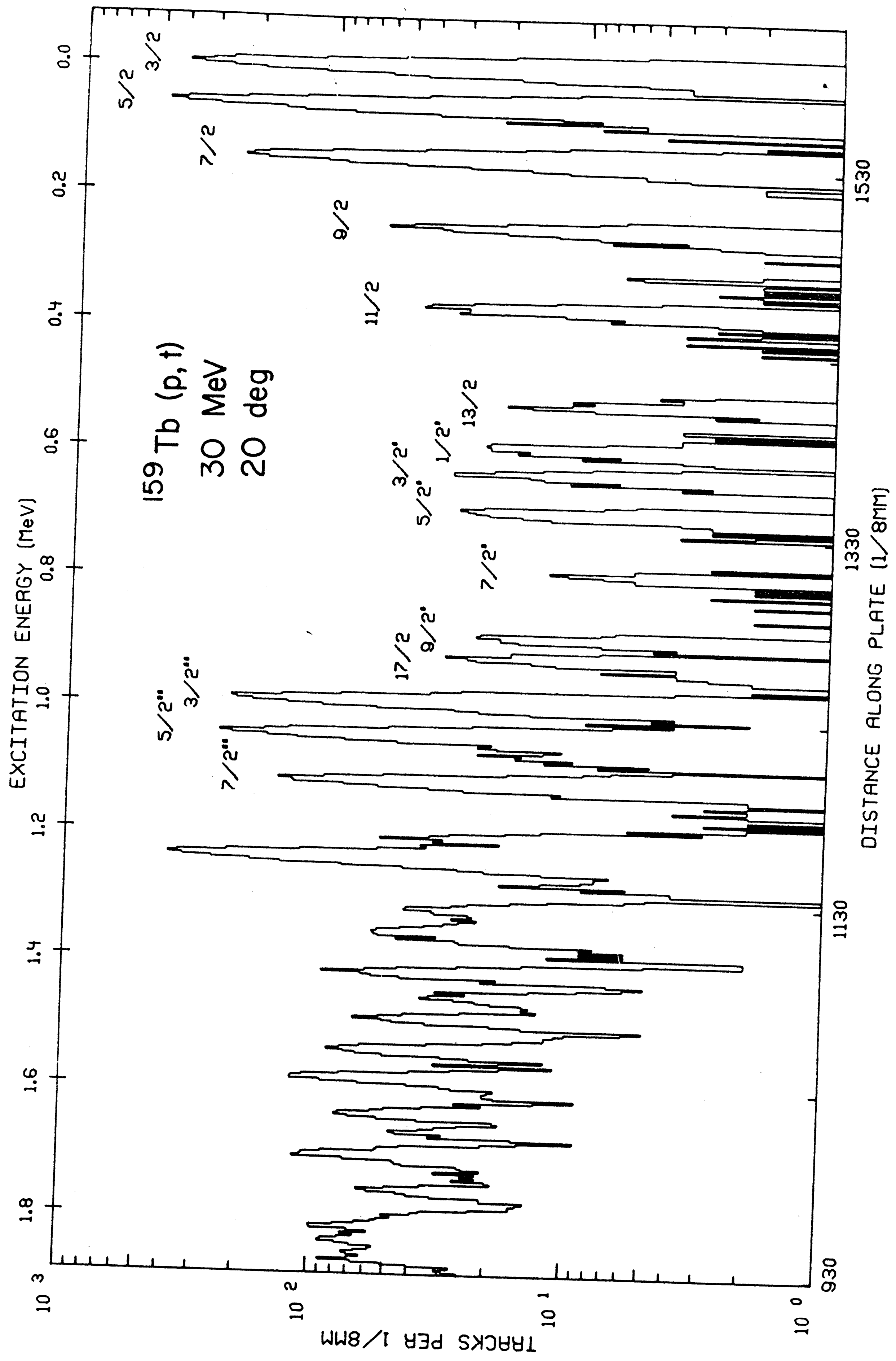
159 Tb (p, t)
30 MeV
20 deg
EXCITATION ENERGY (MeV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DISTANCE ALONG PLATE (1/8MM)
1530
1330
1130
930
TRACKS PER 1/8MM
10 3
10 2
10 1
10 0
5/2
3/2
7/2
9/2
11/2
13/2
1/2'
3/2'
5/2'
7/2'
9/2'
17/2
5/2"
3/2"
7/2"

Figure 1

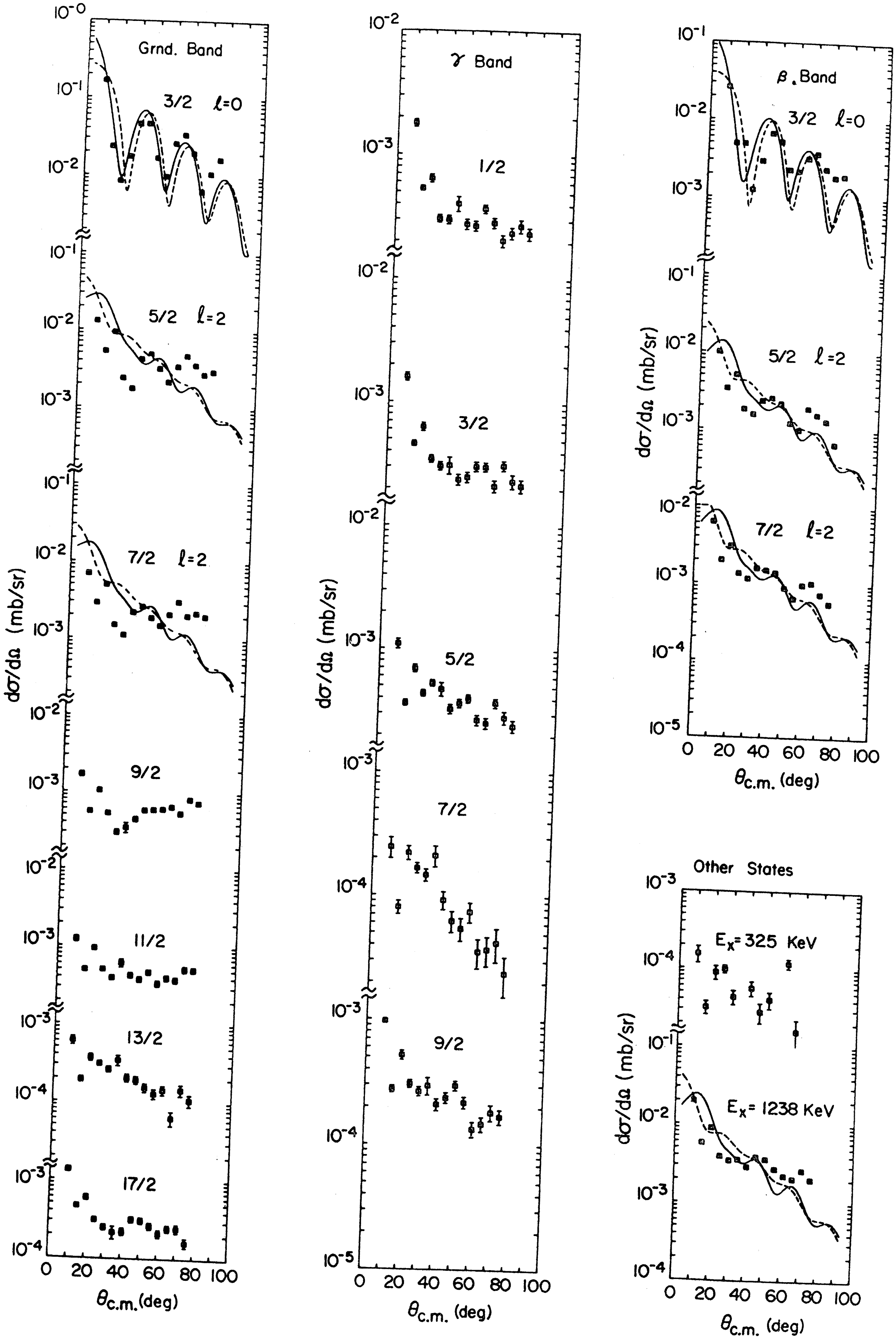
Grnd. Band
3/2 ℓ=0
5/2 ℓ=2
7/2 ℓ=2
9/2
11/2
13/2
17/2
γ Band
1/2
3/2
5/2
7/2
9/2
β Band
3/2 ℓ=0
5/2 ℓ=2
7/2 ℓ=2
Other States
E_X = 325 KeV
E_X = 1238 KeV
dσ/dΩ (mb/sr)
θc.m. (deg)
0 20 40 60 80 100
10^-0
10^-1
10^-2
10^-3
10^-4
10^-5

Figure 2