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Abstract

High angular momentum states in ^{196,197}Bi were populated in the reaction ^{183}W(^{19}F,xn) at a beam energy of 108 MeV, and γ–rays were detected with the Gammasphere array. Two weakly populated rotational bands, with energy spacings characteristic of superdeformation have been found. Both cascades can be assigned unambiguously to the Bi nuclei; however, their isotopic assignment to ^{197}Bi is tentative. The properties of the bands and their possible structures are discussed. Our results represent the first identification of superdeformed bands in a nucleus of the A$\sim$190 mass region with Z>82.

An impressive experimental and theoretical effort has been devoted to exploring the underlying physics of superdeformation in the A$\sim$190 region. Over 40 superdeformed (SD) bands have been identified in the Au, Hg, Tl, and Pb nuclei [1, 2, 3]. The most readily measured experimental quantities for these sequences are the transition energies and intensities. In particular, transition energies, E_γ, can be used to deduce the dynamic moment of inertia, $\Im^{(2)}$, and the behaviour of this quantity can then be compared directly with theory to give information on the underlying microscopic structure of the bands. The $\Im^{(2)}$'s for most of the bands in the A$\sim$190 region show a steady rise with increasing rotational frequency, ω. The quadrupole moments of states in several bands have been established through lifetime measurements [4, 5, 6, 7, 8, 9]. These results confirm the superdeformed nature of the structures and also show that the deformation remains constant over all the states in the measurement range. This suggests that the rise in $\Im^{(2)}$ is not due to centrifugal stretching which would lead to a change in deformation over the band. Instead, the behaviour of $\Im^{(2)}$ has been associated with the gradual alignment of pairs of nucleons occupying specific high–N intruder orbitals (namely, $j_{15/2}$ neutrons and $i_{13/2}$ protons) in the presence of pair correlations [10]. However, mean field calculations with a monopole pair field have not been able to reproduce accurately the absolute magnitudes and slopes of the $\Im^{(2)}$'s [11].

Until the present work, no SD bands had been found in nuclei of the A$\sim$190 region with Z>82, despite many theoretical calculations (see e.g. [12, 13] and references therein) predicting well defined secondary SD minima persisting in the bismuth nuclei. Investigating superdeformation in these isotopes should provide the first experimental evidence concerning the nature of the proton orbitals above Z=82 at large deformation ($\beta_2 \simeq 0.48$). In this work we describe results from a recent experiment aimed at exploring superdeformation in ^{196,197}Bi. High–spin states in these nuclei were populated via the ^{183}W(^{19}F,xn) reaction at an incident beam energy of 108 MeV. The beam, which was provided by the 88–Inch Cyclotron facility at the Lawrence Berkeley Laboratory, was incident on a target consisting of 2×300 μgcm^{-2} stacked ^{183}W foils mounted on thin carbon backings. Gamma–rays were detected with the Gammasphere array [14] which, for this experiment, comprised 36 Compton–suppressed large–volume (~75–80% efficient) HPGe detectors. A total of 8×10^8 three– and higher–fold events were collected.

Two sequences of γ–rays, with properties characteristic of SD bands in this mass region, have been observed. Spectra showing the two bands are presented in fig. 1, while the transition energies are summarized in table 1. The insets of fig. 1 show the relative intensities of the in–band transitions. These show behaviour common to all the SD bands in the A~190 region. Feeding occurs over the top half–dozen transitions or so, followed by a region in which the in–band states are fully fed and the intensity is constant. A rapid depopulation of the band occurs from the lowest one or two levels.

The dominant open channels in the reaction are predicted, by statistical models, to be the 5n (^{197}Bi) and 6n (^{196}Bi) channels, taking approximately 54% and 28% of the total cross–section respectively. The only other channel populated with significant intensity is predicted to be the α4n (^{194}Tl) channel taking approximately 7% of the reaction cross–section. None of the known SD bands in ^{194}Tl [15] were observed in our data, implying that the two new bands are in the Bi nuclei. This is established from the coincidence of the in–band transitions with Bi X–ray lines (see fig. 1). The decay schemes of ^{196,197}Bi are not well known. In addition, the presence of long–lived isomers at low–spin [16, 17] prevented the observation of any low–lying transitions in prompt coincidence with either of the bands. We are therefore unable to establish the mass assignments unambiguously. However, since the reaction was optimized to populate SD states in ^{197}Bi we favour this assignment for both structures. We estimate the upper limit of the total intensity of band 1 to be ~2% of the total 5n reaction channel, while band 2 has ~50% the intensity of band 1.

Fig. 2a shows plots of the $\Im^{(2)}$ moments of inertia for the two bands and also for the known SD bands in the isotones ^{196}Pb [6, 18, 19]and ^{195}Tl [20, 21]. At rotational frequencies above $\omega \simeq 0.2$ MeV$\hbar^{-1}$ the $\Im^{(2)}$ for band 1 has a reduced slope when compared with that of any of the other bands. The $\Im^{(2)}$ of band 2 is very similar to that of band 1 in ^{195}Tl. Indeed, on closer inspection, band 2 in ^{197}Bi and band 1 in ^{195}Tl have 'identical' transition energies (to within ±2 keV) over a sizeable spin range. This can be seen from table 1, which also summarizes the energies for band 1 in ^{195}Tl, and from fig. 2b which shows the difference in transition energies between these two bands.

Estimates of the spins of states in the two bands were made using the method described in [22, 23]. The 166 keV γ–ray of band 1 decays to a level with a fitted spin of 6.4(1) $\hbar$ (I=13/2 $\hbar$, to the closest half–integer value), while the 187 keV γ–ray of band 2 decays to a level with a fitted spin of 7.5(1) $\hbar$ (I=15/2 $\hbar$). Since the fitting procedure yields spins that are very nearly half–integer, the assignment of the bands to ^{197}Bi gains further support. Note also that the spins of the levels in the two bands differ by 1 $\hbar$. This may indicate that the two bands are signature partners. From the energies of the two bands (table 1) it can be seen that band 2 starts approximately at the half points of band 1. However, following the band up in spin the deviation of band 2 from the half points of band 1 steadily increases. This is illustrated in fig. 2b. This indicates that if the bands are signature partners they show some signature splitting. No evidence of 'cross–talk' [24, 25, 26, 21] between the two bands could be found.

The detailed spectroscopic behaviour of a band in an odd–Bi nucleus is principally determined by which state contains the odd proton relative to the neighbouring even–Pb core (^{196}Pb in the case of ^{197}Bi). Fig. 3a presents a single–particle Woods–Saxon calculation for protons with deformation parameters β_2=0.48, β_4=0.07, and γ=0° (a representative deformation for SD bands in the A∼190 region; the values come from the calculations described in [13]). The calculation indicates that the [514]9/2, [651]1/2, and [642]5/2 orbitals all lie close to the Fermi surface. As discussed above, pairing plays an important role in determining the behaviour of SD bands in the A∼190 region. Presented in fig. 3b is a quasiproton routhian diagram calculated for the parameters β_2=0.48, β_4=0.07, γ=0°, and Δ_p=$\Delta_{BCS}(\omega$=0). The inclusion of pairing smears the Fermi surface and the calculation indicates that one quasiproton excitations involving the [642]5/2, [514]9/2, and [651]1/2 levels are all energetically possible. Bands based on these states should be easy to distinguish experimentally.

The lowest calculated one quasiparticle excitations are to the [642]5/2 ($i_{13/2}$) signature partner levels. There is a small splitting between the two signature partners which increases with increasing rotational frequency. The inset of fig. 3b shows experimental routhians for the two bands. Over the experimentally observed range the two new bands do display a splitting in the transition energies (see also fig. 2b). The [642]5/2 orbital is thought to be involved in the configurations of SD bands in the Tl nuclei [15, 20, 27, 28]. Therefore, one might reasonably expect that the $\Im^{(2)}$'s of the ^{197}Bi bands should be similar to those of the bands in ^{195}Tl (an isotone). Indeed, as already noted band 2 in ^{197}Bi and band 1 in ^{195}Tl have 'identical' transition energies over a significant range of spin. However, band 1 in ^{197}Bi has a much flatter $\Im^{(2)}$ above $\omega \simeq 0.2$ MeV$\hbar^{-1}$ than those of the ^{195}Tl bands, which is not easy to explain. There are further problems with this interpretation. The signature partner pair of bands in ^{195}Tl [20, 21] which are based on the [642]5/2 orbital are populated with similar intensities. In addition, dipole cross–talk between these bands in ^{195}Tl has been observed [21]. Neither of these features are seen for our new bands.

The [514]9/2 state should give rise to a strongly coupled structure with K=9/2 (two signature partners with very little signature splitting). The strong coupling model predicts a large B(M1) strength ($\sim$1.9 μ_N^2) [24] which should lead to the observation of strong dipole 'cross–talk' transitions between the two signature partner bands. Furthermore, the two signature partners should have $\Im^{(2)}$ moments of inertia similar to that of the SD band in ^{196}Pb [6, 18, 19] since the intruder occupation is the same ($\nu 7^4 \pi 6^6$). Clearly, none of these features are displayed by the two bands we observe.

The [651]1/2 ($i_{11/2}$) orbital is also an energetically possible one–quasiparticle excitation. This orbital is expected to exhibit immediate signature splitting with the α=–1/2 partner being favoured. The splitting is predicted by the calculation to increase rapidly with increasing rotational frequency. The experimental routhian in fig. 3b indicates that the actual splitting of the two bands is much less and starts later. It is possible that the two new bands are not signature partners. If both the bands are in ^{197}Bi and are not signature partners then it is necessary to invoke a missing band, since at least one configuration must then involve a strongly coupled orbital (either [642]5/2 or [514]9/2). Another possibility is that band 1 is in ^{197}Bi and band 2 is in ^{196}Bi.

One further comment should be made concerning the behaviour of the $\Im^{(2)}$ moments of inertia. The $\Im^{(2)}$'s for the two new bands have much lower slopes than that for the band in ^{196}Pb (see fig. 2a). The odd proton could block the $i_{13/2}$ quasi–proton alignments, flattening the $\Im^{(2)}$'s relative to that of ^{196}Pb. However, the $j_{15/2}$ quasi–neutron alignments should still contribute to the rise in $\Im^{(2)}$. If the bands were in ^{196}Bi (an odd–odd nucleus) then the $j_{15/2}$ quasi–neutron alignments may also be blocked giving a much flatter $\Im^{(2)}$. It should be noted that several SD bands in ^{193,195}Pb [29, 30] have also been found which have similar, exceptionally flat, $\Im^{(2)}$'s. These bands are thought to have the $j_{15/2}$ quasi–neutron alignments blocked by an odd neutron. This behaviour of the $\Im^{(2)}$'s must be addressed, both experimentally and theoretically, in future studies.

To summarize, an experiment with the Gammasphere array using the ^{183}W(^{19}F,xn) reaction at a beam energy of 108 MeV has resulted in the observation of two new SD bands. The new bands can be unambiguously assigned to the Bi nuclei, but the isotopic assignments to ^{197}Bi are tentative. Our results represent the first observation of superdeformed bands in the A$\sim$190 region with Z>82. A number of important experimental questions remain. Firstly, the isotopic and configuration assignments of the bands must be unambiguously established. Secondly, the superdeformed nature of these structures needs to be confirmed through lifetime measurements. Thirdly, SD sequences in other Bi isotopes must be found in order to probe further the nature of the orbitals close to the proton Fermi surface at extreme deformation.

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Table 1: Transition energies (in keV) for the two SD bands in ^{197}Bi. Also given, in the third column, are the transition energies of band 1 in ^{195}Tl. For comparison, this latter set of energies are shown only over the observed frequency range of band 2.

Band 1	Band2	^{195}Tl (Band 1)
166.2(2)		
208.0(2)	186.7(2)	188.0(4)
249.7(2)	229.1(2)	228.8(3)
291.3(2)	269.6(2)	270.0(3)
332.6(2)	310.0(2)	310.5(3)
373.8(2)	351.1(2)	349.9(3)
414.3(2)	390.7(2)	389.8(3)
455.0(2)	430.8(2)	428.9(3)
495.2(2)	468.5(2)	467.2(3)
535.4(2)	507.1(4)	504.5(3)
574.3(2)	545(1)	540.8(3)
614.3(4)		
653(1)		

Figure Captions

Figure 1a: A sum of triple–gated spectra from four–fold coincidence data for Band 1. The inset in the top right shows the relative intensities of transitions in the band, while the inset in the top left shows the coincident Bi X-rays.

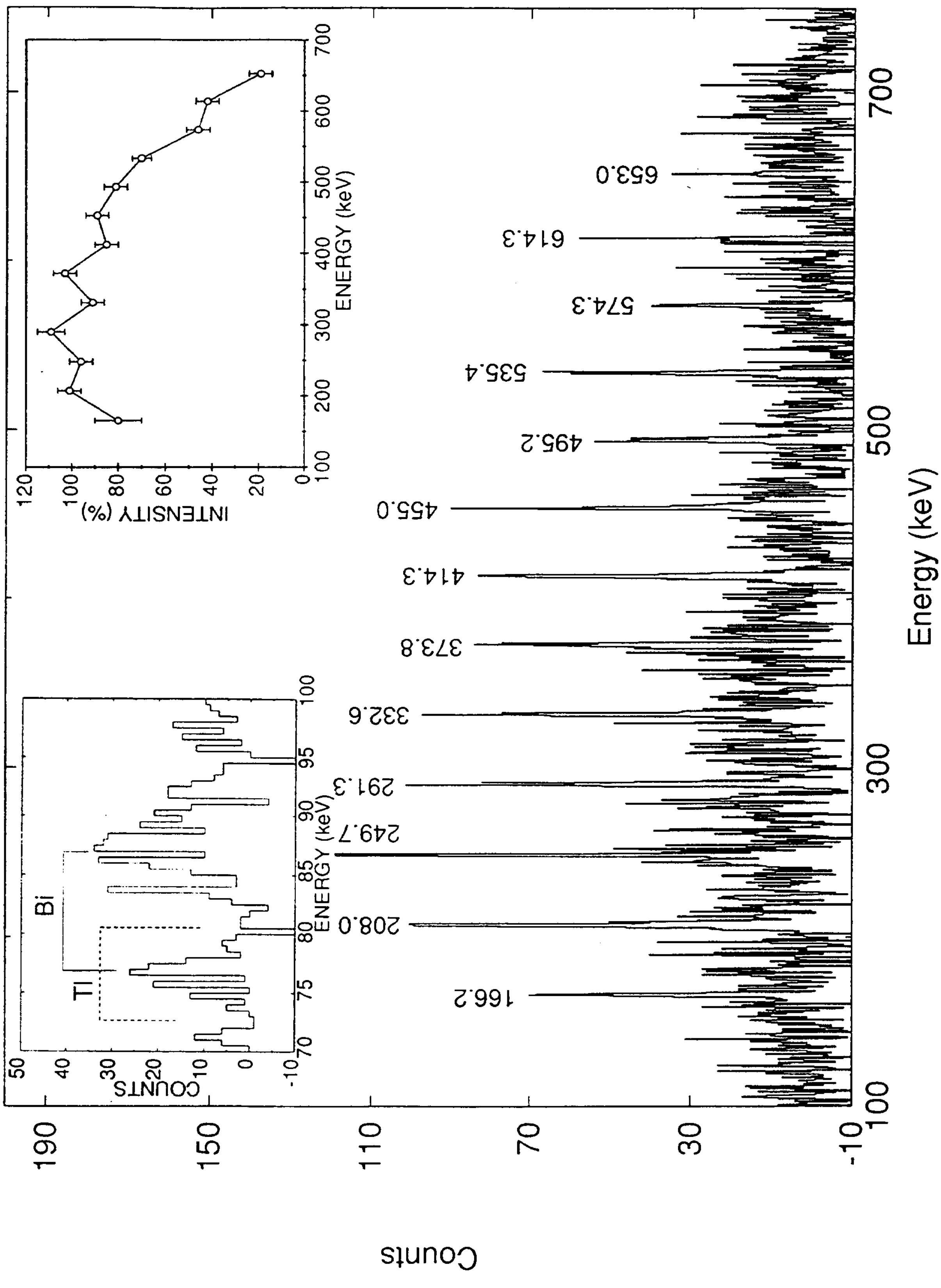
Figure 1b: A sum of double–gated spectra from three–fold coincidence data for Band 2. The inset in the top right shows the relative intensities of transitions in the band, while the inset in the top left shows the coincident Bi X-rays.

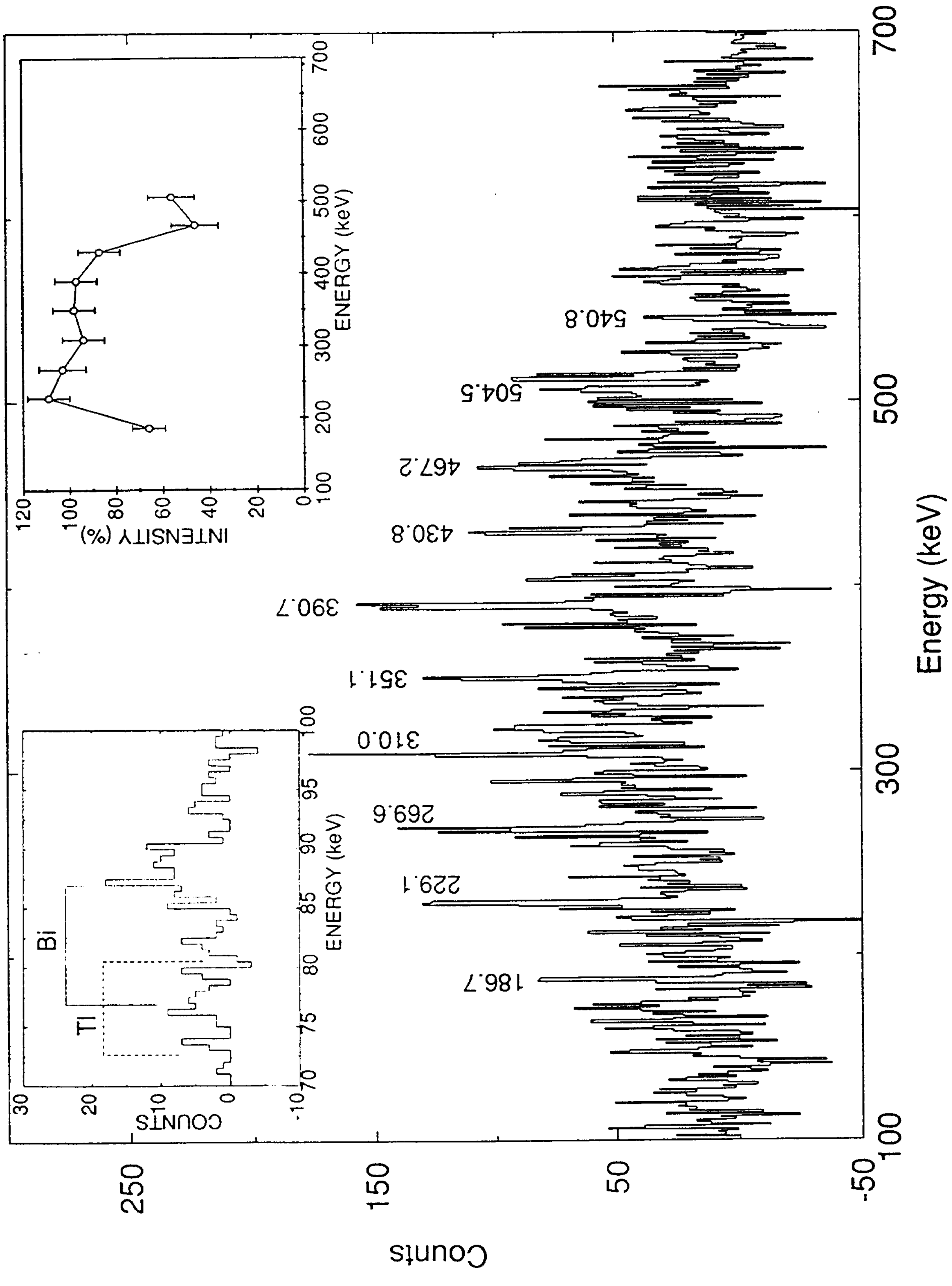
Figure 2a: Plots of the dynamic moments of inertia, $\Im^{(2)}$, as a function of rotational frequency for Band 1 (open circles), Band 2 (closed circles), the SD band in ^{196}Pb (closed squares), and SD bands 1 and 2 in ^{195}Tl (open and closed triangles, respectively).

Figure 2b: Plots showing the difference in transition energies between: i) the half–points of Band 1 and Band 2 (open circles), and ii) Band 2 and band 1 in ^{195}Tl (closed circles).

Figure 3a: Cranked Woods–Saxon single–particle diagram for protons. The deformation parameters used were: β_2=0.48, β_4=0.07, and γ=0.0°. Parity and signature (π,α) of the levels are indicated in the following way: solid=(+,+1/2), dotted=(+,–1/2), dot–dashed=(–,+1/2), and dashed=(–,–1/2).

Figure 3b: Cranked Woods–Saxon quasiparticle diagram for protons. The deformation parameters used were the same as those for figure 3a, while the pairing parameter was taken as Δ_p=$\Delta_{BCS}(\omega$=0). Parity and signature are indicated in the same manner as figure 3a. The inset shows the experimental routhians for the two new bands. A rigid rotor reference with the Harris parameter J$_0$=94.0 $\hbar^2$MeV^{-1} was subtracted. The absolute energy scale is arbitrary and the relative excitation energies of the bands in the diagram assumes that they are signature partners (degenerate at zero rotational frequency).


Counts
190
150
110
70
30
-10
100
300
500
700
Energy (keV)
166.2
208.0
249.7
291.3
332.6
373.8
414.3
455.0
495.2
535.4
574.3
614.3
653.0
COUNTS
50
40
30
20
10
0
-10
70
75
80
85
90
95
100
ENERGY (keV)
Tl
Bi
INTENSITY (%)
120
100
80
60
40
20
0
100
200
300
400
500
600
700
ENERGY (keV)


Counts
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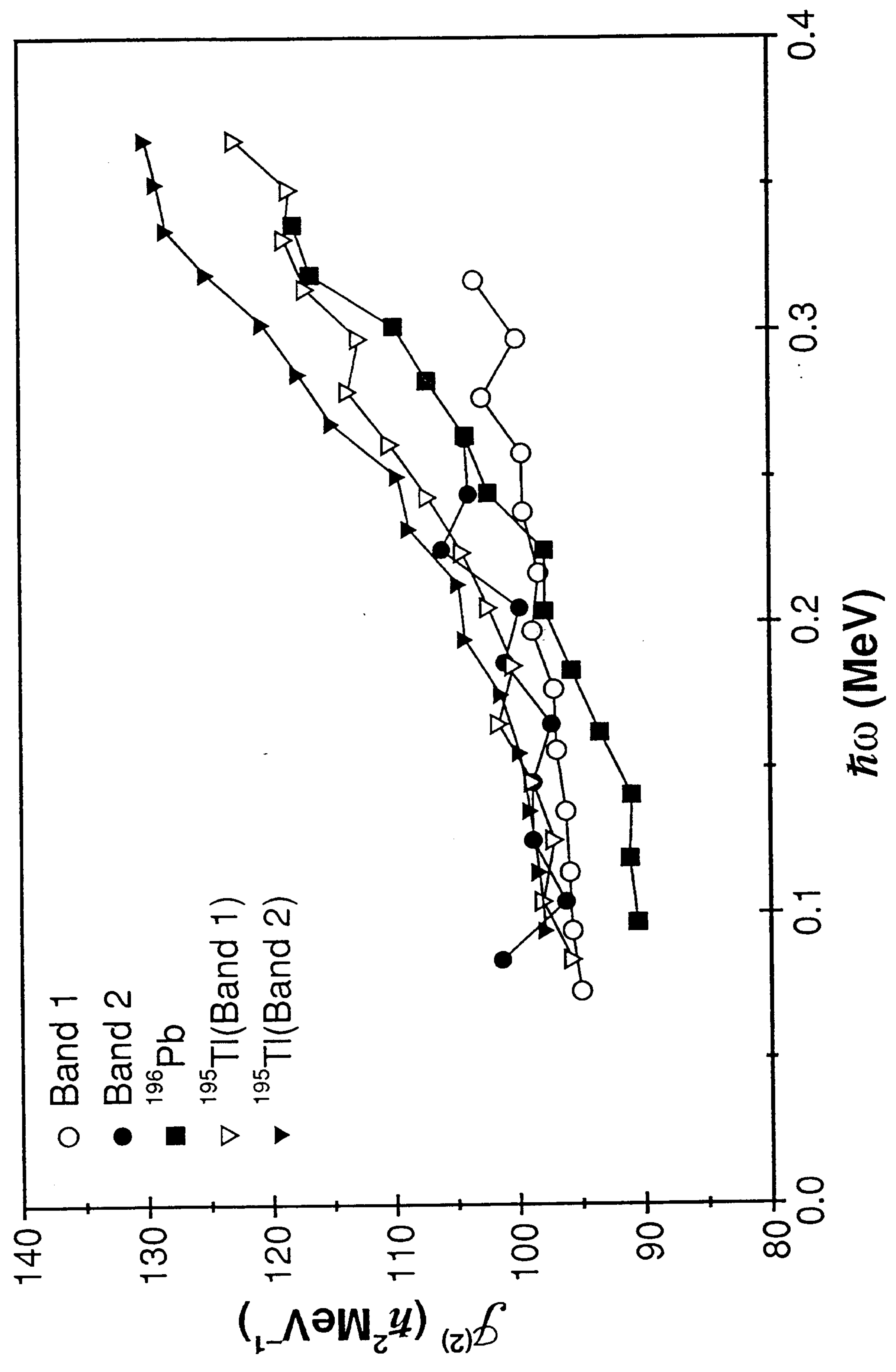
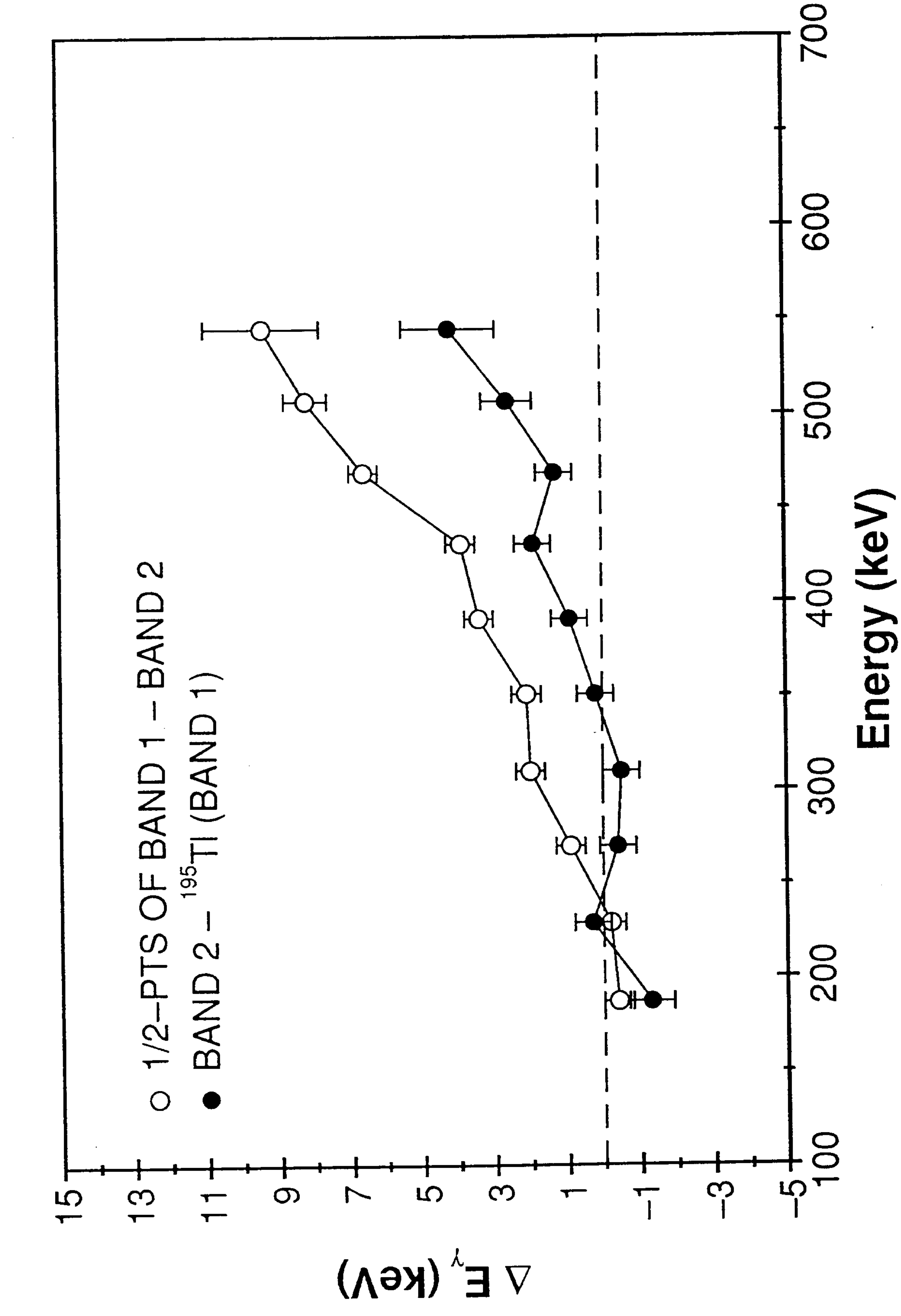
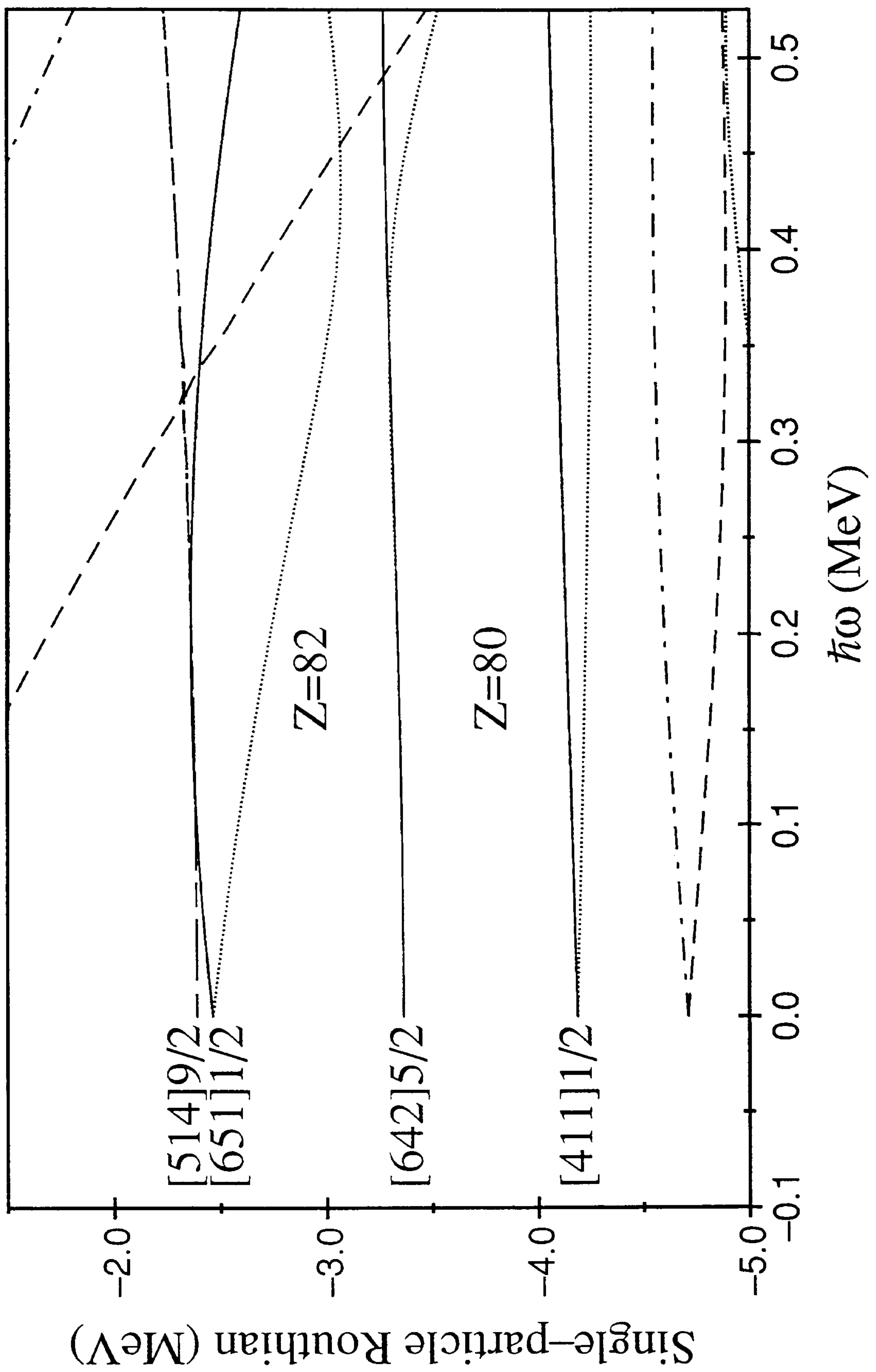
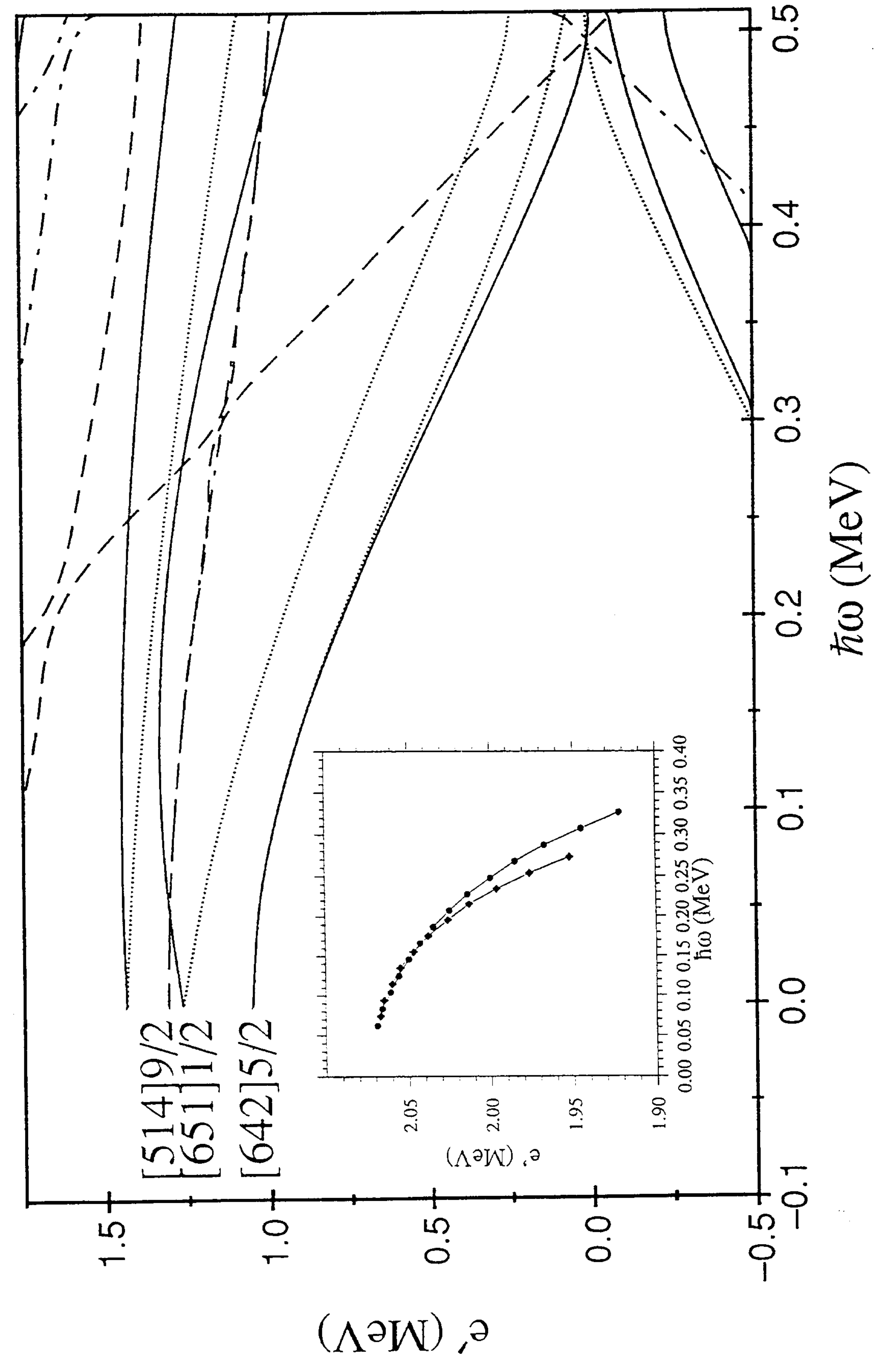
-50
100
300
500
700
Energy (keV)
186.7
229.1
269.6
310.0
351.1
390.7
430.8
467.2
504.5
540.8
COUNTS
30
20
10
0
-10
70
75
80
85
90
95
100
ENERGY (keV)
Tl
Bi
INTENSITY (%)
120
100
80
60
40
20
0
100
200
300
400
500
600
700
ENERGY (keV)


Band 1
Band 2
^{196}Pb
^{195}Tl(Band 1)
^{195}Tl(Band 2)
$\mathcal{J}^{(2)}$ ($\hbar^2$MeV^{-1})
ħω (MeV)
140
130
120
110
100
90
80
0.0
0.1
0.2
0.3
0.4


○ 1/2–PTS OF BAND 1 – BAND 2
● BAND 2 – ^{195}Tl (BAND 1)
ΔE_γ (keV)
15
13
11
9
7
5
3
1
−1
−3
−5
100
200
300
400
500
600
700
Energy (keV)


Single–particle Routhian (MeV)
−2.0
−3.0
−4.0
−5.0
ħω (MeV)
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
[514]9/2
[651]1/2
[642]5/2
[411]1/2
Z=82
Z=80


[514]9/2
[651]1/2
[642]5/2
e' (MeV)
1.5
1.0
0.5
0.0
−0.5
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
ħω (MeV)
e' (MeV)
2.05
2.00
1.95
1.90
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
ħω (MeV)