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## Abstract

A superdeformed band has been observed in the N = 80 nucleus $^{145}$Tb which was produced with the reactions $^{112}$Sn($^{37}$Cl,$2p2n$) and $^{118}$Sn($^{31}$P,$4n$) at bombarding energies of 187 MeV and 160 MeV, respectively. Since superdeformed bands also exist in the three lighter N = 80 isotones $^{142}$Sm, $^{143}$Eu, and $^{144}$Gd, it is now possible to understand the valence-proton configurations of these bands in a systematic way. The $\mathcal{J}^{(2)}$ dynamic moment of inertia in $^{145}$Tb shows no evidence for the $N = 6$ quasiproton crossing that is observed in

$^{144}$Gd. Comparison with Cranked Woods-Saxon and Total Routhian Surface calculations suggests that the proton configuration in $^{145}$Tb is $6^1\otimes[404]^2_{9/2^+}$ in which the quasiproton crossing is blocked. Furthermore, like $^{143}$Eu and $^{142}$Sm, there is no evidence in the $\mathcal{J}^{(2)}$ for the $N=6$ quasineutron crossing predicted by the calculations. This may indicate that static neutron pairing-correlations are quenched at the N = 80 superdeformed shell closure.

27.60.+j, 23.20.Lv, 21.10.Re, 21.60.Ev

The observation of superdeformed (SD) bands in nuclei seems to be correlated with "favoured" particle numbers [1]. This favourability is believed to be due to quantal shell-corrections that arise from energy gaps at these particle numbers for superdeformed shapes. In general, these gaps remain even when the nucleus is rotated, save for a few high-$j$ "intruder" orbitals which cross these regions of low level density. The appearance of the intruder orbitals in superdeformed nuclei arises from the combined influence of large distortion and rapid rotation. Thus, there are two basic ingredients that underpin our understanding of superdeformed bands: shell gaps to stabilize the shape, and intruder orbitals which determine the level spacing in the bands through their contribution to the $\mathcal{J}^{(2)}$ dynamic moment of inertia.

In the familiar spherical closed-shell nuclei, pairing correlations are not important, since there is insufficient energy in the two-body interaction to scatter time-reversed pairs from the vicinity of the Fermi Surface up to the next major shell [2]. Shell gaps at superdeformed shapes may be expected to quench pairing correlations in a similar way. For instance, a large gap is predicted to occur at N = 80 in calculations based on either a Woods-Saxon [3] or a Nilsson [4] potential. The gap is centred on a quadrupole deformation of $\beta_2 \simeq 0.5$. Conjugate gaps exist at Z = 62 and 64, and indeed superdeformed bands have been found in the three N = 80 isotones $^{142}$Sm [5], $^{143}$Eu [6,7] and $^{144}$Gd [8], which have proton number Z = 62, 63 and 64, respectively. The band in $^{144}$Gd shows clear evidence for the effect of proton pairing correlations, since a quasiproton band-crossing is observed. Cranked-Woods-Saxon-Strutinksy calculations predict such a crossing to take place [3]. This crossing is blocked in $^{143}$Eu and $^{142}$Sm, but there is no evidence for a predicted quasineutron crossing. In order to further investigate the favourability of the N = 80 gap and the importance of pairing correlations thereof, it was decided to search for superdeformation in the next N = 80 isotone, $^{145}$Tb.

Some transitions that connect "normal-deformed" states in $^{145}$Tb have been reported in a previous study [9]. Two different fusion-evaporation reactions were employed in the present investigation of $^{145}$Tb. In the first experiment, a beam of $^{37}$Cl ions was provided at an energy of 187 MeV by the upgraded MP tandem accelerator of the TASCC facility at the Chalk River Laboratories of AECL Research. The target consisted of a stack of two $\sim$500$\mu$g/cm$^2$ foils enriched to $\sim$98% in $^{112}$Sn. States in $^{145}$Tb were populated via the $2p2n$ exit channel. The major competition came from $^{145}$Gd [10] ($3pn$), and $^{142}$Gd [9] ($\alpha p2n$). Charged-particle-$\gamma$-$\gamma$ coincidences were collected. The $\gamma$-rays were detected by the $8\pi$ spectrometer, which comprises twenty Compton suppressed HpGe detectors, and a seventy element bismuth germanate (BGO) inner calorimeter from which sum-energy/fold (H/K) information was obtained. A minimum of ten BGO-elements had to fire for the event to be accepted. Charged particles were detected by the ALF-miniball [11] located inside the $8\pi$ spectrometer.

The second $8\pi$ experiment was also undertaken at TASCC with the reaction $^{118}$Sn($^{31}$P,$4n$)$^{145}$Tb at 160 MeV, this time without the ALF-miniball. A target of two $\sim$500$\mu$g/cm$^2$ foils enriched to $\sim$98% in $^{118}$Sn was used. At least ten elements of the BGO-ball plus two HpGe detectors had to fire in prompt coincidence for the event to be accepted. Furthermore, a TDC signal was recorded if a second burst of $\gamma$ rays followed within $\sim$30 nanoseconds of the prompt trigger, such that the number of BGO-ball elements that responded was $8 \geq \mathrm{K_{delay}} \geq 2$. This arrangement was sensitive to isomeric decays with half-lives in the range of $\sim$40-700 nanoseconds, provided the delayed burst had sufficient multiplicity to satisfy the delayed-trigger requirement.

Approximately 75 million events were selected off-line from the first data-set under the conditions of H(MeV) $\geq$ 10 from the BGO-ball, and proton multiplicity $1 \leq M_p \leq 2$ and $\alpha$-particle multiplicity $M_\alpha = 0$ from the ALF-miniball. The energies of the coincident pair recorded in the HPGe array were stored in an $E_\gamma$-$E_\gamma$ correlation matrix in which the ratio of counts in $^{145}$Tb to those in $^{142}$Gd was roughly 2-to-1. Other nuclei ($^{145}$Gd [10], $^{145}$Dy [9], $^{144}$Tb [9], $^{144}$Dy [9]) were present at levels of 10-to-20% of $^{145}$Tb. A candidate for a superdeformed band of ten transitions separated by $\sim$59 keV was found with the computer codes BANDAID [12,13] and SDSLICE [13]. This was tentatively assigned to $^{145}$Tb. There was no evidence for the candidate in a matrix gated by an $\alpha$-particle, which suggested that the candidate did not belong to $^{142}$Gd.

No evidence was found in the second data-set for isomeric decays in $^{145}$Tb which had lifetimes that would initiate the delayed trigger. Hence, channel-selection was obtained from the prompt condition of H(MeV) $\geq 18$ in the BGO-ball. The resultant matrix contained 160 million events, which were split amongst $^{145}$Tb ($4n$), $^{145}$Gd ($p3n$) and $^{142}$Eu [14] ($\alpha 3n$). The candidate was confirmed and extended to fourteen transitions. A summed coincidence spectrum is shown in figure 1. Despite the reduction in background due to the high-H condition, the lower portion of the spectrum from roughly 550-to-950 keV is heavily contaminated, but the higher portion of the spectrum is relatively free of this problem. The total projection of the $\gamma$-$\gamma$ matrix over this region (inset in figure 1) shows that no large peaks obscure the higher-energy SD transitions.

In general, the assignment of a superdeformed band to a nucleus through $\gamma$-$\gamma$ coincidences is not straightforward [13]. This difficulty is compounded in the present case by the fact that there are strong contaminants to $^{145}$Tb in both data sets, even after offline software-filters have been employed. In particular, $^{145}$Gd was populated in both reactions, but previous studies with the $8\pi$ spectrometer [13] did not find any evidence for superdeformed bands in this nucleus. Since these earlier experiments populated $^{145}$Gd via (HI,x$n$) reactions, $^{145}$Tb was, of course, not present. There was no evidence for the new band in these data-sets, and hence the possibility that the band belongs to $^{145}$Gd was discounted. A check on new $8\pi$-data in which $^{142}$Eu was populated via $5n$-evaporation ruled out this possibility in a similar fashion. Hence, the band is assigned to $^{145}$Tb, and is estimated to be populated with a maximum intensity of ~1% relative to the channel.

The $\mathcal{J}^{(2)}$ moment of inertia has been extracted from the differences in transition energies and is displayed in figure 2(a). Shown for comparison are the $\mathcal{J}^{(2)}$ moments of inertia for the SD bands in the other N = 80 isotones, $^{142}$Sm, $^{143}$Eu and $^{144}$Gd. The rise in the $\mathcal{J}^{(2)}$ for $^{144}$Gd is clearly lacking in $^{145}$Tb, as it also is in $^{143}$Eu and $^{142}$Sm. This is a strong indication that the $N = 6$ ($N$ is the major oscillator shell quantum number) quasiproton crossing that causes the $\mathcal{J}^{(2)}$ to rise in $^{144}$Gd is blocked in $^{145}$Tb, as it is in $^{142}$Sm and $^{143}$Eu. This suggests that the proton intruder configuration[1] for the band in $^{145}$Tb is either $\pi 6^1$ like $^{142}$Sm and $^{143}$Eu, or $\pi 6^3$ as in the heavier Tb isotopes. The former configuration would be expected to occur at a deformation similar to that of the other N = 80 isotones, while the latter would be favoured at a larger deformation, similar to the SD bands near A = 150. Both configurations have $(\pi,\alpha) = (+,+1/2)$, and so will be encompassed in Total Routhian Surface (TRS) calculations [3] for this parity-signature specification. The TRS calculations show that a superdeformed (SD) minimum with deformation parameters of $(\beta_2,\beta_4,\gamma) = (0.48,0.05,1.8^\circ)$, becomes yrast at I $\simeq$ 47 $\hbar$ as shown in figure 3(a). These deformation-parameters were used to determine the Woods-Saxon potential from which quasiparticle levels in $^{145}$Tb were generated by the deformation average, pairing self-consistent method [3]. The monopole pairing-gap was determined separately at each frequency by variation after particle-number projection. The $\mathcal{J}^{(2)}$ moment of inertia was extracted from these quasiparticle levels for the yrast $(\pi,\alpha) = (+,+1/2)$ proton-configuration in $^{145}$Tb. For completeness, the calculations were extended to cover the three other N = 80 isotones. In each case, the deformation-parameters were taken from a TRS calculation for the correct configuration. A Strutinksy renormalisation radius [3] of 1.27 fm was employed, which is about half the correction taken for the A = 150 SD bands. The theoretical predictions are displayed as full lines in figure 2 , along with the experimental data.

The most important feature to note is that the quasiproton crossing does not occur in the calculation for $^{145}$Tb. In fact, the only band-crossing that is predicted to occur is that which arises from the alignment of $N = 6$ quasineutrons. This crossing gives the large hump centred near $\hbar\omega \simeq 0.35$ MeV in the calculations presented in figure 2. There is no experimental evidence for this crossing neither here in $^{145}$Tb nor in $^{142}$Sm or $^{143}$Eu. The quasiproton crossing obscures any evidence for this effect in $^{144}$Gd. Previously the

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[1] The individual intruder orbitals are labelled as $N_m$, while the number of occupied intruder orbitals is denoted by $N^m$.

absence of the hump has been attributed to a strong residual neutron-proton interaction between the proton intruder and the aligning $N = 6$ quasineutrons. This is inferred from the observation of similar perturbed band-crossings in high-$j$ intruder bands in the A $\simeq$ 110 [15] and $\simeq$ 130 regions [16]. Though this may also be the case in the N = 80 superdeformed bands, it is conceivable that the neutron pairing correlations are too weak to excite a pair of quasiparticles. In other words, there is no quasineutron crossing, and hence no hump in the $\mathcal{J}^{(2)}$ moments of inertia. The large (~1.2 MeV) gap at N = 80 (see [3]) does suggest that static neutron-pairing correlations should be very weak. An improved agreement with the data is achieved when calculations are performed with unpaired neutrons (but with protons still paired) since the hump is not present, as demonstrated by the dashed lines in figure 2. It should be noted that the presence of a weak static pair-gap would still give rise to the quasineutron crossing, albeit at a reduced frequency and with a smaller effect on the $\mathcal{J}^{(2)}$.

It is now possible to assign valence proton-configurations to the N = 80 superdeformed bands in a systematic manner. The suggested configurations are shown in table 1. A routhian diagram is shown in figure 3(b). The deformation parameters were taken from the TRS calculations for $^{145}$Tb mentioned above. Small changes in deformation are calculated to occur amongst the N = 80 superdeformed bands, but they do not affect figure 3(b) very much. Orbitals which are relevant to the present discussion have been labelled, as have the proton numbers that correspond to the large energy gaps. It is simplest to start with $^{143}$Eu, which has the $6_1$ intruder orbital occupied relative to the Z = 62 gap at $\hbar\omega = 0$ MeV. This orbital is also occupied in $^{142}$Sm, but now as part of a particle-hole excitation from the $[541]_{1/2^-}$ orbital. In the case of $^{144}$Gd, both $N = 6$ proton intruder-orbitals are occupied. It is this pair that de-align at the band-crossing in the paired system and give the rapid increase in the $\mathcal{J}^{(2)}$ for $^{144}$Gd at $\hbar\omega \simeq 0.5$ MeV. In $^{145}$Tb, it is clear that the $6_3$ intruder is too high in energy for it to form part of the yrast configuration. Thus, only the first proton intruder orbital is occupied in $^{145}$Tb which blocks the $N = 6$ quasiproton crossing. This forces the placement of the sixty-fourth and sixty-fifth protons into the signature-partner routhians that originate from the $[404]_{9/2^+}$ upsloping "extruder" orbital. The proton configuration may therefore be designated $6^1 \otimes [404]^2_{9/2^+}$.

An interesting point to note is that $\pi 6^1$ bands are populated with between two- and five times the intensity of the $\pi 6^2$ band. There is no indication from theory as to why this should be so. This bears a remarkable similarity to the highly-deformed bands in the Nd isotopes in the A = 130 region. The three odd-N, $\nu 6^1$ cases $^{133,135,137}$Nd [17,18], are populated with relative intensities of approximately 10%, whereas the two even-N, $\nu 6^2$ cases $^{134,136}$Nd [17,19] are populated at the 1–2% level. Now the intensity is believed to depend strongly on the spin at which the superdeformed yrast-line crosses the "normal" yrast-line (the "crossing-spin"). The lower the crossing-spin, the greater the $\gamma$-ray flux that can be collected at the yrast-line which results in a more intense band. For example, TRS calculations predict similar crossing-spins ($I \simeq 35$–$40\ \hbar$) in $^{144}$Gd and $^{143}$Eu, but the band in $^{143}$Eu is populated with an intensity of ~1.1%, as compared to ~0.2% in $^{144}$Gd. Clearly it would be of interest to locate another $\pi 6^2$ N = 80 superdeformed band. It would also be of interest to find non-yrast superdeformed bands in these nuclei, since the "missing" intensity in $^{144}$Gd may, at least in part, be accounted for by excited superdeformed structures.

In conclusion, a superdeformed band has been found and assigned to the N = 80 nucleus $^{145}$Tb. Like the $\pi 6^1$ bands in $^{142}$Sm$_{80}$ and $^{143}$Eu$_{80}$, there is no evidence for the $N = 6$ quasiproton band-crossing that takes place in $^{144}$Gd$_{80}$. It is suggested that, as in $^{142}$Sm and $^{143}$Eu, the crossing is blocked in $^{145}$Tb, since the proton configuration is assigned as $6^1 \otimes [404]^2_{9/2^+}$. A feature that is not at present understood is that the three $\pi 6^1$ bands $^{142}$Sm, $^{143}$Eu and $^{145}$Tb are populated much more strongly than the $\pi 6^2$ band in $^{144}$Gd. Since no evidence is seen for the predicted $N = 6$ quasineutron crossing it is suggested that the static neutron pairing-correlations are quenched by the large gap at N = 80.

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# FIGURES

FIG. 1. Summed coincidence $\gamma$-ray spectrum that shows the superdeformed band assigned to $^{145}$Tb. Each band-member is indicated by an asterisk; all of these transitions were gated on to produce the spectrum. The transition energies are, in keV, 627.1(4), 687.8(4), 747.0(3), 806.1(5), 864.5(6), 920(1), 980.3(1.1), 1039.3(6), 1097.3(5), 1155.0(9), 1211.9(9), 1271.3(9), 1324(2), 1387(1).

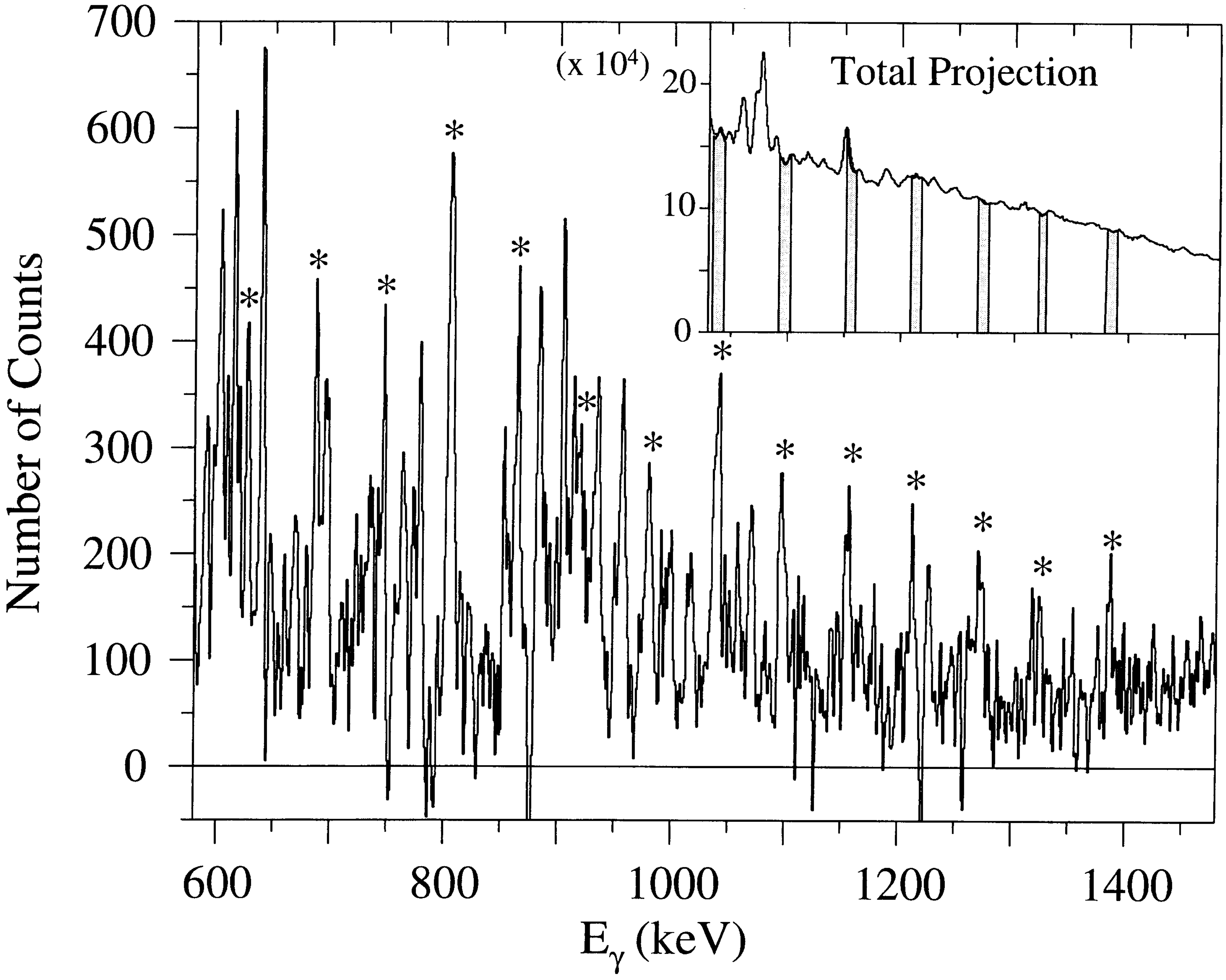
FIG. 2. $\mathcal{J}^{(2)}$ dynamic moments of inertia for the four N = 80 superdeformed bands, (a) $^{145}$Tb, (b) $^{144}$Gd [8], (c) $^{143}$Eu [6,7] and (d) $^{142}$Sm [5]. In each case, the experimental $\mathcal{J}^{(2)}$ (data points) and two theoretical predictions (solid or dashed lines) are shown. The solid lines come from the results of calculations that employed pairing for both protons and neutrons. Calculations in which the neutrons were treated as unpaired, but still employed paired protons, are delineated by the dashed lines. See the text for further details concerning the calculations.

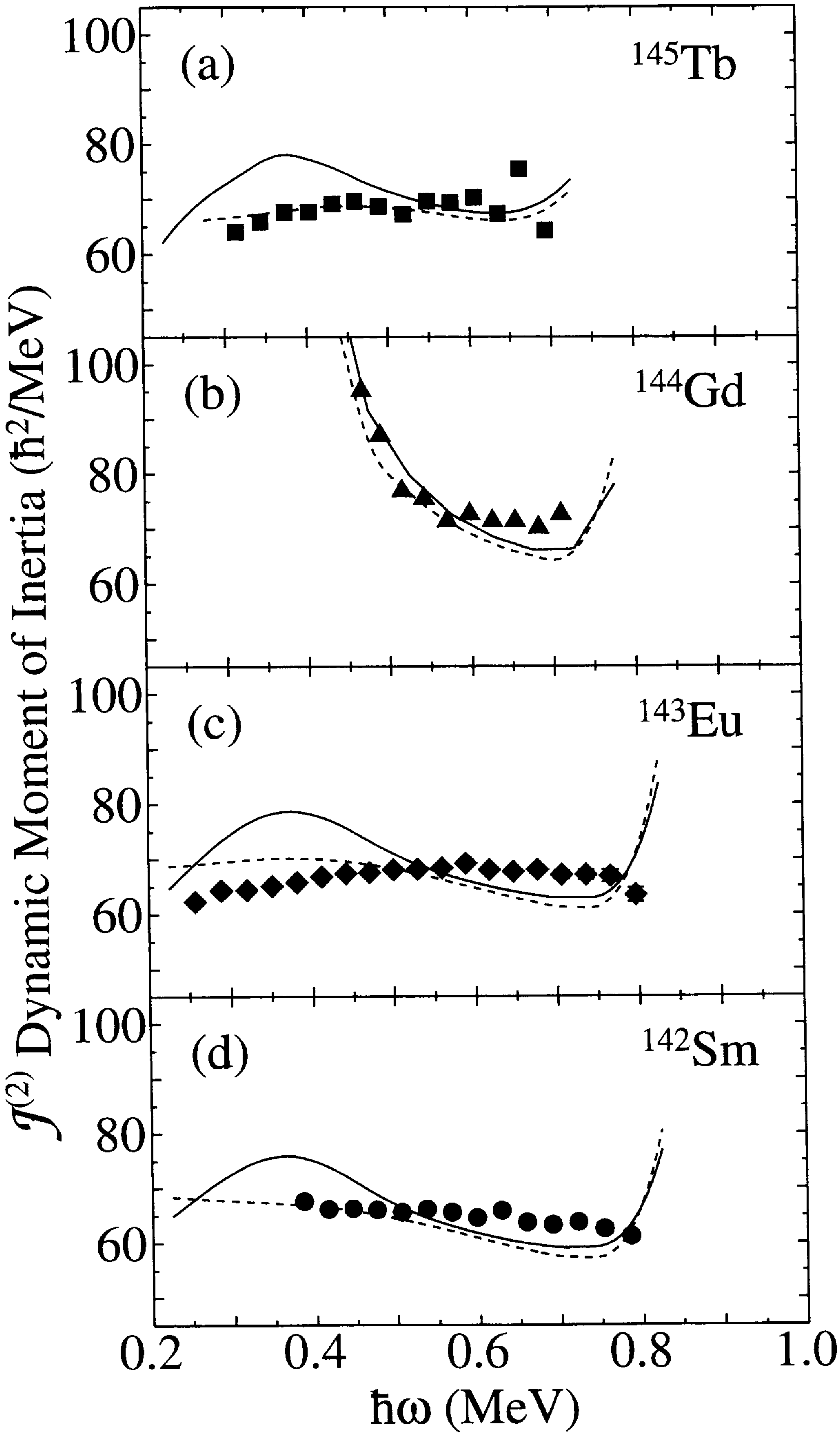
FIG. 3. (a) Total Routhian Surface for the proton $(\pi,\alpha) = (+,+1/2)$ configuration in $^{145}$Tb. The SD-minimum is located at $(\beta_2,\beta_4,\gamma) = (0.48,0.04,1.8^\circ)$, and becomes yrast at $I \simeq 47\ \hbar$, which corresponds to a rotational frequency of $\hbar\omega = 0.59$ MeV. (b) Single-proton routhians for $^{145}$Tb generated from Cranked Shell Model (CSM) calculations based on a Woods-Saxon potential. Important orbitals and particle numbers that correspond to the energy gaps have been labelled. Solid lines correspond to parity-signature $(\pi,\alpha) = (+,+1/2)$, dotted lines to $(+,-1/2)$, dashed lines to $(-,-1/2)$ and dot-dashed lines to $(-,+1/2)$.

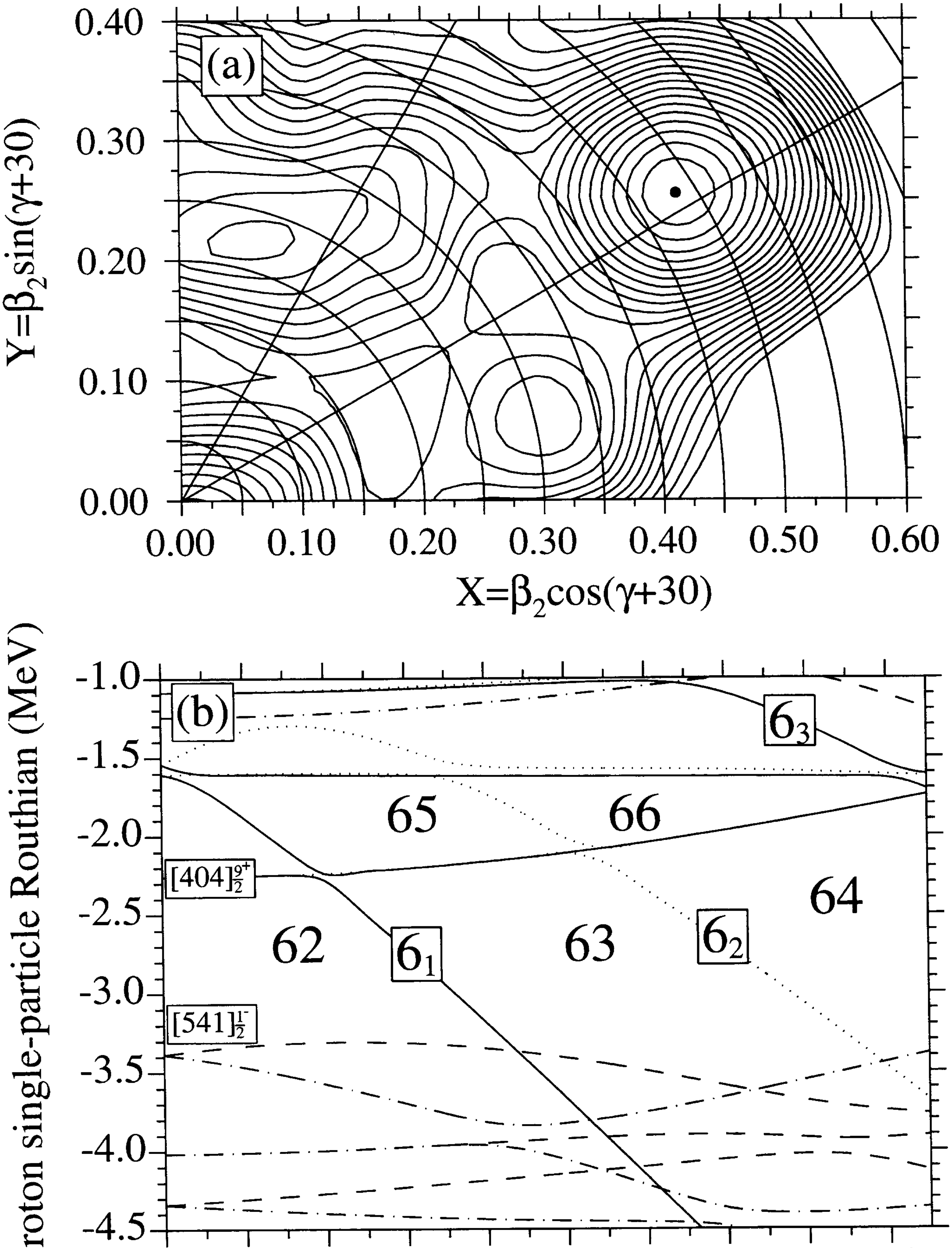
# TABLES

TABLE I. Proposed valence-proton configurations for the N = 80 superdeformed bands. They are given relative to the Z = 62 gap that exists at zero rotational frequency.

| Z | Nucleus | Configuration |
|---|---|---|
| 62 | $^{142}$Sm | $6^1 \otimes [541]^{-1}_{1/2^-}$ |
| 63 | $^{143}$Eu | $6^1$ |
| 64 | $^{144}$Gd | $6^2$ |
| 65 | $^{145}$Tb | $6^1 \otimes [404]^2_{9/2^+}$ |


Number of Counts
700
600
500
400
300
200
100
0
600
800
1000
1200
1400
$E_\gamma$ (keV)
*
(x $10^4$)
20
10
0
Total Projection


(a)
145Tb
(b)
144Gd
(c)
143Eu
(d)
142Sm
100
80
60
0.2
0.4
0.6
0.8
1.0
ℏω (MeV)
𝒥(2) Dynamic Moment of Inertia (ℏ2/MeV)


(a)
Y=$\beta_2\sin(\gamma+30)$
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
X=$\beta_2\cos(\gamma+30)$
(b)
Proton single-particle Routhian (MeV)
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
$6_3$
65
66
$[404]\frac{9}{2}^+$
64
62
$6_1$
63
$6_2$
$[541]\frac{1}{2}^-$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
ħω (MeV)