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Abstract

A superdeformed band has been found in ^{142}Eu. It is populated with 1.2(2)% of the total γ-ray intensity that decayed into ^{142}Eu via the reaction ^{120}Sn(^{27}Al,5n)^{142}Eu at 152 MeV. The strength of the band is similar to that previously reported in ^{143}Eu, where the superdeformed band is populated with an intensity of 1.1(1)%. This is unexpected, since both Total Routhian Surface (TRS) and cranked Modified Oscillator (M.O.) calculations predict that the superdeformed band in ^{143}Eu becomes yrast at lower spin than that in ^{142}Eu. This difference is $\sim$4 $\hbar$ in the M.O. calculations and $\sim$8 $\hbar$ in the TRS. Extrapolation of the "normal"-deformed yrast states in ^{143}Eu shows, however, that a difference of $\sim$8 $\hbar$ in spin corresponds to a change in the relative energy of the superdeformed and normal-deformed yrast lines of only $\sim$1 MeV.

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

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The intensity with which a superdeformed band is populated is believed to depend strongly on the spin at which the band becomes yrast. This is the spin at which the superdeformed yrast line crosses the yrast-line of "normal"-deformed states. The lower the value of this "crossing spin", the more intense will be the band. Most experiments to search for superdeformed bands rely on theoretical predictions of the crossing spin to indicate which nuclei are the most favourable cases to study. For example, nuclei with neutron number N = 80 have long been predicted to be particularly favourable cases for the observation of bands based on a superdeformed shape with $\beta_2 \simeq 0.5$ [1–3]. The discovery of superdeformed bands in the four N = 80 isotones ^{142}Sm [4], ^{143}Eu [5,6], ^{144}Gd [7] and ^{145}Tb [8] would seem to offer ample confirmation that the theoretical predictions are correct. Amongst these cases, the theory predicts that the superdeformed bands in ^{144}Gd and ^{143}Eu should be most favoured, due to their particularly low crossing spins (~35-40 $\hbar$). There is experimental evidence that the crossing spin in ^{143}Eu is ~38-40 $\hbar$ [6]. The experimentally determined intensities of the superdeformed band relative to the total in each respective nucleus are, however, ~0.2% for ^{144}Gd and 1.1% for ^{143}Eu. This drastic difference in intensity is totally unexpected, and suggests that there may be an energy dependence on the proton configurations which is not properly accounted for in the calculations. Given that ^{143}Eu would, on the basis of its strong population, seem to possess the lowest crossing spin of all the N = 80 isotones, it seems reasonable to test this favourability with respect to the addition or removal of a neutron. When a neutron is added to ^{143}Eu, the population of superdeformed states seems to be considerably weakened [9]. In the present experiment, the effect of removing a neutron from ^{143}Eu was investigated. The observation of a superdeformed band in ^{142}Eu is reported. It should be noted that this band is different from the one recently published by the GA.SP collaboration [10], which they have assigned to ^{142}Eu. No evidence was found in the present experiment for this band.

The experiment was performed with the 8π γ-ray spectrometer, which is located at the TASCC facility of the Chalk River Laboratories of AECL Research. The 8π spectrometer consists of twenty Compton-suppressed hyper-pure germanium (HPGe) detectors and seventy one elements of bismuth germanate (BGO). A beam of ^{27}Al ions was provided at an energy of 152 MeV by the upgraded MP tandem accelerator of the TASCC facility. The beam was directed onto a target that consisted of a stack of two ~500μg/cm^2 foils enriched to ~98% in ^{120}Sn. High-spin states in ^{142}Eu [11] were populated in the $5n$ exit channel. States in ^{139}Pm [12], ^{142}Sm [13], ^{141}Sm [14] and ^{141}Eu [15] were also populated. The energies of coincident pairs of γ rays emitted in the de-excitation of these states were recorded in the array of HPGe detectors when at least twelve BGO-elements were also triggered. The time between the detection of each γ ray and the BGO-trigger was also recorded, as well as the number of BGO elements that fired (the "fold", K) and the total energy deposited (the "sum-energy", H). Energy and relative efficiency calibrations of the HPGe detectors were obtained with ^{152}Eu and ^{133}Ba sources.

The data were replayed off line into a standard E_γ-E_γ coincidence matrix under the condition that a "raw" minimum sum-energy of H = 13.4 MeV was recorded in the BGO-ball. Relative to ^{142}Eu, the H-filter reduced the strengths of ^{141}Eu and ^{141}Sm, but left those of ^{142}Sm and ^{139}Pm unaffected. Standard techniques, encoded within the computer programs BANDAID [16,17] and SDSLICE [17], were employed to search the matrix for regular superdeformed bands. Both programs located a promising candidate for a superdeformed (SD) band. Coincidence spectra gated by the prospective SD transitions were projected from the matrix and summed together. This procedure confirmed the existence of the SD band, and a spectrum produced with optimized gates is shown in figure 1. The poor peak-to-background ratio in the spectrum is largely due to the existence of a strong "E2 bump" that arises from many unresolved rotational bands in the quasi-continuum. This underlies the region where the SD transitions reside, and hence degrades the peak-to-total ratio in each coincidence window.

As discussed in previous publications [8,17], the assignment of a superdeformed band in γ-γ data to a particular nucleus through coincidences with known transitions is, in general, untrustworthy. This remains true for the present case, even though all the other strong transitions in the SD-gated spectrum belong to ^{142}Eu. The assignment of the new SD band to ^{142}Eu is based on ruling out the other nuclei that were present in the data. A second matrix was made in which all coincidences from ^{141}Eu and ^{141}Sm were almost all excluded by requiring that $H_{min} = 18.5$ MeV . This condition halved the total number of counts relative to the first matrix, and despite the inherently poorer statistical accuracy, the SD band was still observed with the same intensity relative to ^{142}Eu. Hence the SD band does not belong to either ^{141}Eu or ^{141}Sm. Since the yrast SD band is known in ^{142}Sm, this possibility could be immediately be discounted. The possibility that the band belonged to ^{139}Pm was ruled out from a cross-bombardment check. Data were obtained from an experiment in which ^{139}Pm was populated via $5n$-evaporation, so that ^{142}Eu was not present. There was no evidence for the band.

The intensity of the band relative to ^{142}Eu was estimated from a coincidence spectrum gated by the 761 keV SD transition. An average intensity was extracted for the peaks at 700, 823, 887, 947, 1007 and 1066 keV in this spectrum. This was found to be 2.4 % of the 282-419 coincidence in ^{142}Eu that carries approximately 100 % of the total intensity with which the nucleus is populated [11]. The 282 keV transition resides below a low-lying 8^+ $\tau_m = 9$ns isomer, which attenuated the coincidence intensity in the unbacked target experiment, since a fraction of the nuclei decayed from this state after they had recoiled beyond the focus of the HPGe array. To correct for this effect, a short experiment was performed with a backed target. It was found that the intensity of the 282 keV transition increased by a factor of two, and the corrected relative intensity of the SD band is estimated to be 1.2(2) %.

Mean-field calculations based on either the Modified Oscillator (M.O.) or Woods-Saxon potentials predict the existence of large energy gap at N = 80 centred near $\beta_2 \simeq 0.5$. Since N = 80 may be regarded as a closed neutron shell for superdeformed shapes with $\beta_2 \simeq 0.5$, it seems appropriate to interpret the SD band in ^{142}Eu (N = 79) as a single neutron hole in the "magic" core. A signature partner to the band was not observed, which suggests that the hole must be made in an orbital that is well split from its conjugate routhian. Neutron routhians generated from a cranked Woods-Saxon mean-field [3] appropriate for ^{142}Eu in a superdeformed shape are shown in figure 2. Inspection of the routhians suggests that the hole is probably made in the $\nu 6_4$ orbital that originates from the $\Omega = 3/2$ component of the $i_{13/2}$ spherical multiplet (usually labelled as $6_{3/2}$). This orbital has a signature splitting of $\sim$1 MeV at $\hbar\omega \simeq 0.6$ MeV, which is consistent with the observation of a single band. The two other orbitals that are close to the Fermi surface at zero frequency in figure 2 both originate from the $N_{osc} = 5$ oscillator shell. In terms of their Nilsson labels they are the $[532]3/2^-$ and the [530]1/2$^-$ orbitals.[1] For a prolate shape, the former always resides above the latter, and it is hard to reverse this situation without making *ad hoc* changes to the parameters of the potential, since the orbitals originate from the same major shell. This is not the case for the energies of these two orbitals relative to the $6_{3/2}$ intruder orbital; a small shift would place the [532]3/2$^-$ at the Fermi level. The small signature splitting, of this orbital, however, is inconsistent with the observation of a single band.

The configuration with the hole in $\nu 6_4$ orbital may be labelled as $\{^{143}\mathrm{Eu}\} \otimes \nu {6_4}^{-1}$. In terms of the number of high-N_{osc} intruder orbitals that are occupied, the configuration is $\pi 6^1 \nu 6^3$. With this assignment the band has signature +1 (odd spin) and even parity. The configuration based on a hole in the $\nu\{[532]3/2^-\}(\alpha = -1/2)$ orbital also has odd spin, but negative parity.

The dynamic moment of inertia has been extracted from the differences of successive transition energies in the SD band, and is shown in figure 3(a), where it is compared with ^{143}Eu [5,6] and ^{144}Gd [7]. The rapid rise in the $\mathcal{J}^{(2)}$ of ^{144}Gd at $\hbar\omega \simeq 0.45$ MeV is attributed to the $N_{osc} = 6$ quasiproton crossing [7]. This alignment is blocked in the $\pi 6^1$ configuration that is assigned to ^{143}Eu [5,6]. No evidence is seen for this crossing in ^{142}Eu which suggests that it has the same proton configuration as ^{143}Eu.

Previous attempts to reproduce the $\mathcal{J}^{(2)}$ in ^{143}Eu within the paired Woods-Saxon-Strutinsky cranking approach have met with limited success. This may reflect an inadequacy in the mean-field, pairing correlations or perhaps indicate the need for the inclusion of a residual neutron-proton interaction. Rather than attempting similar calculations for ^{142}Eu, we make use of the constancy of the $\mathcal{J}^{(2)}$ for ^{143}Eu to infer that it is an "inert" superdeformed core. Single-particle or hole excitations with respect to this core can then be addressed in terms of effective alignments [19]. This approach has proved very successful in understanding the systematics of the single-particle configurations in the chain of superdeformed Gadolinium isotopes [17]. The theory is based on the unpaired mean field approach. When comparing pairs of bands in nuclei that differ by only one nucleon it is assumed that changes in pairing are small. With this assumption, the effective alignment obtained in calculations reflects mainly the aligned spin of the extra particle with a minor contribution from changes in deformation. In order to extract an experimental effective alignment, the spins of the two bands that are to be compared need to be known. Since the spins are not known in ^{142}Eu and ^{143}Eu, it is assumed that the 483 keV transition in ^{143}Eu decays to a 37/2 $\hbar$ state[2], and the 700 keV transition in ^{142}Eu decays to either a 27 or a 29 $\hbar$ state (in the analysis, only the relative spins between the two bands are important). The results of this procedure are shown in figure 3(b), together with calculated effective alignments for the $\nu 6_4$ and the $\nu\{[532]3/2^-\}(\alpha = -1/2)$ orbitals obtained from the M.O. potential [18]. At each rotational frequency the energy was minimized with respect to the $(\varepsilon_2, \varepsilon_4, \gamma)$ deformation parameters. The agreement between experiment and calculation for the $\nu 6_4$ orbital, as well as for the $\nu\{[532]3/2^-\}(\alpha = -1/2)$ orbital, is poor. Preliminary calculations in which

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[1] This pair of orbitals forms a pseudo-spin doublet that can be relabelled by $[\widetilde{431}]3/2^-$ and $[\widetilde{431}]1/2^-$.

[2] This value is consistent with the results of Ref: [6].

the effective alignment was extracted from the W.S. potential favour the $\nu\{[532]3/2^-\}(\alpha = -1/2)$ assignment, but the agreement is poor also in this case. It would clearly be of interest to find excited superdeformed bands in ^{142}Eu based on other neutron holes in the N = 80 core.

The most interesting property of the superdeformed band in ^{142}Eu is the intensity with which it was observed. As discussed above, this was determined to be 1.2(2)% relative to the total strength with which ^{142}Eu was populated. This may be compared with the figure of 1.1(1)% for the band in the "magic" N = 80 core, ^{143}Eu [6]. The two experiments, however, differed by $\sim 15\hbar$ in the maximum angular momentum brought into the reaction ($l_{max} \simeq 56$ $\hbar$ for ^{143}Eu and 71 $\hbar$ for ^{142}Eu.) To check whether or not this difference had a significant effect on the population intensities, ^{143}Eu was also studied with the 8π spectrometer. States in ^{143}Eu were populated in the $6n$ channel of the ^{27}Al + ^{122}Sn reaction at a beam energy of 150 MeV, in which the l_{max} was $70\hbar$. The relative intensity of the band was measured to be 1%, and was therefore unaffected by the change in l_{max}.

The observation that the two bands have similar intensities implies that they become yrast at similar spins in each nucleus, but Total Routhian Surface (TRS) calculations predict a difference of about $8\hbar$ between the two cases. For comparison, the crossing spin of the yrast SD band in ^{149}Gd is believed to be ~ 5 $\hbar$ lower than in ^{150}Tb [20]. The band in ^{149}Gd is populated with 1.8% of the channel intensity, while for ^{150}Tb the value is 1%. In the present case, it is instructive to consider a plot of excitation energy versus I(I + 1), as shown in figure 4(a). The normal-deformed yrast states of ^{143}Eu [21] are known to much higher spin and excitation energy than in ^{142}Eu [22]. Hence the normal-deformed (ND) yrast-line in ^{143}Eu can be extrapolated with greater confidence. This has been done assuming a simple rigid-rotor behaviour. Note that over the limited spin-range where the states in ^{142}Eu have been delineated, they approximately follow the same slope as the states in ^{143}Eu. It is possible that the slope becomes less steep at higher spin, as in ^{143}Eu. Superdeformed yrast-lines that correspond to $\mathcal{J}_{eff} = 70$ $\hbar^2$/MeV are shown crossing the ND yrast-line of ^{143}Eu at spins of 38 $\hbar$ and 46 $\hbar$, as extracted from the TRS calculations for ^{143}Eu and ^{142}Eu, respectively. The plot shows that the difference in crossing spin of 8 $\hbar$ corresponds to shifting the SD yrast-line by only ~ 1 MeV. It seems unrealistic to expect that the TRS calculations can predict the relative excitation energies of the non-collective "normal" and superdeformed states at spin ~ 40 $\hbar$ to within ~ 1 MeV. Moreover, in the TRS calculations the "total energy" is minimized with respect to rotational frequency. When one is trying to understand crossing spins, a more correct approach is to calculate the total energy of the nucleus with respect to spin. This we have done with the cranked M.O. model, and the results for various unpaired high-N_{osc} configurations in ^{142}Eu are shown in figure 4(b). The excitation energy of each configuration is shown relative to that of a rigid rotor as a function of spin. It is gratifying to note that the $\pi 6^1 \nu 6^3$ configuration is predicted to be yrast. Furthermore, yrast lines that correspond to "normal-deformed" states are shown on the diagram; the lowest crosses the SD yrast line at 45 $\hbar$. Similar calculations for ^{143}Eu predict a crossing spin of 40.5 $\hbar$. The difference between the two cases is within the typical uncertainty that is expected for this type of calculation.

In conclusion, a superdeformed band has been in observed in ^{142}Eu. The lack of a signature partner suggests that the high-N_{osc} intruder configuration is $\pi 6^1 \nu 6^3$, so that the hole in the N = 80 closed SD shell is made in the $\nu 6_4$ orbital. There is, however, poor agreement between the experimental effective alignment and the predictions of cranked mean field calculations for the $\nu 6_4$ orbital. An alternative scenario would place the hole in the $\nu\{[532]3/2^-\}(\alpha = -1/2)$ orbital, but the agreement between experiment and theory is not much better in this case. The most surprising observation is that the band is populated with a relative intensity of 1.2%. This was unexpected, since TRS calculations predict that the SD band becomes yrast $\sim 8\hbar$ higher in spin than in ^{143}Eu, where the intensity is 1.1(1)%. A smaller difference in crossing spin of $\sim 4\ \hbar$ is predicted by our cranked M.O. calculations. Inspection of the normal and superdeformed yrast lines, however, shows that difference of $\sim 8\ \hbar$ corresponds to a shift of only ~ 1 MeV in the relative excitation energy of the two yrast lines.

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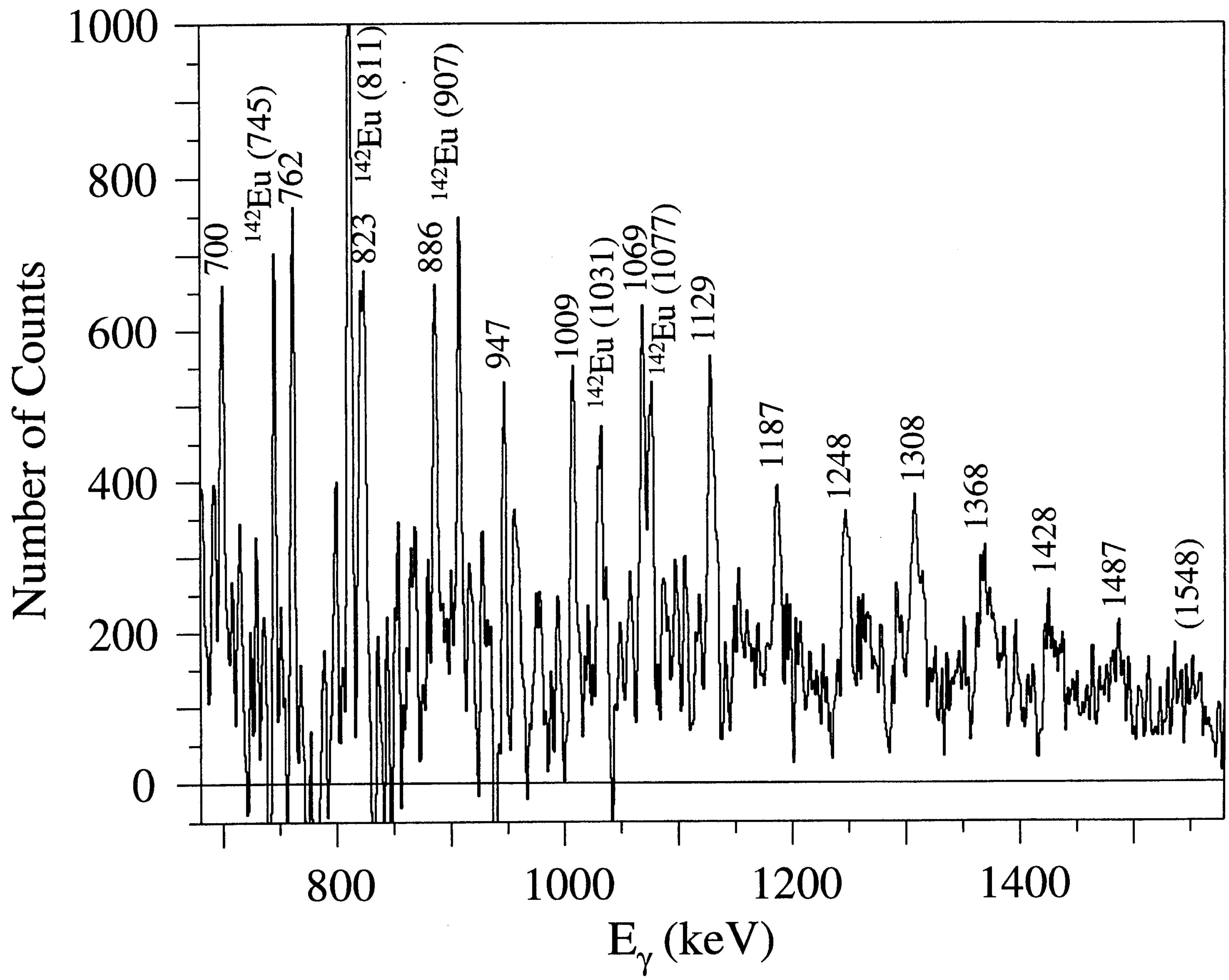
FIGURES

FIG. 1. Summed coincidence spectrum that shows the superdeformed band in ^{142}Eu. Each band member is indicated by its energy in keV. All band members except the 947 keV transition contributed to the spectrum. The energies are listed here with individual statistical errors: 699.7(3) 761.9(3), 822.8(3), 886.3(3), 947.1(3), 1008.3(3), 1069.4(3), 1129.4(4), 1187.1(6), 1247.9(6), 1307.9(1.0), 1368.2(1.2), 1428.4(1.8), 1486.8(2.0), (1548). Peaks that arise from transitions between "normal-deformed" states in ^{142}Eu have been identified.

FIG. 2. Neutron single-particle routhians for ^{142}Eu taken from a Woods-Saxon mean-field parametrized by $(\beta_2, \beta_4, \gamma) = (0.49, 0.04, 1.9^\circ)$. The deformation parameters were taken from Total Routhian Surface (TRS) calculations. The large energy-gap at N = 80 is labelled. Relevant orbitals are also labelled. Solid lines correspond to (parity π, signature α) = (+,+1/2), dotted lines to (+,−1/2), dot-dashed lines to (−,+1/2) and dashed lines to (−,−1/2).

FIG. 3. (a) $\mathcal{J}^{(2)}$ dynamic moments of inertia for the superdeformed bands in ^{142}Eu, ^{143}Eu and ^{144}Gd. (b) Effective alignments for ^{142}Eu derived from the SD bands in ^{143}Eu/^{142}Eu. The theoretical predictions are taken from Modified Oscillator calculations for the neutron 6_4 and $\{[532]3/2^-\}(\alpha = -1/2)$ orbitals.

FIG. 4. (a) Plot of excitation energy versus I(I + 1) for normal and superdeformed states in ^{143,142}Eu. Extrapolation of the normal-deformed (ND) yrast line of ^{143}Eu was assumed to follow a simple I(I + 1) dependence, with an effective rigid-body moment of inertia of $\mathcal{J}_{eff} = 55\ \hbar^2$/MeV. The superdeformed (SD) yrast-line was modelled by $\mathcal{J}_{eff} = 70\ \hbar^2$/MeV, and is shown as solid lines crossing the ND yrast line at (i) $I_{cross} = 38\ \hbar$, and (ii) $I_{cross} = 46\ \hbar$. This shift of 8 $\hbar$ corresponds to changing the relative excitation energy of the SD and ND yrast-lines by ~1 MeV. (b) Results of unpaired Modified Oscillator calculations that show excitation energy (relative to that of a rigid rotor) versus spin for various superdeformed configurations in ^{142}Eu. Also shown are the yrast lines for "normal-deformed" states defined by the four combinations of the (π,α) quantum numbers. The open circles denote terminating states.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600
400
200
0
800
1000
1200
1400
Eγ (keV)
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142Eu (745)
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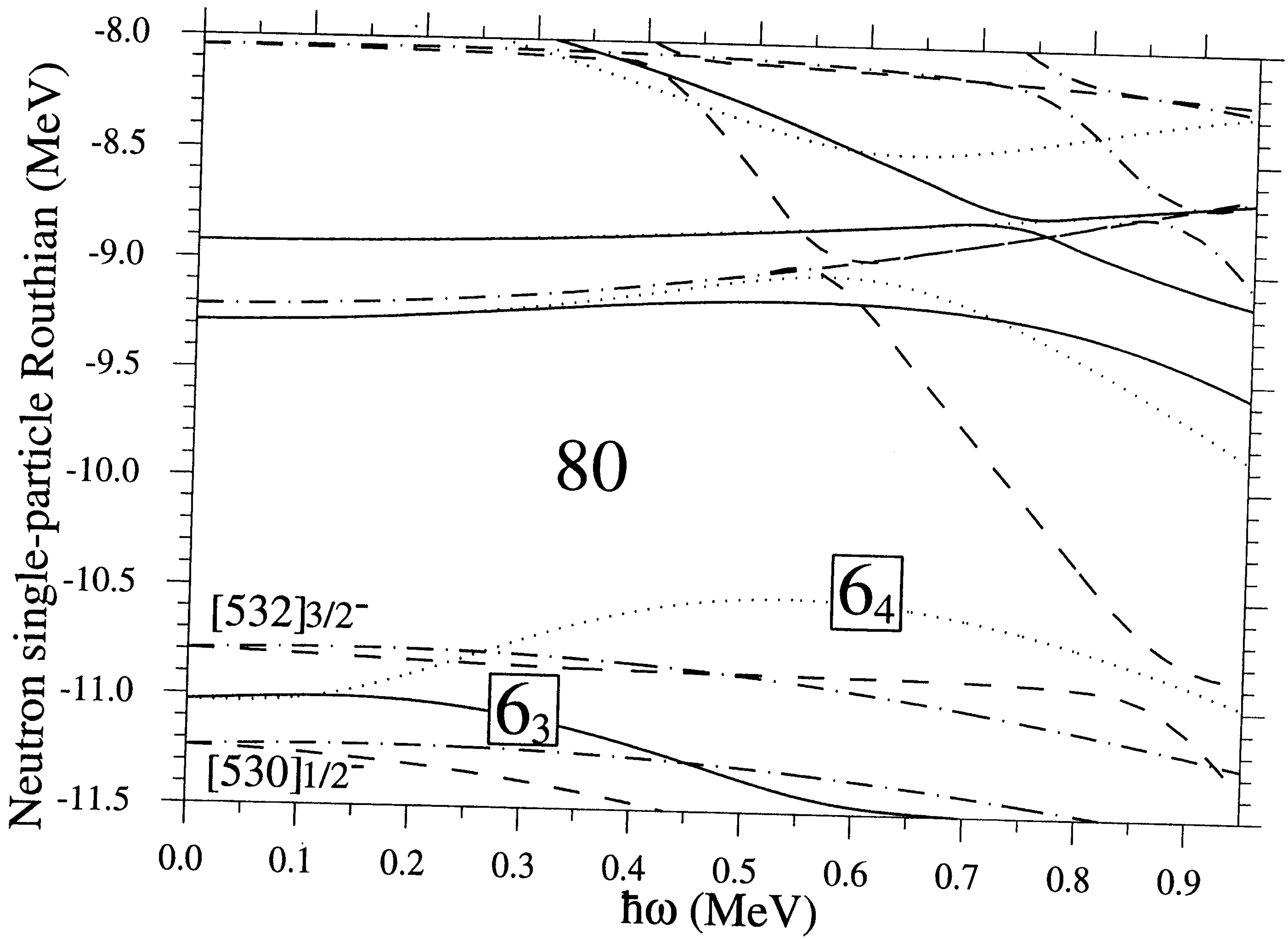
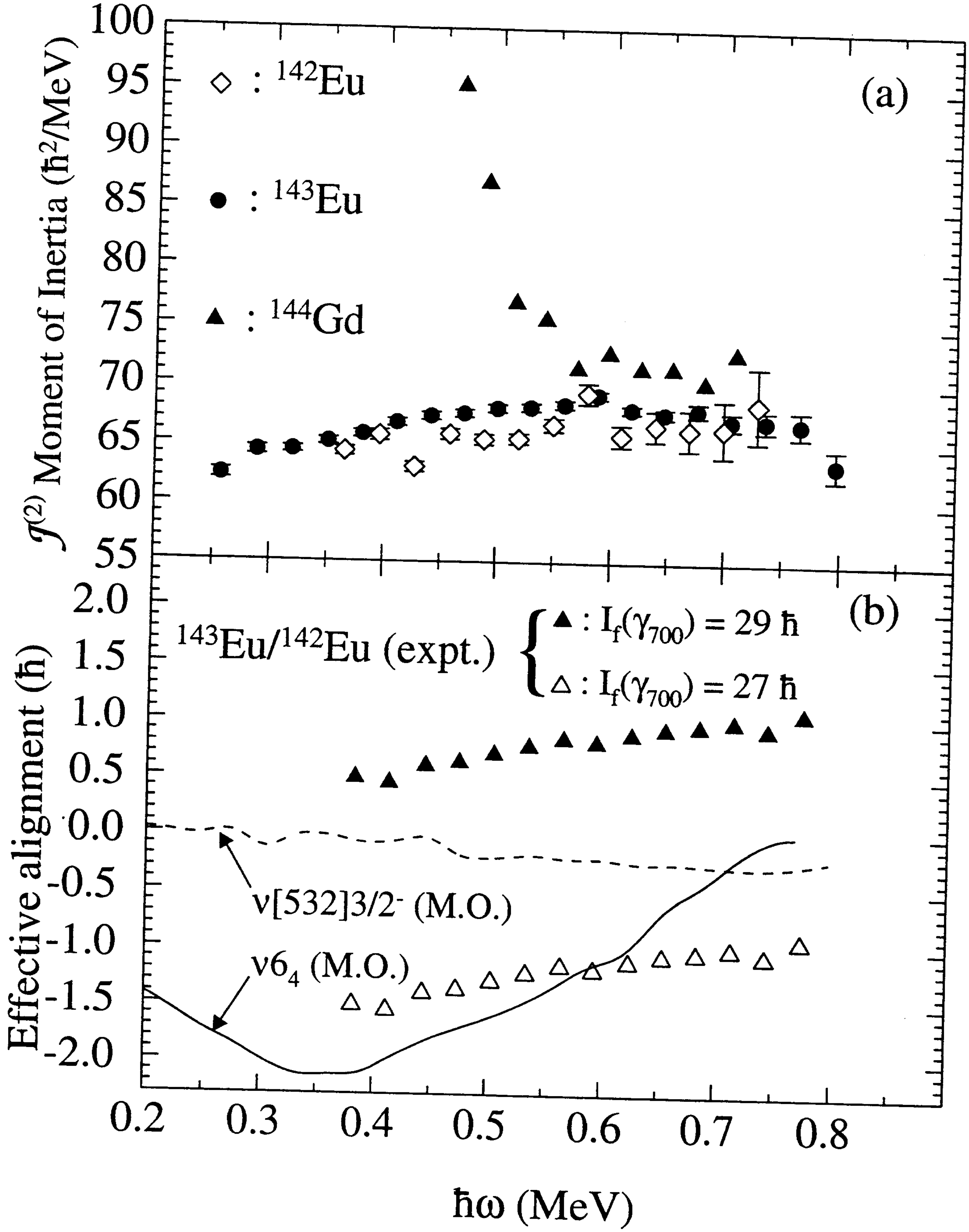
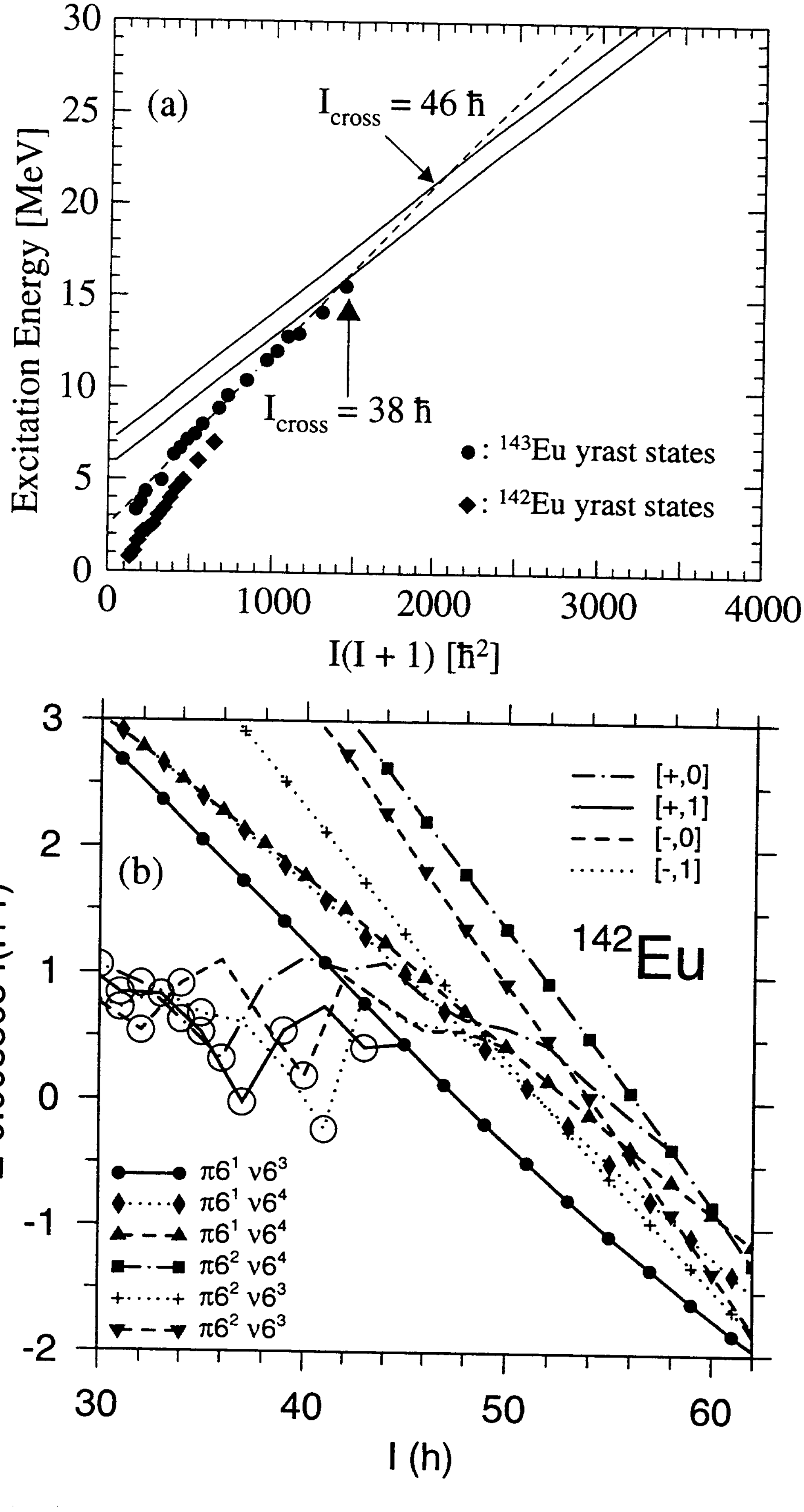
142Eu (811)
823
886
142Eu (907)
947
1009
142Eu (1031)
1069
142Eu (1077)
1129
1187
1248
1308
1368
1428
1487
(1548)


Neutron single-particle Routhian (MeV)
-8.0
-8.5
-9.0
-9.5
-10.0
-10.5
-11.0
-11.5
80
[532]3/2⁻
[530]1/2⁻
6₃
6₄
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
ħω (MeV)



$\mathcal{J}^{(2)}$ Moment of Inertia ($\hbar^2$/MeV)
◇ : ^{142}Eu
● : ^{143}Eu
▲ : ^{144}Gd
(a)
(b)
^{143}Eu/^{142}Eu (expt.)
▲ : $I_f(\gamma_{700})$ = 29 ħ
△ : $I_f(\gamma_{700})$ = 27 ħ
ν[532]3/2$^-$ (M.O.)
ν6_4 (M.O.)
Effective alignment (ħ)
ħω (MeV)



(a)
Excitation Energy [MeV]
I(I + 1) [ħ²]
I_cross = 46 ħ
I_cross = 38 ħ
●: 143Eu yrast states
◆: 142Eu yrast states
(b)
E-0.008363 I(I+1)
I (h)
142Eu
[+,0]
[+,1]
[-,0]
[-,1]
π6¹ ν6³
π6¹ ν6⁴
π6¹ ν6⁴
π6² ν6⁴
π6² ν6³
π6² ν6³