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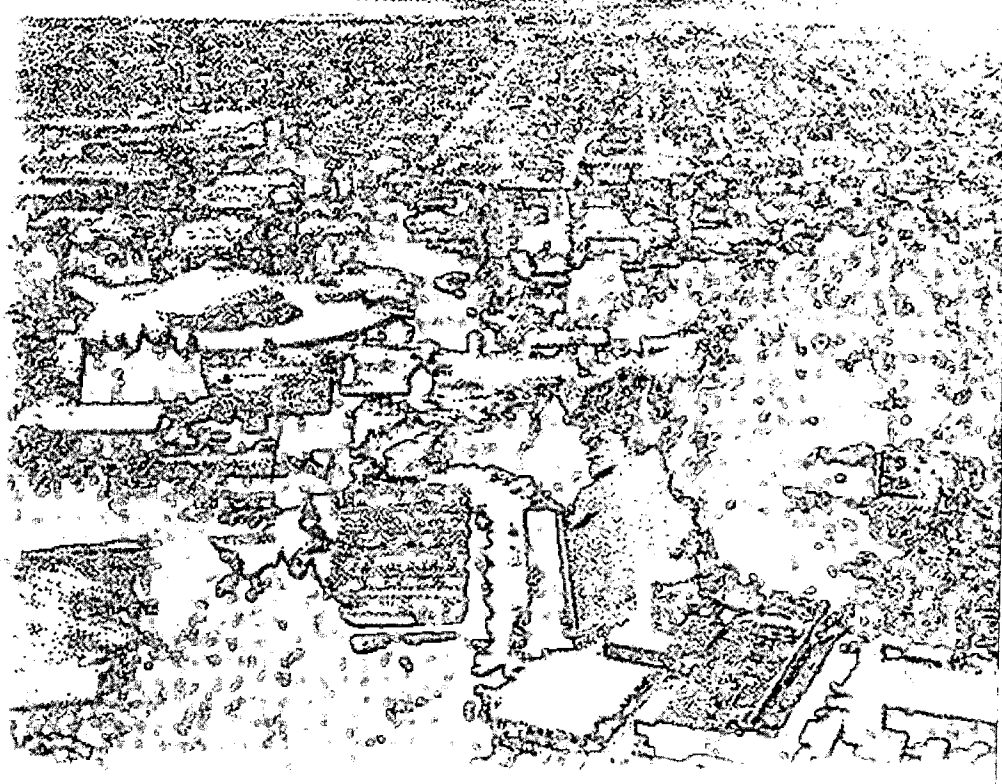
Nuclear Sciences Division

June 1996



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Recycled Paper

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(June 5, 1996)

Abstract

The presence of $\Delta I = 2$ staggering in the three known superdeformed bands of ^{194}Hg has been reexamined in a new experiment with Gammasphere. A relative accuracy of better than 30 eV was achieved for most transition energies. No statistically significant oscillations in the transition energies were found for band 1 while staggering patterns were observed in bands 2 and 3. The statistical significance of the observed effects was analyzed. The patterns display some similarities with expectations based on a band crossing picture, even though such a picture cannot reproduce the observations in a straightforward way. No evidence was found for additional superdeformed bands in ^{194}Hg which could account for possible band-crossings.

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Superdeformed (SD) nuclei are some of the best quantum rotors known. Their characteristic long sequences of equally spaced transition energies provide a unique opportunity to search for unexpected effects on an energy scale rarely achieved elsewhere in nuclear physics. In this context the recent observation of a regular staggering pattern of the transition energies in the yrast SD band in ^{149}Gd [1], where states differing by four units of angular momentum show a similar energy shift of about 60 eV relative to a (smooth) rotational sequence, is particularly intriguing. Evidence for similar effects has been reported in ^{194}Hg [2], ^{148}Gd [3], ^{192}Tl [4] and in some Ce nuclei [5]. These observations have triggered an intense theoretical effort to understand this phenomenon [6–11]. Some discussions connect this effect with the presence of a Y_{44} deformation of the SD shape [6–8]. In this model long, regular staggering sequences are expected. Other studies [9–11] argue that the measured energy differences could be related to band-crossings which would, however, only account for short staggering sequences. Since the observed energy shifts are only of the order of 100 eV or less, which is at the limit achievable with modern γ-ray arrays for SD transitions, it is essential to confirm the reported effects by new measurements with higher statistics utilizing the still increasing efficiency and resolving power of the currently available detector arrays, like Gammasphere [12] and Eurogam II [13]. In this Rapid Communication we report results from a new experiment on the known SD bands in ^{194}Hg [14,15] investigating the previously reported [2] staggering in those bands. The very high statistics obtained in this experiment has made possible the determination of the relative transition energies for these bands with unprecedented accuracy. Clear deviations of the γ-ray energies from a smooth reference, which hereafter we will refer to as staggering patterns, have been established for two SD bands in ^{194}Hg, but the emerging picture differs in several aspects from that reported in Ref. [2].

Superdeformed states in ^{194}Hg were populated in the reaction ^{150}Nd(^{48}Ca,4n) using a 201 MeV ^{48}Ca beam provided by the 88-inch Cyclotron of the Lawrence Berkeley National Laboratory. The emitted γ rays were detected by the Gammasphere array which at the time of the experiment consisted of 70 Compton-suppressed Ge detectors. A stack of two

500 μg/cm^2 thick Nd targets was used with both sides of each target foil covered with a thin layer of gold (450 μg/cm^2 facing the beam and 220 μg/cm^2 on the other side). A total of 1.4×10^9 coincidence events with fold ≥ 4 were recorded on magnetic tape which led, after filtering out random coincidences, to 4.6×10^8, 3.9×10^8, 1.1×10^8, and 3×10^7 triple-, quadruple-, quintuple-, and sextuple-events, respectively, with γ-ray energies below 2 MeV. An energy of 0.125 keV per ADC channel was chosen in order to achieve a high resolution.

Hereafter we give a brief description of the analysis performed to extract the transition energies of the SD bands in ^{194}Hg. An off-line correction of drifts in the ADC gains was performed for each individual detector and they were gain-matched by using γ rays from a ^{152}Eu calibration-source. Gated coincidence spectra were created for each of the three known SD bands in ^{194}Hg using in each case several sets of gating transitions, all leading to very clean spectra of the SD bands. The sorting procedure was such that for each energy in a coincidence event the remaining energies were checked for their occurrence in the gates. The initial energy was then incremented in a one dimensional spectrum corresponding to the maximum number of gates satisfied. In this way triple-gated spectra were created as well as spectra with at least four gates satisfied, which, hereafter, we will call quadruple-gated spectra. Figure 1 shows triple-gated spectra for the three SD bands in ^{194}Hg. Using this sorting method [16] leads to statistically independent spectra for the different gate folds, since a given energy was incremented only once. This procedure also avoids the overweighting of single channels (so-called *spikes*) in the spectra due to the unfolding of high-fold events. To avoid such spikes is crucial for the correct determination of the transition energies, specifically in the quadruple-gated spectra. Different backgrounds were subtracted from the triple-gated spectra in order to be sensitive to systematic effects arising from these subtractions. The background-subtraction procedure involved subtracting varying amounts of an $(n-1)$-fold spectrum as background for an n-fold spectrum. For the present analysis no background was subtracted from the quadruple-gated spectra. The Doppler-shift for SD transitions above 700 keV was found to vary from the average recoil velocity (v/c=0.0200 (5)) for the lower energy transitions due to the fact that these decays occur in the target foils

and their thin gold backing while the recoiling nuclei are still slowing down. The correction method proposed by Cederwall et al. [17] was used to take these effects into account and this improved the peak resolution for those high-energy transitions by 10-15%.

The transition energies E_γ were determined by using a conventional fitting routine from the triple- and quadruple-gated spectra corresponding to different gating conditions. Several fitting procedures were compared and were found to lead to consistent results. In the different spectra analyzed it was found that the E_γ-values for some transitions showed fluctuations of the order of $2-3\sigma$, where σ is the statistical uncertainty of E_γ, resulting from the used fitting procedure. In most of these cases the spectra offered no evidence for systematic problems with these specific transitions. However, the overall distribution of transition-energy values with respect to their average was in good agreement with a statistical distribution: 61% of the data were within 1σ of their average, 31% were in the range 1-2σ and 8% were found to be outside a 2σ range with respect to the corresponding average E_γ. Despite this remarkable statistical behavior (a statistical distribution would give values of 68%, 27%, and 5%), systematic effects due to background subtraction procedures and different gating conditions could not be excluded and have been taken into account in the evaluation of the final uncertainties.

Table I summarizes the transition energies and relative intensities derived in the present experiment for the three SD bands in ^{194}Hg. As stated above the uncertainties given in Table I take into account the uncertainties arising from different background subtractions and gating conditions as well as the possible statistical fluctuations. It must be emphasized that the observed relative intensities in Table I cannot rule out the presence of small contaminating peaks under the SD transitions of interest at a level of $< 5\%$ for band 1 and of $< 10\%$ in bands 2 and 3. Furthermore, some of the yrast transitions in ^{194}Hg [18] that are in true coincidence with the SD bands lead, in specific cases (i.e. for the 746.89-keV transition in band 2 and the 634.60-, 731.70-keV transitions in band 3), to significant uncertainties in the determination of those SD transition energies. The improvement in the overall accuracy of the present measurement over that in Ref [2] is more than a factor of three.

To ensure that the results were not biased by some detail of the data reduction, the same data were analyzed independently in a different manner. In this parallel analysis, the energy measurements were corrected for Doppler shifts (with a constant value of v/c=0.02) and high-fold coincidence events were unpacked in the conventional manner. Double- and triple-gated spectra were background corrected with the operator-based subtraction method of Ref. [19]. Each individual double-gated spectrum was inspected for cleanliness before adding it to the summed spectrum. The measured transition energies and their uncertainties were found to be consistent with those reported in Table I.

For each band the deviation of the γ-ray energies from a smooth reference ΔE_γ was determined by calculating the fourth derivative[1] of the γ-ray energies $E_\gamma(I)$ at a given spin I by:

$$\Delta E_\gamma(I) = \frac{3}{8}\left[E_\gamma(I) - \frac{1}{6}\left[4E_\gamma(I-2) + 4E_\gamma(I+2) - E_\gamma(I-4) - E_\gamma(I+4)\right]\right] \qquad (1)$$

This expression was previously used in Ref. [2] and is identical to the expression for $\Delta^4 E_\gamma(I)$ in Ref. [11]. We chose to use the expression above in order to be able to follow higher order changes in the moments of inertia of the SD bands. The effects discussed below are certainly also visible in all lower derivatives. Figure 2 shows the resulting values of ΔE_γ for the entire frequency range of the three SD bands in ^{194}Hg from the present experiment on the left side and the results from Ref. [2] on the right side. The uncertainties for ΔE_γ given in Fig. 2 are calculated using the standard error propagation method. We are aware that the given uncertainties of the individual ΔE_γ-values do not account for the correlations induced in the staggering pattern by the change of individual E_γ-values. The effect of these correlations will be discussed later in this paper.

Three major conclusions can be drawn about the new results.

(i) Within the quoted uncertainties, band 1 shows no significant deviation from a smooth

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[1]The expression given is in fact the finite difference approximation to the forth derivative d^4E_γ/dI^4 of the transition energies.

behavior over the entire frequency range.

(ii) A clear deviation from a smooth behavior of the γ-ray energies is obvious in band 2 for rotational frequencies above 0.3 MeV. However, this deviation does not correspond to a regular staggering pattern, since a phase inversion is observed at $\hbar\omega = 0.35$ MeV.

(iii) A short regular staggering pattern of the order of ± 50 eV is visible in band 3 in the frequency range $\hbar\omega = 0.26 - 0.34$ MeV. Whether the observed pattern continues or not at higher frequencies remains an open question due to the magnitude of the uncertainties involved.

It is important to note that for most data points the ΔE_γ-values from both the present work and Ref. [2] are consistent within the given uncertainties. However, the resulting staggering plots differ in several aspects. Hereafter a more detailed comparison between the new results and those reported earlier is given.

The previously observed regular staggering pattern of the order of 40 eV in band 1 was not observed. There appears to be a very small staggering with an amplitude of about 20-25 eV in the range of $\hbar\omega = 0.25 - 0.35$ MeV, but it has little statistical significance (see discussion of confidence level below). It is noteworthy that this pattern is in phase with that seen in the previous report.

The low frequency range ($\hbar\omega < 0.25$ MeV) of the stagger plot for band 2 is very similar to that of the previous work. A significant deviation from a smooth behavior sets in for $\hbar\omega \geq 0.3$ MeV, which is somewhat higher in frequency than seen in Ref. [2]. While the staggering starts with the same phase in both measurements, the inversion at $\hbar\omega = 0.35$ MeV was not observed earlier. It is important to realize that the staggering of the high frequency part of band 2 depends critically on the position of the 746.89-keV ($\hbar\omega \approx 0.375$ MeV) transition. The precise determination of this energy is complicated by the presence of the 748.8-keV ($5^- \rightarrow 4^+$) yrast transition [18]. We are, however, confident that this interfering transition has been consistently taken into account, since its centroid and shape have been accurately determined from spectra in coincidence with other yrast transitions.

The staggering pattern for band 3 observed in this work agrees with the previous result only in the frequency range $\hbar\omega = 0.25 - 0.325\,\mathrm{MeV}$. The discrepancy for $\hbar\omega \geq 0.325\,\mathrm{MeV}$ may be linked to the presence of two interfering γ-rays close to the 634.60-keV and 731.70-keV transitions. In both cases, strong yrast transitions (the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ lines) in coincidence with the SD band interfere with the SD transitions. These two transitions have an important influence on the staggering plot in Figure 2. The large uncertainty for the 731.70-keV transition is due to its proximity to the 734.8-keV ($6^+ \rightarrow 4^+$) transition in ^{194}Hg. Therefore, it remains unclear whether the regular staggering in band 3 continues towards higher frequencies. The previously reported staggering pattern is in phase below $\hbar\omega = 0.25\,\mathrm{MeV}$ but the amplitude of only 15 eV is considerably smaller than the previous one of 80 eV.

To evaluate the statistical significance of the staggering pattern an analysis was performed in terms of the confidence level defined in Ref. [2]. In this method the distribution of ΔE_γ values around their average is compared to the distribution obtained when the sign of every other data point is changed. The separation of these distributions in terms of their standard deviation (by definition the standard deviation of both distributions is equal), gives a measure of the significance of the observed effect (including amplitude and regularity). Assuming a regular staggering over the whole frequency range, we have determined the confidence levels for the three SD bands in ^{194}Hg. The confidence level for band 1 is $0.7\,\sigma$, which cannot be called statistically significant and indicates that all ΔE_γ-values are within their uncertainties consistent with $\Delta E_\gamma = 0$. For band 2, a confidence level of $1.6\,\sigma$ was found for a regular staggering over the whole range. Band 3 exhibits the most regular pattern, which is represented by a $3.2\,\sigma$ confidence level. The confidence levels for bands 2 and 3 do not change much if the statistical analysis is restricted to the frequency ranges where the ΔE_γ-values are clearly non-zero. This is due to the fact that not only the amplitudes but also the length and regularity of the patterns have a strong influence on the confidence level.

An additional statistical analysis was performed in order to investigate the fact that

changes of individual E_γ-values will have a correlated influence on the ΔE_γ-plot, since each γ-ray energy is used in the calculation of five ΔE_γ-values (see eq. 1). In this analysis we have determined the probability that the observed staggering plots can be produced by a smooth rotational sequence of γ-ray energies that obey the experimental uncertainties. We find that there is a 47.8% probability that the staggering plot of band 1 is produced by a smooth rotational sequence. For bands 2 and 3 this probability is 10.8% and 0.4%, respectively. One may therefore conclude that the statistical analyses support the presence of significant staggering patterns in bands 2 and 3.

Whether the observed irregular staggering in band 2 and the regular staggering in band 3 are due to an underlying Y_{44} symmetry in the SD Hamiltonian will not be addressed in this report, as the regular pattern calculated in this framework is not observed. It is, however, instructive to compare the observed staggering with the patterns expected from a band-crossing, as discussed in refs. [9–11]. The insets in figure 2 show the staggering that one would expect for the crossing of two bands. Two extreme cases were chosen where the crossing occurs either near levels in the bands (a) or at the midpoint between levels (b). When moving the crossing frequency between those extreme situations a smooth transition between these patterns is expected. The interaction between the bands is assumed to be so weak that the configuration mixing is extremely small and, as a result, no measurable cross talk between the bands occurs. Situation (a) can be approximated by the shift of only one level in the band and (b) by the shift of two levels. It is obvious that the staggering patterns in the insets are very similar to parts of the staggering plots for band 2 and 3. However, none of these patterns can solely account for the experimentally observed staggering. For each of the two SD bands at least two crossings (or level shifts resulting from other processes) would be necessary to account for the observations.

In the present data set, the largest taken so far on this nucleus, no evidence was found for additional SD bands which could be involved in a band crossing even though new SD bands could be identified [20] in ^{195}Hg and the strongest SD band in ^{193}Hg [21] was observed with an intensity of about 3% relative to the yrast SD band in ^{194}Hg. The FWHM of all SD

transitions was carefully checked and was found to be in agreement with the expected values taking intrinsic detector resolution and Doppler broadening into account. We conclude that there is no indication for a new SD band in ^{194}Hg with virtually identical transition energies to those of a known band. Therefore there is no experimental evidence for bands whose possible crossings could account for the observed staggering patterns.

In summary, we have performed a high statistics experiment to test for the previously reported [2] evidence for a $\Delta I = 2$ staggering in the three SD bands in ^{194}Hg. The transition energies have been determined in this work with an accuracy better than 30 eV for most transitions. Overall the staggering patterns from the present work agree within the experimental uncertainties with those reported earlier. The previously reported staggering pattern in band 1 was found not to be statistically significant. However, a significant staggering has been observed for band 2 for frequencies $\hbar\omega \geq 0.3$ MeV. This staggering is not completely regular as it includes one phase inversion. A short regular staggering with an amplitude of 50 eV has been observed in band 3 for $0.25\,\mathrm{MeV} \leq \hbar\omega \leq 0.375\,\mathrm{MeV}$. The staggering patterns that can be induced by a simple band-crossing have been briefly discussed. While the similarities of these patterns with parts of the observed staggering are significant, at least two such crossings would be required in each band to explain the data. It remains unclear which, if either of the proposed mechanisms is responsible for the observed features in the SD bands of ^{194}Hg. Additional experimental evidence is needed for a conclusive interpretation.

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TABLES

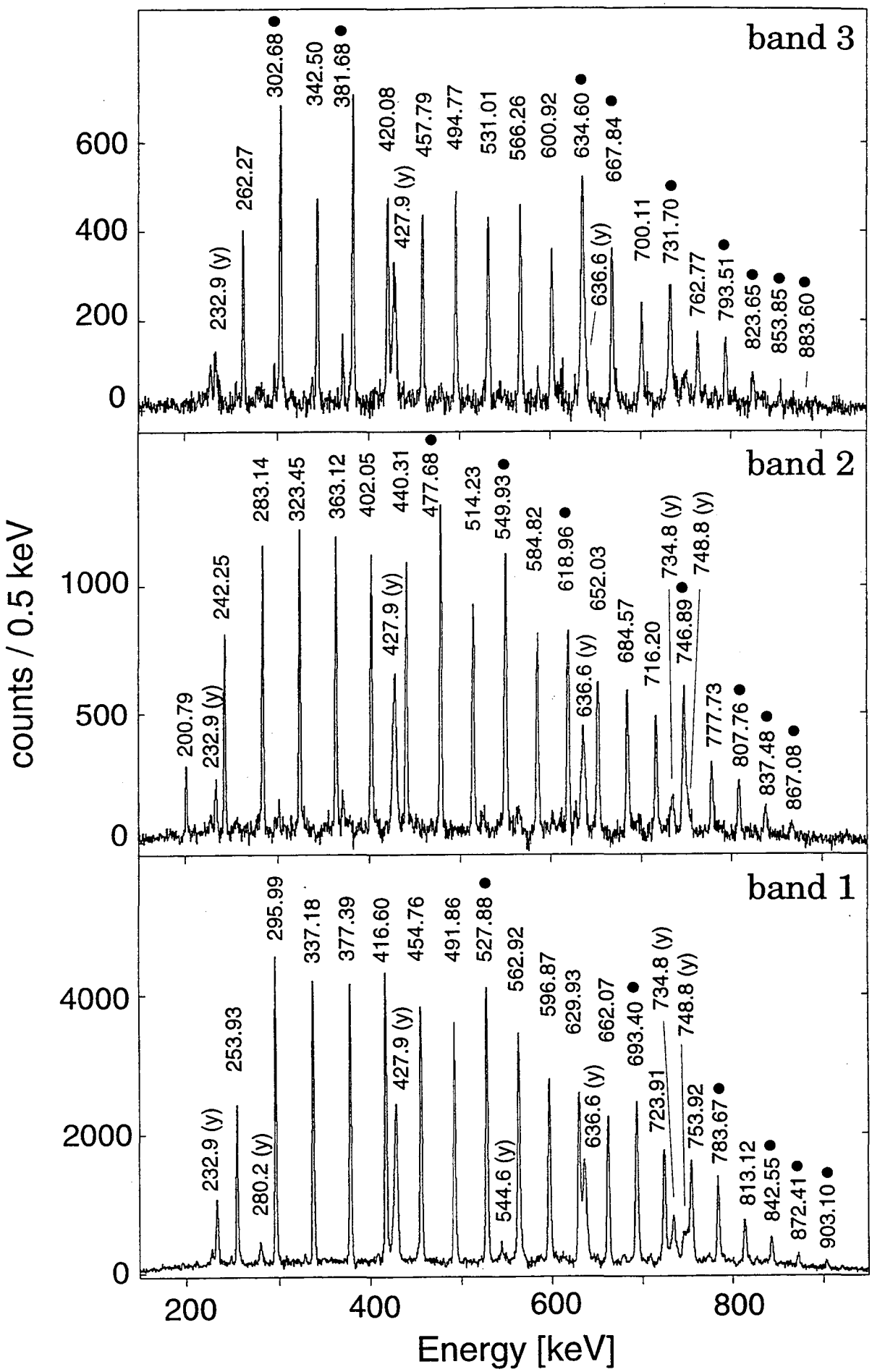
TABLE I. Transition energies and relative intensities for all transitions of the three superdeformed bands in ^{194}Hg as determined in this work. The intensities are corrected for detector efficiency and internal conversion.

^{194}Hg-1		^{194}Hg-2		^{194}Hg-3	
E_γ (keV)	rel. Int. (%)	E_γ (keV)	rel. Int. (%)	E_γ (keV)	rel. Int. (%).
		200.79 (2)	36 (2)		
253.93 (4)	58 (1)	242.25 (1)	75 (1)	262.27 (2)	76 (2)
295.99 (1)	97 (1)	283.14 (1)	100 (1)	302.68 (2)	90 (2)
337.18 (2)	95 (1)	323.45 (4)	97 (1)	342.50 (4)	90 (2)
377.39 (2)	97 (1)	363.12 (3)	100 (2)	381.68 (3)	97 (2)
416.60 (2)	100 (1)	402.05 (4)	100 (2)	420.08 (4)	100 (2)
454.76 (1)	99 (1)	440.31 (2)	102 (2)	457.79 (4)	99 (2)
491.86 (5)	101 (1)	477.68 (3)	101 (2)	494.77 (5)	102 (3)
527.88 (3)	100 (1)	514.23 (3)	100 (2)	531.01 (7)	104 (3)
562.92 (3)	94 (1)	549.93 (4)	102 (2)	566.26 (6)	105 (3)
596.87 (5)	89 (1)	584.82 (5)	99 (2)	600.92 (3)	95 (3)
629.93 (2)	87 (1)	618.96 (2)	89 (2)	634.60 (11)	91 (4)
662.07 (4)	82 (1)	652.03 (3)	86 (2)	667.84 (7)	89 (3)
693.40 (4)	76 (1)	684.57 (7)	84 (2)	700.11 (4)	86 (3)
723.91 (6)	68 (1)	716.20 (5)	71 (2)	731.70 (17)	72 (3)
753.92 (6)	56 (1)	746.89 (19)	54 (3)	762.77 (4)	61 (3)
783.67 (8)	48 (1)	777.73 (4)	44 (2)	793.51 (6)	48 (3)
813.12 (3)	33 (1)	807.76 (8)	35 (2)	823.65 (13)	30 (3)
842.55 (6)	19 (1)	837.48 (7)	18 (2)	853.85 (12)	13 (3)
872.41 (13)	10 (1)	867.08 (24)	8 (2)	883.60 (22)	9 (3)
903.10 (18)	5 (1)				

FIGURES

FIG. 1. Triple gated coincidence spectra for the three superdeformed bands. The transitions marked with filled circles were not used as gates. Strong yrast transitions in ^{194}Hg [18] are labeled with their energy and the symbol "y".

FIG. 2. The left panels show the fourth derivative ΔE_γ (see text for definition) of the γ-ray energies of the three superdeformed bands in ^{194}Hg versus rotational frequency $\hbar\omega$, determined in this work. The right panels show the results from Ref. [2]. The insets show staggering patterns expected from a band crossing scenario with the crossing frequency near a given level (a) and at the midpoint between the two levels (b).


band 3
232.9 (y)
262.27
302.68 ●
342.50
381.68 ●
420.08
427.9 (y)
457.79
494.77
531.01
566.26
600.92
634.60 ●
636.6 (y)
667.84 ●
700.11
731.70 ●
762.77
793.51 ●
823.65 ●
853.85 ●
883.60 ●
band 2
200.79
232.9 (y)
242.25
283.14
323.45
363.12
402.05
427.9 (y)
440.31
477.68 ●
514.23
549.93 ●
584.82
618.96 ●
636.6 (y)
652.03
684.57
716.20
734.8 (y)
746.89 ●
748.8 (y)
777.73
807.76 ●
837.48 ●
867.08 ●
band 1
232.9 (y)
253.93
280.2 (y)
295.99
337.18
377.39
416.60
427.9 (y)
454.76
491.86
527.88 ●
544.6 (y)
562.92
596.87
629.93
636.6 (y)
662.07
693.40 ●
723.91
734.8 (y)
748.8 (y)
753.92
783.67 ●
813.12
842.55 ●
872.41 ●
903.10 ●
counts / 0.5 keV
Energy [keV]
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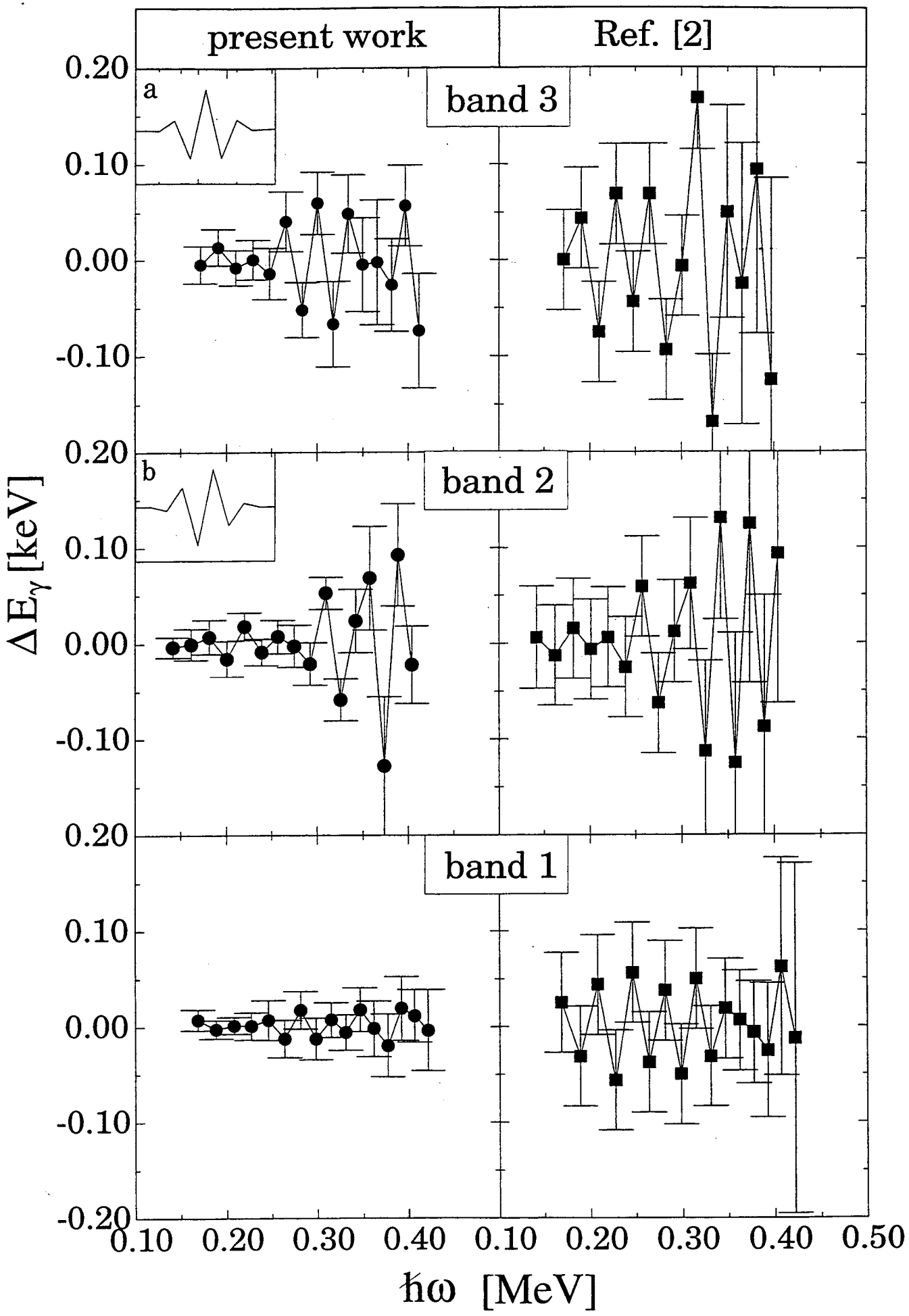
200
400
600
800
1000
500
2000
4000


present work
Ref. [2]
a
band 3
b
band 2
band 1
0.20
0.10
0.00
-0.10
-0.20
ΔE_γ [keV]
0.10
0.20
0.30
0.40
0.50
$\hbar\omega$ [MeV]

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