Evidence for $M1$ Transitions between Superdeformed States in ^{193}Hg

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(Received 19 November 1992)

Two-way decay has been observed between superdeformed bands in ^{193}Hg. It is proposed the decays have $M1$ multipolarity and connect signature partner bands. Candidates for the two-way gamma decays connecting superdeformed bands are observed for the first time.

PACS numbers: 21.10.Re, 23.20.Lv, 27.80.+w

Superdeformed states are associated with extremely large quadrupole deformations, typically $\beta_2 \approx 0.6$ in the mass 150 region [1,2] and $\beta_2 \approx 0.47$ in the mass 190 region [3,4]. The large quadrupole deformations enhance stretched $E2$ transition rates. Indeed both the mass 150 region and the mass 190 region have $B(E2)$ values [2–5] for superdeformed states which are 3 orders of magnitude larger than the corresponding single particle (Weisskopf) units. However, superdeformed bands around mass 190 extend to low frequencies ($\hbar\omega \sim 0.15$ MeV) and spins ($I_f \sim 8$) [6], much lower than for mass 150 nuclei. The large electron conversion coefficients associated with low energy $M1$ decays enhance the total $M1$ transition probability and the $E2$ transition probabilities decrease with decreasing transition energy [$T(E2) \propto E_\gamma^5$]. Thus it is more likely for $M1$ decays to compete with stretched $E2$ decays, resulting in cross talk between superdeformed states.

The first evidence for transitions between superdeformed bands was in ^{193}Hg [7]. Four superdeformed bands were observed and they were assigned as $[512]\frac{5}{2}$ $\alpha = -\frac{1}{2}$ (band 1), $[624]\frac{9}{2}$ $\alpha = \pm\frac{1}{2}$ (bands 2 and 3), and $j_{15/2}$ (band 4). Bands 1 and 3 ($\alpha = -\frac{1}{2}$) have identical transition energies at low spin. A fifth band was proposed (the "missing" $[512]\frac{5}{2}$ $\alpha = +\frac{1}{2}$ band) to have identical transition energies to band 2 ($\alpha = +\frac{1}{2}$) and this will be referred to as band 2′. Band 2′ would then be the signature partner to band 1. In order to clarify the ^{193}Hg superdeformed band assignments and to help prepare the way for the following discussion, a partial level scheme for bands 1, 2, 2′, and 3 is shown in Fig. 1. In Ref. [7] it was suggested that the decay proceeded from band 1 to band 3. The intensity of the cross talk was estimated to be of the order of 30% and it was proposed that the decays are $E1$.

In this paper we report on the first observation of two-way cross talk between superdeformed bands in ^{193}Hg. It is proposed that the cross talk is comprised of $M1$ transitions between superdeformed signature partner bands. In addition, candidates for the $M1$ γ decays are presented for the first time.

Excited states in ^{193}Hg were populated by the reaction ^{176}Yb(^{22}Ne,$5n$)^{193}Hg at a beam energy of 116 MeV. The gamma decay was detected using the high-energy-resolution array (HERA) Ge detector array at the Lawrence Berkeley Laboratory 88 in. cyclotron. The data were sorted into an E_γ-E_γ correlation matrix with

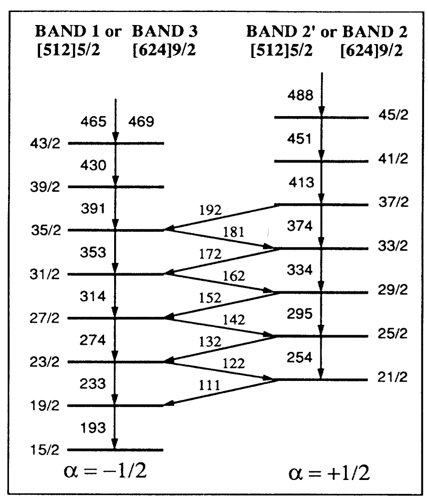

FIG. 1. Schematic partial level scheme for the proposed signature partner bands in ^{193}Hg. Following Ref. [7] we assume that there are two pairs of strongly coupled bands based on the two configurations $[512]\frac{5}{2}$ and $[624]\frac{9}{2}$. The two pairs of bands are "identical" up to the spins shown. Note that bands 2 and 2′ are not resolved and the single rotational sequence observed experimentally is assumed to be two bands. Also shown are $M1$ decays which may be expected to connect the signature partner bands. The $M1$ energies are *calculated* in the limit that the bands are strongly coupled. The spin assignments were derived from a fitting procedure and taken from Ref. [6].

the condition that at least two suppressed Ge detectors were in coincidence with a total γ-ray fold of 14 and higher. Approximately 680 million events were contained in this matrix of which $\sim 60\%$ belonged to ^{193}Hg.

Figure 2(a) shows a γ-ray spectrum in coincidence with the 353 and 391 keV transitions in bands 1 and 3. [It is not possible to say whether the decay is from band 1, band 3, or both since the γ rays from these bands are identical (to within 0.5 keV) below 430 keV.] In addition to these bands, low lying transitions (254, 295, and 334 keV) in band 2 are seen to be in coincidence with the gating transitions. It is estimated that approximately 25% of the intensity from band 1 and/or band 3 goes over to band 2 (at spin $I \approx \frac{31}{2}$).

A spectrum of superdeformed γ rays in coincidence with the 451 keV γ ray in band 2 is shown in Fig. 2(b). Other members of band 2 can be clearly seen. However, this spectrum also contains transitions with energies of 233, 274, 314, and possibly 353 keV. These transition energies correspond to known γ rays in the superdeformed bands 1 and 3. The intensity of the cross talk is of the order of 30% relative to the inband decay (at spin $I \sim \frac{29}{2}$). Furthermore, a spectrum [Fig. 2(c)] gated by the 274 keV γ ray in bands 1 and 3 not only contains all transitions from bands 1 and 3 but also contains all transitions from band 2 starting from the 334 keV γ ray and is indicated in Fig. 2(c) by an asterisk. Note that the spectrum contains no evidence for a 254 or 294 keV superdeformed transition (band 2). This is consistent with bands 1 and 2′ and/or bands 3 and 2 being strongly coupled signature partner bands (Fig. 1). These observations [Figs. 2(a)–2(c)] suggest that not only is there evidence for decays from the $\alpha = -\frac{1}{2}$ to the $\alpha = +\frac{1}{2}$ structure (as observed by Cullen *et al.* [7]), but also from the $\alpha = +\frac{1}{2}$ to the $\alpha = -\frac{1}{2}$ structure. This is the first time that two-way cross talk has been reported between superdeformed bands.

Two-way cross talk, as observed in these data, implies little or no energy splitting between the connecting bands. Since it is proposed [7] that both positive and negative parity superdeformed bands exist, it is possible the decay may be either $E1$ or $M1$. Collective low energy $E1$ transitions between rotational bands of alternating parity may occur [8–10] in the presence of stable octupole deformations. However, ^{193}Hg is not expected [7] to exhibit stable octupole deformations. It is therefore suggested that in this case (^{193}Hg) two-way cross talk would most likely indicate the presence of $M1$ decays.

Calculations [11] specific to ^{193}Hg have shown that $M1$ cross talk of the order of 25% is not unreasonable for the proposed configurations (namely $[512]\frac{5}{2}$ and $[624]\frac{9}{2}$). The possibility that the one-way cross talk observed [7] in ^{193}Hg was more likely to be $M1$ than $E1$ was first mentioned in Ref. [12].

Assuming bands 1 and 2′ and/or bands 3 and 2 are strongly coupled [7], it is possible to predict the transition

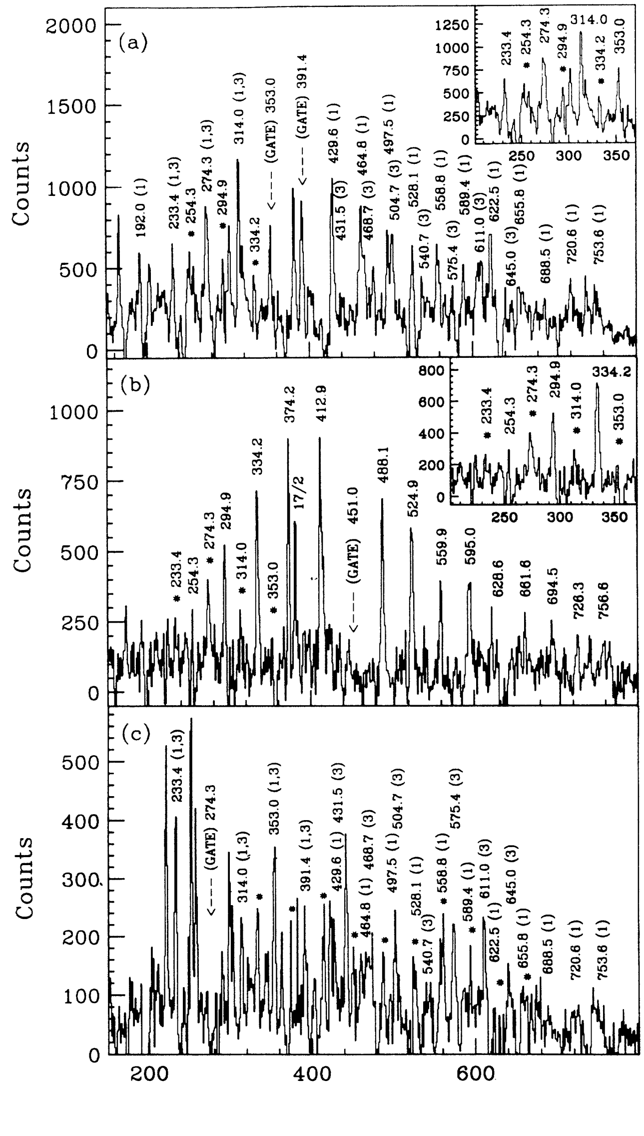

FIG. 2. (a) Spectrum of superdeformed transitions in coincidence with the 353 and 391 keV γ rays in bands 1 and 3. Transitions in bands 1 and 3 are labeled by energy and band assignment. Below 392 keV bands 1 and 3 are identical; at higher energies the bands diverge and are easily resolved. The γ rays marked with "*" correspond to known transitions in band 2. The inset is a section of the same spectrum expanded. (b) Spectrum of superdeformed transitions in coincidence with the 451 keV γ ray in band 2. Transitions in band 2 are labeled by energy. The γ rays marked with "*" correspond to known transitions in bands 1 and 3. The inset is a section of the same spectrum expanded. (c) Same as (a), except the gating transition is now the 274 keV γ ray in bands 1 and 3. Transitions in bands 1 and 3 are labeled by energy and band assignment. The γ rays marked with "*" correspond to transitions in band 2. The lowest γ ray in band 2 ("*") is at 334 keV and the highest is at 661 keV.

energies expected for $M1$ decays between the signature partner bands. For superdeformed states in the spin interval $\frac{21}{2}-\frac{37}{2}$ the $M1$ energies range from 111 to 192 keV and are separated by approximately 10 keV (Fig. 1). The lower portion of Fig. 3 shows a gate on the 391 keV transition in bands 1 and 3, while the upper portion is a section of the total projection spectrum, used to generate the background spectrum. The known superdeformed γ rays from bands 1 and/or 3 are indicated. In addition, at low frequencies there is evidence for a series of weak γ rays within 1 keV of the energies one calculates for $M1$ transitions. The dashed lines correspond to the energies where one may expect to observe $M1$ transitions. The peaks at 142 and 152 keV and to a lesser degree at 182 keV occur in a region where the background (total projection spectrum, upper part of Fig. 3) is relatively "flat" and as such these peaks are rather insensitive to the background subtraction. The gamma ray at 161 keV falls within a region of the spectrum which corresponds to a peak in the total projection and, as a result, is sensitive to background subtraction. For completeness we have also indicated, in brackets, the energies where one would expect to find other $M1$ gamma rays (see Fig. 1). The 132 and 172 keV transitions also correspond to regions in the total projection spectrum where large peaks occur and

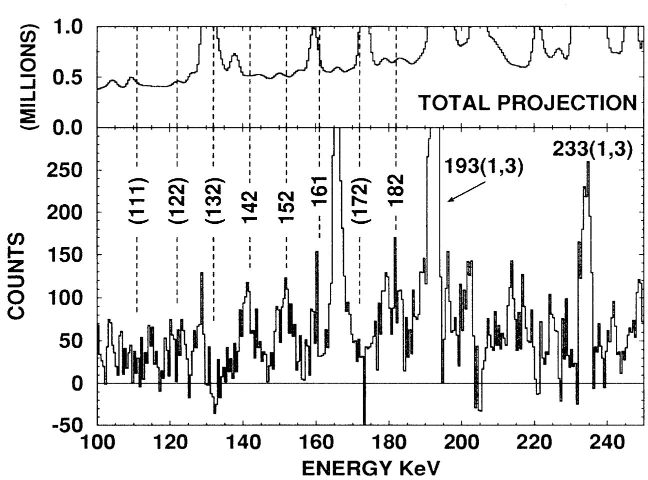

FIG. 3. Spectrum in coincidence with the 391 keV transition in bands 1 and 3. Superdeformed (SD) transitions in bands 1 and 3 are labeled by energy and band assignment. The 192 keV SD peak is a doublet with the $\frac{33}{2}^{+}-\frac{29}{2}^{+}$ 193 keV transition. Other peaks labeled by energy (142, 152, 161, and 182 keV) correspond to where one would expect to see $M1$ γ rays decaying between the two pairs of strongly coupled superdeformed signature partner bands (assumed to be based on the $[512]\frac{5}{2}$ and $[624]\frac{9}{2}$ orbitals). For completeness we also show, in brackets, those energies where one may expect to observe the remaining $M1$ gamma-ray transitions (111, 122, 132, and 172 keV). The upper portion of the figure shows the total projection spectrum. The positions of the proposed $M1$ decays are indicated by a dashed line. See text for more information.

once more we may expect to observe large fluctuations in the final spectrum following background subtraction. For $M1$ transitions and energies as low as 111 and 122 keV, electron conversion is expected to dominate over gamma decay.

It is clear that the energies of the gamma rays shown in Fig. 3 are, within errors, exactly those one would expect for $M1$ decays (Fig. 1). However, the gamma rays are very weak and, as discussed above, several of the peaks are sensitive to the background subtraction. Other superdeformed transitions in bands 1 (and/or 3) and 2 (and/or 2′) are generally more contaminated than the 391 keV gate (Fig. 3); nevertheless, the low energy gamma rays seen in Fig. 3 show up consistently in these other gates. Moreover, a spectrum in coincidence with gamma rays at 142 and 152 keV includes peaks consistent with known inband superdeformed transitions in bands 1 (and/or 3) and 2. Since the gamma rays are weak it was not possible to obtain the multipolarity of the transitions from an angular correlation (directional correlation with oriented nuclei technique) measurement. Finally, one would expect the ratio of the measured γ-ray intensity to the total $M1$ decay intensity to be approximately $\frac{1}{3}$ (due to ce^- decay) whereas the ratio of γ rays to total $E1$ decay intensity would be closer to 1 (very little ce^- decay). The individual intensities for the 142 and 152 keV $M1$ gamma rays are 14(6)% and 15(6)% of the full superdeformed inband intensity respectively or $\sim\frac{1}{2}$ of the total cross talk intensity and hence are more consistent with $M1$ decay. We therefore suggest that the series of low energy transitions (Fig. 3) corresponds to the $M1$ decays between signature partner superdeformed bands (as indicated in Fig. 1).

If it is assumed that ^{193}Hg has the same quadrupole moment as ^{192}Hg (20 eb) [5], then from the measured branching ratios $[(\Delta I=1)/(\Delta I=2)]$ one estimates the $B(M1)$ strength to be of the order of $0.5\mu_N^2$ (for the $[512]\frac{5}{2}$ and the $[624]\frac{9}{2}$ levels, Ref. [11] calculates $B(M1)$ values of 0.5 and 1.0 μ_N^2, respectively). Furthermore, from the measured branching ratios it is also possible to calculate the expected $K\alpha$ x-ray yield due to ce^- decays. For $M1$ transitions in the energy range 111 to 181 keV, one obtains a $K\alpha$ x-ray yield of approximately 0.8 ± 0.2 per cascade (for $E1$ decays this value drops to 0.2 ± 0.06). In Ref. [13] a $K\alpha$ x-ray yield of 1.6 ± 0.4 was measured for band 1 in ^{193}Hg. It is clear that any significant difference between our calculated value (0.8), based on the measured branching ratios, and the measured value (1.6) could easily be due to $M1$ decays between superdeformed transitions which we do not observe.

Because of the very small intensity of the superdeformed bands (1%–2% of the ^{193}Hg channel [7]), it was not possible to decompose the cross talk into contributions from either pair of assumed signature partner bands ($[512]\frac{5}{2}$ or $[624]\frac{9}{2}$). Neither was it possible to rule out the hypothesis that one-way $E1$ cross talk may also proceed from band 1 ($[512]\frac{5}{2}$ $\alpha=-\frac{1}{2}$) to band 2 ($[624]\frac{9}{2}$ $\alpha=+\frac{1}{2}$) as proposed by Cullen *et al.* [7].

In summary, the data presented here confirm the existence of cross talk between superdeformed bands. Unlike previous experiments the decay is observed both ways, indicating the presence of $M1$ transitions. Furthermore, a series of low energy γ-ray transitions has been identified and it is suggested that these correspond to the $M1$ decays between superdeformed bands.

The authors would like to thank M. A. Riley for useful discussions. This work was supported in part by the Office of Energy Research, Division of Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 (LBL) and in part by the U.S. Department of Energy under Contract No. W-7405-ENG-48 (LLNL).

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