Superdeformed band with a unique decay pattern: possible evidence for octupole vibration in $^{190}$Hg

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Abstract

An excited superdeformed (SD) band has been observed in $^{190}$Hg which decays to the lowest-energy (yrast) SD band rather than to the less deformed states as observed in most known SD bands in the $A \sim 150$ and $A \sim 190$ regions. The most plausible interpretation of this very unusual decay pattern associates this band with a collective structure built on an octupole-vibrational phonon in the SD well.

The presence of superdeformed (SD) nuclear states, i.e., states with very elongated shapes, in several regions of the periodic table is now well documented [1–3]. Besides the lowest-energy SD rotational sequence (hereafter referred to as the yrast SD band), excited SD bands have also been found in many nuclei and can be understood in terms of excitations of particles across the Fermi surface in the deformed mean field. However, no excited SD bands have been observed based on collectively vibrating band-heads. The existence of such bands should be expected, since rotational bands associated with quadrupole and octupole vibrations are commonplace features of nuclei at normal prolate deformation. The corresponding excitation energies represent a measure of the stiffness of the nucleus with respect to the deformations involved.

Among the collective vibrational excitations, those associated with the octupole degree of freedom have been predicted to play a significant role in the SD wells of the $A \sim 150$ and $A \sim 190$ nuclei [4–7]. Octupole collectivity is enhanced at these large deformations by the presence near the Fermi surface of many pairs of orbitals with opposite parity and $\Delta l = 3$. Calculations using Hartree-Fock and modified harmonic oscillator mean fields [4–7] predict that in the $A \sim 150$ and $A \sim 190$ regions, the SD minimum in the potential energy surface is far more octupole-soft than the first minimum, and that this softness extends to the non-axially symmetric octupole modes, which are relatively unimportant for shapes with smaller deformations [8]. Cranked Strutinsky calculations with a Woods-Saxon potential [9] even suggest that a reflection-asymmetric, axially non-symmetric min-
imum corresponding to a banana-like shape may become lowest in energy at high spin in some nuclei near \( A \sim 190 \). Attempts to reproduce these calculations within the same cranking approach, but with a differently parametrized Woods-Saxon potential, did not, however, yield the same results [10].

The calculations of Refs. [5] and [7] not only predict the presence at low excitation energy of rotational bands associated with octupole vibrations, but they also suggest a distinct signature for such bands. Very large E1 matrix elements \((B(E1) \sim 10 \times 10^{-3} \text{ W.u.})\) should connect the octupole states to the yrast SD levels. Thus, while the in-band transitions with \( B(E2) \sim 2000 \text{ W.u.} \) prevail in most excited SD bands, in the case of octupole-vibrational SD bands, deexcitation to the yrast SD band may be expected. No clear evidence for strong inter-band E1 transitions has been reported thus far. (Transitions between two SD bands in \(^{193}\text{Hg} \) [12] initially thought to be of E1 multipolarity, were shown to have M1 character instead [13].)

We report here on the discovery of a new SD band in \(^{190}\text{Hg} \) with a unique decay pattern: the band feeds directly into the previously known SD band [11,14]. Furthermore, the transitions linking the two sets of SD states have also been tentatively identified. The properties of the new band agree with those expected for octupole-vibrational SD states.

The experiment was carried out using the early implementation phase of the GAMMASPHERE spectrometer [15] which consists of 32 Compton-suppressed Ge detectors. Excited states in \(^{190}\text{Hg} \) were populated with the reaction \(^{160}\text{Gd} \left( ^{34}\text{S},4n \right) \) at a beam energy of 163 MeV, with a target consisting of a stack of three self-supporting 0.5 mg/cm\(^2\) \(^{160}\text{Gd} \) foils. The beam was provided by the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. Events of interest were selected by requiring that at least three Compton-suppressed detectors fire in prompt coincidence within a time window of 50 ns. A total of 660 million triple and higher-fold coincidence events was recorded. The data were analyzed by sorting all events into a three-dimensional histogram [16]. Double-gated one-dimensional histograms were created using full background-subtraction and proper propagation of errors [17].

The previously known SD band in \(^{190}\text{Hg} \) [11,14] was observed. With the added sensitivity of GAMMASPHERE, it was possible to add a 317.7 keV transition at the bottom of the band (Fig. 1a), and the highest transitions were determined more accurately as well (Fig. 1b). More importantly, the coincidence spectra gated on the members of this band contain transitions belonging to a second band (Fig. 1a), which is populated five times more weakly. This excited band begins
an accelerating pattern of de-excitation to the yrast SD band (Fig. 1c) at a rotational frequency of $\hbar \omega = 0.30$ MeV, and no measurable intensity remains in the band below $\hbar \omega = 0.25$ MeV. This pattern of decay is unlike those of almost all previously observed SD bands in the $A \sim 150$ and $A \sim 190$ regions, in which the nucleus remains in the SD band until finally decaying to the normally deformed states. Based on a spectrum consisting of a sum of double coincidence gates involving only members of the excited band itself, the measured probability of direct decay to the normally deformed states in the present case is measured to be $4 \pm 3\%$. Only two other cases exist in which somewhat similar patterns have been observed; one is due to an accidental degeneracy of levels in $^{150}$Gd [18], and the other involves M1 transitions between signature partners in $^{193}$Hg [13].

The above observations come from measurements of coincidence relationships between the two SD bands, but the inter-band transitions themselves have also been tentatively identified in this experiment (Figs. 1c, 2). All three of these transitions, at 607, 625, and 641 keV, are unfortunately close in energy to other gamma-rays in the spectrum associated with superdeformation in $^{190}$Hg (the 608.1 and 641.5 keV in-band transitions in the excited SD band, and the normally deformed 625.6 keV $4^+ \rightarrow 2^+$ transition fed in the decay of the SD states). The following evidence points toward their placement in the level-scheme of Fig. 2: (1) The intensity of the coincidence between the 543 keV and 641 keV transitions is larger by a factor of $\sim 3$ than it would be if the coincidence were only due to the in-band E2 transitions in the excited SD band. (2) The energy difference between the two paths leading to the $(27^+ \chi^-)$ state (i.e., $625(1) + 558.4(1) - 641(1) - 543.3(3)$ keV) is equal to $-0.9(14)$ keV, consistent with the proposed level-scheme to within 0.6 standard deviations. (3) The centroid of the compound peak near 625 keV peak is shifted downward in gates on the excited SD band, compared to the energy of the normally deformed $4^+ \rightarrow 2^+$ transition (Fig. 1d). The component identified as the inter-band transition is lower than the $4^+ \rightarrow 2^+$ transition by approximately 1.4 keV, or 3 standard deviations. (4) As discussed in more detail below, the coincident intensities between the two SD bands are consistent with the total intensities of the three pairs of overlapping peaks. (5) A sum of double coincidence gates on the 625 keV transition along with low-lying members of the yrast SD band shows the expected enhancement of the 576 and 608 keV lines, compared to a similar coincidence spectrum gated on the 417 keV $2^+ \rightarrow 0^+$ transition (Fig. 1e).

Estimates of the partial widths of the inter-band transitions can be obtained by assuming that the quadrupole moment of the states in the excited band is similar to that of the yrast band, i.e. $Q_0 = 18 \pm 3$ eb [11]. The extracted partial half-lives for the connecting transitions with energies of 641, 625, and 607 keV are then $110 \pm 30$, $120 \pm 30$, and $180 \pm 80$ fs, respectively. These surprisingly small partial half-lives place severe constraints on the possible physical interpretations.

If, for example, the inter-band transitions are of M1 multipolarity, then their strengths are approximately
1.0 W.u., which would be unprecedentedly large \[19\] for configuration-changing transitions in a deformed nucleus. (The mechanism described by Semmes et al. \[13\] for strong M1 branches between signature partners cannot apply here, assuming that the yrast SD band is a \(K = 0\), zero-quasiparticle configuration.) The possibility of E2 multipolarity for the inter-band transitions is unlikely for similar reasons. The strengths required are about 900 W.u., which again is implausibly large for transitions between states with different configurations.

In contrast, E1 transitions with the extracted partial half-lives can be much more easily understood. In this case, the strengths of the inter-band transitions are all consistent with \((8 \pm 2) \times 10^{-3}\) W.u. This E1 rate is three orders of magnitude larger than those typically observed in heavy, deformed nuclei and is similar to those observed in the octupole-unstable normally-deformed states of actinide nuclei \[8\]. The extracted E1 rate is in good agreement with calculations \[5,7\] for the neighboring nucleus \(^{192}\text{Hg}\) which predict a strength of \(11 \times 10^{-3}\) W.u. for transitions from an octupole-vibrational state in the SD well to the zero-phonon yrast SD band (at zero rotational frequency). Transitions of this strength correspond to an electric dipole moment of 0.48(3) e·fm.

Although all but five of the detectors in this experiment were located at forward and backward angles, it is possible to check whether the data are consistent with the angular distributions expected for dipole transitions, since \(\Delta J = 1\) dipole transitions were attenuated relative to \(\Delta J = 2\) quadrupole transitions by a factor of 0.74. This attenuation factor was measured to be 0.7 \pm 0.4 for the transitions linking the excited band to the yrast band, a value which marginally favors \(\Delta J = 1\) dipole assignments. Based on the above evidence, and assuming that the yrast SD band corresponds to a \(K = 0\), zero-quasiparticle configuration with even spin and positive parity, we suggest that the excited band has negative parity, and probably odd spin.

Another unique feature of the excited band is its moment of inertia. The dynamic moments of inertia \(\Omega^\text{(2)}\) for the two SD bands are presented as a function of rotational frequency \(\hbar \omega\) in Fig. 3. The \(\Omega^\text{(2)}\) values for the yrast SD band exhibit the same behavior as those of all other SD bands in even-even nuclei of the \(A \sim 190\) region, i.e. a smooth increase of \(\Omega^\text{(2)}\) occurs with increasing frequency. At the highest frequencies, a sharp rise is noticeable. Such a rise has been qualitatively reproduced in cranked Strutinsky \[14,20\] and cranked Hartree-Fock \[21\] calculations, and is interpreted as being due to a combination of a dynamic reduction in the pairing correlations as a function of spin and a band crossing between the zero-quasiparticle SD band and a rotation-aligned \((j_{15/2})^2\) neutron band. More important for the present discussion is the observation that the excited SD band is characterized by a constant value of \(\Omega^\text{(2)} = 123 \pm 1h^2/\text{MeV}\) (with \(\chi^2 = 3.6\) per degree of freedom) which is about 20% larger than those of the other SD bands in the region. This observation is consistent with the calculations of Ref. \[7\], which predict \(Q_0 = 1.13 \times Q_{\text{yrast}}\) for the octupole vibrational band. (The exact moment of inertia depends on both the deformation and the size of the pair gaps \[3\].) An upward revision of the value of \(Q_0\) by this amount does not increase the extracted E1 strengths significantly compared to the statistical errors.

\[\text{Quasiparticle alignments may lead to an increase in the apparent moment of inertia over some range of spins, but cannot account for the large and constant moment of inertia observed here. The rigid-body moment of inertia is also insensitive to octupole deformation, \[10\] although the actual moment of inertia may show dependence on octupole deformation through a variety of dynamical effects.}\]
Based on the discussion above, the most plausible interpretation is that the excited SD band observed in this experiment is a rotational band built on a one-phonon octupole vibration in the SD well. Experience with normally deformed states shows that the octupole-vibrational bands with $K = 0, 1, 2$ and 3 are ordinarily significantly split, and that the full multiplet is seldom observed. Thus, the observation of a single band in this experiment is not surprising. The octupole multiplets in the normally deformed well are typically mixed significantly at high spin by the Coriolis force, and a similar effect has been predicted to occur in the SD well [6]. All four values of $K$ can contribute to an odd-spin wave-function, but the strong transitions to the $K = 0$ yrast band observed here imply that the $K = 0$ and $K = 1$ components are dominant. The excitation energy of the excited band relative to the SD yrast line varies from 0.40 MeV at the bottom of the band to only 0.15 MeV at the top (assuming odd spin for the excited band). Although the generator coordinate calculations of Refs. [5,7,10] were carried out at zero rotational frequency, RPA calculations have been performed for states with collective rotation [6] giving, at $\hbar \omega = 0.25$ MeV, a predicted excitation energy of 0.7 MeV above the yrast band for the lowest vibrational mode, composed mostly of the $K = 2$ component, and 1.1 MeV for the next vibrational state, which is mainly $K = 0$ and 1. This is in only rough agreement with the observed excitation energy of 0.4 MeV near $\hbar \omega = 0.25$ MeV, but the comparison is not as informative as could be hoped for as the calculations were performed at fixed $\omega$, and thus the states being compared have different angular momenta, since the two SD bands have different moments of inertia.

From the study of octupole bands in the normally deformed well of many nuclei it is well known that, at moderate spins, the wave-functions of these negative parity states are dominated by a small number of two-quasiparticle configurations [8]. (An indication of such an effect is present, for example, in the RPA calculations of Ref. [6] for the $K = 2$ octupole vibration in the SD well of $^{192}$Hg, but not for the $K = 0$, 1 states.) It is interesting to note that, if a similar effect were present in the excited SD band discussed here, most of the lowest two-quasiparticle excitations in $^{190}$Hg would involve a $j_{15/2}$ quasineutron coupled to a quasineutron occupying one of the positive parity orbitals located near the Fermi surface (see Ref. [11] for the relevant quasiparticle spectrum). The occupation of a single $j_{15/2}$ orbital would have the effect of blocking the first rotational alignment of a $j_{15/2}$ neutron pair. Octupole correlations are also predicted to dilute the rotation-aligned character of the quasiparticle orbitals [11]. Both of these effects would influence the $\zeta^{(2)}$ moment of inertia of the excited SD band and result in more constant $\zeta^{(2)}$ values as a function of frequency than in the yrast SD band, in agreement with the observations in Fig. 3.

In conclusion, we have observed an excited SD band in $^{190}$Hg, which has a very unusual decay pattern. A detailed examination of this pattern shows that it differs clearly even from that found in the few other cases where inter-band transitions have been detected between SD states of nuclei in the $A \sim 150$ and $A \sim 190$ regions. The observed properties agree well with those predicted by generator coordinate calculations for a rotational band built on an octupole-vibrational band-head. If this interpretation is correct, then this is the first experimental information to become available regarding the susceptibility to octupole deformation of nuclei in the $A \sim 150$ and $A \sim 190$ regions of superdeformation. At this stage, however, the octupole-vibrational picture is only one possible scenario. Clearly, further theoretical and experimental effort is desirable.

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