Excitation Energies and Spins of a Superdeformed Band in ^{194}Hg from One-Step Discrete Decays to the Yrast Line

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Discrete γ rays directly connecting states of a superdeformed (SD) band in ^{194}Hg to the yrast states have been discovered. Thus, the excitation energies and spins of all members of the lowest SD band are established for the first time, together with their likely parity. The SD band decays from its 10^+ and 12^+ states, which lie 4204.8 and 4407.4 keV above the normal-deformed yrast states of the same spins.

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Superdeformation has been a central focus in the study of nuclear structure. Long cascades of rotational transitions between superdeformed (SD) states have been observed in nuclei with mass ~130, 150, 190 [1,2], and 80 [3]. While the rotational transitions have been easy to detect with modern Ge arrays, it has been much harder to localize the SD bands (in excitation energy and spin) and to link them to the normal-deformed (ND) yrast states. For example, in the mass 150 and 190 regions, the intraband transitions of more than 100 SD bands have been found; yet, despite many attempts, there is no band for which the exact excitation energies, spins, and parity have been conclusively determined. The location of a SD band in ^{143}Eu was proposed [4], based on a two-photon sum-peak technique. However, the low statistics of the peaks suggest that confirmation is needed, and their placements in the level scheme require substantiation by coincidence relationships. In contrast, in the mass 130 region, some strongly deformed bands lie only ~0.8 MeV above the ND yrast states and it has then been possible to identify many of the decay pathways between the SD and less deformed ND states [5]. Therefore, one of the most pressing challenges in the study of superdeformation in the $A = 150$ and 190 regions is the accurate determination of the excitation energies, spins, and parities of the parent levels of the known SD band transitions.

The SD bands in these regions are especially interesting because they lie at high energy, yet they are isolated in a well-defined minimum (false vacuum) at the point where they decay out to the ND states in the true vacuum. The decay is believed to occur when a SD level, embedded in a sea of hot ND states, acquires a small component of a hot compound state, and decays through this component [6]. This description is supported by the measured γ decay spectrum, which has a statistical quasicontinuous character [7], and by its agreement with a calculation of the statistical spectrum [8]. From the measured decay spectrum, Henry *et al.* [7] deduced that the SD state of ^{192}Hg lies 4.3 $\pm$ 0.9 MeV above the ND yrast line at the point of decay. A similar value is expected in ^{194}Hg since its quasicontinuous spectrum [9] is almost identical to that in ^{192}Hg.

Decay from SD bands and from resonant thermal-neutron capture both represent statistical deexcitation of narrow highly excited states. The γ decay spectra contain sharp high-energy primary γ rays (from decays to low-lying states) and low-energy secondary γ rays (from subsequent transitions between the low-lying states), in addition to the quasicontinuous component (from transitions where initial and/or final states lie in a region of high level density). Based on these features, we suggest that a straightforward method to accurately locate a SD band is to find the highest energy primary γ rays, i.e., the direct one-step transitions to the ND yrast states. The exact connections with the yrast transitions can then be defined by coincidence relationships. The average number of steps from a SD state to the yrast line is 3.2 $\pm$ 0.6 in ^{192}Hg [7],

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but there is a distribution in this number. In calculations of the statistical decay from a SD state, which give fair agreement with the measured γ decay spectrum, Døssing *et al.* [8] estimate that direct one-step decay has a branching ratio of up to $\sim 5\%$ and may be detectable. In the mass 190 region, these one-step γ rays should have energies of 3.5–5 MeV [7]. Such high-energy lines present an advantage, since they can arise only in a heavy nucleus when a well-defined decay energy exists, such as from the decay of a sharp highly excited state. The predominant γ rays in this energy domain are statistical γ rays (from feeding and decay of SD bands), which form a smooth distribution because they originate from and/or terminate in a multitude of states. The primary γ rays following neutron capture are dominated by $E1$ transitions [10], and this is likely to apply also in the deexcitation of SD states. Therefore, we might expect that most primary decays from a SD band of a given parity will deexcite to ND states of opposite parity.

Motivated by these expectations, we embarked on a search for very high-energy γ rays coincident with known SD transitions in ^{194}Hg [11]. We have discovered several γ rays between 3.4 and 4.5 MeV, which unambiguously define the excitation energies, spins, and probable parity of one SD band. SD bands in ^{194}Hg were populated using the ^{150}Nd(^{48}Ca, $4n$) reaction. The beam, delivered from the 88" Cyclotron at LBNL, had an energy of 195 MeV (at midtarget). The γ rays were detected using GAMMASPHERE [12], which at the time consisted of 55 Ge detectors, surrounded by BGO Compton shields. Detectors were located at 13 different angles with respect to the beam. The ~ 1 mg/cm^2 Nd target was in intimate contact with a 12 mg/cm^2 Au backing, in which the evaporation residues stopped. The event trigger required at least three Compton-suppressed γ rays and, after imposing a prompt time gate, 1×10^9 events were sorted, resulting in 2×10^9 triple coincidences (including events unpacked from higher-fold coincidences). Relative efficiency and energy calibration of the Ge detectors were performed up to 3.6 MeV using standard sources.

There is no question that the highest-energy one-step γ rays must exist. The question is whether the statistics are good enough to find them. From our accumulated data, triple coincidences produced the maximum number of counts in the spectra, which were nevertheless extremely clean after background subtraction with the method of Ref. [13]. Pairwise gates on lines from the three known SD bands (labeled 1–3) produced one-dimensional spectra, which extended up to 5.5 MeV, and the statistical errors were also computed.

Figure 1(a) shows the high-energy portion of the spectrum in pairwise coincidence with the seven lowest transitions of SD band 1. Three peaks are clearly observed at 3489, 4195, and 4485 keV at a $(5-8)\sigma$ level. We propose that these lines are the one-step γ rays we seek. In addition, a number of weaker candidates are also visible,

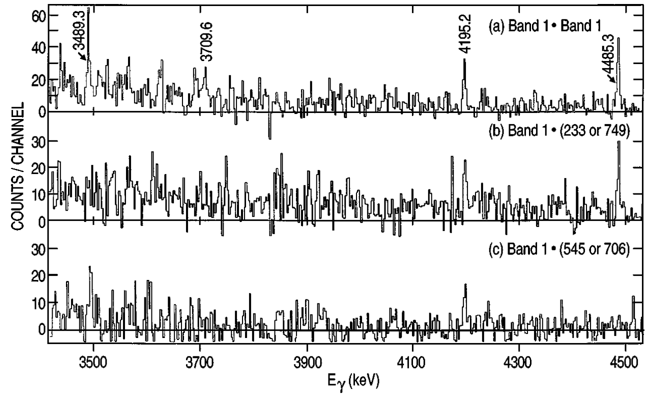

FIG. 1. Spectra from (a) pairwise coincidences of transitions in SD band 1 and (b),(c) pairwise coincidences with a band 1 γ ray and a transition deexciting a ND negative parity level. SD band 1 coincidence gates have energies of 255 to 492 keV. Transitions directly connecting SD and ND yrast levels are labeled in (a); other weaker lines probably feed excited ND levels. The absence of the 4485-keV line in (c) demonstrates that it feeds the ND 9^- level. The 3489-keV line is weak in (b) due to statistical fluctuations.

including one at 3710 keV (3σ level). (The other weaker peaks probably represent decays to excited ND states which have not yet been placed in the decay scheme.) Figures 1(b) and 1(c), which show spectra from pairwise gates on a SD band-1 line and on a γ ray from the negative-parity ND states, indicate that the one-step decays feed negative-parity levels and, specifically, that the 4485-keV transition feeds the ND 9^- level [14]. Pairwise gates on either the 4195- or 4485-keV lines with a band-1 line give spectra which reveal SD band-1 γ rays

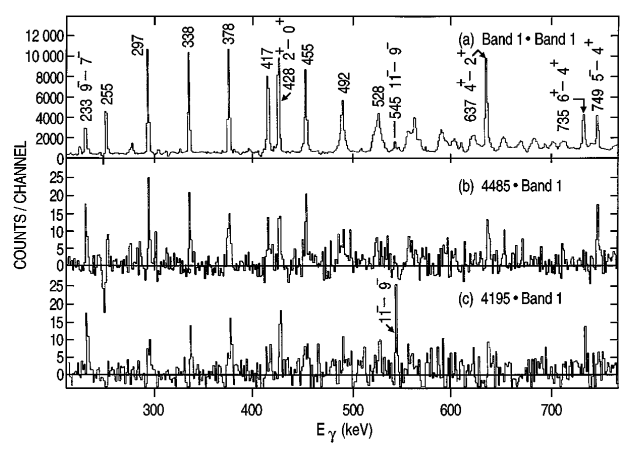

FIG. 2. (a) Low-energy portion of the spectrum in Fig. 1(a). Energies are given for SD band 1 and ND lines. (b),(c) Spectra in pairwise coincidence with the indicated one-step decay lines and one γ ray in SD band 1. The ND $11^- \rightarrow 9^-$ line is absent in (b) but present in (c), indicating that the 4195-keV γ ray feeds the 11^- level. The presence and absence of the 255-keV transition in (b) and (c) help to establish that the 4485- and 4195-keV γ rays deexcite the SD 10^+ and 12^+ levels, respectively [see Fig. 3(a)].

(see Fig. 2) with the expected intensities. Furthermore, the spectra also indicate the specific end points of the one-step decays into the ND negative-parity levels, as well as the decay points from SD band 1. No decay to positive parity yrast states has so far been detected. Like the lowest-energy intraband γ rays [see Fig. 2(a)], the high-energy lines [in Figs. 1(a) and 1(b)] are sharp (with no Doppler shifts at the various detector angles) as they are emitted at the end of the γ cascade, after the evaporation residues have stopped in the Au backing. This observation, the many exact agreements between γ-ray energy differences and level spacings, and, particularly, *the rigorous coincidence relationships* conclusively establish the decay scheme for SD band 1—Fig. 3(a). The relative intensities of the γ rays associated with band 1 are also given in Fig. 3(a). A plot of spin versus energy for members of band 1, as well as for the ND yrast states, is given in Fig. 3(b).

The angular anisotropies of the 3489-, 4195-, and 4485-keV band-1 γ rays (typical $A2 = -0.53 \pm 0.33$) indicate dipole character and rule out stretched quadrupole transitions. These data, together with the decay branches to final states of several spins, permit firm spin assignments for the SD states. We cannot yet distinguish between $E1$ or $M1$ emission; however, as previously discussed, $E1$ multipolarity is strongly favored. Since all of the decays are to negative parity levels, it is very probable that all have $E1$ character. Hence, the parity of band 1 is most likely positive.

The intraband intensities show that 43% and 54% of the decay out of band 1 occurs from the $I, \pi = 12^+$ and 10^+ SD levels, respectively. As expected, the one-step γ rays to the yrast states also originate from these levels, but they carry only a small fraction of the decay out of the SD states: 3.3% and 1.5% from the 12^+ and 10^+ SD levels, respectively. This is consistent with our estimate of $\sim$5% [8], which was discussed above. However, this agreement may be fortuitous. We have not yet been able to locate high-energy lines from SD band 2 or from the yrast SD band in ^{192}Hg, which has statistics (from a separate experiment) comparable to that of band 1 in ^{194}Hg, while band 3 has only a pair of candidate transitions. In addition, whereas we have seen three decay branches from the 12^+ SD level, only a single branch from the 10^+ level has been detected. Such γ-transition strength fluctuations may arise due to the complex compound state through which the SD level decays. For a sufficiently complex state, the fluctuations will have a Porter-Thomas distribution [15], but it has not been determined if this is applicable here. On account of these fluctuations, sufficiently high statistics are required to be assured of finding the one-step transitions. By the same token, they can help to make the transitions observable; ^{194}Hg probably represents one such fortunate case.

If the reasonable assumption is made that the quadrupole moment [16] of band 1 is constant, the partial

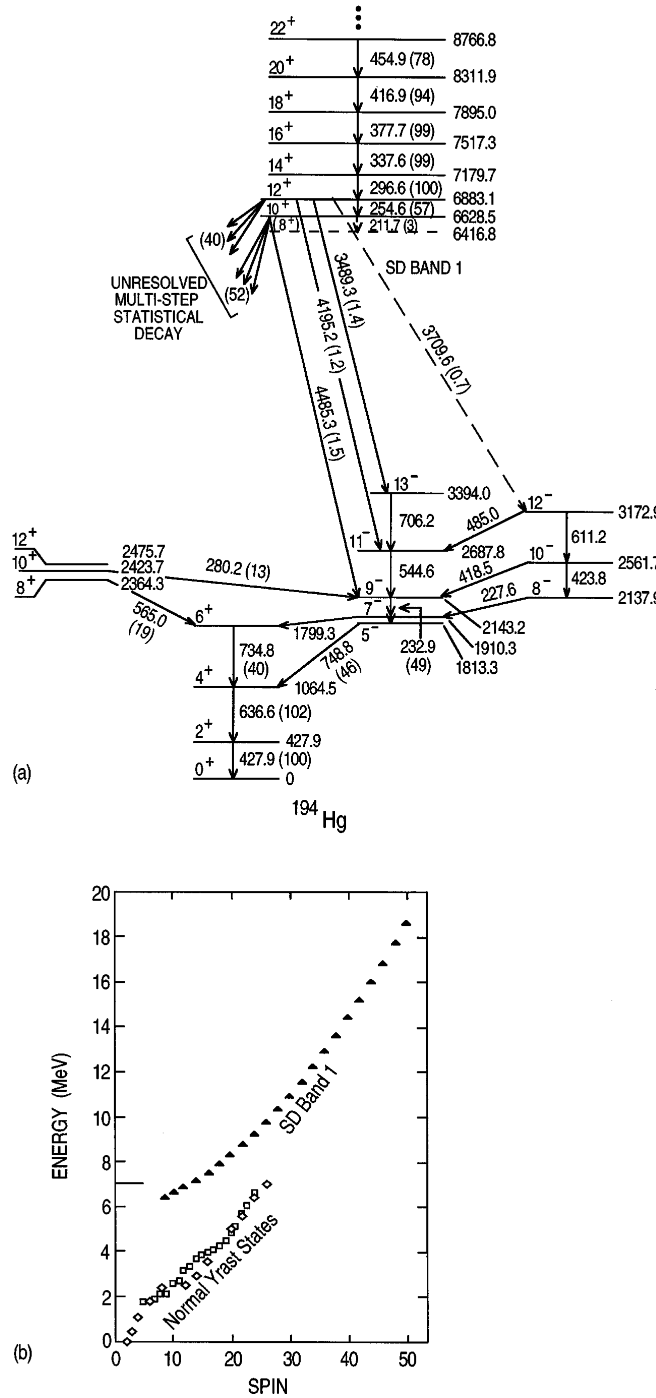

FIG. 3. (a) Decay scheme of SD band 1 in ^{194}Hg. The excitation energies and spin assignments are firm, while the parity is very probable. The relative intensities of transitions are given in parentheses. Dashed lines indicate tentative assignments. The ND level scheme was taken from Ref. [14]. (b) Energy vs spin diagram for SD and ND states in ^{194}Hg.

decay rates for the total statistical decay and for the one-step branches can be determined. The transition strengths for the latter corresponds to $\sim 7 \times 10^{-9}$ or 8×10^{-5} Weisskopf units (W.u.), for $E1$ or $M1$ multipolarity, respectively. In either case, these represent very highly retarded transitions, which suggests a very weak mixing between SD and ND states. The ratio [17] of the observed SD decay rate to a calculated ND statistical decay rate (using a standard γ strength function based on the giant dipole resonance) yields an $\sim$0.6% admixture (squared amplitude) of a ND compound state in the SD state, which is responsible for the decay. This implies that the one-step decays from the ND compound state have strengths of 10^{-6} or 10^{-2} W.u. for $E1$ or $M1$ transitions, respectively. The $E1$ rate is at the low end of the range [18] for primary $E1$ γ rays from neutron capture.

The excitation energy of a SD band above the yrast line is determined accurately for the first time. For band 1 in ^{194}Hg, the 10^+ SD level lies 4204.8 $\pm$ 0.5 keV above the 10^+ ND yrast level. This value is close to the excitation energy of 4.3 $\pm$ 0.9 MeV reported [7] for the yrast SD band of ^{192}Hg. At the point of decay, the SD band 1 excitation energy for ^{194}Hg is high (4.2 MeV) compared to the values of $\sim$0.8 MeV for the $A = 130$ region [5], 2.8 MeV for fission isomers [19], and the proposed value of 3.6 MeV for ^{143}Eu [4]. From an extrapolation of the $\Im^{(2)}$ moment of inertia to zero frequency, we estimate that the $I = 0$ level for SD band 1 in ^{194}Hg lies at 6017 keV. There is now an accurate benchmark against which theory can compare; theoretical predictions [20–23] give values of 4.6, 4.9, 5.0, and 6.9 MeV, respectively, which do not agree with the experimental value.

The members of band 1 have spins which span $10\hbar$ to $50\hbar$ and have only even spins and, most likely, positive parity. No other band with the same intensity exists which could be its signature partner with odd spin. Thus, band 1 has the same properties as the usual ground band with $K = 0$ and, being the lowest one in the SD well of ^{194}Hg, behaves as the "ground" band in the false vacuum. Pair correlations which are present in SD bands in the $A = 190$ region [20] lead to $K = 0$ for the ground band. The spins for band 1 are in agreement with those derived [24] from a fit of $\Im^{(2)}$ vs $\hbar\omega$ and an extrapolation to zero frequency.

The determination of the spins and of the most probable parity of the SD levels is an important result of this work. Although this has been performed for only one SD band, this first case is significant. With an approximate tenfold increase in statistics expected with the full GAMMASPHERE and EUROGAM arrays, it should be possible to find the one-step decays of most SD bands and to characterize their quantum numbers. So far, without knowledge of spins, it has been possible to test theory using only rotational frequencies (transition energies) and assumed spins. More incisive and stringent tests of models requires exact knowledge of the spin and parity quantum numbers. As one example, we shall soon be able to determine the spin difference of states emitting γ rays of the same energy. This has been a major issue in understanding the identical band puzzle, the phenomenon where rotational bands in different nuclei have surprisingly similar energies [2,25,26]. With the imminent completion of the large Ge arrays, we are poised for new insights into SD bands.

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