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DECAY OF SUPERDEFORMED BANDS

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One of the major challenges in the study of superdeformation is to directly connect the large number of superdeformed bands now known to the yrast states. In this way, excitation energies, spins and parities can be assigned to the levels in the second well which is essential to establish the collective and single-particle components of these bands. This paper will review some of the progress which has been made to understand the decay of superdeformed bands using the new arrays including the measurement of the total decay spectrum and the establishment of direct one-step decays from the superdeformed band to the yrast line in ¹⁹⁴Hg.

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1 Introduction

With the building and utilization of the new γ -ray arrays, Gammasphere, Eurogam and Gasp, a new realm of detection sensitivity has opened up for nuclear structure studies at high spin. The study of superdeformation illustrates how this new sensitivity has enabled one to probe in detail states in the second well. For example, new regions of superdeformation have been established¹, known regions have been extended², transitions between superdeformed (SD) bands, both of $M1$ and $E1$ character, have been observed^{3,4}, and detailed lifetime measurements have been performed^{5,6,7}. All of these results have advanced our understanding of superdeformation. However, even with this explosion of new results, little progress has been made in connecting SD bands with yrast states whose spins and parities have been established.

In the mass 130 region, some strongly deformed bands lie only ~ 0.8 MeV above the normal deformed (ND) yrast states, and it has been possible to identify many of the decay pathways between the SD and less deformed ND states⁸. In addition, the excitation energy of a SD band in ^{143}Eu was proposed⁹ based on a 2-photon sum-peak technique. However, the low statistics of the peaks suggests that confirmation is needed, and their placements in the level scheme require substantiation by coincidence relationships.

In contrast to these findings, there is no band for which the exact excitation energies, spins and parity have been conclusively determined in the $A=150$ and 190 superdeformed regions, even though, the intraband transitions of more than 150 SD bands have been found. Therefore, one of the most pressing challenges in the study of superdeformation in these regions is the determination of these observables. This paper will concentrate on our attempts at measuring and understanding the decay of SD bands in the $A=190$ SD region. Specifically, results are presented on the measurement and calculation of the decay spectrum associated with a SD band in ^{192}Hg ^{10,11}, and the establishment of one-step decays from the SD band to the yrast line in ^{194}Hg ¹².

2 Feeding of the Superdeformed Band

With the identification of a superdeformed band in ^{152}Dy ¹³, important features concerning both feeding and decay of the SD band were already revealed by the intensity profile for intraband transitions. This profile displayed three distinct regions: (1) an increase in intensity with decreasing spin which is associated with the feeding of the band, (2) a region of constant intensity marking the end of the feeding region, and (3) a rapid loss of intensity over the last two or three transitions where the band decays towards the yrast states. With the

establishment of more SD bands in neighboring nuclei¹⁴, and the discovery of the $A \sim 190$ SD region¹⁵, it became clear that this intensity pattern first observed in ¹⁵²Dy was a general feature of SD bands.

In many ways, the understanding of the mechanism behind the decay of superdeformed bands has its origins in attempts to understand how these bands are fed. Schiffer and Herskind¹⁶ initiated some of the first attempts to calculate the feeding of SD bands. Moore *et al.*¹⁸ added critical experimental information to this topic by measuring the average entry points in the energy-spin (E,I) plane for both normal and SD states in ¹⁹²Hg and ¹⁵²Dy. Lauritsen *et al.*¹⁷ measured, for the first time, the entry distribution of a superdeformed band, and showed that the entry distribution associated with the SD band originates from the higher spin components of the total entry distribution. In addition, the SD distribution was reproduced using a model which tracks the history of the γ cascade by Monte Carlo simulation starting at the entry point in the E,I plane as determined from the measured total entry distribution. In these simulations mixing between normal and SD states was included and γ -transition probabilities were governed by the relative level densities and the barrier separating the two potential wells.

The model calculation not only reproduced the measured SD entry distribution, but also described correctly all observables associated with the feeding of the SD band, namely the band intensity and its variation with spin, and the quasicontinuum $E2$ spectra associated with excited states in the second well. By combining constraints obtained from the model and from the measured SD entry distribution, it was suggested¹⁷ that the SD band in ¹⁹²Hg had an excitation energy between 5.2 and 6.2 MeV at $I=0$ which corresponds to an excitation energy of 3.3–4.3 MeV at the point the SD band decays ($I \sim 10\hbar$).

3 Measurement of the Decay Spectrum

With the coming on line of the new arrays, there were several proposals put forth to describe the decay of a SD band. Vigezzi *et al.*¹⁹ suggested that the decay results from statistical mixing between the localized SD state and highly excited ND states. If this proposed mechanism is correct, the decay spectrum should be statistical in nature. Another proposal²⁰ suggested that the decay is due to an overlap of only the collective wavefunctions of SD and ND states with a predicted decay spectrum consisting of a few $E2$ transitions well localized in energy. Unfortunately, the data which preceded the new arrays was not of sufficient quality to answer this question.

In order to address this problem, an experiment was performed on ¹⁹²Hg with EUROGAM I²² which contained at that time 43 Compton Suppressed

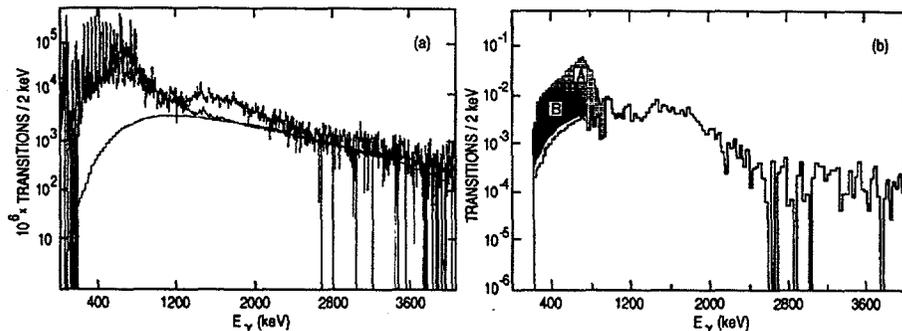


Figure 1: (a) Spectra coincident with pairs of known SD lines (dark histogram) and with the $2 \rightarrow 0$ ground state transition in ^{192}Hg . The smooth line represents the calculated statistical feeding spectrum. (b) Difference between the spectrum coincident with the SD band and the calculated spectrum of statistical feeding γ rays shown in (a). Known discrete lines have also been removed and the spectrum contracted to 32-keV-wide bins. The prominent $E2$ peak and a $M1/E2$ -component are shaded and labeled A and B, respectively. The remaining spectrum (thick histogram) is from the decay of SD states.

Ge detectors. SD states in ^{192}Hg were populated in the $^{160}\text{Gd}(^{36}\text{S},4n)$ reaction at a beam energy of 159 MeV. A 1 mg/cm^2 Gd target backed by 10 mg/cm^2 Au was used. Details of this work have been published previously in ref. ¹⁰.

In order to study the decay properties, a spectrum of the known SD band²¹ was extracted from the data by placing pairwise coincidence gates on SD lines. This spectrum was then properly background subtracted and corrected for neutron interactions, coincidence summing, detector response and photopeak efficiency. The resulting spectrum is shown in Fig. 1a, and it represents all γ rays which are in coincidence with the SD band, including transitions associated with feeding and decay. For comparison, the spectrum of all γ rays in ^{192}Hg , obtained by gating on the $2^+ \rightarrow 0^+$ transition is also given in the figure, and each spectrum is normalized so that the ground state transition has unit intensity. Clearly, there are differences between the two spectra. For example, the SD spectrum contains a broad component ranging from 1.3 to 2.3 MeV as well as a broad peak centered around 690 keV which has $E2$ multipolarity.

To extract the spectrum of γ rays connecting SD to ND states from the total spectrum, transitions which (i) feed the SD band, (ii) connect SD band members, and (iii) connect ND states at the end of the cascade must be removed. The sharp lines emitted in stages (ii) and (iii) are easily identified, the challenge is to separate the feeding and decay γ rays. In order to subtract out γ rays associated with statistical feeding into the SD well, a calculation of

this spectrum must be performed. This is accomplished by using the model developed by Lauritsen *et al.*¹⁷ and briefly described in the preceding section. It should be stressed that the parameters of the model have already been determined from the entry distribution analysis described above. Thus, the calculated statistical feeding spectrum, which is shown in Fig. 1a as a smooth line, is not a fit to the decay spectrum. The spectrum resulting from the subtraction of the calculated statistical γ rays and the known discrete lines from the total spectrum is given in Fig. 1b.

Angular distribution data show that the γ rays above 1 MeV in Fig. 1b are of dipole character, but below 1 MeV, there are at least two components, one of $E2$ character and one with mixed $M1/E2$ multipolarity. These components are shaded and labeled A and B in the figure. Doppler shifts are observed for the $E2$ bump, and tentatively for the $M1/E2$ component indicating that these transitions are emitted from the nucleus while the recoil is still moving in the target. From a previous lifetime measurement on the SD band of $^{192}\text{Hg}^{24}$, where a similar backed target was used, it was established that the bottom four transitions in the SD band are emitted when the nucleus has come to a stop in the target. Thus, any transition associated with the decay will also be emitted when the recoil is at rest. This suggests that components A and B can be associated primarily with the feeding of the SD band. The $E2$ bump originates mainly from unresolved collective SD transitions, while the $M1/E2$ component is probably from the last stage of the feeding. What remains under the thick line is the spectrum of γ rays which connect the SD band with the yrast transitions or the so-called decay spectrum.

The decay spectrum shown in Fig. 1b has a quasicontinuum component of dipole character with a statistical distribution, apart from the prominent bump between 1.3 and 2.3 MeV. This spectrum confirms previous proposals^{19,25} that an SD level decays to ND states when it acquires a small component of a hot compound state, and decays through this component. From the decay spectrum, one can deduce that the SD state of ^{192}Hg lies 4.3 ± 0.9 MeV above the yrast line at the point of decay, and the average number of steps in the decay from a SD state to the yrast line is 3.2 ± 0.6 . The bump centered around 1.6 MeV indicates a clustering of transitions in this energy region and is unexpected based on the statistical nature of the decay. It was speculated in ref.¹⁰ that this bump arises from a redistribution of levels due to pairing.

4 Calculating the Decay Spectrum

Statistical decay from a sharp state and the associated decay spectrum provide a probe of the level density (ρ) of normal states in a specific region of excitation

energy and spin. Motivated by this and the speculation that the shape of the decay spectrum is determined by pairing in the first well, a program was undertaken by Døssing *et al.*¹¹ to calculate the statistical γ -decay spectrum from an excited nuclear state by explicitly including effects of pairing as a function of the number of excited quasiparticles. Three different treatments of the pairing interaction were considered, all based on the BCS wave function. Details of the calculation can be found in ref. ¹¹.

Fig. 2 shows statistical decay spectra calculated without (panel a) and with pairing (panels b-d); in the latter case, the level densities are obtained with diagonalized states for even-even, odd-even and odd-odd combinations of particle numbers. The initial excitation energy above the yrast line (U) is chosen as 4.3 MeV, the value deduced¹⁰ for the superdeformed band in ¹⁹²Hg when it decays out to the normal states. With no pairing, the monotonically increasing temperature of the unpaired level density leads to a smooth statistical decay spectrum; the spectra from the different decay steps are gently displaced relative to each other, combining to form a smooth spectrum for the whole cascade. With pairing, the spectra display local fluctuations, which result not only from fluctuations of the level density at low U but also from the high degeneracy of some of the excitations and the underlying equidistant single-particle spectrum. Since the degeneracies are an artifact of the model, we also show spectra smoothed by a Gaussian of width 0.3 MeV.

For the even-even nucleus, comparison of the spectra with and without pairing shows that in the former case there is depleted yield for $E_\gamma < 1.2$ MeV, and also between 3.2 and 4 MeV. Both features are due to the pairing gap below the energy for $\nu = 2$ quasiparticle excitations. The ensuing compression of the spectrum, together with the last step transitions across the gap to the lowest-lying state, give rise to a broad bump centered around 1.6 MeV, illustrating how the shape of the decay spectrum reflects perturbations of the level density due to pairing. A direct comparison of the calculated decay spectrum with that measured for the SD band of ¹⁹²Hg shows good qualitative agreement, especially when a reduced ground state pair gap of $\Delta_0 \sim 0.7$ MeV is used¹¹.

For the odd-even and odd-odd cases, there is no gap in the level spectrum, but the effects of pairing on the level densities persist and produce a similar, but less pronounced, bump in the statistical spectrum. This feature, which is absent in the unpaired case, manifests the effects of pairing. However, the filling of the pair gap gives rise to a major difference from the even-even spectrum: there is now appreciable yield at low energy. The differences in the calculated spectra for even-even, odd-even and odd-odd nuclei are significant and suggest a direct experimental test of the model. Preliminary comparisons with the measured spectra for decay out of superdeformed bands in ¹⁹²Hg¹⁰, ¹⁹⁴Hg²⁷

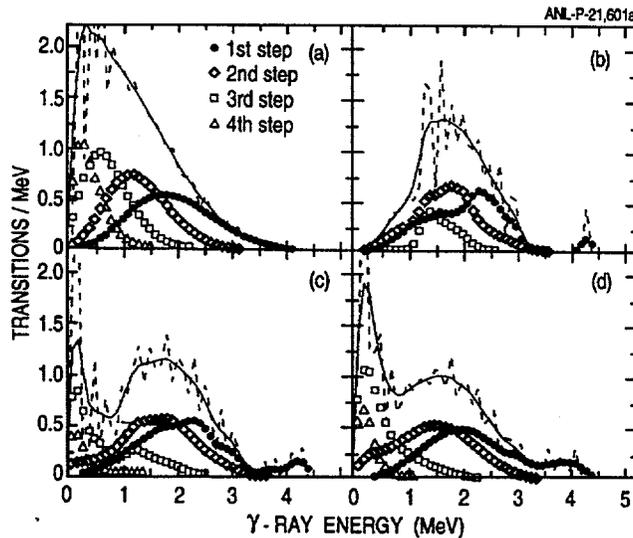


Figure 2: Statistical decay spectra, with 100-keV bins, for initial energy $U = 4.3$ MeV (dashed lines) calculated with (a) the unpaired even-even level density, and (b-d) with the level densities obtained in the diagonalization procedure with (b) even-even, (c) odd-even and (d) odd-odd particle numbers. The solid lines in the panels are obtained by folding the spectra by a Gaussian function of FWHM = 0.3 MeV, chosen to be equal to the distance between doubly degenerate neutron single-particle levels. The contributions to the full spectrum from individual cascade steps, denoted by the symbols in panel (a), are also folded by the Gaussian function.

and $^{191}\text{Hg}^{27}$ show encouraging qualitative agreement in the overall features. Namely, in the odd-A case (^{191}Hg), there is excess yield below 500 keV which is not present in the even-even cases. One aspect of the calculation which is beyond the range of the data is a spike at 4.3 MeV (see panel b) which corresponds to a direct transition to the yrast line. Such a direct transition is calculated to occur $\sim 2\text{-}5\%$ of the time and is expected to be further reduced by fragmentation from decay to several final states. We suggest that if spins and excitation energies are to be firmly established for SD bands, it is these transitions which one should pursue.

5 One-Step Decays to the Yrast Band

While the extraction of the decay spectrum in ^{192}Hg reveals much about the nature of the decay, it can only place limits on the excitation energy and

spins of the SD band. The calculations described above predict that about 5% of the SD decay should proceed via one-step transitions to the yrast states, and indeed, this picture is one which is observed in resonant thermal-neutron capture which is another example of statistical deexcitation of narrow highly-excited states.

In the mass 190 region, these one-step γ rays should have energies of 3.5 - 5 MeV¹⁰. Such high-energy lines present an advantage, since they can only arise in a heavy nucleus when a well-defined decay energy exists, such as from the decay of a sharp highly-excited state. As discussed in the previous section, 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 $E1$ transitions²⁶, 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 ¹⁹⁴Hg²⁸ and ¹⁹²Hg²¹. SD bands in ¹⁹²Hg and ¹⁹⁴Hg were populated using the ¹⁴⁸Nd(⁴⁸Ca,4n) and ¹⁵⁰Nd(⁴⁸Ca,4n) reactions, respectively. The beam, delivered from the 88 inch Cyclotron at LBNL, had an energy of 195 MeV (at mid-target). The γ rays were detected using Gammasphere²⁹, which at the time consisted of 55 Compton-suppressed Ge detectors. The ~ 1 mg/cm² Nd target was evaporated on a 12 mg/cm² Au backing, in which the evaporation residues stopped. The event trigger required at least 3 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). In order to analyze the data, pairwise gates on lines from the 3 known SD bands in ¹⁹⁴Hg and the yrast SD band in ¹⁹²Hg were placed on the data to produce 1-dimensional spectra extending up to 5.5 MeV. Background subtraction of these spectra were performed following the method described by Crowell *et al.*³⁰, and the statistical errors were computed.

Fig. 3a shows the high-energy portion of the spectrum in pairwise coincidence with the 7 lowest transitions of SD Band 1 in ¹⁹⁴Hg. Three peaks are clearly observed at 3489, 4195 and 4485 keV at a 5-8 σ level. In addition, a number of weaker candidates are also visible, including one at 3710 keV (3 σ level). Fig. 3b,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⁻ level³¹. Pairwise gates on either the 4195- or 4485-keV

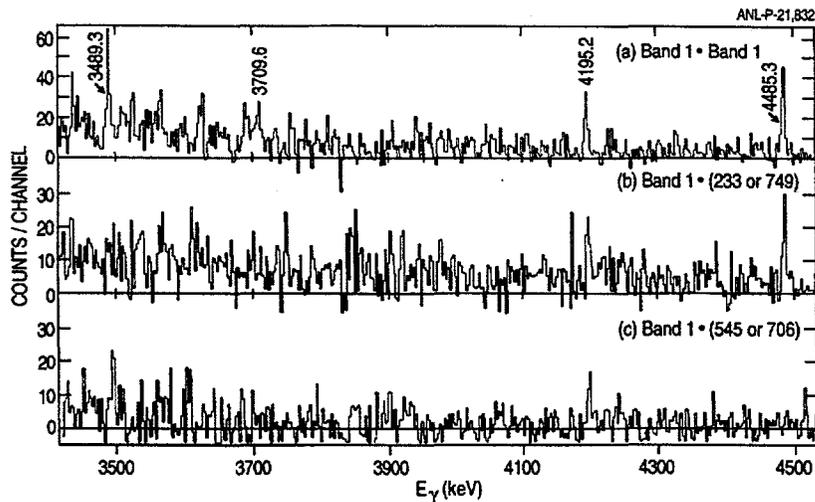


Figure 3: Spectra from (a) pairwise coincidences of transitions in SD band 1 and (b,c) pairwise coincidences with a band 1 γ ray and a transition deexciting a ND negative parity level. Transitions directly connecting SD and ND yrast levels are labelled in (a). The absence of the 4485-keV line in (c) demonstrates that it feeds the ND 9^- level. The 3489-keV line is weak in (b) due to statistical fluctuations.

lines with a band-1 line give spectra which reveal SD band-1 γ rays (see Fig. 4) 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 direct decays to positive parity yrast states have so far been detected. Like the lowest-energy intraband γ rays (see Fig. 4), the high-energy lines (in Fig. 3) are sharp 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 (see Fig. 5). Thus, these four high-energy γ rays are transitions which directly link the SD band to the yrast states. (The other weaker peaks observed in the spectrum probably represent decays to excited ND states which have not yet been placed in the decay scheme.)

The angular anisotropies of the 3489-, 4195- and 4485-keV band-1 γ rays (typical $A_2 = -0.53 \pm 0.33$) indicate dipole character and rule out stretched quadrupole transitions. These data, together with the decay branches to final

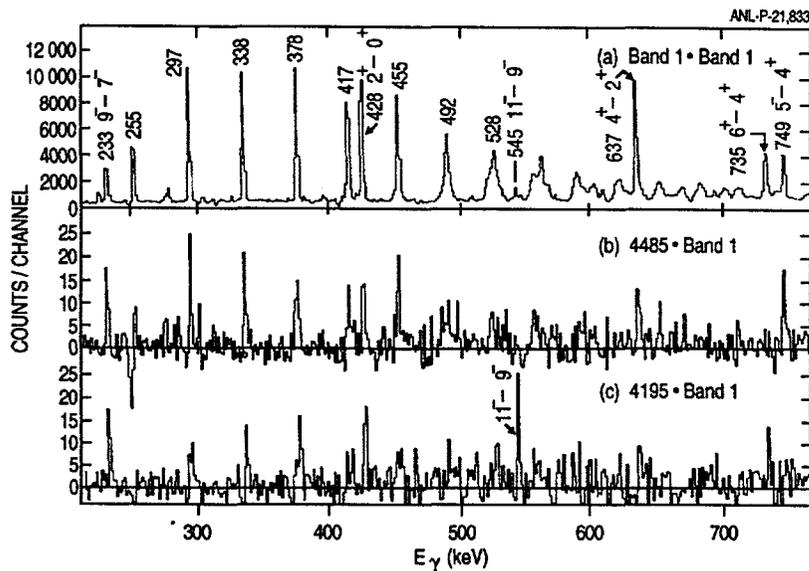
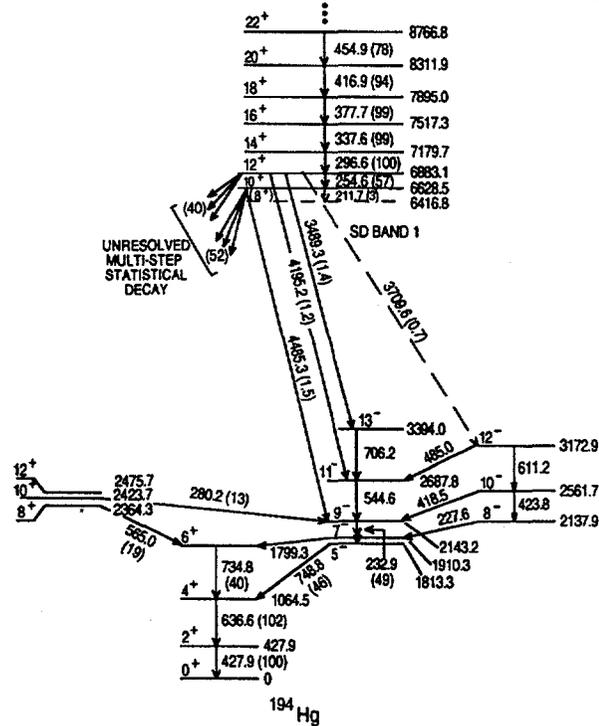


Figure 4: (a) Low-energy portion of the spectrum in Fig. 1(a). Energies are given for SD band 1 and ND lines. (b-c) Spectra in pairwise coincidence with the indicated one-step decay lines and one γ ray in SD band 1. The ND $11^- \rightarrow 9^-$ line is absent in (b) but present in (c), indicating that 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.

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 relative intensities of the γ rays associated with band 1 are given in Fig. 5. 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^+ SD and 10^+ SD levels, respectively. This is consistent with our estimate of $\sim 5\%$ ¹¹, 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 ¹⁹²Hg, which has statistics comparable to that of band 1 in ¹⁹⁴Hg (band 3 only has a pair of candidates



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 (WU), 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 ratio³³ 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} WU for $E1$ or $M1$ transitions, respectively. The $E1$ rate is at the low end of the range³⁴ for primary $E1$ γ rays from neutron capture.

The 10^+ SD level lies 4204.8 ± 0.5 keV above the 10^+ ND yrast level. This value is close to the excitation energy of 4.3 ± 0.9 MeV reported¹⁰ 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 ~ 0.8 MeV for the $A=130$ region⁸, 2.8 MeV for fission isomers³⁵, and the proposed value of 3.6 MeV for ^{143}Eu ⁹. From an extrapolation of the $\mathfrak{S}^{(2)}$ 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^{36,37,38,39} give values of 4.6, 4.9, 5.0, 6.9 MeV, respectively, which do not agree with the experimental value.

The members of band 1 have even spins, which span 10 to $50 \hbar$, and, most likely, positive parity. No other band with the same intensity exists which could be its signature partner. Thus, Band 1 has the same properties as the usual ground state rotational band with $K=0$. As a result, we conclude that band 1 is the "ground" band in the second well for ^{194}Hg . In addition, it should be noted that the spins for band 1 are in agreement with those derived⁴⁰ from a fit of $\mathfrak{S}^{(2)}$ vs $\hbar\omega$.

6 Summary

Progress has been made over the last few years in understanding why superdeformed bands decay rapidly to the ground state. The measurement of the decay spectrum in ^{192}Hg shows that this decay is statistical in nature and the features of the spectrum can be qualitatively reproduced by adding pairing to a statistical model calculation. In our most recent experiment at Gammasphere, excitation energy, spins and the most probable parity of SD levels in ^{194}Hg have been measured by identifying the direct one-step decays from the SD band to the known yrast states. So far, without knowledge of spins, it has been possible to test theory for states in the second well using only rotational

frequencies (transition energies) and assumed spins. More incisive and stringent tests of models require exact knowledge of the spin and parity quantum numbers. With the measurement of one step decays in other SD bands, it soon should be possible 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^{15,41,42}. With the imminent completion of the large Ge arrays, we are poised for new insights into SD bands.

Acknowledgments

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