Discrete–Line Transitions from Superdeformed to Yrast States in ^{194}Hg and ^{192}Hg

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Discrete–line γ-ray decay from superdeformed (SD) to yrast states in ^{194,192}Hg has been studied with the Gammasphere spectrometer. The previously established decay for the yrast SD band of ^{194}Hg has been characterized further. In addition, one–step decays have been observed for ^{194}Hg SD band 3, which fixes the excitation energy and spin of the last observed level of this band at $E^* = 7.455$ MeV, $J = 11\hbar$. So far no direct decays from superdeformed to yrast states have been observed in ^{192}Hg or in ^{194}Hg band 2, a result which is consistent with fluctuations of the transition strengths.

High–spin superdeformed (SD) bands have been known for some time now [1] , and a considerable effort has been devoted to understanding their many fascinating properties, *e.g.* the exact nature of excited bands and the physical origin of the identical bands phenomenon. Progress on these fronts has in the past been impeded by the fact that the spins and excitation energies of these SD bands could not be measured by traditional discrete–line γ spectroscopy, *i.e.* by the straightforward application of coincidence relationships and energy differences (the Ritz principle) to deduce with confidence a level scheme. At the point of decay–out, the lowest members of the SD bands are located at very high excitation energies relative to the yrast line. The coupling to excited "normal–deformed" (ND) states is very weak, but once the wave function picks up a small component of the hot ND states, the decay can proceed via a multitude of paths which are difficult to resolve. The branching ratio for a primary γ decay directly from a SD state to a ND yrast or near–yrast level is very small, and until recently, the ever–evolving γ-ray spectroscopy arrays simply did not have the sensitivity to detect these primary decays. Early attempts to measure the

spins and excitation energies of SD bands [2-4] did not or could not use coincidence and Ritz principle information, and therefore were not fully satisfactory.

Recently, a network of primary decays from ^{194}Hg SD band 1 to yrast states [5] was observed. Shortly thereafter, experiments on ^{194}Pb [6] revealed a network comprising both "one–step" primary decays from SD to yrast levels and "two–step" decays, that is, primary decays to non–yrast ND states where the deexcitations from these previously unknown ND states to the yrast line were also observed.

Clearly, the third–generation γ-ray detector arrays have reached one of their most important milestones; they have the sensitivity to measure the spin and excitation energies of SD states directly through traditional discrete–line spectroscopy methods. Two new Gammasphere experiments have been undertaken to search for the one–step decays from SD bands 2 and 3 of ^{194}Hg, and band 1 of ^{192}Hg. The main motivation behind these experiments lies in the fascinating, and always controversial, problem of identical bands: one of the excited bands of ^{194}Hg (band 3) is isospectral with ^{192}Hg band 1, that is, the in-band γ rays have the same energy. Determining the spins and parities

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of these two bands would constrain the possible explanations for identical bands, for example, by ascertaining whether or not states emitting γ rays of the same energy also have the same spin and parity. Furthermore, measuring the excitation energies of bands 2 and 3 in ^{194}Hg would lend further insight into the nature of these excitations, namely whether they are two–quasiparticle excitations or whether they pertain to octupole vibrations or some other collective excitation mode. Finally, by better characterizing the one–step decay network for band 1 (including measurements of the transition probabilities), it was hoped to gain insight about the nature of the fluctuations in transition intensity.

At the time of the experiments, Gammasphere comprised 85 high–purity germanium detectors. The reactions employed were ^{150}Nd$(^{48}$Ca,4n$)^{194}$Hg at E_{beam}=202 MeV and ^{160}Gd$(^{36}$S,4n$)^{192}$Hg at E_{beam}=160 MeV. In both cases, the targets were backed with a $\sim$ 15 mg/cm^2 Au layer. The first, highest-spin transitions in the SD cascade were emitted while the recoiling Hg nucleus was in flight. In contrast, the lowest transitions in the band were emitted from a fully stopped nucleus, as were all of the normal deformed lines following the decay–out. This provided a *distinctive signature* for primary decay γ rays; they also had to be *fully stopped* and their peaks had to be *sharp*.

The sum of double–gated γ–γ–γ coincidence spectra of band 1 of ^{194}Hg and ^{192}Hg are shown in Figure 1, which demonstrates the quality of the data. Most of the analyses have been done with triple–coincidence events. For the high–energy primary transitions, this yields the best tradeoff between statistics and background, and therefore the best sensitivity.

In the new data on ^{194}Hg, the previously-reported [5]4485, 4195 and 3489 keV lines associated with the primary decay of SD states, as well as their coincidence relationships with intraband SD and yrast transitions, are spectacularly reproduced. In addition, two more primary transitions have been added to the decay scheme; a 3942 keV "one–step" decay from the 12$^+$ SD state to the 13$^-$ ND state, and a 3565 keV transition which de–excites the 10$^+$ SD state. The level fed by the latter transition should be highly non–yrast, and there is evidence in the coincidence spectrum for a 919 keV decay to the 9$^-$ yrast state which completes this "two–step" path.
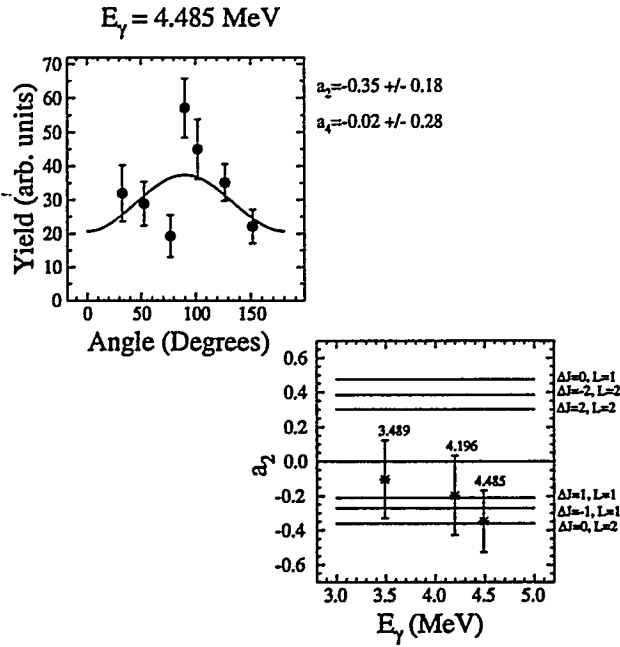
For three primary transitions, angular distributions have been measured and A_2/A_0 coefficients extracted. (See Figure 2.) The new data show with much greater confidence that the A_2/A_0 coefficient
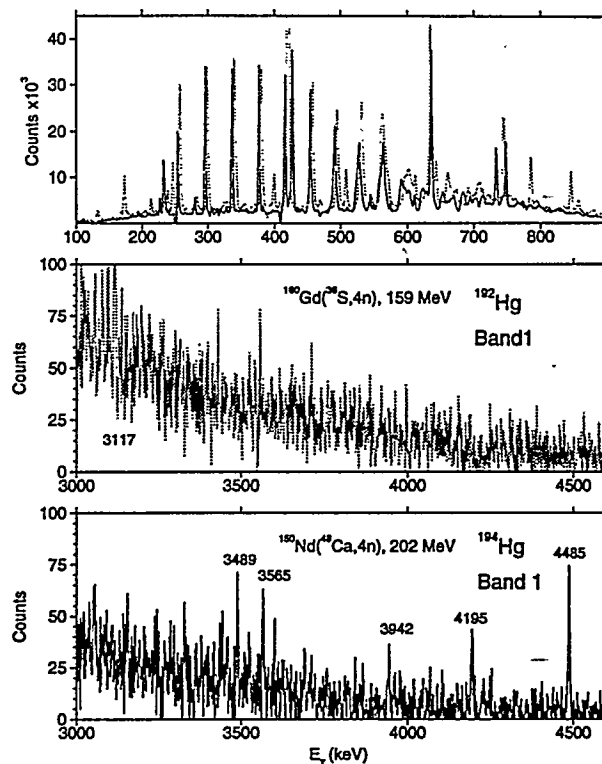
Figure 1: Sums of double–gated coincidence spectra on ^{192}Hg band 1 (gray) and ^{194}Hg band 1 (black). Top panel: low–energy portion of both spectra, overlaid, showing the SD band members. Note that the higher–energy transitions of the SD band become broadened due to Doppler shift. Middle and bottom panels: High–energy portion of these spectra in the range where one–step decays would be expected.

of the 4485 keV line is negative and consistent with stretched or anti–stretched dipole radiation. The measured A_2/A_0 values for the 3489 and 4195 keV transitions also favour the same multipole character. Furthermore, the coefficients all rule out the possibility of stretched quadrupole transitions or dipole transitions with a spin change of 0. All of these results are fully consistent with the spin assigments given previously. Dipole transitions are more likely E1 in nature than M1, since neutron capture data [7] show that the transition rate for the former should be five times that of the latter.
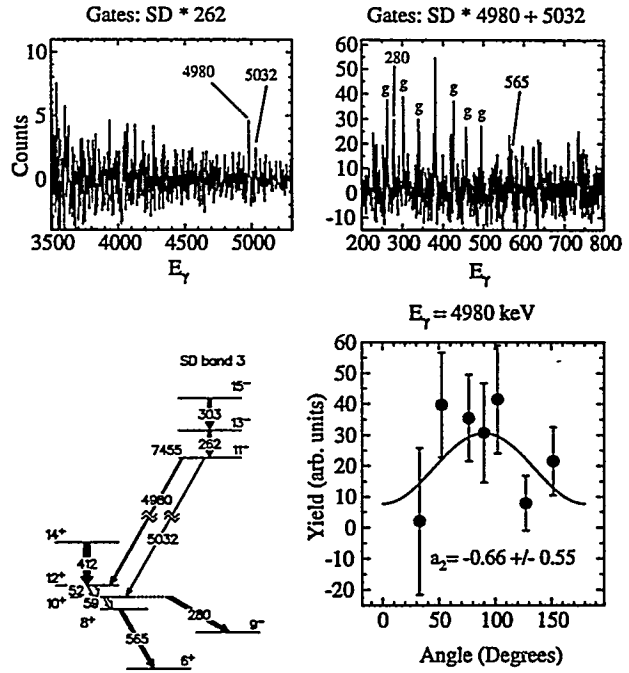
For ^{194}Hg band 3, which is isospectral to ^{192}Hg band 1, two γ rays with energies of 4980 and 5032 keV have been assigned as one–step primary transitions de–exciting the SD band. Figure 3 shows how these transitions have been placed. In the top–left coincidence spectrum, which is the sum

Figure 2: Top left panel: angular distribution and best polynomial fit for the 4485 keV primary transition. Bottom right panel: extracted A_2/A_0 coefficients for the three strongest primary transitions associated with ^{194}Hg SD band 1, compared with expected values for indicated multipolarities and spin–changes.

Figure 3: Details of the primary transitions of band 3. Top left: spectrum gated once on the 262 keV SD transition and once on the remaining members of the SD band. Top right: spectrum gated once on all SD transitions and once on the primary transitions. Bottom left: proposed level scheme. Bottom right: angular distribution and best polynomial fit for the 4980 keV γ ray.

of double–gates where one of the gating transitions was always the last transition observed in the band, both primary lines are present, indicating they must both be emitted from the bottom of the band. In the coincidence spectrum where one gate is part of the SD band and the second gate is either of the primary lines, there is clear evidence for the γ rays associated with the positive–parity ground state band. Finally, the difference in measured γ-ray energies between these two primary lines, 52±2 keV, corresponds to the energy difference betwen the 12^+ and 10^+ levels. Based on this evidence the level scheme shown in Figure 3 is proposed, and the last observed state of band 3 is assigned as $J^\pi = 11^-$ at an excitation energy of 7.455 MeV. Here again, the parity is expected on the basis of relative E1/M1 strengths seen in neutron capture. The measured angular distribution of the 4980 keV primary line yields a negative A_2 coefficient, consistent with an anti–stretched dipole character.

Knowing the spins and excitation energies of both ^{194}Hg SD bands 1 and 3, we can calculate the experimental routhians e' in the prescription of Bengston and Frauendorf [8] . The Harris

parameters have been adjusted to match the dynamic moment $\mathcal{J}^{(2)}$ of band 1, and the results are shown in Figure 4. If the routhians are extrapolated to zero rotational frequency, their difference is about $\Delta e'_0 = 0.8$ MeV. Any model of the band 3 excitation, whether collective (e.g. octupole phonon) or quasiparticle, must account for this energy. For example, it has been proposed [9] that the lowest excitations in the even–Hg SD well are octupole vibrations, and the calculated routhians for the $K = 2$ octupole component yield slopes which compare favourably to the experimental data, although the excitation energy $\Delta e'_0 = 1.1$ MeV is a bit too high. By contrast, if band 3 is interpreted as a two–quasiparticle excitation [10] , then in a simple BCS picture, this places an upper limit of 0.4 MeV on the pairing gap at zero rotational frequency, compared to neutron pairing gaps of typically ~ 0.8 MeV adopted for such calculations [11] . (It should be noted that a self–consistent solution to a two–quasiparticle system could yield $\Delta e'_0 < 2\Delta_{\text{BCS}}$.) Clearly there is a need for more
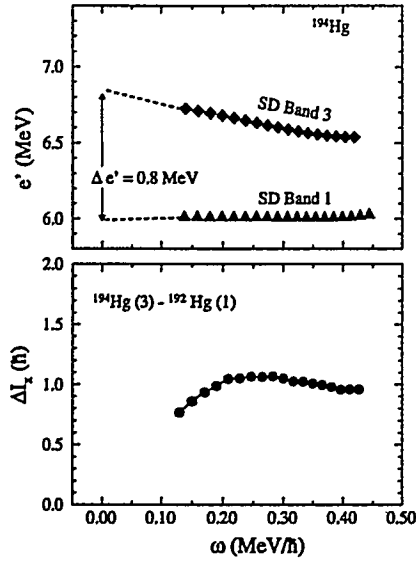
Figure 4: Upper panel, routhians for ^{194}Hg bands 1 and 3. Lower panel, difference in spin projection I_x between ^{194}Hg band 3 and its isospectral partner ^{192}Hg band 1.

detailed theoretical predictions (*e.g.* crossover M1 strengths for bands 2 and 3 and intraband E1 strength to band 1) before the exact nature of the excitation leading to band 3 can be determined.

As presented above, band 3 has odd spin and negative parity. Since band 1 of ^{192}Hg is believed to be the vacuum SD band and, hence, should have even spin and positive parity, one may conclude that states emitting γ rays of the same energy do not necessarily have the same spin and parity. Another way of looking at this feature is to project the spins onto the rotation axis and look at the difference between ^{194}Hg band 3 and ^{192}Hg band 1. This is presented in Figure 4; it is clear that at high ω, states with the same rotational frequency, and hence emitting γ rays with the same energies, have one extra unit of projected spin in ^{194}Hg band 3 than ^{192}Hg band 1.

It is believed that the states in ^{192}Hg SD band 1 *almost certainly* have even spin and positive parity. Nevertheless, it is essential to confirm this expectation through the detection of the primary decays. Figure 1 shows that data of comparable quality were accumulated for bands 1 in both ^{192}Hg and ^{194}Hg. Assuming that the SD bands in these nuclei have roughly the same excitation energy, then all other things being equal, it would seem reasonable to expect to see primary decays from the

^{192}Hg SD to normal states with the same quality as was seen in ^{194}Hg. Yet, the high–energy portion of the spectrum, where the ^{192}Hg one-step transitions are expected, is remarkably free of any salient candidates. In fact, out of all of the peak–like fluctuations in the spectrum, only a line at 3117 keV near the low end of the spectrum has been very tentatively placed as the first component of a two–step cascade to the yrast line, where one possible candidate for a second step is a 696 keV transition to the 10^+ ND state. With this information it is not possible to make any statements regarding the spin or parity of this band, but the analysis is on-going. It should be noted that for ^{194}Hg band 2, which is likely to be a signature partner to band 3 (based on the transition energies of one being midway between those of the other), no respectable candidates for a network of primary decays could be observed, even though the expected energies are known.

Reduced transition_probabilities for the observed primary transitions were calculated and tabulated (see Table 1). It was assumed that the transition quadrupole moment of the low–spin members of the SD band is the same as that measured recently by Moore *et al.* [12] at higher spin. These primary transitions are extremely retarded, for example the two transitions from the 12^+ state of band 1, have values of about 10^{-8} of a Weisskopf unit.

There are fluctuations in the strengths of the primary γ rays from the SD levels, which can be understood in the following manner. A SD state exists in a sea of highly excited normal states (ND*). These ND* states are complex, much like the compound states populated in neutron capture. The SD band mixes with one or two of the nearest-lying ND* states, *i.e.* its wave function acquires a small admixture of this ND state,

$$|\Psi\rangle = |SD\rangle + \alpha|ND^*\rangle.$$

The decay then occurs due to this admixed component, *i.e.*

$$\langle ND|\mathcal{M}|\Psi\rangle \simeq \alpha\langle ND|\mathcal{M}|ND^*\rangle.$$

If the ND* states are indeed compound states, then they should not be charactarized by any quantum numbers apart from spin and parity, and the transition strengths $|\langle\mathcal{M}\rangle|^2$ of primary decays should exhibit the same Porter–Thomas fluctuations as seen in neutron capture. At the current sensitivity levels, this would be manifest in observing the one–step decays only when one is fortunate enough to select a case which samples the high–strength portion of the distribution.

Band, Q_0 (eb)	E_γ (keV)	$J_i^\pi \to J_f^\pi$	I_γ/I_{SD} (%)	$B(E1)$ (W.u.)	$B(M1)$ (W.u.)
^{194}Hg Band 1, 18.4 ± 1.1	3489	$12^+ \to 13^-$	1.2(1)	$2.8(3) \times 10^{-8}$	
	3565	$10^+ \to$?	0.5(1)	$< 8 \times 10^{-7}$	$< 9 \times 10^{-5}$
	3942	$10^+ \to 11^-$	0.3(1)	$< 8 \times 10^{-7}$	
	4195	$12^+ \to 11^-$	0.8(1)	$1.1(3) \times 10^{-8}$	
	4485	$10^+ \to 9^-$	1.0(1)	$< 4 \times 10^{-7}$	
	(3710)	$12^+ \to 12^-$	< 0.2	$< 4 \times 10^{-9}$	
	(4076)	$10^+ \to 10^-$			
	(4205)	$10^+ \to 10^+$			
	(4408)	$12^+ \to 12^+$			$< 3 \times 10^{-7}$
^{194}Hg Band 3 17.7 ± 1.4	4980	$11^{(-)} \to 12^+$	3.7(8)	$< 2 \times 10^{-7}$	$< 2 \times 10^{-5}$
	5032	$11^{(-)} \to 10^+$	2.0(6)	$< 1 \times 10^{-7}$	$< 1 \times 10^{-5}$

Table 1: Reduced transition rates for ^{194}Hg SD decay–out primary transitions.

In ^{192}Hg, only one primary transition can be tentatively placed as part of a two–step decay. ^{194}Hg band 1 exhibits a robust network of strong one–step transitions to the yrast line. In ^{194}Hg band 2, there are no reputable candidates for primary decays, and band 3 has two one–step decays directly to the yrast line. Clearly the primary decays are governed by some form of transition strength fluctuation, although whether it has a Porter–Thomas distribution is an open question which we hope to answer in the near future.

One interesting observation is that in the decay of ^{194}Hg band 1, four dipole transitions with $\Delta J = \pm 1\hbar$ are observed. However, there was no evidence for $\Delta J = 0$ transitions to yrast states, with or without a parity change. The non-observation of the $\Delta J = 0$ transitions may hint at the persistence of some quantum number (beyond spin and parity) in the ND* states at excitations of ~ 4.3 MeV above yrast. It is interesting to note that the Clebsch–Gordon coefficient $\langle J, 0; 1, 0 | J, 0 \rangle$ is identically 0 for all J. One might expect this to be relevant, for example, to $K = 0$ components in the intrinsic frame. SD band 1 is very likely a $K = 0$ band, and one might speculate that if it coupled only to the $K = 0$ components of the hot ND* states, and if in turn the near–yrast states are mostly $K = 0$, then dipole transitions with no spin change might be suppressed.

In conclusion, a new study of the primary decays of the SD states of ^{194}Hg has shown that

the level fed by the 262 keV transition of band 3 is a $J^\pi = 11^-$ state at an excitation energy of 7.455 MeV. This gives band 3 an excitation energy of ~ 0.8 MeV relative to band 1 at zero rotational frequency. The spins of the states in band 3 are likely $1\hbar$ higher than those in ^{192}Hg band 1 that emit γ rays of the same energy. The transition rates for the primary transitions are very retarded, typically 10^{-8} Weisskopf units.

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