Landau-Zener Crossing in Superdeformed ^{193}Hg: Evidence for Octupole Correlations in Superdeformed Nuclei

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Four, possibly five, superdeformed bands have been observed in ^{193}Hg. Two of these bands have strikingly different dynamical moments of inertia from all previously observed superdeformed bands in this region. This behavior can be understood in terms of a level or band crossing. Evidence for transitions between two superdeformed bands is observed for the first time. This, together with the reduced alignments observed and the strong interaction between the crossing bands, is the first experimental evidence supporting the prediction for strong octupole correlations in superdeformed nuclei.

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The discovery[1] of discrete superdeformed (SD) states in nuclei allows models for describing the quantum mechanics of conglomerations of strongly interacting nucleons to be tested at extreme values of the quadrupole distortion of the mean field. To date, SD spectroscopy has given us much information concerning the behavior of the moments of inertia in SD nuclei. For example, it has been shown[2-4] that for SD nuclei near $A=150$ the variation in the dynamical moment of inertia $\mathcal{J}^{(2)}$ with rotational frequency $\hbar\omega$ is dependent on the proton and neutron occupation of high-N intruder orbitals. The recent discovery[5] of a SD band down to very low rotational frequency and spin in ^{191}Hg has inspired considerable experimental effort[6] to study the systematics of superdeformation in this new $A=190$ SD region. Prior to this work, it has been found that the behavior of the moments of inertia for all SD bands near $A=190$ are very similar to each other as the high-N intruder-orbital configurations change very little throughout the region.[7] In this Letter we report on the observation of four, possibly five, SD bands in ^{193}Hg, two of which have strikingly different behavior from other SD bands and which we suggest cross each other while interacting strongly. In addition, there is evidence for the decay from one of the SD bands to another by electric dipole transitions. The proposed $E1$ transitions, the strength of the mixing between the crossing SD bands, and the observed reduction in the alignment of the intruder neutron orbital are the first experimental evidence for the existence of strong octupole correlations in SD nuclei.

The nucleus ^{193}Hg was populated at high spin by the reaction ^{150}Nd(^{48}Ca,5n) at beam energies of 205 and 213 MeV. The beam was provided by the tandem Van de Graaff accelerator at the Nuclear Structure Facility, Daresbury Laboratory. The target consisted of two stacked 500-μg cm^{-2} self-supporting foils of ^{150}Nd. γ rays were detected in the multidetector array TESSA3 (Ref. 8) which comprises 16 escape-suppressed spectrometers and a compact 50-element crystal ball of bismuth germanate (BGO) detectors. The data comprised the energy deposited in each of the escape-suppressed Ge detectors and the summed energy and fold recorded by the BGO ball for each event. A total of $\sim 110\times10^6$ Ge-Ge-BGO coincidence events were recorded at each beam energy.

Four rotational-band sequences assigned to ^{193}Hg have been observed in these data with γ-ray energy spacings characteristic of superdeformation. These bands, labeled 1-4, are shown in Figs. 1(a)-1(d). The relative intensities of bands 1-4 are measured to be 1.6%, 2.1%, 0.9%, and 1.1%, respectively, of ^{193}Hg. At low energies, $E_\gamma < 450$ keV, the γ-ray energies in bands 1 and 3 are almost identical, making them difficult to separate, and are exactly midway between the γ-ray energies of band 2. Above $E_\gamma = 450$ keV the γ-ray energies in band 1 become lower than those in band 3, allowing the two bands to be clearly distinguished. Bands 1-3 are all placed in ^{193}Hg by their observed coincidence with known[9] γ rays in ^{193}Hg. Band 4 is assigned to ^{193}Hg since it is most strongly observed at the 213-MeV bombarding energy and by its close relationship with band 1 (see below). Bands 2 and 3 have also been observed in a parallel

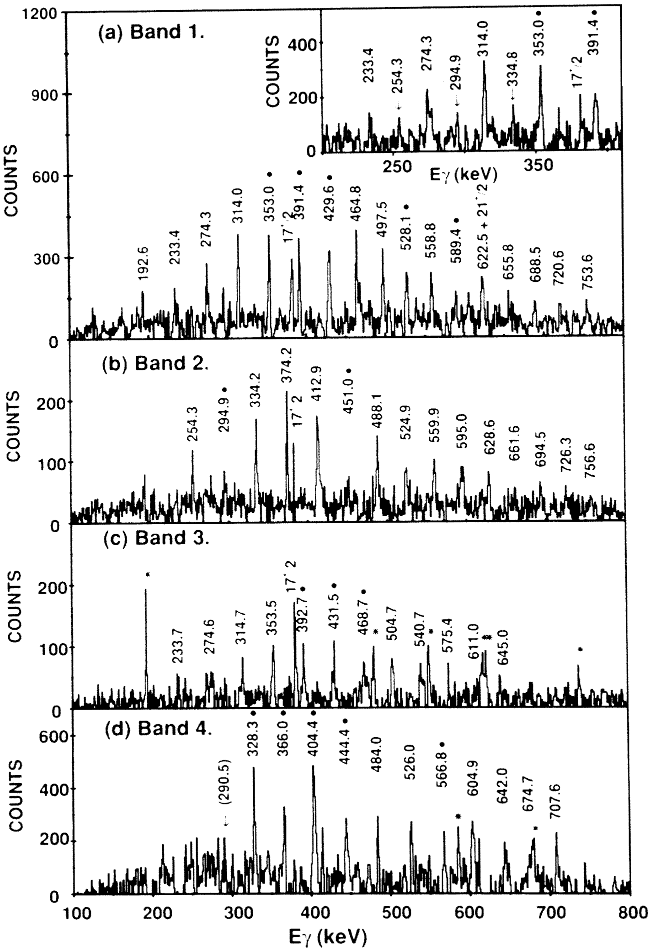

FIG. 1. Summed coincidence γ-ray spectra for the four SD sequences observed in ^{193}Hg. Energies are given in keV. Transitions on which gates have been set are marked with a closed circle, and known contaminant γ rays are marked with an asterisk. The inset to (a) shows the low-energy portion of the spectrum in coincidence with the 353- and 391-keV transitions mainly in band 1 and illustrates the cross talk to band 2 (254, 295, and 335 keV).

study.[10]

As the SD bands in the Hg isotopes extend to low rotational frequencies, a simple cranking-model analysis may be used to estimate the spins of the SD levels using the cranking formulas $\mathcal{J}^{(2)} = dI_x/d\omega$, $I_x = [I(I+1) - K^2]^{1/2}$, $\omega = dE/dI_x$ and the parametrization $\mathcal{J}^{(2)} = \alpha + \beta\omega^2$ and $I_x = \alpha\omega + \beta\omega^3/3 + i_0$. For all except intruder neutron orbitals with $N=7$, the calculated Routhians[7] do not exhibit any single-particle alignment at low frequency so that $i_0 \approx 0$. The spins of the lowest SD levels in bands 1, 2, and 3 were estimated to be $\frac{15}{2}$, $\frac{21}{2}$, and $\frac{19}{2}$, respectively. The lowest spin in band 4 is estimated to be $\frac{27}{2}$ from its relationship with band 1. Hence band 2 is estimated to have signature $\alpha = +\frac{1}{2}$ and bands 1, 3, and 4 to have $\alpha = -\frac{1}{2}$. A similar method for assigning spins has been developed in Ref. 11.

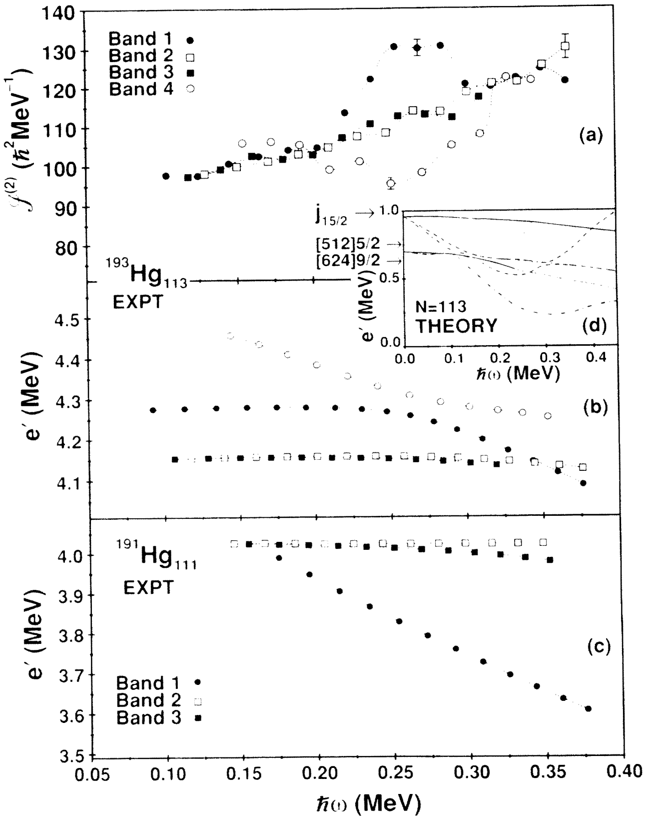

FIG. 2. (a) Plot of the dynamical moment of inertia $\mathcal{J}^{(2)}$ against rotational frequency $\hbar\omega$ for the four SD bands in ^{193}Hg. Typical error bars are indicated. (b) Experimental Routhians for SD bands in ^{193}Hg. (c) Same as (b), but for ^{191}Hg (Refs. 5 and 13). The excitation energy of the SD bands has been chosen arbitrarily but with certain conditions (see text). The Harris-parameter values $\mathcal{J}_0 = 94\hbar^2$ MeV^{-1} and $\mathcal{J}_1 = 73\hbar^4$ MeV^{-3} were chosen to give a flat trajectory for band 3 in ^{191}Hg. (d) Theoretical Woods-Saxon quasineutron Routhians ($\beta_2 = 0.47$, $\beta_4 = 0.06$, and $\gamma = 0°$) with constant pairing for ^{193}Hg. The parity and signature (π,α) of the individual levels are indicated in the following way: $(\pi,\alpha) = (+,\frac{1}{2})$, solid line; $(+,-\frac{1}{2})$, dotted line; $(-,\frac{1}{2})$, dashed line; $(-,-\frac{1}{2})$, dot-dashed line.

The $\mathcal{J}^{(2)}$ as a function of $\hbar\omega$ for the four SD bands in ^{193}Hg is shown in Fig. 2(a). The $\mathcal{J}^{(2)}$ of bands 2 and 3 increases smoothly with rotational frequency, behavior which is consistent with all other SD bands in this region.[6] In contrast, bands 1 and 4 show anomalous behavior centered at $\hbar\omega = 0.27$ MeV with band 1 displaying an increase in $\mathcal{J}^{(2)}$ and band 4 a decrease. We believe this anomalous behavior in the two bands is correlated and that it may be interpreted in terms of a level or band crossing. This is demonstrated from the Routhian plot of the experimental data presented in Fig. 2(b) where the relative excitation energy of the bands is chosen arbitrarily but with the conditions that bands 2 and 3 exhibit zero splitting at low frequency and that bands 1 and 4 reproduce the interaction strength (see below) measured between them at their crossing point. In Fig. 2(b) the Routhian trajectory for band 4 is down sloping and approaches the Routhian of band 1 with an exchange of character (i.e., slope or alignment) at the crossing point ($\hbar\omega = 0.27$ MeV). This level-crossing pattern is a classic example of a Landau-Zener-type crossing[12] first discussed in atomic physics in the early 1930's.

In order to characterize the level or band crossing and assign configurations to all the bands, the experimental data are compared with the predictions of cranked-shell-model calculations. In such calculations [see Fig. 2(d), which shows calculated Routhians using the Woods-Saxon potential], strongly down-sloping intruder orbitals from the $N=7$ $j_{15/2}$ shell cross four closely spaced orbitals, namely, the $N=6$ $[624]\frac{9}{2}$ $(+,\pm\frac{1}{2})$ and $N=5$ $[512]\frac{5}{2}$ $(-,\pm\frac{1}{2})$ orbitals. The $N=7$ orbitals are signature split with the $\alpha=-\frac{1}{2}$ being favored. At low frequency, band 4 is interpreted as the $j_{15/2}$ $\alpha=-\frac{1}{2}$ intruder band and band 1 as the $[512]\frac{5}{2}$ $(-,-\frac{1}{2})$ orbital. Extrapolation of bands 1 and 4 to zero frequency means that the energy separation between the $[512]\frac{5}{2}$ and $j_{15/2}$ orbitals is ~ 370 keV [see Fig. 2(b)]. This is reproduced reasonably well at ~ 250 keV in our pairing and deformation self-consistent Woods-Saxon calculations and also Fig. 2(d). This is the first measure of the relative energy of single-particle states for SD shapes. The crossing observed between bands 1 and 4 is interpreted as the crossing between these $N=5$ and $N=7$ $\alpha=-\frac{1}{2}$ orbitals at which point the configurations are interchanged. However, there is a large inconsistency between experiment and theory of the relative alignment between the crossing orbitals ($i_{\text{expt}}=1.3\hbar$, cf. $i_{\text{theo}}\sim 3\hbar$), resulting in an underestimation of the crossing frequency ($\hbar\omega_{\text{expt}}=0.27$ MeV, cf. $\hbar\omega_{\text{theo}}=0.13$ MeV). (Although a reduction in pairing would lower the effective $j_{15/2}$ alignment, it cannot explain the other anomalous features discussed below.) In addition, the crossing is predicted to be a weak interaction while, experimentally, a strong interaction is observed ($V_{\text{int}}\approx 26$ keV from a simple two-level mixing calculation) with the interaction region extending over many (6-7) transitions.

Band 3, which has the same assigned signature as bands 1 and 4, is unaffected by the crossing and therefore must have opposite parity. It is assigned to be the $[624]\frac{9}{2}$ $\alpha=-\frac{1}{2}$ orbital. Band 2 ($\alpha=+\frac{1}{2}$) which has γ-ray energies exactly between those of band 3 is assigned to be the signature partner to band 3. Indeed, the calculations predict that the $[624]\frac{9}{2}$ orbitals display very little splitting. Similarly the calculations also predict that there should be a partner to band 1 (the $[512]\frac{5}{2}$ $\alpha=+\frac{1}{2}$). The intensity of band 2 is anomalously high, being twice the intensity of its signature partner band 3 and it is suggested that band 2 could actually be two bands with identical γ-ray energies as were bands 1 and 3 before the crossing region. To summarize, we have shown that qualitatively the overall behavior and number of experimental SD bands correlate rather well with that expected from theoretical calculations, e.g., Fig. 2(d). Band 1 can be labeled $[512]\frac{5}{2}$ $\alpha=-\frac{1}{2}$ at low frequency ($\hbar\omega < 0.2$ MeV) and $j_{15/2}$ above $\hbar\omega \approx 0.3$ MeV. The γ rays comprising band 2 may be two sequences labeled $[512]\frac{5}{2}$ and $[624]\frac{9}{2}$ $\alpha=+\frac{1}{2}$. Band 3 can be labeled $[624]\frac{9}{2}$ $\alpha=-\frac{1}{2}$. Band 4 is $j_{15/2}$ $\alpha=-\frac{1}{2}$ at low frequency but has $[512]\frac{5}{2}$ character above $\hbar\omega \approx 0.3$ MeV.

In Fig. 2(c) the experimental Routhians of the three SD bands[5,13] in ^{191}Hg are plotted. As in Fig. 2(b) the excitation energy of the bands is chosen arbitrarily but with the condition that bands 2 and 3 exhibit zero splitting at low frequency. Band 1 is the favored $j_{15/2}$ ($\alpha=-\frac{1}{2}$) band, while bands 2 and 3 are the two signatures of the $[642]\frac{3}{2}$ orbital and thus have opposite parity to band 1. All three trajectories behave in a smooth manner showing no band crossings. This is consistent with theoretical predictions since in ^{191}Hg, in contrast to ^{193}Hg, the $j_{15/2}$ level is the lowest-energy negative-parity level at low frequency.[13] Therefore, this aligned $j_{15/2}$ trajectory will not cross any other negative-parity levels with increasing frequency. Another interesting comparison between ^{191}Hg and ^{193}Hg is that the γ-ray energies of bands 2 and 3 in both nuclei are the same to within a few keV over the whole spin range,[14,15] and in addition the $j_{15/2}$ bands in both nuclei have remarkably similar energies at high frequency. These data, together with similar identifies observed in this region,[16] are consistent with the predicted[7,17] SD subshell closure at $N=112$.

A new and surprising feature observed in the ^{193}Hg data is shown in the inset of Fig. 1(a). Gates placed on the 391- and 353-keV transitions (dominantly from band 1) give a coincidence spectrum which not only contains the lower members of band 1 (and 3) but also the lower γ rays of band 2 (254, 295, and 335 keV). This spectrum indicates that about 30% of the SD to SD decay intensity crosses from the $\alpha=-\frac{1}{2}$ to the $\alpha=+\frac{1}{2}$ structure. Since SD bands of both parities exist in ^{193}Hg, the (so far unobserved) dipole connecting transitions may be either magnetic (no parity change) or electric (parity change) in nature. Taking $Q_0=19\,e\,\text{b}$ [corresponding to in-band $B(E2)$'s of ~ 2000 W.u. (Weisskopf units)] for SD bands in the Hg region[5,13] and zero energy separation for bands 1, 2, and 3 would require dipole transition strengths of about 2.0 W.u. for $M1$ and 1.5×10^{-2} W.u. for $E1$. The $M1$ strength seems much too strong and hence $E1$ transitions seem more plausible. In addition, any energy separation between the SD bands of opposite parity would increase the possible $E1$ transition energies, reducing the $E1$ strength required to compete with the in-band $E2$ transitions. Other evidence for $E1$ transitions is that the cross talk seems to only occur from band 1 to band 2 and not vice versa.

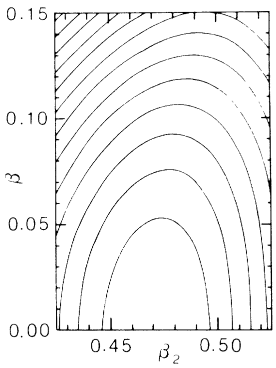

FIG. 3. Calculated Woods-Saxon energy surface including pairing for ^{192}Hg in the (β_2,β_3) plane illustrating the softness of the SD shape in the octupole degree of freedom. Contours are separated by 200 keV. At each β_2,β_3 point the total energy has been minimized with respect to β_4 and β_5.

One possible mechanism which would explain all the unexpected features discussed above, namely, the reduced alignments, the strong band interaction, and the cross talk between the SD bands in ^{193}Hg, is that octupole correlations are present. In Fig. 3 our calculation of the potential-energy surface of quadrupole β_2 versus octupole β_3 deformation is plotted for ^{192}Hg. This shows that the ^{192}Hg core is very soft to octupole deformation and thus strong dynamical octupole correlations should be present in ^{192}Hg and neighboring nuclei. We would comment that similar β_3 softness for the SD shape has also been calculated by Dudek and co-workers[18] and Åberg and Höller;[19] see also Mizutori *et al.*[20] It is well known in the heavier Ra,Th region that the lowest quasiparticle bands are strongly octupole mixed and as a result display lower effective alignments than expected for pure high-j states.[21-23] We believe this same phenomenon is responsible in ^{193}Hg for the smaller than expected alignment of the $j_{15/2}$ band. In addition, this octupole mixing would also explain the strong interaction of bands 1 ($N=5$) and 4 ($N=7$) at their crossing near $\hbar\omega=0.27$ MeV. This is analogous to the strong band interactions mediated through the octupole coupling seen in nuclei near ^{222}Th.[22,23] Indeed this "smoothing" effect of the octupole correlations is, we feel, partly responsible for the unusual similarity of SD bands in the $A=190$ region. Moreover, the octupole coupling together with reduced electric dipole polarizability due to the low-lying giant dipole resonance[24] would allow $E1$ transitions to compete with the in-band SD $E2$ transitions. We also suggest that octupole correlations could play an important role in the population and decay of SD bands. A new speculation is that low-lying octupole vibrational SD bands should exist, for example, in the doubly magic SD systems ^{152}Dy and ^{192}Hg.

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