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Observation of superdeformation in ^{192}Hg

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A γ-ray cascade in ^{192}Hg consisting of seventeen members is reported. The transition spacing is characteristic of a superdeformed band, and we propose it to be the second instance of superdeformation in the Hg region. We find the lowest spin in the band is likely to be $8\hbar$ using a new method for obtaining spins in some superdeformed nuclei.

Several theoretical calculations[1-5] have predicted secondary minima in the potential-energy surfaces of the moderately neutron-deficient Hg nuclei at the collective coordinates corresponding to $(\beta,\gamma)=(0.54,0)$. Quasistationary states in these minima are therefore characterized by large prolate deformation and major/minor axis ratio equal to 1.6. Weiss and co-workers[1,2] have shown the early results of microscopic three-dimensional Hartree-Fock calculations for the Hg isotopes in 1987. Detailed potential-energy landscapes obtained with the Skyrme potential together with a pairing term are presented in Ref. 2. Girod *et al.*[3] used the constrained triaxial Hartree-Fock-Bogoliubov approach and the Gogny interaction. Chasman[5] has done calculations for nuclides near $A=190$ using the cranked Strutinsky method with a Woods-Saxon potential. Whatever the approach, all calculations predict a secondary minimum in the energy surface at large prolate deformation for Hg nuclei near $A=194$, and suggest a new region of superdeformation (SD). Predictions include the depth of the SD minimum, its excitation relative to the normal minimum, and moments of inertia for SD bands. These calculations predict deeper secondary minima at lower excitation than those in the $A=152$ region. Moore *et al.*[6] studied ^{191}Hg and found a γ-ray cascade characteristic of a SD band. Direct lifetime measurements supported the highly collective nature of the band [$Q_t=18(3)$ eb corresponding to $\beta=0.55$].

We report observation of a SD band in the nucleus ^{192}Hg, located simultaneously by us and by the Argonne group,[7] and describe the evidence for the second such band in this mass region. We also propose a method for finding spins in such bands.

We populated levels in ^{192}Hg with the ^{176}Yb(^{22}Ne, $6n$)^{192}Hg reaction at $E(^{22}\text{Ne})=122$ MeV. At this energy, the compound nucleus ^{196}Hg has an excitation energy 78 MeV and a maximum angular momentum, $l_{\max}\sim 49\hbar$. Beam currents on the order of 2 pnA struck a target of three stacked ^{176}Yb foils ($\sim$450, 450, and 700 mg/cm^2 thick) mounted at the center of the 21-Ge-detector array HERA. The beam was produced by the Lawrence Berkeley Laboratory 88-Inch Cyclotron. Just before this experiment, HERA was augmented by an inner 4π "ball" of 40 bismuth germanate (BGO) detectors. Approximately 600 million events were collected onto magnetic tape for subsequent analysis. Double Ge coincidences with ball multiplicity condition $M\geq 8$ and all higher-order Ge coincidences were recorded. The fraction of triple or higher-order Ge coincidences under these conditions was $\sim$25% and the observed ratio of $^{192}\text{Hg}(2^+\rightarrow 0^+)/^{193}\text{Hg}(\frac{17}{2}^+\rightarrow\frac{13}{2}^+)=3/1$.

Initial sorting of the data into a two-parameter matrix symmetric in E_γ was done with BGO ball conditions of multiplicity ≥ 11 and sum energy ≥ 6 MeV. Gates were set channel by channel on this matrix to search for bands of interest. A cascade of seventeen γ rays was found in these data with energy spacings characteristic of an elongated nuclear system. Cascade members at 496 and 341 keV were relatively clean of contaminants, and another two-dimensional matrix gated by the 496 keV line was generated from the triples and higher-order coincidence data. Figure 1 illustrates the spectrum obtained by summing over all the other SD lines in this matrix (except the ones at 215 and 732 keV). The seventeen γ rays we propose as members of a SD band in ^{192}Hg are labeled by their γ-ray energy. The highest transition energy is 793.4 keV. (We could not establish an in-band γ ray at 823 keV as there is an intense γ ray at this energy and background subtraction is difficult.) The energy spacing between transitions increases from 30 to 43 keV with decreasing γ-ray energy. The lowest transition observed has an energy of 214.6 keV. This γ ray is weak; however, it is in the spectra gated by the lowest members of the band and also in spectra generated with double gates on members of the band. Although the 215-keV peak is heavily contaminated, all the lines of the band up to an energy of 496 keV are in the spectrum produced with a gate on this line. Based on the energy systematics of the band, we assign the 215-keV γ ray as the lowest member of the cascade. The ^{22}Ne reaction populated the SD band with an intensity approximately 2% of the ^{192}Hg $2^+\rightarrow 0^+$ transition, under the data-sorting conditions described above.

The relative intensities of the band members corrected

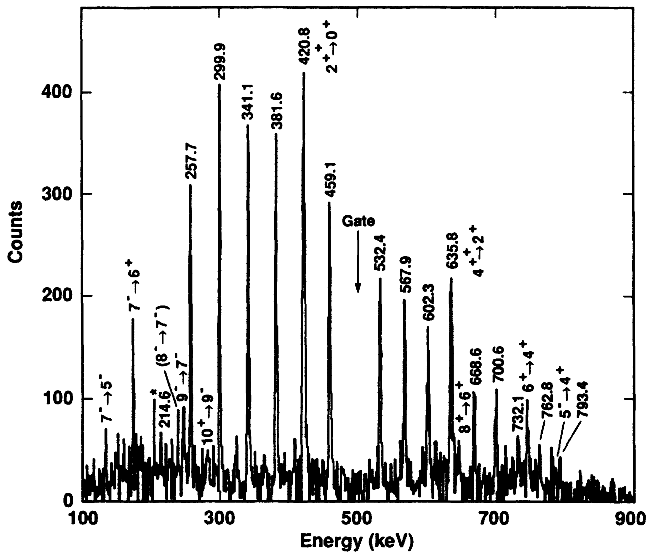

FIG. 1. Spectrum in coincidence with the transition $E_\gamma = 496$ keV and the sum of all other band members (except for the 215- and 732-keV members). Members of the SD band are labeled by transition energy. Errors are on the order of 0.15 keV except for the 214.6-, 635.8-, and 793.4-keV transitions which are 0.25, 0.5, and 0.5-keV, respectively. Known ^{192}Hg low-lying transitions are identified by $I_i^\pi \rightarrow I_f^\pi$, and transitions in ^{193}Hg are labeled by *.

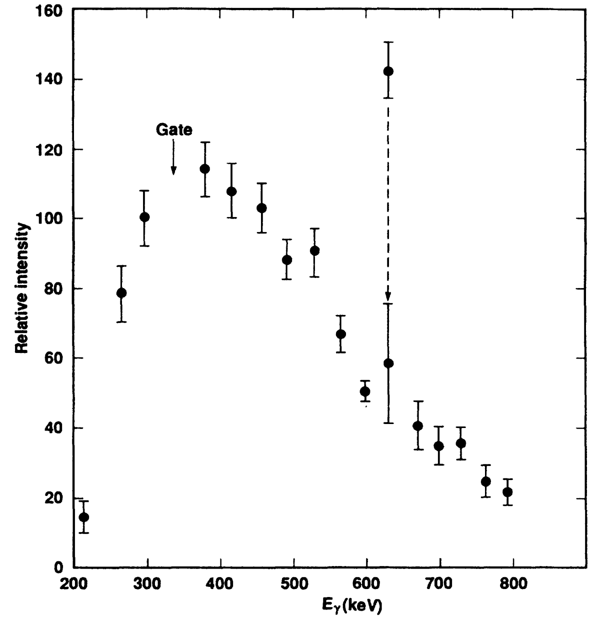

FIG. 2. Relative population of the SD band in ^{192}Hg normalized to the yield of the 299.9-keV transition. The spectrum was in coincidence with the 341-keV transition. An estimated contribution from the $4 \rightarrow 2$ transition at 635 keV is indicated.

for internal conversion and spectrometer efficiency are plotted in Fig. 2. The figure is obtained from the twofold coincidence data with the 341-keV line as a gate. Normalization is to the 300-keV γ-ray intensity (100). The intensity is > 80 for the six transitions with E_γ between 300 and 532 keV, followed by a decrease to 21(4) with increasing E_γ. The intensity of the 635-keV transition is consistently high because it coincides with the $6^+ \rightarrow 4^+$ transition. Approximately nine of the seventeen transitions have intensity ≥ 50. The pattern is similar to that reported[6] for ^{191}Hg. Following the procedure of Ref. 8, the directional correlation of band members was extracted in order to determine multipolarity. The correlation ratio R for a γ ray in a gated spectrum is the sum of the counts in detectors at $\sim 90°$ with respect to the beam divided by the sum of the counts in the detectors at $\sim 0°$ and $\sim 180°$. The mean correlation ratio R for the seven transitions in the band ($E_\gamma = 258$, 300, 341, 421, 459, 568, and 602 keV) with sufficient statistics for analysis is 1.00(5) when obtained with a known stretched $E2$ transition. For this geometry, known stretched $E2$ transitions were measured to have $R = 0.99(2)$ while known $E1$ transitions were measured to have $R = 0.54(3)$. We conclude that the measured transitions are stretched $L = 2$ and assume this for the other band members.

The double-coincidence data were also analyzed to obtain the population of low-lying states of ^{192}Hg produced through decay of the SD band. Analysis of these data was facilitated by the detailed work on the Hg isotopes reported by Hubel *et al.*[9] Results are summarized in Fig. 3, with the intensity of the SD band normalized to 100. Yrast states having spins between 4 and 10 are observed to be populated, with an average entry spin near six.

The transitions of the band are regular in spacing and extend to low energies. The relative transition energies in a rotational band are sensitive to spin at low angular momentum and therefore we have the opportunity to make spin assignments. We use an expansion similar to that of Harris,[10] with energy terms up to ω^6, and expand

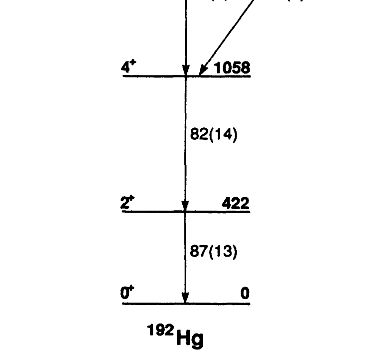

FIG. 3. The intensity of low-lying transitions in ^{192}Hg coincident with the decay of the SD band (normalized to 100). The $7^- \rightarrow 5^-$ intensity is based on the $7^- \rightarrow 6^+$ intensity and the branching ratio of Ref. 9. Errors are statistical.

$\mathcal{J}^{(2)}$ as

$$\mathcal{J}^{(2)} = 2\alpha + 4\beta\omega^2 + 6\gamma\omega^4 . \quad (1)$$

The expansion coefficients α, β, and γ were determined from a least-squares fit to $\mathcal{J}^{(2)}$. Next, I was determined from

$$I + \tfrac{1}{2} = 2\alpha\omega + \tfrac{4}{3}\beta\omega^3 + \tfrac{6}{5}\gamma\omega^5 , \quad (2)$$

where I is the intermediate spin. Strictly speaking, this analysis gives the spin minus the aligned spin $(I-i)$ rather than I; however, in this case, an even-even nucleus at low spin, it seems likely that the aligned spin is either 0 or ~ 10 (from the alignment of a pair of high-j particles). As discussed below, the feeding into the yrast sequence makes values of $i \sim 10$ $(I \sim 20)$ unlikely, so we assume $i = 0$ and therefore the analysis gives I. In general, this method results in a minimum for I. We find that the lowest transition (215 keV) corresponds to $I_i \rightarrow I_f = 10 \rightarrow 8$ (all spins are found to be within $0.1\hbar$ of the corresponding rotational values). This procedure is not sensitive to the number of transitions included or the presence of the 215-keV transition. For example, excluding the 215-keV transition, the 258-keV transition is still found to be $12 \rightarrow 10$. Thus, we have a sensitive and internally consistent procedure to make spin assignments to the SD band. An analysis using the simple $I(I+1)$ relationship for the energies of the lowest few members of the band gives the same spin assignments. Forcing I to be two units higher or lower increases the rms deviation by about 2 orders of magnitude.

Using the above spins for the ^{192}Hg SD band, we can determine the average angular momentum difference between depopulation of the SD band and entry to the yrast levels. Here, the SD exit is close to $I = 10$, and the average entry spin to the yrast states is ~ 6, giving an average spin change of $4\hbar$. This is already more than generally assumed in the $A = 152$ region, and an aligned spin $i \sim 10$ would seem to make the average spin change unreasonably large. The lowest spin observed in this ^{192}Hg band is $6\hbar$–$8\hbar$ lower than that deduced in the same way for the ^{191}Hg band. This may be due to a shallower SD potential-energy minimum in ^{191}Hg.

In general, the required large increase in surface energy prevents nuclei from existing with very elongated shapes. However, in heavy nuclei the large Coulomb energy tends to counter the surface-energy term, as does the centrifugal term at high spins. In these cases the total potential-energy surface is flattened so that when the shell effects favor very elongated shapes, they can produce minima, giving rise to SD bands. The present Hg region, with lowest observed SD spins around ten, falls between the actinides (lowest spin 0) and the mass 150 region (lowest spin around 25). Whether this trend illustrates the combination of Coulomb and centrifugal energies necessary to stabilize such shapes and prevent decay out of the band, or is just an accident of the few cases so far observed, is not yet clear.

We have not been able to determine the excitation energy of the SD band on the basis of linking transitions at this time. A search of the data for prominent γ-ray transitions with energy up to 4.09 MeV or for combinations of

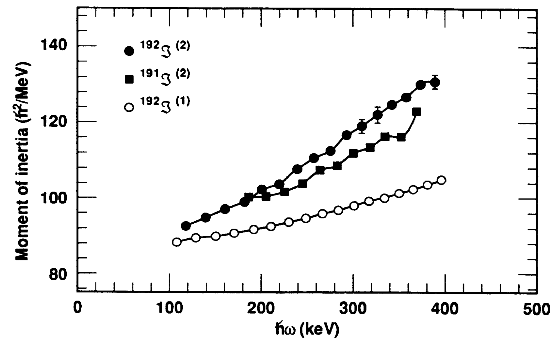

FIG. 4. Kinematic (○) and dynamic (●) moments of inertia for ^{192}Hg, and for comparison, the dynamic moment of inertia (Ref. 6) of ^{191}Hg (■).

transitions connecting the SD band with low-lying states in ^{192}Hg has so far proved unsuccessful.

The dynamic moment of inertia $\mathcal{J}^{(2)}$ obtained from the observed γ-ray energies is plotted in Fig. 4. The curve is fairly smooth, and $\mathcal{J}^{(2)}$ reaches a rather high value, 130.9(32) $\hbar^2$/MeV at $\hbar\omega = 389$ keV. Centrifugal stretching, gradual loss of pairing, and/or changing alignments may be the reasons $\mathcal{J}^{(2)}$ increases with $\hbar\omega$. The moment of inertia predicted by Chasman is 109 $\hbar^2$/MeV at $I = 35$, while the microscopic Hartree-Fock calculations[11] produce a geometric moment of inertia of 120 $\hbar^2$/MeV.

In summary, a SD band in ^{192}Hg has been proposed. There is evidence for seventeen members of a γ-ray cascade, beginning at 215 keV and ending at 793 keV. We have rather convincing evidence that the lowest spin observed in the band is eight. Transition spacings decrease from 43 to 30 keV with increasing transition energy, and $\mathcal{J}^{(2)}$ increases from 93 to 131 $\hbar^2$/MeV. Where possible, angular correlation measurements indicate stretched quadrupole transitions. This is the second observation of superdeformation in the neutron-deficient Hg isotopes. Theory predicts that the second minima becomes deeper with increasing neutron number in the Hg nuclides, and that many other nuclides in this region will exhibit superdeformation. The present data on ^{192}Hg are being analyzed more fully, and additional experiments to map out the region of superdeformation are underway.

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