Observation of Superdeformation in ^{191}Hg

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The first observation of superdeformation in the mass region $A \simeq 190$ is reported. A rotational band of twelve transitions with an average energy spacing of 37 keV, an average moment of inertia $\mathcal{J}^{(2)}$ of 110 $\hbar^2 \mathrm{MeV}^{-1}$, and an average quadrupole moment of 18 ± 3 eb has been observed in ^{191}Hg; this band persists at low rotational frequency. These results are in excellent agreement with a calculation that predicts an ellipsoidal axis ratio of 1.65:1 for the superdeformed shape in this nucleus.

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Superdeformation was first proposed[1] some twenty years ago to explain the fission isomers observed in some actinide nuclei.[2] Fission isomers are found in nuclei trapped in a metastable minimum associated with very elongated ellipsoidal shapes (axis ratio of roughly 2:1). The interest in the mechanisms responsible for these exotic shapes (i.e., mainly shell effects) has increased enormously with the discovery of a superdeformed band of nineteen discrete lines in ^{152}Dy (Ref. 3) and in several neighboring nuclei.[4-7] In all cases, the axis ratio is approximately 1.9:1. Nuclei with large deformations have been reported[8] at high spin in the $A = 135$ mass region (axis ratio of 1.45:1) and fragmentary evidence exists around $A = 180$ and 105 (Ref. 9).

One of the intriguing questions concerning superdeformation is whether there are other experimentally accessible regions of the periodic table where superdeformation occurs. Here, we report the discovery of a rotational band of twelve transitions in the nucleus ^{191}Hg with properties consistent with superdeformation. This study was motivated by cranked Strutinsky calculations by Chasman,[10] who found that deep minima in the total energy surface at very large deformation exist for many nuclei in the region $A \sim 185$–205. The axis ratios in these nuclei are calculated to be ~ 1.65:1. These minima were found to become yrast at spins above $30\hbar$ in many cases. Furthermore, they were shown to persist even to the lowest spins. Superdeformed shapes with axis ratios greater than 1.45:1 have also been obtained at $I = 0$ for some nuclei of this region in the calculations of Ref. 11.

The experiment was carried out at the Argonne superconducting linear accelerator ATLAS using the Argonne–Notre Dame BGO γ-ray facility which consists of fifty hexagonal BGO elements surrounded by twelve Compton-suppressed Ge spectrometers (CSG's). The states of ^{191}Hg were populated by the reaction ^{160}Gd(^{36}S,$5n$) at a beam energy of 172 MeV. The ^{160}Gd target consisted of two isotopically enriched 500-μg/cm^2 self-supporting foils stacked together. The recoiling nuclei and the beam were stopped in a thick Pb foil located 10 cm from the target, outside the focus of the CSG's. Under the experimental conditions the compound nucleus is formed at an excitation energy of 71 MeV and a maximum angular momentum in excess of $50\hbar$. With a threshold of four on the number of array elements firing in coincidence with at least two CSG's, 2.3×10^8 events were recorded. In addition to the energy and time information measured in the CSG's, the γ-ray sum energy, the prompt and delayed multiplicities, and the hit pattern of the array were stored on magnetic tape.

In the analysis, only events where at least fourteen detectors of the array fired in prompt coincidence with the CSG's were considered. This constraint enhances the relative yield of the highest-spin states by selecting the events with high γ-ray multiplicity (the fold distribution of known transition[12] in ^{191}Hg peaks at thirteen). The final γ-γ coincidence matrix contained 95×10^6 events, of which 60% were in the $5n$ reaction channel. The remaining events belong mainly to the $6n$ channel; no measurable yield was found for $4n$ evaporation.

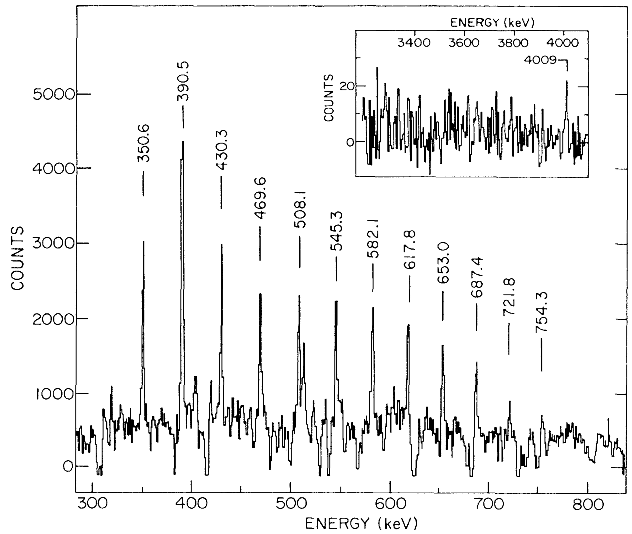

FIG. 1. γ-ray spectrum in ^{191}Hg obtained by summing coincidence gates on selected transitions (351, 471, 508, 545, 582, and 653 keV). The γ ray at 514 keV is an identified contaminant (seen only in the 508-keV gate). Inset: The high-energy end portion of this spectrum, with the 4009-keV line discussed in the text.

The analysis of the data revealed the presence of a band of twelve coincident transitions extending from 350 to 754 keV with an average energy difference of 37 keV, i.e., consistent with the spacing expected for a superdeformed shape.[10] The spectrum presented in Fig. 1 is the sum of spectra in coincidence with the cleanest gates. The $E2$ multipolarity of all the γ rays was inferred from directional correlation ratios obtained with a procedure described in Ref. 13. Under the multiplicity condition outlined above, the total flow through the band represents 2% of the ^{191}Hg intensity. One of the transitions in the band has the same energy (390.5 keV) as the previously assigned[12] $\frac{17}{2}^+$-$\frac{13}{2}^+$ transition in ^{191}Hg. The intensity of this transition is always larger than that of any other transition in the band by about 25% (see below for more details), and it is proposed that the excess intensity comes from the decay of the band, at least partly, through the $\frac{17}{2}^+$ state. This supports the assignment of the newly observed band in ^{191}Hg. The fold and the sum-energy distributions measured in coincidence with the twelve transitions were found to peak at values only slightly higher than those of known γ rays in ^{191}Hg: This result is also consistent with an assignment in ^{191}Hg. Finally, the coincidence data contain evidence for a second band of transitions with energy separations similar to those reported above but, with an intensity smaller by a factor of ~ 2.5. No firm placement could be made although there is tentative evidence[14] for an assignment in ^{190}Hg.

Figure 2(a) presents the intensity pattern for the transitions in the new band derived from the analysis of the coincidence gates. The intensity is seen to decrease gradually with increasing γ-ray energy. At the bottom of the cascade, the intensity remains essentially constant over the last 3-4 transitions, except for the excess counts in the 390-keV transition discussed above. No coincident γ ray at an energy lower than 350 keV having more than 5% of the intensity of the 350-keV line was observed. Thus, the main decay out of the band towards the yrast line occurs from the lowest state observed.

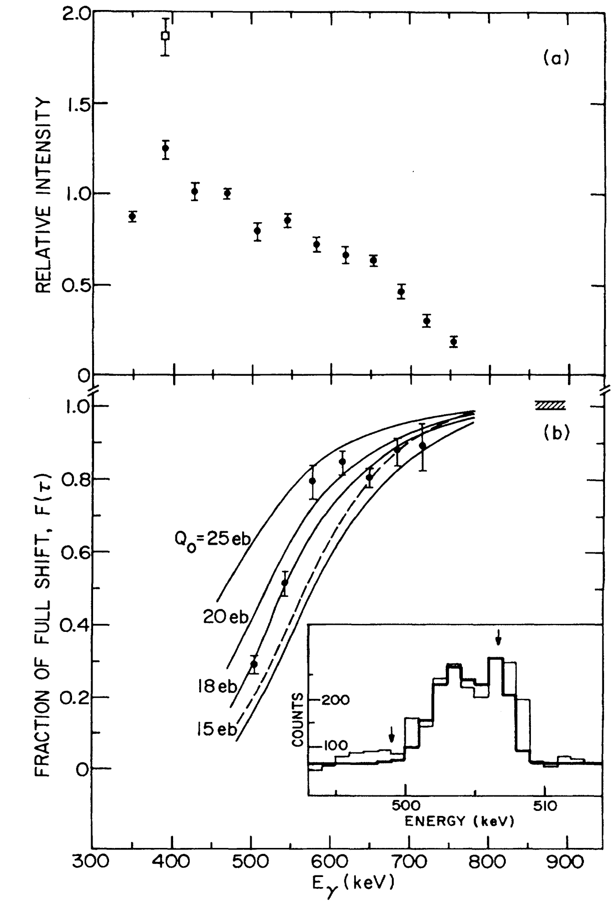

FIG. 2. (a) Relative intensity of the γ rays in the new band of ^{191}Hg as measured in the thin-target experiment. The intensity of the 390-keV line in the thick-target measurement is also given (□). (b) Measured fraction of Doppler shift for all transitions of the band with $580 \lesssim E_\gamma \lesssim 721$ keV. Calculated shifts are given for various quadrupole moments; solid curves include side feeding (see text), dashed curve assumes infinitely fast side feeding with $Q_0 = 15$ eb. The shaded area shows the spread in full shift due to the slowing down of the beam across the target. Inset: The line shape of the 508-keV transition measured at 146°; experiment (thin line) and calculation with $Q_0 = 18$ eb (thick line); arrows indicate energies corresponding to full and zero Doppler shift.

As discussed above, the average dynamic moment of inertia $\mathcal{J}^{(2)}$ for the new band is consistent with a superdeformed shape. However, since particle alignment coupled with a strong interaction can result in large apparent values of the moment of inertia, a more direct determination of the nuclear shape is desirable. Therefore a measurement of lifetimes was performed using the Doppler-shift attenuation method. In this second experiment, the target consisted of a 1.0-mg/cm^2 ^{160}Gd foil on which 14 mg/cm^2 of Au was evaporated; all other experimental conditions were identical to those described above. With analysis conditions similar to those discussed above a coincidence matrix of 69×10^6 events was obtained. The analysis was complicated by reactions induced in the Au backing by the ^{36}S beam. The same procedure and approximations made in lifetime studies of the superdeformed bands in ^{152}Dy, ^{149}Gd, and ^{132}Ce (Refs. 3, 4, and 8) were used here. Figure 2(b) presents the measured fraction of full Doppler shift F for the highest transitions in the band. The lowest transitions were fully stopped and no data could be obtained for the 470-keV line because of a contaminant γ ray in the spectrum. The calculated curves in Fig. 2(b) represent values of F for various quadrupole moments Q_0 under the assumption of a constant deformation. The data are consistent with $Q_0 = 18 \pm 3$ eb, where the errors include uncertainties in the slowing down process and in the side-feeding intensities. The full curves in Fig. 2(b) take into account side feeding; the lifetime of the side feeding to a state of spin I was assumed to be identical to the lifetime of the $I+2$ state in the band. Similar results were obtained when a constant feeding time of 30 fs was assumed—the difference between the highest data points and the calculated full Doppler shift for recoils formed in the center of the target suggests a feeding time of this order. In any case, the measured shifts clearly indicate very fast transitions and impose a lower bound of $Q_0 \sim 15$ eb [obtained by comparing to calculations with infinitely fast side feeding—see dashed curve in Fig. 2(b)]. The inset in Fig. 2(b) shows the broadened line shape of the 508-keV transition which compares well with the calculated line shape obtained by using $Q_0 = 18$ eb. Using the relation between Q_0 and β given in Ref. 15, the measured value of Q_0 implies a deformation $\beta = 0.55$, in agreement with the value calculated in Ref. 10. We conclude that a superdeformed (SD) band has been observed in ^{191}Hg.

The location in energy of the SD band with respect to the yrast line and its decay towards the ground state or excited states is an important issue for which the following information is available. (i) An excess in intensity was observed for the 390-keV γ ray [see also Fig. 2(a)]. Since this excess is only 25% and not 100% in the thin-target experiment one must conclude that either part of the decay proceeds directly to the ground state via unobserved transitions, or the lowest state in the new band has a lifetime long enough for the ^{191}Hg nuclei to recoil out of the sight of the CSG's before the decay occurs. Within the time resolution of the experiment (~ 8 ns)

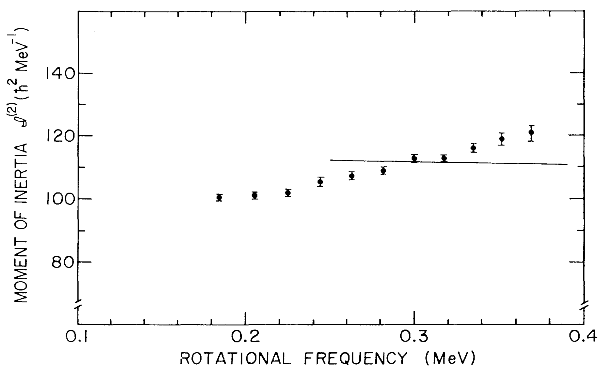

FIG. 3. Dynamic moment of inertia $\mathcal{J}^{(2)} = 4\hbar^2/\Delta E_\gamma$ for the superdeformed band in ^{191}Hg. The line is the result of the calculations of Ref. 11 and corresponds to a β value of 0.55.

and the limited statistical accuracy, no measurable lifetime was found. (ii) The presence of an isomer is favored by the thick-target measurement in which the excess intensity in the 390-keV γ ray is 86% [square in Fig. 2(a)], i.e., significantly larger. (iii) The spectra from individual coincidence gates in the thin-target measurement contain evidence for a 4009-keV γ ray (inset in Fig. 1) which may be a link between the SD band and the $\frac{17}{2}^+$ yrast state. Its intensity relative to that of the SD band (16 ± 9)% is consistent with this assignment, but the uncertainties are large because of the reduced CSG efficiency at this high energy. The thick-target experiment yielded no additional information because of the lower statistics and the increased background in the spectrum. Hence, the placement of this line is still tentative. It should also be noted that if the decay out of the new band were similar to the statistical decay out of the superdeformed bands around $A \simeq 150$ (Refs. 3-7), this 4009-keV γ ray would only represent the strongest of many statistical decay paths. In any case, the data suggest that the lowest level of the new sequence is located at least 4.4 MeV above the ground state in ^{191}Hg. Clearly, more experimental work will be necessary to study the decay of the SD band in detail and it is not possible to assign definite spins to the SD states.

The measured and calculated moments of intertia $\mathcal{J}^{(2)}$ are compared as a function of the rotational frequency $\hbar\omega$ in Fig. 3. Since the cranked Strutinsky calculations[10] do not include pairing, they are not reliable at low spin and frequency and no calculated values are presented below $\hbar\omega = 0.25$ MeV. As stated above, the agreement between data and calculations is very good even though the smooth, small increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$ is not reproduced in the calculations. The calculated SD minimum can be associated with the large shell gap in the proton single-particle spectrum at $Z=80$ of ~ 2 MeV at $I=0$ which is maintained at $I=40$. There are also smaller gaps of ~ 0.7 MeV in the neutron single-particle spectrum at $N=112$ and 116 at $I=0$; the N

$=112$ gap is reduced to ~ 0.4 MeV at $I=40$, while the gap at $N=116$ remains the same. The data indicate that the SD band maintains its character at low frequency and the change in the value of $\mathcal{J}^{(2)}$ is small. Calculations of the pairing correlation energy at $\hbar\omega=0$ and $\beta=0.55$ result in a value which is only about $\frac{1}{2}$ that obtained for a rotational nucleus with average deformation. Hence, the effect of pairing on $\mathcal{J}^{(2)}$ is expected to be smail, as seen in the data. Detailed calculations of $\mathcal{J}^{(2)}$ including pairing will be carried out.

In summary, a superdeformed band of twelve transitions has been found in ^{191}Hg with an average moment of inertia $\mathcal{J}^{(2)}$ of 110 $\hbar^2$MeV^{-1} and an intrinsic quadrupole moment of 18 ± 3 eb. The data are in excellent agreement with cranked Strutinsky calculations and provide strong support for the existence of the large new region of superdeformation as discussed in Ref. 10. Further study of this region may lead to the discovery of more superdeformed nuclei. This may allow us to answer some of the open questions about the nature of the superdeformed single-particle potential; for example, the possibility of large changes in the neutron spin-orbit potential at large deformations.[16]

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