PHYSICAL REVIEW C VOLUME 41, NUMBER 1 JANUARY 1990

Superdeformed band in ^{192}Hg

D. Ye,[(a)] R. V. F. Janssens,[(b)] M. P. Carpenter,[(b)] E. F. Moore,[(b)] R. R. Chasman,[(b)] I. Ahmad,[(b)] K. B. Beard,[(a)] Ph. Benet,[(c)] M. W. Drigert,[(d)] P. B. Fernandez,[(b)] U. Garg,[(a)] T. L. Khoo,[(b)] S. L. Ridley,[(b),*] and F. L. H. Wolfs[(b)]

[(a)]*University of Notre Dame, Notre Dame, Indiana 46556*

[(b)]*Argonne National Laboratory, Argonne, Illinois 60439*

[(c)]*Purdue University, West Lafayette, Indiana 47907*

[(d)]*Idaho National Engineering Laboratory, EG&G Idaho Incorporated, Idaho Falls, Idaho 83415*

(Received 7 September 1989)

The observation of a superdeformed band in the nucleus ^{192}Hg is reported. The band has sixteen transitions with an average energy spacing of 36 keV and an average dynamic moment of inertia $\mathcal{J}^{(2)}$ of 112 $\hbar^2$MeV^{-1}. This band persists to rather low rotational frequency ($\hbar\omega \sim 0.125$ MeV) and is proposed to extend in spin from 10^+ to 42^+. No transitions linking the superdeformed states and the low deformation yrast levels were found and the decay out of the superdeformed band appears to be statistical. This is the second case of superdeformation in the $A \sim 190$ region.

Recently, we have reported the first observation of superdeformation in the mass $A \sim 190$ region.[1] A rotational band of twelve transitions with an average energy spacing of 37 keV, an average dynamic moment of inertia $\mathcal{J}^{(2)}$ of 110 $\hbar^2$MeV^{-1}, and an average quadrupole moment of 18 ± 3 eb was observed in ^{191}Hg. This band persists at rotational frequencies $\hbar\omega$ as low as 0.175 MeV. These results were found to be in excellent agreement with cranked Strutinsky Wood-Saxon calculations by Chasman[2] which predict a spheroidal shape with an axis ratio of 1.65:1 for the superdeformed shape in this nucleus. The calculations of Ref. 2 found deep minima in the total-energy surface at similar very large deformations for many nuclei in the region $A \sim 185$–205. These minima are calculated to be yrast at spins above $30\hbar$ in many cases and, furthermore, are found to presist to low spins. Large deformations have also been calculated by Åberg[3] in cranking calculations using a modified oscillator potential. Superdeformed shapes have also recently been obtained at spin $I=0$ for some nuclei in this region in several Hartree-Fock calculations.[4-6]

Clearly, it is of interest to find experimental evidence for other superdeformed bands in this region in order to address some of the questions prompted by the results of Ref. 1 and the calculations mentioned above. For example, the existence of an entire region of superdeformation needs to be established. Also, additional information on the properties of the superdeformed bands is very desirable. In contrast with the superdeformed bands in the $A \sim 150$ region[7] (where the decay out of the superdeformed band towards the ground state feeds several yrast states with varying intensities over an angular momentum range $\Delta I \sim 3\hbar$–$6\hbar$) the superdeformed band in ^{191}Hg was found to decay only to the $\frac{17}{2}^+$ yrast state. It was not possible to obtain a firm indication of the spins of the superdeformed states nor to assess whether the link between the superdeformed states and the yrast levels is statistical in nature as in the $A \sim 150$ region or occurs only through a few specific transitions. While the average value of $\mathcal{J}^{(2)}$ was found to be in agreement with the calculations of Ref. 2, a smooth increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$ was not reproduced. It is important to study this behavior in other superdeformed nuclei with the hope that it will contribute to the understanding of the underlying microscopic structure as is the case in the $A \sim 150$ region.[8,9]

We report here on the discovery of a band of sixteen transitions in ^{192}Hg with properties consistent with superdeformation. This band is shown to extend to even lower frequencies than in ^{191}Hg ($\hbar\omega > 0.125$ MeV) and to feed a number of yrast and near yrast levels, thereby suggesting statistical decay out of the superdeformed minimum. The data also allow us to propose spin values for the superdeformed states. As a consequence, values are derived for both the static and dynamic moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ which are found to increase with $\hbar\omega$ as in ^{191}Hg. This band in ^{192}Hg has also been observed in an independent experiment by Becker *et al.*[10]

The experimental conditions for the present measurements were similar to those used in our studies[1,11] of ^{191}Hg. The states were populated with the (^{36}S,$4n$) reaction using 162 MeV beams delivered by the Argonne superconducting linear accelerator ATLAS. The γ rays were detected with the Argonne-Notre Dame bismuth germanate (BGO) γ-ray facility where a sum-energy multiplicity array of 50 hexagonal BGO elements is surrounded by twelve Compton-suppressed Ge spectrometers. The ^{160}Gd target consisted of two 500 μg/cm^2 self-supporting foils (enrichment $> 97\%$) stacked together. A thick Pb foil placed 10 cm downstream from the target (outside of the "focus" of the Ge counters) was used to stop the beam and the recoiling Hg nuclei. With a threshold of four on the number of array elements firing in coincidence with at least two Compton-suppressed Ge detectors, a total of 7.2×10^7 events were recorded and stored on magnetic tape for subsequent analysis. Each event contained the following information: the energy and time information measured in the suppressed Ge detectors, the γ-ray sum energy, the prompt multiplicity, and the hit pattern of the array.

The results presented below were obtained from a γ-γ

coincidence matrix where high multiplicity events were selected by requiring that at least ten detectors of the array fired in prompt coincidence with the Ge detectors. The fold distribution for events in the $4n$ reaction channel was found to peak at fourteen. Events from the strongly competing $5n$ channel are characterized by a fold distribution peaking at ten and are partially suppressed by the gating condition. The coincidence matrix contained 4.9×10^7 events of which about 42% are in the $4n$ reaction channel. (The remaining events are in the $3n$ and $5n$ channels with respective yields of 3% and 55%).

A new band of sixteen transitions extending in energy from 257 to 792 keV was observed in coincidence spectra generated from the matrix. The band was seen in individual spectra gated on each transition. The spectrum shown in Fig. 1 was obtained by summing the strongest and cleanest coincidence gates (257, 300, 341, 381, and 496 keV) and all the new transitions are labeled by their measured γ-ray energy. Also indicated in Fig. 1 are the lines corresponding to known transitions[12] in ^{192}Hg. The band feeds the known levels up to 8^+ in the positive-parity yrast sequence and up to the 9^- in the negative-parity band. It is apparent from Fig. 1 that one of the transitions in the band is only about 2 keV lower in energy than the 2^+-0^+ ground-state transition in ^{192}Hg and the resulting line shape is rather broad. Another transition coincides in energy with the 4^+-2^+ transition. We note that a similar situation is present in ^{191}Hg where the $\frac{17}{2}^+$-$\frac{13}{2}^+$ transition was found to have the same energy as the second member of the superdeformed band.[1] A weak 215-keV transition is reported as the lowest member of the band in Ref. 10. This line is present in our spectra as well, but a major fraction of its intensity is due to a contaminant from another strong γ ray in ^{192}Hg. Consequently, we have no conclusive evidence for its assignment in the new band. The stretched-$E2$ character of all the transitions was established from the angular correlation measured at 34.5°, 90°, and 145.5° with respect to the beam. The total flow through the band represents 1.9% of all transitions in ^{192}Hg. Under the multiplicity gating conditions mentioned above, the corresponding number is 4%.

The energy spacing between γ rays in the new sequence decreases from 42.4 to 30.1 keV with increasing transition energy. The average value of 36 keV is close to that reported for the superdeformed band in ^{191}Hg (37 keV).[1] The corresponding average moment of inertia $\mathcal{J}^{(2)}$ is 112 $\hbar^2$ MeV^{-1} and compares well not only with the average value for ^{191}Hg (110 $\hbar^2$MeV^{-1}), but with the calculated value of Ref. 2 (109 $\hbar^2$MeV^{-1}). In addition, the band has many properties similar to those observed in ^{191}Hg (transition energies, intensity pattern, etc.). Therefore, this band is referred to as a superdeformed band and it is assumed to correspond to the rotation of the ^{192}Hg nucleus with a very large prolate deformation.

The intensity distribution along the superdeformed band is presented in Fig. 2 for the spectrum gated by the 341-keV line. The contributions of the 2^+-0^+ and 4^+-2^+ transitions (see above) were not removed: this explains the abnormally high intensity of the corresponding points in Fig. 2. The decreasing intensity seen at frequencies $\hbar\omega > 0.23$ MeV presumably reflects the initial feeding population. At lower frequencies, the intensity remains essentially constant and the decay out of the band towards the yrast line occurs mainly from the lowest level, even though there is a decay branch of about 10% from the second state. Transitions which link the superdeformed band with the known yrast states could not be found: No γ ray with intensity > 5% of the 341-keV line and energy < 4.9 MeV was observed. It is likely that many different decay paths share the intensity. This assumption is supported by the observation that the feeding into the yrast states is spread over several states belonging

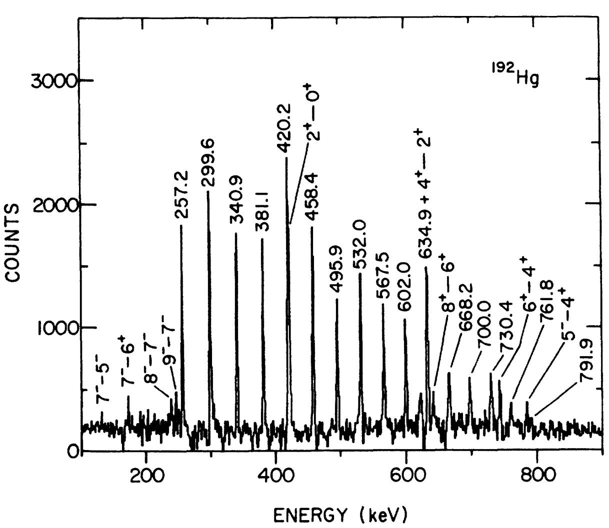

FIG. 1. γ-ray spectrum in ^{192}Hg obtained by summing five clean coincidence gates on transitions of 257, 300, 341, 381, and 496 keV. The γ ray at 629 keV is an identified contaminant (seen in the 257-keV gate only).

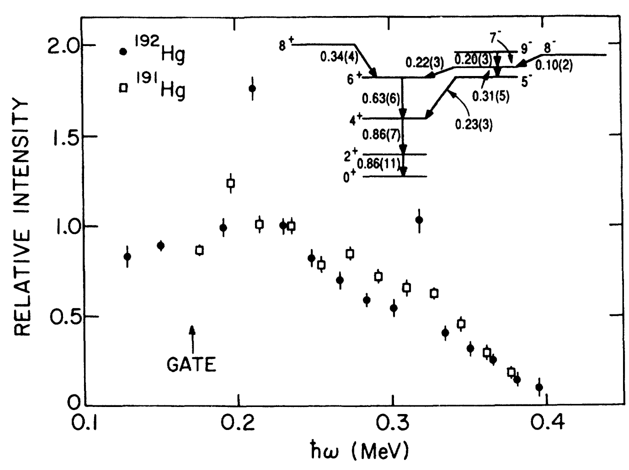

FIG. 2. Relative transition intensity of the γ rays in the superdeformed band of ^{192}Hg as obtained from the coincidence spectrum obtained by gating on the 341-keV transition. The data are normalized to the 381-keV transition. The data for ^{191}Hg (Ref. 1) are given for comparison. The inset presents the feeding from the ^{192}Hg superdeformed band into the yrast line.

to two bands of opposite parity. The relevant feeding pattern of the latter states is presented as an inset in Fig. 2. The resulting average entry spin into the yrast states is $\sim 8\hbar$.

The spin of the lowest level in the superdeformed band (fed by the 257-keV transition) was estimated to be $10\hbar$. This value follows from the deexcitation pattern out of the superdeformed band (Fig. 2), the average entry spin into the yrast states ($8\hbar$), and the assumption of a $\Delta I = 2\hbar$ angular momentum removal by the transitions linking the superdeformed states and the yrast line. The highest spin reported here is then $42\hbar$. Because of the uncertainties inherent to the procedure outlined above, the error on the proposed spins could be as large as $3\hbar$.

It is interesting to compare the present data with the results obtained for the superdeformed band in ^{191}Hg (Ref. 1) as well as for superdeformed bands in the $A \sim 150$ region.[7-9] The total γ-ray intensity flowing through the superdeformed bands is similar in the two Hg isotopes ($\sim 2\%$) and is larger by a factor of ~ 2 than for superdeformed bands near $A = 150$. For $\hbar\omega > 0.17$ MeV, the intensity pattern as a function of rotational frequency is remarkably similar in the two Hg nuclei (Fig. 2): 50% of the feeding into the superdeformed band occurs at $\hbar\omega = 0.31$ and 0.34 MeV and the decay out occurs very suddenly at $\hbar\omega = 0.13$ and 0.18 MeV for ^{192}Hg and ^{191}Hg, respectively. The intensity patterns for the two cases are even more similar when considered as a function of spin (assuming $I \sim 21/2\hbar$ for the lowest state in the superdeformed band of ^{191}Hg): in both cases, 50% feeding occurs at $I \sim 30\hbar$ and decay out at $I \sim 10\hbar$. The only difference between the two isotopes is that feeding into the "normal" yrast states occurs over several states in ^{192}Hg, while feeding into a single state has been identified in ^{191}Hg. However, in both cases the average entry spin into the yrast states is similar ($\sim 8\hbar$).

The intensity patterns shown in Fig. 2 are similar to those reported in the superdeformed nuclei with $A \sim 150$, but the spins and frequencies for the $A \sim 150$ region are always significantly higher. The average feeding into the superdeformed bands of the $A \sim 150$ region occurs for $I \simeq 55\hbar$; we believe that the lower entry spin into the corresponding bands in the Hg isotopes is due to the lower fission barrier in the $A \sim 190$ region.[13] The large difference in the spin at which the decay occurs in the two regions ($I \sim 25\hbar$ for $A \sim 150$ vs $I \sim 10\hbar$ for $A \sim 190$) contains substantive physics information since several factors affect the decay: the well depth W and the excitation energy E^* of the superdeformed minimum; the level density of the normal states at E^*; and pairing, which has a large influence on the inertial mass parameter.[14,15] The persistence of the superdeformed band to lower spin in the Hg isotopes may imply a larger well depth W of the superdeformed minimum. At $I \sim 25\hbar$, W is calculated[16] to be around 1.5 MeV in the $A \sim 150$ region, whereas it is probably at least 0.5 MeV deeper for the Hg Isotopes at $I \sim 10\hbar$. (There is as yet no firm calculation of W at spin 10, because pairing needs to be included in the calculations of Ref. 2. However, at spin 40, $W \sim 3.5$ MeV for the Hg isotopes[2] while $W \sim 2.5$ MeV for the $A \sim 150$ nuclei.[16]) We note that both cranked Strutinsky[2] and Hartree-Fock[4-6] calculations predict that the superdeformed well presists in ^{192}Hg to spin 0. However, the data show that the decay out of the superdeformed well occurs at higher spin.

The static and dynamic moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ derived for ^{192}Hg are presented in Fig. 3 as a function of rotational frequency together with the published values[1] of $\mathcal{J}^{(2)}$ for ^{191}Hg. It is striking that (1) $\mathcal{J}^{(2)}$ is significantly larger than $\mathcal{J}^{(1)}$ over a large frequency range, (2) there is a large (40%) monotonic increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$, and (3) the $\mathcal{J}^{(2)}$ values for both Hg isotopes are very close over the entire frequency range. All of these observations are not only a challenge for theory to explain, but also provide insight into the structure of nuclei at large deformation. The calculations of Ref. 2 reproduce the average experimental values of $\mathcal{J}^{(2)}$ satisfactorily, but not the increase with $\hbar\omega$.

Mean-field calculations which attempt to reproduce the variation of $\mathcal{J}^{(2)}$ as a function of $\hbar\omega$ for the superdeformed bands in the $A \sim 150$ region have suggested that these variations may be attributed to three major factors: (i) changes in pairing at large deformations,[9] (ii) occupation of specific high-j intruder orbitals[8,9] ($N = 6$ protons and $N = 7$ neutrons), and (iii) shape changes as a function of rotational frequency. These three factors could separately or cooperatively contribute to variations of $\mathcal{J}^{(2)}$ with $\hbar\omega$. The data on $\mathcal{J}^{(2)}$ for ^{191,192}Hg provide a test of the importance of these factors for superdeformed bands near $A \sim 190$.

Lifetime data are available for the bands in ^{191}Hg (Ref. 1) and ^{192}Hg (Ref. 17) from measurements with the Doppler-shift attenuation method, which indicate an essentially constant quadrupole moment. The maximum change in deformation allowed by the data cannot reproduce the large increase in $\mathcal{J}^{(2)}$ in the superdeformed band of either nucleus.[17] In an attempt to understand if the in-

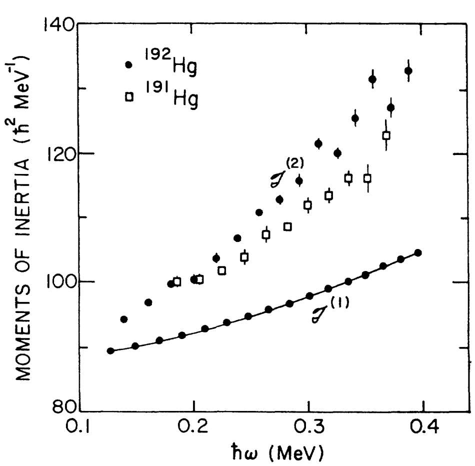

FIG. 3. Static [$\mathcal{J}^{(1)} = (2I-1)\hbar^2/E_\gamma$] and dynamic ($\mathcal{J}^{(2)} = 4\hbar^2/\Delta E_\gamma$) moments of inertia for ^{192}Hg. The dynamic moment of inertia of ^{191}Hg (Ref. 1) is also given. The computation of $\mathcal{J}^{(1)}$ assumes that the lowest level in the band has a spin $I = 10\hbar$. This value is uncertain by $\sim 3\hbar$ (see text for details). The data points for $\mathcal{J}^{(1)}$ are joined by a line to guide the eye.

crease in $\mathcal{J}^{(2)}$ could be attributed to high-j single-particle intruder orbitals (with no pairing, as is done in Ref. 8 for the $A\sim150$ region), we have examined calculated routhians (Ref. 3) which indicate that for $N=112$ and $Z=80$, four $N=7$ neutron orbitals and four $N=6$ proton orbitals are involved. The separate contributions of the protons and neutrons each result in an essentially constant $\mathcal{J}^{(2)}$ with increasing $\hbar\omega$. This is consistent with the calculations of Ref. 2 (mentioned above) which do not include pairing and also yield an almost constant $\mathcal{J}^{(2)}$. Thus, neither shape effects nor the occupation of high-j single-particle intruder orbitals can explain the pronounced increase in $\mathcal{J}^{(2)}$.

This points to the need to include the effects of pairing as done in Ref. 9. If pair correlations are present at low frequency in the superdeformed bands of the Hg nuclei, an increase in $\mathcal{J}^{(2)}$ could reflect a gradual decrease in pairing or the rotational alignment of one or more pairs of quasiparticles. In order to evaluate the latter possibility, we have performed cranked shell model calculations with the Warsaw-Lund code which uses a Wood-Saxon potential[18] with the universal parameters given in Ref. 19 to calculate quasiparticle routhians and $\mathcal{J}^{(2)}$ values for elongated shapes ($\beta_2=0.45$–0.55) in ^{191,192}Hg. While specific results depend on the deformation and the pairing gap used, the following general conclusions can be drawn. (i) An alignment of a $N=7$ neutron pair is calculated to occur in ^{192}Hg within $0.15<\hbar\omega<0.3$ MeV. This alignment is blocked in ^{191}Hg by the presence of an odd neutron in the orbital involved. As a consequence a significant change in $\mathcal{J}^{(2)}$ is expected in the frequency range given above for ^{192}Hg, but not for ^{191}Hg. This difference between isotopes is not seen in the data (Fig. 3). In the framework of our calculations this can only be reproduced if the value of the neutron pairing is significantly reduced. This finding suggests that proton effects are partly responsible for the similar increases of $\mathcal{J}^{(2)}$ in ^{191}Hg and ^{192}Hg. (ii) An alignment of a pair of $N=6$ protons is calculated to occur between $0.25<\hbar\omega<0.4$ MeV. An increase in $\mathcal{J}^{(2)}$ will result, but again the exact details are dependent on the deformation and pairing used. This increase should be similar in the two Hg isotopes as seen in the data. Clearly, the conjectures outlined above are qualitative and need to be substantiated further by detailed calculations which minimize the energy with respect to pairing and deformation as done in Ref. 9.

In summary, a superdeformed band of sixteen transitions has been found in ^{192}Hg and the data provide further evidence for the existence of a new region of superdeformation near $A\sim190$. The large increase of the moments of inertia with rotational frequency ($\mathcal{J}^{(2)}$ increases by 40%) provides insight on the underlying microscopic structure and on pairing at very large deformation.

This work was supported by the U.S. Department of Energy, Nuclear Physics Division, under Contracts No. W-31-109-ENG-38, No. DE-AC07-76IDO1570, and No. DE-FG02-87ER40346, and by the National Science Foundation under Grant No. PHY88-02279.

*Permanent address: Hampton University, Hampton, VA 23668.

[1]E. F. Moore *et al.*, Phys. Rev. Lett. **63**, 360 (1989).
[2]R. R. Chasman, Phys. Lett. B **219**, 227 (1989).
[3]S. Åberg, Phys. Scr. **25**, 23 (1982); and (private communication).
[4]P. Bonche, S. J. Krieger, P. Quentin, M. S. Weiss, J. Meyer, M. Meyer, H. Flocard, and P. H. Heenen, Nucl. Phys. (to be published).
[5]M. Girod, J. P. Delaroche, and J. F. Berger, Phys. Rev. C **38**, 1519 (1988).
[6]M. Girod, J. P. Delaroche, D. Gogny, and J. F. Berger, Phys. Rev. Lett. **62**, 2452 (1989).
[7]P. Fallon *et al.*, Phys. Lett. B **218**, 137 (1989), and references therein.
[8]T. Bengtsson, I. Ragnarsson, and S. Åberg, Phys. Lett. B **208**, 39 (1988).
[9]W. Nazarewicz, R. Wyss, and A. Johnson, Phys. Lett. B **225**, 208 (1989).
[10]J. Becker, N. Roy, E. A. Henry, M. A. Deleplanque, C. W. Beausang, R. M. Diamond, J. A. Draper, F. S. Stephens, J. A. Cizewski, and M. J. Brinkman, preceding paper, Phys. Rev. C **41**, R9 (1990).
[11]D. Ye *et al.* (unpublished).
[12]H. Hübel, A. P. Byrne, S. Ogaza, A. E. Stuchbery, G. D. Dracoulis, and M. Guttormsen, Nucl. Phys. **A453**, 316 (1986).
[13]R. V. F. Janssens *et al.* (unpublished).
[14]G. Bertsch, Phys. Lett. B **95**, 157 (1980).
[15]F. Barranco, R. A. Broglia, and G. F. Bertch, Phys. Rev. Lett. **60**, 507 (1988).
[16]R. R. Chasman, Phys. Lett. B **187**, 219 (1987).
[17]E. F. Moore *et al.* (unpublished).
[18]W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).
[19]J. Dudek, Z. Szymanski, and T. Werner, Phys. Rev. C **23**, 929 (1981).