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CONF-890686--3

DE90 002208

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Observation of Superdeformation in ^{191}Hg

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Abstract: The first observation of superdeformation in the A≃190 mass region is reported. A rotational band of 12 transitions with an average energy spacing of 37 keV, an average moment of inertia of 110 $\hbar^2$ MeV^{-1}, and an average quadrupole moment of 18 ± 3 eb has been observed in ^{191}Hg. 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. Evidence for another discrete superdeformed band and superdeformed structures in the quasi-continuum was also found in the data.

Superdeformation was first proposed (Strutinsky 1967) some twenty years ago to explain the fission isomers observed in some actinide nuclei (Polikanov et al. 1962). Fission isomers are found in nuclei trapped in a metastable minimum associated with very elongated ellipsiodal 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 (Twin et al. 1986) and in several neighboring nuclei (Hass et al. 1988, Deleplanque et al. 1988, Rathke et al. 1988, Fallon et al. 1988). Nuclei with large deformations have been reported (Kirwan et al. 1987) at high spin in the A≃135 mass region and fragmentary evidence exists around A≃180 and 105 (Burde et al. 1988).

In this contribution we report the discovery of a rotational band of twelve transitions in the nucleus ^{191}Hg having properties consistent with superdeformation. This study was motivated by the results of cranked Strutinsky calculations by Chasman (Chasman 1989), who found that deep secondary minima in the total energy surface exist for many nuclei in the region A≃186-205. 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 some cases and were shown to persist even to the lowest spins. Superdeformed shapes with axis ratios >1.45:1 have also been obtained at I=0 for some nuclei in this region in the calculations of (Girod et al. 1988).

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The experiment was carried out at the Argonne superconducting linear accelerator ATLAS using the Argonne-Notre Dame BGO γ-ray facility which consists of 50 hexagonal BGO elements surrounded by 12 Compton suppressed Ge spectrometers (CSG's). The states in ^{191}Hg were populated by the reaction ^{160}Gd(^{36}S,5n) at a beam energy of 172 MeV. The target consisted of two isotopically enriched 500 μg/cm^2 self-supporting foils stacked together. Under the experimental conditions the compound nucleus is formed with an excitation energy of 71 MeV and a maximum angular momentum in excess of 50 $\hbar$. In the analysis, only events where at least 14 of the array detectors fired in coincidence with the CSG's were considered. The final γ-γ coincidence matrix contained 95 x 10^6 events, of which 60% were in the 5n channel. The remaining events belong mainly to the 6n channel; no measurable yield was found for 4n evaporation.

A band of twelve coincident transitions, extending from 350 to 754 keV with an average energy spacing of 37 keV, corresponding to an average dynamic moment of inertia of 110 $\hbar^2$ MeV^{-1}, was observed and is shown in Fig. 1. The stretched E2 character of the γ-rays was established

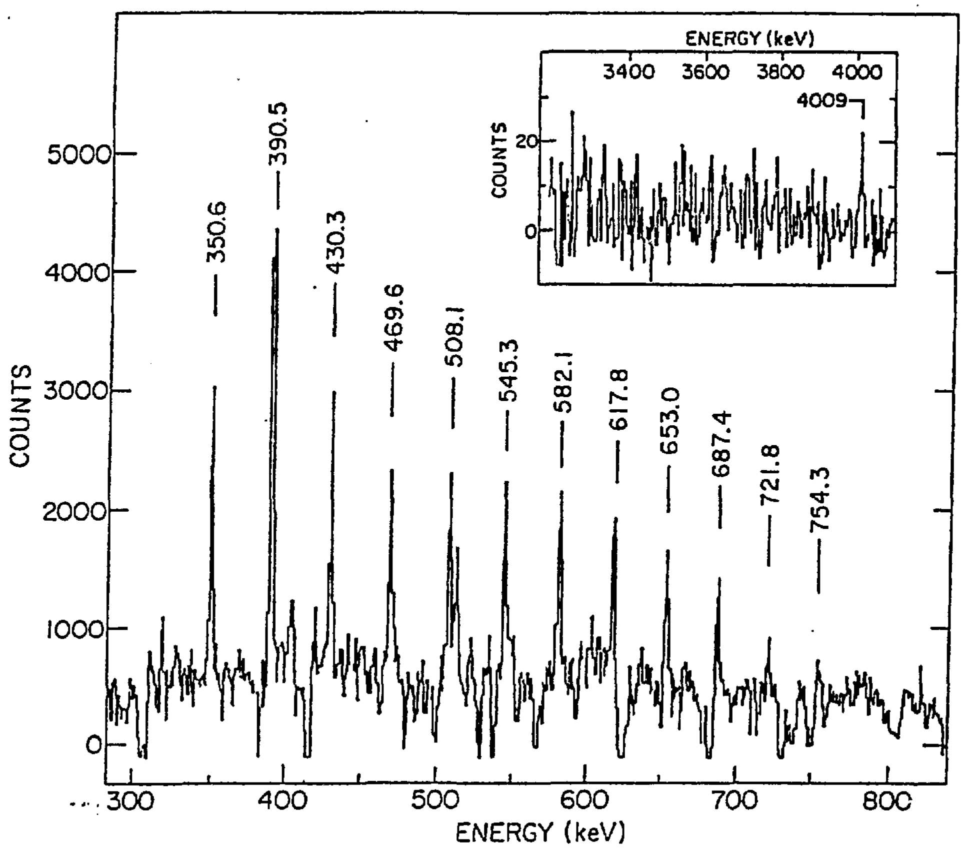

Fig. 1. γ-ray spectrum in ^{191}Hg obtained by summing coincidence gates on selected transitions (351, 471, 508, 545, 582, and 653 keV). The γ-ray at 514 keV is an identified contaminant (seen only in the 508-keV gate). Inset: The high-energy end portion of this spectrum, with the 4009-keV line discussed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

from the angular correlations. Under the multiplicity condition described above, the flow through the SD 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 (Hübel et al. 1986) $17/2^+ - 13/2^+$ transition in ^{191}Hg. The intensity of this transition is about 25% greater than any other transition in the band and it is proposed that the excess intensity arises from the decay of the band, at least partly, through the $17/2^+$ state. This result supports the assignment of the band in ^{191}Hg. The fold and sum-energy distributions measured in coincidence with transitions in the band peak at values only slightly larger than those of known γ-rays in ^{191}Hg: this result is also consistent with an assignment in ^{191}Hg.

Figure 2 presents the intensity pattern for the transitions in the new band derived from the analysis of the coincidence gates. The relative

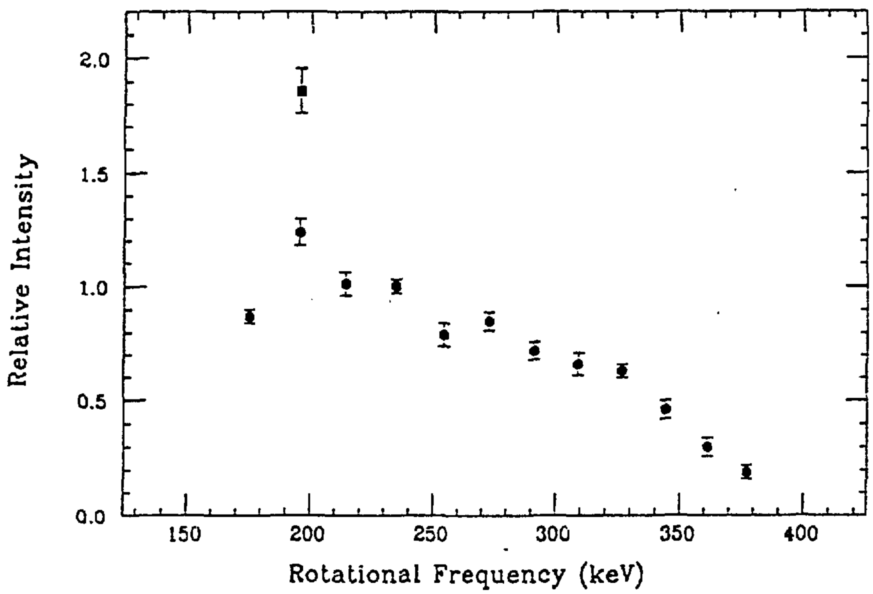

Fig. 2. Relative intensity of the γ-rays in the new band of ^{191}Hg as measured in the thin-target experiment. The intensity of the 390-keV line in the thick-target measurement is also given (■).

intensity is seen to decrease with increasing γ-ray energy. At the bottom of the cascade, the intensity remains essentially constant over the last 3-4 transitions, with the exception of the excess strength in the 390 keV γ-ray as discussed above. The decay out of the band is abrupt; no coincident γ-ray having an energy less than 350 keV and an intensity of 5% of the 350 keV line was observed. Thus, the main decay out of the band towards the yrast line occurs from the lowest transition observed in the cascade.

As discussed above, the average dynamic moment of inertia $\mathfrak{J}^{(2)}$ for the new band is consistent with a superdeformed shape. However, since single 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 required. A second experiment was performed to measure the transition quadrupole moment in the band using the Doppler shift attenuation method (DSAM). In this 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 outlined above.

The same procedure and approximations made in lifetime studies of the superdeformed bands in ^{152}Dy, ^{149}Gd, and ^{132}Ce (Twin et al. 1986, Hass et al. 1988, Kirwan et al. 1987) were used here. Figure 3 presents the measured fraction of the full Doppler shift F for the highest

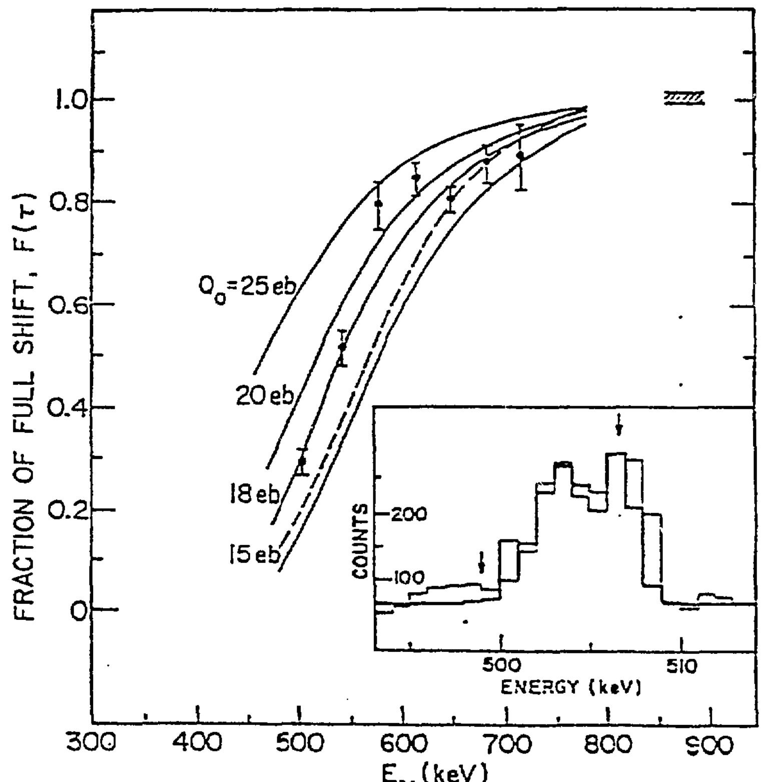

Fig. 3. Measured fraction of the full Doppler shift for all transitions in the band with $508 \lesssim E_\gamma \lesssim 721$ keV. Calculated shifts are given for various quadrupole moments; solid curves include side feeding (see text), dashed curve assumes infinitely fast side feeding with Q_0=15 eb. 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 146^0; experiment (thin line) and calculation with Q_0=18 eb (thick line); arrows indicate energies corresponding to full and zero Doppler shift.

transitions in the band. The lowest transitions were fully stopped or contaminated by other γ-rays in the spectrum. The calculated curves in Fig. 3 represent values of F for various quadrupole moment Q_0 values under the assumption of a constant deformation. The data are consistent with Q_0=18±3 eb, where the errors include uncertainties in the slowing down process and in the side-feeding intensities. The full curves in Fig. 3 take into account side feeding; the side-feeding lifetime into a state of spin I was assumed to be equal to the lifetime of the I+2 state in the band. Similar results were obtained when a constant side-feeding time of 30 fs was assumed - the difference between the highest data points and the calculated full shift for recoils formed in the center of the target suggests a delay in the feeding of these states of this order. In any case, the measured shifts clearly indicate very fast transitions and impose a lower bound on the quadrupole moment of Q_0 ~15 eb [obtained by comparison to calculations with infinitely fast side feeding-see dashed curve in Fig. 3]. The inset in Fig. 3 shows the broadened line shape for the 508 keV transition which compares nicely with the calculated line shape obtained when a Q_0 value of 18 eb is used. Using the relation between Q_0 and β given in (Löbner et al. 1970), the measured value of Q_0 implies a deformation of β=0.55, in excellent agreement with the calculated value of (Chasman 1989). We conclude that this band is based on a superdeformed configuration in ^{191}Hg.

One question of considerable importance is the location in energy of the SD band with respect to the yrast line and its decay towards the ground state. The following information was obtained in this study: (i) An excess intensity was observed in the 390 keV γ-ray [see Fig. 2]. 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 to allow the ^{191}Hg nuclei to recoil out of focus of the CSG's before the full intensity of the decay is observed. (ii) The latter explanation is favored by the thick-target measurement in which the excess intensity in the 390 keV γ-ray is 86% [square in Fig. 2]. (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 $17/2^+$ yrast state. Its intensity relative to that of the SD band (16±9)% is consistent with this assignment, but the uncertainties are large due to the reduced efficiency of the CSG's at such high energies. The thick target data yielded no new information on the 4009 keV γ-ray primarily due to lower statistics. Hence the placement of this line is still tentative. Clearly, more experimental work is necessary to study the decay out of the SD band in detail and it is not possible to assign definite spins to the members of this band at this time.

The coincidence data contain evidence for a second band of transitions with energy spacings similar to those in ^{191}Hg, but with an intensity smaller by a factor of ~2.5. No firm placement could be made, although there is tentative evidence for an assignment in ^{190}Hg (Ye et al.). Figure 4 presents the dynamic moment of inertia $\mathfrak{J}^{(2)}$ as a function of rotational frequency $\hbar\omega$ for the band in ^{191}Hg and for this weaker band. Both bands display very similar behavior, with a gradual increase in the $\mathfrak{J}^{(2)}$ value with increasing $\hbar\omega$. The solid line in Fig. 4 shows the calculated[10] value of $\mathfrak{J}^{(2)}$. Although the calculations do not reproduce the gradual increase in $\mathfrak{J}^{(2)}$, the average value of 110 $\hbar^2$ MeV^{-1} is in excellent agreement with the data.

The possibility of populating excited superdeformed bands which appear in the quasi-continuum (non-discrete superdeformation) was also investigated. An E_γ-E_γ correlation matrix was constructed from the thin

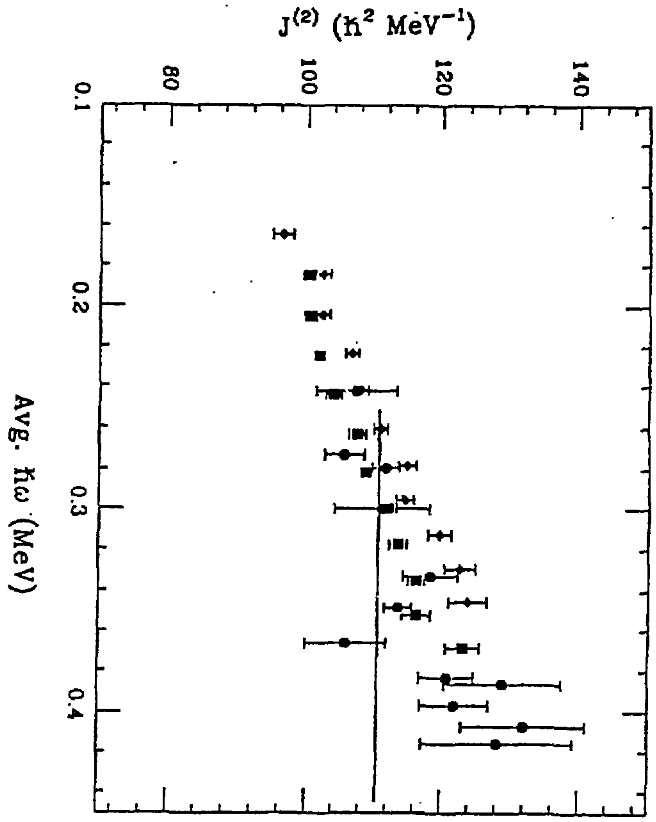

Fig. 4. Dynamic moment of inertia $\mathfrak{J}^{(2)}=4\hbar^2/\Delta E_\gamma$ for the superdeformed band in ^{191}Hg (■), the weaker discrete band discussed in text (♦), and the continuum SD γ-rays (•). The line is the result of the calculations of (Chasman 1989) and corresponds to a β value of 0.55.

target data. Uncorrelated events were subtracted out using the method proposed in (Anderson et al. 1979), modified according to (De Voight et al. 1981) to account for the large photoefficiency of the CSG's. The symmetrized matrix was sliced along the x-axis and the resulcing spectra were offset in such a way that channel zero corresponds to the $E_{\gamma 1}=E_{\gamma 2}$ main diagonal. The location of the first ridge in the spectra obtained in this manner will be at the position corresponding to the separation of the γ-ray energies in the cascade. The advantage of slicing in this manner is that it is a simple matter to set gates at energies corresponding to the known lines in the discrete SD band(s) and in between them, as well as to avoid gating on strong contaminant lines. Gates were set on the energies in between the known discrete SD lines in 2-3 keV steps over a wide energy range. The slices revealed intensity in the first ridge for energies of $480 \lesssim E_\gamma \lesssim 840$ keV (discrete SD lines are found for $30 \lesssim E_\gamma \lesssim 750$ keV). No statistically significant intensity in the second ridge was observed in the slices gated on the continuum regions. The absence of a second ridge in the continuum gates implies that the non-discrete SD cascades are quite short, consisting on average of two transitions. From the position of the first ridge in the gated slices, the dynamic moment of inertia $\mathfrak{J}^{(2)}$ was determined. Figure 4 presents the $\mathfrak{J}^{(2)}$ values for the non-discrete superdeformed bands as a function of $\hbar\omega$. Although the error bars are large, the overall trend is remarkably

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similar to that seen in the discrete SD bands. In particular, the smooth increase of $\mathfrak{J}^{(2)}$ as a function of $\hbar\omega$ seems to continue beyond the frequency corresponding to the last discrete SD line.

To investigate the mechanisms responsible for the population of superdeformed bands in this mass region, an excitation function is currently being performed at Argonne. The beam energy for the second step in the excitation function was 167 MeV, the other experimental conditions were identical to those described above for the thin target run at 172 MeV. Figure 5 shows the relative population of states in the

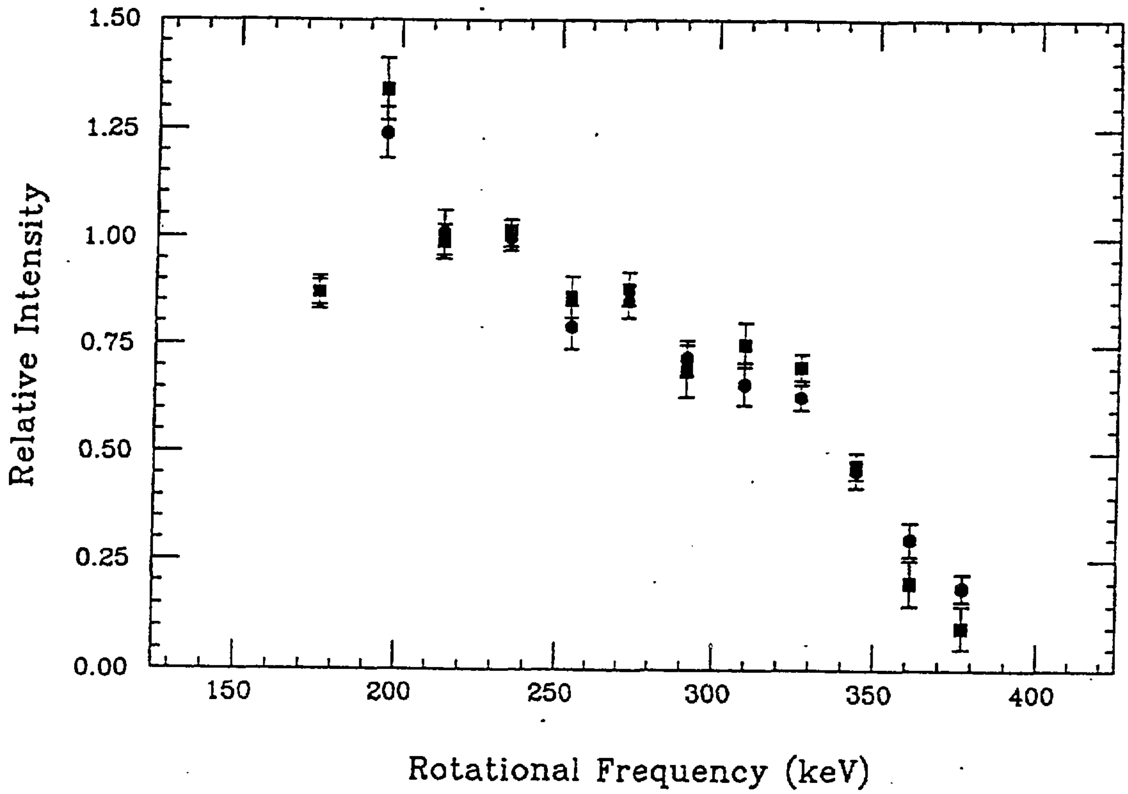

Fig. 5. Relative intensity of the γ-rays in the SD band in ^{191}Hg as measured at 172 MeV (•), and at 167 Mev (■). The relative intensities at each energy were obtained from the analysis of the same coincident gates.

SD band in ^{191}Hg at both 172 and 167 MeV. Within the error bars, the two patterns are identical with the possible exception of the two highest γ-rays. The overall population of the SD band in ^{191}Hg, however, decreases from 2.0% to about 1.2% at the lower beam energy. In contrast to the behavior in the SD band in ^{191}Hg, the high spin members of the weaker band described above are populated much less strongly than at 172 MeV. This result is also consistent with an assignment in ^{190}Hg but at this stage in the analysis it is not possible to draw any definite conclusions. Although the analysis of the excitation function data is still in progress, the results already obtained for the SD band in ^{191}Hg are consistent with those reported (Nolan and Twin 1988) for the SD band in ^{152}Dy.

As a byproduct of the search for supe.deformation in the Hg isotopes, considerably more information has been obtained on the 'normal' spectroscopy of these nuclei. One of the more interesting results is the observation of level structure consistent with single-particle excitations in ^{191}Hg (Ye et al.). The previously published (Hübel et al. 1986) level scheme for ^{191}Hg has been interpreted in terms of the collective rotation of a weakly deformed oblate system. Figure 6

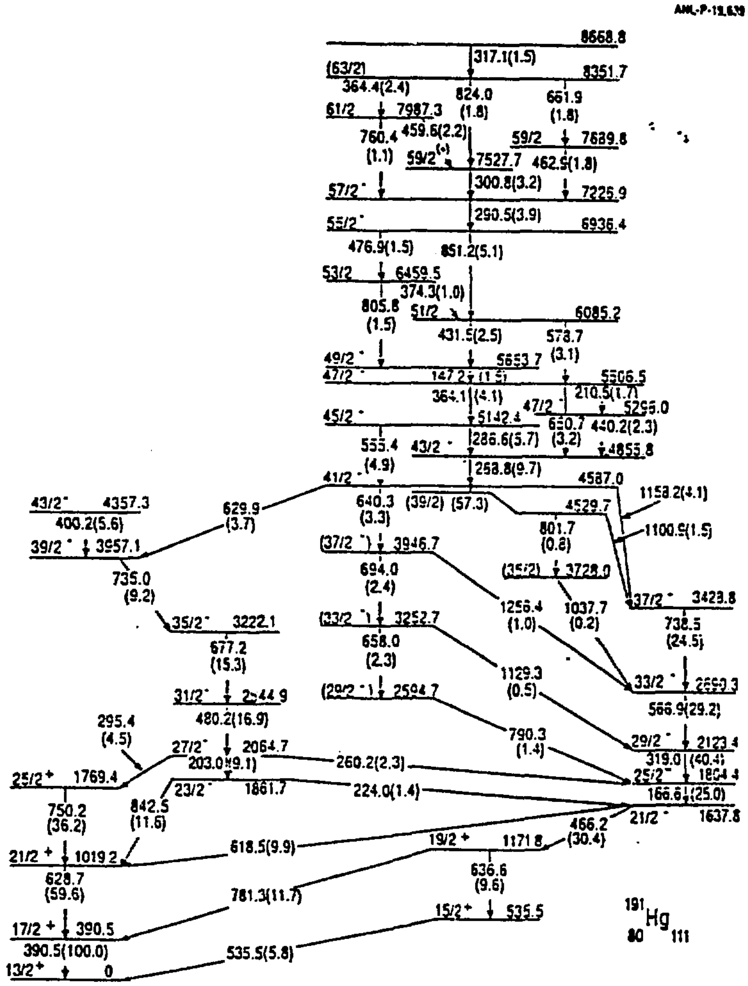

Fig. 6. Partial level scheme of ^{191}Hg showing the new level structure discussed in the text. The uncertainty on the γ-ray energy varies from 0.2 keV for the strong transitions to 0.5 keV for the weakest lines. Gamma-ray intensities are given in parentheses for all levels associated with the new sequence.

presents the partial level scheme relevant to the discussion below. For spins lower than 41/2, the band structure shows the regular level patterns and connecting E2 transitions characteristic of collective rotation. Above spin 41/2, however, the level scheme displays very irregular level spacing in marked contrast to the other band structures in the nucleus. In addition, a large number of dipole and quadrupole transitions compete in the decay. Furthermore, the $41/2^-$ state was found to be isomeric with a mean lifetime of 5±1 ns and is seen to decay to several rotational structures. These features point to a very different character for the levels in this band when compared to the rotational yrast states at lower excitation energy. These properties are very similar to those observed in nuclei in the beginning of the rare earth region. For example, the yrast lines of ^{152}Dy (Khoo et al. 1978) or ^{148}Gd (Piiparinen et al. 1987) are irregular and several isomers with decay rates typical of single-particle transitions are present. In these cases, the angular momentum is generated by the alignment of the spins of individual nucleons along a symmetry axis. We propose that the new level structure in ^{191}Hg is also of single-particle character. The present study represents the first experimental observation of this mode of excitation in this mass region.

In summary, a band of twelve coincident transitions has been seen in ^{191}Hg with an average moment of inertia $\mathfrak{J}^{(2)}$ of 110 $\hbar^2$ MeV^{-1} and an intrinsic quadrupole moment of 18±3 eb. The data are in excellent agreement with the results of cranked Strutinsky calculations and provide strong support for the existence of the large new region of superdeformation as discussed in (Chasman 1989). There is evidence in our data that superdeformation in this mass region is not limited to the case of ^{191}Hg. This is provided by the existence of another, much weaker, band with similar properties to the SD band in ^{191}Hg which has very tentatively been assigned to ^{190}Hg. Our data also contains evidence for superdeformed continuum γ-rays. These non-yrast superdeformed structures have moment of inertia values that show very similar trends to those seen in the discrete SD bands. Thus, it appears that excited SD bands are being populated in the present reaction. Finally, a great deal of new information has been obtained regarding the "normal" spectroscopy of ^{191}Hg. Specifically, a new band in ^{191}Hg has been found with properties consistent with single-particle excitations. These results, when taken together, show that the nucleus ^{191}Hg exhibits the competition between very different shapes and modes of excitation. Therefore, this nucleus and presumably others in this mass region should provide a very fruitful testing ground for the predictions of various nuclear models.

This work was supported by the U.S. Department of Energy, Nuclear Physics Division, under Contracts No. W-31-109-ENG-38, No. DE-AC07-76ID01570, No. DE-FG02-87ER40346 and the National Science Foundation under Grants No. PHY88-02279 and No. PHY87-19661.

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