Evidence for Strongly Deformed Shapes in ^{186}Hg †

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By means of γ-ray spectroscopy following (heavy ion, xn) reactions, we have established a level scheme for the yrast states in ^{186}Hg up to the 14^+ state. From the spectrum we conclude that ^{186}Hg makes a rather sudden angular-momentum–induced change in deformation from small values at low spins to rather large values at higher spins. This is in qualitative agreement with several potential-energy surface calculations, and leads to an interpretation of previously measured large isotopic shifts in rms radii from ^{187}Hg to ^{183,185}Hg as a sudden onset of stable quadrupole deformation.

Recently in an optical-pumping experiment a strong deviation has been reported of the isotopic shift (IS) of the 2537-Å spectral line for the nuclei ^{185}Hg and ^{183}Hg from the smoothly varying isotopic shifts in the heavier Hg nuclei with $A = 187$ to 204.[1] The IS is related to the change in nuclear charge radius, $\delta\langle r^2\rangle$, and for the nuclei ^{183,185}Hg a charge volume has been determined which is as big as that of ^{196}Hg. The IS can also be written in terms of a change of the deformation squared, $\delta\langle\beta^2\rangle$, and values of $\delta\langle\beta^2\rangle = 0.061$ and 0.051 have been reported for the nuclei ^{183}Hg and ^{185}Hg, respectively, relative to an extrapolation of the values for the heavier Hg nuclei.

This discovery has raised the question as to whether these anomalous IS's are due to a sudden onset of static quadrupole deformation in the light Hg nuclei which, with $Z = 80$, are almost proton magic. (The IS yields the change in the square of the deformation; this may contain dynamic contributions as well as the purely static one.) Earlier measurements[2] of the α decay of ^{188}Pd into ^{184}Hg did not show any rotational fine structure, and in case this α decay is not strongly hindered a lower limit of 300 keV for E_{2^+} in ^{184}Hg has been set. If so, the conclusion has been drawn that ^{184}Hg can hardly be a rotational nucleus with a deformation of $\beta = 0.25$–0.30, a value suggested by the IS measurements on the odd-mass nuclei. Therefore, with reference to theoretical calculations[3,4] the existence of "bubble" nuclei with low density in the center has been considered as a possible explanation for the anomalous IS measurements.[2]

In the present Letter we report on some results of in-beam and off-beam γ-ray spectroscopy on ^{186}Hg following (heavy ion, xn) reactions performed at the heavy-ion linear accelerator at Lawrence Berkeley Laboratory. Figure 1 shows part of the γ-ray spectrum obtained from bombarding a lead-backed ^{162}Dy target of 1 mg/cm^2 thickness with ^{28}Si at 135-MeV incident energy. In-beam and off-beam excitation-function measurements as well as cross bombardments with ^{40}Ar on ^{150}Sm and ^{20}Ne on ^{170}Yb show that the lines marked as transitions in ^{186}Hg are associated with the mass chain $A = 186$. Particle-γ coincidence experiments verified that they do not originate from the evaporation of charged particles, so we conclude that they really are transitions in ^{186}Hg. γ-γ coincidence measurements show that they all are in cascade with each other, and their angular distributions, measured at 90°, 45°, and 0°, indicate that they have stretched $E2$ multipolarity. Table I lists the A_2 terms of their angular distributions (neglecting A_4 terms). The crucial point is the ordering of the levels. This has been determined by measuring the relative intensities of these de-excitation γ rays in three different modes: from

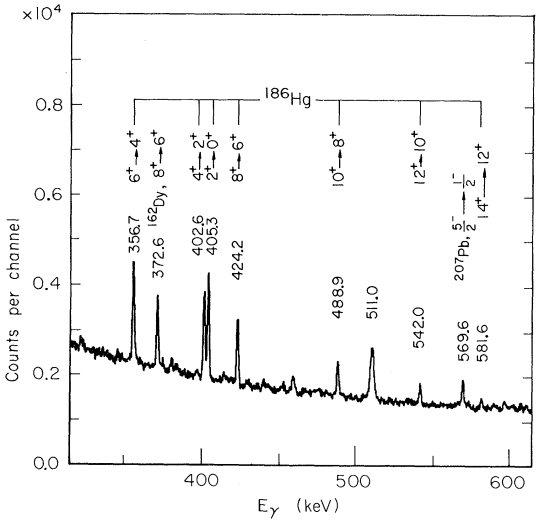

FIG. 1. Part of the γ spectrum obtained by bombarding a 1-mg/cm^2-thick lead-backed target of ^{162}Dy with ^{28}Si ions of 135 MeV. The arguments which led to the assignments of the lines are given in the text.

TABLE I. Properties of transitions in ^{186}Hg. Column a, in beam (^{162}Dy + ^{22}Si, 135 MeV); column b, decay of an isomeric state with $t_{1/2} = 100 \pm 10$ μsec; and column c, β decay of ^{186}Tl.

Transition	Energy	A_2	Relative intensities a	b	c	$\frac{\hbar^2}{2\mathcal{J}}$	Energies in ^{184}Pt	^{190}Hg
$2^+ \rightarrow 0^+$	405.3	0.17	100	100	100	67.5	162.1	416.4
$4^+ \rightarrow 2^+$	402.6	0.18	84	79	50	28.8	272.7	625.1
$6^+ \rightarrow 4^+$	356.7	0.22	76	48	30	16.2	362.5	730.2
$8^+ \rightarrow 6^+$	424.2	0.23	63	21	20	14.1	431.6	
$10^+ \rightarrow 8^+$	488.9	0.26	41			12.9	475.8	
$12^+ \rightarrow 10^+$	542.0	0.17	27			11.8		
$14^+ \rightarrow 12^+$	581.6	0.38	16			10.8		

in-beam spectra (^{162}Dy + ^{28}Si at 135 MeV), from the decay of a (100 ± 10)-μsec isomeric state in ^{186}Hg, and from β decay of ^{186}Tl (which was produced in the reaction ^{159}Tb + ^{32}S at 164.5, 178, and 191 MeV). The results are listed in Table I as columns a, b, and c, respectively. They leave little doubt about our assignment of the level ordering for the states in ^{186}Hg. (It should be noted here that the nature of the isomeric state in ^{186}Hg and its mode of decay are not clear at this time.)

The pattern of these states in ^{186}Hg is very peculiar. The 405.3-keV energy of the 2^+ state is reduced by only a few keV from the 2^+ energies of the heavier even-even Hg nuclei which scatter around 420 ± 10 keV in the Hg isotopes with $188 \leq A \leq 198$. But whereas the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transition energies increase significantly and about equally in the heavier Hg isotopes, one observes a drop to 402.6 and 356.7 keV, respectively, in the case of ^{186}Hg. For comparison, Table I shows the energies of the corresponding transitions in ^{190}Hg which might be considered as representative for the heavier Hg isotopes. Above the 4^+ level the transitions connecting the states with higher angular momentum in ^{186}Hg then increase monotonically in energy (in fact, linearly in a plot of $2\mathcal{J}/\hbar^2$ versus $\hbar^2\omega^2$). This suggests that in the ground state and the first excited 2^+ state, ^{186}Hg is not much different from the heavier Hg isotopes with a deformation of $|\beta| \approx 0.1$. At higher angular momenta it then makes a rather sudden change toward larger deformation which it keeps approximately constant up to the 14^+ state. This assumption gets support from the similarity of the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $10^+ \rightarrow 8^+$ transition energies in ^{186}Hg with those of the isotone ^{184}Pt (see Table I), which is a reasonably good rotational nucleus. An estimate of the magnitude of the deformation based on the energy of the $6^+ \rightarrow 4^+$ transition in ^{186}Hg yields $|\beta| \approx 0.25$.

This behavior of the yrast states in ^{186}Hg can be understood in terms of a potential-energy surface which has a minimum near $|\beta| \approx 0$ and a second minimum (or shoulder) at a larger deformation and higher energy. The energy of the lowest $2^+ \rightarrow 0^+$ transition (in the first well) would then be relatively high. At larger spins the centrifugal energy term, proportional to $(\hbar^2/2\mathcal{J})I(I+1)$, will concentrate the wave function at larger deformation, so that there will be a rapid change to transition energies characteristic of the more deformed well. The fact that we do not see a transition from the 4^+ state to a second 2^+ state suggests that there is no deep second minimum at $|\beta| \lesssim 0.3$. This interpretation is very consistent with recent potential-energy–surface calculations for even-even Hg isotopes.[5-7] The ground-state potential-energy surfaces show a minimum at small oblate deformation and a widening at larger prolate deformation for the heavy Hg isotopes. This widening develops into a shallow second minimum which is dropping with decreasing mass number, and it becomes the absolute minimum at $A = 182$. In ^{186}Hg the oblate minimum is only 0.5 MeV lower than the prolate one, which could explain the experimentally observed energy spacings. Negative deformation for the ground states of these light Hg isotopes is not unreasonable because oblate deformation has been measured in nearby Pt isotopes,[8] and oblate deformation for the heavy Hg isotopes is implied by the observation[9] of decoupled bands in ^{195,197,199}Hg. The potential calculations describe the nuclei only in their ground states. The calculations do not include zero-point vibrational energies, but their qualitative agreement with the experimental spectrum of ^{186}Hg makes it desirable to undertake an

investigation of the dynamics in order to make a more quantitative comparison.

The process we are describing in ^{186}Hg is reminiscent of the so-called "backbending" observed in the ground-state rotational bands of some rare-earth (and other) deformed nuclei.[10] Backbending refers to some anomalous behavior occuring in these rotational bands around $I = 14$, and one explanation[11] proposed for it is somewhat similar to the one we have suggested for the present case—specifically, it involved a generalized centrifugal stretching, with the backbending produced by irregularities in the potential energy surface. It does not seem very likely to us that the behavior in ^{186}Hg is related to the general "backbending" phenomena. The situation is quite different, in that ^{186}Hg is believed to be nearly spherical (slightly oblate) in the ground state, changing by $I = 6$ to a prolate shape with appreciable deformation. Nothing like this can be happening in the already deformed backbending nuclei. Furthermore, the character of the band in ^{186}Hg both before and after the irregular behavior differs from anything seen in backbending nuclei. Thus, although it might be tempting to try to group together all anomalies in ground-state collective bands, we feel that the behavior observed here for ^{186}Hg is probably not related to the previously known backbending process.

In conclusion, we believe that the energy spectrum has provided evidence for angular-momentum–induced change in the deformation of the ^{186}Hg yrast states. Preliminary lifetime measurements also indicate that the absolute value of the deformation increases by about a factor of 2 in going from the $2^+ \rightarrow 0^+$ to the $6^+ \rightarrow 4^+$ transition. To our knowledge, such large changes have not been observed previously. Such a picture can provide a basis for understanding the large rms radii observed by Bonn *et al.*[1] for ^{183}Hg and ^{185}Hg. A spin of $\frac{1}{2}$ has been determined for these nuclei,[1] and it seems likely that the $\frac{1}{2}[521]$ Nilsson orbit, which decreases appreciably in energy as β increases, becomes the ground state in these nuclei. The gain in energy of this orbit with increasing deformation (specialization energy) is no doubt partly responsible for the sudden onset of ground-state deformation at just this point in the odd-A Hg nuclei.

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