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New oblate band in ^{196}Hg with quenched $M1$ strength

B. Cederwall, M.-A. Deleplanque, F. Azaiez, R. M. Diamond, P. Fallon, W. Korten, I.-Y. Lee, A. O. Macchiavelli, J. R. B. Oliveira, and F. S. Stephens
Lawrence Berkeley Laboratory, Berkeley, California 94720

W. H. Kelly and D. T. Vo
Iowa State University, Ames, Iowa 50011

J. A. Becker, M. J. Brinkman, E. A. Henry, J. R. Hughes, A. Kuhnert, M. A. Stoyer, and T. F. Wang
Lawrence Livermore National Laboratory, Livermore, California 94550

J. E. Draper, C. Duyar, and E. Rubel
Physics Department, University of California, Davis, California 95616

J. deBoer
Universität München, Am Coulombwall 1, D-8046 Garching, Germany
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High-spin states in the nucleus ^{196}Hg were populated in the reaction ^{192}Os(^{9}Be,$5n$) at a beam energy of 65 MeV. A regular rotational-like $\Delta I = 1$ band has been observed up to an excitation energy of $E^* \approx 8.7$ MeV and spin $I \approx 30\hbar$. This is the second observation of a band of this character in a mercury isotope. The experimental results are compared with mean field calculations and semiclassical estimates based on the Dönau-Frauendorf formalism. The mercury bands show significantly lower $B(M1)/B(E2)$ branching ratios as compared with similar bands in light lead nuclei. This difference may be more readily explained by a difference in single-particle structure rather than by large differences in deformation between the lead and mercury configurations.

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Recently, discoveries of intense dipole bands persisting up to high spins have been made in the mass 190 region. Such "oblate" structures have been observed in $^{194,196-201}$Pb, Refs. [1–10] and recently in ^{193}Hg [11]. A number of questions are associated with the structure of these bands, in particular, with reference to their regular rotational-like or irregular patterns and with the competition between $M1$ and crossover $E2$ transitions. In the lead nuclei both regular and irregular cascades have been observed, but so far the irregular bands appear only in the lightest isotopes and the regular bands are more favored in the heavier isotopes. For only a few cases, linking transitions have been established between a dipole band and the known low-lying structures. The dipole bands observed in the majority of the lead nuclei exhibit large $B(M1)/B(E2)$ branching ratios of the order of $20\mu_N^2/e^2\,\mathrm{b}^2$ [11]. Moreover, a lifetime measurement for ^{198}Pb has determined large $B(M1)$ strengths of 0.5 to 4 Weisskopf units and modest $B(E2)$ strengths of 10 to 15 Weisskopf units [7]. Because of the large experimental $B(M1)$ values, the intrinsic configurations of these bands must involve high-j orbitals which have large magnetic moment components perpendicular to the total angular momentum axis. The properties of the bands suggest quasiparticle configurations built on high-K $\pi h_{9/2}^2$, $\pi i_{13/2}^2$, or $\pi h_{9/2} i_{13/2}$ structures. The bands in the lead nuclei have generally been interpreted as weakly collective, based on deformation aligned $h_{9/2} i_{13/2}$ or $h_{9/2}^2$ proton structures coupled to rotation-aligned $i_{13/2}$ neutron holes. The measured $B(M1)/B(E2)$ ratios for the recently discovered $\Delta I = 1$ band in ^{193}Hg [11] are substantially lower than for the lead isotopes leading to the question of whether this implies a different intrinsic structure for such bands below the spherical $Z = 82$ shell gap, or if deformation effects may play an important role. The possibilities of either a reduced $B(M1)$ strength due to aligned $h_{11/2}$ proton holes or increased $B(E2)$ values resulting from a larger β_2 deformation are suggested in Ref. [11]. We report here a new $\Delta I = 1$ band observed in ^{196}Hg, which, similarly to the previously observed band in ^{193}Hg, exhibits significantly smaller $B(M1)/B(E2)$ ratios compared with the lead isotopes. We conclude that this difference may be accounted for by an intrinsic configuration built on two deformation-aligned $h_{9/2}$ protons coupled to rotation-aligned $h_{11/2}$ proton and $i_{13/2}$ neutron hole states rather than by major differences in deformation.

The experiment was performed at the Lawrence Berkeley Laboratory 88-Inch Cyclotron facility. A 65-MeV beam of ^{9}Be was used to bombard a target consisting of three thin self-supporting ^{192}Os foils of thickness 0.31 mg/cm^2, 0.32 mg/cm^2, and 0.36 mg/cm^2. The γ rays emitted in the reactions were detected in the HERA detector array, consisting of 20 Compton-suppressed Ge detectors and a 4π inner calorimeter of 40 BGO detectors. All Compton-suppressed threefold and higher-fold events were recorded and the twofold events were recorded when γ rays were detected in at least four BGO elements in coincidence with two Ge detectors. With these restrictions a total of approximately 75×10^6 events were stored on magnetic tape for subsequent off-line analysis.

A new band structure is observed in ^{196}Hg showing the characteristics of a $\Delta I = 1$ rotational band with a moderate, almost spin-independent, signature splitting. The band is strongly populated with an intensity of approximately 19% of the $2^+ \rightarrow 0^+$ transition in this nucleus. The quality of the data is illustrated by the coincidence-gated spectra shown in Fig. 1, with the partial level scheme for the band as an inset. The level scheme is based on the coincidence and energy relations of the γ-ray transitions which are consistent with stretched $\Delta I = 1$ and crossover $\Delta I = 2$ transitions. The decay out of the band proceeds mainly into the $I = 19^-$ and $I = 21^-$ states of the "ABCE" structure (see Ref. [12] for details of the previously known level scheme) but it is fragmented into several decay paths. We have therefore not been able to establish firm linking transitions to the previously known states, but we have tentatively assigned a 1405-keV line as a linking transition from the lowest observed level in the band to the previously mentioned $I = 21^-$ state (not shown in the level scheme). Thus we have assigned an excitation energy of $E^* \geq 6.4$ MeV and a tentative lowest level spin of $I \geq 22\hbar$ to this new band structure. The 1405-keV transition only carries about 20% of the total band intensity, and although we have found other transitions depopulating the band we have not been able to place them. However, the coincidence relations show that the depopulation of the band starts above the assigned bandhead, accounting for the missing intensity below spin $I = (24\hbar)$. Based on a theoretical configuration assignment, the band is tentatively assigned positive parity (see below).

Information on the multipolarity was obtained for a few transitions from directional correlation orientation (DCO) ratios. In an E_γ-E_γ correlation matrix, γ rays detected in the Ge detectors at angles 37°, 152°, and 154° relative to the beam were sorted versus those detected in the 79° and 103° angle detectors. By gating on known quadrupole transitions the DCO ratios $R = I_\gamma(\sim 90°, \sim 30°)/I_\gamma(\sim 30°, \sim 90°)$ could be obtained. Here the $I_\gamma(\sim 30°, \sim 90°)$ is the intensity in the 79° and 103° detectors when gating on the 37°, 152°, and 154° detectors, etc. A ratio, R, close to 1 is expected for stretched quadrupole transitions whereas a pure stretched dipole transition is expected to have R close to 0.5. Due to severe contamination in the spectra and relatively low statistics the DCO ratios could only be obtained accurately for three dipole transitions (157, 178,

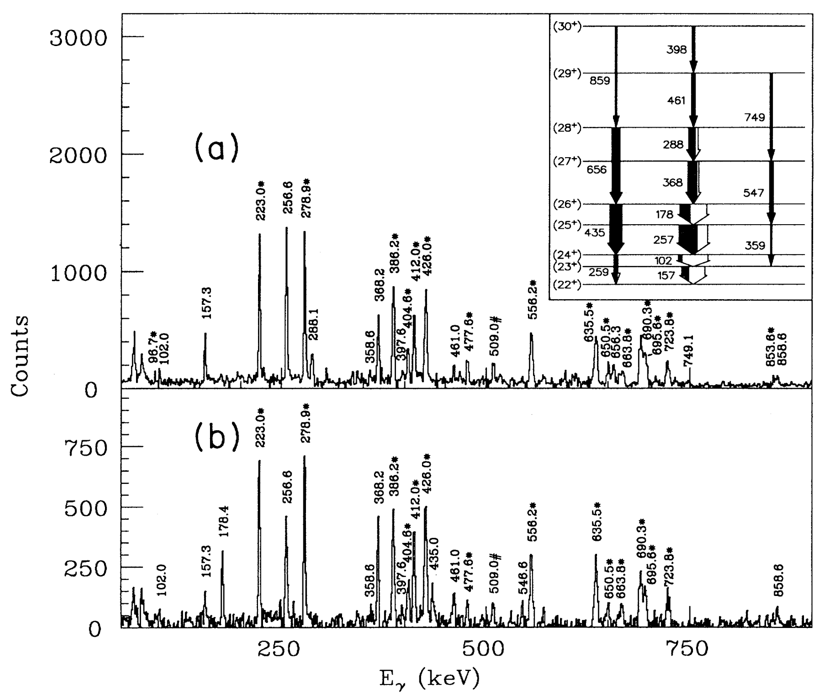

FIG. 1. Gamma-ray spectra in coincidence with the 178.4-keV (a) and the 288.1-keV (b) transitions belonging to the $\Delta I = 1$ band in ^{196}Hg. The peaks marked with a "*" represent transitions from the decay within the previously established level scheme [12] and a "#" marks a transition connected to the decay out of the band into the previously known states. Peaks at 1007.0 keV and 1405.0 keV are present outside the scale in the figure and are tentatively assigned to the decay out of the band. Of those, the 1405-keV transition is tentatively assigned as a direct linking transition between the bandhead and the previously observed 21^- state [12]. The 509.0-keV transition was also observed in Ref. [12]. The two lowest energy peaks are due to the Hg x rays. The partial level scheme obtained in the present work is shown in the upper right inset. The γ-ray transitions are labeled by their energy in keV. The widths of the arrows represent the intensities of the transitions (the white parts are corrections due to the expected internal conversion). The transitions thought to depopulate the band are not shown and account for the missing intensity in the band below $I = (24)$.

and 257 keV) and one crossover quadrupole transition (547 keV). The DCO ratios for the dipole transitions were all within $R = 0.50 \pm 0.15$ and for the 547-keV crossover transition the DCO ratio was found to be 1.16 ± 0.14. As a check, the DCO ratios for the stronger $E2$ transitions in the previously known level scheme were measured and found to be close to 1. Thus, the DCO ratios confirm the assigned level scheme of stretched dipole and crossover quadrupole transitions. In Fig. 2 the Routhians of the two signatures of the new $\Delta I = 1$ band are plotted in comparison with those of the previously known [12] "AB" and "ABCE" bands. We have chosen a rigid-rotor Harris reference with $J_0 = 45\hbar^2$/MeV which roughly reproduces the rotational pattern of the "AB" configuration. The $\Delta I = 1$ band is most favored by rotation and does indeed cross the low-lying yrast structures at $\hbar\omega \approx 0.30$ MeV. The signature splitting is moderate, around 80–90 keV. It is interesting to note how the signature splitting of the band seems to be almost independent of the rotational frequency, not increasing with frequency as expected from the normal Coriolis mixing. The high spin of the apparent bandhead and the strongly downsloping character of the band relative to the AB configuration in the Routhian plot also suggest that aligned high-j structures are involved in the intrinsic configuration.

We have extracted $B(M1)/B(E2)$ ratios for some of the states in the $\Delta I = 1$ band, assuming the $E2/M1$ mixing ratios for the $\Delta I = 1$ transitions are negligible. The $B(M1)/B(E2)$ ratios are shown in Fig. 3 together with theoretical estimates based on the Dönau-Frauendorf formalism [13] (solid lines). Similarly to what was found for the $\Delta I = 1$ band in ^{193}Hg [11] the observed values are significantly smaller than the ones measured in the lead isotopes. We therefore investigated whether this could be understood as a difference in the proton structure between the Pb and Hg nuclei. For the theoretical estimates we have chosen configurations based on deformation-aligned high-Ω $i_{13/2}$ and $h_{9/2}$ protons coupled to rotation-aligned $i_{13/2}$ neutron holes and/or $h_{11/2}$ proton holes, which approach the Fermi surface at

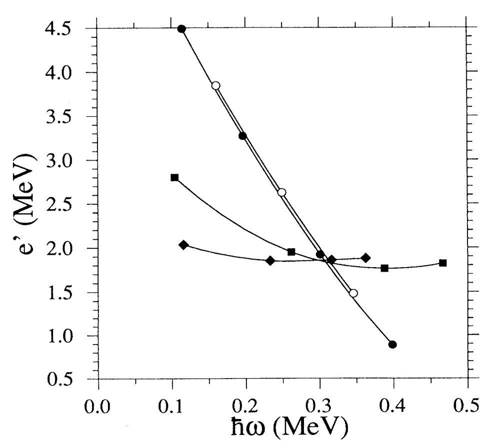

FIG. 2. Experimental Routhians for the $\Delta I = 1$ band (circles) and the "AB" (diamonds) and "ABCE" (squares) bands in ^{196}Hg. A rigid-rotor reference with $J_0 = 45\hbar^2$/MeV has been subtracted.

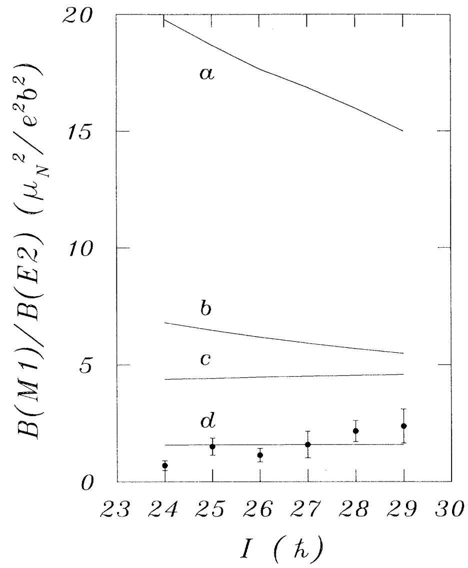

FIG. 3. Experimental $B(M1; I \to I-1)/B(E2; I \to I-2)$ values for the $\Delta I = 1$ band in ^{196}Hg. The solid lines are model predictions based on the semiclassical Dönau-Frauendorf formalism (see text) for the $\pi h_{9/2} i_{13/2} \otimes \nu(i_{13/2})^{-2}$ configuration (a), the $\pi h_{9/2}^2 \otimes \nu(i_{13/2})^{-2}$ configuration (b), the $\pi h_{9/2} i_{13/2} (h_{11/2})^{-2} \otimes \nu(i_{13/2})^{-2}$ configuration (c), and the $\pi h_{9/2}^2 (h_{11/2})^{-2} \otimes \nu(i_{13/2})^{-2}$ configuration (d).

moderate oblate deformation. A quadrupole moment, $Q = 3.6\ e$b, corresponding to the deformation parameters of the most favored oblate high-K minimum in the total Routhian surface calculations (see below) was used in the calculation shown in Fig. 3. The gyromagnetic factors were taken as $0.7 g_{\text{Schmidt}}$ of the corresponding spherical state for the $i_{13/2}$ proton and from empirical values for nuclei in this mass region [14] for the other orbitals. For the rotational gyromagnetic factor, g_R, the value $Z/A = 0.408$ was used. It was also assumed that the $h_{9/2}$ and $i_{13/2}$ protons are strongly coupled to the core and the proton $h_{11/2}$ and neutron $i_{13/2}$ holes are rotation aligned. In the figure calculated values based on the $\pi h_{9/2} i_{13/2} \otimes \nu i_{13/2}^{-2}$ configuration are labeled by a and the $\pi h_{9/2}^2 \otimes \nu i_{13/2}^{-2}$ configuration is labeled by b. Calculated values obtained by coupling these configurations to aligned $h_{11/2}^{-2}$ proton hole states are labeled by c and d, respectively. The calculated values for the $\pi h_{9/2}^2 h_{11/2}^{-2} \otimes \nu i_{13/2}^{-2}$ configuration (labeled d) are in the best agreement with the experimental values for the ^{196}Hg $\Delta I = 1$ band. Furthermore, the estimate for the $\pi h_{9/2} i_{13/2} \otimes \nu i_{13/2}^{-2}$ configuration follows well the larger $B(M1)/B(E2)$ ratios measured in the lead nuclei. The results suggest that there is indeed a difference in the proton structure between the Pb and Hg nuclei involving a different high-K proton configuration ($h_{9/2}^2$) and aligned $h_{11/2}$ proton orbitals.

In order to investigate the possibility of significant differences in deformation between the observed $\Delta I = 1$ structures in the lead and mercury isotopes we have performed total Routhian surface (TRS) calculations for ^{196}Hg and a few Pb nuclei. The TRS calculations are based [15,16] on a deformed Woods-Saxon potential and the Strutinsky shell-correction formalism with a monopole-pairing interaction. In the calculations the total Routhian of the nucleus is minimized with respect to the deformation parameters β_2, β_4, and γ at different rotational frequencies and for different configurations. Following the description in Ref. [17] the minima in the lowest TRS's of ^{196}Hg were assigned to the relevant quasiparticle configurations. According to the TRS calculations, the ground state of ^{196}Hg is predicted to be weakly deformed oblate with deformation parameters $(\beta_2, \gamma, \beta_4) = (0.12, -63°, -0.031)$. The first quasiparticle alignments ($i_{13/2}$ quasineutrons) are predicted to occur at $\hbar\omega \approx 0.15$ MeV followed by alignments of $h_{11/2}$ quasiprotons. The aligned $\nu i_{13/2}^{-2}$ and $\pi h_{11/2}^{-2}$ configurations tend to drive the nuclear shape towards slightly increased β_2 values and increased negative γ values leading to triaxial shapes at high rotational frequencies but this will have only a limited effect on the quadrupole moment. The high-K $\pi h_{9/2} i_{13/2}$ configuration coupled to the aligned $\pi h_{11/2}^{-2}$ and $\nu i_{13/2}^{-2}$ hole configurations is predicted to result in a minimum at $(\beta_2, \gamma, \beta_4) = (0.135, -75°, -0.028)$. This configuration, but without aligned $h_{11/2}$ quasiprotons, has been predicted to be favored in the neighboring lead isotopes, e.g., ^{197,198}Pb [5,6], producing a collective oblate minimum with a deformation of $\beta_2 \approx 0.11$–0.12. However, in the present calculations for ^{196}Hg a minimum based on the $\pi h_{9/2}^2$ high-K configuration coupled to the previously mentioned aligned $\pi h_{11/2}^{-2}$ and $\nu i_{13/2}^{-2}$ hole configurations is the most favored. This near-collective oblate minimum has deformation parameters $(\beta_2, \gamma, \beta_4) = (0.139, -72°, -0.035)$. As mentioned above the slightly triaxial shape is induced by the rotation-aligned quasiparticles. This result is consistent with the calculated $B(M1)/B(E2)$ values discussed above. It should be noted that there is a considerable inherent uncertainty in the TRS calculations when many quasiparticles are involved and the calculated detailed deformations should be taken with care. However, it is clear that within the framework of the present TRS calculations only small differences in deformation are expected between the favored near-collective oblate configurations in the Pb and Hg nuclei. These small differences in deformation could explain only a very small fraction of the differences in the observed $B(M1)/B(E2)$ ratios. Based on our TRS results and the semiclassical calculations of the $B(M1)/B(E2)$ ratios we must therefore conclude that the most probable cause for the smaller $B(M1)/B(E2)$ ratios in the Hg nuclei is a structural difference due to a coupling of aligned $h_{11/2}$ proton hole states to a high-K $h_{9/2}^2$ proton configuration.

Experimentally, the $\Delta I = 1$ band is found to be very favored by the rotation, supporting the theoretical interpretation of a substantial component of rotation-aligned structures in the configuration. Also the tentative spin of the lowest observed state ($22\hbar$) is in agreement with the assigned configuration, $\pi h_{9/2}^2 h_{11/2}^{-2} \otimes \nu i_{13/2}^{-2}$.

In summary, we have observed a high-spin $\Delta I = 1$ band in ^{196}Hg. TRS calculations predict a favored minimum built from high-Ω $h_{9/2}^2$ protons and rotation-aligned proton $h_{11/2}^{-2}$ and neutron $i_{13/2}^{-2}$ hole configurations at near-collective oblate shape. Theoretical estimates of the $B(M1)/B(E2)$ ratios assuming the above configuration and deformation parameters reproduce well the experimental $B(M1)/B(E2)$ values as well as those observed for the lead nuclei, with the aligned $\pi h_{11/2}^{-2}$ configuration absent and the high-K component of the configuration exchanged to $\pi h_{9/2} i_{13/2}$ for the higher-Z Pb nuclei. This means that the lower $B(M1)/B(E2)$ ratios in ^{193}Hg and ^{196}Hg may well be explained by a different single-particle structure and that deformation effects, for which no strong evidence is found in the TRS calculations, may not be important.

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