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# Collective band in $^{193}$Hg with $E_x \geq 5.7$ MeV

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The nucleus $^{193}$Hg was populated in the reaction $^{176}$Yb($^{22}$Ne,5$n$) at the incident energy $E(^{22}\mathrm{Ne}) = 110$ MeV. Reaction $\gamma$ rays were detected with a Ge-detector array. A new "collective" structure was observed at $E_x > 5.7$ MeV. The states of the structure extend from $I \geq 47/2$ to $I+10$, and they decay with competing dipole and quadrupole transitions. The structure is populated very strongly in this reaction: the lowest member is produced with $\sim 20\%$ of the $^{193}$Hg cross section.

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A number of recent reports have been made of rotational bands in the neutron-deficient Pb nuclei, including $^{192}$Pb [1], $^{194}$Pb [2,3], $^{196}$Pb [4], $^{197}$Pb [5,6], $^{198}$Pb [7,8], $^{199-200}$Pb [9], and $^{201}$Pb [10]. These band members are connected by $L = 1$ transitions, with crossover $L = 2$ transitions observed at the higher $\gamma$-ray energies. These bands include regular and irregular patterns of $\gamma$-ray energies. Conversion coefficients determined from intensity balance suggest that the $L = 1$ transitions are $M1$, and with the assumptions that the quadrupole transitions are $E2$ and the multipole mixing ratio $\delta = 0$, the ratio $B(M1)/B(E2)$ in $\mu^2/(e\ \mathrm{b})^2$ varies from $\sim 20$ ($^{197}$Pb) to 40 ($^{199}$Pb). Lifetimes have been measured for the regular bands in $^{198}$Pb by Wang *et al.* [7], who report $B(M1) \sim 0.5-4$ W.u. and $B(E2)$ (with rather large errors) $\sim 10-20$ W.u. Estimates of the bandhead excitations are 4 – 6 MeV; they are not known precisely, since the transitions connecting these bands with known yrast levels have not, in general, been observed. The bands have generally been interpreted as collectively oblate, involving deformation-aligned high-$j$ proton configurations such as $\pi(s_{1/2}^{-2}h_{9/2}i_{13/2})$, and rotation-aligned $i_{13/2}^{-n}$ neutrons. We report here, for the first time, evidence for a similar configuration in a Hg isotope, $^{193}$Hg.

The data were obtained in a study of $^{193}$Hg at the 88-Inch Cyclotron Facility at Lawrence Berkeley Laboratory. The nucleus $^{193}$Hg was produced in the reaction $^{176}$Yb($^{22}$Ne,5$n$) at $E(^{22}\mathrm{Ne}) = 110$ MeV. The target was a stack of three foils of enriched $^{176}$Yb, each foil $\sim 0.5$ mg/cm$^2$ thick. Reaction $\gamma$ rays were detected with the large Ge-detector array, HERA. The array included 20 Compton-suppressed detectors, but it was without BGO central ball elements at the time of this experiment. The beam was stopped in a Faraday cup $\sim 2$ m downstream from the target. Recoiling $^{193}$Hg escape the sensitive detection volume in a few ns. Therefore, delayed $\gamma$ rays produced in the decay of any isomeric states with lifetimes much longer than a few ns would not be observed in this arrangement. Approximately $200 \times 10^6$ coincident events were obtained in this experiment. Of these, $\sim 20\%$ were threefold- or higher-fold events.

The list mode data recorded at run time were sorted subsequently into two-dimensional (2D) matrices for analysis of coincidence relationships and directional correlations. Analysis of the symmetrized $E_\gamma$ vs $E_\gamma$ matrix established a new structure in $^{193}$Hg, illustrated in the partial level scheme presented in Fig. 1. It consists of 12 direct transitions, with competing crossover transitions observed in nearly all cases. Analysis of the directional correlation matrix established that the direct transitions with $E_\gamma = 160$, 197, 235, 284, 368, 370, and 397 keV and the crossover transitions with $E_\gamma = 520$, 727, 765, 772, and 962 keV are consistent with stretched $L = 1$ and $L = 2$ transitions, respectively. Intensity balance arguments, in general, favored multipolarity $M1$ for the $L = 1$ transitions, since low-energy $M1$ transitions are highly converted in this nucleus. A detailed coincidence intensity balance required the 160- and 235-keV $\gamma$ rays to have $ML = M1$. The possible 572-keV crossover transition ($E_\gamma = [375 + 197]$ keV; $I + 5 \rightarrow I + 3$) in the new structure is obscured by a known 573-keV transition (band $ABE$) identified in the study of $^{193}$Hg by Hübel *et al.* [11], populated strongly in the present reaction, and in the decay of the structure. Intensities are not given for the 497.8- and 517-keV $\gamma$ rays, because they are weak and contaminated in the spectrum. The 357-keV transition is a doublet, $(I + 6 \rightarrow I + 4)$ and $(I + 7 \rightarrow I + 6)$. The multipolarity of the 449.3 keV transition could not be obtained from these data. The $\gamma$-ray energies of the new structure are uncertain to $\sim 0.2$ keV, relative to the energies quoted by Hübel *et al.* and the intensities are

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uncertain to 10%.

The decay of the band occurs primarily from the level labeled $I$ (with the exception of a possible weak decay from level $I+1$) probably by means of a large number of weak parallel cascades, none of which has been identified completely. This suggests that the bandhead lies in a region of high level density and above the yrast line. These cascades populate many of the quasiparticle bands at lower $E_x$ identified in Ref. [11], which are illustrated in Fig. 2: the branching (*in percent*) to the bands labeled $A$, $ABC$, $ABCDF$, and $ABCDE$ in Fig. 2 is given at the bottom of Fig. 1. Levels with a wide range of spin are populated in the decay, including known levels with spins as low as $I = 33/2$ ($E_x = 2555$ keV), as high as $I = 47/2$ ($E_x = 4907.0$ and 5406.8 keV), and also levels with $I \geq 49/2$.

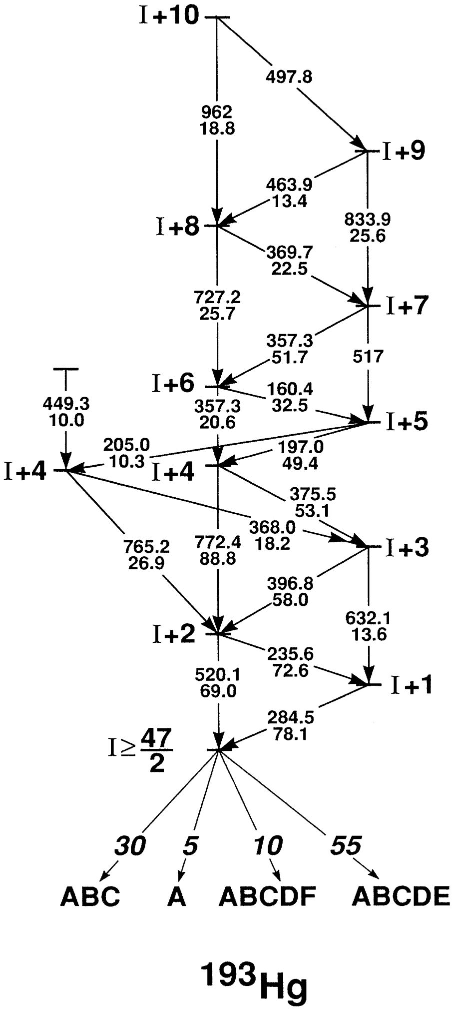

FIG. 1. Partial level scheme for the irregular band in $^{193}$Hg. The branching of this band (in %) to the quasiparticle bands illustrated in Fig. 2 is given at the bottom of the figure. The $\gamma$ rays are labeled with transition energy and intensity. The intensity is given relative to the population of the yrast $13/2^+$ level, taken as 1000.

Direct transitions connecting this new structure to the quasiparticle bands of Fig. 2 were not observed, and therefore $E_x$ and $I$ are not known precisely. Some $\gamma$ rays of the parallel cascades depopulating the new structure gain enough intensity for identification when they feed the known levels, e.g., those with $E_\gamma =$ 105, 123, 156, 558, 785, 1115, 1153, 1241, 1169, 1363, and 1511 keV. Analysis of the data is consistent with $E_x \geq$ 5.7 MeV and $I \geq$ 47/2 for the bottom of the band. There is a weak branch to the band $ABCEF$. It is difficult to say whether there is a doublet of levels near $E_x = 5302$ keV, although the 5407 keV doublet (5406.8 − 5407.7-keV) does seem to be real. The level at $E_x$ = 5407 keV branches in two paths. The levels suggested at, e.g., $E_x$ = 3670 and 4277 keV are part of the unresolved decay of the new band. The partial level scheme illustrated in Fig. 2 has been extended by us somewhat beyond the earlier work. In addition, the level at $E_x$ = 5406.8 keV is more likely $I$ = 47/2 than 49/2 since the 873.5- and 589.1-keV transitions appear to be dipole. The new structure is populated strongly in the reaction, primarily above the states labeled $I+4$. The summed intensity of the 520.1- and 284.5-keV $\gamma$ rays, corrected for internal conversion, is $\sim$ 20% relative to the summed population of the yrast $13/2^+$ level.

The new structure was also observed in data collected at $E(^{22}\mathrm{Ne})=$ 122 MeV, and in data collected in $^{48}$Ca bombardments of $^{150}$Nd at $E(^{48}\mathrm{Ca})$ = 205 and 210 MeV. Isotopic assignment of the new structure is based primarily on the observation of the coincidence relationships discussed above; however, the cross bombardment results (including results of Ref. [11]) strengthen the assignment. Some $\gamma$ rays of the new structure, e.g., the transitions with $E_\gamma$ = 160, 197, 284, 235, and 772 keV, were previously assigned to $^{193}$Hg in Ref. [11]. However, they were not placed in the decay scheme, presumably because the intensity of these transitions in the $^{13}$C bombardment was weak, and the decay of the structure is fragmented.

The cascade illustrated in Fig. 1 suggests signature partners of the same intrinsic state with some signature splitting. Both partners undergo band crossing with an alignment gain $\sim 4\hbar$ (most likely $i_{13/2}$ neutrons). The small dynamic moment of inertia ($\mathcal{J}^{(2)} \sim 16\hbar^2/\mathrm{MeV}$) is typical of similar bands is this region that are oblate. Weak interaction between crossing bands is typical of this mass region; the closeness of the two $I+4$ levels provides an upper limit of 4 keV for the interaction strength of the band crossing. We assume all competing $L = 1$ and $L = 2$ transitions of the new structure are $M1$ and $E2$, with multipole mixing $\delta = 0$, and compute $B(M1)/B(E2)$. This ratio is illustrated in Fig. 3 for the new structure. Ratios from two $I+4$ states are included in the figure; the ratio calculated from the decay of the $I+4$ state populated by the 449.3-keV $\gamma$ ray is distinguished by an open circle. Individual values of the ratio are similar, with median value $B(M1)/B(E2) = 2.14$. These data suggest that the new band in $^{193}$Hg is collective. Values of $B(M1)/B(E2)$ for bands in Pb isotopes listed previously are included in Fig. 3 for subsequent discussion.

The $M1$ transitions suggest that high $K$ bands involv-

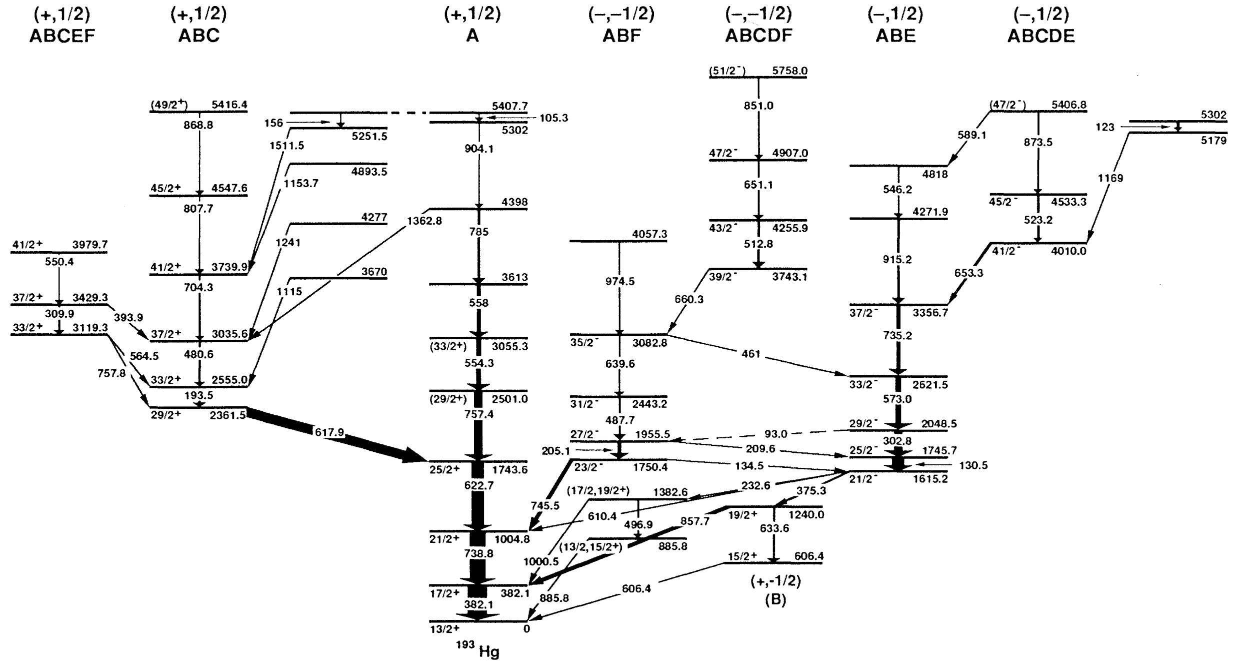

FIG. 2. A partial level scheme for $^{193}$Hg illustrating the levels identified in the decay of the new structure. Most of these levels are known from Ref. [11].

ing proton excitations are important in the structure, since $g_K$ is large and positive for proton orbitals and the $M1$ transition rate increases with $K^2$:

$$B(M1) = (3/4\pi)K^2(g_K - g_R)^2\langle IK10|I-1,K\rangle^2, \quad (1)$$

where $g_R$ is the collective $g$ factor, $g_R \approx Z/A$. High-$K$ proton orbitals are present across the spherical $Z = 82$ gap for oblate deformation, based on, e.g., $h_{9/2}, i_{13/2}$, and $f_{7/2}$ orbitals. Experimental and theoretical studies in $^{194,196}$Pb of $\pi$(2p-2h) (two-particle–two-hole) excitations have been discussed in Refs. [12–15]. They find $I^\pi = 11^-$ states consistent with oblate deformation and the configuration $\pi(s_{1/2}^{-2}i_{13/2}h_{9/2})$. The strong $M1$ transitions of the new band are consistent with oblate deformation, and deformation-aligned proton orbitals. The high excitation of the band is consistent with promotion of protons across the shell gap and with small deformation. Many quasineutron bands in $^{193}$Hg are populated in the decay of the new structure, none with any great intensity, which suggests a structure for the new band quite different from the low-lying quasineutron bands. The bandhead spin ($I \geq 47/2\hbar$) suggests that neutron excitations are also involved, presumably low-$K$ $i_{13/2}$ neutron holes which align rapidly with the rotation axis. The bandhead spin is easily made of proton excitations such as $\pi(h_{11/2}^{-2}i_{13/2}h_{9/2})$ or $\pi(d_{3/2}^{-2}i_{13/2}h_{9/2})$ configurations, and neutron excitations such as $\nu(i_{13/2})^{-3}$. Alignment of valence protons and neutrons along different symmetry axes suggests that a tilted axis cranking analysis [16] might be appropriate.

Total Routhian surface (TRS) calculations done following the procedure described by Wyss *et al.* [17] produce an oblate-collective minimum around cranking frequencies $\hbar\omega_x = 0.15 - 0.30$ MeV, for the 1-, 3-, and 5-quasineutron configurations populated in the decay of the new band. The TRS surfaces for the neutron configuration $\nu\frac{1}{2}[660]$ (A) is illustrated in Fig. 4(a). Adding quasiproton excitations to the calculation shifts the minimum from the oblate axis towards the prolate noncollective axis. This is illustrated in Fig. 4(b), the TRS for the configuration $\nu\frac{1}{2}[660]$ (A),

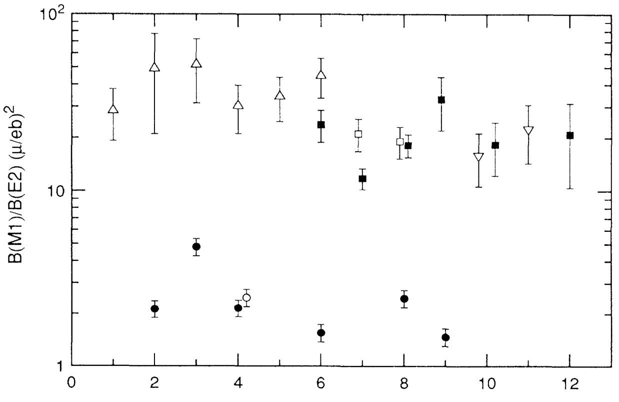

FIG. 3. The ratio $B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$ for the $^{193}$Hg cascade illustrated in Fig. 1 (•, ∘). This quantity is also presented for certain bands in $^{197}$Pb (■, □), $^{198}$Pb (▽), and $^{199}$Pb (△). The abcissa is the increase in $I$ measured from the bandhead spin. Certain abcissa values have been displaced for presentation clarity. Details and references are given in the text.

and $\pi(\frac{1}{2}^-[550]^{-2}\,\frac{9}{2}^-[505]\,\frac{13}{2}^+[606])$ (EFKO). Addition of four quasiprotons still produces a minimum, but it is calculated to be triaxial. There are two other points: *(i)* the spins achieved are in the range of the proposed bandhead spin $I \geq 47/2$, and *(ii)* expanding the neutron orbitals to $ABC$ results in a TRS similar to Fig. 4(b).

The structure proposed for this band involves orbitals similar to those suggested for the bands recently reported in neutron-deficient Pb isotopes and interpreted as oblate high-$K$ bands [1–10]. These bandheads have high excitation, $E_x \sim$ 4–6 MeV, bandhead spin $I \sim 20$, and $M1$ and $E2$ transitions compete in the cascade. However, the transition rates are not characteristic of strongly collective bands, at least for $^{198}$Pb. Wang *et al.* report (with large errors) that $B(E2) \sim 12$ W.u. in $^{198}$Pb. The ratio $B(M1)/B(E2)$ is illustrated in Fig. 3 for $^{193}$Hg and also for the bands identified as oblate in $^{197-200}$Pb. $B(M1)/B(E2)$ values are not shown for $^{194}$Pb, because recent data still under analysis show that the decay scheme for the irregular band is not yet established [18]. $B(M1)/B(E2)$ for $^{193}$Hg is considerably lower than that for $^{197-200}$Pb. Assuming constant $M1$ strength, the $B(M1)/B(E2)$ values suggest collectivity in $^{193}$Hg $\sim 10\times$ that of the regular structures in $^{198}$Pb. It is likely, however, that the smaller value of $B(M1)/B(E2)$ in $^{193}$Hg results from both a decrease in $B(M1)$ and an increase in $B(E2)$: low-$K$ $\pi h_{11/2}$ hole states align quickly, and they will decrease $B(M1)$. Increasing collectivity with increasing distance in $Z, N$ from the doubly closed shell nucleus $^{208}$Pb is, of course, expected.

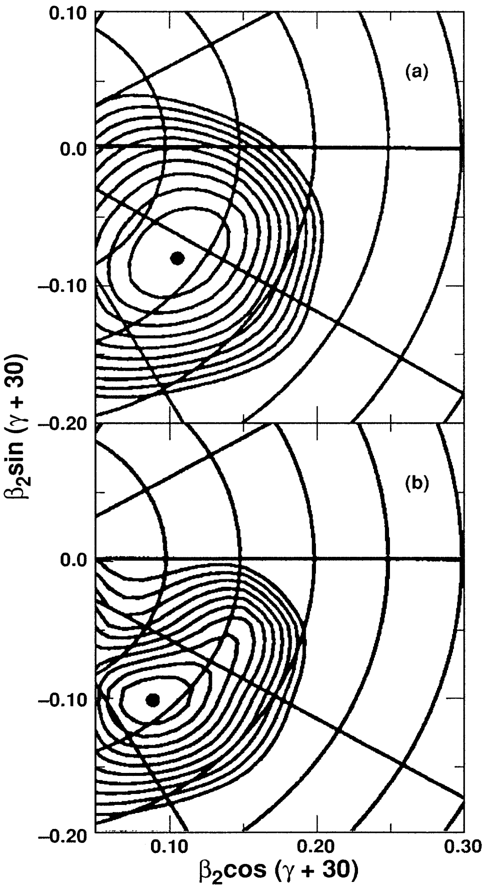

FIG. 4. Routhian surfaces (energy surfaces in the rotating frame of reference at constant rotational frequency) for (a) the neutron A configuration $\nu\frac{1}{2}[660]$ at $\hbar\omega_x$=0.28 MeV, $I_x$=18.9$\hbar$, $\beta_2$=0.135, and (b) the neutron A configuration and the proton EFKO configuration $\pi(\frac{1}{2}^-[550]^{-2}\,\frac{9}{2}^-[505]\,\frac{13}{2}^+[606])$, at $\hbar\omega_x = 0.28$ MeV, $I_x = 31.9\hbar$, $\beta_2 = 0.138$.

Ye *et al.* [19,20] have reported a structure in $^{191}$Hg, which is populated at the 15% level in the $^{160}$Gd($^{36}$S,5$n$) reaction at $E(^{36}\mathrm{S}) = 169$ MeV. The bandhead has $E_x = 4587$ keV, $I^\pi = 41/2^-$. The energy spectrum of the band is irregular, and the band members decay with $M1$ and $E2$ transitions of comparable branching ratios. The decay of the structure occurs in four parallel branches, only to $\pi = -$ states. A prolate noncollective interpretation has been offered, together with a number of possible configurations, e.g., $(\pi h_{11/2})^{-2}_{10}\nu[(i_{13/2})^{-4}_{10}(p_{3/2})_{1/2}]_{21/2}$ (in the notation of Refs. [19,20]). This band shares the strong population with the $^{193}$Hg band, and $M1$ and $E2$ decays compete favorably in both bands. However, there are a number of differences. The $^{193}$Hg bandhead has more than 1 MeV greater excitation, and spin ($> 3\hbar$). The $^{193}$Hg band has a regular energy spectrum (with a backbend), and finally both positive and negative parity states with a wide variety of angular momenta are populated in the decay of the $^{193}$Hg band. The interpretations of the $^{193}$Hg band presented here and of the $^{191}$Hg level structure of Ref. [19] both highlight the shape driving effects of high-$j$ protons. It is likely that the level structures in both nuclei have, in fact, a common origin. It is possible that with decreasing neutron number the minimum in the total energy surface moves farther and farther away from the oblate-collective axis towards the prolate noncollective one.

The intense population of these new bands ($\sim$ 20% in this case) in fusion-evaporation reactions seems to be a general feature in this mass region. $M1$ transitions compete favorably with $E2$ transitions within these bands. Assuming that the lifetimes measured in the $^{198}$Pb bands are typical, the $M1$ transitions are very strong compared with global averages. Strong $M1$ transitions often occur at 2p-2h excitations associated with the breakup of closed (sub)shells [21].

The intensity of population of these $M1$ bands has important implications, especially for nuclei near closed shells. It reminds us that the quasicontinuum yield of $\gamma$ radiation contains significant $M1$ transition strength [22–24], and that the detailed Monte Carlo calculations that model the $\gamma$-ray spectrum of the fusion evaporation reaction need to include $M1$ radiation to match the measured energy spectrum and angular distribution at low $E_\gamma$. The transition matrix element connecting states of the yrast line may be an $M1$ matrix element, and not $E2$, in certain regions of $I$ and possibly for a significant excitation.

In conclusion, a new band has been found in $^{193}$Hg with characteristics of a collective structure. The band consists of $L = 1$ and $L = 2$ transitions with roughly equal intensities. It is strongly populated in the heavy-ion fusion evaporation reaction, contributing some 20% to the reaction channel at $E(^{22}\text{Ne}) = 110$ MeV. The excitation, bandhead spin, $\mathcal{J}^{(2)}$, $\gamma$-ray cascade, and decay of this band suggest that proton excitations across a shell gap are involved, along with aligned $i_{13/2}$ neutrons. $B(M1)/B(E2)$ values suggest the presence of rotation-aligned $h_{11/2}$ protons in the configuration. There have been recent reports of $L = 1$ collective oblate bands at high excitation in the somewhat neutron-deficient Pb isotopes, and the orbitals that contribute to the structure of these bands may well be similar to those in this new structure in $^{193}$Hg.

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