Crossing of Near-Spherical and Deformed Bands in ^{186,188}Hg and New Isotopes ^{186,188}Tl†

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New isotopes ^{186,188}Tl ($T_{1/2}{}^{186} = 4.5^{+1.0}_{-1.5}$ and 28 ± 2 sec and $T_{1/2}{}^{188} = 71 \pm 1$ sec, respectively) have been identified. Conversion-electron, γ, γ-γ, and e-γ studies helped establish in ^{186,188}Hg two bands, one built on a slightly deformed ground state and one on a more strongly deformed shape with 0^+ band heads at 522 and 824.5 keV, respectively. Their crossing explains the anomalous behavior of $\mathcal{I}$ in the yrast cascades. States above and below the crossing in both bands support the existence of a well-defined second minimum in ^{188}Hg.

Recent in-beam studies[1-3] of the energies and lifetimes of the yrast cascade states in ^{184,186}Hg have revealed a sudden shift from levels built on a ground state with small deformation to ones with large deformation. The shift from slightly deformed states to ones with large deformation occurs at lower energy and lower spins in ^{184}Hg than in ^{186}Hg. Such shape transitions can occur if there is a second minimum in the potential at large deformation. A crucial test to establish the existence and nature of such second minima and the shape transitions in the mercury isotopes is to find low-spin states in the second minimum as recently found for a shape isomer in the actinide

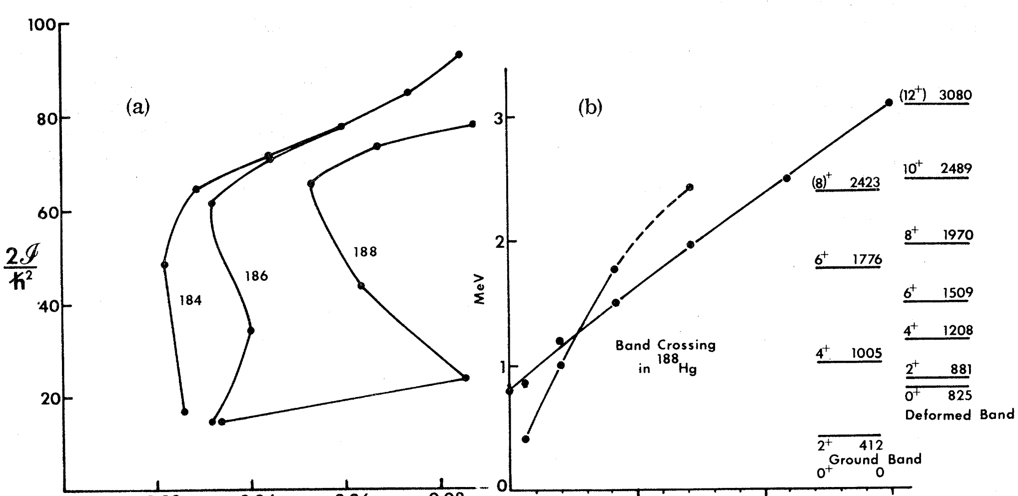

FIG. 1. (a) Plots of the moment of inertia versus $(\hbar\omega)^2$ [R. A. Sorensen, Rev. Mod. Phys. 45, 353 (1973), Eq. (14(d)] for the yrast cascades in ^{184,186,188}Hg. (b) The two strong cascades observed in the decay $^{188}\text{Tl} \rightarrow {}^{188}\text{Hg}$ are shown and the level energies compared to the simple rotational spin dependence $I(I+1)$ for the energy.

region.[4] We have identified the new isotopes ^{186,188}Tl with $T_{1/2}{}^{186} = 4.5^{+1.0}_{-1.5}$ and 28 ± 2 sec and $T_{1/2}{}^{188} = 71 \pm 1$ sec, respectively. These decays provide evidence in ^{186,188}Hg for 0^+ and 2^+ states in the second minimum. These data offer a new challenge to our understanding (see, for example, Frauendorf and Pashkevich[5]) of the origin of these states with large deformation. Also, in a review of the "backbending" of moments of inertia, Ward[6] noted that our preliminary results[7] on ^{188}Hg suggested evidence for the first time in this region for a band with large deformation crossing the ground band, but branching ratios were needed to confirm such. Our new ^{188}Hg data indeed provide a simple band-crossing explanation of the markedly different behavior of the moments of inertia with spin for the mercury yrast states [Fig. 1(a)] compared to rare-earth nuclei.[6]

Beams of 143–145-MeV ^{16}O from the Oak Ridge National Laboratory isochronous cyclotron incident on ^{181}Ta were used to produce ^{186,188}Tl at the UNISOR isotope-separator facility with a much higher-efficiency ion source. Improved ^{186}Tl results were obtained with 168-MeV ^{14}N incident on 99%-enriched ^{182}W. On-line, multiscale γ-ray and conversion-electron singles and γ-γ and e-γ coincidence data were measured with Ge(Li) and Si(Li) detectors on both isotopes.

The ^{188}Hg levels are shown in Fig. 2. Spins and parities were assigned from α_K data. The α_K and e-γ coincidence data show that the K and L electrons of an 824.5-keV transition result from $E0$ decays to the ^{188}Hg ground state. The $2^+ \rightarrow 2^+$ transition from the 881-keV level either is dominantly $M1$ or has a sizable $E0$ admixture and similarly for the $4^+ \rightarrow 4^+$ transition from the 1208-keV level. Nine levels are associated with two bands shown in Fig. 1(b).

The 1208-keV, 4^+ level strongly decays to the higher-energy, 881-keV, 2^+ level rather than to the 412-keV one with $B(E2{:}4 \rightarrow 2, 881)/B(E2{:}4 \rightarrow 2, 412) = 81 \pm 5$. For the 1509-keV, 6^+ yrast level, the $B(E2)$ ratio of transitions to the 4^+, 1208-keV and 4^+, 1005-keV levels is 4.9 ± 0.3. The new 6^+, 1777-keV level is close in energy to the slightly deformed level[8] at 1773 keV in ^{190}Hg. From this level, $B(E2{:}6 \rightarrow 4, 1208)/B(E2{:}6 \rightarrow 4, 1005) = 1.35 \pm 0.11$. The 2423-keV even-parity level tentatively is spin 8. Again it is close to the 8^+ yrast state in ^{190}Hg at 2456 keV.[8] The $B(E2)$ ratio to the 1777- and 1509-keV, 6^+ levels is 45 ± 10 to strongly suggest that the 2423-keV level is the 8^+ member of the ground band. The 0^+, 825-keV state has a dominate $E0$ decay strength to the ground state. Coincidence data show that a second 412-keV γ ray to the first 2^+ state is $<4\%$.

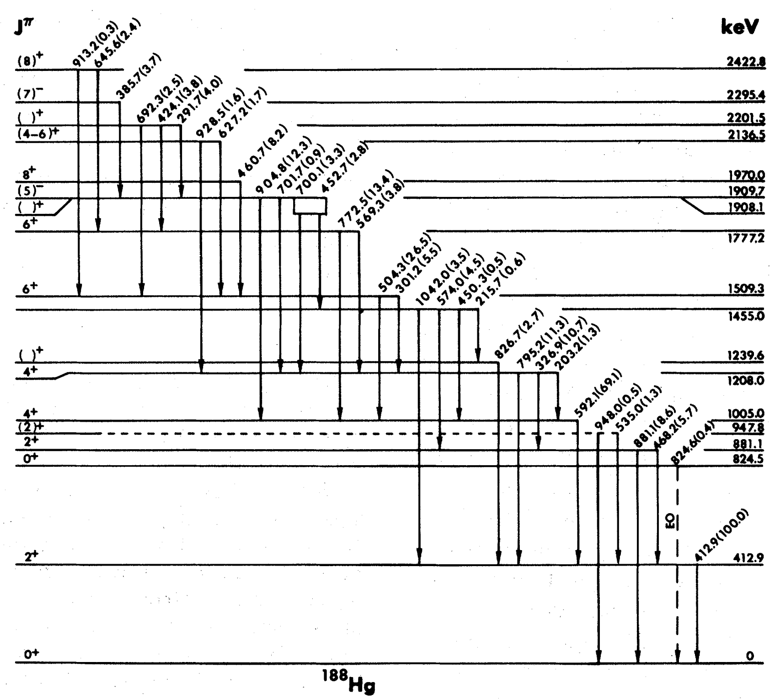

FIG. 2. The decay scheme of 71-sec, primarily high-spin ^{188}Tl to ^{188}Hg.

On this same scale, the $E0$ intensity is 0.4%. Though not definitively established, the possible large $E0$ admixtures in the 2-2 and 4-4 transitions are characteristic of transitions between β vibrational and ground bands in deformed nuclei but not in vibrational nuclei. Large $E0$ strengths are characteristic of $\Delta K=0$ transitions in deformed nuclei and are expected because of the sensitivity of the $E0$ decay to the mean square radius.

The decay properties of the two strongest cascades observed clearly suggest their division into two bands, one built on a slightly deformed ground state and one built on a more strongly deformed shape with a 0^+ band head at 825 keV as shown in Fig. 1(b). The moment-of-inertia plots for each of these bands in ^{188}Hg then show a smooth variation with energy in contrast to those in Fig. 1(a) for the yrast cascades. The 0^+ and 6^+ to (12^+) [the 10^+ and (12^+) are from Proetel, Diamond, and Stephens[9]] states were fitted by $E_0+AI(I+1)+BI^2(I+1)^2$. The calculated (experimental) energies are 825 (825), 927 (881), 1159 (1208), 1510 (1509), 1964 (1970), 2496 (2489), and 3078 (3080) for $A=0.0170$ and $B=-1.63\times10^{-5}$. The deviations in energies of the 2^+ and 4^+ members may be explained by their mixing with nearby states. Such mixing may also account for the branching ratio from the 1777-keV level. These data show that the crossing of these two bands is responsible for the anomalous moment of inertia of the yrast cascade and that crossing does not terminate either band. These data provide the first clear evidence in heavy nuclei for the influence of a band of high β deformation crossing the ground band. Recently a similar, almost identical, behavior to $^{184-188}$Hg was observed at low spin in the yrast cascade[10] in ^{72}Se.

The ground band to the tentative (8^+) state in ^{188}Hg is similar in energy to the yrast bands[8,9] in $^{190-198}$Hg, including the drop of the 8^+-level energy over the $I(I+1)$ prediction in every case. That drop and the drastic lowering of the 10^+ yrast states in $^{194-198}$Hg are interpreted in terms of $\pi h_{11/2}{}^{-2}$ excitations.[9] The similarity of our ground band to those in $^{190-198}$Hg and the lack of any change in the energy sequence at 8^+ to 10^+ in the strongly deformed band indicates that these proton-hole states find it easier to align themselves with the slightly deformed band than with the more strongly deformed one. The apparent persistence of these separate collective motions is surprising. The ^{188}Hg levels offer a remarkable richness of motions to test our theoretical understandings.

Analysis of the primary features of I_γ and I_e multiscale and γ-γ and e-γ coincidence studies of the ^{186}Tl decay now confirm our ^{188}Hg interpretation. A 373.9-keV transition has a $4.5^{+1.0}_{-1.5}$-sec half-life and is assigned as an isomeric decay in ^{186}Tl. Our I_e and e-γ data show that an $E0$ transition of 522 ± 1 keV feeds the ground state to establish a 0^+ level at this energy in ^{186}Hg and that a 215.8-keV transition is $E0+E2(+M1)$ and feeds the first 2^+ state to establish a 2^+ level at 621.0 keV. These two states are interpreted as the band head and first excited state in the strongly deformed band seen at higher spins in the yrast cascade.[1,3] Transitions seemingly associated with higher-spin states in the band built on a near-spherical ground state are also seen. These data confirm the same coexistence and crossing of bands built on near-spherical and deformed shapes in ^{186}Hg as seen in ^{188}Hg, except that the deformed band has dropped in energy as expected from recent theoretical[5] and experimental[1,3] studies.

In the most recent detailed calculations in $^{184-188}$Hg, Frauendorf and Pashkevich[5] found that the $^{184-188}$Hg ground states were slightly oblate ($\beta\approx-0.1$) with a second minimum about $\beta\approx0.3$ for a well-deformed prolate shape. Pashkevich[11] pointed out that their ^{188}Hg potential-energy surface has such a shallow second minimum that it seems unlikely that one should see the 0^+ and 2^+ states in that well. Their second minima are much deeper in ^{184,186}Hg. They did not consider γ instability which could give rise to a higher barrier[11] in ^{188}Hg. However, that is only one of several possible explanations.

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Coulomb Excitation of High-Spin States in ^{238}U†

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Coulomb excitation with Kr and Xe ions has excited the ground-state band of ^{238}U up to the 22^+ (tentatively 24^+) state and the lowest octupole vibrational band up to 19^-. No back-bending is observed. The behavior of the octupole band at high spins suggests a Coriolis-induced alignment of the rotational and vibrational angular momenta.

The strong electromagnetic interaction produced in the encounter of a deformed target nucleus by a heavy projectile excites high-spin states in the ground-state rotational band and in rotational bands built on collective states coupled to the ground-state band. Such multiple Coulomb excitation is a powerful tool for investigating collective nuclear properties at high rotational frequencies. Of special interest are the rotational bands of the strongly deformed actinide nuclei, which cannot be studied by (HI, $xn\gamma$) reactions because of the strong fission competition. In the present Letter we report levels in the ground-state and octupole-vibrational bands of ^{238}U excited by Kr and Xe ions up to $I\sim 20\hbar$. From such studies one obtains the level energies and their branching ratios for γ decay. One can then, in principle, obtain transition probabilities from the Coulomb-excitation cross sections for exciting these states. Such quantities are of considerable interest, as is a careful study of these cross sections for new effects possibly occurring in these very strong electromagnetic interactions. However, accurate cross-section analyses cannot be made at present, mainly because of the lack of fully quantum-mechanical-calculated cross sections. The quantum-mechanical code that exists[1] becomes prohibitively expensive to run above $\sim 10\hbar$, and no reliable methods for extrapolation to higher-spin values are known. Thus a meaningful discussion of the Coulomb-excitation yields must be postponed, and the present Letter will deal with the level energies and decay properties observed in the ground and octupole bands of ^{238}U.

Thick metallic targets, enriched in ^{238}U, were bombarded at the Lawrence Berkely Laboratory SuperHILAC with beams of ^{84}Kr (385 ± 5 MeV), ^{86}Kr (394 ± 6 MeV), ^{132}Xe (605 ± 20 MeV), and ^{136}Xe (640 ± 40 MeV). The decay γ rays were observed by two (~ 40 cm^3) coaxial Ge(Li) detectors at $\theta_\gamma = 0°$ and $\theta_\gamma = 90°$ with respect to the beam direction and 4–5 cm from the target. Singles, γ–backscattered-projectile, and γ-γ coincidences were simultaneously stored. The low-energy portion of the singles γ-ray spectrum and the γ-γ coincidence spectrum is shown in Fig. 1 for the ^{136}Xe bombardment. Almost all the lines shown here belong to the ground-state and lowest-energy octupole bands of ^{238}U. We do not see many lines of the higher vibrational bands, and are at