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Shape isomerism and spectroscopy of ^{177}Hg

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High spin states in the ^{177}Hg nucleus were populated by the ^{144}Sm(^{36}Ar,3n)^{177}Hg reaction at a beam energy of 178 MeV. The emitted prompt γ rays were detected with the Jurosphere γ-ray spectrometer, while the recoiling nuclei were identified using an active stopper at the focal plane of the gas-filled separator RITU. A quasi-rotational band that decays to an isomeric state with a half-life $t_{1/2}$=1.50±0.15 μs and its subsequent γ decay to the ground state of ^{177}Hg have been observed for the first time. Based on the observed decays from this isomeric state, we suggest that the spin of the ground state of ^{177}Hg is $J^{\pi}=7/2^{-}$. In addition, a sequence of transitions that bypass this isomeric state has also been observed. Evidence for shape coexistence is presented. The properties of the observed states are discussed in terms of the systematics of the mercury nuclei in this transitional region.

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The study of neutron-deficient isotopes in the Os-Pt-Hg region has burgeoned in recent years through the application of the recoil decay tagging (RDT) [1,2] technique. These nuclei, with $A\approx175$, are of interest due to the wide variety of nuclear shapes and excitation mechanisms that are expected to compete for the yrast structure [3]. This feature is known as shape coexistence and the Os-Pt-Hg region of nuclear chart provides some of the best cases of this phenomenon [4–17]. An excellent example is the ^{179}Hg nucleus where three different structures have been observed and associated with near-spherical ($\beta_2<0.15$), oblate ($\beta_2=-0.15$), and prolate ($\beta_2\approx0.25$) configurations [5,18]. In the odd-A, neutron-deficient Hg isotopes ^{179,181,183,185}Hg, the γ-ray decay is often observed to an $13/2^+$ isomeric state originating from the oblate $i_{13/2}$ configuration [5,18–21].

In most of these nuclei the γ decay to the ground state has not been observed and complementary methods such as α-decay studies need to be employed in order to establish the spin and parity of the ground and isomeric states and excitation energy of the isomeric states. This method is demonstrated in the recent example of the complementary works using γ-ray spectroscopy by Kondev *et al.* [5] and α spectroscopy by Jenkins *et al.* [18] of ^{179}Hg. These works established the relative excitation energies of the three different nuclear shapes. It is expected that its neighboring odd-A isotope ^{177}Hg will also exhibit evidence for shape coexistence.

A preliminary study of ^{177}Hg has been reported previously [6], in which seven γ-ray transitions were identified. Three of these transitions, at 621, 536, and 638 keV were tentatively assigned to form the sequence $25/2^+\rightarrow21/2^+\rightarrow17/2^+\rightarrow13/2^+$, based on intensity arguments. This sequence was presumed to feed a $13/2^+$ state, but the excitation energy of this state relative to the ground state was not determined. In addition, the spin of the ground state of ^{177}Hg is unknown, although its α decay and half-life are known [22].

In this work we report the first identification of a long lived ($t_{1/2}$=1.5 μs) isomeric state and the first observation of its subsequent γ decay to the ground state of ^{177}Hg. This isomer is interpreted as being the $13/2^+$ bandhead and the electromagnetic properties of its decay suggest that the ground state of ^{177}Hg is $J^{\pi}=7/2^{-}$. A sequence of six transitions that decay to this isomer has been identified from recoil-α-γ-γ data. This band has the characteristics of a deformed prolate structure above $21/2^+$. In addition, a weakly deformed band associated with an almost spherical shape that is built on the ground state and bypasses the isomeric state is observed. The properties of these bands are compared with the systematics of the region and with theoretical predictions from the cranked Woods-Saxon shell model.

The ^{177}Hg nucleus was populated using the reaction ^{144}Sm(^{36}Ar,3n)^{177}Hg. The ^{36}Ar beam was accelerated to 178 MeV by the K-130 cyclotron at the University of Jyväskylä. The ^{144}Sm target, of thickness 500 μg/cm^2, was positioned at the focal point of the Jurosphere γ-ray array. At the time of this experiment Jurosphere consisted of 5 Nord-Ball [23] at 79° relative to the beam direction, 5 TESSA [24] at 101°, and 15 Eurogam Phase I [25], 10 at 134° and 5 at 158°, Ge detectors in suppression shields. This array was used to detect "prompt" γ rays emitted at the target position. The recoiling evaporation residues entered the gas-filled separator RITU [26] and were implanted, $\approx$0.5 μs later, into a 16-strip, 80 mm×35 mm position-sensitive Si detector. This detector covered $\approx$70% of the recoil distribution at the focal plane. Three TESSA-type Ge detectors were situated at the focal plane of RITU in order to detect delayed (isomeric) γ rays that were emitted within $\approx$30 μs of a recoil arriving.

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The energies, positions, and times of the implanted recoils and any subsequent α decays were recorded, as were any γ rays detected by Jurosphere in coincidence with a recoil implantation. The position sensitivity and the relative time data were used to determine correlations between the recoils, α particles, and the prompt and delayed γ rays.

During this experiment, a total of 6.2×10^8 recoil-α-γ^n (prompt) ($n\geqslant1$) coincidences were collected. Approximately 38% of these coincidences accounted for events in which two or more γ rays were detected by Jurosphere. The most abundant fusion evaporation channels observed in these data were the $p2n$ (^{177}Au) and $2p2n$ (^{176}Pt) evaporation channels. The strongest peak in the α spectrum observed at the focal plane of RITU was the decay of ^{177}Au (E_α $=6.118\pm0.009$ MeV, $t_{1/2}=1300\pm200$ ms [22]). The α decays of ^{177}Hg ($E_\alpha=6.577\pm0.009$ MeV, $t_{1/2}=114\pm15$ ms [22]) were observed at an intensity of 12% of the α decay of ^{177}Au. The production cross section for ^{177}Hg was estimated from the data to be ≈18 μb. A total of 8.5×10^4 recoil-α-γ^n (prompt) ($n\geqslant1$) events were recorded associated with the α decay of ^{177}Hg.

These data were sorted off-line using standard RDT analysis techniques [1,2] to tag the α decay of ^{177}Hg and correlate these to the prompt γ rays measured at the target position of the Jurosphere array. In order to determine the level scheme of ^{177}Hg a series of prompt (target position) and delayed (focal plane) recoil-α-γ and recoil-α-γ-γ selected histograms were sorted from the data. The two-dimensional γ-γ matrices were analyzed using the ESCL8R graphical analysis software package [27]. A prompt (detected by Jurosphere) recoil-α γ spectrum, obtained by selecting the ^{177}Hg α decay is shown in Fig. 1(a). A corresponding delayed spectrum is shown in Fig. 1(b). The presence of mercury x rays in both these spectra confirm the assignment of these γ rays to an isotope of mercury.

The presence of an isomeric state that decays via the 77-keV and 246-keV γ rays to the ground state was determined from an α tagged, delayed γ spectrum. The placement of this isomer, at an excitation energy of 323 keV, in the level scheme of ^{177}Hg was then determined from the recoil-α-γ(prompt)-γ(delayed) data. The spectrum of the delayed γ rays in coincidence with the 638 keV prompt transition is shown in Fig. 1(c) and clearly shows the 77- and 246-keV transitions.

The lifetime of the state depopulated by the 246-keV transition was determined to be $t_{1/2}=1.50\pm0.15$ μs from a fit to the recoil-γ(delayed) TAC (time to amplitude converter) spectrum. The TAC was started by the implantation of a recoil in the silicon detector and stopped by the measurement of a 246-keV γ ray in one of the focal plane detectors, inset to Fig. 1(c). In the heavier odd-A Hg isotopes a similar isomeric state is observed and assigned to be based on the oblate $\nu[606]\frac{13}{2}^+$ Nilsson state. Therefore, we tentatively assign the 323 keV state as $J^\pi=13/2^+$.

The proposed level scheme for ^{177}Hg is shown in Fig. 2. The transitions above the 323-keV isomeric state were identified and ordered from the recoil-α-$\gamma_{\rm prompt}$-$\gamma_{\rm prompt}$ coincidence data. A spectrum of these prompt γ rays is presented in Fig. 1(d). The level scheme shown in Fig. 2 differs from that

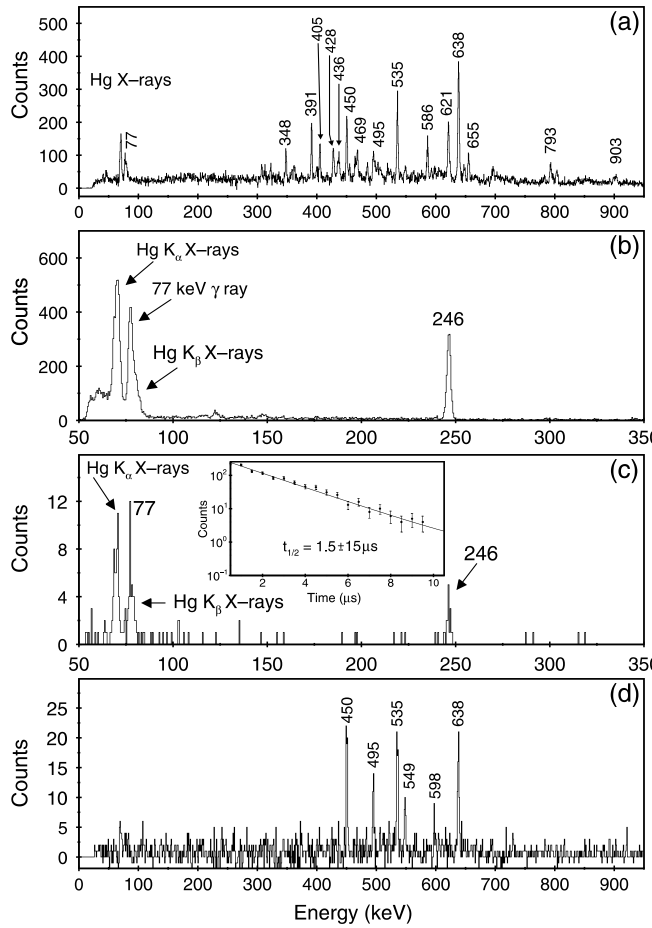

FIG. 1. (a) A recoil-α-γ spectrum obtained by gating on the 6.577-MeV α decay of ^{177}Hg [22]. Transitions assigned to ^{177}Hg are marked by their energy. (b) A recoil-α-γ spectrum of the "delayed" transitions assigned to ^{177}Hg. (c) A spectrum of the delayed transitions in coincidence with the 638-keV prompt transition in ^{177}Hg. The inset shows a TAC spectrum gated on the delayed 246-keV transition in ^{177}Hg. The solid line represents a least-squares fit to the data. A flat background, determined by the average number of counts above 8 μs, has been used. (d) A spectrum of the prompt γ rays obtained in coincidence with the 638-, 535-, 450-, 495-, and 549-keV γ rays in the recoil-α-γ-γ data.

suggested in Ref. [6] since the 638-keV and the 621-keV transitions are not in coincidence. The 621-keV transition bypasses the isomeric state (at 323 keV) and decays to the state at 77 keV. Several transitions identified as belonging to ^{177}Hg, labeled in Fig. 1(a), have not been placed in the level scheme, Fig. 2, due to insufficient γ-γ statistics. However, the data show that 391-, 436-, and 586-keV γ rays feed the $13/2^+$ isomeric state.

In order to suggest the J^π of the ground state we have determined the internal conversion coefficient (α_{ic}) for the 246-keV transition that depopulates the 323-keV isomeric state and compared the measured lifetime with the Weisskopf single-particle estimates. The internal conversion coefficient could not be measured directly, however it was inferred by measuring the intensities of the K_α(Hg), K_β(Hg), and 246 keV transitions (the 77-keV transition cannot undergo K conversion). The conversion coefficient determined for the

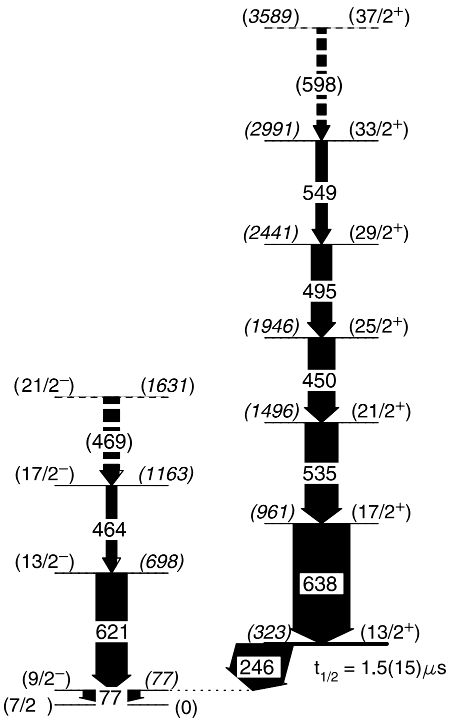

FIG. 2. The level scheme of ^{177}Hg. Transition energies are given to the nearest keV. For the 621 keV, 469 keV, 464 keV, and all transitions above the isomer the widths of the arrows are proportional to the measured prompt γ-ray intensity. For the 77-keV and 246-keV transitions the width of the arrow is proportional to the measured delayed γ-ray intensity. Dashed levels/arrows and parentheses denote tentative assignments.

246-keV transition is α_{ic}=2.39±0.43, which is only consistent with an $M2$ transition [28]. The 77-keV state therefore could have a J^{π} of 13/2$^-$, 11/2$^-$, or 9/2$^-$. The former two possibilities suggest that the 246-keV transition is unstretched, resulting in an $E1$ admixture in the decay from the 13/2$^+$ isomeric state. The Weisskopf single-particle estimates suggest a lifetime of 14.4 fs for a state in ^{177}Hg decaying via a 246-keV $E1$, which is not consistent with the value of 1.5 μs measured in the experiment. This statement is also true when the expected hindrance of $\approx 10^5$ for the experimental case of $E1$ transitions when comparing theory and experiment. In addition, evidence for such a transition should be observable in the prompt data, which is not the case. Hence the 77-keV state is assigned to be J^{π}=9/2$^-$. The multipolarity of the 77-keV transition that decays to the ground state cannot be unambiguously determined from these data. However, if this state decays via an $E2$ transition, then a lifetime of 3.33 μs would be expected, whereas an $E1$ or $M1$ transition would yield a lifetime of 453 fs or 46.5 ps, respectively, consistent with the prompt decay observed experimentally. Since the $2f_{7/2}$ and the $1h_{9/2}$ orbitals are the only realistic candidates for occupation [29], the ground state is either 9/2$^-$ or 7/2$^-$, which implies that the 77-keV γ ray is an $M1$. If the ground state spin were 9/2$^-$ a competing 323-keV $M2$ decay direct from the 13/2$^+$ isomeric state to the ground state would be expected; but this is not observed in the data, Figs. 1(b) and 1(c). Furthermore, the neighboring Hg isotope ^{177}Hg [18] has a ground-state spin of J^{π}=7/2$^-$, which indicates that the ground-state spin of ^{177}Hg is more likely to be J^{π}=7/2$^-$. In addition, the ground state in ^{179}Hg is also fed by an $M1$ and $M2$ cascade [18].

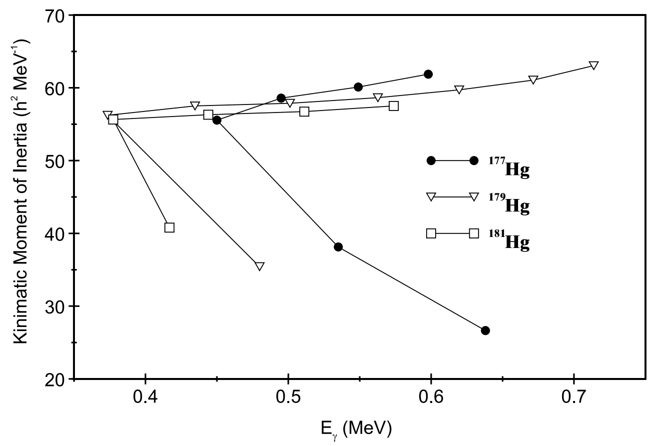

FIG. 3. The kinematic moment of inertia as a function of E_{γ} for the yrast bands in ^{177}Hg (this work), ^{179}Hg [5], and ^{181}Hg [19] above the 13/2$^+$ isomer.

The ground state of ^{177}Hg is obtained by placing the odd neutron in the $f_{7/2}$ or $h_{9/2}$ orbitals which are close to the Fermi surface for small prolate deformation. Total Routhian surface (TRS) calculations [29] were preformed to predict the lowest lying configurations in ^{177}Hg. These calculations predict a weakly deformed structure with $\beta_2 \approx 0.1$ based on the ground state. We therefore assign the states that feed the ground state, bypassing the isomer, to correspond to this minimum. This structure is similar to that seen in band 1 of ^{179}Hg [5]. In addition, comparable structures have been observed in ^{174,175,176}Pt [30–32] where a weakly deformed shape has been invoked to explain the ground state of ^{175}Pt [31] and the low-spin characteristics in the yrast bands of ^{174,176}Pt [30,32].

The high-spin yrast structure of ^{177}Hg comprises the sequence that feeds the 13/2$^+$ isomeric state. In order to interpret this structure the kinematic moment of inertia for the states has been plotted as a function of E_{γ}, Fig. 3, and compared with the similar bands in ^{179}Hg [5] and ^{181}Hg [19].

The rapid gain in the moment of inertia as a function of γ-ray energy for ^{177}Hg up to 21/2$^+$ followed by an almost constant gain, Fig. 3, is a characteristic of a shape change, in this case from a weakly deformed oblate to a prolate deformed structure. Above 21/2$^+$ the moment of inertia follows the trend established in the heavier isotopes ^{179,181,183}Hg [5,19,21]. The moment of inertia is a characteristic of a prolate deformed structure. Indeed in ^{179}Hg and ^{181}Hg this rotational band has been assigned a configuration involving the occupation of the prolate deformation driving $i_{13/2}$ orbital. TRS calculations were preformed to predict the lowest lying configuration for such a band in ^{177}Hg. These calculations predict a prolate deformed minimum at β=0.22. The lowest lying $i_{13/2}$ orbital at this deformation is the $[642]\frac{5}{2}^+$ Nilsson state.

The apparent shape change visible in Fig. 3 merits some discussion in terms of the systematics of the region. A two-band mixing model has previously been used by Lane *et al.* to fit the level energies of the $i_{13/2}$ neutron bands in ^{183,185,187}Hg [21]. The resulting parameter values were consistent with two coexisting bands of different deformations, as observed in even-even Hg isotopes. However, the band-mixing analysis for odd-mass Hg isotopes is more problematic because the K values, signature splitting, and alignment of each band have to be taken into account. (These are all zero in the even-mass isotopes.) Extending this analysis to ^{179,181}Hg is difficult because the bandhead energies of the two structures are so close that few oblate states are observed to constrain the fit parameters. In the case of ^{177}Hg, the low production cross section and the consequent low level of statistics mean that the signature partner bands could not be identified, so the signature splitting parameters cannot be extracted. Therefore in all three cases the estimated bandhead energy differences are rather uncertain. However, from consideration of results with a range of plausible parameter values and from Fig. 3 it is clear that the oblate-prolate bandhead energy difference in ^{177}Hg is significantly larger than in ^{179,181,183,185}Hg, mirroring the roughly parabolic increase in energy difference moving away from the neutron mid-shell seen in even-even isotopes. It is interesting to note that the change in structure in the yrast sequence of states occurs at a higher spin in ^{177}Hg$(21/2^+)$ than in the heavier isotopes ^{179}Hg and ^{181}Hg where the change occurs at $(17/2^+)$. This is also consistent with the changing oblate-prolate bandhead energy difference of these isotopes.

Excited structures in the extremely neutron-deficient nucleus ^{177}Hg have been firmly established for the first time. This is the lightest odd-A Hg nucleus in which excited states are known. A quasi-rotational band that decays to an isomeric state with $t_{1/2}=1.50\pm0.15$ μs has been observed and its decay to the ground state has been established. Three distinct nuclear shapes/excitation mechanisms have been identified and compared with the systematics of the region. From these data it is clear that the weakly deformed (oblate) states become non-yrast at high excitation energies. The structure that bypasses the isomer and feeds the ground state directly is interpreted as a weakly deformed near-spherical shape.

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