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First observation of excited states in $^{175}Hg_{95}$

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Excited states of the neutron-deficient nucleus ^{175}Hg, populated using fusion-evaporation reactions, are reported for the first time. The spin and parity of the ground state has been determined to be $I^\pi = 7/2^-$ through measurements of the α decay to the daughter nucleus ^{171}Pt. A structure based on an isomeric state [$T_{1/2} = 0.34(3)\,\mu$s] with $I^\pi = 13/2^+$ and its decay path to the ground state have been established. The observed structures are interpreted in terms of single-particle configurations, and the trends of coexisting shapes in neighboring nuclei are discussed.

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The element $_{80}$Hg has proved to be scientific curiosity for many years and this has not been lost on the atomic nuclei of Hg, in which some of the most widely varying shape phenomena have been observed. In the case of the neutron-deficient isotopes [1–7], evidence has been found for shape coexistence in which different shapes compete for the lowest energy structure in the same nucleus. Spherical shapes, associated with the close proximity to the $Z = 82$ shell gap, in addition to oblate and prolate shapes resulting from particle-hole excitations to high-Ω and low-Ω intruder orbitals, respectively, compete for the yrast structure of neutron-deficient Hg nuclei. The extent of the competition between these configurations, particularly the oblate and prolate shapes, is observed to change as the neutron number varies [8].

In this work the evolution of these shapes and the structure of the Hg isotopes toward the $N = 82$ shell closure is augmented with a study of ^{175}Hg, which has 21 fewer neutrons than the lightest stable isotope. Odd-mass nuclei are particularly useful in allowing the active single-particle orbitals to be identified. Studies of the odd-A Hg nuclei ^{177}Hg [2] and ^{179}Hg [4,5] have revealed the coexistence of three distinct shapes and have identified the single-particle orbits thought to be responsible. In the present study of ^{175}Hg, excitations based on single-neutron states have been identified for the first time. Previous studies of ^{175}Hg have been limited to the decay of the ground state by means of α decay to its daughter ^{171}Pt [9–12] and, more recently, the population and decay of its ground state via the proton decay of ^{176}Tl [13].

The reason for the lack of detailed spectroscopic information for ^{175}Hg is the difficulty in its production. Using fusion-evaporation reactions, the optimum mechanism for populating such exotic nuclei is via neutron evaporation. However, in this extremely neutron-deficient region, these channels are very unfavorable, with the evaporation of charged particles and fission dominating the cross section. Nonetheless, the highly selective recoil-decay tagging (RDT) technique [14–16] has proved successful in identifying the excited states of many neutron-deficient nuclei in the vicinity of the $Z = 82$ spherical shell closure [17]. RDT involves the exploitation of high-efficiency γ-ray detector arrays, which are coupled to recoil separators and focal plane detector systems. By correlating characteristic radiation (α particles, protons, or γ rays), observed at the focal plane, with fusion-evaporation residues and prompt γ radiation emitted at the target position, the study of excited states of nuclei produced with cross sections down to a few tens of nanobarns is possible [18].

The RDT technique has been utilized to study excited states of ^{175}Hg following the reaction ^{92}Mo(^{86}Sr^{17+}, $3n$) at a beam energy of 403 MeV. The beam, provided by the K130 cyclotron of the University of Jyväskylä, bombarded a self-supporting 600 μg/cm^2 ^{92}Mo target (of 98% isotopic enrichment), which was located at the center of the JUROGAM γ-ray detector array, which consisted of 43 escape-suppressed Ge detectors [19]. The recoiling fusion-evaporation residues (recoils) were transported to the focal plane of the RITU He-filled magnetic separator [20]. The GREAT spectrometer, which consisted of a multi-wire proportional chamber (MWPC), two double-sided silicon strip detectors (DSSDs), a planar Ge detector, a clover Ge detector, and an array of Si PIN diodes, was located at the focal plane. This spectrometer facilitated the spectroscopy of α particles, delayed γ rays, and conversion electrons following the decay of the implanted recoils. The MWPC provided energy-loss and time-of-flight information (in conjunction with the DSSDs) and allowed the recoils of interest to be distinguished from the background of scattered beam and radioactive decays. The Total Data Readout system [21] was employed to record time-stamped events observed in each of the constituent detectors. In this way, it was possible in the offline analysis to correlate events with a characteristic α decay and unambiguously assign any prompt and delayed γ rays or conversion electrons to the decay of a specific nucleus.

The data were sorted using the GRAIN software package [22]. Conditions were set such that only those events were accepted in which an implanted recoil into the DSSDs was followed by the detection of an α particle within 50 ms. The

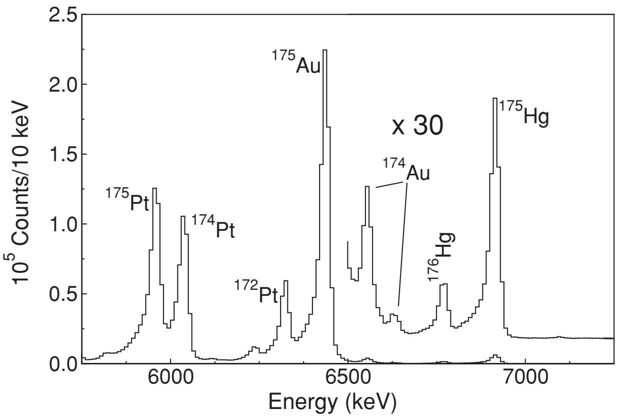

FIG. 1. Spectrum showing all α particles observed within 50 ms of the implantation of a recoil in the DSSDs.

resulting α-particle energy spectrum is shown in Fig. 1. A total of 25000 recoil-α(^{175}Hg) coincidences were collected, and the cross section for the production of ^{175}Hg was estimated to be $\sim$1.5 μb. The α particles associated with the decay of ^{175}Hg [10] were observed at 6913(5) keV. The time elapsed between the implantation of a recoil in the DSSDs and the detection of a ^{175}Hg α particle was also measured, resulting in a half-life for ^{175}Hg of 10(1) ms. This value has been corrected for the $\sim$400 Hz average implantation rate, observed across the entire area of the DSSDs, in accordance with the method of Leino *et al.* [23]. This value, while not as precise as that of Rowe *et al.* [12] [10.8(4) ms], is consistent with all prior measurements [9–11].

The ground-state spin and parity of ^{175}Hg were determined through an analysis of the α-decay properties. The Rasmussen [24] formalism for calculating reduced α-decay widths was utilized; and assuming a branching ratio of 100% and $\Delta l = 0$ emission, a reduced width of $\delta^2 = 54(5)$ keV is obtained. This value indicates that there is no change in spin and parity involved in the α decay of ^{175}Hg. The ground-state spins and parities of the α-decay chain partners ^{163}W, ^{167}Os, and ^{171}Pt have been established as $7/2^-$ [25], and the present measurement therefore establishes the ground state of ^{175}Hg to also be $I^\pi = 7/2^-$. This measurement is consistent with the observations of Kettunen *et al.* [13] in which the ground state of ^{175}Hg was populated via a $\Delta\ell = 0$ proton decay of the ^{176}Tl ground state leading to the assignment of $I^\pi = 7/2^-$ or $9/2^-$ for the ^{175}Hg ground state.

Figure 2(a) shows all γ rays observed at the focal plane that have been correlated with the α decay of ^{175}Hg following within 50 ms of the implantation of a recoil. Three distinct peaks have been observed at energies of 71, 80, and 414 keV. The 80 and 414 keV transitions are in prompt coincidence at the focal plane.

Using the PIN-diode detectors of the GREAT spectrometer [26], it was possible to measure directly the internal conversion of the 414 keV transition. A conversion electron energy spectrum, correlated with the α decay of ^{175}Hg, is shown in Fig. 2(b). Two peaks were identified and associated with internal conversion electrons competing with the 414 keV γ-ray transition. The lower energy peak was identified as

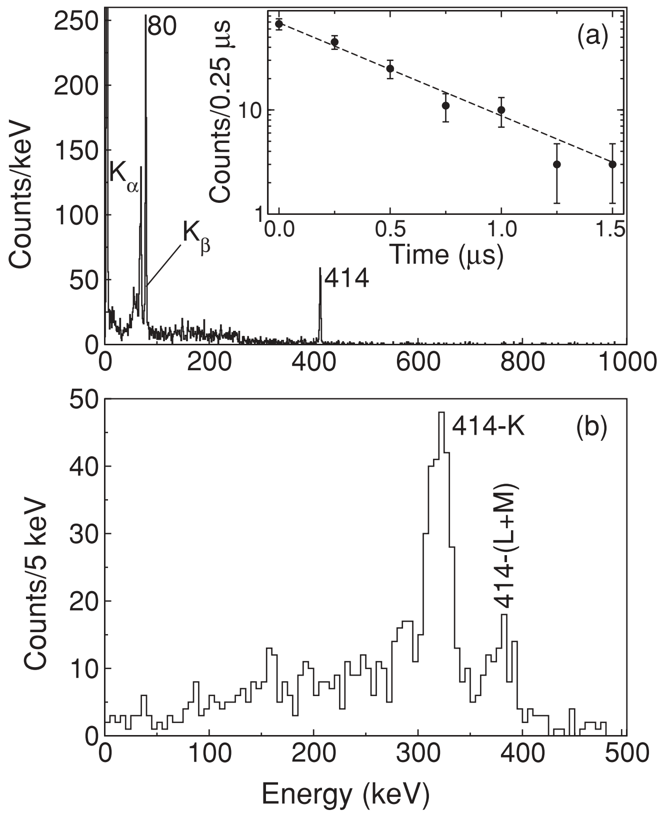

FIG. 2. (a) Spectrum showing delayed γ rays correlated with ^{175}Hg α decays. The inset shows the distribution of time intervals between the implantation of a recoil and the detection of a 414 keV γ ray. The dashed line is the result of a least-squares fit to the data. (b) ^{175}Hg α-tagged conversion electron spectrum as observed with the PIN-diode detectors.

corresponding to the emission of electrons from the atomic K shell, while the higher energy peak is related to emissions from the L and M shells. A comparison of the number of observed 414 keV γ rays and the number of conversion electrons yields internal conversion coefficients (ICCs) of $\alpha_K = 0.36(11)$ and $\alpha_{(L+M)} = 0.10(3)$. These values correspond well with theoretical values of 0.38 and 0.10 calculated using the code BrIcc [27], assuming the 414 keV γ ray is of $M2$ multipolarity. The ICCs corresponding to other multipolarities are inconsistent with the experimental values. In addition to the direct measurements performed using the PIN-diode detectors, the K conversion coefficient was obtained through a comparison of the number of observed 414 keV γ rays and K_α x rays. Note the K_α x rays can only arise from conversion of the 414 keV transition, since the binding energy is 83 keV [28]. An α_K of 0.45(10) was determined using this method, which is consistent with both the PIN-diode result and the theoretical prediction for an $M2$ multipolarity.

The inset of Fig. 2(a) shows the distribution of measurements of the time interval between the implantation of a recoil and the detection of a 414 keV γ ray in one of the focal plane Ge detectors. A least-squares fit to the data yielded a half-life of 0.34(3) μs. Weisskopf estimates of the lifetime for a 414 keV $M2$ decay are consistent with a decay from this isomeric state.

The K_α and K_β x-ray lines for Hg are reported [28] to have energies of 71 and 80 keV, respectively. Accordingly, the lowest energy of the lines in Fig. 2(a) is associated with the K_α x-ray line. The second photopeak will, in part, be associated with the K_β transition, which has an intensity of ~25% of the K_α(Hg) transition [28]. However, the efficiency-corrected intensity measurements show that the 71 keV peak has an intensity 73(13)% of the 80 keV peak. This leads to the conclusion that an 80 keV transition must also result from the γ decay of an excited state of ^{175}Hg.

It was not possible to measure directly an ICC for the 80 keV transition, since the apparatus was not sensitive to such low-energy electrons. However, the efficiency-corrected intensity of the 414 keV γ-ray transition is approximately three times that of the 80 keV γ ray. At the focal plane, all of the feeding of the first excited state is via the 414 keV transition depopulating the isomeric state. Therefore, the difference in efficiency-corrected γ-ray intensity must be due to internal conversion. Using BRICC [27], total ICCs were calculated yielding values of 0.156 for an 80 keV $E1$ transition, 2.74 for $M1$, and 14.12 if the transition was $E2$ in nature. Higher multipolarities result in higher ICCs. The measured value of $I_\gamma(414\text{ keV})/I_\gamma(80\text{ keV}) \sim 3$ is only consistent with the 80 keV transition having $M1$ multipolarity.

Figure 3(a) shows all prompt γ rays observed in JUROGAM and correlated with the α decay of ^{175}Hg. Seven clear photopeaks are observed in addition to the characteristic Hg K_α x-ray line. The transition at 80 keV is assumed to be the decay of the first excited state, which is also populated by the decay of the isomeric state. The fact that this state decays via a prompt transition supports the earlier argument that the 80 keV decay is a dipole, since Weisskopf estimates suggest this transition would have a half-life of 0.4 ps, 0.9 ps, or 0.2 μs if the multipolarity were $E1$, $M1$, or $E2$, respectively.

A lack of sufficient prompt γ-ray statistics prevented a γ-γ analysis. However, coincidences between prompt events and those observed at the focal plane permitted a level scheme for ^{175}Hg to be proposed. Figure 3(b) shows ^{175}Hg α-correlated prompt transitions observed in delayed coincidence with either an 80 or 414 keV delayed γ ray or associated conversion electrons. Transitions of energy 614, 687, and 728 keV are common to both Figs. 3(a) and 3(b). Accordingly, these decays were placed in the level scheme, shown in Fig. 4, as feeding the isomeric state and have been ordered based on their efficiency-corrected intensities. The γ rays feeding the isomer are assumed to be of stretched $E2$ character such that the band is tentatively observed to a spin of 25/2. The prompt 651 keV transition is the most intense transition that is not observed in coincidence with events at the focal plane. This transition is therefore assumed to bypass the $13/2^+$ isomer and is assigned to directly feed the first excited state. A lack of statistics prevented the location of the 708 and 843 keV γ-ray transitions, seen in Fig. 3(a), to be fitted into the ^{175}Hg level scheme.

Kondev *et al.* [4] established the ground-state spin and parity of ^{179}Hg as $7/2^-$ and argued that this state is likely to result from the unpaired neutron occupying $K = 7/2 f_{7/2}$ or $h_{9/2}$ orbitals. It was also suggested that the ground state must be near-spherical ($\beta_2 < 0.15$) in order for such orbitals to lie

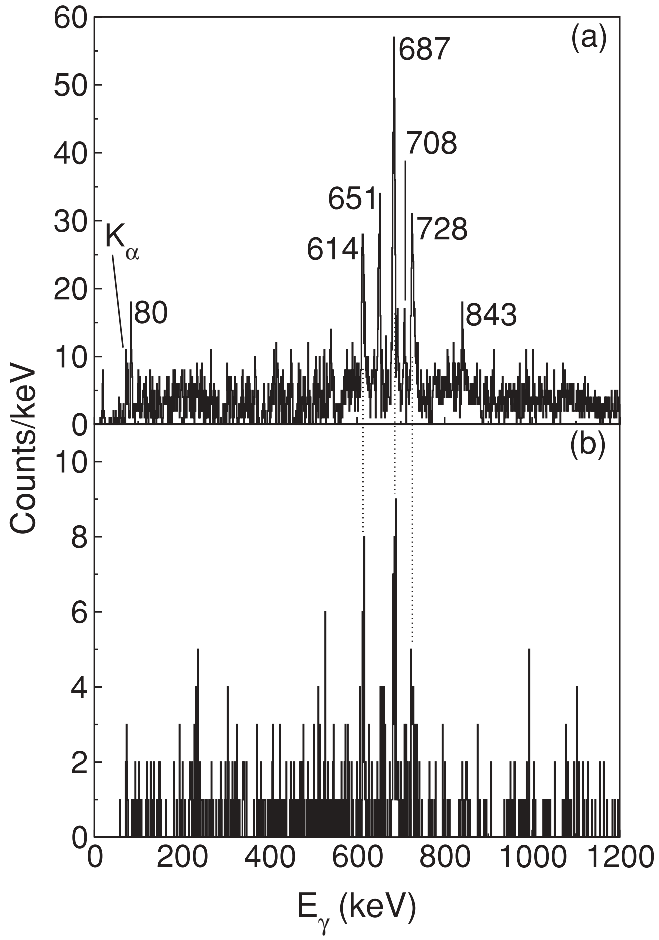

FIG. 3. (a) Energy spectrum of prompt γ rays, correlated with the α decay of ^{175}Hg. (b) Same as (a) but with the added condition that only those transitions observed in coincidence with delayed γ rays of 80 or 414 keV or associated conversion electrons are shown.

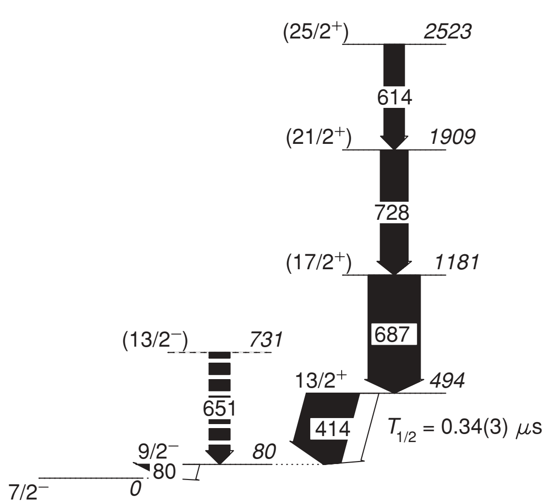

FIG. 4. Proposed level scheme for ^{175}Hg as deduced in the present study. Arrow widths are proportional to the efficiency-corrected intensities of the transitions, while unfilled regions indicate the extent of internal conversion.

close to the Fermi surface. These measurements and arguments were subsequently confirmed by Jenkins *et al.* [5]. The same configurations were assumed to constitute the tentative $7/2^-$ ground state of ^{177}Hg [2]. In addition, total Routhian surface calculations [2] predicted a weakly deformed minimum at $\beta_2 \approx 0.1$ to correspond to the ground state of ^{177}Hg.

The ground state of ^{175}Hg and the first excited state at $9/2^-$ are most likely the $f_{7/2}$ and $h_{9/2}$ single-particle configurations, respectively. In both ^{177}Hg and ^{179}Hg, the first excited state is also reported as having $I^\pi = 9/2^-$. This state and connected higher lying states were assumed to arise from weakly deformed near-spherical excitations [2,4]. In ^{175}Hg the tentative transition at 651 keV, which bypasses the isomeric level, is assumed to have a similar origin.

The present work establishes that the isomeric state at 494 keV has $I^\pi = 13/2^+$, which is consistent with observations of heavier odd-A Hg nuclei [2,5] in which this state is associated with the coupling of an $i_{13/2}$ neutron to an oblate deformed core. This state in ^{175}Hg is also most likely to correspond to the unpaired neutron occupying the $i_{13/2}$ state. The deduced $B(M2)$ of 0.16(1) W.u. suggests the decay of the isomeric state is hindered by a factor of 6 compared with the single-particle estimate. In previous studies of nuclei in this region, such as Refs. [5,29], where hindrances of this magnitude have been measured, they have been attributed to changes in shape. For ^{183}Tl, the large hindrance of 18 reported for the decay of the $13/2^+$ isomer, was attributed to the decay of the prolate state to an oblate $9/2^-$ level. The hindrance of 5 reported for ^{179}Hg [5] was associated with an oblate $(13/2^+)$ to near-spherical $(9/2^-)$ change of shape. The similar hindrance observed in ^{175}Hg is also consistent with evidence for shape coexistence in which a weakly deformed oblate configuration competes with spherical configurations at low spin.

Figure 5 shows the kinematic moment of inertia plotted as a function of γ-ray energy for the yrast sequences of even- and odd-mass Hg nuclei in the vicinity of ^{175}Hg. For the odd-A isotopes, the spin of the yrast bandhead (13/2) has been subtracted from each of the states to allow a more direct comparison with the even-A counterparts. For $A > 176$, the initial rapid gain in moment of inertia followed by a gradual gain as a function of γ-ray energy was interpreted in previous studies [1,2] in terms of a change of shape. This shape change was associated with the crossing of the low-lying oblate $i_{13/2}$ band by an excited prolate configuration [1,2]. Systematics suggest that the excitation energy at which the prolate band is observed to cross the oblate band in odd-A Hg nuclei is minimized at $N = 101$ and increases roughly parabolically away from this minimum. In ^{179}Hg$_{99}$ the crossing was observed to occur 854 keV [4] above the $13/2^+$ isomeric state, while in ^{177}Hg$_{97}$ the energy increased to 1623 keV [2]. This trend suggests that the yrast states of ^{175}Hg have not been observed to sufficiently high energy or spin to observe the crossing and hence the prolate structure. Indeed, based on the parabolic dependence, the crossing of the two configurations might be expected at ≈2.5 MeV above the 494 keV isomeric state.

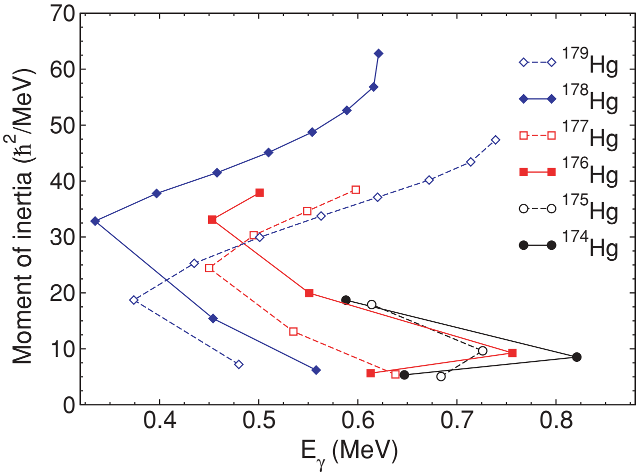

FIG. 5. (Color online) Kinematic moment of inertia as a function of γ-ray energy for the yrast sequences in Hg nuclei with $94 \leqslant N \leqslant 99$. For odd-$A$ isotopes, the spin of the yrast bandhead, 13/2, has been subtracted. Data other than those reported here were extracted from Refs. [1–4,17].

The similarities observed in Fig. 5 between ^{175}Hg and its immediate even-even neighbors (^{174}Hg and ^{176}Hg) suggest ^{175}Hg can be treated equally as an $i_{13/2}$ neutron or neutron-hole weakly coupled as a spectator to the ^{174}Hg or ^{176}Hg cores.

To summarize, selective RDT techniques have allowed the decay of excited states of ^{175}Hg to be measured for the first time. Measurements of the α-decay properties to the daughter nucleus ^{171}Pt have allowed the spin and parity of the ^{175}Hg ground state to be established as $I^\pi = 7/2^-$. In addition, an isomeric state $[T_{1/2} = 0.34(3)\,\mu s]$ at an excitation energy of 494 keV has been observed and established to be $I^\pi = 13/2^+$. A band based on the isomeric state, which may have an oblate deformation, and a near-spherical configuration observed to bypass the isomer have been identified. The crossing of the oblate configuration by an excited prolate band, as reported in the heavier odd-A Hg isotopes, has not been observed and will require further investigation to higher spin.

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