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Probing the shape of ^{176}Hg along the yrast line

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In-beam γ-ray and γ-γ coincidence measurements have been made for the very neutron-deficient nucleus ^{176}Hg using the recoil-decay tagging (RDT) technique. The irregular yrast sequence observed up to $I=10\hbar$ indicates that the prolate intruder band, seen in heavier Hg isotopes near the neutron midshell, crosses the nearly spherical ground-state band of ^{176}Hg above $I=6\hbar$. [S0556-2813(98)50512-2]

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In neutron deficient even-mass Hg isotopes the properties of the weakly oblate ground-state band remain rather constant with decreasing neutron number until in ^{188}Hg, where the band is crossed by an intruding deformed band associated with a prolate-deformed energy minimum [1–3]. The prolate states minimize their energies in ^{182}Hg [4] but they still lie above the ground state [5] which evolves from the oblate shape towards a spherical shape [3,4,6].

Recently, yrast levels up to $I^{\pi}=12^{+}$ in ^{178}Hg were identified [6] using the recoil-decay tagging (RDT) technique. In accordance with the theoretical predictions [3], a further increase in the excitation energy of the prolate band was observed. In the same experiment three relatively high-energy γ rays were unambiguously assigned to ^{176}Hg. They were tentatively associated with an $E2$ cascade de-exciting the lowest 2^{+}, 4^{+}, and 6^{+} states in ^{176}Hg. On the basis of this experimental information the question of a possible appearance of a prolate structure in ^{176}Hg still remained unresolved.

In the present work we have carried out an improved in-beam γ-ray spectroscopy study of ^{176}Hg to confirm the tentative assignments of Ref. [6] and to probe further its yrast line towards higher spin. The nucleus ^{176}Hg lies close to the proton drip line and therefore the cross sections for any heavy ion induced fusion-evaporation reaction required to produce it are of the order of a few μb. Prompt γ rays from ^{176}Hg were resolved from those arising from the dominant background of fission and other reaction products using the characteristic properties of the α decay of ^{176}Hg ($E_{\alpha}=6750$ keV, $t_{1/2}=(18\pm10)$ ms [7]) in a RDT [8,9] measurement.

The experiment was carried out at the Accelerator Laboratory of the University of Jyväskylä. Excited states of ^{176}Hg were populated via the ^{144}Sm(^{36}Ar,4n) fusion evaporation channel. The ^{36}Ar beam was delivered at an energy of 190 MeV by the JYFL (Department of Physics, University of Jyväskylä) cyclotron. The target consisted of a single 500 μg/cm^2 self-supporting metallic ^{144}Sm foil of 92.4% enrichment. Prompt γ rays were detected by the JUROSPHERE array consisting of 12 TESSA-type [10] and 13 Eurogam Phase I [11] Compton suppressed Ge detectors. The TESSA detectors were placed at angles of 78° and 101° and the Eurogam detectors at angles of 134° and 158° with respect to the beam direction. The total photopeak efficiency of the array for 1.3 MeV γ rays was about 1.5%.

The gas-filled recoil separator RITU (recoil ion transport unit) [12] was used to separate fusion-evaporation residues from the unwanted nuclei such as the primary beam and fission products. RITU is a charge and velocity focusing

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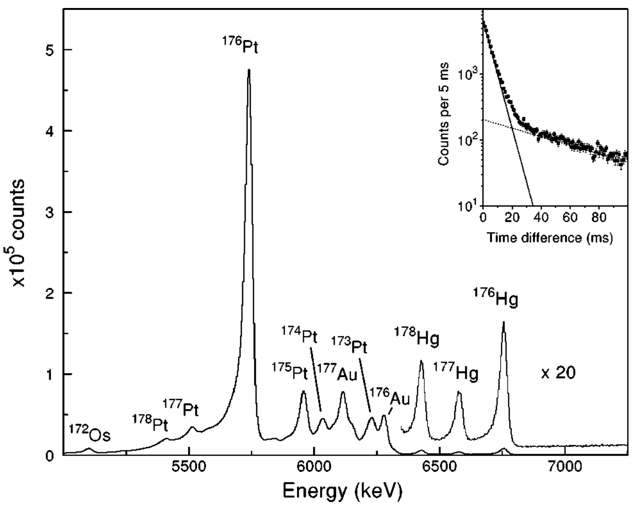

FIG. 1. Energy spectrum of α particles observed within a 100 ms time interval after the detection of a recoil at the same position in the Si strip detector. In the inset the distribution of recoil-α time differences for events in the ^{176}Hg peak is shown. The solid line is assigned to the decay of ^{176}Hg, while the dashed line represents the random background from false correlations.

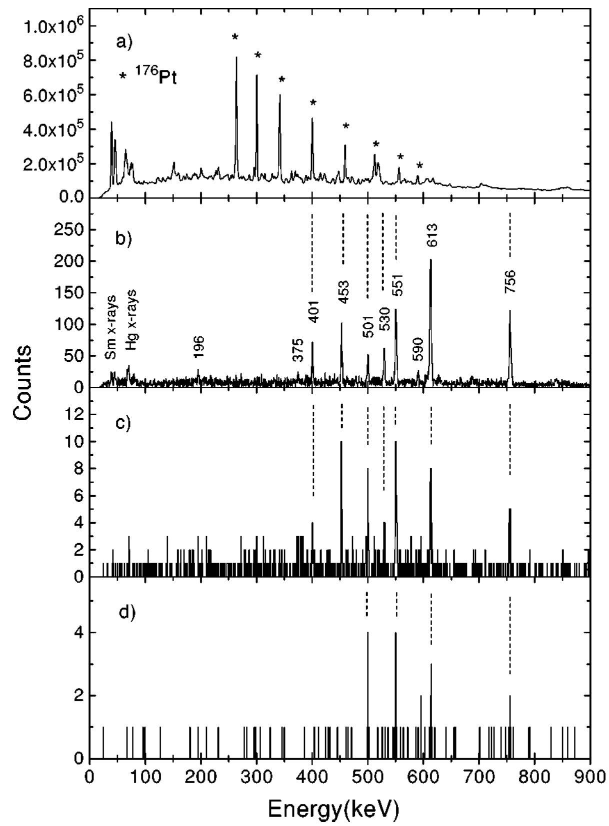

FIG. 2. (a) Energy spectrum of γ rays in coincidence with fusion-evaporation residues detected in the RITU focal plane Si detector. (b) γ-ray energy spectrum obtained by gating with fusion-evaporation residues and tagging with ^{176}Hg α decays. (c) Sum of the recoil-gated and α-tagged γ-γ coincidence spectra gated on the seven strongest transitions in the spectrum of (b). (d) Recoil-gated and α-tagged coincidence spectrum gated on the 453 keV transition.

magnetic device, designed for collecting recoiling fusion-evaporation residues with high efficiency. Separated fusion-evaporation residues were implanted into a 80 mm(horizontal)$\times$35 mm(vertical) Si strip detector covering about 70% of the recoil distribution at the focal plane. The Si detector was also used to detect the subsequent α decay of the implanted recoils. The transmission of the fusion-evaporation residues through RITU was determined from the fraction of the strongest γ-γ coincidences in ^{176}Pt [13] which were also in coincidence with recoils detected in the focal plane Si detector. The value obtained was about 27%. Approximately 50% of the α particles emitted by the recoils were detected with full energy. At a typical beam intensity of 15 particle nA, limited by the Ge singles counting rates, the total counting rate in the Si strip detector was about 800 counts/s. The effective Si-detector granularity of about 200 was sufficiently high to allow the selection of the ^{176}Hg recoils through correlation with their subsequent α decay.

Signals from the Si strip detector for the energy, position and the detection time of the recoils and α particles were recorded. Individual γ-ray energies and γ-γ coincidence events were collected when occurring in coincidence with detected recoils.

The events corresponding to the observation of a recoil together with a subsequent α decay at the same position in the Si detector within a maximum time interval of 100 ms were selected in the data analysis. The resulting α-particle energy spectrum is shown in Fig. 1. The α decay peaks labeled in this figure were identified using the known α-particle energies of the other isotopes produced in this reaction. Approximately 240 hours of effective beam time yielded about 90 000 recorded ^{176}Hg α decays from which the estimated cross section for the reaction ^{144}Sm(^{36}Ar,4n)^{176}Hg is deduced to be about 5 μb. The half-life of ^{176}Hg was determined from the spectrum of time differences between correlated recoil- ^{176}Hg α pairs, shown in the inset of Fig. 1. Using the method described in Ref. [14], the value obtained was $t_{1/2}=(21\pm3)$ ms. This is consistent with the earlier value of $t_{1/2}=(18\pm10)$ ms reported in Ref. [7].

The energy spectrum of γ rays obtained in coincidence with detected recoils is shown in Fig. 2(a). It is dominated by γ rays from ^{176}Pt produced in the (^{36}Ar,2p2n) fusion-evaporation channel. These γ rays are absent in Fig. 2(b), which shows a recoil-gated γ-ray spectrum obtained by correlating with the ^{176}Hg α decay. In this spectrum there are seven strong lines (400.9, 453.2, 500.5, 529.9, 551.0, 613.3, and 756.4 keV) which we firmly assign to originate from ^{176}Hg. Three of these (551.0, 613.3, and 756.4 keV) were seen by Carpenter *et al.* [6]. In addition, there are clear peaks at energies of 195.5, 375.1, and 590.4 keV which can be assigned to ^{176}Hg due to the fact that the RDT method provides a unique identification of the tagged γ rays. In order to construct the level scheme, recoil-gated α-tagged γ-γ coincidence data were required. Examples of coincidence spectra are shown in the two lowest parts of Fig. 2: Fig. 2(c) is a sum of the coincidence spectra gated on the seven strongest peaks of Fig. 2(b), and Fig. 2(d) is a spectrum gated on the 453.2 keV peak. The two spectra demonstrate that the 453.2, 500.5, 551.0, 613.3, and 756.4 keV γ rays are emitted as a cascade.

The intensity ratio of γ rays observed by the Ge detectors at 134° and 158° to those observed by the 79° and 101° Ge

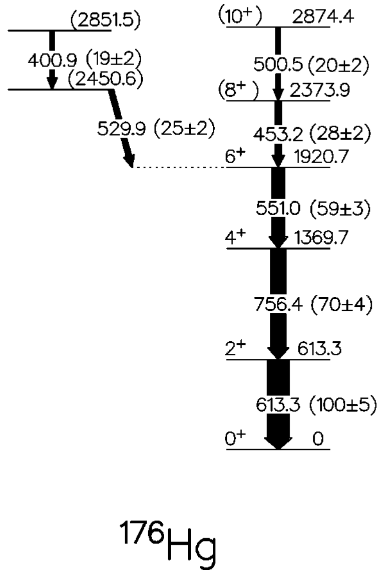

FIG. 3. Level scheme of ^{176}Hg deduced from the present data. The γ-ray energies are accurate to within 0.3 keV. The measured intensities are given in parentheses next to the transition energies.

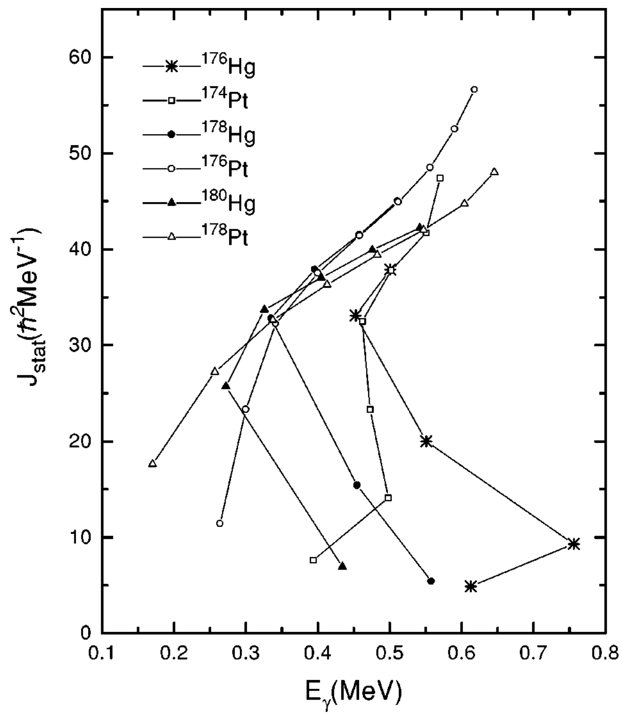

FIG. 4. Static moments of inertia (J_{stat}) as a function of γ-ray energy, derived from the experimental yrast level energies for the Hg and Pt isotones with $N=96$ (the present work and [16]), $N=98$ [6,13], and $N=100$ [4,21].

detectors was 1.25(15) for the known $E2$ transitions in ^{176}Pt marked in Fig. 2(a). Ratios for the 551.0, 613.3, and 756.4 keV transitions in ^{176}Hg were extracted and they were within the errors of the ^{176}Pt $E2$ transitions thus confirming their $E2$ character. For the weaker 453.2 and 500.5 keV transitions only tentative $E2$ assignments were possible. These arguments together with γ-ray coincidence and intensity information were used to generate the decay scheme of Fig. 3. The placement and the cascade character of the 529.9 and 400.9 keV γ rays remains tentative.

Our results confirm the earlier tentative assignments of the ^{176}Hg level scheme [6] up to the 6^+ level. It is interesting to span the level-energy systematics of even-mass Hg isotopes down to ^{176}Hg. The energies of the first excited 2^+ and 4^+ states in ^{176}Hg lie higher than in any other Hg isotope except the closed-shell nucleus $^{206}\text{Hg}_{126}$. In accordance with the theoretical predictions [3], the rise in the 2^+ and 4^+ level energies suggests a transition towards a spherical ground state as already pointed out in Ref. [6].

The similarity between the observed intruder prolate bands in the even-mass Pt, Hg, and Pb isotopes close to the neutron midshell is well known [15]. In Fig. 4 the static moments of inertia (J_{stat}) derived from the experimental yrast-level energies for the Hg and Pt isotones with $N=96$, 98, and 100 are plotted as a function of γ-ray energy. In this figure the appearance of the prolate band is manifested by the change towards a slightly increasing and smoothly behaving J_{stat}. Similarities in the J_{stat} values are especially striking between pairs of isotones. Furthermore, the values extracted from the (10^+) to (8^+) and (8^+) to (6^+) transitions observed in the present work are very close to the corresponding values for ^{174}Pt [16]. The change in J_{stat} at $E_\gamma \approx 0.5$ MeV for the yrast line in ^{176}Hg can be regarded as being due to a crossing prolate band, as seen in ^{174}Pt [16].

In order to extract the energy difference between the assumed prolate and weakly-oblate bandheads from the present data for ^{176}Hg we used a simple two-band mixing model similar to that in Ref. [15]. A value of about 1300 keV was extracted using the VMI (variable moment of inertia) parameters and a prolate-oblate interaction strength (about 100 keV) which reproduced the ^{178}Hg level scheme of Ref. [6]. Allowing a larger interaction strength (about 200 keV) and varying the VMI parameters did not significantly alter the estimated unperturbed bandhead energy value. The extracted value is about 600 keV higher than in ^{178}Hg revealing a rapid increase in the excitation energy of the prolate intruder structure with decreasing neutron number.

In the Nilsson-Strutinsky calculations at zero spin of Refs. [3,17], no well-developed prolate minimum but a shoulder in the potential energy curve was predicted. The corresponding prolate configuration lies at about 1 MeV above a shallow near-spherical ground state. At higher spin, because of its large moment of inertia, this configuration is expected to be favored energetically, thus giving rise to irregular behavior of the yrast band as observed in the present work.

The tentatively observed non-yrast levels could be due to negative-parity states similar to those seen in even-mass Hg isotopes with $A \geqslant 186$ [18–20]. Due to the intruding prolate bands these negative-parity states in Hg isotopes close to the neutron midshell lie higher above the yrast line and are therefore not observed.

To summarize, yrast states up to $I=10\hbar$ have been studied in the very neutron-deficient nucleus ^{176}Hg using the RDT technique. The experimental setup was sufficiently sensitive to allow the collection of γ-γ coincidence data for this nucleus, which was produced with a cross section of about 5 μb. The deduced yrast sequence of γ-ray transitions can be associated with a nearly-spherical ground state band which is crossed at $I=6\hbar$ by a prolate intruder band similar to those seen at much lower excitation energies in Hg isotopes near the neutron midshell.

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