Excited States in ^{176,178}Hg and Shape Coexistence in Very Neutron-Deficient Hg Isotopes

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Excited states have been observed for the first time in the neutron-deficient ^{176,178}Hg nuclei using the recoil-decay tagging (RDT) technique in which prompt γ rays are associated with a particular isotope through a correlation with the characteristic ground state α decay. Below $N = 102$, the excitation energy of a rotational band built on a prolate shape ($\beta_2 \sim 0.25$) increases with decreasing mass to the point where there is no longer any evidence for its presence at low spin in ^{176}Hg. The data are in qualitative agreement with recent mean field calculations. [S0031-9007(97)03166-9]

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The chain of Hg isotopes with $180 \leq A \leq 196$ displays a broad variety of nuclear structure phenomena. For $N \geq 110$, the yrast structure at low spin is dominated by weakly deformed oblate rotational bands ($\beta_2 \sim -0.15$) [1]. At moderate spins ($I \sim 20\hbar$), these bands coexist with noncollective prolate ($\gamma = -120°$) excitations [2], and, at the highest spins ($I \sim 40\hbar$), superdeformed states are populated as well [3]. The lighter Hg isotopes ($100 \leq N \leq 110$) exhibit shape coexistence: Sequences of states associated with the small oblate deformation ($\beta_2 \leq -0.15$) characteristic of the ground state coexist with well-developed rotational bands associated with a prolate shape ($\beta_2 \sim 0.25$) [4]. From the level systematics in the even-even Hg isotopes and, in particular, from data on ^{180}Hg [5], the lightest Hg nucleus for which excited states are known, it has been concluded that the excited prolate minimum lies lowest in energy relative to the oblate ground state for neutron number $N = 102$, i.e., in ^{182}Hg. Recent Nilsson-Strutinsky calculations [6] using a Woods-Saxon potential indicate that for neutron number $N < 100$ the oblate ground state evolves steadily as a function of decreasing N towards a spherical shape, while the prolate minimum disappears and gives way to a new minimum at large deformation ($\beta_2 = 0.5 - 0.56$) which is located between 3.5 and 5 MeV above the ground state.

It is clearly of interest to pursue the exploration of the structure of the Hg isotopes towards lower neutron numbers in order to study the evolution of the various minima in the potential energy surface. However, this task becomes increasingly difficult as one approaches the proton drip line. The heavy-ion-induced fusion reactions required to produce the nuclei of interest are dominated by the fission process which results in a very large, unwanted background in the γ-ray spectra. Moreover, the small remaining evaporation-residue cross section is fragmented into many channels. These severe experimental difficulties are overcome by using the recoil-decay tagging (RDT) technique [7], where in-beam γ rays emitted in the decay of excited levels in a nucleus of interest are correlated with the subsequent α decay of the ground/isomeric state. To further enhance the sensitivity of the experiment, the α-decay measurement is performed following the selection of the evaporation residues through the use of a recoil mass separator. Excited states have been unambiguously established in ^{176}Hg and ^{178}Hg, and the excitation energy of the prolate minimum has been inferred from the data. The results are in qualitative agreement with the mean field calculations mentioned above [6].

Excited states in $^{176-179}$Hg were populated with the ^{103}Rh (^{78}Kr, pxn) reactions using 340 and 380 MeV beams delivered by the ATLAS superconducting linear accelerator at Argonne National Laboratory. The Rh target consisted of a single 475 μg/cm^2 self-supporting foil. Prompt γ rays were measured with the AYEBALL array [8], which consisted of an ensemble of 15 Compton-suppressed Ge detectors [7 large- ($\sim$70%), and 8 small-volume (25%) Ge detectors] and 2 low-energy photon spectrometers (LEP) arranged in a spherical geometry around the target. The total photopeak efficiency of the array for 1.3 MeV γ rays was $\sim$1%. The evaporation residues recoiled out of the target into the fragment mass analyzer (FMA), an 8.2-m-long spectrometer which separates reaction products from the beam and disperses them according to their mass/charge (M/Q) ratio at the focal plane [9]. The position of the residues at the FMA focal plane was determined with a position-sensitive parallel-

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grid avalanche counter (PGAC). These residues were subsequently implanted in a 16 mm $\times$ 16 mm, 60 μm thick double-sided Si strip detector (DSSD) located 40 cm behind the PGAC. This DSSD was also used to measure the subsequent α decay of the implanted recoils. The 48×48 segmentation of the DSSD provided effective spatial and time correlations between an implant and the subsequent α decays. Events were written to tape either when the PGAC detector fired in prompt coincidence with the DSSD or when a charged-particle decay was detected in the DSSD. For the coincidence events including the PGAC counter, both the γ-ray array and the DSSD parameters were read out. Further details about the experimental technique can be found in Refs. [10,11].

The spectrum of γ rays in coincidence with $A = 178$ residues, obtained at a beam energy of 340 MeV, is presented in Fig. 1(a). Most of the intense lines in the spectrum correspond to the deexcitation of states in ^{178}Pt [12]. However, the spectrum also contains a number of other transitions whose origin was unknown prior to the present study. The latter are assigned to a particular nucleus from the correlation with characteristic α decays as measured in the DSSD. The spectrum of α particles correlated with $A = 178$ residues is given in the inset in Fig. 1(a). Characteristic α lines from ^{178}Pt (5.45 MeV) [13], ^{178}Au (5.85, 5.92, and 5.95 MeV) [14], and ^{178}Hg (6.43 MeV) [15] were unambiguously identified. [In addition, three other α lines at 6.71, 6.79, and 6.87 MeV are correlated with $A = 178$. These three lines are, in turn, all followed by α decay to the same daughter nucleus, ^{174}Au. They have been associated with the decay of the previously unknown isotope ^{178}Tl [16].] Figure 1(b) shows the γ-ray spectrum obtained by tagging on the ^{178}Hg α line: There are γ rays which are common to this spectrum and to the mass-gated one of Fig. 1(a), but the γ rays associated with ^{178}Pt are absent. On the basis of the α-γ correlations, the transitions labeled by their energy in Fig. 1(b) are assigned to the deexcitation of levels in ^{178}Hg. Their placement in the ^{178}Hg level scheme (second inset in Fig. 1) was confirmed from the analysis of the coincidence relationships derived from the γ-γ matrix gated on residues. This is illustrated by Fig. 1(c), where the sum of coincidence spectra gated on the strongest ^{178}Hg transitions is seen to be nearly identical to the α-γ spectrum of Fig. 1(b). The ordering of the transitions is based on intensity considerations. The measured angular distribution of the most intense γ rays establishes their stretched $E2$ character, thereby confirming the spin values given in Fig. 1. As can be inferred from Fig. 1(c), the γ-ray coincidence data are rather limited in statistics, and the placement of weaker ^{178}Hg transitions into the level scheme was not possible.

In order to identify states in ^{176}Hg, the beam energy was increased to 380 MeV. The γ-ray spectrum measured in coincidence with $A = 176$ residues [Fig. 2(a)] is dominated by transitions in ^{176}Pt [12]. The inset of Fig. 2(a)

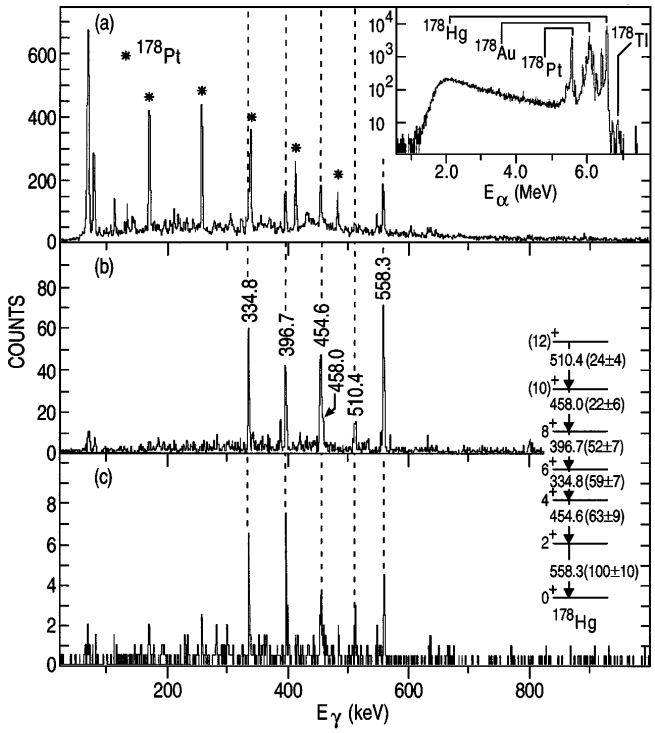

FIG. 1. Sample spectra relevant for the ^{178}Hg data: (a) projection of all γ rays in coincidence with mass $A = 178$; (b) γ rays correlated with the ^{178}Hg α decay (the charged-particle spectrum is shown in the top inset); (c) sum of coincidence spectra gated on the transitions assigned to the ^{178}Hg level scheme given in the second inset. The measured total intensities are given in parenthesis next to the transition energies in the level scheme. See text for a detailed discussion.

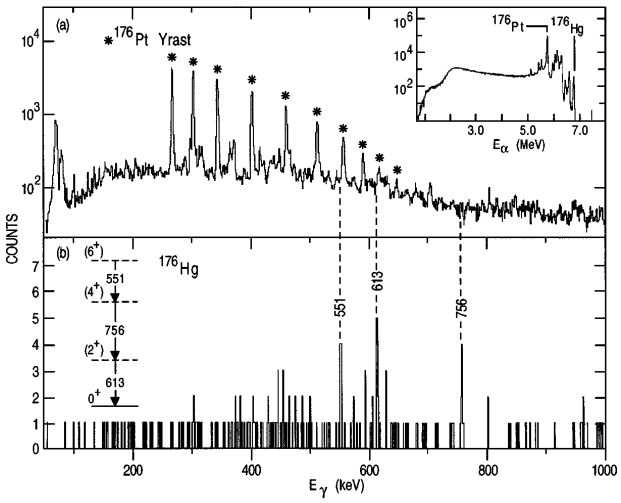

FIG. 2. Sample spectra relevant for the ^{176}Hg data: (a) projection of all γ rays in coincidence with mass $A = 176$; (b) γ rays correlated with the ^{176}Hg α line. The charged-particle spectrum from the DSSD is shown in the top inset. The second inset shows the level scheme for ^{176}Hg deduced from the present measurements. The levels are marked as dashed lines to indicate that the ordering is uncertain. See text for a detailed discussion.

presents the decay spectrum measured in the DSSD: α lines associated with the decay of both ^{176}Pt (E_α = 5.75 MeV) [13] and ^{176}Hg (E_α = 6.75 MeV) [17] are present. It is worth noting that the ^{176}Pt α line dominates the ^{176}Hg one by a ratio of $\sim$300 : 1. Nevertheless, transitions were unambiguously assigned to ^{176}Hg from the α-γ correlations: This is shown in Fig. 2(b), where three γ rays are observed. The data set was not sufficient to confirm the ordering of the transitions from the inspection of a γ-γ coincidence matrix. Rather, the three γ rays of 613, 756, and 551 keV were placed in the level scheme of Fig. 2 on the basis of their relative intensities (100 $\pm$ 25, 71 $\pm$ 21, and 58 $\pm$ 19, respectively). Because of the limited statistics, this ordering should be regarded as tentative. These transitions are assumed to represent the $6^+ - 4^+ - 2^+ - 0^+$ cascade on the basis of systematics.

The data presented here can be compared with the systematics of low-level excitations throughout the Hg isotopic chain (Fig. 3) as well as with the recent mean field calculations of Ref. [6]. These calculations predict a change in the potential energy surface at low spin when going from ^{180}Hg to ^{170}Hg. The oblate ground state which coexists at low spin with the excited prolate minimum is calculated to give way progressively (with decreasing mass) to a single, spherical minimum. In these calculations, ^{176}Hg and ^{178}Hg can then be regarded as transitional nuclei with potential energy surfaces calculated to be nearly flat over the deformation region $\beta_2 = -0.15$ to 0.15. Experimental evidence for this gradual change in ground state deformation would come from (i) an increase in the 2^+ energies in the ground band with decreasing mass as well as from (ii) the disappearance of the deformed prolate band.

From Fig. 3 it is clear that the excitation energy of the first 2^+ level increases substantially below ^{180}Hg: While this state is located around 400 keV in all even-even Hg isotopes with $180 \leq A \leq 196$, the excitation energy exceeds 550 keV in ^{178}Hg and 600 keV in ^{176}Hg. However, some caution is in order, as it should be realized that the actual 2^+ excitation energy can be lowered by the interaction with the 2^+ state in the prolate band. A recent band-mixing calculation [18], using the prescription described in Ref. [19], deduces the unperturbed 2^+ energies to be 426 keV in ^{184}Hg, and 574 and 573 keV in ^{182}Hg and ^{180}Hg, respectively. Using the same procedure with the present data results in an unperturbed 2^+ excitation energy of 582 keV in ^{178}Hg and 623 (or 756) keV in ^{176}Hg. Thus, the data suggest that the transition towards a spherical ground state starts around midshell, i.e., in ^{182}Hg, and that the shape change occurs gradually with decreasing mass. [In addition, Ref. [18] has compared the unperturbed 2^+ energies for a number of nuclei in this region as a function of the product of valence protons and valence neutrons ($N_\pi N_\nu$). The present data are consistent with the trend of increasing 2^+ energies with decreasing $N_\pi N_\nu$.]

The present data also provide new information about the evolution of the excitation energy of the prolate band with mass (Fig. 3). In most even-even Hg isotopes with $N < 110$, the presence of the prolate band is readily visible from the inspection of the yrast sequence: The energy of the γ-ray transitions decreases drastically at the point where this band (with its larger moment of inertia) crosses the ground band. In fact, in several isotopes, level sequences built on both prolate and oblate structures are observed before and after the crossing, and, as a result, it is possible to extract the location in energy of the unperturbed prolate and oblate states as well as the interaction strength between the two bands [4]. Additional supporting information is often provided by α-decay work, as fine-structure studies have identified the 0^+ excited state associated with the prolate band down to ^{182}Hg [20]. Typically, the interaction strength between the two bands is deduced to be of the order 80–100 keV. In cases where only the yrast sequence is observed, the interaction strength and the excitation energy of the unperturbed levels cannot be extracted directly from the data. Reliable estimates of these quantities can, however, be obtained from a simple two-band-mixing model, such as the one presented in Ref. [19]. The two unperturbed bands were described with a VMI parametrization, and the model parameters (i.e., the VMI parameters for each band, the interaction strength, and the relative excitation energy of the band heads) were derived from a fit to the data. During this procedure, it was checked that the fitting parameters remained close to values reported in a systematic study of neighboring nuclei [18]. With this technique, the unperturbed prolate band head of ^{178}Hg is calculated to lie $\sim$710 keV above the unperturbed ground state, and the interaction strength between the two bands is about 100 keV. Thus, the unperturbed prolate band, which is located 334 keV above the ground state in ^{184}Hg and is at its lowest energy in ^{182}Hg (264 keV) [18], continues to rise from 387 keV to 710 keV between ^{180}Hg

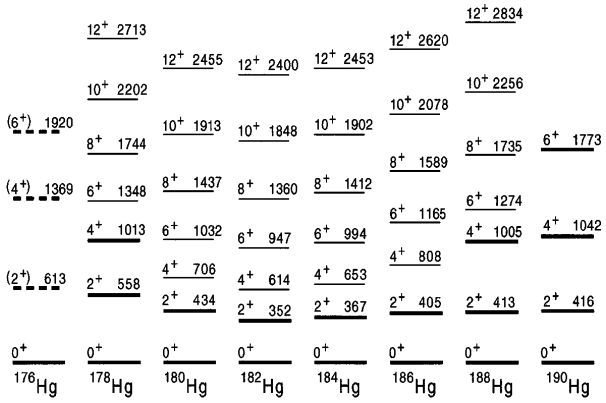

FIG. 3. Systematics of the low spin, yrast level structure in the even-even Hg isotopes, including the data on the two most neutron-deficient nuclei which were obtained in the present work. Thick lines correspond to states of the same intrinsic structure as the ground state. Thin lines are for the levels associated with the structure of prolate deformation.

and ^{178}Hg, in agreement with the mean field calculations of Ref. [6].

Furthermore, these same calculations [6] do not show a prolate minimum at zero spin for $N = 96$. This is not inconsistent with the proposed level scheme for ^{176}Hg. The three ^{176}Hg transitions have energies >550 keV, in contrast with the ^{178}Hg spectrum where the well-developed rotational (prolate) sequence starts with a 335 keV γ ray and all transitions placed in the level structure have $E_\gamma <$ 560 keV. On the basis of the present data, which are limited to the first three excited states, the presence of a prolate minimum can, however, not be entirely ruled out. For example, it is conceivable that the proposed 6^+-4^+ transition has a lower energy than the 4^+-2^+ one because of the compression in energy of the 6^+ level by the interaction with an excited prolate band. If this band interaction were present, the prolate band head would be located $\sim$1300 keV above the ground state, using the two-band-mixing model described above with the VMI parameters of the ^{178}Hg prolate band and a 100 keV interaction strength. Even though the ordering in the ^{176}Hg cascade is uncertain (see discussion above), any reordering of the transitions would imply a higher excitation energy for the prolate band, within the two-band-mixing model. Thus, at the very least, the present data indicate that the excitation energy of the prolate band increases rapidly with decreasing mass number, and the minimum may well have disappeared by $N = 96$, as predicted by the calculations. The excitation energy of the prolate minimum below $N =$ 102 mirrors the behavior seen above this number (Fig. 3): A rapid rise is seen for $N = 110$ with the prolate 0^+ state jumping from 825 keV at $N = 108$ to 1279 keV.

To summarize, the long chain of Hg isotopes has been extended towards the proton drip line by obtaining spectroscopic information on the yrast sequences of ^{178}Hg and ^{176}Hg. The detection sensitivity required to extract the weak signals from the copious fission background was provided by the RDT technique. The analysis of the data now indicates that the level structure associated with prolate deformation coexists with the oblate (or nearly spherical) ground state from $N = 110$ all the way down to at least $N = 98$. The prolate minimum comes closest in energy to the ground state at $N = 102$, and, as illustrated in Fig. 3, its behavior with N appears to be rather symmetric around $N = 102$. This behavior is in qualitative agreement with the recent mean field calculations of Ref. [6].

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