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First observation of excited structures in neutron-deficient ^{179}Hg: evidence for multiple shape coexistence

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Abstract

Excited structures in the neutron-deficient nucleus ^{179}Hg have been established for the first time using the Gammasphere spectrometer in conjunction with the fragment mass analyzer. Competing states originating from *three* different minima associated with nearly spherical, oblate, and prolate deformations were found. This result can be contrasted with the situation in heavier odd-mass Hg isotopes where only two minima (oblate and prolate) have been seen. The implications of these three shapes at low spin and excitation energy are discussed in the general context of shape coexistence in this mass region.

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The observation of excitations associated with different shapes in a single nucleus is a phenomenon commonly referred to as shape coexistence, and nuclei around the $Z = 82$ shell gap provide some of the best examples known so far. While the observed spherical shapes are attributed to the $Z = 82$ shell

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closure, the deformed shapes have been associated with particle–hole excitations into $h_{9/2}$, $f_{7/2}$ and $i_{13/2}$ low-Ω (prolate) and high-Ω (oblate) proton intruder orbitals [1,2]. Furthermore, calculations by Bengtsson and Nazarewicz [3], and Nazarewicz [4], as well as systematic studies of mid-shell ($N \sim 104$) nuclei by Dracoulis [5] have stressed the importance of more complicated multi-particle–hole excitations in the formation of the deformed minima.

Neutron-deficient, even–even Hg ($Z = 80$) isotopes exhibit a coexistence at low spin between two shapes: a weakly deformed *oblate* ground state and a more deformed, excited, *prolate* band. The energy difference between the two minima exhibits a parabolic trend as a function of neutron number and minimizes around mid-shell with a magnitude of ~ 260 keV [6]. Starting around mid-shell, the ground state deformation decreases steadily with decreasing neutron number and a near spherical shape is reached by ^{176}Hg ($N = 96$) [7]. In contrast, the ground states of the odd-mass, ^{181,183,185}Hg ($N = 101, 103, 105$) isotopes are associated with a prolate shape. This was first determined from the measured changes in the nuclear mean square charge radii and magnetic moments [8,9]. Additional compelling evidence of shape coexistence comes from the discovery of rotational bands built on the ground states in these nuclei [10–12]. In addition, a weakly-deformed, *oblate* high-spin ($J^\pi = 13/2^+$) isomer has been identified in each of the three odd-mass Hg isotopes, albeit the excitation energies have not been established. The mechanism responsible for this preferred prolate shape at low spin in the odd-mass isotopes is still not understood, and several explanations have been proposed [13,14]. Interestingly, the ^{186}Pb ($N = 104$) and ^{175}Au ($N = 96$) nuclei have recently been observed to form *three* minima at low spin, associated with near-spherical, oblate, and prolate shapes [15,16].

Based on the experimental results available at present, it is hard to predict which type of structures will be observed in the neutron-deficient odd-A Hg isotopes ($N < 100$). In particular, it is of interest to map out the evolution of the single-particle states for both the prolate and oblate shapes in the lightest odd-A isotopes and to compare these with trends observed in the even–even Hg neighbors [7,17–19]. This Letter reports on the first observation of excited structures in the neutron-deficient, odd-mass nucleus ^{179}Hg ($N = 99$). In contrast to the heavier odd-mass Hg isotopes, competing states originating from *three* different minima were observed. They are associated with a nearly spherical, a weakly-deformed oblate, and a well-deformed prolate shape. It is worth noting that this is the lightest odd-mass Hg isotope where excited structures have been identified.

Excited states in ^{179}Hg were populated with the ^{90}Zr(^{90}Zr, n) reaction using 369 and 380 MeV beams delivered by the ATLAS superconducting linear accelerator at Argonne National Laboratory. The target consisted of a self-supporting, ~ 500 µg/cm^2 thick foil enriched up to 97.65% in ^{90}Zr. Due to the large negative Q value (−157.3 MeV [20]) for this reaction, the compound nucleus was formed at the relatively low excitation energies of $E^* = 23.5$ and 29.0 MeV (assuming production in the middle of the target), thus, minimizing competition from fission and charged particle evaporation. In order to accommodate beam intensities as high as 5 pn$A$, the targets were mounted on a rotating wheel, and the beam was wobbled ±2.5 mm vertically across the target by a magnetic steerer. Prompt γ rays were measured with the Gammasphere array [22], consisting, for these experiments, of 101 large volume escape-suppressed Ge detectors. Evaporation residues recoiled out of the target into the Argonne Fragment Mass Analyzer (FMA) where they were dispersed at the focal plane according to their mass-to-charge (M/q) ratio [21]. A 7 µg/cm^2 thick carbon foil was located ~ 8 cm behind the target to reset the charge state distribution of the recoils. A position-sensitive parallel grid avalanche counter (PGAC), located at the focal plane, provided the M/q information as well as time of arrival and energy-loss signals of the evaporation residues. The recoiling nuclei were subsequently implanted into a 40×40 strips (40 mm × 40 mm, ~ 60 µm thick), double-sided silicon strip detector (DSSD) located 40 cm behind the PGAC. The DSSD was used not only to detect the implantation of a residue, but also to measure its subsequent α decay(s). By utilizing this experimental setup, the Recoil Decay Tagging (RDT) technique[23] could be used to provide unambiguous nuclide identification to in-beam γ rays. During the experiment, a total of 5.8×10^7 events were written to tape either when two or more Gammasphere detectors fired in coincidence with the PGAC, or when a recoil (implant event) or charged-particle (decay event) was detected in the DSSD.

To isolate the ^{179}Hg residues and the corresponding prompt γ rays from the dominant background originating from scattered beam, fission products, and de-excitations in neighboring isotopes, coincidence gates were placed in the off-line analysis on (i) the time of flight of the evaporation residues from the target to the focal plane, (ii) the PGAC positions corresponding to three charge states ($q = 31$, 32 and 33) of ions with the appropriate $A = 179$ mass focus, and (iii) the two-dimensional histogram of the energy of recoils measured in the DSSD vs. the time of flight from the PGAC to the DSSD. The data were then sorted in prompt γ–γ coincidence matrices gated in several ways on the information from the PGAC and the DSSD as detailed, for example, in Ref. [19]. In general, the most stringent coincidence relationships involved a correlation with mass 179 and the characteristic ^{179}Hg α-decay line of $E_\alpha = 6288(5)$ keV [25]. The spectrum showing the γ rays correlated with this α line is presented in Fig. 1(a). Most of the γ rays placed in the ^{179}Hg level scheme (Fig. 2) were established from such data. Levels with spins as high as $(49/2)\hbar$ have been observed even though the bombarding energy was only slightly above the Coulomb barrier. For the weakest transitions, coincidence events gated only on mass 179 were also used. This approach takes advantage of the higher statistics of these data, while relying on the power of the high-fold γ-ray coincidence relationships to provide unambiguous placements. Sample coincidence spectra for the three main sequences seen in the experiment are presented in Figs. 1(b)–(d). Information on the multipolarity of the transitions was obtained from mass- and α-gated angular distribution data. For the weaker γ rays, $I_\gamma(34°)/I_\gamma(90°)$ anisotropy ratios were used instead (see Ref. [19] for details). A two-dimensional histogram with the energies of the first generation α decays on one axis and the difference between the implantation and α-decay times on the other was also constructed. The α energy, $E_\alpha = 6286(4)$ keV, and half-life, $T_{1/2} = 1.00(5)$ s, measured here are in good agreement with previously reported values [25].

Based on the deduced α-decay reduced widths, which are sensitive to changes in the angular momenta between initial and final states, and on the known experimental information about the daughter (^{175}Pt) [24,25] and grand-daughter (^{171}Os) [26] nuclei, the ground state of ^{179}Hg is firmly assigned $J^\pi = 7/2^-$. Specifically, following the prescription by Preston [27], the measured hindrance factor for the 6286(4) keV α transition was determined to be 1.31(7), using a radius parameter $r_0(^{175}\mathrm{Pt})$ of 1.556(3) fm deduced as an average from data on the neighboring even–even ^{174}Pt ($N = 96$) and ^{176}Pt ($N = 98$) nuclei [28]. This small value argues for a $l = 0$ decay and establishes the ^{179}Hg ground state to have the same $J^\pi = 7/2^-$ quantum numbers as those of the corresponding state in the ^{175}Pt daughter. In contrast, the heavier isotopes ^{181,183,185}Hg have a $1/2^-$ ground state spin and parity [10–12]. Three collective bands have been placed in the level scheme shown in Fig. 2. They are associated with a well deformed prolate deformation due to similarities with neighboring odd-N nuclei. Band 1 consists of two rotational cascades connected at low spins by $\Delta J = 1$ transitions and is observed up to $(43/2^-)$. The $15/2^-$ and $17/2^-$ in-band levels decay via the 331.5 and 392.1 keV stretched quadrupole transitions to intermediate levels. A second rotational band, band 2 in Fig. 2, consisting of a single cascade of stretched quadrupole transitions is observed up to $(45/2^-)$. Based on similarities with the heavier ^{181,183,185}Hg isotopes [10–12], and with the isotone ^{177}Pt [29], the lowest in-band level is assigned $(5/2^-)$. Two transitions, with energies of 215.8 and 400.4 keV, appear to be associated with the depopulation of the band to the $7/2^-$ ground state, but their exact placement could not be established. Band 3 consists of two rotational cascades linked by $\Delta J = 1$ transitions. The spins and parity of the in-band levels follow from the measured angular correlations and from the assumption that the band decays into a $(13/2^+)$ isomeric state originating from the *oblate* $i_{13/2}$ configuration as assigned in the heavier odd-A Hg isotopes [10–12]. The band transfers most of its intensity to the oblate isomeric state from the $(17/2^+)$ and $(15/2^+)$ in-band levels, rather than from the lower spin members, via the 479.9 keV E2 ($A_2/A_0 = 0.23(7)$, $A_4/A_0 = -0.01(9)$) and the 378.1 keV M1/E2 ($A_2/A_0 = -0.20(11)$) transitions presumably due to the interaction between the prolate and oblate $(13/2^+)$, and possibly the $(17/2^+)$, states. With regards to the proposed long-lived state, it must have a significant γ-ray decay branch since the γ rays that precede the isomer were found to be correlated

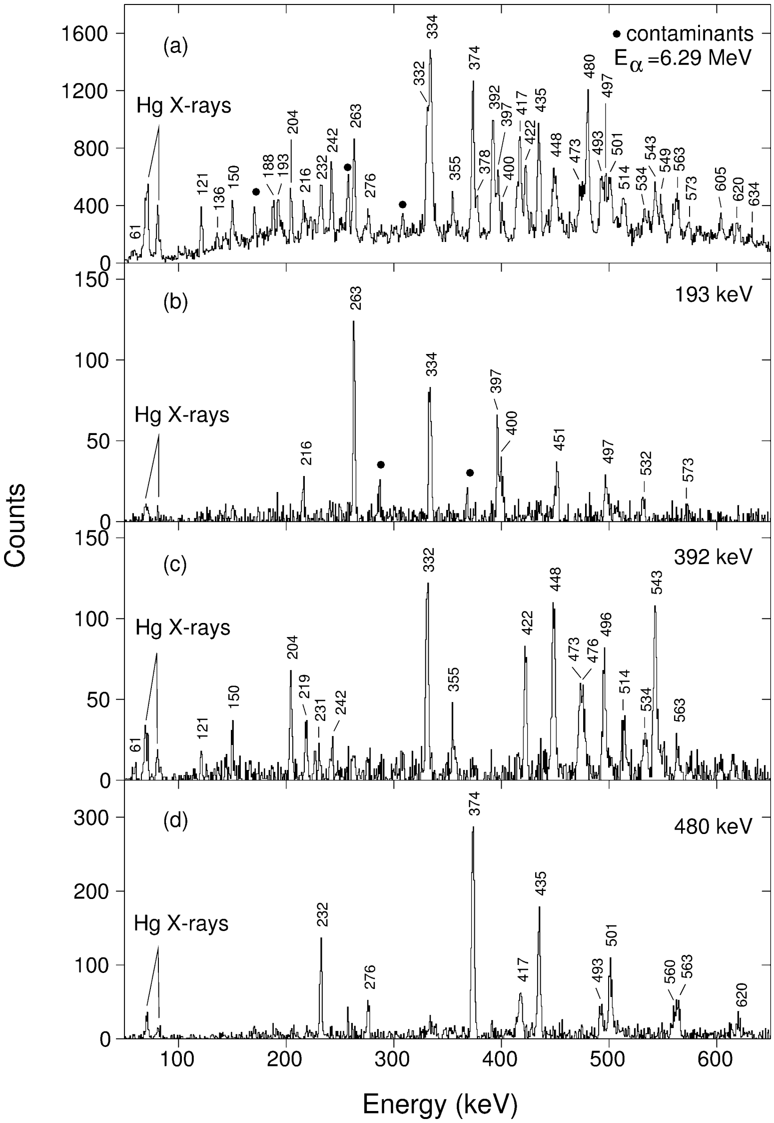

Fig. 1. (a) Spectrum of γ rays in coincidence with the ^{179}Hg α-line of $E_\alpha = 6286(4)$ keV. (b)–(d) Sample, background-subtracted, γ-ray coincidence spectra from the recoil-γ–γ matrix. The gating transitions are indicated. The contaminant γ rays correspond to identified transitions in ^{179}Au.

with the α decay of the ground state. From the present work, the excitation energy of the isomer remains unknown as no linking transitions to the $7/2^-$ ground state were found, presumably because of the long lifetime of the former.[3]

The interpretation of the level structure in terms of the associated configurations and shapes is based on (i) measured properties such as spin, parity, branching

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[3] A recent, dedicated delayed coincidence measurement of the properties of the α decay of ^{183}Pb into ^{179}Hg by Jenkins et al. [30] confirms the presence of the $i_{13/2}$ isomer and places this state at an excitation energy of ~ 170 keV with a half-life of ~ 5 μs. Thus, the structure of this isomer is analogous to that of the isomers seen in the heavier odd-A Hg isotopes where, as stated above, the oblate shape is established firmly from the measured isotope shifts [9].

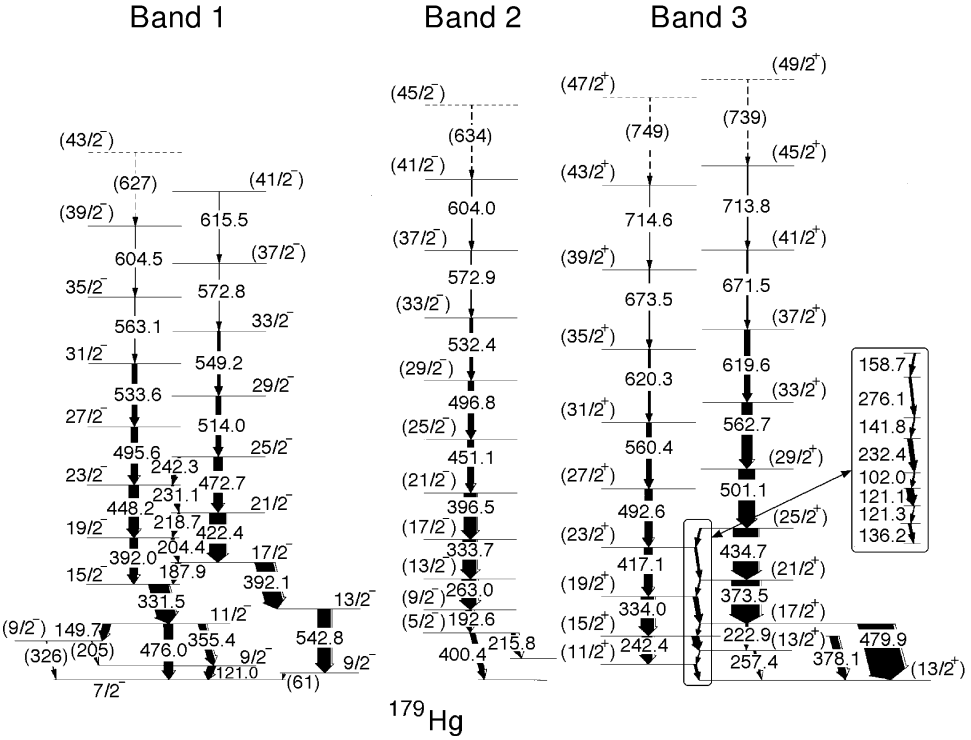

Fig. 2. Proposed ^{179}Hg level scheme. For each transition the width of the arrow is proportional to the measured γ-ray intensity. Tentative placements are indicated by dashed lines. Tentative spin-parity assignments are given in parenthesis. The relative excitation energies of bands 2 and 3 with respect to band 1 are unknown (see text for details).

ratios and alignments, (ii) considerations about which neutron orbitals lie nearest to the Fermi surface, and (iii) similarities with structures observed in neighboring odd-mass Hg and Pt nuclei. Due to the strong presence of E2 cascades connecting the ground state with band 1, one might be inclined to associate the $7/2^-$ state with the rotational structure. However, the sequence develops its regular rotational character only above the $15/2^-$ level. Thus, the ground state is most likely not a member of band 1. This property is strikingly evident in the alignment plot shown in Fig. 3 where a sharp gain in alignment and a reduction in frequency can be seen at low spin. In addition, the decay out of the $11/2^-$ state is somewhat fragmented giving further evidence that the configuration of the ground state is different from that of band 1.

An assignment of a well deformed prolate configuration to the ground state of ^{179}Hg is not easily explained by considering the orbitals nearest to the Fermi surface. For $\beta_2 \sim 0.25$, the available states are the

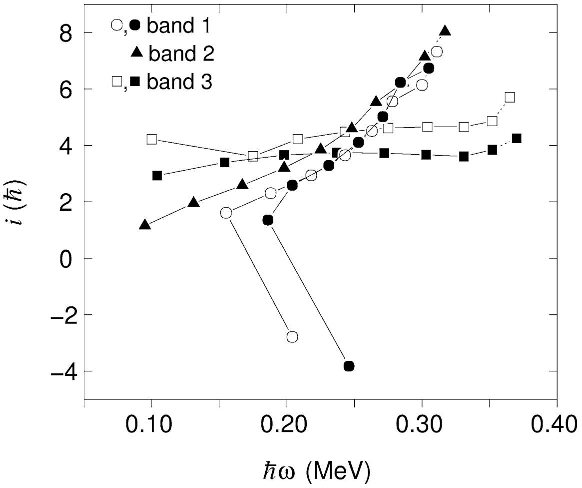

Fig. 3. Aligned angular momenta, i, as a function of rotational frequencies, $\hbar\omega$, for the bands observed in ^{179}Hg. In all cases a common reference was subtracted with the Harris parameters of $J_0 = 28\,\hbar^2$ MeV^{-1} and $J_1 = 160\,\hbar^4$ MeV^{-3}.

$5/2^-[512]$ ($f_{7/2}$), $7/2^+[633]$ ($i_{13/2}$) and $1/2^-[521]$ ($p_{3/2}$) orbitals, and none of these provides the correct spin and parity for the band head. Another possibility is to assign the ground state to a configuration associated with a weakly deformed oblate shape. However, the orbitals closest to the Fermi surface for $\beta_2 \sim -0.15$ ($13/2^+[606]$ ($i_{13/2}$) and $1/2^-[541]$ ($h_{9/2}$)) are also incompatible with the $7/2^-$ assignment. Two likely candidates for the ground-state configuration are the $7/2^-[514]$ and $7/2^-[503]$ orbitals arising from the $f_{7/2}$ and $h_{9/2}$ shells, respectively. These orbitals come close to the Fermi level only for very small prolate deformations ($\beta_2 < 0.15$). Such a nearly spherical shape has been invoked to account for the low-spin properties in the yrast bands of ^{174,176}Pt [31–33] and for the ground state of ^{175}Pt [34]. It is also the most probable assignment for the ground state of ^{179}Hg. With this in mind, it is likely that the $9/2^-$ level that decays by the 121.0 keV γ ray, and the $11/2^-$ level, which decays to the ground state via a 476.0 keV transition, are members of a weakly deformed band associated with the ground state. It also appears that the ground-state configuration mixes with other single-particle states as indicated by the fragmented decay of the $11/2^-$ state to two other non-yrast $9/2^-$ states.

The three rotational bands observed to high spin are interpreted as prolate-deformed based on similarities to neighboring odd-N nuclei, and the configuration assignments are rather straightforward. Band 1 is associated with the $5/2^-[512]$ configuration, and is nearly identical to the rotational sequence built on the same orbital in the isotone, ^{177}Pt [29]. A g_K factor of $-0.36(3)$ extracted from the measured branching ratios, assuming $Q_0 = 7.0\ e\,\mathrm{b}$ and $g_R = 0.3$, compares well with the value of $g_K = -0.4$ predicted for the $5/2^-[512]$ neutron orbital using a Woods–Saxon potential [36] with deformation parameters $\beta_2 = 0.24$ and $\beta_4 = 0.021$. The sign of the g_K values has been unambiguously determined from the measured negative angular distribution coefficients of the strongest $\Delta J = 1$ in-band transitions at 187.9 keV ($A_2/A_0 = -0.36(9)$) and 204.4 keV ($A_2/A_0 = -0.45(7)$). The observation of a single rotational sequence without a signature partner is usually associated with a low-Ω ($\Omega = 1/2$) configuration, and this is the case for band 2. Taking into account the orbitals expected near the Fermi surface, as well as similarities with structures reported in the heavier ^{181,183,185}Hg [10–12] isotopes and in the isotone ^{177}Pt [29], band 2 is assigned the $1/2^-[521]$ ($p_{3/2}$) configuration. As mentioned previously, band 3 is assumed to feed the $13/2^+$ isomer, and it is given the $7/2^+[633]$ (mixed $i_{13/2}$) assignment. This band exhibits signature splitting as expected for $i_{13/2}$ excitations built on a prolate shape with moderate deformation ($\beta_2 = 0.25$). In addition, the measured $g_K = -0.05(1)$ value compares well with the expectation of -0.06, deduced when the alignment of the strongly Coriolis mixed $i_{13/2}$ orbital is taken into account in accordance with Ref. [35]. Further support for the configuration assignments proposed above comes from the alignment properties shown in Fig. 3. For example, the upbend observed for bands 1 and 2 at $\hbar\omega \sim 0.24$ MeV results from an alignment of a pair of $i_{13/2}$ quasineutrons. In band 3, the first band crossing does not occur until $\hbar\omega \sim 0.37$ MeV. This observation finds a natural explanation if the $i_{13/2}$ orbital is involved in the configuration of band 3, but not in the configuration of bands 1 and 2. It is worth re-emphasizing that the satisfactory picture that emerges, e.g., an interpretation of the bands as collective prolate structures requires the deformations to be quite large ($\beta_2 \sim 0.25$). Specifically, the properties of the bands (alignments, g_K-factors, etc.) cannot be satisfactorily explained if the ground state deformation ($\beta_2 < 0.15$) is assumed to be associated with these bands.

Total Routhian Surface (TRS) calculations based on a Woods–Saxon potential (see, for example, [37]) were examined to ascertain the predicted deformations for the lowest lying one-quasiparticle prolate deformed states (see Table 1). Earlier particle-rotor model calculations predicted the deformation of the $1/2^-[521]$ band in ^{177}Pt to be approximately 20% larger than that associated with the $5/2^-[512]$ orbital [29]. Similar calculations for ^{179}Hg yield quadrupole deformations of $\beta_2 = 0.265$ and 0.243 which are in agreement with the predictions of the TRS calcu-

Table 1
Equilibrium deformations for prolate structures in ^{179}Hg extracted from the TRS calculations at $\hbar\omega = 50$ keV

Configuration	β_2	β_4	γ (deg)
$1/2^-[521]$	0.260	0.023	−2.1
$5/2^-[512]$	0.240	0.021	−1.4
$7/2^+[633]$	0.256	0.022	−4.6

lations ($\beta_2 = 0.260$ and 0.240) for these two orbitals. The similarity in deformation of the negative-parity, prolate structures in ^{177}Pt and ^{179}Hg implies that the addition of two extra protons does not change significantly the deformation driving properties of these configurations.

In summary, we have identified for the first time excited structures in the neutron-deficient nucleus ^{179}Hg. Along with three prolate deformed bands, structures associated with an oblate and a near spherical shape are also observed. While the observation of a third shape is somewhat unexpected, it is not necessarily surprising in light of the shift towards sphericity observed in ^{176,178}Hg [7], and of the recent observation of a triad of similar shapes in ^{175}Au [16].

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