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# Confirmation of triple shape coexistence in $^{179}$Hg: Focal plane spectroscopy of the $\alpha$ decay of $^{183}$Pb

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The $\alpha$ decay of $^{183}$Pb has been studied in detail at the focal plane of the RITU gas-filled separator. The four previously known $\alpha$ decay branches have been ordered into the decay of two isomers in $^{183}$Pb. The deduced decay scheme and the interpretation of the inferred $\alpha$ decay hindrance factors and $\gamma$ rays observed at the focal plane are strongly in favor of the recent suggestion of triple shape coexistence—oblate, prolate, and near-spherical in the daughter nucleus $^{179}$Hg.

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Shape coexistence is a common phenomenon in the light lead and mercury isotopes [1]. While all the known lead isotopes are believed to have spherical ground states, it is now well-established that, in the light lead nuclei, a prolate intruder configuration becomes yrast at low spin, reaching a minimum for neutron number $N=103$ [2,3]. The most impressive example to date of shape coexistence in the light lead nuclei has been found in $^{186}$Pb, where the lowest three states populated in the $\alpha$ decay of $^{190}$Po all have $J^{\pi}=0^{+}$ and were inferred to be associated with spherical, oblate, and prolate minima, respectively [4].

In the light odd-$A$ mercury isotopes, $^{181,183,185}$Hg, a similar situation pertains. However, in this case the competition is between low-lying prolate rotational bands and excited configurations built on a $13/2^{+}$ oblate isomer [5–7]. Two recent studies by Kondev *et al.* have supplied evidence for a new phenomenon in the context of both the light mercury and gold isotopes, namely, the existence of three different shapes: oblate, prolate, *and* near-spherical, at low excitation in $^{179}$Hg [8] and $^{175}$Au [9]. In the case of $^{179}$Hg, the basis of this assignment rests on the interpretation of a high-spin decay scheme obtained by correlating $\gamma$ rays detected in the Gammasphere array with recoils and the characteristic $^{179}$Hg $\alpha$ decay at the focal plane of the Fragment Mass Analyzer (FMA) [8]. This analysis of the $^{179}$Hg decay scheme differs strongly from the known oblate/prolate shape coexistence in the heavier odd-$A$ mercury isotopes and it is, therefore, necessary to obtain additional information to further constrain this interpretation.

An independent approach to the issue of shape coexistence, and a technique which has been successfully employed in locating the triplet of $0^{+}$ states in $^{186}$Pb [4] among others, is to study the $\alpha$ decay into the nucleus of interest. $\alpha$ decay may be particularly revealing since it is very sensitive to the structure of low-lying states in both the parent and daughter nuclei. Analysis of decay branches, lifetimes, $\gamma$ rays correlated with $\alpha$ decays at the focal plane, and especially $\alpha$ decay hindrance factors, may be highly instructive.

In the present Rapid Communication, we have aimed to investigate the claimed shape coexistence in $^{179}$Hg by studying the $\alpha$ decay of $^{183}$Pb. A 200 MeV $^{42}$Ca beam from the $K=130$ cyclotron at the University of Jyväskylä was incident on a target consisting of two stacked 500 $\mu$g/cm$^2$ self-supporting $^{144}$Sm metallic foils, producing $^{183}$Pb via the $^{144}$Sm($^{42}$Ca,3$n$) reaction. Gamma rays at the target position were detected by the JUROSPHERE II array consisting of seven TESSA-type [10], five Nordball [11], and 15 Eurogam Phase I detectors [12]. Fusion-evaporation residues were separated from scattered beam and fission products using the RITU gas-filled separator. The fusion products were implanted in a 80 mm×35 mm silicon strip detector at the focal plane. The subsequent $\alpha$ decay of these residues was recorded in the strip detector and the $\alpha$ decay spectrum was calibrated using the known activities of $^{180}$Hg, $^{179}$Hg, and $^{176}$Pt. The focal plane was surrounded by three Nordball [11] and two TESSA-type [10] Ge detectors affording a total efficiency of about 1% at 1.3 MeV.

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TABLE I. $\alpha$ particle energies, $Q_\alpha$ values, absolute intensities, branching ratios, and $\alpha$ decay hindrance factors (HF) for the $\alpha$ decay of $^{183}$Pb. HF are calculated assuming no angular momentum change, $\Delta L=0$, and under the assumption that $\alpha_{br}=100\%$ taken from systematics. HF are evaluated relative to the reduced $\alpha$ widths for the $0^+ \rightarrow 0^+$ $\alpha$ decays of the neighboring even-even lead nuclei using the Rasmussen prescription [23]. The table is divided into those decays from the low-spin isomer (top) and the high-spin isomer (bottom).

| From Ref. [16] | | Present work | | | | |
|---|---|---|---|---|---|---|
| $E_\alpha$ (keV) | $I_\alpha$ (%) | $E_\alpha$ (keV) | $Q_\alpha$ (keV) | $I_\alpha$ (%) | Branch (%) | HF |
| 6579(15) | 5.5(20) | 6570(10) | 6717(10) | 4.3(6) | 28(4) | 2.0(4) |
| 6781(15) | 20(4) | 6775(7) | 6926(7) | 11.0(8) | 72(5) | 4.4(5) |
| 6712(10) | 72(4) | 6698(5) | 6848(5) | 82.7(5.4) | 97(6) | 1.3(1) |
| 6874(15) | 2.5(10) | 6860(11) | 7013(11) | 1.9(5) | 3(1) | 203(55) |

Two $\alpha$ decay lines were initially reported for $^{183}$Pb by Schrewe *et al.* [13]; this original work was subsequently confirmed by Toth *et al.* [14]. Later work such as that of Keller *et al.* [15] and Toth *et al.* [16] resolved four distinct $\alpha$ decays (see Table I). However, prior to the present work, the detailed $\alpha$ decay scheme for $^{183}$Pb had not been established, and it was assumed that the four $\alpha$ decays represented branches from a single $\alpha$ decaying state. The present work confirms the existence of these four previously known $\alpha$ decays (see Fig. 1) and, for the first time, with the added possibility of studying correlations with $\gamma$ rays in *both* prompt and delayed coincidence with the $\alpha$ decay at the focal plane, we have been able to construct a consistent scheme for the $\alpha$ decay of $^{183}$Pb (see Fig. 2).

Each of the four observed $\alpha$ lines is seen to be correlated with the single known $\alpha$ line in the daughter nucleus, $^{179}$Hg (see Fig. 3). This clearly demonstrates that all of the $\alpha$ decays proceed directly or indirectly to a single $\alpha$-decaying state in $^{179}$Hg. Moreover, measuring the lifetimes associated with the four $\alpha$ decays allows them to be divided into two pairs of decays from two different states—one with a half-life of 415(20) ms and one with a half-life of 535(30) ms (see Fig. 2). These values supersede earlier half-life measurements in the literature which present only one half-life for all the observed activity, variously quoted as 300(80) ms [13] and a later value of 433(236) ms [17]. The details of the observed $\alpha$ decays are presented in Table I and exhibit good correspondence in terms of $\alpha$ particle energies and branching ratios with the earlier work of Toth *et al.* [16]. Since in this earlier work the activity was not implanted in the detector but rather was transported and implanted on a rotating wheel with a detector at some distance away, the effects of electron summing will have been minimal [16], and we can safely infer from the close correspondence in branching ratios between these independent studies, that the $\alpha$ peaks observed in the present work originate solely from $\alpha$ decays and do not represent spurious peaks due to electron summing.

Observing coincidences with $\gamma$ rays at the focal plane, we find that the 6698(5) keV and 6570(10) keV $\alpha$ decays feed excited states in $^{179}$Hg which decay by $\gamma$ emission. The 6698(5) keV $\alpha$ decay is correlated with two $\gamma$ rays with energies of 110.8(3) and 60.6(2) keV which are in prompt coincidence with each other, but in delayed coincidence with the emission of the $\alpha$ particle [see Fig. 4 (bottom)]. The half-life of the isomeric state at 172 keV from which these transitions decay is determined to be 6.4(9) $\mu$s by fitting the time difference between the 6698(5) keV $\alpha$ decay and the

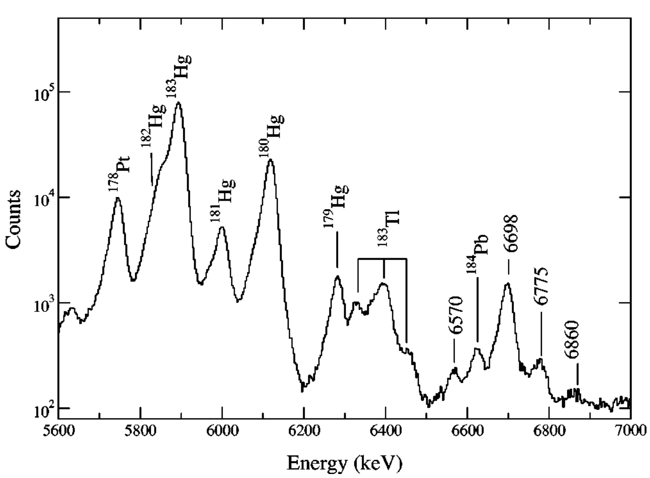


FIG. 1. Total $\alpha$ spectrum obtained in the present work. The $\alpha$ lines associated with $^{183}$Pb are marked with their $\alpha$ particle energy. $\alpha$ decays associated with other nuclei are labeled according to their origin.

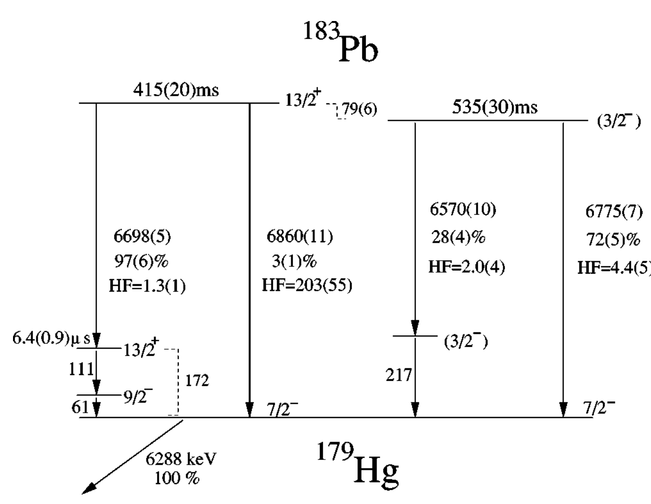


FIG. 2. Decay scheme showing the $\alpha$ decay of two isomers in $^{183}$Pb to low-lying states in $^{179}$Hg.

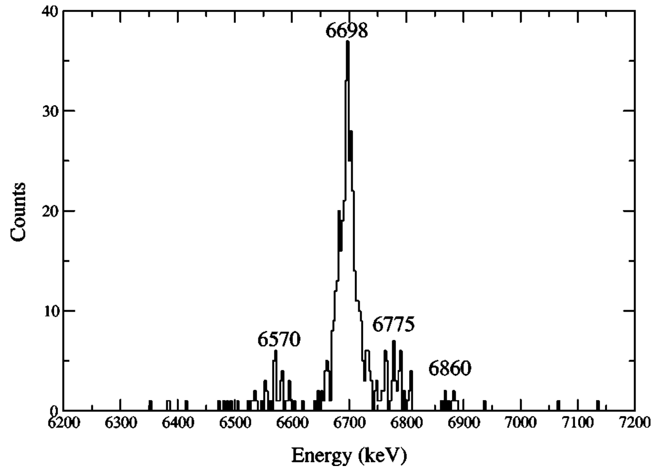


FIG. 3. $\alpha$-particle energy spectrum for parent $\alpha$ decays in $^{183}$Pb, correlated with a subsequent $^{179}$Hg $\alpha$ decay of 6288 keV, within a search time of 1 s.

subsequent 111 and 61 keV $\gamma$ rays or associated x rays from a total of 933(31) coincident events.

By matching the intensity of the observed $\gamma$ rays to the intensity of the coincident 6698(5) keV $\alpha$ decay we may straightforwardly obtain total conversion coefficients for the two $\gamma$ rays. This yields a total conversion coefficient for the 111 keV transition of a $\alpha_{tot}=46.3(8.5)$ which corresponds to the calculated value, $\alpha_{tot}=47.3$ for an $M2$ transition [18]. Moreover, since $K$ shell internal conversion may only occur for the 111 keV transition and not the 61 keV transition, we can also obtain $\alpha_K=43(10)$ for the 111 keV, which is consistent with the expected $\alpha_K=31.5$ [18]. The half-life of 6.4(9) $\mu$s associated with this transition is comparable to the Weisskopf estimate for an $M2$ transition of 1.2 $\mu$s. Applying the same methodology, we obtain a total conversion coefficient, $\alpha_{tot}=5.6(7)$ for the 61 keV transition, in close conformity to the expected value, $\alpha_{tot}=6.3$ for an $M1$ transition.

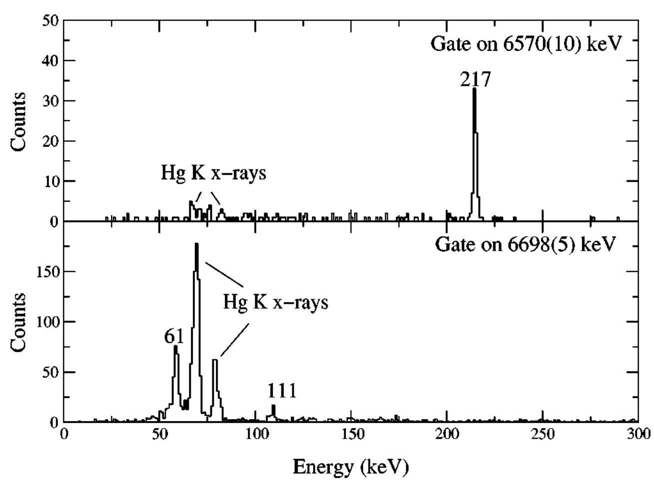


FIG. 4. Gamma rays coincident with $\alpha$ particles at the focal plane of the RITU spectrometer: (top) $\gamma$ rays in prompt coincidence with the 6570(10) keV $\alpha$ decay; (bottom) $\gamma$ rays in delayed coincidence with the 6698(5) keV $\alpha$ decay.

The 6570(10) keV $\alpha$ decay was found to be in prompt coincidence with a 217 keV $\gamma$ ray [see Fig. 4 (top)]. No delayed gamma rays were observed in coincidence with this $\alpha$ line. Since the 217 keV transition is in prompt coincidence with the $\alpha$ decay, the available multipolarities are limited to $E1$, $E2$, and $M1/E2$. The observed $K$ x-ray lines allow a conversion coefficient of $\alpha_K=0.16(5)$ to be deduced for the 217 keV transition. Given that $\alpha_K(E1)$ is calculated to be 0.05, $E1$ multipolarity can be ruled out. The measured conversion coefficient is close to that expected for an $E2$ ($\alpha_K=0.14$) transition and much smaller than that for a pure $M1$ transition; $\alpha_K=0.75$ [18]. However, given the extended nature of the source and, hence, the inherent uncertainties in the efficiency of $\gamma$-ray detection at the focal plane, we cannot rule out the possibility that it is a mixed $M1/E2$ transition with a large $E2$ admixture.

Using the recoil-decay-tagging (RDT) technique, it was possible to correlate $\gamma$ rays at the target position measured by the JUROSPHERE II array with each of the two $\alpha$ decaying states. The results of this analysis will be reported in detail elsewhere [19].

The light lead nuclei are all believed to be spherical at low excitation energy due to the presence of the $Z=82$ shell gap. Long-lived isomeric states in the light odd-$A$ lead nuclei are produced by coupling a neutron single particle to the spherical core, leading to the systematic appearance of two $\alpha$-decaying isomeric states with very similar half-lives. For example, in $^{185}$Pb, two isomers have been located and have been shown by means of laser spectroscopy to have spin/parities of $3/2^-$ and $13/2^+$, respectively [20]. Two isomers with the same spin/parity as those in $^{185}$Pb are also proposed for $^{187}$Pb [21,22]. These two isomers arise naturally from placing the odd neutron in the $p_{3/2}$ and $i_{13/2}$ orbitals, respectively. Isomers of similar origin should occur in $^{183}$Pb, although for lower neutron numbers it will become progressively more favorable to create a hole in the neutron $h_{9/2}$ shell, leading to the possibility of a spin/parity of $9/2^-$ for the low spin isomer.

Let us review the decay of the two $\alpha$-emitting states in $^{183}$Pb in turn, in view of the expectations from the behavior of the heavier odd-$A$ lead nuclei. The strongest $\alpha$ line observed in the present work of 6698(5) keV would be most consistent with a $13/2^+ \rightarrow 13/2^+$ decay. Indeed, the strongest $\alpha$ decay from both $^{185}$Pb [20] and $^{187}$Pb [21] has been given such an assignment. This is not surprising, since the $13/2^+$ state serves as an yrast-trap catching the majority of the flux from high spin states populated in a fusion-evaporation reaction. While the $13/2^+$ state in the lead nuclei is a spherical single particle state, in the odd-$A$ mercury isotopes the $13/2^+$ state is believed to correspond to the weak coupling of an $i_{13/2}$ neutron with an oblate core. Using the Rasmussen formalism [23], we extract a hindrance factor for the 6698(5) keV $\alpha$ decay of 1.3(1), i.e., essentially unhindered, which is entirely expected for a transition connecting states with the same spin/parity, corresponding to the one-step removal of two protons to change from the $\pi(0p-0h)$ lead core to the $\pi(0p-2h)$ oblate mercury core. The inferred $13/2^+$ state in $^{179}$Hg decays by $\gamma$-ray transitions of 60.6(2) keV and

110.8(3) keV with multipolarities deduced to be $M1$ and $M2$, respectively. Assuming a stretched cascade, this implies that they decay to a state with $J^{\pi}$ of $7/2^-$. This is in complete conformity with the spin/parity of $7/2^-$ assigned to the ground state of $^{179}$Hg by Kondev *et al.* [8]. Moreover, the $9/2^-$ state at 61 keV to which the 111 keV $\gamma$ ray decays, coincides with the location of a $9/2^-$ state in the in-beam decay scheme of Kondev *et al.* [8]. The ground-state spin/parity of $^{179}$Hg was assigned on the basis of the unhindered $\alpha$ decay to a $7/2^-$ state in $^{175}$Pt [24], followed by an unhindered $\alpha$ decay to the first excited state of $^{171}$Os [25] which has been assigned a spin/parity of $7/2^-$ as a member of the $5/2^-[523]$ ground-state band [26].

A consistent interpretation of the low-lying states in $^{179}$Hg now emerges and, in contrast to $^{181,183}$Hg where the separation of the $13/2^+$ isomer and the $1/2^-$ ground state is unknown [5,6], it has been possible to extract the energy separation between the oblate $13/2^+$ isomer and the ground state in $^{179}$Hg, which is 172 keV (see Fig. 2). We note in passing that the associated half-life for the $M2$ decay from the $13/2^+$ state in $^{179}$Hg implies a hindrance factor relative to the Weisskopf estimate of 5.2(7). For comparison, the hindrance of the $M2$ transition in the present work is of similar order to the decay from the $13/2^+$ isomer in $^{183}$Tl [27], where the large hindrance is attributable to the decay connecting a prolate $13/2^+$ bandhead to a weakly oblate $9/2^-$ state.

Kondev *et al.* argue on the basis of their decay scheme that the ground state of $^{179}$Hg does not have a large prolate deformation, but is near-spherical with a weak prolate deformation ($\epsilon_2 \sim 0.15$) [8]. Their argument rests on several factors. Firstly, from their decay scheme it is clear that considerable structural change occurs at low excitation energy with a number of levels with irregular energy spacing in the first 700 keV. There is evidence for a sequence built on the ground state with a very low moment of inertia, indicative of a low deformation. This sequence is crossed around spin $15/2^-$ by a well-deformed, strongly-coupled band which was assigned a $5/2^-[512]$ configuration. The only plausible manner in which to account for the existence of the $7/2^-$ ground state is to place the odd neutron in the $h_{9/2}$ or $f_{7/2}$ orbitals which only lie near the Fermi surface at small prolate deformations [8]. By establishing a spin/parity of $7/2^-$ for the $^{179}$Hg ground state in the present work, we require similar arguments to explain the parentage of the ground state. Moreover, the fact that we do observe a 6860(11) keV $\alpha$ decay from the $13/2^+$ state in $^{183}$Pb to the $^{179}$Hg ground state indicates major structural differences between $^{179}$Hg and the heavier odd-$A$ mercury isotopes, $^{181,183}$Hg since a second $\alpha$ decay branch from the $13/2^+$ isomer has not been observed in $^{185,187}$Pb [20]. This is unsurprising since the latter $\alpha$ decays should be highly forbidden as they involve both a major structural change *and* a large change in angular momentum, given that $^{181,183}$Hg have $J^{\pi}=1/2^-$ ground states arising from the strong coupling of a $p_{3/2}$ neutron to a prolate $\pi(4p\text{-}6h)$ core. The deduced hindrance factor for the 6860(11) keV decay is 203(55) [or 67(18) if the angular momentum dependence, $\Delta L=3$, is taken into account]. This is too large for a decay from a spherical state in the parent to a spherical state in the daughter with change in angular momentum, which would have a more typical hindrance factor around four. Large hindrance factors are most commonly associated with structural change between parent and daughter states. For example, $\alpha$ decays have not been observed from the spherical $3/2^-$ isomer in $^{185}$Pb and $^{187}$Pb to the $1/2^-$ ground state in the daughter nuclei (the bandhead of the $1/2^-[521]$ prolate configuration). The lower limits for the hindrance factors, calculated for $\Delta L=0$, for such $\alpha$ decays were set at around 600 and 500 for $^{185}$Pb and $^{187}$Pb, respectively [20]. The hindrance factor associated with the 6860(11) keV $\alpha$ decay in the present work is large, indicating structural change, but is significantly lower than the values associated with the highly forbidden decays in $^{185,187}$Pb, especially when the angular momentum change ($\Delta L=3$) is taken into account. We conclude that the deduced hindrance factor for the $\alpha$ decay is not inconsistent with the structural change associated with a decay connecting a spherical state in $^{183}$Pb with the ground state of $^{179}$Hg which has been suggested to arise from the coupling of a $h_{9/2}$ or $f_{7/2}$ neutron to a weakly-deformed prolate core [8].

The 6775 keV $\alpha$ decay from the low spin isomer also feeds the $7/2^-$ ground state in $^{179}$Hg directly. The low hindrance factor of 4.4(5) for this decay again points to a decay from a spherical isomer in $^{183}$Pb to a near spherical ground state in $^{179}$Hg. However, the hindrance factor is around four, suggesting a modest change in angular momentum. The second branch from the low spin isomer has an $\alpha$-particle energy of 6570 keV and feeds an excited state 217 keV above the ground state. On the basis of associated x-ray intensities, the $\gamma$ ray which deexcites this state is most likely an $E2$ transition, although our analysis cannot exclude the possibility of it being a mixed $M1/E2$ deexcitation. The inferred hindrance factor for the 6570 keV $\alpha$ decay is very low [2.0(4)] and would be most consistent with an $\alpha$ decay connecting states of the same spin and parity in the parent and daughter. Accepting this usual interpretation for the hindrance factor leads to two different scenarios depending on whether the $J^{\pi}$ values of the low spin isomer in $^{183}$Pb remain $3/2^-$, as in the heavier odd-$A$ lead nuclei or have changed to $9/2^-$ due to the ability to access the $h_{9/2}$ orbital. The former possibility seems the more likely as the 6570 keV $\alpha$ decay would correspond to a favored $3/2^-$ to $3/2^-$ $\alpha$ decay with a subsequent decay to the $^{179}$Hg ground state by a 217 keV $E2$ transition—the most likely multipolarity deduced from the observed $K$ x-ray yield. The alternate possibility involves a $9/2^-$ assignment to the $^{183}$Pb isomer which would be difficult to reconcile with the possibility of a relatively fast $M2$ transition (half-life $\sim\mu$s) connecting the two isomers in $^{183}$Pb—our decay scheme implies a separation between the high and low spin isomer in $^{183}$Pb of 79(6) keV. The relative $\alpha$ intensities and half-lives of the isomers in $^{183}$Pb do not support such competition. We, therefore, strongly prefer the $3/2^-$ assignment to the low spin isomer in $^{183}$Pb. Clearly, it would be desirable to more rigorously assign the spin/parities of both isomers directly. Such a determination has recently been performed for both isomers in $^{185}$Pb by Andreyev *et al.* [20] using resonance laser ion spectroscopy.

Let us review the information supplied by the detailed $\alpha$ decay spectroscopy of $^{183}$Pb. Firstly, it is clear that a pronounced structural change has taken place on moving from $^{181,183}$Hg to $^{179}$Hg. We have observed a second $\alpha$ branch from the 13/2$^{+}$ isomer in $^{183}$Pb to the ground state of $^{179}$Hg. Such an $\alpha$ branch has not been observed in the heavier lead nuclei, nor would it be expected to be since such a decay would correspond to considerable structural rearrangement as well as a large change in angular momentum from $J^{\pi}=13/2^{+}$ to $J^{\pi}=1/2^{-}$. The observed hindrance factor of the 13/2$^{+}$ to 7/2$^{-}$ $\alpha$ decay in $^{183}$Pb is inconsistent with a decay between a spherical state in the parent and a spherical state in the daughter nucleus. The magnitude of the hindrance factor suggests structural change and would be consistent with the $\alpha$ decay connecting a spherical state in the parent with a weakly prolate deformed state in the daughter. Our confirmation of the ground-state spin/parity of $^{179}$Hg and the properties of the $\alpha$ decays from $^{183}$Pb support the suggestion that the ground state of $^{179}$Hg is near spherical made by Kondev *et al.* on the basis of their in-beam $^{179}$Hg decay scheme [8]. This near spherical configuration completes the triplet of shapes—prolate, oblate, and near spherical near the ground state in $^{179}$Hg.

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[1] R. Julin, K. Helariutta, and M. Muikku J. Phys. G **27**, R109 (2001).
[2] J.F.C. Cocks *et al.*, Eur. Phys. J. A **3**, 17 (1998).
[3] D.G. Jenkins *et al.*, Phys. Rev. C **62**, 021302(R) (2000).
[4] A.N. Andreyev *et al.*, Nature (London) **405**, 430 (2000).
[5] P.G. Varmette *et al.*, Phys. Lett. B **410**, 103 (1997).
[6] D.T. Shi *et al.*, Phys. Rev. C **51**, 1720 (1995); G.J. Lane *et al.*, Nucl. Phys. **A589**, 129 (1995).
[7] F. Hannachi, Z. Phys. A **330**, 15 (1988).
[8] F.G. Kondev *et al.*, Phys. Lett. B **528**, 221 (2002).
[9] F.G. Kondev *et al.*, Phys. Lett. B **512**, 268 (2001).
[10] P.J. Nolan, D.W. Gifford, and P.J. Twin, Nucl. Instrum. Methods Phys. Res. A **236**, 95 (1985).
[11] M. Moszÿnski, J.H. Bjerrard, J.J. Gaardhoje, B. Herskind, P. Knudsen, and G. Sletten, Nucl. Instrum. Methods Phys. Res. A **280**, 73 (1989).
[12] C.W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992).
[13] H.J. Schrewe *et al.*, Phys. Lett. **91B**, 46 (1980).
[14] K.S. Toth *et al.*, Phys. Rev. C **35**, 2330 (1987).
[15] J.G. Keller, K.-H. Schmidt, F.P. Hessberger, G. Münzenberg, W. Reisdorf, H.-G. Clerc, and C.-C. Sahm, Nucl. Phys. **A452**, 173 (1986).
[16] K.S. Toth *et al.*, Phys. Rev. C **39**, 1150 (1989).
[17] J. Schneider, GSI Report No. GSI-84-3, 1984.
[18] F. Rosel, H.M. Friess, K. Aldrer, and H.C. Pauli, At. Data Nucl. Data Tables **21**, 291 (1978).
[19] D. G. Jenkins *et al.* (to be published).
[20] A.N. Andreyev, Eur. Phys. J. A **14**, 63 (2002).
[21] A.N. Andreyev *et al.*, Phys. Rev. Lett. **82**, 1819 (1999).
[22] P. Misaelidis *et al.*, Z. Phys. A **301**, 199 (1981).
[23] J.O. Rasmussen, Phys. Rev. **113**, 1593 (1959).
[24] F.G. Kondev *et al.*, Nucl. Phys. **A682**, 487c (2001).
[25] E. Hagberg, P.G. Hansen, P. Hornshoj, B. Jonsson, S. Mattsson, and P. Tidemand-Petersson, Nucl. Phys. **A318**, 29 (1979).
[26] R.A. Bark, G.D. Dracoulis, and A.E. Stuchberry, Nucl. Phys. **A514**, 503 (1990).
[27] M. Muikku *et al.*, Phys. Rev. C **64**, 044308 (2001).