α-decay of the new isotope 187Po: Probing prolate structures beyond the neutron mid-shell at N = 104

A. N. Andreyev,1,7 S. Antalic,2 D. Ackermann,3,8 S. Franchoo,4 F. P. Heßberger,3 S. Hofmann,3,9 M. Huysse,5 I. Kojouharov,2 B. Kindler,2 P. Kuusiniemi,3 S. R. Lesher,2 B. Lommel,3 R. Mann,3 G. Münzenberg,3,8 K. Nishio,3,10 R. D. Page,6 J. J. Ressler,2 B. Streicher,2 S. Saro,2 B. Sulignano,3 P. Van Duppen,5 D. Wiseman,9 and R. Wyss11

1TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3
2Department of Nuclear Physics and Biophysics, Comenius University, Bratislava SK-84248, Slovakia
3Gesellschaft für Schwerionenforschung, Planckstrasse 1, D-64291 Darmstadt, Germany
4IPN Orsay, F-91406 Orsay Cedex, France
5Instituut voor Kern-en Stralingsfysica, K.U. Leuven, University of Leuven, B-3001 Leuven, Belgium
6Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom
7Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A-1S6
8Institut für Physik, Johannes Gutenberg-University, D-55099 Mainz, Germany
9Physikalisches Institut, J.W. Goethe-Universität, D-60054 Frankfurt, Germany
10Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
11Department of Physics, Royal Institute of Technology, 104 05 Stockholm, Sweden

(Received 7 February 2006; published 25 April 2006)

The new neutron-deficient isotope 187Po has been identified in the complete fusion reaction 46Ti+144Sm → 187Po+3n at the velocity filter SHIP. Striking features of the 187Po α decay are the strongly-hindered decay to the spherical ground state and unhindered decay to a surprisingly low-lying deformed excited state at 286 keV in the daughter nucleus 185Pb. Based on the potential energy surface calculations, the 185Pb ground state and the 286 keV excited state in 185Pb were interpreted as being of prolate origin. The systematic deviation of the α-decay properties in the lightest odd-A Po isotopes relative to the smooth behavior in the even-A neighbors is discussed. Improved data for the decay of 187Bi10+5 were also obtained.

DOI: 10.1103/PhysRevC.73.044324
PACS number(s): 23.60.+e, 27.70.+q

I. INTRODUCTION

In the neutron-deficient Po isotopes the richest examples of shape coexistence at low excitation energy can be found. Historically, the first work in which shape coexistence in these nuclei was discussed was the Nilsson-Strutinsky calculations in 189Po by May et al. [1]. The authors suggested a gradual change of the Po ground state (g.s.) from a nearly spherical configuration around the neutron shell closure at N = 104 (190Po), to an oblate configuration in the vicinity of 189Po, with a prolate ground state expected close to and beyond the neutron mid-shell at N = 104 (188Po). It is important to stress that practically all modern approaches, based both on improved Nilsson-Strutinsky methods or on self-consistent Hartree-Fock-Bogoliubov calculations, are in agreement with the earlier study by May et al., see discussion, e.g., in Refs. [2,3].

These theoretical findings are strongly supported by complementary data both from in-beam studies, see, e.g., Refs. [4,5] and particle (β and α) decay (e.g., Refs. [6–12]), which provided extensive systematics on the evolution of shape coexistence in the long sequence of 188–210Po isotopes. However, due to low production cross sections and high background from fission, the most neutron-deficient Po nuclei cannot presently be investigated with in-beam techniques. 189Po being the lightest Po isotope studied by this method so far [5,13] (the current cross section limit for this technique is σ ∼ 50 nb).

On the other hand, α decay has proven to be a sensitive tool to study shape coexistence in nuclei, providing information on both parent and daughter states involved in the decay, see, e.g., Refs. [14,15]. Furthermore, nuclei with production cross sections in the subnanobarn region become accessible. A recent example of such work is our α-decay study of the neutron-deficient isotopes 188,189Po (see Ref. [12] and references therein), which are presently not accessible by any other methods.

A striking observation in the 189Po α decay was that the 7532 keV g.s. → g.s. α decay to the spherical ground state in the daughter isotope 185Pb was hindered by a factor of ~77 (in terms of reduced α widths as defined by Rasmussen [16]) relative to the 7259 keV fine structure (f.s.) α decay to an excited state at 278 keV in 185Pb [12]. A similar pattern, though with a lower hindrance factor (HF) of ~12 for the 7910 keV g.s. → g.s. decay relative to the 7355 keV fine structure α decay was also observed in the neighboring isotope 188Po [11]. Combined with the potential energy surface calculations, these data provided the first experimental evidence that the ground states of 188,189Po and the excited states in their respective daughters 184,185Pb, fed by unhindered fine structure decays, are of prolate origin, see details in Refs. [11,12]. The sphericity of the ground states in the isotopes 184,185Pb was recently proved by the charge radii measurements [17].

The present study extends our previous work in this region, performed at the velocity filter SHIP of the GSI in Darmstadt [18,19] and reports on an α-decay study of the new isotope 187Po. The data for the new isotopes 186Po and 192At, identified in the same experiment, will be discussed elsewhere [20,21].
A detailed discussion of the experimental method was given in our recent paper, which dealt with the identification of a new isotope $^{192}$At [20] performed in the same experiment (by using the $^{51}$V beam). Therefore, only a short description of the experimental procedure will be given here.

The nucleus $^{187}$Po was produced in the $^{144}$Sm($^{46}$Ti,$\alpha$) $^{187}$Po complete fusion reaction. A pulsed $^{46}$Ti beam (5 ms on/15 ms off) with an intensity of $\sim$200 pNA was provided by the UNILAC heavy ion accelerator of the GSI. The measurements were performed at six beam energies in the range of 202–242 MeV in the middle of the target to estimate the maxima of the excitation functions for different evaporation channels. The data for $^{187}$Po were collected at the energy of $E_{\text{Ti}}$ = 224(1) MeV in front of the target. Eight 400 $\mu$g/cm$^2$ thick $^{144}$Sm targets were mounted on a target wheel, rotating synchronously with the UNILAC macro-pulsing. The targets were produced by evaporating $^{144}$SmF$_3$ material (96.47% enriched) onto a carbon backing of 40 $\mu$g/cm$^2$ thickness and covered with a 10 $\mu$g/cm$^2$ carbon layer to increase the radiative cooling and reduce the sputtering of the material.

After separation by the velocity filter SHIP [18] the recoiling evaporation residues were implanted into a 300 $\mu$m thick, 35 × 80 mm$^2$ 16-strip position-sensitive silicon detector (PSSD), where their subsequent particle decays were measured [19].

The usual detection system consisting of six silicon BOX detectors, three time-of-flight detectors [22] and a “veto” detector, which are described in detail in Refs. [20,23] was used. The time-of-flight detectors (TOF) installed in front of the BOX+PSSD system allowed us to distinguish the reaction products from the scattered beam particles. More importantly, decay events in the PSSD could be distinguished from the implantation events by requiring an anticoincidence condition between the signals from the PSSD and from at least one of the TOF detectors.

A large-volume four-fold segmented Clover-type germanium detector was installed behind the PSSD for the recoil-$\gamma$ and/or $\alpha$-$\gamma$ [$\Delta T(\text{particle-}$)$\gamma) \leq 5 \mu s$] coincidence measurements. The absolute efficiency calibration for this detector is described in Ref. [24].

## III. EXPERIMENTAL RESULTS

### A. $\alpha$ decay of $^{187}$Po

Figure 1(a) shows a part of the $\alpha$ spectrum measured in the PSSD in anticoincidence with the signals from the TOF and veto detectors. The peaks at 6699(5) keV [$^{195m}$Po [25], not shown in Fig. 1(a)], at 6842(6) keV ($^{194}$Po [25]) and at 7612(15) keV ($^{187}$Bi$^\text{m}$ [26]) were used for $\alpha$-energy calibration in this energy region. As shown below, three nuclides contribute to the peak at $E_\alpha = 7000(20)\text{ keV}$: $^{187}$Po$^\text{m}$ ($E_\alpha = 7004(5)\text{ keV}$ [25]), $^{188}$Bi$^\text{m}$ ($E_\alpha = 6992(5)\text{ keV}$ [27]) and $^{187}$Bi$^\text{m}$ ($E_\alpha = 7000(8)\text{ keV}$ [26]). The $A(Po) \geq 190$ isotopes were produced in reactions on the admixtures of the heavier $^{\text{Sm}}$ isotopes in the target, while the $^{187,188}$Bi isotopes were produced in the $p,2n$ and $p,1n$ channels of the studied reaction, respectively. Figure 1(b) shows the same spectrum as in Fig. 1(a), but registered within the time interval of $\Delta T(\text{recoil-}\alpha_1) \leq 7 \text{ ms}$ after the recoil implantation, which clearly enhances the $\alpha$ peaks from the short-lived activities (e.g., $^{187}$Bi$^\text{m}$).

The $\alpha$ decay at $E_\alpha = 7528(15)\text{ keV}$ in Fig. 1(b) and 1(c) is attributed to the new isotope $^{187}$Po as it clearly correlates with both known $\alpha$ decays of the $I^+ = 3/2^+$ ground state of the daughter isotope $^{185}$Pb ($T_{1/2} = 535(30)\text{ ms}$, $E_\alpha = 6570(10)\text{ keV}$, $I_a = 28(4)\%$) and $E_\alpha = 6775(7)\text{ keV}$, $I_a = 72(5)\%$ [28], see Fig. 2). Furthermore, it also correlates with the $\alpha$ decay of the grand-daughter nucleus $^{179}$Hg ($E_\alpha = 6288(5)\text{ keV}$, $T_{1/2} = 1.09 \text{ s}$ [29]). The good match of the measured decay properties with the literature data for the daughter isotopes proves that the parent decay at 7528 keV originates from $^{187}$Po. A half-life value of $T_{1/2} = 1.40(25)\text{ ms}$ was deduced for $^{187}$Po.

![Figure 1](https://example.com/fig1.png)
A few other groups of correlated decays in Fig. 1(c) are readily understood as due to the decay of other known nuclei. Two groups of correlated events starting from the $E_{\alpha_1} = 7000$ keV decay are due to correlation of $^{187}$Bi$^\alpha$ with the complex $\alpha$ decay of its daughter $^{183}$Tl$^\alpha$ (three $\alpha$ lines in the region of 6333–6456 [30], see Fig. 3) and with the 5905 keV decay of its grand-daughter $^{183}$Hg (after $\beta$ decay of $^{183}$Tl). A single correlated recoil-$\alpha_1(7912$ keV)$-\alpha_2(6626$ keV) event is due to the decay of $^{185}$Po [11]. Note that two events at 7912(15) keV are also present in the recoil-$\alpha_1$ spectrum in Fig. 1(b), one of them is the same as in Fig. 1(c). The events seen in correlations with the 7720 keV decay will be discussed in the next section.

Figure 1(d) shows the plot of recoil-$[\alpha_1,\gamma]$ events for the time intervals of $\Delta T(recoil-\alpha_1) \leq 100$ ms and $\Delta T(\alpha_1,\gamma) \leq 5$ ms. Though the former time interval is not optimal for the decay of $^{187}$Po, it was chosen to include the events from the decay of $^{187}$Bi$^\alpha$ [$T_{1/2} = 40(2)$ ms, see discussion below]. The group of coincident $\alpha_1(6992$ keV)$-\gamma(118$ keV) events originates from the known decay of $^{185}$Bi$^{\pi 2}$ [27], while the $\alpha_1(7260$ keV)$-\gamma(108$ keV) group is due to the decay of $^{186}$Bi [31].

Figure 1(d) shows that the 7528 keV decay of $^{187}$Po is in coincidence with the 286(1) keV $\gamma$ decay (five events) and with the Pb $K$-x rays. This identifies an excited state at 286 keV above the 3/2$^-$ ground state in $^{183}$Pb. From the ratio of the number of full energy 286 keV decays and Pb $K$-x rays in coincidence with the 7528 keV decay, the $K$-shell conversion coefficient of $\alpha_K = 0.7(4)$ was deduced. This tentatively establishes $M1$ multipolarity for the 286 keV transition as the calculated conversion coefficients are [32]: $\alpha_K(E1) = 0.027$, $\alpha_K(E2) = 0.073$, $\alpha_K(M1) = 0.42$, $\alpha_K(M2) = 1.46$.

Based on the full $Q_\gamma$-value analysis [$Q_{\alpha,\text{full}} = Q_\alpha (7528$ keV)$+E_\gamma(286$ keV)], a full-energy crossover transition with the energy of $E_\gamma = 7808(15)$ keV feeding directly to the 3/2$^-$ ground state of $^{183}$Pb could be expected. A single $\alpha$ decay at 7796(15) keV in Fig. 1(b) which occurred 1.1 ms after the recoil implantation could be considered as a candidate for this crossover transition. Using this single event as an upper limit for the intensity of the tentative crossover transition, the decay scheme of $^{187}$Po was constructed as shown in Fig. 2. The discussion of spin-parity for the newly identified states will be given in the following sections.

A comment on four recoil-$\alpha_1(7720(20)$ keV)$-\alpha_2(6600–6800$ keV) correlated events, marked by the rectangle in Fig. 1(c), should be made here. The energy and half-life values of the $\alpha_2$ decays are in agreement with the decay properties

FIG. 3. Decay scheme of $^{187}$Bi deduced in this work. Shown are $\alpha$-decay energies $E_\alpha$, relative intensities $I_\alpha$, reduced $\alpha$ widths $\delta_\alpha^2$ and hindrance factor values HF. The HF values were calculated relative to the unhindered 7000 keV decay of $^{187}$Bi$^\alpha$, for which HF = 1 was assumed. All $I^\pi$ assignments are tentative and shown in brackets. The data for $^{183}$Tl are taken from Refs. [29,30], except for the $\alpha$-branching ratio of $b_{\alpha}(^{183}$Tl$^{\pi m}) = 1.5(3)$% and position of the excited state at $E^+ = 273(1)$ keV measured in our study.

FIG. 2. Decay scheme of $^{187}$Po deduced in this work. Shown are $\alpha$-decay energies $E_\alpha$, intensities $I_\alpha$, reduced $\alpha$ widths $\delta_\alpha^2$ and hindrance factor values HF. The tentative 7808 keV decay is shown by the dashed line. The $I^\pi$ assignments in $^{187}$Po and of the 286 keV state in $^{183}$Pb are tentative and based on a combination of the PES/PPR calculations and $\alpha$ decay hindrance factors, see text for details. Note that both $I^\pi = 1/2^-$ or $5/2^-$ are possible for $^{187}$Po and for the 286 keV state in $^{183}$Pb, but the $I^\pi$ assignments must be the same for both states. The HF values for both $\alpha$-decaying states in $^{183}$Pb were deduced in [17]. The decay scheme of $^{185}$Pb was taken from [28].
of both isomeric states in $^{183}$Pb, see Fig. 2, thus the parent $\alpha_1$ decays must originate from $^{187}$Po. One of the sources for these events could be the energy summing in the PSSD of the 7528 keV decay and Pb K-shell conversion electrons from the subsequent 286 keV transitions, which gives the full-energy peak at $\sim$7726 keV. On the other hand, the 7720(20) keV decay could be the decay of a second $\alpha$-decaying state in $^{187}$Po ($T_{1/2} \sim 0.5$ ms).

However, the low number of correlated events prevents us from drawing a firm conclusion on the nature of observed recoil-$\alpha(7720(20) \text{ keV})$-$\alpha_2(6600–6800 \text{ keV})$ correlated events.

### B. $\alpha$ decay of $^{187}$Bi

The previous $\alpha$-decay data for $^{187}$Bi$_{m,g}$ come mainly from the study in Ref. [26]. However, only a relatively low number of counts was observed for some of the $\alpha$ decays, e.g., $\leq$ 15 events for the 7612 keV decay of $^{187}$Bi$^g$ and for the 7212 keV decay of $^{187}$Bi$^m$ (see Fig. 1 of Ref. [26]). Due to this, some assignments were tentative and no experimental uncertainties were given for the relative intensities of different $\alpha$ lines (see Table I).

In the present experiment, we collected a number of $^{187}$Bi$_{m,g}$ $\alpha$ decays at least one order of magnitude larger than in any of the three earlier studies of this nucleus [26,33,34]. This resulted in improved $\alpha$-decay data for both isomeric states in this nucleus, see Fig. 3 and Table I.

Due to some contamination from $^{193}$Po$_{m}$ [$E_x = 7004(5) \text{ keV}$] and $^{188}$Bi$_{m,g}$ [$E_x = 6992(5) \text{ keV}$], the strongest $\alpha$ decay of $^{187}$Bi$^g$ at 7000 keV was not used in our study for improved half-life determination of this nucleus. Instead, the second strongest decay of $^{187}$Bi$^g$ at 7612(5) keV (relative intensity $I_{\alpha,rel} = 9\%$, Fig. 3) was used with $\sim$750 correlated events obtained for the $\Delta T[\text{recoil}-\alpha(7612 \text{ keV})] \leq 500$ ms time interval. For comparison, this value is still $\sim$10 times larger than the number of counts in the main 7000 keV peak of $^{187}$Bi$^g$ in Fig. 1 of Ref. [26]. The deduced half-life value of $T_{1/2} = 40(2)$ ms for $^{187}$Bi$^g$ is consistent with but more precise than any of the three previously reported values of $T_{1/2} = 32(3)$ ms [26], $T_{1/2} = 45(11)$ ms [33] and $T_{1/2} = 35^{+14}_{-8}$ ms [34].

A half-life value of $T_{1/2} = 370(20)$ ms was deduced for the 7721(10) keV $\alpha$ decay of $^{187}$Bi$^m$ [950 recoil-$\alpha(7721 \text{ keV})$ events]. This is a more precise value in comparison with two earlier measurements of $T_{1/2} = 290^{+30}_{-20}$ ms [26] and $T_{1/2} = 310^{+190}_{-90}$ ms [34], both based on a handful of observed events only.

The improved energy precision for the 7612(5) keV and 7000(5) keV transitions establishes a more precise value of 625(7) keV for the excitation energy of the 9/2$^-$ intruder state in $^{183}$Tl (the previous value was 625(17) keV [26]). Similarly, the 7721(10) and 7612(5) keV decays provide a more precise value of 112(11) keV for the excitation energy of the 1/2$^+$ intruder state in $^{187}$Bi relative to the 9/2$^-$ ground state (the previous value was 112(21) keV [26]).

The group of 19 $\alpha(7342(15) \text{ keV})\gamma(273(1) \text{ keV})$ events in Fig. 1(d) has a full $Q_{\alpha}$-value that is in good agreement with the $Q_{\alpha}$-value for the 7612 keV decay of $^{187}$Bi$^g$. The measured half-life of $T_{1/2} = 40(10)$ ms for the 7342 keV decay agrees well with the half-life of $^{187}$Bi$^g$. On these grounds the 7342 keV decay was assigned as proceeding from the 9/2$^-$ ground state of $^{187}$Bi toward presumably the 3/2$^+$ state at 273 keV in the daughter nuclide $^{183}$Tl, which further deexcites to the 1/2$^+$ ground state in this nucleus. Based on the ratio of the number of the full energy 273 keV decays and Tl K-x rays in coincidence with the 7342 keV decay, a $K$-shell conversion coefficient of $\alpha_K = 0.55(15)$ was deduced. From the comparison with the calculated values of $\alpha_K$ for the M1, M2, E1, E2 multiplicities taken from Ref. [32], the experimental value suggests an M1 multipolarity for the 273 keV transition, supporting the $I^ = 3/2^+$ assignment for the 273 keV excited state in $^{183}$Tl. Thus, our data provide the direct measurement for the excitation energy of the $3/2^+$ in $^{183}$Tl as $E^* = 273(1) \text{ keV}$. This is a more precise value in comparison with $E^* = 250(34)$ keV deduced in Ref. [26], in which no $\gamma$-decay measurements were performed and the excitation energy was deduced from a few 7367(30) keV $\alpha$ decays tentatively assigned as the $9/2^- \rightarrow 3/2^+$ transition of $^{187}$Bi$^g$. The absolute intensity of the 7342 keV line was calculated based on the number of recoil-$[\alpha(7342)\gamma(273 \text{ keV})]$ coincidences in Fig. 1(d), normalized on the corresponding $\gamma$-ray efficiency and conversion coefficient of the 273 keV $\gamma$ ray.

To deduce the relative intensities of the 7000(5), 7342(15) and 7612(5) keV lines of $^{187}$Bi$^g$ we had to estimate the contributions of $^{193}$Po$_{m}$ ($E_x = 7004 \text{ keV}$) and of

<table>
<thead>
<tr>
<th>Isomer, $I^*$</th>
<th>$T_{1/2}$ [ms]</th>
<th>$E_x$ [keV]</th>
<th>$I_{\alpha,rel} [%]$</th>
<th>$I_{l\rightarrow I_f}$</th>
<th>$\delta_v^g$ [keV]</th>
<th>HF</th>
<th>$T_{1/2}$ [ms]</th>
<th>$E_x$ [keV]</th>
<th>$I_{\alpha,rel} [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{187}$Bi$^g$, (9/2$^-$)</td>
<td>40(2)</td>
<td>7000(5)</td>
<td>88(4)</td>
<td>(9/2$^-$) $\rightarrow$ (9/2$^-$)</td>
<td>69(4)</td>
<td>1</td>
<td>32(3)</td>
<td>7000(8)</td>
<td>88.3</td>
</tr>
<tr>
<td></td>
<td>7342(15)</td>
<td>3.0(7)</td>
<td>(9/2$^-$) $\rightarrow$ (3/2$^+$)</td>
<td>0.17(4)</td>
<td>400(100)</td>
<td>7367(30)</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7612(5)</td>
<td>9.0(5)</td>
<td>(9/2$^-$) $\rightarrow$ (1/2$^+$)</td>
<td>0.075(5)</td>
<td>920(70)</td>
<td>7612(15)</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{187}$Bi$^m$, (1/2$^+$)</td>
<td>0.370(20)</td>
<td>7721(10)</td>
<td>100</td>
<td>(1/2$^+$) $\rightarrow$ (1/2$^+$)</td>
<td>43(3)</td>
<td>1.60(16)</td>
<td>0.29$^{+0.09}_{-0.05}$</td>
<td>7721(15)</td>
<td>100</td>
</tr>
</tbody>
</table>

TABLE I. Our measured decay data for $^{187}$Bi together with the earlier data from Ref. [26]. Shown are isomer assignments, $\alpha$-decay energies $E_x$, relative intensities $I_{\alpha,rel}$, reduced $\alpha$ widths $\delta_v^g$, hindrance factors HF. The reduced $\alpha$ widths were calculated with the Rasmussen prescription [16] by assuming $\Delta L = 0$ decays. The HF values were calculated relative to the unhindered (9/2$^-$) $\rightarrow$ (9/2$^-$) decay of $^{187}$Bi$^g$, for which HF = 1 was assumed. All $I^*$ assignments are tentative and shown in brackets. Note that no experimental errors were given in Ref. [26] for the relative intensities of different $\alpha$ lines in $^{187}$Bi$^g$. |
the excitation function for $^{187}$Bi and thus, for $^{187}$Po. The data of the target, which corresponds to the measured maximum of the $^{187}$Bi $\gamma$-ray efficiency and conversion coefficient of the 118 keV $\gamma$ ray. The absolute amount of $^{187}$Po in the 7000 keV line was estimated by using the intensity of $^{193}$Po $^{g}$ ($E_g = 6949$ keV [25]) and the typical isomeric ratio, observed in complete-fusion reactions, of $I(187$Po$^m)/I(187$Po$^g) \sim 2.0(2)$ (see, e.g., Fig. 1 of Ref. [11]).

Finally, the relative intensities of the three lines were deduced, which allowed us to calculated the reduced $\alpha$ widths $\delta_2^r$ and hindrance factor values as shown in Fig. 3 and Table I. The HF values were calculated relative to the $9/2^+$ ground state, as observed in the heavier odd-A Bi isotopes, representing a good example of unhindered $\alpha$ decay in this mass region, as it connects two identical single particle configurations in the parent and daughter nuclei, see Ref. [35] and references therein.

An isomeric ratio of $I(187$Bi$^g)/I(187$Bi$^m) = 7.0(2)$ was determined, which follows the trend of the preferential population in the complete-fusion reactions of the $9/2^-$ ground state relative to the $1/2^+$ isomeric state, observed in the heavier odd-A $\alpha$-decaying Bi isotopes. In this respect, the sudden change to the preferential population of the $1/2^+$ state in $^{185}$Bi along with the nonobservation of the $9/2^-$ state in this nucleus is not yet understood, see also discussion in Ref. [35].

C. $\alpha$-branching ratio of $^{183}$Tl$^m$

The $\alpha$-branching ratio for $^{183}$Tl$^m$ was deduced by using the mother-daughter intensity relations and comparing the number of the $E_g = 7000$ keV decays of $^{187}$Bi$^g$ in the singles $\alpha$ spectrum in Fig. 1(a) and the number of $\alpha_1$ (7000 keV, $\alpha_2$ (6300–6500 keV, $^{183}$Tl$^m$) correlated events for the time $\Delta T(\alpha_1-\alpha_2) \leq 200$ ms. The former number was corrected for the contribution of $^{189}$Po$^m$ and $^{188}$Bi as described above. The correlation time interval was chosen equal to four half-lives of $^{183}$Tl$^m$ ($T_{1/2}(^{183}$Tl$^m) = 53.3(3)$ ms [30]) to specifically enhance the $^{187}$Bi$^g$-$^{183}$Tl$^m$ correlations. The resulting value of $b_\alpha(^{183}$Tl$^m) = 1.5(3)$% is in agreement with the two previously measured values of $\sim 1.5$% (one observed correlated event only) [26] and $\sim 2$% from Ref. [30]. Note that no experimental errors were given for $b_\alpha$ in both studies [26,30].

No $\alpha$- or $\beta$-branching ratio estimate was possible for $^{183}$Tl$^g$ in our study.

D. Production cross sections of $^{187}$Po and $^{187}$Bi

The cross-section values of $\sigma(^{187}$Po) = 0.8(3) nb and $\sigma(^{187}$Bi) = 200(80) nb were deduced at the beam energy of 224 MeV in front of the target $\sim 1220(1)$ MeV in the middle of the target, which corresponds to the measured maximum of the excitation function for $^{185}$Bi and thus, for $^{187}$Po. The data follow the systematic trend of the Po and Bi cross sections discussed in our recent study [36].
general trend in the lead region that the oblate configuration increases in energy beyond the neutron mid-shell at \( N = 104 \), while the prolate minimum appears to minimize its excitation energy around \( N = 100–104 \), see, e.g., Refs. [4,37,38].

Based on the PES calculations, the g.s. of \(^{187}\text{Po}\) and the excited state at 286 keV in \(^{183}\text{Pb}\) are assigned as prolate configurations. The PPR calculations suggest two close-lying negative-parity configurations in these nuclei: the 5/2\(^-\) [512] Nilsson state of mixed \( 2f_{7/2}^{-1}h_{9/2} \) origin and the 1/2\(^-\) [521] state from the \( 2f_{5/2} \) orbital. Their close proximity in the calculations is due to the fact that for the neutron numbers of \( N = 101,103 \) the corresponding single particle orbitals cross at a prolate deformation of \( \beta_2 \approx 0.24 \), which is similar to the deformations predicted for the prolate minima in \(^{185}\text{Pb}\) and \(^{187}\text{Po}\). This theoretical conclusion is confirmed by the well-established systematics of the lowest excited states in the isotope chains with \( N = 101 \) and \( N = 103 \). For example, all prolate-deformed \( N = 101 \) odd-\( A \) isotopes of \(^{183}\text{Pb} \) (\(^{169}\text{Er},^{171}\text{Yb},^{173}\text{Hf},^{175}\text{W},^{177}\text{Os},^{179}\text{Pt}, \text{and}^{181}\text{Hg}\)) have the 1/2\(^-\) [521] ground state with a close-lying excited 5/2\(^-\) [512] state within 100–150 keV (where known) [29]. It is instructive to mention, that both \( I^\pi = 5/2^- \) and 1/2\(^-\) assignments would be possible for the 286 keV state in \(^{183}\text{Pb}\) based on the \( I^\pi = 3/2^- \) assignment for the ground state of \(^{185}\text{Pb}\) [17] and the M1 multipolarity of the 286 keV transition.

Similarly, in the prolate-deformed \( N = 103 \) isotones of \(^{187}\text{Po}\), some nuclei have a 5/2\(^-\) [512] g.s. state (e.g., \(^{171}\text{Er},^{173}\text{Yb}, \text{and}^{175}\text{Hf}\)), while others have the 1/2\(^-\) [521] ground state (e.g., \(^{177}\text{W},^{179}\text{Os},^{181}\text{Pt}, \text{and}^{183}\text{Hg}\)), with both configurations lying quite close in energy [29].

To summarize, both theoretical calculations and experimental systematics strongly point toward the \( I^\pi = 1/2^- \) or 5/2\(^-\) assignments for the g.s. of \(^{187}\text{Po}\) and for the 286 keV excited state in \(^{183}\text{Pb}\). The actual \( I^\pi \) values will however depend on specific details for each isotope and are difficult to establish based on the above data alone.

Therefore, we used \(^{187}\text{Po} \rightarrow^{183}\text{Pb} \) \( \alpha \)-decay pattern to shed more light on the \( I^\pi \) assignments in both isotopes. It is well known that unhindered \( \alpha \) decay connects states of same spin, parity and configuration, while the decays connecting different Nilsson configurations are strongly hindered. As a relevant example we quote the case of the \( \alpha \) decay of \(^{181}\text{Hg} \) (\( N = 101 \)), in which the 1/2\(^-\) [521] \( \rightarrow 1/2^- [521] \) \( \alpha \) decay is unhindered (\( HF_\alpha = 0.6 \)), while the 1/2\(^-\) [521] \( \rightarrow 5/2^- [512] \) \( \alpha \) decay is hindered by a factor of \( HF_\alpha = 422 \) [29].

The 7258 keV decay of \(^{187}\text{Po} \) feeding to the 286 keV state in \(^{183}\text{Pb} \) can be considered as unhindered as its reduced \( \alpha \) width is comparable with (in fact \( \sim 1.5 \) times larger than) the reduced \( \alpha \) width of the unhindered 9/2\(^-\) \( \rightarrow 9/2^- 7000 \) keV decay of \(^{187}\text{Bi} \) (cf. Figs. 2 and 3). As discussed above and in Ref. [35], the 9/2\(^-\) \( \rightarrow 9/2^- \) \( \alpha \) decays in the odd-\( A \) Bi isotopes provide a good example of unhindered decay in this region of nuclei. Therefore, based on the unhindered nature of the 7528 keV \( \alpha \) decay we have to assume that it connects two states with the same Nilsson configuration and it is either of the 1/2\(^-\) \( \rightarrow 1/2^- \) or 5/2\(^-\) \( \rightarrow 5/2^- \) type. That is why we indicated both 1/2\(^-\) or 5/2\(^-\) as possible \( I^\pi \) values for \(^{187}\text{Po} \) and for the 286 keV state in \(^{183}\text{Pb} \) in Fig. 2, but most probably the \( I^\pi \) assignments must be the same for both states.

In such a case the strong retardation (\( HF_\alpha \geq 360 \)) of the tentatively observed 7808 keV decay to the 3/2\(^-\) g.s. in \(^{183}\text{Pb} \) is readily understood as due to the large configuration difference involving the decay between the strongly prolate 1/2\(^-\) or 5/2\(^-\) state in \(^{187}\text{Po} \) and the spherical 3/2\(^-\) configuration in \(^{183}\text{Pb} \).

To conclude this section, our \( \alpha \)-decay data along with the PES/PPR calculations provide unique evidence on the prolate deformation of the 286 keV excited state in \(^{183}\text{Pb} \) and of the isotope \(^{187}\text{Po} \).

B. Peculiarities in the \( \alpha \)-decay characteristics of the lightest Po isotopes

Figures 5(a) and (b) show the systematics of the \( \alpha \)-decay energies and partial \( \alpha \)-decay half-lives for isotopes \(^{186–202}\text{Po} \). Both figures demonstrate that the \( \alpha \)-decay energies and partial half-lives of the 3/2\(^-\) ground states and of the 13/2\(^+\) isomers in the odd-\( A \) isotopes \(^{191–201}\text{Po} \) follow well the smooth trend of the \( 0^+_g \rightarrow 0^+_g \) \( \alpha \) decays in their even-\( A \) neighbors (with the exception of the half-life value of \(^{191}\text{Po} \), see below). The close resemblance of the \( \alpha \)-decay properties of the odd-\( A \) and even-\( A \) Po isotopes in this region was interpreted in a simple picture in which the corresponding states in the odd-\( A \) Po and Pb nuclei are produced by a weak coupling of the valence 3\( p_{3/2} \) or 1\( i_{13/2} \) neutron to the nearly spherical even-\( A \) core. In this approach, the odd neutron is considered as a spectator and is not actively involved in the \( \alpha \)-decay process, except for a small correction

![FIG. 5. (Color online) \( \alpha \)-decay systematics in Po isotopes:](image-url)
in the \( \alpha \)-particle formation probability due to the blocking effect. As discussed in Ref. [9], the occupation of an orbital at the Fermi surface by an odd particle will reduce the \( \alpha \)-particle formation probability as it reduces the pairing correlations. Clearly, the blocking effect will have a larger influence in a smaller shell like 3\( j_\ell \)/2 in comparison with a larger one such as 1\( i_\ell \)/2. This is most probably responsible for systematically longer half-lives of the 3/2\(^-\) g.s. in comparison with the 13/2\(^+\) states in 193-Po. This effect is seen more clearly when discussed in terms of reduced \( \alpha \) widths or hindrance factor values, in which the energy dependence is removed from the consideration, see details in Ref. [9]. It is important to note that the weak coupling scheme is also valid for the yrast excited states, see extensive systematics in, e.g., Ref. [4] and references therein.

The \( \alpha \) decay of \(^{191}\)Po (\( I^\pi = 13/2^+ \)) demonstrated a first case of a clear deviation from the smooth behavior in the light odd-A Po isotopes. The striking observation, discussed in detail in Ref. [7], was that although the \( \alpha \)-decay energies of \(^{191}\)Po and \(^{194}\)Po are different by only 40 keV [Fig. 5(a)], their total half-lives are different by a factor of 4.2, or by a factor of 6.9 if their partial \( \alpha \)-decay half-lives are compared, see Fig. 5(b). This phenomenon was interpreted as due to onset of oblate deformation in \(^{191}\)Po (\( I^\pi = 13/2^+ \)), while the \( I^\pi = 3/2^- \) ground state of \(^{191}\)Po continued to be nearly spherical. Thus, the conclusion on shape staggering between two \( \alpha \)-decaying isomers in \(^{191}\)Po was drawn [7], which was further confirmed by a dedicated in-beam study of this nucleus [10].

The \( \alpha \) decays of \(^{189}\)Po [12] and of the new isotope \(^{187}\)Po (Fig. 2) appear to be even more interesting, as in both cases clear deviations from the systematics are seen both in their \( \alpha \)-decay energies and in partial half-life values. For example, Fig. 5(a) shows that the largest-energy \( \alpha \) decays of these isotopes (7808 and 7532 keV) are lower by \( \sim 200 \) keV (\(^{189}\)Po) or by \( \sim 300 \) keV (\(^{187}\)Po) relative to the smoothly increasing trend in the even-A Po isotopes. The possibility that this deviation is due to missing \( \alpha \) decays of higher energy (by \( \sim 200–300 \) keV) to the ground state is quite unlikely. Indeed, this scenario would require that the 7808 keV decay of \(^{187}\)Po (Fig. 2) and the 7532 keV decay of \(^{189}\)Po [12] feed to excited states at \( E^\pi \sim 200–300 \) keV in \(^{183,185}\)Pb, rather than to their ground states as presently assigned. This, in turn, would require the subsequent deexcitation from these states to the 3/2\(^-\) ground states. However, no evidence for such transitions as well as for the higher-energy \( \alpha \) decays was observed in case of \(^{189}\)Po, for which a larger number of counts was registered in comparison with \(^{187}\)Po. Though due to a lower number of observed decays such a scenario cannot be ruled out completely for \(^{187}\)Po, the similarity of its decay pattern to that of \(^{189}\)Po implies that no higher-energy \( \alpha \)-decay branches are present in \(^{187}\)Po as well. Based on the level systematics in the odd-A Pb isotopes, we also discard the possibility that the above-mentioned (hypothetical) excited states are long-lived isomeric states and their decay would not be seen within the time interval of \( \Delta t(\alpha - \gamma) \leq 5 \) \( \mu s \) used in our experiments.

Clearly related to the \( \alpha \)-energy irregularities, Fig. 5(b) demonstrates the retarded partial half-lives of the highest-energy 7808 and 7532 keV decays of \(^{187,189}\)Po, which are longer than the average of their respective even-A neighbors by a factor of \( \sim 40 \) for \(^{189}\)Po or by a factor of \( \sim 500 \) for \(^{187}\)Po. As shown by the PES calculations in this work and in Refs. [10,12], such a behavior can be interpreted as due to a structure/shape change from the spherical configuration in the heavier 193-201 Po isotopes to a prolate configuration in 187,189 Po. The structure/shape changing \( \alpha \) decays of 187,189 Po toward the spherical g.s. in the Pb isotopes are therefore strongly hindered.

On the other hand, it seems that the fine-structure 7528 keV (\(^{187}\)Po) and 7259 keV (\(^{189}\)Po) decays, shown by the closed down triangles in Fig. 5(b), follow the same trend as the decay of their even-A neighbors and of the heavier odd-A 193–201 Po isotopes. All these decays proceed between the states of similar structure/shape in parent and daughter nuclei, and therefore are unhindered.

Following the ideas presented in Ref. [39], it is tempting to speculate that the extra binding due to the strong deformation in 187,189 Po could then lead to their reduced \( Q_{\alpha} \)-decay energy toward the spherical ground state in the daughter Pb isotopes. However, it is interesting to note that no (or much less) of similar effect is seen in the \( \alpha \)-decay energies of the even-A 186,188 Po [see Fig. 5(a)], which were interpreted as being of prolite origin as well [11,21]. The latter is probably due to the fact that the shape coexistence occurs at low energy and, therefore, some mixing of different configurations (spHERICAL, oblate, prolote) is expected in the predominantly prolate \( 0^+ \) ground states of 186,188 Po, which also leads to lower hindrance factor values of HF \( \leq 20 \) [11,21]. In contrast to this, \( \alpha \) decays of 187,189 Po proceed from a pure Nilsson single particle state, which results in the above-mentioned peculiarities in their \( \alpha \) decay properties and much larger hindrance factors for the decay to the spherical ground state in the Pb isotopes. All above issues will be the subject of a dedicated forthcoming study [40].

V. CONCLUSIONS

By using the complete fusion reaction \(^{46}\)Ti+\(^{144}\)Sm \( \rightarrow \) \(^{187}\)Po+3\( n \) the new neutron-deficient isotope \(^{187}\)Po has been identified at the velocity filter SHIP. Similarly to the earlier studied isotope \(^{189}\)Po, striking features of the \(^{187}\)Po \( \alpha \) decay include the strongly-hindered decay to the ground state and unhindered decay to the low-lying deformed excited state at 286 keV in the daughter nucleus \(^{185}\)Pb.

Based on potential energy surface calculations, the \(^{187}\)Po ground state and the observed excited state in \(^{183}\)Pb were interpreted as being of prolote origin. The systematic deviation of the \( \alpha \)-decay properties in the lightest odd-A Po isotopes from the smooth behavior in the even-A neighbors is underlined.

Improved \( \alpha \)-decay data including more precise half-life values were measured for \(^{187}\)Bi\(^{m-}\). The excitation energy of \(^{187}\)Bi\(^{m-}\) and of the 9/2\(^-\) and 3/2\(^+\) excited states in \(^{183}\)Tl were measured with better precision compared to previous studies.

While it is shown that the \( \alpha \)-decay method has unparalleled sensitivity in identifying the low-lying excited states in the daughter nuclei, it would be important to perform in-beam studies of \(^{183,185}\)Pb with the aim to find strongly-coupled
rotation bands built on top of the prolate intruder bandheads suggested by our studies.

ACKNOWLEDGMENTS

We thank the UNILAC staff for providing the stable and high intensity $^{46}$Ti beam. A.N.A. and J.J.R. were partially supported by the NSERC of Canada. This work was supported by the European Commission within the Sixth Framework Programme through I3-EURONS (contract no. RI3-CT-2004-506065), by the FWO-Vlaanderen and by the Interuniversity Attraction Poles Programme - Belgian State - Federal Office for Scientific, Technical and Cultural Affairs (IAP grant P5/07) and UK EPSRC.

[40] M. Huyse et al., in preparation.