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Short note

Alpha decay of the new isotopes ^{188,189}Po

A.N. Andreyev[1], D. Ackermann[2], P. Cagarda[3], J. Gerl[2], F. Heßberger[2], S. Hofmann[2], M. Huyse[1], A. Keenan[4], H. Kettunen[5], A. Kleinböhl[2], A. Lavrentiev[6], M. Leino[5], B. Lommel[2], M. Matos[3], G. Münzenberg[2], C. Moore[4], C.D. O'Leary[4], R.D. Page[4], S. Reshitko[2], S. Saro[3], C. Schlegel[2], H. Schaffner[2], M. Taylor[4], P. Van Duppen[1], L. Weissman[1], R. Wyss[7]

[1] Instituut voor Kern- en Stralingsfysica, University of Leuven, Celestijnenlaan 200 D, 3001 Leuven, Belgium
[2] Gesellschaft fur Schwerionenforschung Darmstadt, Postfach 110541, 6100 Darmstadt, Germany
[3] Department of Nuclear Physics,Comenius University, Bratislava, Slovakia
[4] Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK
[5] Department of Physics, University of Jyväskylä, 40351 Jyväskylä, Finland
[6] Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, 141980, Dubna, Russia
[7] Department of Physics, Royal Institute of Technology, 104 05 Stockholm, Sweden

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Abstract. New neutron-deficient isotopes ^{188,189}Po have been produced in the complete fusion reaction of ^{52}Cr ions with a ^{142}Nd target at the velocity filter SHIP. The evaporation residues were separated in-flight and subsequently identified on the basis of $\alpha - \gamma$ and α-conversion electron coincidence measurements and of α-α position and time correlations. In ^{189}Po a ground state to ground state α decay with $E_{\alpha1}$=7540(20) keV, $T_{1/2}$=5(1) ms and two fine structure α-decays at $E_{\alpha2}$=7264(15) keV and $E_{\alpha3}$=7316(15) keV have been observed. In ^{188}Po ($T_{1/2}$=400^{+200}_{-150} μs) a ground state to ground state α decay at E_α=7915(25) keV and a fine structure α decay at E_α=7350(40) keV have been found. Improved data on the α-decay of ^{189}Bi were obtained.

PACS. 23.60.+e α decay – 27.70.+q $150 \leq A \leq 189$ – 27.80.+w $190 \leq A \leq 219$

1 Introduction

Alpha-decay studies of very neutron-deficient nuclei are often the only method to obtain the spectroscopic and mass information on the nuclei close to the proton drip line. In addition, α decay is well suited to study and identify low-lying excited states, especially intruder states, in the daughter nuclei yielding direct information on the excitation energy, decay pattern and configurations involved (see, for example [1,2]).

The present work on the alpha decay properties of ^{188,189}Po is a continuation of our long-term investigation on the intruder states and shape coexistence in the vicinity of the Z=82 shell closure [1–6]. A striking feature, when moving to mid-shell for the neutrons at N=104, is the increasing importance of the fine structure α decay towards excited states in the daughter lead nuclei. For example, in ^{192}Po [3,4,7] the reduced width of the fine structure decay is about two times larger than for the ground state to ground state decay, while in ^{191m}Po this is already ∼20 times larger [2]. These data clearly demonstrate that the deformed intruder π(4p-2h) component becomes a dominant configuration in the ground state of polonium nuclei around mid-shell. This phenomenon together with a dramatic lowering of the excitation energy of the intruder π(2p-2h) oblate states in the daughter lead nuclei slows down the decay towards the π(0p-0h) spherical ground state compared to fine structure decay towards these intruder states.

In this paper we report on the observation of the new isotopes ^{188,189}Po and on the identification, via fine structure α-decay, of excited states in the daughter nuclei ^{184,185}Pb. This study is a part of an experiment, undertaken at the velocity filter SHIP (GSI, Darmstadt) [8,9], in which shape coexistence phenomena in the mid-shell and near mid-shell isotopes $^{188-190}$Po and their daughter products $^{184-186}$Pb have been studied. A full account of this experiment will be given elsewhere [10].

2 Experimental set-up

The new isotopes ^{188,189}Po have been produced at the velocity filter SHIP in the 6n- and 5n- evaporation channels

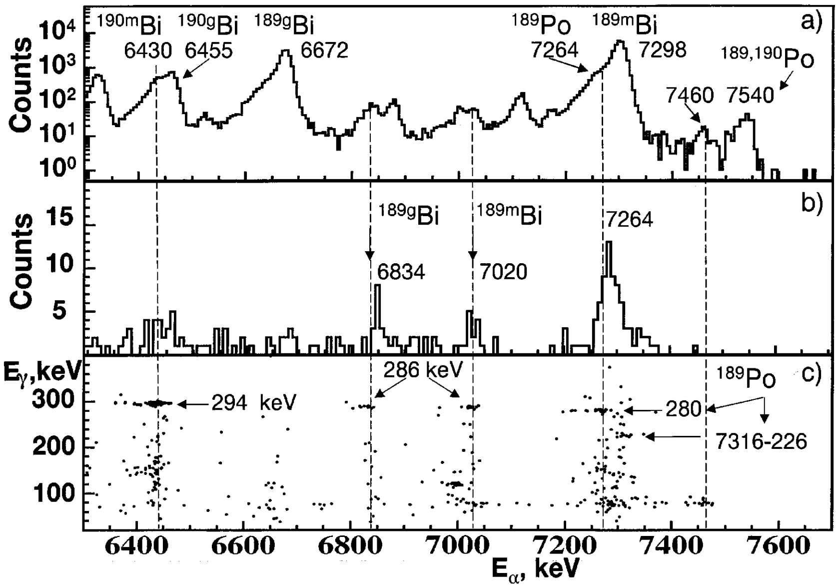

Fig. 1. a) Energy spectrum of α-decays in the PSSD correlated with an implant within 30 ms; b) The same spectrum as in (a), but a coincidence with the electrons in the box detector is required; c) α-γ coincidence matrix for α-decays, shown in a). Arrows point to α-peaks and to α-γ coincidence events that are labelled with the α and the γ decay energy (in keV) and the isotope the α-decay belongs to

respectively of the complete fusion reaction of ^{52}Cr ions with a ^{142}Nd target. A 200 pnA ^{52}Cr pulsed beam (5 ms ON/15 ms OFF) was delivered by the UNILAC heavy ion accelerator. The beam energy was changed within the E(^{52}Cr)=239-307 MeV range by retuning the accelerator in order to allow excitation function measurements. To withstand the high beam intensity eight targets, made of isotopically enriched $^{142}NdF_3$ material (99.8% enrichment, 290μg/cm^2 thickness), were mounted on the target wheel, rotating synchronously with the macrostructure of the UNILAC beam. The target material was evaporated onto a carbon backing of 50 μg/cm^2 thickness and covered with an additional layer of 10 μg/cm^2 of carbon. The evaporation residues after separation were implanted into a 300 μm thick, 35×80 mm^2 16-strip position-sensitive silicon detector (PSSD), where their subsequent α decays were measured. Each strip is 5 mm wide and position sensitive along the strip. Typical energy resolution of each strip was about 18 keV, while relative position resolution was about 200 μm FWHM for the α-decays of a decay chain and about 400 μm for the implant-α events. In front of the PSSD six similar silicon detectors (called further electron or box detectors) were mounted, facing the PSSD and forming a seven cm-deep box. They used to detect conversion electrons in coincidence with the α-particles. These detectors measured also alphas and electrons, escaping from the strip detector in the backward hemisphere and leaving only a part of their energy in the strip detector. Behind the strip detector a four-fold segmented Clover detector was installed for α-γ and α-X ray coincidence measurements. The relative efficiency curve of the Clover detector was measured by using a mixed ^{133}Ba/^{152}Eu source, while the absolute efficiency was obtained by normalizing this curve on the measured efficiency for the E=294 keV γ transition in ^{186}Tl, as explained further in the text. The absolute efficiency measurement for the electron detectors was obtained by using the measured data for ^{190}Bi (see the next section). The observed nuclei have been identified by excitation function analysis, α-decay energies and half-life values and by using the method of generic parent-daughter α-decays. In addition, in the data analysis, α-decays in the strip detector were searched for in a prompt coincidence with either the low-energy signals in the electron detectors or with γ events in the Ge detectors. For further details on the experimental method see [9,10].

3 Experimental results

The data for the ^{189}Po nucleus were mainly collected at the beam energy of E(^{52}Cr)=272.0(5) MeV, corresponding to the maximum of the 5n-channel according to calculations with the statistical model code HIVAP. Figure 1(a) shows the spectrum of α-decays correlated with the recoil implants within a maximum time interval of 30 ms between the implant and the α-decay. We stress that even under such a condition the spectrum is dominated by the α decays of the $^{188-191}$Bi isotopes abundantly produced in the pxn- evaporation channels. Figure 1(b) shows the same spectrum but under an additional condition of coincidence of α-particles with any signal in the electron detectors, while Fig. 1(c) shows a two-dimensional spectrum of α-particles in coincidence with γ-rays, registered in the Clover detector. As in the Fig. 1(a,b) a coincidence with an implant within the time interval of 30 ms is required to produce Fig. 1(c). We note that due to electronic thresholds we were not able to record the low-energy part ($E<450$ keV) of the spectrum in the electron detectors, corresponding to the conversion electron signals. Instead, as a signature for the registration of the electrons we used the TAC signal, corresponding to the time difference between any signal in the PSSD and any signal in the box detectors.

The absolute electron efficiency determination was done by using the abundantly produced E_α=6430(10) keV

α-decay of ^{190}Bi. In Fig. 1(c) the 6430(10) keV-294(1) keV α-γ coincident pairs are clearly observed and identified as the known α-decay of ^{190m}Bi to an excited state at 294 keV in the daughter ^{186}Tl, decaying by an E1 gamma transition [11]. Despite low theoretical conversion coefficient of α_{tot}=0.025 [12] the coincidences between the 6430(10) keV α-particles and conversion electrons (TAC signal), resulting from the 294 keV transition have been observed, see Fig. 1(b). We stress that there is a small shift of about 5-10 keV to higher energies of the α-decay energies deduced from the α-e$^-$ spectrum, compared to those from the α-γ spectrum. This shift is due to summing of the full α-decay energy with the partial energy, left by the electron in the PSSD, while escaping to the backward detector. The energies of the peaks labelled in Fig. 1(b) are corrected for this effect.

The absolute electron efficiency ϵ_e can then be deduced from the relation between the number of 6430 keV α-events from the Fig. 1(a), the number of α-e$^-$ coincident events from Fig. 1(b) and the theoretical conversion coefficient α_{tot}. A similar procedure can be followed for determining the absolute γ efficiency ϵ_γ of the Clover detector. The deduced efficiencies are ϵ_γ=5.5(4)% for the 294 keV γ-rays and ϵ_e=37(5)% for corresponding conversion electrons with the energy of about 220 keV. We note that the last value is in good agreement with calculations using the GEANT Monte-Carlo code [13].

In order to explain the analysis procedure, we will first discuss the α decay of the known ^{189m,g}Bi isotopes. The $9/2^-$ ground state of ^{189}Bi has a known α-decay branch to the 286 keV $3/2^+$ excited level in ^{185}Tl and this can be seen in Fig. 1(c) as a group of 6834(15) keV-286(1) keV $\alpha-\gamma$ events. A second group at 7020(15) keV-286(1) keV indicates a previously unknown α-decay towards the same level. The half-life (T$_{1/2}$=$5.2^{+1.8}_{-1.1}$ ms) and the sum Q-value energy attribute this branch to the decay of the $1/2^+$ isomeric state in ^{189}Bi, for which an improved half-life value of 5.0(1) ms was obtained in this study. These α-lines are also seen in Fig. 1(b) and in both cases a conversion coefficient of α_{tot}=0.18(7) was deduced, consistent with the literature value [14]. The new fine structure $1/2^+ \rightarrow 3/2^+$ α- decay of ^{189m}Bi extends the systematics of similar decays in the odd-mass $^{187-193}$Bi nuclei (see [5, 15,16] and refs. therein).

The new isotope ^{189}Po was identified by observing nineteen 7264(15) keV-280(1) keV α-γ events in Fig. 1(c) and 78(9) 7264(25) keV-e$^-$ α-e$^-$ coincidences in Fig. 1(b). The half-life values of these two groups of events, deduced from the time interval between an implant and the first α-γ or α-e$^-$ coincidence pair, are very similar and the combined data give T$_{1/2}$=5(1) ms. In Fig. 1(a) the peak at 7264 keV can be seen as a small shoulder on the α-peak of the much more abundantly produced ^{189m}Bi (E$_\alpha$=7298(10) keV, T$_{1/2}$ = 5.0(1) ms). We stress that the 7298 keV α-decay of ^{189m}Bi does not have any coincident γ-rays or electrons and therefore is completely suppressed in Fig. 1(b) and (c). On the basis of these data a g.s.→g.s. α-decay energy of E$_\alpha$=7540(20) keV can be deduced and, indeed, an α-peak with a similar energy is present in Fig. 1(a). This peak is mixed with the α-line of ^{190}Po, for which more precise data compared to the literature (see, [4] and refs. therein) are deduced from our experiment (E$_\alpha$=7535(10) keV, T$_{1/2}$=2.45(5) ms). By using the recoil-$\alpha_1-\alpha_2$ correlation analysis we deduced the number of the 7535 keV α-particles of ^{190}Po for which the decay properties of the daughter nuclides are known better than in the case of ^{189}Po. Then by subtracting this number from the total number of α-counts in the sum peak we estimated the intensity of the 7540 keV g.s.→g.s. α-decay of ^{189}Po.

By comparing the number of 7264 keV-280 keV α-γ and 7264 keV-e$^-$ pairs in Fig. 1(b) and Fig. 1(c), a conversion coefficient of $\alpha_{tot}=0.61(15)$ was obtained for the 280 keV γ-transition. This high conversion coefficient is responsible for an artificial line at 7460(20) keV in Fig. 1(a) as the K- conversion electrons (E$_e$ ∼190 keV) of the 280 keV transition can sum up in the PSSD with the 7264 keV α-line. This α-e$^-$ summation line is also present in Fig. 1(c) as it is coincident with the characteristic X-rays of Pb. Such summing effect was discussed in detail in [17] and our GEANT calculations confirm that the thickness of the PSSD is enough to stop all such electrons.

One final group of α-γ coincidences not yet discussed is the six 7316(15) keV-226(1) keV, T$_{1/2}$=7.5^{+3}_{-2} ms α-γ coincident pairs giving a sum Q-value energy of 7700(20) keV, similar to the Q$_\alpha$-value of 7703 keV for the ground state to ground state α-decay of ^{189}Po. On these grounds we assign the 7316 keV α-decay as a fine structure decay of ^{189}Po to an excited state at E*=226 keV in the daughter nucleus ^{185}Pb. However, we note that another explanation is possible (see the next section).

The assignment of two fine structure decays (7264 keV and 7316 keV) and of the g.s.→g.s. decay (7540 keV) to ^{189}Po is further supported by their correlations to known α-decays of the daughter nuclei ^{185}Pb and ^{181}Hg and by the excitation function measurements.

At the ^{52}Cr beam energies of 288.0(5) MeV and 294.0(5) MeV, corresponding to the calculated maximum of the 6n- evaporation channel, seven three-fold recoil-α_1-α_2 time-position correlated events were observed with E$_{\alpha1}$=7915 (25) keV, T$_{1/2}$=400^{+200}_{-150} μs and E$_{\alpha2}$= 6618(20) keV, T$_{1/2}$= 315 $^{+170}_{-80}$ ms. The latter is consistent with the decay properties of ^{184}Pb [18]. Furthermore, two time-position correlations of the E$_{\alpha1}$= 7915(25) keV decay with the α-decays at E$_{\alpha3}$= 6120(20) keV of the granddaughter ^{180}Hg nucleus were found. The ratio of granddaughter to daughter correlations is consistent with the alpha branching value α_{br}=48(2)% of ^{180}Hg [18]. On the basis of these data we assign the 7915(25) keV line to the α decay of ^{188}Po.

Fine structure in the α-decay of ^{188}Po has been found by the observation of three recoil- α_1(7350(40) keV) - α_2(6620(20) keV, T$_{1/2}$=530^{+700}_{-200} ms) correlation chains. The half-life value of the first alpha decay (T$_{1/2}$=200^{+265}_{-80} μs) is consistent with the half-life of the g.s→g.s. 7915 keV decay, while the α-decay properties of the second are consistent with those of ^{184}Pb. Therefore, we interpret this decay as a fine structure α-decay of ^{188}Po to an excited

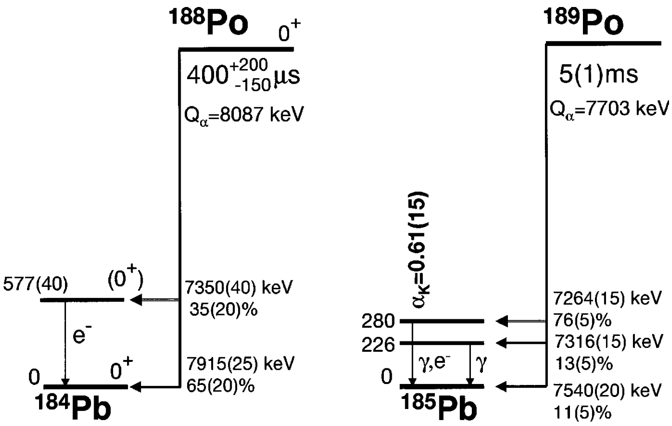

Fig. 2. a) Decay schemes of the new ^{188,189}Po isotopes. Indicated are α-decay energies, intensities and half-life values

state at E*=577(40) keV in the daughter ^{184}Pb nucleus. Moreover, for one of these events we observed an α-e$^-$ coincidence of the first α-decay with an electron in the electron detector. Taking into account the measured efficiency of the electron detector (37(5)%), this indicates that within this limited statistics every alpha decay is followed by the emission of an electron.

The deduced α-decay schemes of ^{188,189}Po are shown in Fig. 2 and will be discussed in the next section.

4 Discussion

The appearance of high spin $13/2^+$ and low spin $3/2^-$ α-decaying states in the odd-mass polonium nuclei with 191 $\leq$A$\leq$ 201 is a well established pattern, see [2,19]. Our recent studies [2,5,6] presented first evidence for the Δl=0 fine-structure α-decays of $^{191m-197m}$Po and of $^{191g-195g}$Po to excited levels in the corresponding daughter lead nuclei. Furthermore, an increased importance of the fine structure decay compared to the Δl=0 α-decay towards the lowest state was clearly demonstrated. These excited $13/2^+$ and $3/2^-$ states decrease in energy by moving towards the mid-shell nucleus ^{187}Pb and follow closely the excitation energy of the 0^+ intruder states in the neighbouring even-mass lead isotopes. Another important observation is that the energy difference between the highest energy α-transitions for the $13/2^+$ and $3/2^-$ α-decaying states decreases from $\sim$100 keV in $^{195-201}$Po over $\sim$60 keV in ^{193}Po to $\sim$40 keV in ^{191}Po. Half-life values of these isomeric states are also very similar ($T_{1/2}(3/2^-)/T_{1/2}(13/2^+)\leq 2$), with the only exception in ^{191}Po for which the decay of the $13/2^+$ isomeric state is about 5 times longer than of the $3/2^-$ isomer [2]. The above arguments suggest that in ^{189}Po one should also expect two α-decaying states with similar transition α-decay energies and half-life values along with the strong fine-structure α-decay branches to excited states in ^{185}Pb. The latter were indeed observed in our experiment as discussed above and shown in Fig. 2. The former statement is consistent with the fact that these two fine structure α-decays have the same sum α-γ Q-value and similar half-lives ($T_{1/2}$=5(1) ms and $T_{1/2}=7.5^{+3}_{-2}$ ms, respectively). Therefore, tentatively, our data could indicate the existence of two α-decaying states in ^{189}Po with very similar transition α-decay energies of about 7540 keV, but with different fine structure α-decay schemes. Unfortunately, due to the limited statistics it is impossible at this moment to disentangle these decays and therefore we put them in one decay scheme, see Fig. 2.

One should briefly mention that, quite surprisingly, the low excitation energy of these two states is at variance with the trend of the oblate 0^+, $13/2^+$ and $3/2^-$ intruder states in the heavier even- and odd- mass lead nuclei, indicating that they are, most probably, associated with the predicted prolate deformed states, intruding to very low energy in $^{184-188}$Pb [20].

The observation of a strong fine structure α-decay in ^{188}Po to the 577(40) keV excited level in ^{184}Pb and the high conversion coefficient suggest an E0 multipolarity for the 577 keV transition. This tentatively defines 0^+ for the spin and parity of the 577 keV excited state in ^{184}Pb. We note that the only available information on the excited states in ^{184}Pb comes from a recent in-beam study at the RITU gas-filled separator, where the yrast prolate rotational band, starting from the 2^+ state at E*=702 keV, was observed [21]. Therefore, the 577(40) keV state, observed in the current study, is the first excited state in the ^{184}Pb nucleus and could be a bandhead of this band. By using a variable moment of inertia fit to the higher-lying members of the rotational band an (unperturbed) position of E*=610 keV for the 0^+ prolate bandhead in ^{184}Pb was deduced in [21] which is in reasonable agreement with the experimentally measured (perturbed) excitation energy of 577(40) keV. However, one should keep in mind that the experimental systematics of 0^+ oblate bandheads in the even-mass $^{186-202}$Pb nuclei suggest that an oblate 0^+ bandhead could be expected at a similar excitation energy in ^{184}Pb [10]. Moreover, the mixing and interaction of two or, even, three 0^+ states (spherical, oblate and prolate) will certainly perturb their positions, similar to the case of ^{188}Pb, discussed in detail in [7]. Therefore, on the basis of the present data it is not possible to make an unambiguous conclusion on the origin of the state at 577(40) keV. In a forthcoming paper [10] we will present a detailed discussion of the systematics of the fine structure α-decays in the lightest polonium nuclei.

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