FINE STRUCTURE IN THE ALPHA-DECAY OF THE NEUTRON-DEFICIENT ^{191}Po AND ^{191}Bi ISOTOPES

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The α-decay properties of the neutron-deficient ^{191}Po and ^{191}Bi nuclei have been investigated at the RITU gas-filled separator using the 5n and p4n evaporation channels of the ^{36}Ar+^{160}Dy$\rightarrow$^{196}Po* reaction. In contrast to previous studies two α-decaying isomeric states were observed in the decay of ^{191}Po. Evidence was found for α-decay to excited levels in the ^{187}Pb daughter nucleus. The tentative interpretation of these levels could be a weak coupling of the odd neutron to an intruder $2p$–$2h$ deformed 0^+ state in the even-even core. The difference in the reduced α widths of the α transitions towards the ground state and excited state points to a deformed $13/2^+$ isomeric state in ^{191}Po. Branching ratios of $b_\alpha(^{187m}\mathrm{Pb})$=12(2)% and $b_\alpha(^{187g}\mathrm{Pb})$=7(2)% have been experimentally measured. For ^{191}Bi two new alpha-lines have been observed. A more precise half-life value of $T_{1/2}$ = 115(10)ms was determined for ^{191m}Bi.

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1. Introduction

Recently, in the framework of a long-term program to study shape coexistence and intruder states in the region near $Z = 82$, new data on the alpha-decay of the very neutron-deficient ^{190}Po nuclei have been obtained [1]. These data confirmed the conclusion, made in [2], that in contrast to heavier even-even Rn and Ra nuclei, the reduced α-widths of ground state to ground state alpha decay of ^{190,192,194,196}Po reach a saturation value of $\delta^2 \approx 55$ keV. A possible explanation of such a behavior could be a mixing of the 0^+ intruder $\pi(4p\text{–}2h)$ state into the normal $\pi(2p)$ ground state in light Po isotopes [1, 2] resulting in an onset of deformation in the ground state of the lightest Po isotopes. Recent studies of the fine structure in the α decay of ^{192}Po seem to confirm this conclusion [3] by revealing a strong feeding to a corresponding $\pi(2p\text{–}2h)$ 0_2^+ state in ^{188}Pb. This indicates that in ^{192}Po the ground state has a dominant $\pi(4p\text{–}2h)$, probably, oblately deformed intruder configuration. However, although presently such deformed $\pi(2p\text{–}2h)$ states are known in even Pb isotopes from $A = 208$ down to $A = 188$ [3, 4], very little is know about such states in odd-mass Pb-nuclei.

Recent in-beam studies of light odd-mass Pb and Po isotopes identified the structure of the lowest excited states in the ^{187,189,191}Pb [5, 6] and in the ^{193,195,197}Po isotopes [7] and gave further evidence that the structure of the first excited states in the odd-mass Pb and Po nuclei can be interpreted as a weak coupling of the odd $i_{13/2}$ neutron to the low-lying near-spherical states of the even-even core. A similar coupling of the odd neutron to the members of the deformed band resulting from a proton-pair excitation across the $Z = 82$ closed shell has been observed in ^{191,195,197}Pb [6, 8, 9].

The main purpose of the present work is a detailed α-decay study of odd-mass ^{191}Po and its daughter ^{187}Pb nucleus, through which we aim to obtain information on the intruder states. In previous experiments on ^{191}Po only 'one' α-decaying state was observed ($E_\alpha = 7314(20)$ keV and $T_{1/2} = (15.5^{+6.0}_{-2.5})$ ms [10], $E_\alpha = 7330(15)$ keV and $T_{1/2} = (27^{+22}_{-8})$ ms [11]) in contrast to all heavier odd-mass Po isotopes with masses $193 \leq A \leq 201$ (see *e.g.* [2]).

2. Experimental details

2.1. ^{191mg}*Po and* ^{187mg}*Pb isotopes*

The experiments have been performed at the gas-filled recoil separator RITU [12]. A pulsed beam (2 ms ON/8 ms OFF) of ^{36}Ar was used with an initial energy of 196 MeV on a ^{160}Dy target (thickness = 500μg/cm^2, 67.1% enriched). As the excitation functions behavior was important for the identification of the nuclei, we performed the measurements at five beam energies covering the range of $E_{\rm lab}$=175-193 MeV in the center of the target. Nickel degrader foils were used to change the beam energy. The evaporation residues (EvRs), after passing through the separator, were implanted into a position-sensitive silicon detector (PSSD), divided into sixteen independent strips. The identification of the nuclides has mainly been done by the observation of genetically correlated α-decay chains and by the excitation functions. Other technical details about the separator and the electronics can be found elsewhere [1, 12]. A high-purity germanium detector was installed 2 cm behind the PSSD, outside the vacuum chamber, giving the possibility to take α-γ and α-X ray coincidences.

The alpha spectrum, collected between beam pulses and summed over all five beam energies, is shown in Fig. 1.

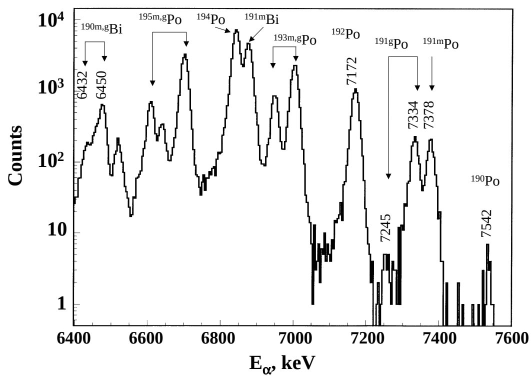

Fig. 1. An example of alpha-spectrum, observed in the ^{36}Ar+^{160}Dy→^{196}Po* reaction between beam pulses and summed over all five beam energies, used in the work.

In the α-energy region where ^{191}Po was expected, two α-lines were observed with a similar intensity of $\approx$ 1500 counts. Their excitation functions are in agreement with a $5n$ reaction channel. The half-life behavior of these two alpha-lines is given in Fig. 2. The α line at 7334(10) keV showed a half-life of 22(1) ms while the α line at 7378(10) keV showed a half-life of 98(8) ms. Due to their difference in half-life values, these two α-transitions are assigned to the α decay of two isomers in ^{191}Po.

Further proof for this assignment and establishment of the decay pattern is provided by the correlations of these alpha-decays with known alpha-decays of the daughter ^{187m,g}Pb isotopes. Previous decay studies of ^{187m,g}Pb (see, [13] and Refs. therein) identified two isomeric states with tentative spin assignments of $13/2^+$ (E_α = 6073(10) keV, $T_{1/2}$=18.3(3)s) and $3/2^-$ ($E_{\alpha 1}$ = 5993(10) keV, $I_{\alpha 1}$ = 40%, and $E_{\alpha 2}$ = 6194(10), $I_{\alpha 2}$ = 60%, $T_{1/2}$ = 15.2(3) s). From the detailed analysis of the correlation data we found about 80 three-fold correlations of the type EvR-α_1(7378(10) keV)-α_2(6070(15) keV) and about 60 three-fold correlations of the type EvR-α_1(7334(10) keV)-α_2(6000-6260 keV). The broad energy interval for α_2-decay in the latter case was stipulated by summing of the energies of alpha-particles from ^{187g}Pb with coincident conversion electrons, resulting from highly converted transitions in ^{183}Hg as discussed in [13]. The decay scheme of ^{191}Po, based on our data and on the data from [13, 14] for daughter activities is

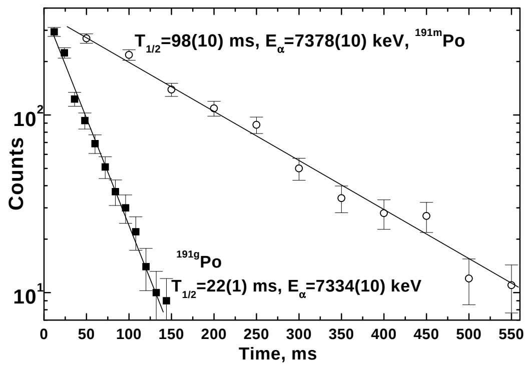

Fig. 2. Decay curves for $E_\alpha = 7334(10)$ keV and $E_\alpha = 7378(10)$ keV α-lines in ^{191}Po.

shown in Fig. 3. It should be noted that not only three-fold (recoil-α_1-α_2) but also four-fold correlations were observed where the fourth registered events were the gamma-decays of the excited levels, populated by the alpha-decay of ^{187g}Pb (see [13] and Fig. 3). Based on the systematics for heavier odd-mass Hg, Pb and Po isotopes and on the hindrance factors, a low spin value of $3/2^-$ and a high spin value of $13/2^+$ have been tentatively assigned to the ground and to the isomeric states in ^{191}Po, respectively. A weak α-line with the energy of 7254(15) keV (see Fig. 1) and a half-life value of 22(6) ms has been assigned as a crossover transition from the low spin $3/2^-$ ground state in ^{191}Po to the high spin $13/2^+$ isomeric state in ^{187}Pb (see Fig. 3).

Fine structure α-lines in the decay of ^{191m,g}Po were identified from the analysis of the prompt α-γ coincidence matrix, shown in Fig. 4. Except for strong α-γ transitions corresponding to known cases of ^{190,192}Bi [15] one sees α-γ coincident pairs with $E_\alpha = 6888(15)$ keV and $E_\gamma = 494(1)$ keV ($T_{1/2}(\alpha - \gamma)$<10 ns), and $E_\alpha = 6960(15)$ keV and $E_\gamma = 375(1)$ keV. From the time difference for pairs of EvR-[α-γ] events the half-life value of 116(30) ms has been deduced for the 6888-keV α line and a half-life value of 15^{+8}_{-4} ms for the 6960-keV α line. On the basis of the sum-energy balance, half-life values, and the behavior of the excitation functions the α-line with $E_\alpha = 6888(15)$ keV has been assigned to ^{191m}Po. An admixture of an E0-component was found in the 494-keV transition based on α-Pb X-ray coincidences. This results in a spin value of $13/2^+$ for the excited state at 494 keV and a hindrance factor (HF) of HF=0.64(15) for the 6888-keV α line. The α line at 6960 keV has tentatively been assigned to the decay of the ^{191}Po ground state on the basis of its half-life behavior and the sum-energy balance. By using similar arguments, this results in an $3/2^-$ excited

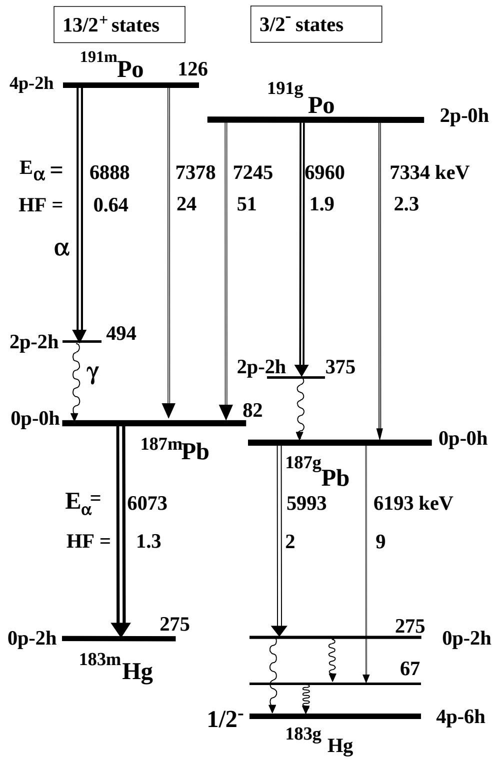

Fig. 3. Proposed alpha-decay scheme of ^{191m,g}Po. Numbers near the arrows indicate the α-decay energies and hindrance factors. See text for details.

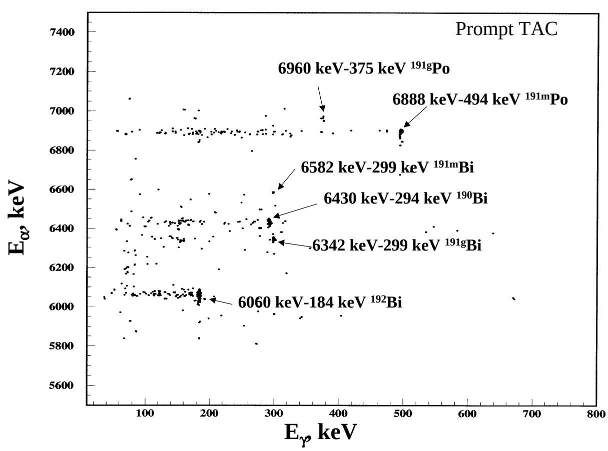

Fig. 4. Prompt α-γ coincidence matrix.

state at 375 keV and a HF of 1.9 for the 6960-keV fine-structure α line. The hindrance factor is defined as the ratio of the reduced α width, using the method of Rasmussen [17], of the transition relative to the reduced α width of the ground-state to ground-state transition in the even-even neighbouring nuclei.

In an earlier work [16] an alpha-branching ratio of b_α (^{187}Pb, E_α = 6073 keV)= 2% was estimated in a rather model-dependent way from comparison of the cross-section values for different Pb-Po isotopes. For the second isomer in ^{187}Pb no information on the alpha-branching ratio was known before our study. In our work these values could be directly measured by comparing the numbers of registered EvR-α_1(^{191}Po) and EvR-α_1(^{191}Po)-α_2(^{187}Pb) correlations for each α-line of ^{191}Po. From these data we derived new alpha-branching ratios of b_α(^{187m}Pb)=12(2)% and b_α(^{187g}Pb)=7(2)%. It is important that our value of b_α(^{187m}Pb)=12(2)% results in the hindrance factor of HF=1.3 for 6070 keV alpha-decay in ^{187m}Pb thus providing experimental evidence for favored character of this transition and proving the tentative conclusion of [13] that the corresponding states in ^{187m}Pb and ^{183}Hg have similar structures.

2.2. ^{191m,g}Bi

In addition to three earlier known alpha-lines in the α-decay of ^{191}Bi (see [18] and Refs. therein) two new alpha transitions were identified from the analysis of the α-γ prompt coincident spectrum, shown in Fig. 4. The decay scheme of ^{191m,g}Bi, based on the data from the literature and on our new data is shown in Fig. 5 and will be discussed below.

The sum of alpha and gamma decay energies for the group of events with E_α=6342(15) keV and E_γ=299(1) keV is equal to the α-decay energy of the $9/2^- \rightarrow 1/2^+$ groundstate to groundstate E_α=6640(10)keV alpha transition in the ^{191g}Bi$\rightarrow$^{187g}Tl decay chain. The excitation function for the E_α=6342(15) keV α-line, built on the basis of α-γ events, is similar to the excitation functions of the E_α=6640(10)keV and E_α=6311(10)keV α-lines. On these grounds we assign this decay as a transition from the $9/2^-$ ground state of ^{191}Bi to the known $3/2^+$ excited state at $E = 299$ keV in ^{187}Tl and a value of 0.78% for the relative intensity of this α-line could be deduced. Half-life values of all these α-transitions are too long to be measured in our experiment ($T_{1/2}$=(12$\pm$1)s [18]).

From the analysis of the time distribution between implantation of EvRs and their first α-decay with the energy of E_α=6876 keV (see Fig. 1) we deduced a more precise half-life value of ^{191m}Bi: $T_{1/2}$ = 115(10) ms, compared to the previously reported value of $T_{1/2}$ = 150(15) ms [19]. A weak (I_α=0.24%) α line at 6582(15) keV, coincident with gammas at E_γ = 299(1)

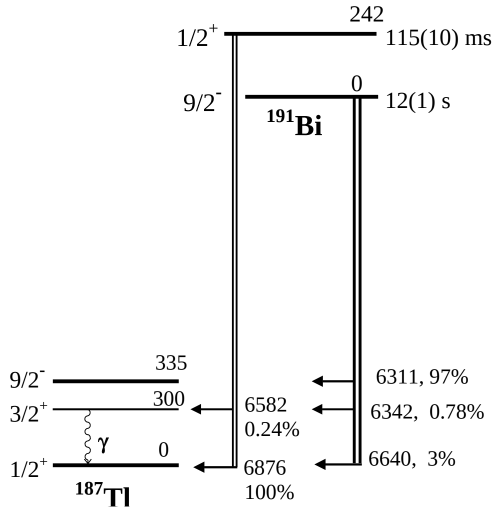

Fig. 5. Decay scheme of ^{191m,g}Bi.

keV has tentatively been assigned to the decay of the ^{191}Bi $1/2^+$ isomeric state to the $3/2^+$ excited state in ^{187}Tl. The assignment was done on the basis of the half-life behavior and the sum-energy balance.

3. Discussion

We would like to stress that although the α-decay energy of the $13/2^+$ isomeric state in ^{191}Po is slightly higher than the decay energy of the $3/2^-$ ground state, its half life is about 4 times longer. This is due to the strong hindrance (HF = 24) of the transition from the $13/2^+$ isomer in Po to the $13/2^+$ isomer in Pb. On the contrary, the decay of the $13/2^+$ isomer to the second $13/2^+$ state in ^{187}Pb is slightly faster than the ground-state to ground-state decay of the even-even neighbours. Total potential-energy calculations, similar to those, described in [20], indicate that for all odd Po nuclei ($189 \leq A \leq 199$) a slightly deformed ($\beta_2 \sim 0.1$) configuration is lowest in energy as well for the positive as for the negative parity states. But there are two exceptions: in ^{191}Po the positive parity states have their minimum at $\beta_2 = 0.22$ and $\gamma = -60$, and in ^{189}Po the negative parity states have a similar minimum. Such a minimum can be explained by the specific interaction of the proton $4p$–$2h$ configurations with the valence neutrons. This $4p$–$2h$ configuration can decay to a $13/2^+$ state originating from the coupling to the $2p$–$2h$ excited state in the even-even Pb neighbours, but not to the $0p$–$0h$ $13/2^+$ isomeric state. The ^{191}Po $3/2^-$ ground state is expected to have a $2p$–$0h$ configuration and can thus decay to the $0p$–$0h$ ground state in Pb and to the $3/2^-$ excited state originating from the coupling of the $3/2^-$ neutron to the $2p-2h$ 0^+ intruder state in the even–even Pb neighbour, see [1,2].

The observation of two α-decaying isomeric states in ^{191}Po with similar decay energies but different half-lives together with the evidence for fine structure in both decays leads to the identification of proton $2p$–$2h$ based states in ^{187}Pb. Due to the observation of strongly retarded $l=0$ α decay between the two $13/2^+$ isomers in the ^{191}Po-^{187}Pb α-decay chain, and of normal $l=0$ α decay between the $13/2^+$ isomer and the $13/2^+$ excited state and between the $3/2^-$ ground states, evidence is found for shape staggering in ^{191}Po.

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