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Short note

New microsecond isomers in ^{189,190}Bi

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Abstract. New microsecond isomers in the neutron-deficient isotopes ^{189g,190}Bi have been identified after in-flight separation by the velocity filter SHIP. The evaporation residues were identified on the basis of delayed recoil-γ/X-ray, recoil-γ/X-ray-α and excitation function measurements. The systematics of the $[\pi 1i_{13/2}]13/2^+$ excited states in the odd-mass Bi nuclei is discussed.

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

1 Introduction

Nuclei in the vicinity of closed shells represent a unique laboratory for studies of specific combinations of valence nucleons (both protons and neutrons), often leading to shape coexistence and/or to isomeric states. This is especially true for the neutron-deficient nuclei near the $Z = 82$ closed shell where the presence of unique parity high-j orbitals such as $\nu 1i_{13/2}$ or $\pi 1i_{13/2}$ close to the Fermi surface provides the best conditions for the appearance of isomeric states [1–5]. In the neutron-deficient odd-mass Bi nuclei this leads to the appearance of the $\pi 13/2^+$ states [1], which for $A \leq 195$ decay to the $9/2^-$ ground state by an $M2$ transition [3,6]. In the even-mass nuclei a coupling of the valence $\pi 3s_{1/2}$ or $\pi 1h_{9/2}$ proton particle or hole to the $\nu 1i_{13/2}$, $\nu 2f_{5/2}$ or $\nu 3p_{3/2}$ neutron leads to a multiplet of states, some of which are isomeric [2,4,5]. The study of such states provides a crucial test for the shell model and helps to fix parameters in the shell model calculations.

In this work we report on the observation of the microsecond isomeric states in ^{189g,190}Bi. This work is a part of an experiment [7] to study very neutron-deficient Pb-Bi-Po nuclei in the neutron mid-shell region around $N = 104$, performed at the velocity filter SHIP at GSI, Darmstadt [8,9].

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2 Experimental set-up

A detailed description of the experimental set-up has been given in [9,7] and here we present only specific features pertinent to the current study. The isotopes ^{189,190}Bi were produced in the p4n and p3n evaporation channels, respectively, of the complete fusion reaction of ^{52}Cr ions with a ^{142}Nd (99.8% enrichment, 290 μg/cm^2 thickness) target. A 200 pnA ^{52}Cr pulsed beam (5.5 ms ON/14.5 ms OFF) was provided by the UNILAC heavy ion accelerator. In order to allow excitation function measurements, eight beam energies in the range $E(^{52}\mathrm{Cr}) = 239$–$307$ MeV at the front of the target were used. 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. After separation by the velocity filter SHIP, the evaporation residues (EVRs) were implanted into a position-sensitive silicon detector (PSSD), where their subsequent α-decays were measured. Behind the PSSD a four-fold segmented Compton-unsuppressed Ge Clover detector was installed for prompt and delayed (up to 5 μs) α-γ/X-ray coincidence measurements allowing information on long-lived isomeric states to be collected.

The measurements exploited the Recoil Decay Tagging (RDT) method [10,11], using the characteristic α-decay of the implanted nuclei to tag delayed gamma radiation,

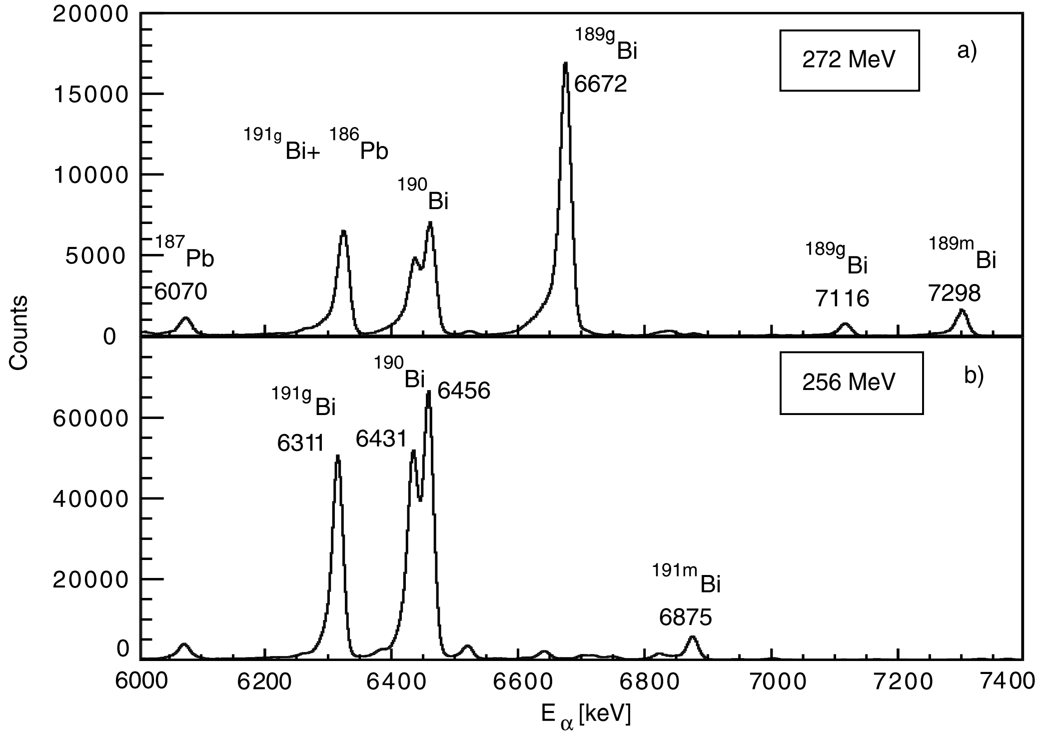

Fig. 1. α-decay spectra in the PSSD, collected between beam pulses at the beam energy of a) 272 MeV and b) 256 MeV. Some intense peaks relevant for discussion are labelled with the α decay energy (in keV) and the isotope the α decay belongs to.

emitted by the EVRs in the isomeric state and measured by the Clover detector. Unfortunately, for technical reasons we could not use any TAC or TDC to measure the half-life values of the isomeric decays directly in this experiment. However, we were able to extract half-life estimates using the method outlined in the next section.

The data from the PSSD, including possible prompt/delayed coincidences with the Clover detector, were stored on tape when any event (EVRs or α-decay) in the PSSD was registered.

3 Experimental results

3.1 ^{189g}Bi

Figure 1a shows the spectrum of α-decays registered between beam pulses at the beam energy of 272.0(5) MeV. The strongest peak at E_α = 6672 keV corresponds to the decay of the $9/2^-$ ground state in ^{189}Bi ($T_{1/2}$ = 680 ms [1]).

Figure 2a shows the γ-ray spectrum measured at this beam energy by the Clover detector in coincidence with recoils registered in the PSSD within the coincidence time interval of 5 μs. The decays of the known 12^+, 11^- and 10^+ microsecond isomeric states in ^{190}Pb are responsible for the γ-peaks at 339, 407, 455, 507, 516, 540 and 774 keV [12]. The γ-line at 273 keV corresponds to the decay of a new isomeric state in ^{190}Bi and will be discussed later. The origin of the 306 keV γ-decay could not be identified in this work.

The γ-transition, observed at 357(1) keV, has an excitation function similar in shape and position to the 6672 keV α-line of ^{189g}Bi and on this basis we assign this transition to ^{189}Bi. Figure 2b shows the same spectrum as in fig. 2a, but with an additional condition that the EVR-γ pair is correlated within the time interval of 2 s with an α-decay in the energy range of E_α = 6640–6700 keV, corresponding to the decay of the $9/2^-$ ground state in ^{189}Bi. Figure 2b has also been corrected for background from random coincidences. As a background spectrum we used the spectrum from fig. 2a, normalised to the same number of the (random) γ-decays of ^{190}Pb as in fig. 2b before the background was subtracted. In fig. 2b, besides a peak at E_γ = 357(1) keV coincidences with the K-X rays of Bi are also observed. Thus, the excitation function behaviour, coincidence with the Bi K-X rays and the condition of correlation with the α-decay of ^{189g}Bi establishes the origin of the 357 keV γ-line as the ^{189g}Bi nucleus.

By comparing the number of the K-X rays and γ-rays in fig. 2b, corrected for the corresponding efficiencies [7], a conversion coefficient of α_K = 0.9(1) can be deduced. This value is consistent with the theoretical value of α_K(357 keV, $M2$) = 0.77 [13] and this establishes the spin and the parity of the 357 keV excited state in ^{189g}Bi as $13/2^+$. We assume that this state decays by the $M2$ transition directly to the $9/2^-$ ground state of ^{189}Bi, as in the cases of ^{195}Bi [3] and ^{191,193}Bi [6].

As was mentioned in sect. 2, we were not able to directly measure the half-life values for the isomeric states, but in some cases a reliable estimate can be given. The

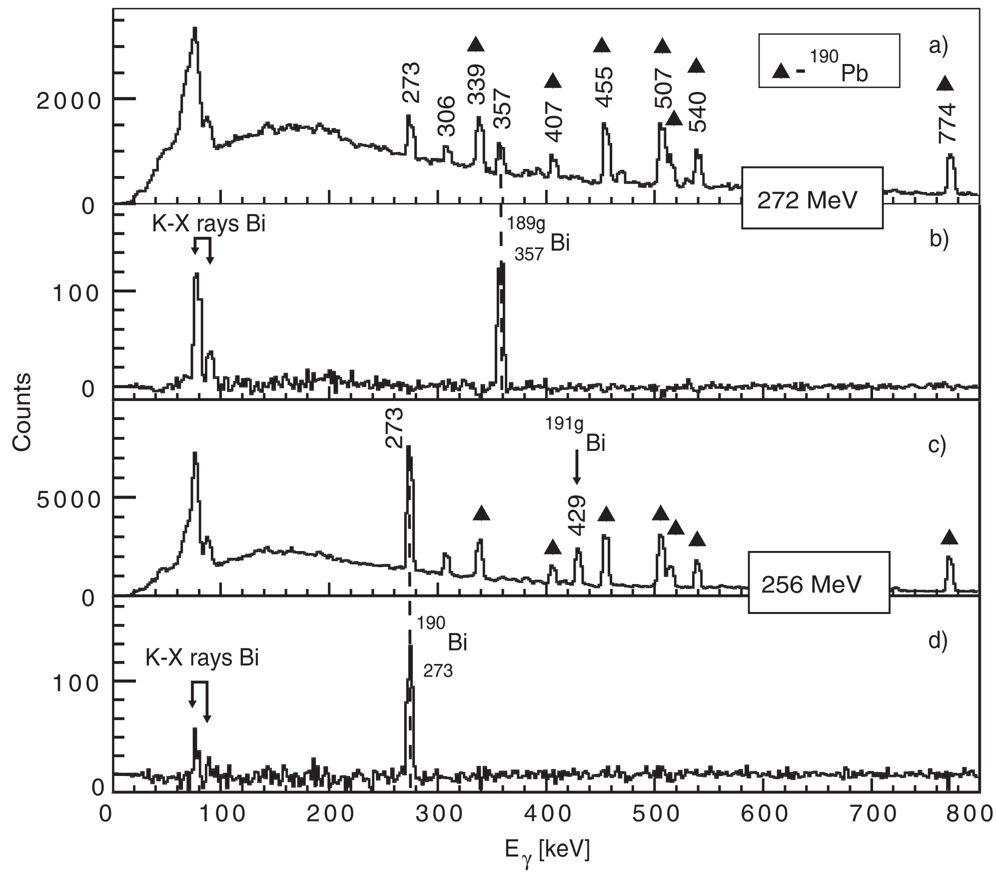

Fig. 2. a) recoil-γ and b) background-subtracted recoil-γ-α spectra for ^{189}Bi; c) and d) the same as a) and b), but for ^{190}Bi. See the main text for details.

half-life, $T_{1/2}$, of the isomeric state at 357 keV was estimated from the decay loss of the ^{189}Bi nuclei in this short-lived isomeric state during the flight through SHIP using the radioactive decay law formula $N_\gamma = N(^{189}\mathrm{Bi}) \times \exp(-\ln 2 \times \mathrm{TOF}/T_{1/2})$. In this formula $N(^{189}\mathrm{Bi})$ denotes the number of ^{189}Bi EVRs, calculated from the number of the 6672 keV α-decays (fig. 1a) and the known branching ratio ($b_\alpha = (50\text{–}100)\%$ [1]), while N_γ denotes the number of the background-subtracted 357 keV γ-decays (fig. 2a), corrected for the conversion coefficient and γ-efficiency [7]. The flight time TOF of the EVRs through the SHIP can be reliably calculated starting from the beam energy and taking into account all the energy losses of the projectiles and of the EVRs in the target backings, target material itself and in the carbon charge reset foil [9]. In this case we assumed that all the feeding of the $9/2^-$ ground state proceeds via the $13/2^+$ isomer. Under this assumption, we deduced a lower limit of $T_{1/2} \geq 360(120)$ ns for the half-life value of the 357 keV transition. We stress that any de-excitation path that by-passes this isomer will only increase its half-life. On the other hand, based on the coincidence interval of 0–5 μs for the delayed EVRs-γ events, one can conclude that the upper limit for the half-life of this state should be in the microsecond range. The given uncertainty is mainly determined by the uncertainty of the branching ratio, b_α, of ^{189}Bi.

By comparing the experimental half-life limit and a calculated half-life value, based on the Weisskopf estimate [1], a retardation factor >5 can be deduced. This limit is in reasonable agreement with the retardation factors of $\approx$ 10–20, deduced for the $13/2^+ \rightarrow 9/2^-$ $M2$ transitions in ^{191,195}Bi.

3.2 ^{190}Bi

Figure 1b shows the spectrum of α-decays registered between beam pulses at the beam energy of 256.0(5) MeV. The strongest peaks in this spectrum belong to $[\pi 1h_{9/2} \otimes \nu 1i_{13/2}]_{10^-}$ ($E_\alpha = 6456$ keV, $T_{1/2} = 5.9$ s) and $[\pi 1h_{9/2} \otimes \nu 3p_{3/2}]_{3^+}$ ($E_\alpha = 6431$ keV, $T_{1/2} = 5.7$ s) isomeric states in ^{190}Bi [4], and the $[\pi 1h_{9/2}]_{9/2^-}$ ground state of ^{191}Bi ($E_\alpha = 6311$ keV, $T_{1/2} = 12$ s) [1].

Figure 2c shows the γ-ray spectrum, similar to fig. 2a, but measured at this beam energy. The γ-line at 429 keV corresponds to the decay of recently studied $13/2^+$ isomeric state ($E^* = 429$ keV, $T_{1/2} = 533(7)$ ns) in ^{191}Bi [6].

The only unknown γ-transition, observed at 273(1) keV, has an excitation function similar in shape and position to those of the 6431 keV and 6456 keV α-lines of ^{190}Bi and on this basis we assign this transition to ^{190}Bi. To distinguish to which of the two isomeric states (3^+ or 10^-) in ^{190}Bi this line decays we used the RDT method. Figure 2d shows the same spectrum as in fig. 2c, but with an additional condition that the EVR-γ pair is correlated with an α-decay in the energy range of E_α = 6450–6470 keV, corresponding to the 10^- isomer in ^{190}Bi. Similar to fig. 2b, fig. 2d has been corrected for background from random coincidences. As a background spectrum we used the spectrum from fig. 2c, normalized to the same number of the (random) γ-decays of ^{190}Pb as in fig. 2d before the background was subtracted. In fig. 2d, besides a peak at E_γ = 273(1) keV weak coincidences with the K-X rays of Bi are also observed and a conversion coefficient of $\alpha_K = 0.20(5)$ can be deduced.

Note that a similar background subtraction procedure was performed for the EVR-γ-6431 keV coincident events with a gate of E_α = 6410–6440 keV on the α-decay of the 3^+ isomer in ^{190}Bi. In this case a weak peak at 273 keV in the gated γ-spectrum was also observed with an intensity about 8 times less than in the case of the correlation with the 6456 keV line. We stress that the ratio of the intensities I(6456 keV)/I(6431 keV) $\approx$ 1.35 was estimated from fig. 1b and therefore these weak coincidences are understood as being produced by the low-energy tail of the 6456 keV line under the 6431 keV line.

Thus, based on the excitation function measurements and on the recoil-γ-α correlation analysis, we assign the γ-transition at 273 keV as occurring on top of the high-spin $[\pi 1h_{9/2} \otimes \nu 1i_{13/2}]_{10^-}$ isomer of ^{190}Bi.

The half-life of the isomeric state decaying by the 273 keV transition in ^{190}Bi was estimated by using the same method, outlined above for $^{189\mathrm{g}}$Bi. In this case we compare the number of the 6456 keV α-decays and 273 keV γ-decays of ^{190}Bi from fig. 1b and fig. 2c (background-subtracted), respectively, combined with the calculated TOF of the recoils through the SHIP at this beam energy. Under the assumption that the whole de-excitation to the 10^- state in ^{190}Bi proceeds via the isomeric state, decaying by the 273 keV transition, we deduced its lower half-life limit as $T_{1/2} \geq 500(100)$ ns. The given uncertainty is mainly determined by the uncertainties of the branching ratio of ^{190}Bi and of the conversion coefficient.

4 Discussion

4.1 $^{189\mathrm{g}}$Bi

The $13/2^+$ states in the lightest Bi isotopes were interpreted as the $\pi 1i_{13/2}$ proton states and their nearly constant excitation energy for $N > 114$ and a downward behaviour below $N = 114$ (see fig. 3) were attributed to specific proton-neutron interaction, see discussion in [3].

We point out, that another important effect may be responsible for the lowering of the $13/2^+$ proton states in the odd-mass Bi nuclei when moving towards the neutron mid-shell. Namely, it is well established that in spherical nuclei with one particle (hole) outside a closed shell the core polarization effect due to particle-octupole vibration coupling is among the strongest effects [14,15]. In the case of Bi isotopes one would expect coupling and mixing of the $1i_{13/2}$ single-particle proton state to the $13/2^+$ member of the $[3^- \otimes \pi 2f_{7/2}]$ octupole multiplet based on the octupole vibrational 3^- core state in the neighbouring even-mass lead core. Although in the even-even lead nuclei around the mid-shell such 3^- states have not yet been observed, the 3^- state is expected to drop in excitation energy approaching the mid-shell, where the octupole vibration is expected to be most developed. Indeed, in the lightest lead isotope ^{196}Pb in which the 3^- state is known, it lies at the excitation energy of 1.992 MeV compared to 2.614 MeV in ^{208}Pb [1]. Therefore, the mixed $13/2^+$ state should follow the same downward behaviour. As such, a $13/2^+$ state should be not a pure single-particle state, but a mixed one, a more collective structure with a possible collective band is expected to be built on top of such a state. This is exactly what has been observed recently in an in-beam study of $^{191\mathrm{g},193\mathrm{g}}$Bi where rotation-like, strongly coupled bands have been found, built on top of the $13/2^+$ isomeric state [6].

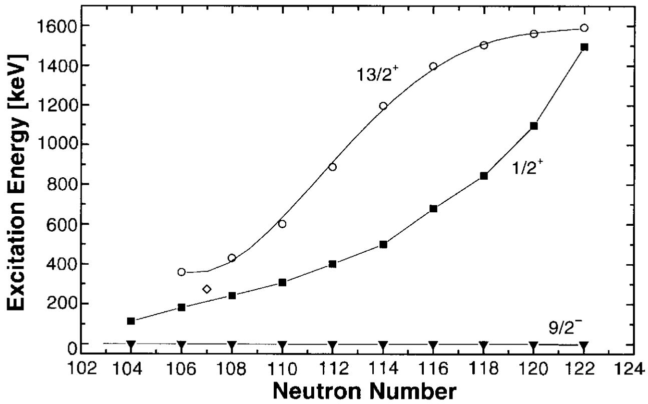

Fig. 3. Energy systematics of the $13/2^+$ and $1/2^+$ excited states relative to the $9/2^-$ ground state in the odd-mass Bi isotopes. The position of the 273 keV state in ^{190}Bi is shown by an open diamond.

Interestingly, the behaviour of the proton $13/2^+$ states in odd-mass Bi (Z = 83) nuclei is very similar to the behaviour of the neutron $13/2^+_1$ states in the N = 83 isotones in the $50 \leq Z \leq 82$ shell. In the latter case the excitation energy of the $13/2^+_1$ states follows closely that of the 3^-_1 octupole vibrational state in the core N = 82 isotones. This was satisfactorily explained by the particle-octupole vibration coupling calculations as a result of the mixing between the $\nu 1i_{13/2}$ single-particle state and $13/2^+$ member of the $[3^- \otimes \nu 2f_{7/2}]$ octupole multiplet [14]. Such a similarity suggests that the same underlying mechanism may be responsible for the behaviour of some of the $13/2^+$ proton and neutron states in the Z = 83 and N = 83 nuclei, respectively.

More detailed calculations will be necessary to disentangle the contributions from the proton-neutron interaction and from the particle-vibration coupling mechanisms, discussed above. However, it will require information on the 3^- states in the even-mass core lead nuclei in this region, which is absent for the moment (except in ^{196}Pb [1]).

4.2 ^{190}Bi

The configuration of the isomeric state decaying by the 273 keV transition in ^{190}Bi could not be established from the present data due to large variety of possible configurations, which can result from the coupling between the valence proton and neutron.

Indeed, as shown in fig. 3, in vicinity of the neutron mid-shell at $N = 104$ at least three possible configurations for the valence proton in the Bi isotopes should be considered: $9/2^-[\pi 1h_{9/2}]$ ground state along with excited $1/2^+[\pi 3s_{1/2}]$ and $13/2^+[\pi 1i_{13/2}]$ configurations. In the neighbours of ^{190}Bi (^{189}Bi ($N = 106$), ^{191}Bi ($N = 108$)) the two latter configurations have been observed within the excitation energy range of 200–400 keV only above the $9/2^-$ ground state. Coupling of these valence protons with the odd valence neutrons close to the Fermi surface ($3p_{3/2}$, $2f_{5/2}$, $1i_{13/2}$) can result in different configurations, some of them becoming isomeric.

For example, in the neutron-deficient odd-odd Bi isotopes three multiplets of the states arise from the coupling of the $1h_{9/2}$ valence proton with these valence neutrons: $[\pi 1h_{9/2} \otimes \nu 3p_{3/2}]_{3^+-6^+}$, $[\pi 1h_{9/2} \otimes \nu 2f_{5/2}]_{2^+-7^+}$ and $[\pi 1h_{9/2} \otimes \nu 1i_{13/2}]_{2^--11^-}$ (see [4,5] and references therein).

We also stress a possibility to create multiplets of the intruder states in ^{190}Bi by coupling a valence neutron with the $1/2^+[\pi 3s_{1/2}]$ (2p-1h) intruder state in the odd-mass ^{189}Bi isotope which results from the promotion of one of the $\pi 3s_{1/2}$ protons across the $Z = 82$ shell gap to the $\pi 1h_{9/2}$ orbital. In ^{191}Bi ($N = 108$) such an intruder configuration comes down in energy as low as ≈ 200 keV [16, 17], see fig. 3.

All this can result in a rather complex interplay of the normal and intruder states, coexisting at the similar excitation energy in ^{190}Bi and without additional experimental data one cannot proceed with the configuration assignment.

One of the possible ways to clarify the nature of this state would be an in-beam study of the excited states built on top of this isomer. It is well established that in the bismuth isotopes the (1p-0h) normal states based on the $\pi 1h_{9/2}$ proton are spherical, while the (2p-1h) intruder states based on the $\pi 3s_{1/2}$ proton are oblately deformed [18]. Therefore, by studying the excited states built on top of this isomer a clear distinction between these two scenarios could be possible.

In conclusion, we identified two new microsecond isomers in ^{189,190}Bi. These results will be useful for future in-beam studies of these isotopes, for which no data on the excited states is available and which are quite difficult to study by the RDT method due to their rather long half-lives. With the new results these difficulties can be overcome as one can use the Isomer Decay Tagging (IDT) method [19] instead of the RDT method. The IDT method exploits the delayed (in the μs range) γ radiation from the decay of isomeric states detected at the focal plane of a recoil separator to tag the prompt radiation emitted at the target position and therefore the limitation on the half-life value of the nucleus under study becomes less important.

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