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Letter

Prolate deformation in the ^{187,189}Bi isotopes

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Abstract. Prompt and delayed gamma-ray spectroscopy of very neutron deficient bismuth isotopes ^{187,189}Bi has been performed using the recoil decay tagging method. A rotational band has been observed in ^{189}Bi and is interpreted as a complete decoupling of a single proton from the deformed lead core. The results for ^{187}Bi suggest a similar structure and coupling scheme. This study gives the first evidence for a prolate band in a light bismuth nucleus and confirms the prolate character of the low-lying rotational band observed in the core nuclei ^{188}Pb and ^{186}Pb.

PACS. 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

The semi-magic neutron-deficient lead nuclei exhibit a large variety of nuclear shapes [1].This is particularly true for the ^{186,188}Pb isotopes in which states with spherical, oblate and prolate shapes are found to coexist within a very small energy range [2–6]. In these nuclei, most of the observed collective structures have been understood as proton excitations across the Z=82 shell gap. The study of neighbouring bismuth isotopes could help to identify the single-proton orbitals involved in the deformation of the lead nuclei. Prompt in-beam γ-ray spectroscopy has been performed for the first time in ^{189}Bi and ^{187}Bi in order to search for collective structures with the odd proton coupled to the different deformed lead cores.

A series of experiments has been performed at the University of Jyväskylä (Finland) using three different reactions: ^{109}Ag(^{82}Kr, 2n)^{189}Bi, ^{109}Ag(^{83}Kr, 3n)^{189}Bi and ^{107}Ag(^{83}Kr, 3n)^{187}Bi. The beams were provided by the K130 cyclotron facility at the energies of 337, 340 and 339 MeV for the three experiments, respectively. The fusion-evaporation residues were selected by the gas-filled separator RITU [7] and identified event-by-event by using their alpha-decay characteristics in order to apply the recoil decay tagging (RDT) technique [8]. Prompt γ rays were detected at the target position using the Jurosphere II array comprised of 27 Compton-suppressed HPGe detectors with an absolute photopeak efficiency of 1.7 % at 1.3 MeV. Delayed γ rays were detected at the RITU focal plane with a HPGe detector (absolute photopeak efficiency of 0.6 % at 1.3 MeV) which was replaced by a more efficient setup of BGO detectors for the ^{109}Ag(^{83}Kr, 3n) experiment (absolute efficiency of about 15 % at 1.3 MeV). Details of the experimental conditions can be found in our earlier report [9], in which the results on the isomeric states in ^{187,189}Bi and, in particular, the systematics of the $13/2^+$ isomers decaying via a M2 transition to the $9/2^-$ ground states are discussed.

During the ^{109}Ag(^{83}Kr, 3n) experiment, 120 000 ^{189}Bi nuclei were identified by the RDT technique (correlation in time and position of a recoil with the ^{189}Bi $9/2^-$ ground state α-decay (E_α=6674(5) keV, $T_{1/2}$=667(13) ms, searching time of 2 s)). The deduced production cross section for ^{189}Bi is around 12 μb. The spectrum of prompt γ rays in coincidence with these events is presented in Fig. 1 a). The Bi X-rays observed in the spectrum confirm the correct identification (the recoil-gated spectrum, not correlated with a specific α decay, is dominated by Pb X-rays.). In order to distinguish whether these γ transitions feed the $13/2^+$ isomer [9,10], an additional tagging condition

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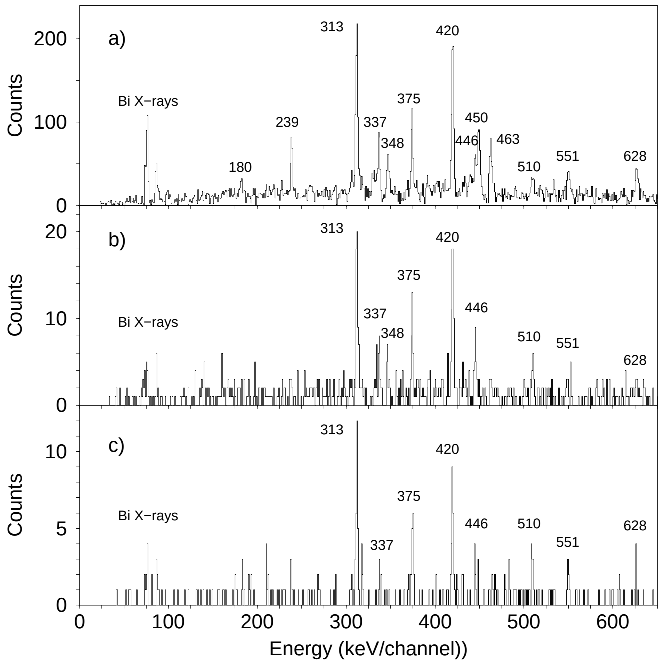

Fig. 1. Singles γ-ray spectra tagged a) with the ^{189}Bi ground state α-decay b) with the ^{189}Bi ground state α-decay and the isomeric $13/2^+ \rightarrow 9/2^-$ transition. c) Sum of the 313, 375 and 420 keV gates set on the ^{189}Bi-decay tagged events

on the isomeric 357 keV ($13/2^+ \rightarrow 9/2^-$, $T_{1/2}$=880(50) ms) transition (observed at the focal plane before the α-decay) was applied. The energy resolution of the BGO detectors was sufficient in this case since the 357 keV transition was the only delayed transition observed during the ^{109}Ag(^{82}Kr, 2n) experiment when using a high resolution HPGe detector at the focal plane [9]. The result is shown in Fig. 1 b). Nine transitions are unambiguously observed feeding the isomer. The six transitions at 313, 375, 420, 446, 510 and 551 keV are also seen in mutual coincidences. This is illustrated in Fig. 1 c) which shows a coincidence spectrum with gates set on the three strongest transitions. The deduced level scheme of ^{189}Bi is shown in Fig. 3 a). The ordering of the transitions was deduced from their observed intensities. Angular distributions could be measured for the lowest three transitions. They are consistent with stretched E2 character. Given the regularity of a typical rotational band, stretched E2 character can also be proposed for the upper part of the band. Assuming that the observed transitions are directly built on the isomeric state, the spins given in Fig. 3 a) can be assigned. Seven other transitions (180, 239, 337, 348, 450, 463 and 628 keV) could not be placed into the level scheme but the 337, 348 and 628 keV transitions are clearly identified to feed the isomer (see Fig. 1 b)). During the same experiment 10 000 ^{189}Bi nuclei were correlated with the α decay of the $1/2^+$ isomer using the same technique. Many gamma transitions have been observed in coincidence with this alpha decay but due to the lack of statistics (in particular the lack of $\gamma - \gamma$ coincidences) a partial level scheme above this $1/2^+$ isomer can not be proposed.

In order to interpret these results, the new rotational structure observed in ^{189}Bi is compared in Fig. 3 a) with the rotational band observed in the neighbouring even-even nucleus ^{188}Pb [11]. The similarities between the transition energies of the two bands are striking. An extrapolation of the rotational sequence observed at higher spins to spin $13/2^+$ using the Variable Moment of Inertia (VMI) model leads to an energy around 260 keV for the $17/2^+ \rightarrow 13/2^+$ in-band transition. In this scenario, the band is built on a second (non-observed) $13/2^+$ state ($\sim$160 keV above the $13/2^+$ isomer). The $17/2^+ \rightarrow 13/2^+$ in-band transition ($\sim$260 keV) is therefore energetically unfavored (compared to the 420 keV linking transition to the $13/2^+$ isomer) and consequently not observed. This situation is identical to the one observed in ^{188}Pb where the band is built on an excited 0^+ state and no in-band $2^+ \rightarrow 0^+$ transition populating the band head is observed.

The data set of the ^{107}Ag(^{83}Kr, 3n) reaction represents only 900 correlated recoils (time and position) with the α decay of the $9/2^-$ ground state in ^{187}Bi (E_α=7000(5) keV, $T_{1/2}$=45(11) ms, searching time of 150 ms). The production cross section for ^{187}Bi is around 40 nb. The coincident prompt γ-ray spectrum is presented in Fig. 2. The very small number of counts observed in this spectrum requires a few considerations about its significance. The spectrum contains a total of 130 counts up to an energy of 2 MeV. There are 96 counts in the energy range between 50 and 650 keV, for which the efficiency of the spectrometer and the γ-ray density of a typical spectrum in this mass region are highest. We can therefore concentrate on the counts observed in this energy range. Fig. 2 shows the spectrum with two different dispersions (2 and 3 keV/channel: the best dispersion for a low-statistics spectrum is of the order of the detector resolution, *i.e.* between 2 and 3 keV/channel). The spectra contain an average of μ = 0.32, and 0.48 counts per channel, respectively. One may use these values and Poisson statistics to calculate the probabilities of finding a certain number of counts in a

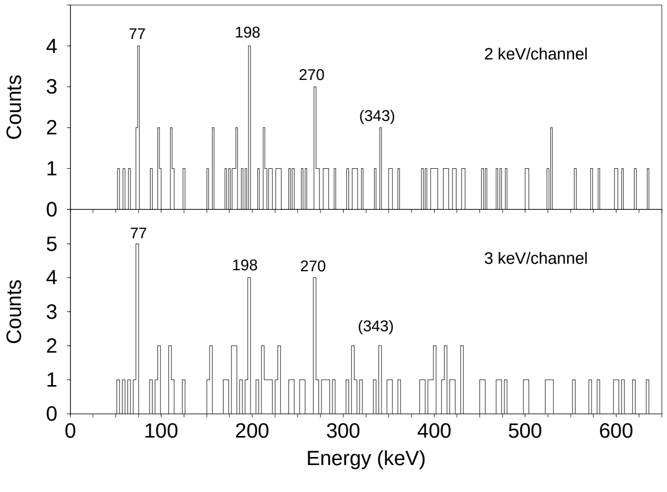

Fig. 2. Singles γ-ray spectrum with two different dispersions (2 and 3 keV/channel) tagged with the ^{187}Bi ground state α-decay.

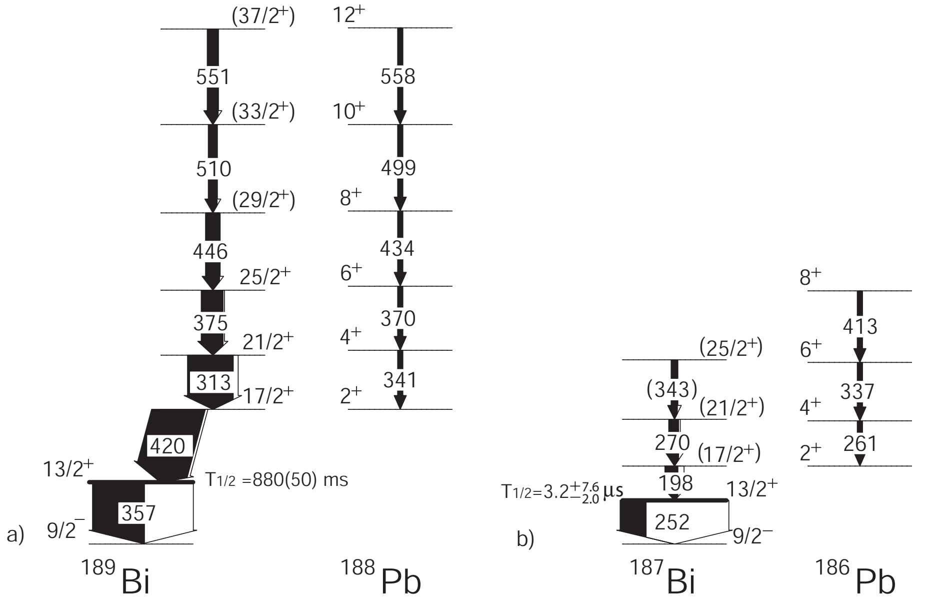

Fig. 3. Partial level scheme (this work and [9,10] for the isomeric transitions) for a) ^{189}Bi and b) ^{187}Bi. The rotational prolate bands observed in the neighbouring even-even lead isotopes [11,12] are given for comparison (with excitation energies relative to the proposed $17/2^+$ states)

channel assuming a random distribution of the counts. By comparing the expectation values $< N_k >$ for the number of channels with $k = 0, 1, 2,...$ counts with the number N_k of observed channels, one can identify the peaks that are significant above a random distribution of counts. For a random distribution with $\mu = 0.32$ (spectrum with a dispersion of 2 keV/channel) the expectation value to find a channel with four counts is only $< N_4 >= 0.10$ with $\sigma = 0.31$. Consequently, finding two channels with four counts is 6.6 standard deviations outside the expectation value. Therefore, it can be safely assumed that the peaks at 77 and 198 keV are real transitions correlated with the α decay of ^{187}Bi. In the spectrum with 3 keV/channel binning, one finds a significance of 6.0σ for the peak with five counts (77 keV) and 3.3σ for the two peaks with four counts (198 and 270 keV), which shows that the peak at 270 keV is also real. The observation of the Bi X-rays line at 77 keV is an additional confirmation for the correct identification of the spectrum with ^{187}Bi using the RDT method. The energy spacing between the two peaks at 198 and 270 keV is 72 keV. It is interesting to note that there is another peak with the same energy spacing at 343 keV. Even though the significance for the peaks with two counts is only 1 and 0.6 σ (2 and 3 KeV/channel dispersion, respectively), the regularity suggests that it might be the next transition in a rotational band. As in ^{189}Bi, this scenario is further supported by the similarity of this cascade with the prolate rotational band in the even-even neighbour ^{186}Pb [11,12]. Due to the very low statistics, gating on the delayed $13/2^+ \rightarrow 9/2^-$ transition [9] was not possible. The proposed level scheme for ^{187}Bi is presented in Fig. 3 b) together with a partial level scheme of ^{186}Pb. The rotational band is proposed to be built directly on the $13/2^+$ isomer but in view of the available experimental informations it can not be excluded that the band head and the isomeric state are two different $13/2^+$ states.

The very similar features of rotational bands observed in ^{187,189}Bi and ^{186,188}Pb suggest that the spin of the bismuth states is obtained by simply adding a j=$13/2^+$ particle spin to the corresponding lead states (rotation-aligned coupling scheme) [14]. It has been experimentally investigated in detail and validated in many cases, for example in several odd-mass Er (involving the $i_{13/2}$ neutron orbital) and La (involving the $h_{11/2}$ proton and neutron orbitals) [13]. In contrast to the erbium or lanthanum nuclei, in ^{187,189}Bi the rotation-aligned particle is not coupled to the deformed ground state of the neighbouring even-even nucleus but to the excited prolate core corresponding to the excited 0^+ state observed in ^{186,188}Pb respectively [2–4]. An interesting particularity of this rotation-aligned coupling model is the fact that the deformation must have a well defined sign : a prolate (oblate) deformation at the beginning (end) of a major shell [14]. The ^{187,189}Bi nuclei appear here as text-book examples i) just above the Z=82 closed shell (the rotation-aligned band must be prolate deformed) and ii) with the high-j $i_{13/2}$ intruder proton orbital (1/2[660] Nilsson orbital) available (a full alignment with the rotational axis corresponds to a spin 13/2). This interpretation gives then the first evidence of a prolate band based on the 1/2[660] Nilsson orbital in this light-bismuth region, but also confirms the prolate character of the low-lying rotational bands observed in ^{186,188}Pb [11,12]. In the heavier odd-mass isotopes ^{191}Bi and ^{193}Bi, strongly coupled bands based on the $13/2^+$ isomers have been observed [15]. They have been interpreted as strongly coupled oblate bands based on the 13/2[606] orbital. As for the lead case the neutron mid-shell appears here as a transition region for the deformation. Such a scenario is also confirmed by Potential Energy Surface calculations, for which the crossing of the 13/2[606] oblate orbital with the 1/2[660] prolate orbital is predicted around ^{187,189}Bi [16].

In summary, a rotational band has been observed by γ-ray spectroscopy combined with the RDT technique in ^{189}Bi. A similar structure is tentatively proposed in ^{187}Bi. The resemblance of the transition energies of these bands with the rotational bands observed in the neighbouring even lead isotopes is remarkable. They are interpreted as rotation-aligned bands built on the $i_{13/2}$ intruder proton orbital which indicate a prolate deformation in these nuclei. They consequently confirm the prolate deformation of the rotational bands observed in ^{188}Pb and ^{186}Pb. This study gives the first evidence for a transition from oblate shapes associated with strongly coupled band in heavier isotopes ^{191,193}Bi to prolate shapes with a rotational alignment scheme in ^{187,189}Bi.

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