Spectroscopy of the very neutron-deficient ^{189}Bi

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Abstract. The neutron-deficient isotope ^{189}Bi has been studied at the University of Jyväskylä using alpha-decay, isomer and prompt gamma-ray spectroscopy. The structure of ^{189}Bi can be understood by the coupling of an unpaired proton to the ^{188}Pb core, in which spherical, prolate, and oblate shapes were found to coexist. Improved data on alpha-decay and prompt gamma-ray spectroscopy have been obtained, giving further insight into the shape coexistence phenomenon in the neutron-deficient lead region.

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INTRODUCTION

Neutron deficient Bi nuclei lie in a region where a variety of nuclear shapes coexist at low excitation energies. In the lead isotopes close to the neutron mid-shell, shape coexistence has been established with a competition between the spherical ground-state and oblate and prolate excited states. These deformed shapes are due to proton particle-hole excitations across the Z=82 shell gap [1]. In the even-even Pb isotopes, shape coexistence is characterised by excited 0^+ states at low excitation energies, which decay exclusively or partially via E0 conversion-electron transitions to the ground-state. Information on the mixing of the wave functions, and therefore on the shape mixing, can be deduced by studying the E0 strength $\rho^2(0)$. However, the assignment of single-particle configurations to the shape-coexisting states is difficult in the even-even isotopes, because the 0^+ states have similar spectroscopic characteristics. An alternative to investigate shape coexistence in this region is the study of the neighboring proton-odd Bi isotopes. The coupling of the odd proton to the Pb core is a sensitive probe and characteristic of the underlying structure and shape, so that gamma and/or conversion-electron spectroscopy can provide a deeper understanding of the complex shape mixing in the light Pb region. The relevant orbitals and single-particle states for ^{189}Bi are illustrated in Fig. 1.

Spectroscopic information has been obtained for the odd-mass Bi isotopes up to the proton drip line at ^{185}Bi. The ground-state has spin-parity $9/2^-$ in the isotopes with $A = 187$ to 209, and low-lying $1/2^+$ and $13/2^+$ isomers have been identified in some cases. In experiments performed at the University of Jyväskylä, $13/2^+$ isomers have been

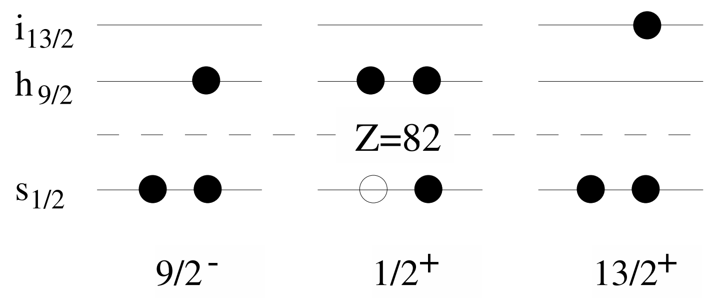

FIGURE 1. Single particles states across the $Z = 82$ spherical shell gap.

observed in ^{187,189}Bi [2] and ^{191,193}Bi [3]. The $1/2^+$ state becomes the ground-state in ^{185}Bi, which was found to be a proton emitter [4]. The $1/2^+$ state originates from the $s_{1/2}$ orbital below the $Z = 82$ shell gap and is thus a 2p-1h state. The $13/2^+$ state arises from the excitation of the last proton to the $i_{13/2}$ orbital. The structure of the heavier Bi isotopes with $A > 193$ can be explained by the coupling of a $h_{9/2}$ or $i_{13/2}$ proton to spherical states in the $A-1$ Pb core [5]. The picture changes in ^{191,193}Bi: a rather regular band with a strongly coupled character is built on the $13/2^+$ isomer, indicating an oblate shape [3].

The structure changes again in ^{189}Bi: in a previous experiment a rotational band was observed on top of the $13/2^+$ isomer in which the unpaired proton is decoupled from the deformed ^{188}Pb core. This result gives the first evidence for a prolate band in a light bismuth nucleus [6]. Many additional transitions have been observed above the $1/2^+$ isomer. It seems likely that the observed transitions originate from a strongly-coupled band, but the level scheme above the $1/2^+$ isomer could not be firmly established due to the limited statistics [7]. As for the Pb isotopes, a transition from prolate to oblate shapes occurs in the light Bi isotopes around neutron mid-shell. This scenario is supported by calculations of the potential energy surface, which predict the crossing of the 13/2[606] oblate orbital with the 1/2[660] prolate orbital around ^{187,189}Bi [8].

An experiment under improved experimental conditions, leading to higher statistics, has been performed in order to clarify the single-particle structure of ^{189}Bi, and in particular to obtain more information of the rotation band built on the $1/2^+$ state. Preliminary results of this experiment are reported in this proceeding.

EXPERIMENTAL TECHNIQUE

The experiment was performed at the University of Jyväskylä using the fusion-evaporation reaction ^{109}Ag(^{83}Kr,3n)^{189}Bi at a beam energy of 357 MeV. The ^{109}Ag had a thickness of 750 μg/cm^2. Prompt gamma rays were detected using the JUROGAM array of 43 Compton suppressed germanium detectors with a photopeak efficiency of $\sim 4\%$ at 1.3 MeV. The fusion-evaporation recoils were separated from the scattered beam and parasitic reactions using the gas-filled separator RITU [9]. Recoils, α radioactivity, and delayed gamma or electron transitions were detected using the focal plane detection setup GREAT [10]. The multi-wire proportional counter of GREAT was used to identify recoiling ions by measuring the energy loss and time of flight. The ions were implanted into two double-sided silicon strip detectors (DSSD) of 300 μm thickness. Conversion-electrons were detected by a tunnel of PIN diodes upstream from the DSSD. Gamma rays from the implanted ions were detected in a planar Ge detector placed directly behind the DSSD and in a large segmented Ge clover detector. The Recoil Decay Tagging (RDT) technique was used to unambiguously identify the ^{189}Bi ions and correlate these events with prompt gamma rays emitted at the target position. A trigger-less, so-called Total Data Readout (TDR) [11] data acquisition system was used during the experiment, recording time-stamped signals from the different sub-systems independently. Events are reconstructed off-line using the time correlations.

RESULTS

Decay spectroscopy

Figure 2 shows the energy spectrum of the first alpha radioactivity correlated with the implantation of fusion-evaporation residues using a maximum correlation time of 32 s.

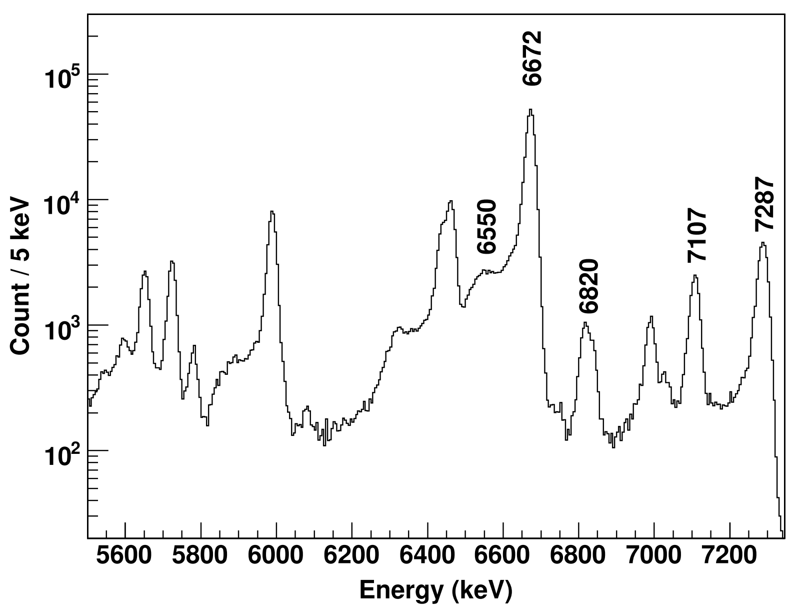

FIGURE 2. Alpha decay spectrum of fusion-evaporation residues after implantation into the double-sided silicon detector of the GREAT array.

The transitions which are labeled with their energies in keV correspond to the decay of ^{189}Bi. The other, unlabeled lines correspond to other fusion-evaporation channels (^{190}Bi, ^{188,189}Pb) or to the decay of the daughter isotopes of the implanted nuclei. Due to the higher level of statistics, it was possible to determine the half-lives of the alpha-decaying states with higher precision compared to earlier works [6] [7]. The revised half-lifes are shown in table 1. Note that the line at 7107 keV line is now identified as a doublet of

TABLE 1. ^{189}Bi alpha-decay half-lifes.

Energy (keV)	half-life
6672	689 ± 2 ms
7107	681 ± 8 ms
	5.4 ± 0.2 ms
7287	5.0 ± 0.1 ms

two components corresponding to the decay from the ground-state and $1/2^+$ isomer, respectively (see Fig. 3).

Delayed gamma rays were detected in the planar and Ge clover detectors at the focal plane of RITU. The isomeric $13/2^+$ state decays via a M2 transition of 357 keV to the ground-state. Using recoil-gamma-alpha correlations, a half-life of 888 ± 32 ns is deduced for the $13/2^+$ state. The partial level scheme deduced from the alpha-decay fine structure and delayed gamma spectroscopy is shown in figure 3.

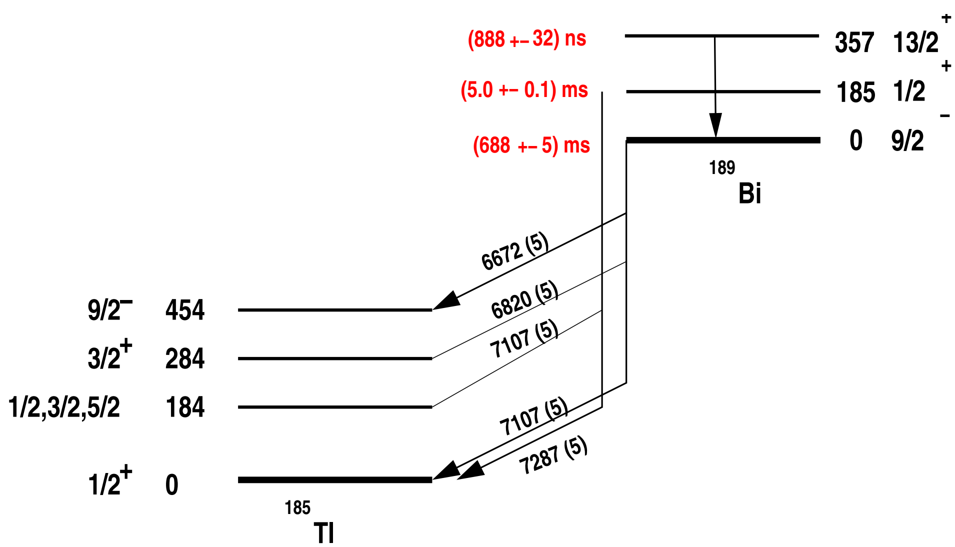

FIGURE 3. Partial decay scheme of ^{189}Bi and the daughter nucleus ^{185}Tl.

Prompt gamma-ray spectroscopy

Prompt gamma-ray spectra detected with the JUROGAM array around the target and correlated with the alpha decay of ^{189}Bi are presented in figure 4. Panel a) corresponds to prompt gamma-ray transitions in coincidence with the $9/2^- \rightarrow 9/2^-$ α transition at 6672 keV. The spectrum of panel b) was obtained by requiring that, in addition to the α decay of ^{189}Bi, the isomeric γ transition of 357 keV from the $13/2^+$ state was detected at the focal plane, and that one of either the 313, 375 or 420 keV transitions was observed in prompt coincidence around the target. This spectrum confirms the rotational band built on the isomeric $13/2^+$ state. The band is almost isospectral to the prolate rotational band observed in ^{188}Pb, which indicates a rotational alignment scheme. The $13/2^+$ band-head of this rotational band can be interpreted as the aligned $i_{13/2}$ orbital with the Nilsson configuration 1/2[660], similar to the cases of ^{191,193}Bi [3]. As suggested in Ref. [6], the $13/2^{+}$ isomeric state observed at 357 keV can be interpreted as the 13/2[606] orbital favoring an oblate shape. Therefore, we expect the presence of an unobserved prolate $13/2^{+}$ state as the band-head of the observed rotational band. Search for this state has not been conclusive.

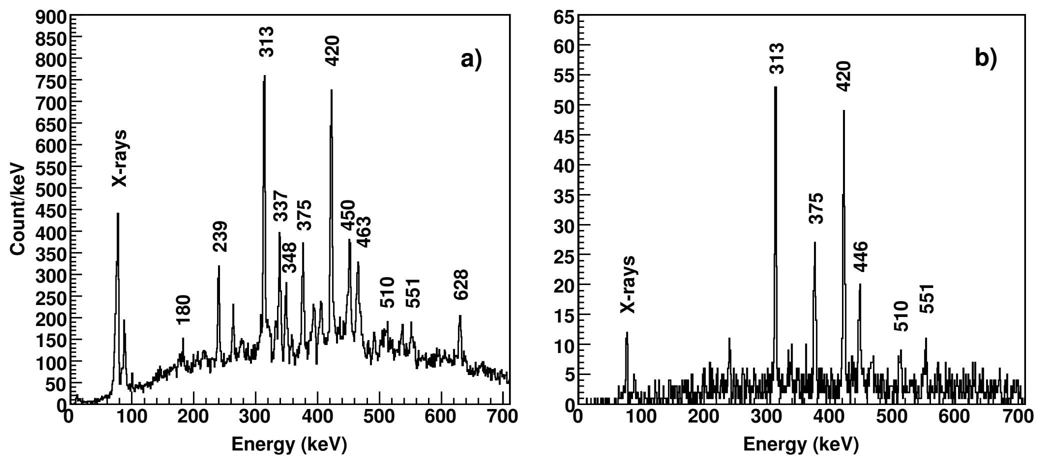

FIGURE 4. Prompt gamma-ray spectra a) gated on the 6672 keV alpha line b) gamma-gamma coincidences gated on the 357 keV isomeric transition.

Figure 5 shows the spectrum of prompt γ rays correlated with the 7287 keV α transition from the $1/2^{+}$ isomer with 5 ms half-live. Two rotational sequences which are shifted with respect to each other depending on the decoupling parameter a are expected to be observed on top of this state with $K = 1/2$. A level scheme corresponding to a prolate band built on the 1/2[400] Nilsson orbital has been tentatively proposed based on the singles spectrum from the earlier work [7]. Although a large gain in statistics has been obtained in the present experiment, the statistics is still not sufficient to firmly establish the rotational sequence built on the $1/2^{+}$ isomer by evaluating $\gamma - \gamma$ coincidences. However, based on the $\gamma - \gamma$ correlation obtained, the level scheme proposed in Ref. [7] can be rejected. The properties of the $1/2^{+}$ band-head, and in particular its oblate or prolate character remains therefore to be clarified.

CONCLUSION

New data on the neutron-deficient ^{189}Bi nucleus has been obtained at the University of Jyväskylä using the JUROGAM, RITU and GREAT devices. Revised half-lives for the $9/2^{-}$ ground-state, $1/2^{+}$ and $13/2^{+}$ isomeric states have been obtained. The alpha-decay line at 7107 keV could be identified as a doublet. Rotational structures built on the isomeric $1/2^{+}$ and $13/2^{+}$ states have been studied using the RDT and isomer tagging techniques. A large gain in statistics has been obtained compared to a previous experiment. The prolate character of the rotational band built above the isomeric $13/2^{+}$

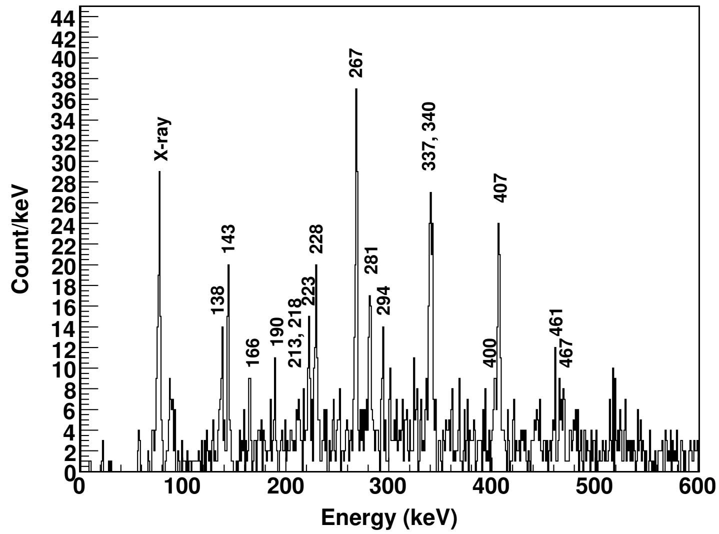

FIGURE 5. Prompt gamma-ray spectrum correlated with the 7287 keV α alpha decay from the isomeric $1/2^+$ state.

state was confirmed. However, it can be suspected that this state is not the band head of the rotational sequence; it seems more likely to have an oblate character based on the 13/2[606] orbital. Although a large gain in statistics has been obtained compared to the earlier measurement, it has not been possible to clarify the rotational sequence built on the $1/2^+$ isomer.

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