Eur. Phys. J. A **18**, 31–37 (2003)
DOI 10.1140/epja/i2003-10066-6

THE EUROPEAN PHYSICAL JOURNAL A

Isomeric and ground-state decay of ^{215}Bi

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Received: 3 March 2003 / Revised version: 10 June 2003 /
Published online: 9 October 2003 –
Communicated by C. Signorini

Abstract. A new high-spin isomer in ^{215}Bi, with a half-life of 36.9(6) s, has been identified at the PSB-ISOLDE on-line mass separator using the pulsed-release technique combined with the element selective RILIS source. A decay scheme of ^{215m}Bi was constructed and complemented with the low-spin structure observed in ^{215g}Bi decay. The population of a cascade on top of the $\left(\nu g_{9/2}\right)^5_{9/2+}$ level in ^{215}Po provides evidence for Gamow-Teller β-decay of the high-spin ^{215}Bi isomer.

PACS. 23.20.Lv γ transitions and level energies – 27.80.+w $190 \leq A \leq 219$ – 29.30.Kv X- and γ-ray spectroscopy

1 Introduction

The neutron-rich Tl, Pb and Bi isotopes are of exceptional interest to trace the evolution of nuclear structure and single-particle levels away from the doubly magic ^{208}Pb towards the neutron-rich side of the nuclear chart. However, experimentally these neutron-rich nuclei are difficult to study. The lack of information is largely due to the difficulties encountered in producing isotopic samples at on-line mass separators that are pure enough to enable spectroscopic studies. A new experimental technique, based on a pulsed release of the generated activity, has successfully been pioneered at ISOLDE and allowed to considerably reduce the isobaric contamination in the mass chains $A = 215$ to 218 [1,2].

The present work is focused on the decay properties of $A = 215$ samples presently produced with enough yield to allow for detailed spectroscopic investigations. We report on a new high-spin γ-ray cascade observed in ^{215}Bi and a new high-spin level structure in ^{215}Po fed in β-decay of ^{215m}Bi connected with the previously known 294 keV level in ^{215}Po [3–5]. An interpretation of this activity as a new isomer in ^{215}Bi was confirmed in another experiment performed with the Resonance Ionization Laser Ion Source (RILIS) [6,7], described in sect. 2. A discussion of the results and the construction of the level schemes are given in sects. 3 and 4. Section 4 also contains a tentative model interpretation of the level schemes.

2 Experimental procedure

Two experiments were carried out at the ISOLDE facility at CERN. In the first experiment, a 55 g/cm^2 target of $^{232}ThC_2$ combined with a hot-plasma ion source [8]

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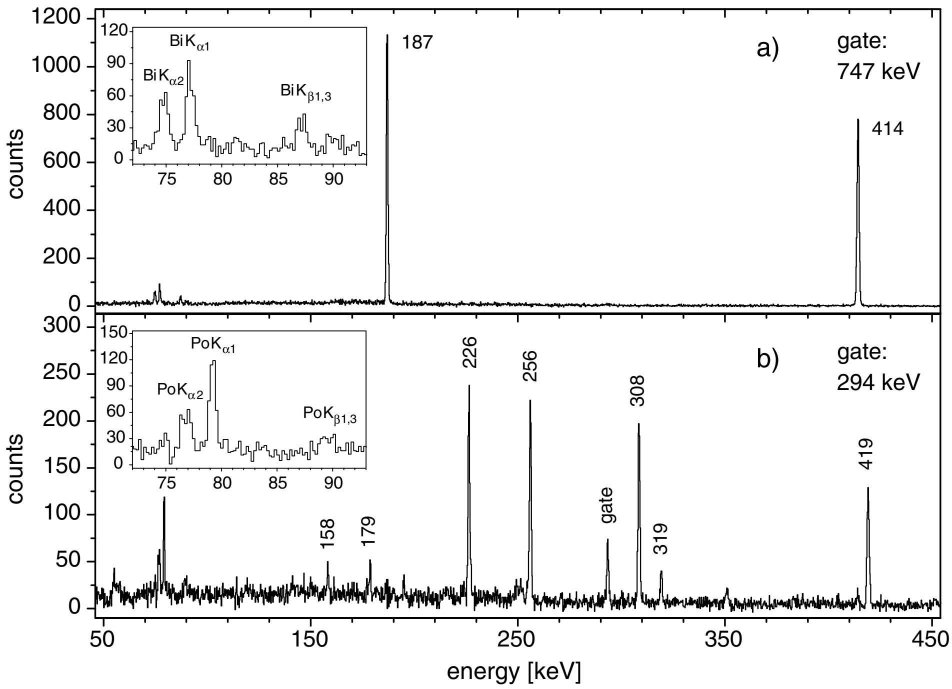

Fig. 1. The γ-ray spectra in coincidence with (a) the 747 keV transition in ^{215}Bi and (b) the 294 keV transition in ^{215}Po. The insets show the KX-rays part of the spectra. Peak energies are rounded values, given in keV. Data from hot-plasma ISOLDE ion source [8].

was bombarded with a pulsed beam of 1 GeV protons with an intensity of 2.8×10^{13} particles per pulse. The ion beam extracted from the source was mass separated by using the ISOLDE general-purpose separator. After the proton beam impact, the mass separator was blocked for 50 milliseconds before the radioactive atoms were implanted onto an aluminized mylar tape in front of the detection system. This considerably reduced unwanted isobaric contamination of short-living, alpha-decaying Rn, Fr and Ra isotopes. This technique known as "pulsed-release method" [1] was crucial for the success of this experiment.

The detector system consisted of a 450 mm^2, 500 μm thick silicon plate for detecting α-particles, placed 10.5 mm from the source, a 3850 mm^2, 20 mm thick LEGe-type germanium detector with a 300 μm beryllium window for detecting low-energy X- and γ-rays, and a large, coaxial germanium detector with a relative efficiency of 60% for 1.3 MeV γ-rays. There was a 0.5 mm thin β plastic scintillator placed between the collection tape and the LEGe detector. The silicon and plastic detectors were used to distinguish beta-delayed or alpha-delayed radiation from background and isomeric cascades. The detectors were arranged in a close geometry. The energy calibration of the detectors was done with external calibrated sources as well as internally with well-known "background" γ lines. The efficiencies of the X- and γ-ray detectors were deduced with calibrated γ-ray sources. The efficiency of the α detector was deduced in two ways: a geometrical one using the solid angle and a relative one by comparing the 2^+–0^+ γ-ray intensity in the β-decay of ^{216}Bi measured with a Ge detector with the α-intensity of the ^{216}Po daughter. Both values agree within error bars. The average value is equal to 0.16 ± 0.01.

The data acquisition was blocked during the implantation period, thus only registering radiation during the beam-off periods in an event-by-event as well as in a single-spectra mode. The latter contained all the events registered by the α, X and γ detectors in the respective multiscaling cycles recorded as disk files, whereas coincidence data were stored as list-mode files on a magnetic tape. Data in coincidence mode were recorded if any two of the detectors registered an event. The collection tape was moved after every implantation-decay cycle to reduce the background counts coming from unwanted long-lived activity.

The PS Booster accelerator delivered protons during a 14.4 seconds long super cycle consisting of 12 equidistant pulses. There were three different combinations of the beam-on and beam-off times for the measurements in the $A = 215$ isobaric chain. Firstly, a 3 super cycles long collection was followed by a beam-off period of the same length and the single spectra were recorded in a 8×5 s multiscaling cycle. Secondly, a 3 super cycles long collection was followed by a 6 super cycles long (86.4 s) beam-off period and the single multispectra were recorded in a 8×10 s cycle. In the above cases 6 proton pulses per super cycle were used. Finally, there was a measurement using three equidistant proton pulses, out of the twelve available in one super cycle. The activity was collected for 1.3 s just after one proton pulse and then the single spectra were recorded in 8×0.4 s multiscaling mode during a beam-off period equal to the length of the three unused

Table 1. Energies, intensities (in % per decay), deduced multipolarities and coincidence relations for the first cascade in the decay of ^{215m}Bi.

E_γ (keV)	I_γ	Multipolarities	Coincident γ lines
186.8(1)	52(2)	$E2$	414.1, 746.6
414.1(1)	76(3)	$E2$	KX Bi, 186.8, 746.6
746.6(1)	75(3)	($E2$)	KX Bi, 186.8, 414.1

proton pulses. In this way there were three beam-on and -off cycles within one super cycle.

In the second experiment the pulsed-release technique was complemented with the element selectivity available from the RILIS source at ISOLDE. The ^{215}Bi activity was produced by spallation of a UC_x target (50 g/cm^2 of ^{238}U and about 10 g/cm^2 of carbon) by a 1.4 GeV proton beam with intensity of 3×10^{13} protons per pulse. Two proton pulses, spaced by 2.4 s in each super cycle of 16.8 s, were sent to the target. After selective ionization in the RILIS source, nuclei were accelerated to 60 keV, mass separated and deposited on the collection tape transporting activity from the implantation point to a lead-shielded decay point. The setup included one germanium and one silicon detector at the implantation point and three germanium detectors at the decay point.

3 Experimental results

3.1 High-spin cascades

Two cascades of γ transitions were observed in the spectra at mass $A = 215$. The first one consists of three previously unknown γ lines of 187, 414 and 747 keV, the last two of them are in coincidence with the KX-rays of bismuth. The respective coincidence relations are presented in table 1 and fig. 1(a). These three lines have an average half-life of 37.1(5) s (see fig. 2). The internal K conversion coefficient for the 187 keV transition, found by the fluorescence method, is $\alpha_K = 0.24(3)$. Theoretical α_K values for a 187 keV transition based on [9] are 0.077 ($E1$), 1.47 ($M1$) and 0.197 ($E2$). The experimental value is of the order of magnitude of the theoretical α_K for an $E2$-type transition. The coincidence relations, the relative intensities of the three lines in the single spectra together with the intensity ratio of the 414 and 747 keV transitions observed in the gamma coincidence spectrum gated by the 187 keV line, suggest that the three γ lines form a cascade of three transitions. The multipolarities and intensities given in table 1 will be discussed further on.

Several coincident transitions creating the second cascade in the $A = 215$ isobaric chain, are in coincidence with the KX-rays of polonium. The relations are shown in table 2 and fig. 1(b). For the γ lines with sufficient intensity half-lives were deduced —see fig. 3. A half-life of 36.4(8) s was determined as a weighted average of the

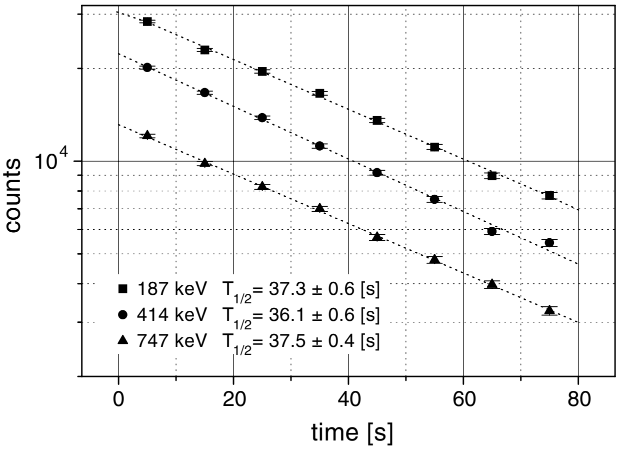

Fig. 2. Decay curves of the γ lines from the first cascade in the decay of ^{215m}Bi.

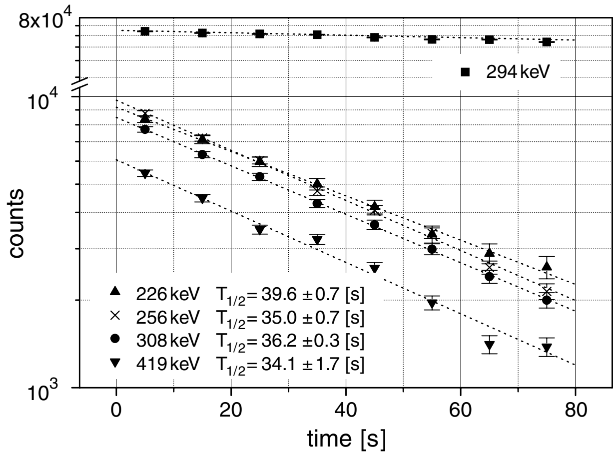

Fig. 3. Decay curves of the γ lines observed in the second cascade in the decay of ^{215m}Bi. Note the different half-life behavior of the 294 keV line resulting from its different population mechanism.

half-life values of the γ lines 226, 256, 308 and 419 keV. The only γ-ray, showing a different half-life behavior than the other coincident γ-rays (see fig. 3) is the previously known [3–5] transition of 294 keV. The 294 keV level in ^{215}Po, depopulated by a γ transition of the same energy, was observed earlier as relatively weakly populated in the α-decay of ^{219}Rn [3,5]. This level is strongly populated in the 7.7(2) m β^--decay of the ^{215}Bi ground state [4]. There are no coincidence relations observed linking the second cascade to γ lines reported in [3–5] as accompanying the 294 keV transition.

The γ-gated electron spectra measured with the silicon detector indicate no trace of coincident β-particles for the 187, 414 and 747 keV cascade, while for the 226, 256, 308 and 419 keV cascade there is clear evidence of coincidences with betas and conversion electrons. The same coincidences with betas and conversion electrons are observed for the previously known 294 keV transition.

In a preliminary account of the results of this experiment [10] the suggestion was made that the first cascade

Table 2. Energies, intensities (in % per decay), suggested multipolarities and observed coincidence relations for γ transitions in the second cascade in the decay of ^{215m}Bi.

E_γ (keV)	I_γ	Multipolarities	I_{tot}	Coincident γ lines
158.2(2)	3.2(4)	($E2$)	6.8(9)	255.9, 293.5, 308.4, 419.1, 498.0
178.7(4)	2.2(3)	($M1$)	7.2(10)	226.3, 255.9, 293.5, 308.4, 319.1, 419.1
226.3(1)	18.0(10)	$E2$	23.7(13)	KX Po, 158.2, 178.7, 255.9, 293.5, 308.4, 319.1, 419.1, 498.0
255.9(4)	21.9(9)	E1	22.9(9)	KX Po, 158.2, 178.7, 226.3, 293.5, 308.4, 319.1, 419.1, 498.0
293.5(1)	14.7(5)[a]	$M1$	22.9(8)	KX Po, 158.2, 178.7, 226.3, 255.9, 308.4, 319.1, 419.1, 498.0
308.4(1)	22.2(11)	$E2$	24.9(13)	KX Po, 158.2, 178.7, 226.3, 255.9, 293.5, 319.1, 419.1, 498.0
319.1(3)	4.0(4)	($M1$)	5.7(6)	178.7, 226.3, 255.9, 293.5, 308.4, 419.1
419.1(2)	20(2)	$E2$	24.4(24)	KX Po, 158.2, 178.7, 226.3, 255.9, 293.5, 308.4, 319.1, 498.0
498.0(1)	15.4(10)	($E2$)	15.9(11)	KX Po, 226.3, 255.9, 293.5, 308.4, 419.1

([a]) This intensity was deduced from coincidence relations.

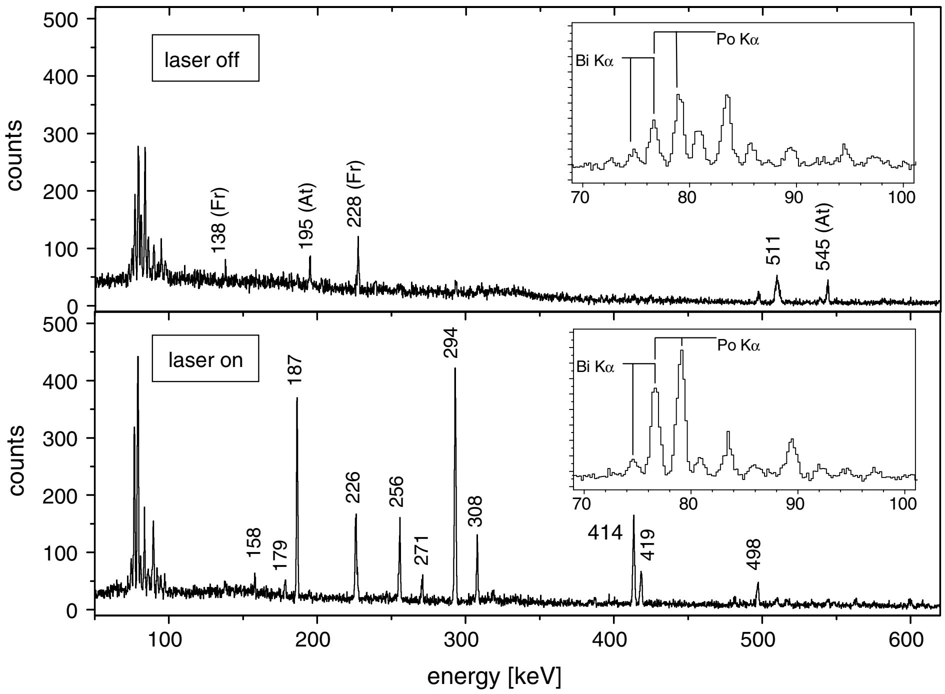

Fig. 4. The gamma spectra recorded in the LEGe detector with use of the laser ion source for off- and on-resonance measurements. There is a clear enhancement of gamma transitions following the decay of ^{215g,m}Bi in the spectrum taken with laser on. The region of the KX-rays is shown in the inset. Peak energies are rounded and given in keV.

originated from the unobserved ^{215}Pb decay. To verify this, a second experiment was designed. This experiment was carried out at the ISOLDE on-line separator combined with the RILIS source set to selective ionization of bismuth atoms. Spectra taken with and without laser ionization are shown in fig. 4. In the on-resonance spectrum one can clearly observe all transitions from the two cascades with relative intensities, exactly the same as in the main experiment. Both cascades originate from a ^{215m}Bi isomer, decaying as well internally (the first cascade) as by β-decay to levels in ^{215}Po (the second cascade). The intensity of both cascades, given in tables 1 and 2, are relative to a 100% decay of this isomer. The coincidence and intensity relations, together with the multipolarities from KX-ray intensities all point to a built-up of angular momentum in both cascades. This leads to a decay scheme as presented in fig. 5, the half-life of the isomer in ^{215}Bi is the average of the half-lives of the two cascades. As this decay scheme is the result of experimental findings and theoretical considerations it will further be explained in the discussion section.

In order to match the high spin value ($\approx 29/2$) of the isomer in ^{215}Bi, a number of transitions in the first cascade do remain unobserved. Their energy must lie below 80 keV as we do not observe Bi KX-rays in coincidence with the 187 keV line. In the second experiment the laser light was also set to selectively ionize Pb isotopes. The β-decay of ^{215}Pb was observed in this experiment and will be published elsewhere [11].

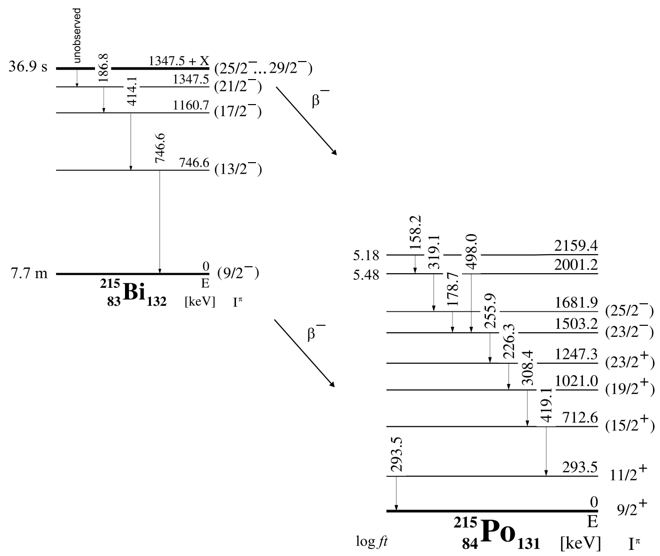

Fig. 5. Decay scheme of the high-spin isomer of ^{215}Bi.

The decay scheme shown in fig. 5 explains all experimental data, including the similar half-lives for both γ cascades and the result of β-γ coincidences.

The ordering of the γ-rays in a particular cascade could not be deduced and therefore the presented decay scheme is only one of the possibilities.

3.2 The beta-decay of the ^{215}Bi ground state

In the mass chain $A = 215$, besides the high-spin isomeric branch reported in the previous section, we observed several γ transitions known as accompanying the β^--decay of the ground state of ^{215}Bi with a half-life of 7.7(2) m [4] or seen in the α-decay of ^{219}Rn with a half-life of 3.96(5) s [3,5]. The new transitions were found through γ-γ coincidences. Two more lines (1294.5 and 1399.2 keV) fit energetically to the level scheme and show no coincidences with other lines, so they were placed as ground-state transitions. The results are presented in table 3. The gamma lines labelled with the superscript (a) come from a contamination from ^{213}Fr. This 34.6 s isotope is strongly produced ($\sim 10^9$ atoms/s), effectively surface-ionized and is not suppressed by the pulsed-release method. The high-mass tail of the ^{213}Fr isotope peak extends to mass 215; it is in the EC decay of its daughter ^{209}At that the contaminating γ lines are emitted.

All γ lines not marked with "n", were already reported in [3–5]. Figure 6 shows the extended decay scheme of ^{215}Bi, based on the coincidence relations given in table 3.

The decay of ^{215}Po proceeds through a 1.78 ms α-decay, therefore the apparent half-life of this α line in our spectra will be dictated by the feeding pattern of 36 s (7.7 m) when fed through $^{215\text{m}}$Bi ($^{215\text{g}}$Bi). From the decomposition of the time structure of α-decay we obtained $\frac{I_\alpha(7.7\text{ m})}{I_\alpha(36\text{ s})} = 11(3)$. In a single spectrum we observe the total intensity of 294 keV line. Whereas in coincidence with the lines belonging to the 256, 226, 308 and 419 keV cascade we observe only the 36 seconds contribution relative to the intensities of other gamma lines in the cascade. On that basis a similar ratio can be obtained for the 294 keV line $\frac{I_{294}(7.7\text{ m})}{I_{294}(36\text{ s})} = 13.9(11)$. Within the error bars these numbers are identical giving no evidence for ground-state feeding of ^{215}Po. Also from the comparison of the α-ray intensity and the γ-ray intensities no evidence was found for

Table 3. Energies, intensities (in % per decay) and coincidence relations for γ transitions observed in the decay of ^{215}Bi ground state, "n" marks the newly introduced γ lines.

E_γ (keV)	I_γ	Coincident γ lines
271.1(1)	2.9(1)	564.4, 806.5, 905, 1023.1, 1127.7
293.5(1)	35.2(11)	384, 542.7, 784
384(1)	0.2(1)	
401.6(10)	0.7(1)	
517.5(2)	1.5(1)	776.9,
542.7(25)n	0.3(1)	
564.4(5)	1.0(1)	271.1
609.0(5)	1.0(1)	
677.6(10)	0.6(1)	
776.9(1)n	1.2(2)	517.5
784(2)n	0.5(1)	
806.5(22)n	0.6(1)	271.1
836.3(10)	0.9(1)	
905(2)n	0.3(1)	
1023.1(12)n	0.9(1)	271.1, 544.4[(a)], 781.3[(a)] 789.4[(a)]
1104.5(5)n	2.2(1)	
1127.7(7)n	0.7(1)	271.1
1294.5(3)n	0.9(1)	
1399.2(4)n	1.2(1)	

([a]) From EC decay of ^{209}At.

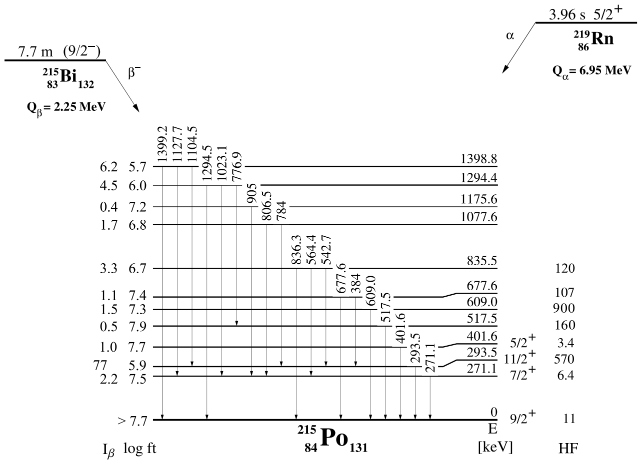

Fig. 6. The energy levels fed in the β^--decay of the ^{215}Bi ground state. Spin and parity assignments come from [3,4] and are partially based on the hindrance factors (HF) from the α-decay of ^{219}Rn to levels in ^{215}Po [5]. The Q_β and Q_α, together with the half-lives are from [12].

ground-state feeding. Absolute gamma-intensities are presented in table 3 assuming no ground-state feeding. Beta-intensities and lower limits for the $\log ft$ values (as they are based on γ-ray intensity balances) are given in fig. 6.

4 Discussion

In table 2 the multipolarities of the γ lines in the ^{215}Po cascade are given under the assumption that the total intensity of all γ lines in the cascade should be identical and equal to 23.8(4)% (this value is the mean of I_{tot} in table 2 from the lines 226.3, 255.9, 293.5, 308.4 and 419.1 keV). It made us ascribe the $E1$ multipolarity to the 255.9 keV transition, as for $E2$ multipolarity its total intensity would be 26.3(11)%. The total intensity of the short-lived component of the 293.5 keV $M1$ transition, based on the γ-γ coincidence measurement, is equal to 22.9(8)%. Out of the coincidence and energy relations of the 178.7, 319.1 and 498.0 keV lines, the 498.0 keV γ line can be placed as the crossover of the 319.1-178.7 cascade. Assuming an $M1$ character for the 178.7 and 319.1 keV line and $E2$ or $M1$ for the 498.0 keV transition, the total intensity going through this parallel branch amounts to 23%. For the 158.2, 226.3 and 308.4 keV transitions an $M1$ multipolarity is excluded, as we do not observe enough coincident X-rays. The 255.9 keV $E1$ transition was placed above the $M1$-$E2$-$E2$-$E2$ cascade in ^{215}Po to obtain negative-parity structure at an excitation energy about 1500 keV, close to the predicted $i_{13/2}$ excitation in the ^{208}Pb core. The proposed level scheme of fig. 5 is based on all the considerations mentioned above and on the sequence of parity-changing shell-model orbitals active for neutrons and protons. The isomeric state in ^{215}Bi can then be interpreted as the configuration of

$$\left\{\left[(\nu g_{9/2})^5_{9/2+} \otimes \nu i_{11/2+}\right]_{10+} \otimes \pi h_{9/2-}\right\}_{25/2-\ldots 29/2-}$$

and it decays via Gamow-Teller beta transitions to the final state in ^{215}Po, contained the

$$\left\{(\nu g_{9/2})^5_{9/2+} \otimes \left[\pi i_{13/2+} \otimes \pi h_{9/2-}\right]_{11-}\right\}_{13/2-\ldots 31/2-}$$

configuration, transforming an $i_{11/2}$ neutron into an $i_{13/2}$ proton.

This seems to be well supported by the experimental $\log ft$ values. The β-decay from the $(25/2^- \ldots 29/2^-)$ ^{215}Bi isomer has two main branches with allowed character, the first to the 2001.2 keV level ($\log ft = 5.48(13)$) and the second to the 2159.4 keV level ($\log ft = 5.18(12)$). For $\log ft$ calculations we assumed that the isomeric state energy in ^{215}Bi lies 40 keV (+80, −40) higher than the last observed level, see sect. 3.1.

Our scenario based on model predictions for the isomeric level allow its spins and parities from $25/2^-$ to $29/2^-$. The estimation of the partial half-life for the isomeric transition of energy within the mentioned energy limits prefers $M3$ multipolarity and $27/2^-$ spin value for the isomeric level.

The ^{215}Bi ground state (see fig. 6), presumably having $I^\pi = 9/2^-$ according to the shell model and systematics, decays strongly to the $11/2^+$ level at 294 keV and has no measurable feeding to the $9/2^+$ ground state. This is in contrast with the lower-mass Bi decays where strong feeding to the ground state was observed but the lack of ground-state feeding is also observed with decay of ^{217}Bi [13]. It is not clear yet what phenomenon causes this change. It could be that next to the $\nu g_{9/2} \rightarrow \pi h_{9/2}$ forbidden transition also the $\nu i_{11/2} \rightarrow \pi h_{9/2}$ forbidden transition starts to play a role. Due to the increased Q_β value another possibility opens: the $\nu i_{11/2}$ neutron could also decay by a GT transition to the $\pi i_{13/2}$ state. Furthermore collectivity can set in and change the feeding pattern.

The different decays observed in the $A = 215$ isobaric chain can only be explained by the occurrence of an isomeric state in ^{215}Bi which is probably an *yrast* trap produced in spallation reaction directly. An isomeric ratio calculated for isomeric and ground-state production is equal to 0.02. In the neighborhood a short-lived (70 ns) $21/2^-$ isomer de-exciting via the 97.4 keV $E2$ transition was reported in ^{211}Bi [14]. Also a similar isomeric state is known to exist in ^{211}Po [15] with spin 25/2 and positive parity. It decays with a half-life of 25 s by the 34 keV $M4$ γ transition.

5 Conclusions

A new level scheme in ^{215}Bi and a new high-spin structure in ^{215}Po were established in on-line isotope separator studies of the exotic, neutron-rich part of the isobaric mass $A = 215$ chain. The isomeric decay can be readily interpreted from the isomer configuration

$$\left\{\left[(\nu g_{9/2})^5_{9/2+} \otimes \nu i_{11/2+}\right]_{10+} \otimes \pi h_{9/2-}\right\}_{25/2-\ldots 29/2-}$$

in ^{215}Bi. The population of a high-spin cascade in ^{215}Po provides evidence for Gamow-Teller β-decay transforming an $i_{11/2}$ neutron into an $i_{13/2}$ proton. Additionally, the decay scheme of $^{215\text{g}}$Bi was confirmed and extended. This work has also demonstrated the unique possibilities of the ISOLDE on-line separator, combined with the pulsed-release technique and with the element selective RILIS source, for studies of exotic, neutron-rich nuclei beyond Pb.

This work was supported in part by the Access to Large Scale Facility program under the Training and Mobility of Researchers program of the European Union Contract HPRI-CT-1999-00018 "Inter University Attraction Poles Program-Belgian State-Federal Office for Scientific, Technical and Cultural Affair" and also by the Bilateral Scientific Technological Cooperation between Poland and Flanders (BIL00/14). One of the authors (J.K.) was supported by the Polish Committee for Scientific Research KBN under grant No. 2 P03B 034 22. K.V.d.V. is Research Assistant of the FWO-Vlaanderen.

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