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Behavior of intruder based states in light Bi and Tl isotopes: the study of ^{187}Bi α decay

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Abstract. The excitation energies of the single-particle normal and intruder levels in both ^{183}Tl and ^{187}Bi were measured for the first time via the α decay of ^{187}Bi produced in the ^{97}Mo(^{92}Mo,pn)^{187}Bi reaction. The previously unobserved ^{187}Bi ground state ($h_{9/2}$) to ^{183}Tl ground state ($s_{1/2}$) α transition was identified, establishing the ^{187}Bi intruder state excitation energy to be 112(21) keV, 70 keV less than that of the same level in ^{189}Bi.

PACS. 23.60.+e α decay

1 Introduction

For neutron deficient spherical nuclei near Z = 82, with filled $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ orbitals and unfilled $h_{9/2}$, $i_{13/2}$ orbitals one observes [1] in odd-Z, even-N isotopes lowlying $9/2^-$ and $1/2^+$ states for Z < 82 and Z > 82 respectively. These states are called "proton intruder" excitations. In this paper, we are reporting new data for the α decay of ^{187}Bi to levels in ^{183}Tl that reveal new features of the structure of particle-hole intruder states in this mass region. Our data clearly establish two things, the position of the $1/2^+$ low-spin state in ^{187}Bi at 112(21) keV, (this state has previously been estimated to be at 60 keV [2]), and the position of the $h_{9/2}$ intruder hole state in ^{183}Tl as 631(17) keV. This state had previously been tentatively placed at ≈ 550 keV [3,4]. We also have evidence for the position of the $d_{3/2}$ single-proton hole state in ^{183}Tl at 250(34) keV; this state had previously been estimated at 280 keV [4], and listed in the Nuclear Data Sheets at 387(22) [3].

There has been much experimental evidence showing that the excitation energies of intruder states exhibit a parabola-like dependence versus neutron number with a minimum when N is midway between major neutron shell closures. This behavior has been observed in both the Z = 50 and Z = 82 regions [1,5], and is the result mainly of the strongly attractive proton-neutron force between the "intruder" protons and the available valence neutrons. Hence, the maximum binding energy is expected to be near the mid-point of the accompanying neutron shell [6].

The picture presented above for the $h_{9/2}$ intruder in Z < 82 nuclei is quite well realized for the Tl isotopes, where the excitation energy of the $9/2^-$ intruder state has a parabolic shape with a minimum at N = 108. However, the excitation energy of the $1/2^+$ intruder in Bi isotopes continues to drop as one proceeds from N = 108 (^{191}Bi; 242 keV) [2] to N= 106 (^{189}Bi; 182 keV) [7] Further, a continuation of the downward trend to N = 104 (60 keV) was inferred by Coenen et al. [2] on the basis of ^{187}Bi α-decay data [8] with poor statistics. The systematics of the $1/2^+$ intruder state of the Bi isotopes suggested in Ref. [2] would represent something completely new for the odd-A intruders, as it would be expected that if the parabolic minima was to occur somewhere near the neutron midshell, one would see a "flattening out" of this curve. If the downward shape of the curve is as suggested in Ref. [2] were to continue to N=102, then the energies of the $s_{1/2}$

Table 1. Alpha-decay energies, half-lives, relative intensities, and reduced widths in the decay of ^{187}Bi

Peak#	E_α(keV)	$t_{1/2}$(ms)	I_α	$I_i \rightarrow I_f$	δ^2(keV)	HF
1	7000(8)	32(3)	88.3	$9/2^- \rightarrow 9/2^-$	82(10)	1
2	7367(30)	21^{29}_{8}	3.7	$9/2^- \rightarrow 3/2^+$	0.2(1)	410
3	7612(15)	25^{+9}_{-5}	8.0	$9/2^- \rightarrow 1/2^+$	0.08(1)	1025
4	7721(15)	$0.29^{+0.09}_{-0.05}$	100	$1/2^+ \rightarrow 1/2^+$	31(10)	2.6

and $h_{9/2}$ states in ^{185}Bi would be nearly identical. To see if this continued drop was indeed correct we reinvestigated the α decay of ^{187}Bi.

2 Experimental Results and Setup

Bismuth-187 was produced by bombarding a 1-mg/cm^2 thick target of ^{97}Mo (93% enrichment) with 420-MeV ^{92}Mo ions accelerated at the Argonne National Laboratory ATLAS facility. Following production, recoils of interest were passed through a fragment mass analyzer [9] and a gas-filled parallel grid avalanche counter (PGAC) for A/Q identification, and then implanted into a 60-micron thick double-sided silicon strip detector (DSSD) with 40 horizontal and 40 vertical strips. This strip arrangement results in a total of 1600 pixels. For each event in the DSSD, the time, energy, and event type (recoil or decay, depending on whether it is in coincidence with the PGAC or not) were recorded. Subsequent decays in a pixel can then be correlated with the parent, thus allowing for nuclidic identification.

Figure 1(a) shows the total decay spectrum accumulated over a period of ≈3 days with an average beam intensity of 2 pnA. One observes the well-known Hg and Pb α peaks arising from the larger reaction channels. In addition, there are events above 7 MeV that we assign to ^{186}Bi [10] and ^{187}Bi. Figure 1(b) shows the same decay spectrum correlated with a previous recoil of mass 187, and a time between decay and implantation of < 250 ms. Four peaks (labeled 1-4) in this spectrum are assigned to ^{187}Bi decay. A further constraint on the time between implantation and decay of < 1 ms results in Fig. 1(c). A comparison of Figs. 1(b) and 1(c) clearly demonstrates that peak 4 has a much shorter half-life than peaks 1-3 so that, as in the case of heavier odd-A Bi isotopes, there are two α-emitting states in ^{187}Bi. Following the systematics of the heavier odd-mass Bi isotopes, we assign the longer-lived species to the ^{187}Bi $9/2^-$ ground state, and the shorter-lived radioactivity to the $1/2^+$ isomer. The relevant information on ^{187}Bi α decay is summarized in Table I, while Fig. 2 shows our proposed scheme for the α decay of ^{187}Bi. These assignments are bolstered by the fact that of the two states, the longer-lived level had a far greater yield (≈7/1) as would be expected when high- and low-spin radioactivities are produced in heavy-ion reactions.

The individual half-lives for peaks 1-3 are consistent with each other and lead to our adopted value of 32(3) ms for the $9/2^-$ ground state. This compares with the 35(4) ms half-life reported by Schneider [8] who observed only one transition, 6986(10) keV, which presumably corresponds to our 7000(8)-keV transition. The previous study also reported only one transition from the $s_{1/2}$ isomer with an energy of 7583(10) keV and a half-life of 0.8(6) ms. This half-life agrees only marginally with the $0.29^{+0.09}_{-0.05}$-ms value that we adopt for the $s_{1/2}$ isomer, while the decay energy is not in agreement with the value of 7721(15) keV that we measured for the transition assigned to the $s_{1/2}$ isomer. Our data therefore cast doubt on the original

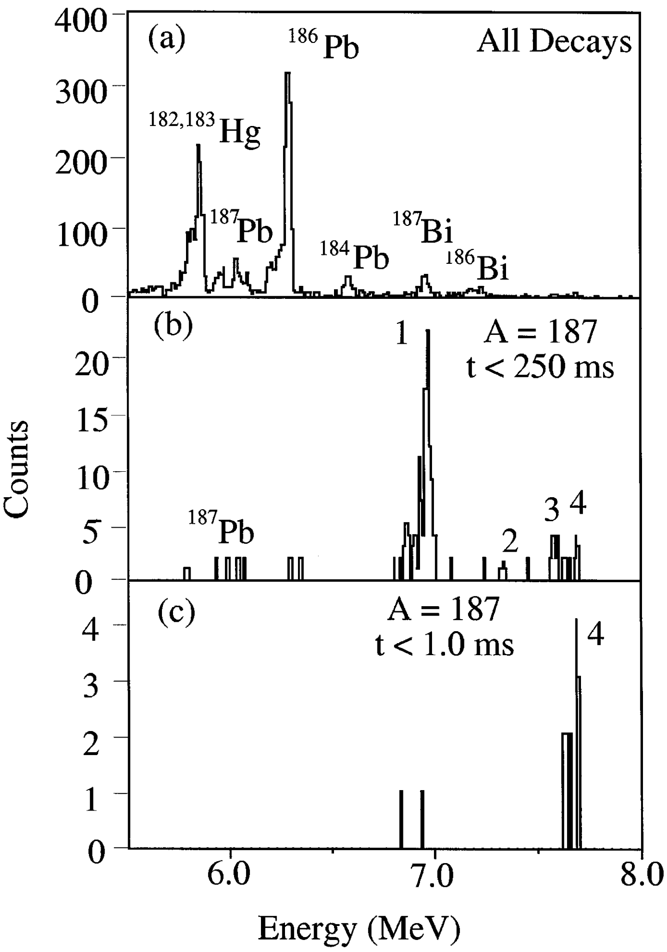

Fig. 1. Alpha-particle spectrum recorded in the DSSD during ^{92}Mo bombardments of ^{97}Mo. Part (a) shows the total decay spectrum. Part (b) is the spectrum obtained by gating on A = 187 recoils, and with a time between decay and recoil implantation of < 250 ms. In part (c) there is a further constraint on the time of < 1.0 ms. Numbered peaks are discussed in the text

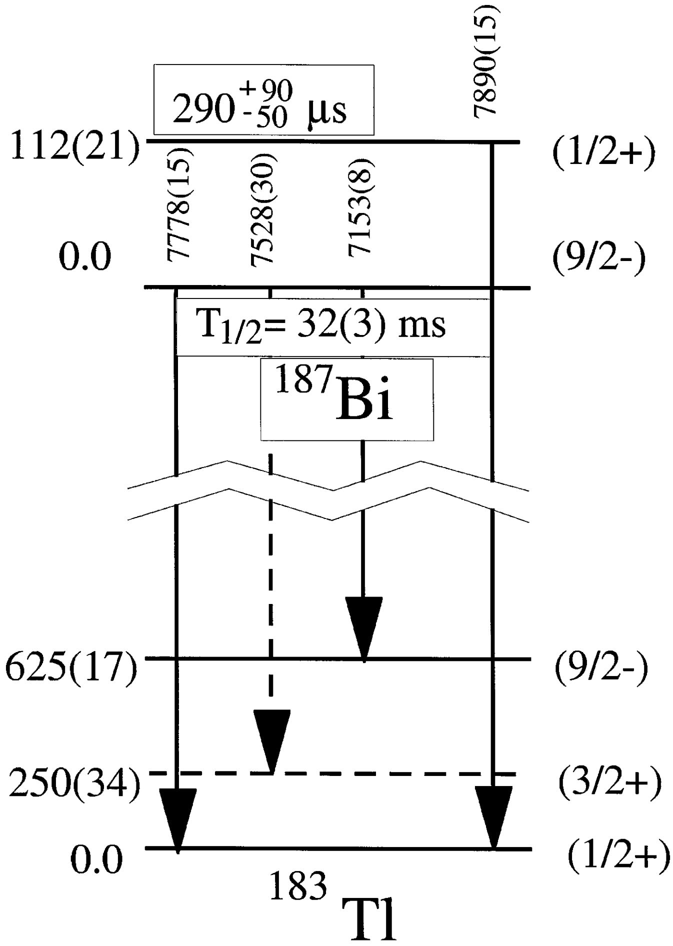

Fig. 2. Alpha-decay scheme for ^{187}Bi. Note that energies shown for the α transitions are Q_α values

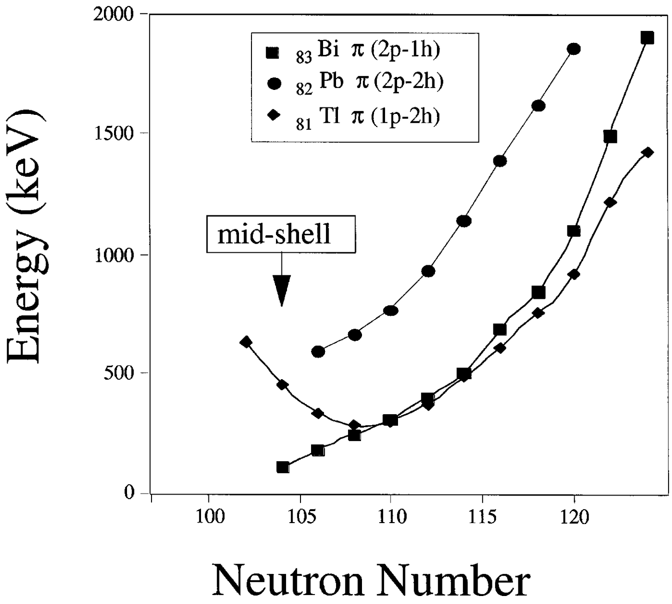

Fig. 3. Plot of the intruder state excitation energies versus N for nuclei near the Z = 82 closed proton shells, containing the energies of odd-mass Tl π(1p-2h), Bi π(2p-1h), and even-mass Pb π(2p-2h) isotopes

identification of the ^{187}Bi $s_{1/2}$ state claimed in Ref. [8]. Further evidence that the 32-ms activity represents ^{187}Bi α decay was established by observing that peaks 1 and 3 are correlated with ^{183}Hg 5.91-MeV α particles which originate from the sequence: ^{187}Bi $\rightarrow$ ^{183}Tl $\rightarrow$ ^{183}Hg$\rightarrow$ ^{179}Pt. The second step is not detected in our experiment since the thin DSSD is not sensitive to either positron or electron-capture decays. Peak 1 is also correlated with one 6.38-MeV α particle which we assign to the α decay of the known [4] $9/2^-$ isomer in ^{183}Tl. These correlations allow for the first experimental determination of the ^{183}Tl^m α-branching ratio, namely a value of $\approx$1.5%. However, due to the low statistics (i.e. one correlated event), this is not conclusive. Peak 2 is not correlated with any a particles from ^{183}Hg; however, this can easily be explained due to the low statistics.

3 Discussion

On the basis of the decay data in Table I and using the formalism developed by Rasmussen [11] α reduced widths (δ^2) were calculated for the four ^{187}Bi transitions, assuming that they all involve $\Delta\ell = 0$ transfers. These widths (included in Table I) are to be compared with δ^2 values for ground-state-to-ground-state (s-wave) transitions for neighboring even-even α emitters which range from about 40 to 90 keV for Po and Pb nuclei [7]. Hindrance factors (HF) are defined as the ratio of s-wave δ^2 values to those of transitions under consideration. On that basis the 7000-keV transition (peak 1) is clearly unhindered reinforcing the statement given above that it connects the $h_{9/2}$ states in ^{187}Bi and ^{183}Tl. For further discussion we have assigned a HF of 1 to the 7000-keV peak and with that normalization have deduced HF for the remaining four transitions. Peaks 2 and 3 have HF of 410 and 1025, respectively. They are similar in value to HF observed (see the discussion in Ref. [7]) in heavier Bi isotopes for transitions originating from the $h_{9/2}$ ground state and proceeding to $d_{3/2}$ excited and $s_{1/2}$ ground states in the Tl daughters. Thus, our data provide evidence that the new 250(34)-keV level, established by the 7367- and 7000-keV transitions, represents the previously unobserved $d_{3/2}$ state in ^{183}Tl. Its 250-keV excitation is consistent with the energy systematics for the $d_{3/2}$ level, which from ^{185}Tl to ^{201}Tl, is located between 285 and 385 keV [12]. However, it does not agree with the 387(22)-keV value listed in Nuclear Data Sheets for A = 183 [3]. The 7612- and 7000-keV transitions determine the excitation energy of the $h_{9/2}$ intruder state in ^{183}Tl to be 625(17) keV. As in the case of the $d_{3/2}$ level, this energy is substantially different from the adopted [3] value of $\approx$550 keV which was deduced by Schrewe et al. [4] based primarily on the 60-ms half-life that they measured for ^{183}Tl^m. Our measured value emphasizes the parabolic behavior of the Tl $\pi h_{9/2}$ intruder states (see Fig. 3).

According to the rules for level assignments adopted by Nuclear Data Sheets, α decays with HF less than four are considered to be unhindered. On this basis, the transition assigned to the ^{187}Bi $s_{1/2}$ isomer is unhindered. We propose that the 7721-keV transition (peak 4) proceeds to the ^{183}Tl $s_{1/2}$ ground state. The difference between the energies of peaks 3 and 4 establish for the first time the excitation energy of the $1/2^+$ ^{187}Bi isomer as 112(21) keV. Thus the downward trend of the $s_{1/2}$ intruder observed for ^{189}Bi continues to ^{187}Bi.

The behavior of the intruder states near Z = 82 (Tl, Pb and Bi) are presented in Fig. 3, where their excitation energies are plotted as a function of neutron number. As shown in the figure, the 1p-2h intruder states in Tl follow closely a parabolic shape but the curve for the 2p-1h (Bi) intruder states shows no sign of leveling off. The overall shape of the Bi curve seems to follow more closely that of the known Pb 2p-2h intruder states. This may well be due to mixing with an underlying Pb core structure in the light Bi isotopes.

We note the recent measurements [13] in which two 0^+ states have been established in ^{186}Pb, a weakly deformed oblate intruder configuration and a strongly deformed prolate intruder configurations. If a similar situation exists in the light Bi isotopes, we may be observing a crossing of two different $1/2^+$ states, the expected $1/2^+$ 2p-1h states at higher mass whose systematic behavior parallels that of the $9/2^-$ 1p-2h intruder in the Tl nuclides, and the prolate $1/2^+$ state that might be better viewed as a prolate Nilsson $1/2^+[660]$ state. It should be stressed however, that with the current data a firm conclusion cannot safely be reached.

In conclusion, we have investigated the α decay of ^{187}Bi to ^{183}Tl and have observed the previously unidentified ^{187}Bi ground state ($h_{9/2}$) to ^{183}Tl ground state ($s_{1/2}$) α transition, establishing the ^{187}Bi intruder state ($s_{1/2}$) excitation energy to be 112(21) keV. Previously its excitation had been estimated as low as 60 keV [2]. This work also establishes the excitation of the ($h_{9/2}$) state in ^{183}Tl to be 625(17) and provides evidence that the ($d_{3/2}$) state lies at 250(31) keV.

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