α Decay of Neutron-Deficient Odd Bi Nuclei: Shell-Model Intruder States in Tl and Bi Isotopes

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The α decay of mass-separated Bi isotopes is studied to characterize the shell-model intruder states in the odd-mass Tl and Bi isotopes. Allowed α decay is observed between the $^{189-195}$Bi $\pi h_{9/2}$ ground states and the $^{185-191}$Tl $\pi h_{9/2}$ intruder states and between the $^{191-197}$Bi $\pi s_{1/2}$ intruder states and the $^{187-193}$Tl $\pi s_{1/2}$ ground states. The observation of forbidden α branches provides excitation energies for the intruder states in ^{189,191}Tl and ^{189,191,193,195}Bi and confirms the intruder-state excitation energies in ^{185,187}Tl.

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Shell-model intruder states are now widely recognized[1] as a low-energy degree of freedom in nuclei near to closed shells. This is especially dramatic near $Z = 82$ where $\pi h_{9/2}$ and $\pi i_{13/2}$ particle states are observed[1] to intrude to very low energies in the odd-mass Tl and Au isotopes. In a reciprocal manner, the $\pi s_{1/2}$ hole state is observed[1] to intrude to low energy in the odd-mass Bi isotopes. While the empirical systematics of intruder-state energies are

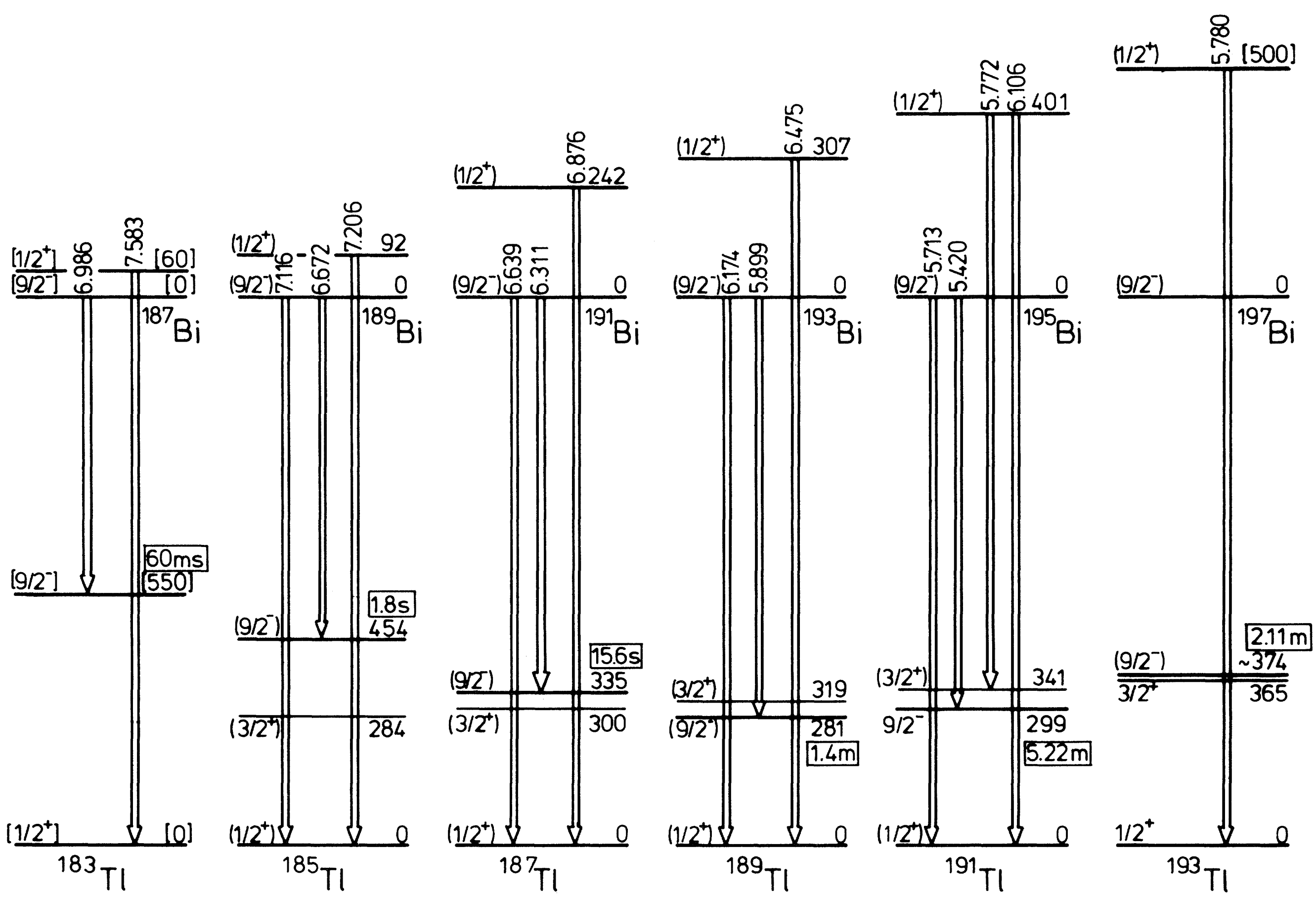

FIG. 1. Low-energy systematics in the odd-mass Tl isotopes and the α-decay schemes of the odd-mass Bi isotopes. The data on the odd-mass Tl isotopes are taken from Ref. 1 (except for the excitation energies of the $\frac{9}{2}^-$ states in ^{189,191}Tl which are deduced from this work). The spin of ^{191}Tl (5.22 min) has recently been determined (Ref. 2) to be $\frac{9}{2}$. The α-decay schemes for the Bi isotopes are deduced from this work and Ref. 3 (^{187m,g}Bi, ^{189m}Bi). Spin-parity assignments in parentheses are probable but not certain. Quantities in square brackets (^{183}Tl) are based on systematics. The error in the excitation energies of the Bi $\frac{1}{2}^+$ intruder states and the ^{189,191}Tl $\frac{9}{2}^-$ intruder states is ± 7 keV.

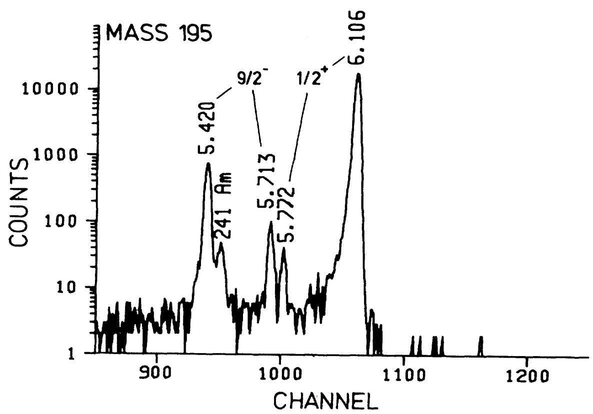

FIG. 2. The α spectrum obtained for $A=195$. Lines assigned to the decay of ^{195}Bi isotopes are marked by energy (in megaelectronvolts) and $\frac{9}{2}^-$ or $\frac{1}{2}^+$ to indicate ground-state or isomeric-state (intruder state) decay.

now fairly well understood qualitatively a quantitative theory is not yet available. This is primarily because most of the experimental systematics are for relatively narrow mass regions which do not reveal the behavior of these states over a major shell.

We report here on the identification and location of the $\pi s_{1/2}$ intruder state in the very neutron-deficient Bi isotopes. This provides a systematic of the $\pi s_{1/2}$ intruder-state excitation energy from the neutron-shell closure at $N=126$ (^{209}Bi) almost to the neutron mid-shell at $N=104$. This is achieved by studying the α decay of the $\pi s_{1/2}$ intruder states in ^{191,193,195,197}Bi and the α decay of the $\pi h_{9/2}$ ground states in ^{189,191,193,195}Bi. The decays are typically characterized by unhindered α decay for the ^{A}Bi $\pi s_{1/2}$ intruder state $\rightarrow$ $^{A-4}$Tl $\pi s_{1/2}$ ground state and ^{A}Bi $\pi h_{9/2}$ ground state $\rightarrow$ $^{A-4}$Tl $\pi h_{9/2}$ intruder state transitions and strongly hindered α decay for the ^{A}Bi $\pi h_{9/2}$ ground state $\rightarrow$ $^{A-4}$Tl $\pi s_{1/2}$ ground state transitions. These decay branches are illustrated in Fig. 1. Evidently, it is a straightforward task to deduce the excitation energies of the intruder states in ^{185,187,189,191}Tl and in ^{191,193,195}Bi. By combination of the present data with information[3] on the α decay of ^{189m}Bi it is also possible to deduce the excitation energy of the ^{189}Bi intruder

TABLE I. Results of our measurements for the α-decay energies and half-lives of $^{189-197}$Bi. Values from previous work are shown for comparison. Also given are data for ^{187}Bi and ^{189m}Bi, and assignments to Bi ground states (g) and isomeric states (m).

	This work			Others			
A	E_α (MeV)[a]	$T_{1/2}$ (s)		E_α (MeV)	$T_{1/2}$ (s)		Ref.
197	5.780	329 ± 50		5.77	~ 600	m	8
		293 ± 45[b]	m				
195	5.420	160 ± 11		5.43 ± 0.01	170 ± 20	g	8
	5.713		g				
		187 ± 5[b]					
	6.106	87 ± 1		6.11 ± 0.01	90 ± 5	m	8
	5.772		m				
		100 ± 15[b]					
193	5.899	63 ± 5		5.90 ± 0.01	64 ± 4	g	8,9
	6.174	90 ± 48		6.18 ± 0.02		m	8
			g	6.18		g	9
		69 ± 3[b]					
	6.475	1.9 ± 0.4	m	6.48 ± 0.01	3.5 ± 0.2	m	8,9
191	6.311	12 ± 1		6.32 ± 0.01	13 ± 1	g	8,9
	6.639	14 ± 3	g	6.63 ± 0.02	20 ± 15	m	8
				6.63		g	9
		12 ± 1[b]					
	6.876		m	6.86 ± 0.02	20 ± 15	m	8,9
				6.86	0.150 ± 0.015	m	10
189	6.672		g	6.675 ± 0.010	0.680 ± 0.030	g	3
	7.116[c]						
				7.206 ± 0.020	~ 0.005	m	3
187				6.986 ± 0.010	0.035 ± 0.004	g	3
				7.585 ± 0.010	0.008 ± 0.006	m	3

[a]Error in E_α: ±0.005 MeV.
[b]$T_{1/2}$ for β^+/EC decay (see Ref. 12).
[c]Deduced from two spectrum counts, error ±0.015 MeV.

TABLE II. Adopted Q_α values, α-transition assignments, adopted half-lives, relative α branching, estimate of total α branching, and deduced hindrance factors f.

$A_{\rm bi}$	Q_α (MeV)	$I_i \to I_f$	$T_{1/2}$ (s)	$\alpha_{\rm br}$ (%) Rel.	$\alpha_{\rm br}$ (%) Abs.	f [e] Rel.	f [e] Abs.
197	5.900	$1/2^+ \to 1/2^+$	309 ±33[a]		$15 \leq \alpha_{\rm br} \leq 95$		$0.1 \leq f \leq 0.8$
195	5.534	$9/2^- \to 9/2^-$	182 ±5[a]	100	$0.01 \leq \alpha_{\rm br} \leq 0.05$	1	$1.1 \leq f \leq 9.7$
	5.833	$9/2^- \to 1/2^+$		10 ±1		300 ±30	
	6.234	$1/2^+ \to 1/2^+$	87 ±1[a]	100	$16 \leq \alpha_{\rm br} \leq 49$	1	$1.0 \leq f \leq 5.8$
	5.893	$1/2^+ \to 3/2^+$		0.16 ±0.02		19 ±3	
193	6.024	$9/2^- \to 9/2^-$	67 ±3[a]	100	$2 \leq \alpha_{\rm br} \leq 8$	1	$0.5 \leq f \leq 3.5$
	6.305	$9/2^- \to 1/2^+$		4.4 ±0.5		380 ±40	
	6.612	$1/2^+ \to 1/2^+$	3.2 ±0.2[b]		$50 \leq \alpha_{\rm br} \leq 100$[f]		$0.3 \leq f \leq 1.2$
191	6.446	$9/2^- \to 9/2^-$	12 ±1[a]	100	$40 \leq \alpha_{\rm br} \leq 77$	1	$0.7 \leq f \leq 2.6$
	6.781	$9/2^- \to 1/2^+$		3.0 ±0.3		690 ±70	
	7.023	$1/2^+ \to 1/2^+$	0.150 ±0.015[c]		$50 \leq \alpha_{\rm br} \leq 100$		$1.2 \leq f \leq 3.8$
189	6.816	$9/2^- \to 9/2^-$	0.680 ±0.030[d]	100	$50 \leq \alpha_{\rm br} \leq 100$	1	$1.2 \leq f \leq 4.6$
	7.270	$9/2^- \to 1/2^+$		5 ±3		750 ±500	
	7.362[d]	$1/2^+ \to 1/2^+$	~0.005[d]		$50 \leq \alpha_{\rm br} \leq 100$		$0.5 \leq f \leq 3.0$
187	7.139[d]	$9/2^- \to 9/2^-$	0.035 ±0.004[d]		$50 \leq \alpha_{\rm br} \leq 100$		$0.6 \leq f \leq 2.4$
	7.749[d]	$1/2^+ \to 1/2^+$	0.008 ±0.006[d]		$50 \leq \alpha_{\rm br} \leq 100$		$0.4 \leq f \leq 6.9$

[a] $T_{1/2}$ weighted average of β^+/EC and α decay results (see Table I).
[b] $T_{1/2}$ weighted average of our result and Ref. 7.
[c] Reference 9.
[d] Reference 3.
[e] Hindrance factors are calculated (Ref. 13) as relative α widths normalized to the neighboring even-even nuclei ($f=1$).
[f] This value was confirmed in a "mother-daughter" decay study of ^{197m}At (see text).

state. Some preliminary results from measurements on these α decays have been reported[4,5] already.

The experiments were carried out at the Leuven Isotope Separator On-Line to the Cyclone cyclotron located at Louvain-la-Neuve (LISOL facility[6]). The ^{191,193,195,197}Bi isotopes were produced in the reactions $^{\rm nat}$Ir(5 mg/cm^2)(≤ 127 MeV ^{14}N,pxn), $^{\rm nat}$Re(16 mg/cm^2)(≤ 110 MeV ^{16}O,xn), and ^{181}Ta(8 mg/cm^2)-(≤ 230 MeV ^{20}Ne,xn). For the production of the ^{189}Bi isotope the reaction ^{165}Ho(5 mg/cm^2)(≤ 280 MeV ^{32}S,xn) was used. The activities so produced were mass separated and implanted into an aluminized Mylar tape which periodically moved the activity. Time-sequential α and γ spectra were recorded in order to obtain half-life information.

As an illustration the α spectrum of mass 195 is shown in Fig. 2. In Table I the results of our measurements are presented and compared with previous measurements. The assignments of the various α lines are generally self-evident from the measured half-lives and the previously known low-lying structure of the odd-mass Tl isotopes (see, e.g., Ref. 1 and Fig. 1). However, a number of points need clarification:

(a) The weak lines in the ^{191,193}Bi decays at 6.639 and 6.174 MeV, respectively, were originally assigned by Le Beyec *et al.*[7] as isomeric-state decays. On the basis of $Q_{\rm ground}$ systematics, Vakhtel *et al.*[8] suggested that these α lines, to the contrary, belong to the ground-state decays. Half-life measurements by Leino, Yashita, and Ghiorso[9] indicated that in ^{191}Bi the 6.639- and 6.876-MeV α lines do not belong to the same decaying state.

(b) Because of the delay time in the ion source (~4 s for Bi) the 5-ms ^{189m}Bi α decay was not observed.

(c) The ^{195m}Bi α decay is observed to populate also the 341-keV excited state in ^{191}Tl which has a probable[10] J^π of $\frac{3}{2}^+$. Population of the corresponding state[11] at 319 keV in ^{189}Tl following α decay of ^{193m}Bi cannot be determined because of the intense $\frac{9}{2}^- \to \frac{1}{2}^+$ α line at nearly the same energy.

(d) Where available, α-decay half-lives were compared with β^+/EC-decay half-lives (see Table I).

In Table II adopted Q_α values, α-transition assignments, adopted half-lives, relative α branching, estimates of total α branching, and deduced hindrance factors are given. Relative α branching was determined from relative intensities of α lines observed in the various spectra (see, e.g., Fig. 2). To obtain the total α-branching estimates, use was made of β^+/EC decay-scheme data[12] for ^{191,193,195,197}Bi $\to$ ^{191,193,195,197}Pb. Hindrance factors were calculated by the method of Rasmussen.[13] The absolute α branch of ^{193m}Bi was checked in a "mother-daughter"

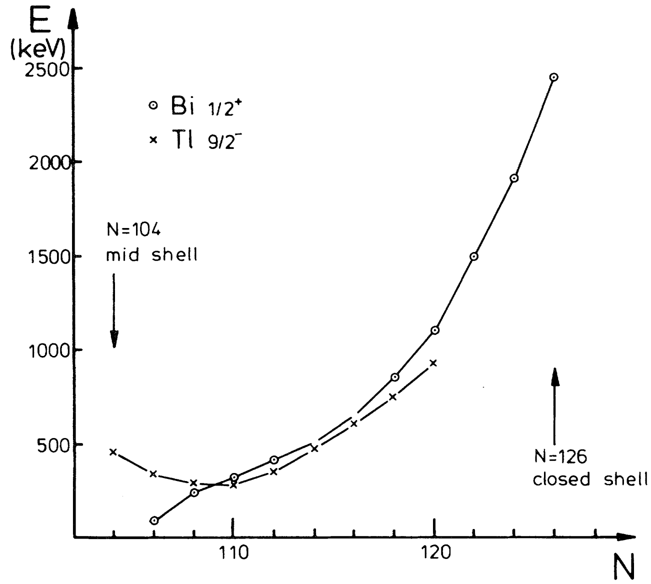

FIG. 3. The systematics of the odd-mass Tl and Bi intruder states. The data are taken from Ref. 1 and this work.

decay study of the chain ^{197m}At → ^{193m}Bi → ^{189}Tl (Ref. 14). A value of 112% ± 26% was obtained.

The systematics of the Tl and Bi intruder-state energies are shown in Fig. 3. This confirms the basic picture proposed by Vakhtel *et al.*,[8] extends it to ^{189}Bi, and provides, for the first time, energies for ^{189,191}Tl and ^{189,191,193,195}Bi. From this work it is shown that the absolute α-hindrance factors provide a strong spectroscopic fingerprint[1] for the intruder states in the odd-mass Tl and Bi isotopes.

An obvious extension is to the odd-odd Tl and Bi isotopes. Studies of the α decays of ^{190,192,194}Bi are in progress at LISOL (for a preliminary report, see Ref. 5). Further, an extension to the At α decays can be made. A study[14] of ^{197}At → ^{193}Bi indicates two α-decaying states in ^{197}At, one of which feeds the ^{193}Bi intruder state: The data are consistent with it being the $\frac{1}{2}^+$ intruder state. A more subtle aspect to these α-decay studies is that in many of the cases here, they are the *only* way to determine the intruder-state excitation energies. This is because the $\frac{1}{2}^+ \leftrightarrow \frac{9}{2}^-$ $M4$ transitions are observed[15] to be the most strongly hindered $M4$ transitions known in any odd-mass nuclei. Consequently, the resulting isomers have no observable isomeric transition for $E_{\mathrm{trans}} \leq 700$ keV [cf. ^{199}Bi (Ref. 15)]. Thus, the study of intruder states far from stability for $Z > 82$ may only be possible by use of α decay.

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