STUDY OF LEVELS IN ^{208}At HAVING SIX VALENCE NUCLEONS

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Abstract

Levels in ^{208}At have been populated in the ^{209}Bi(α,5n) reaction. It is observed that the yrast cascade from high-spin states in ^{208}At is divided into two parallel cascades. It is proposed that one of them originates mainly from proton excitations, while the other derives mainly from neutron hole excitations.

Two isomeric states are observed. There is a 46(3) ns isomeric state, which can be identified as arising mainly from the $(\pi h_{9/2}\, \nu i_{13/2}^{-1})_{10^-}$ interaction, and a 1.5(2) μs isomeric state, which can be identified as the $[\pi(h_{9/2}^2 i_{13/2})_{29/2^+}\, \nu f_{5/2}^{-1}(j^{-2})_{0^+}]_{16^-}$ state.

1. Introduction

In our studies of the applicability of the shell model in the lead region, we have found that nuclei with up to four valence particles are well described in terms of the model [1]. Also, for the case of ^{204}Bi with six valence particles, it is found that the energy levels can be calculated using only a "moderate" configuration mixing [2].

High-spin states in the lead region have been observed up to $J^\pi = 22^+$ [3] using an α-beam and up to $J^\pi = 30^+$ [4] using a ^{13}C-beam. It is observed that the yrast line in the lead region is built up from valence nucleon states, but when the spin is close to or above the spin J(max) generated by the valence particles, excitation of the ^{208}Pb-core is also observed. In the present investigation we continue our study of astatine isotopes [5] with the ^{208}At nucleus which so far has an almost unknown nuclear structure [6]. $^{208}_{85}At_{123}$ has three protons and three neutron holes $(\pi^3\nu^{-3})$ as compared to the core of ^{208}Pb. One can thus regard ^{208}At as a nucleus where the three protons corresponding to ^{211}At interact with the three neutron holes in ^{205}Pb. The level scheme of ^{208}At can, on the other hand, be compared with that of ^{210}At, where we have the $(\pi^3\nu^{-1})$ interaction, and ^{206}Bi, where the $(\pi\nu^{-3})$ interaction occurs.

2. Experimental procedure and results

The high-spin states in ^{208}At were studied through the ^{209}Bi(α,5n)^{208}At reaction using α-particles from the Stockholm 225 cm cyclotron. The energy of the α-beam was varied from 51 to 59 MeV. 59 MeV α-energy represents an optimal beam energy and intensity combination for producing ^{208}At with this cyclotron. The experimental information from singles γ-ray spectra, γ-ray angular distribution measurements and conversion electron spectra is presented in Table 1.

The singles spectra were recorded both with a high-resolution 4 cm^3 planar detector and with high-efficiency 60 cm^3 coaxial Ge(Li) detectors.

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Table 1. Properties of transitions in ^{208}At populated in the ^{209}Bi(α,5n) reaction at E_α = 59 MeV.

E_γ (keV)	I_γ (%)	A_{22}	A_{44}	α_K^{exp}	α_K^{th}	Sugg. Mult.
44.5	2.1					M1
71.7	26					M1
74.2	3.7					
76.2	23					M1
104.2	3.9					
115.7	1.6	0.25(13)	-0.01(18)			
145.9	6.0	0.17(8)	-0.19(11)			
149.4	21	<0				M1
186.5	100	0.08(1)	-0.17(2)			E1
226.0	5.8	-0.09(1)	-0.18(1)			
253.6	7.1	0.32(7)	0.10(10)			
278.7	32	0.09(11)	-0.55(16)	0.81	0.58	M1
286.3	5.3	-0.32(4)	-0.28(6)	0.74		
288.2	6.4	-0.25(3)	-0.25(5)			
345.2	6.5	-0.20(4)	-0.48(6)	0.51	0.32	M1
351.9	6.3	0.14(2)	-0.17(4)	0.29		
354.4	16	-0.22(1)	-0.21(2)			
396.0	58	0.38(5)	-0.12(7)	0.036	0.038	E2
454.2	8.1	-0.10(3)	-0.13(5)	0.081	0.15	M1
467.1	70	0.36(4)	-0.10(6)	0.043	0.027	E2
469.1	17	-0.26(2)	-0.03(3)			
472.2	25	0.12(4)	-0.16(6)	0.090	0.14 0.066	(M1) E3
481.9	4.9	0.57(3)	-0.28(3)			
490.5	7.5	-0.29(2)	-0.10(3)	0.19	0.13	M1
499.9	3.3	-0.19(16)	-0.26(22)			
502.6	11	-0.31(4)	-0.22(6)	0.23	0.12	M1
533.8	14[d]	>0		(0.12)		
542.1	10	-0.16(5)	0.05(7)	0.14	0.10	M1
545.6	33[d]	>0				
553.1	22	-0.44(2)	-0.07(3)	0.087	0.093	M1
558.2	73	0.31(3)	-0.14(4)	0.027	0.019	E2
567.5	6.8	0.11(5)	-0.07(6)			
577.7	62[d]	>0		(0.077)		
620.1	9.8	-0.15(8)	-0.10(11)	0.030		
630.7	8.4	>0				
701.3	10	0.07(9)	-0.10(12)			
716.7	14	-0.35(4)	-0.13(7)	0.030	0.048	M1
750.9	29	0.19(4)	-0.03(6)	0.033	0.044 0.024	(M1) E3
788.2	69	0.32(27)	0.14(35)	0.0096	0.0096	E2
832.2	168	0.30(3)	-0.08(5)	0.0075	0.0087	E2

[d] Double.

The γ-rays belonging to ^{208}At were assigned using the information from excitation functions, and γ-spectra recorded in coincidence with the At X-ray peaks in addition to the summed coincidence information. The strongest transitions were also assigned to astatine through the conversion electron measurements.

The time measurements were performed using both the natural bursts of the cyclotron, 104 ns apart, as well as bursts selected by an electrostatic system which was tuned to pick out every eleventh pulse. The time measurements revealed two isomeric states in ^{208}At. One of these appeared to have a half-life 46(3) ns being depopulated mainly by the

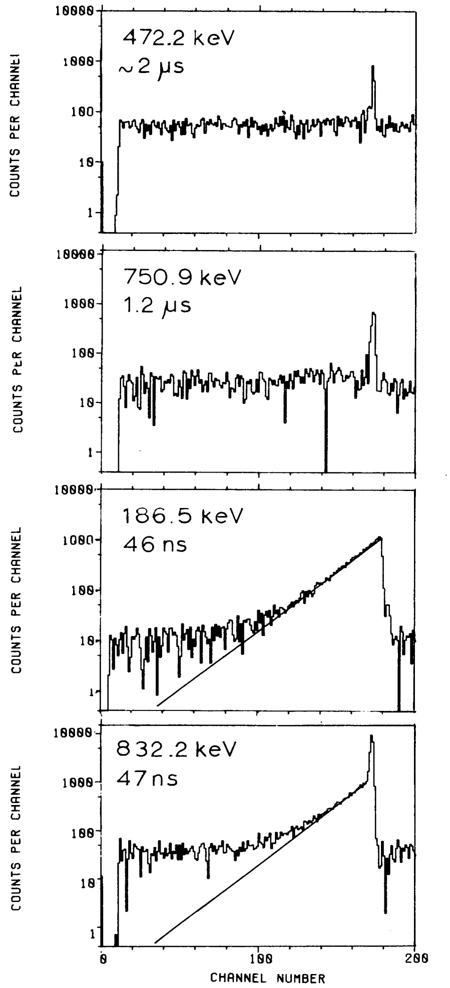

Fig. 1. Decay curves of some of the transitions depopulating the 1.5(2) μs and 46(2) ns isomeric states in ^{208}At.

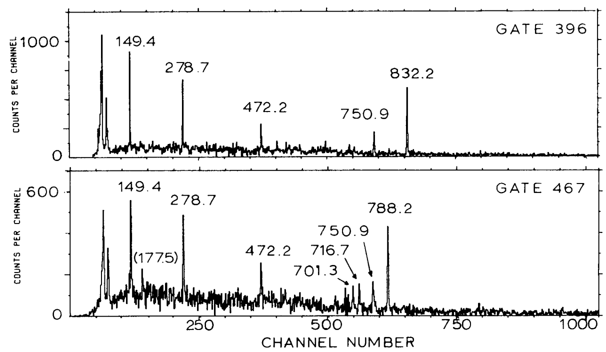

Fig. 2. Coincidence spectra obtained by setting gates on the 396.0 and 467.1 keV transitions in the yrast cascade depopulating the 1.5(2) μs isomeric state in ^{208}At.

71.7, 186.5 and 832.2 keV transitions, (cf. Fig. 1), and the other a 1.5(2) μs half-life appearing in many transitions, for instance, in the 149.4, 278.7, 396.0, 467.1, 472.2, 750.9, 788.2 and 832.2 keV transitions (Fig. 1). The transitions 186.5 (46(3) ns) and 472.2 and 750.9 keV (1.5(2) μs) were found to be isomeric.

Three-parameter γγt-coincidence measurements were carried out at E_α = 59 MeV. These were performed in two steps using two 60 cm^3 coaxial Ge(Li) detectors and a 60 cm^3 coaxial detector together with a 4 cm^3 planar detector. Some gated spectra are shown in Fig. 2.

The coincidence measurements reveal that the yrast cascade from the high-spin states is divided into two parallel branches. One branch contains the decay of the 1.5 μs isomeric state and the other branch feeds into the 46 ns isomeric state.

The decay order of the transitions feeding into the 46 ns isomeric state is difficult to determine because several of the observed gamma transitions are doublets or triplets. Thus the composite line at 542-545 keV turned out to be a guartet where the 545 keV peak contains strong ^{209}Po activity and a double peak from ^{208}At. Furthermore, the 534 keV peak is double and the 577 keV peak is found to be very complex. This latter peak gains intensity from the (α,3n), (α,4n) and (α,5n) channels, e.g. 576.4 keV in ^{210}At and 577.0 and 577.4 keV in ^{209}At. A double peak is also found in the ^{208}At spectrum, where the strongest part (~45% relative intensity, Table 1) feeds the 558.2 keV transition and has the energy 577.7 keV determined from the gated spectra.

Angular distribution measurements were performed at five angles between 90° and 150°. The data were normalized to include dead time and geometric effects and fitted to the function

$$W(\theta) = A_0 + A_2P_2 + A_4P_4$$

The coefficients $A_{nn} = A_n/A_0$ are presented in Table 1.

Conversion electron measurements were performed using the TARM[7] electron spectrometer which utilizes a solenoid magnetic field to transport the electrons from the target to a cooled Si(Li) detector. Targets consisting of 0.6 mg/cm^2 ^{209}Bi evaporated on carbon foils were used. The spectrometer was calibrated using both a ^{152}Eu source and the ^{208}Po target activity[8]). The conversion electron data were stored on magnetic tapes as two parameter E_et-events and thus prompt, singles and delayed conversion electron spectra were obtained. The conversion electron intensities were normalized to the 788.2 keV transition for which a pure E2 multipolarity was assumed. The conversion coefficients obtained for ^{209}At, i.e. for the 424.2, 596.5 and 725.1 keV transitions, are in agreement with those previously reported [5b]). The information from the conversion electron measurement is given in Table 1.

3. Spin and parity assingments
the level scheme of ^{208}At

Spin-parity 6^+ is proposed for the ground-state of ^{208}At through shell model considerations and α-decay properties [6]). The strongest γ-ray observed in the ^{209}Bi(α,5n) reaction is the 832.2 keV transition (cf. Table 1). In coincidence with this transition is the 71.7 keV transition, which is prompt; this suggests M1-multipolarity for the transition. The conversion coefficient for an M1-transition of 71.7 keV is 6.1 giving a total intensity which is almost the same as that of the 832.2 keV transition. We propose that the 71.7 keV transition is a ground-state transition and that the first excited state, as observed in these experiments, is a 7^+-state. The 903.9 keV state depopu-

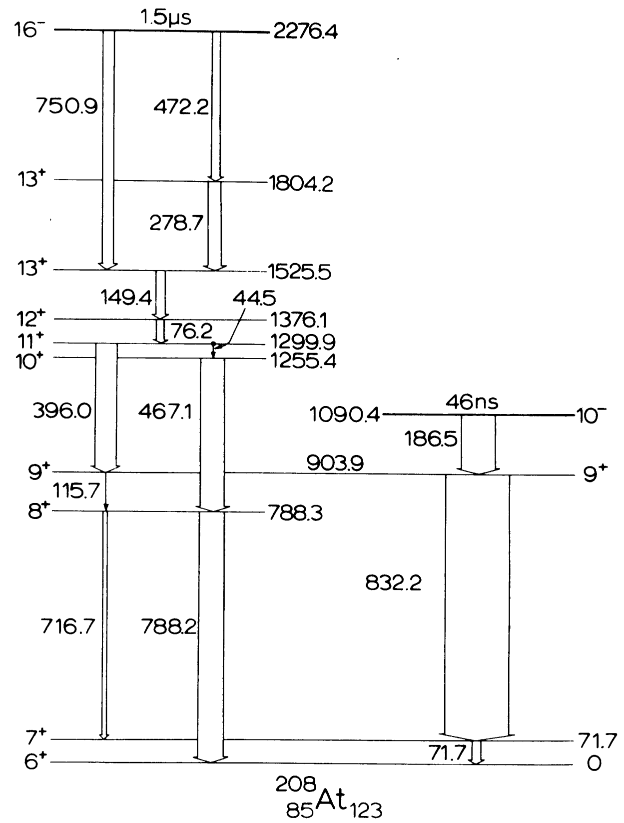

Fig. 3. The decay scheme of ^{208}At as obtained in the ^{209}Bi(α,5n) reaction.

lated by the 832.2 keV E2-transition is then a 9^+-state, see Figure 3.

The 903.9 keV state is populated by the 186.5 and 396.0 keV transitions. The latter transition is an E2-transition (cf. Table 1) giving an 11^+-state at 1299.9 keV. The 1299.9 keV state is also depopulated by the 44.5 keV transition (Fig. 3). The most probable multipolarity for this transition is M1, because no half-life is observed for the transitions depopulating the 1299.9 keV state. The requirement that the delayed intensity from the above-lying 1.5 μs isomeric state should be conserved is also in agreement with the multipolarity M1 for the 44.5 keV transition. The multipolarity E2 for the 467.1 and 788.2 keV transitions, which appear in the yrast cascade together with the 44.5 keV transition (cf. Fig. 3) and the M1 transition of 716.7 keV (Table 1 and Fig. 3) determines the spin-parity of the 788.3, 1255.4 and 1299.9 keV states as 8^+, 10^+ and 11^+, respectively.

The suggested M1 multipolarity (Table 2) for the 76.2 and 149.4 keV transitions gives spin-parity 12^+ and 13^+ for the states at 1376.1 and 1525.5 keV, respectively. The small intensity discrepancies appearing in Table 2 indicate that a branching which is not yet observed may occur from the 10^+ or 11^+ state.

The conversion coefficient of the 278.7 keV transition supports an M1 transition and the positive A_2-coefficient indicates a non-stretched transition. $J^\pi = 13^+$ is suggested for the state at 1804.2 keV. The 750.9 and 472.2 keV transitions may be either M1 or E3 as a result of the conversion electron measurement, but a positive A_2-coefficient

Table 2. Delayed intensities and conversion coefficients for the transitions depopulating the 1.5 μs isomeric state in ^{208}At.

E_γ	I_γ (del)	Multip. meas.	ass.	Conv. coeff.	I_{tot} (del)	I_{tot} (%)
44.5			M1	26.3		
76.2	105		M1	5.48	679	99
149.4	134		M1	4.13	686	100
278.7	175	M1		0.721	302	44
396.0	259	E2		0.061	275	40
467.1	252	E2		0.049	264	38
472.2	227	E3		0.143	259	38
750.9	291	E3		0.037	302	44

for both (Table 1) suggests that the E3-alternative is to be preferred. Multipolarity M1 for the two transitions would give $J^\pi = 13^+$, 14^+ for the state at 2276.4 keV, with preference for $J^\pi = 13^+$ due to the positive A_2-coefficients of the two transitions. It is, on the other hand, unlikely that a non-yrast 13^+ state would be so strongly populated. Therefore the E3-multipolarity assignment is to be preferred also from that point of view; this gives $J^\pi = 16^-$ for the 2276.4 keV state. This state is then isomeric, which is supported by the fact that almost no prompt component is observed in the 750.9 and 472.2 keV transitions. The small prompt component in the two transitions (cf. Fig. 1) can be explained by a small contamination, which could not be separated. The strong attenuation ($A_{22} \sim 0.2$) of the E3-transitions is to be expected, in view of the long half-life.

The J^π-value 10^- is proposed for the 46 ns isomeric state at 1090.4 keV. Since the isomeric (Fig. 1) 186.5 keV transition depopulating this state could not be resolved in the conversion electron measurement, the multipolarity of this transition has not been determined. The half-life 46(3) ns observed for the isomeric transition is too short for a typical E3- or M2-transition in the lead region and too long for an E2-transition; thus the most probable multipolarity for this transition is E1. The measured angular distribution coefficients $A_{22} = 0.08(1)$, $A_{44} = -0.17(2)$ may also be fitted with the theoretical distribution of an E1-transition with suitable mixing.

The intensity of the transitions depopulating the 16^- and 10^- isomeric states indicates a strong feeding into these states from higher states. The number of transitions feeding the 10^- isomeric state, according to the coincidence measurements, indicates that we observe the decay of states having $J \geq 20$.

4. Discussion

The structure of the ^{208}At nucleus is determined by six valence nucleons and a core of ^{208}Pb. In the description of the nuclear excitations one can use a configuration space where all six valence nucleons interact with each other, but the calculations, which have not yet been performed, may be simplified by using known multiparticle configurations, viz., the known three-proton levels of ^{211}At and the known three-neutron-hole levels of ^{205}Pb. The observed decay-pattern shows two independent yrast cascades, which may be interpreted as depending mainly on proton excitations in one case and on neutron excitations in the other case. Although the feeding into the 10^- state is not shown in Figure 3, this feeding is independent of the yrast cascade depopulating the 1.5 μs isomeric state.

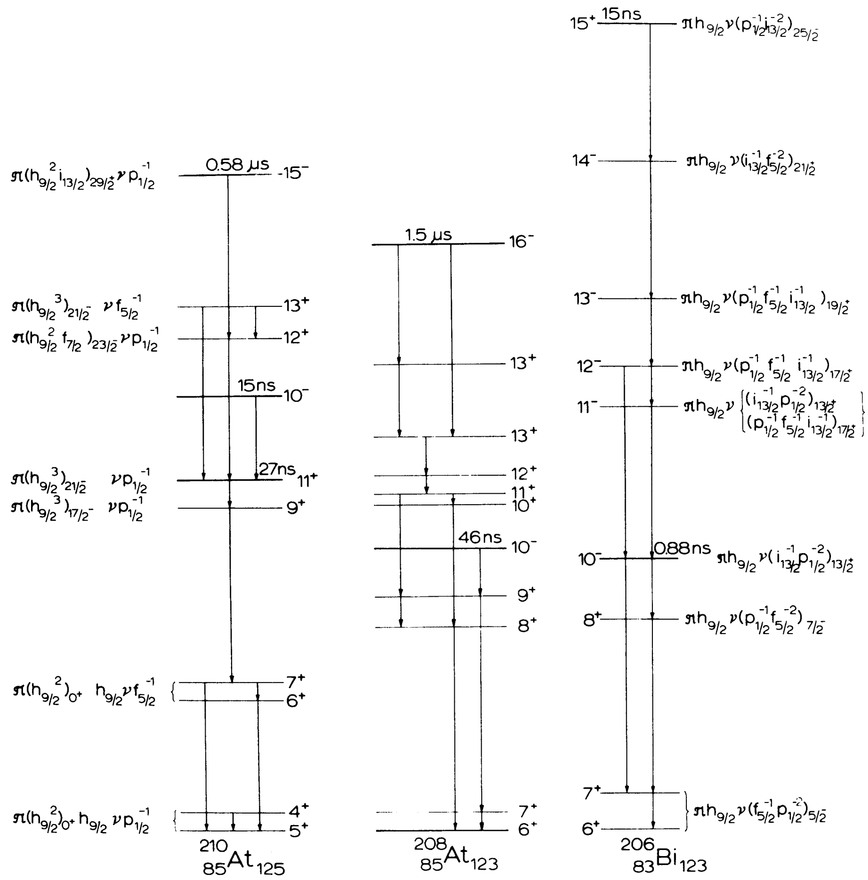

Fig. 4. The level scheme of ^{208}At compared to that of ^{210}At [5c] and ^{206}Bi [9].

As indicated in Figure 4, the 1.5 μs isomeric state and its decay may be compared with excited states of ^{210}At [5c]. Accordingly, the excited states of ^{208}At may be described as $\pi^3\nu^{-1}(j^{-2})_{0^+}$ excitations, i.e. the excitations of ^{211}At coupled to a neutron-hole in the ^{206}Pb-core. On the other hand, excitations of the main configuration $\pi(j^2)_{0^+}+\nu^{-3}$ may also occur in the yrast cascade feeding the 10^- state, and the excited states of ^{208}At may in this case be compared to the excited states of ^{206}Bi (cf. Fig. 4).

The observed reduced transition rate for the 472.2 keV E3-transition is 61400 e^2fm^6, which is of the same order as for a typical $\pi i_{13/2} \to \pi f_{7/2}$ transition in the lead region. Thus for the $\pi(h^2_{9/2} i_{13/2})_{29/2^+} \to \pi(h^2_{9/2} f_{7/2})_{23/2^-}$ transition in ^{211}At, the B(E3) value 51000 e^2fm^6 is found [10]. The B(E3) value of the 750.9 keV transition is 3000 e^2fm^6, which is of the same order as for the spin-flip $\pi(h_{9/2} i_{13/2})_{11^-} \to \pi(h^2_{9/2})_{8^+}$ transition observed [11] in ^{210}Po. The measured [12] B(E3) value of the corresponding $\pi i_{13/2} \to \pi h_{9/2}$ transition in ^{209}Bi is 22000 e^2fm^6. According to these B(E3) values the most probable configuration of the 1.5 μs isomeric state is $\pi(h^2_{9/2} i_{13/2})_{29/2^+}\ \nu f^{-1}_{5/2}(j^{-2})_{0^+}$, while the configuration of the second 13^+ state is $\pi(h^2_{9/2} f_{7/2})_{23/2^-}\ \nu f^{-1}_{5/2}(j^{-2})_{0^+}$ and for the first 13^+ state it is $\pi(h^3_{9/2})_{21/2^-}\ \nu f^{-1}_{5/2}(j^{-2})_{0^+}$. The $16^- \to 13^+_1$ transition may also occur through a mixing of the 13^+_2 configuration into the 13^+_1 state and then the faster E3-transition will determine the transition rate of the slower E3-transition.

From the nuclear level systematics shown in Figure 5 the most probable configuration for the 46 ns 10^- isomeric state is $\pi(j^2)_{0^+}\ h_{9/2}\nu i^{-1}_{13/2}(j^{-2})_{0^+}$, which also is in agreement with the calculated energy for this state in ^{208}At [13]. This 10^- state, arising from the $\pi h_{9/2}\nu i^{-1}_{13/2}$ interaction, is isomeric in the ms-region in the even Bi-isotopes, indicating that the transition strength is determined mainly by the $\nu i^{-1}_{13/2} \to \nu f^{-1}_{5/2}$ transition, while the half-life in the At-isotopes is in the ns-region due to the possibility of an E1-transition.

The 6^+ and 7^+ excited states show also a systematic behaviour. These states are due to the $\pi h_{9/2}\nu f^{-1}_{5/2}$ interaction, which seems to be rather pure in the considered nuclei.

A more extensive report, which includes the transitions feeding the isomeric states, is in preparation.

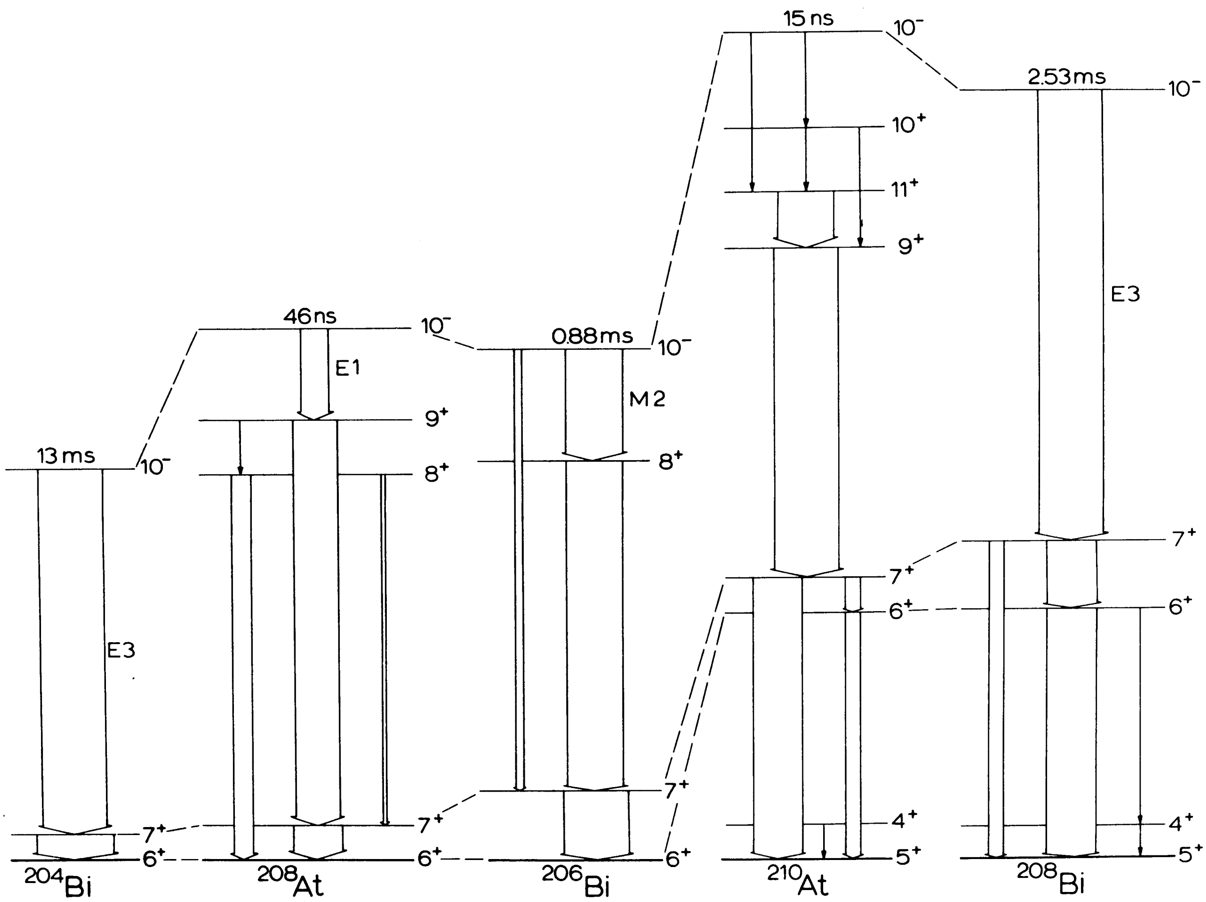

Fig. 5. Level systematics showing the $(\pi h_{9/2}\nu i_{13/2}^{-1})_{10^-}$ state and states below this in even Bi isotopes compared to ^{210}At and ^{208}At.

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