BRIEF REPORTS

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Shell model level structure in ^{215}At

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Mass separated sources of ^{223}Ac with ^{219}Fr in secular equilibrium were used to study the level structure of ^{215}At following alpha decay of ^{219}Fr. The levels in ^{215}At can be interpreted in terms of the $\pi(h_{9/2})^3\ \nu(g_{9/2})^4$, $\pi(h_{9/2})^2\ f_{7/2}\ \nu(g_{9/2})^4$, and $\pi(h_{9/2})^2\ i_{13/2}\ \nu(g_{9/2})^4$ shell model configurations. No evidence for reflection asymmetry is found.

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In the process [1] of studying the level structure of ^{219}Fr following the alpha decay of ^{223}Ac, we produced not only the alpha spectra of ^{223}Ac ($t_{1/2} = 2.2$ min), but also the alpha spectra of ^{219}Fr ($t_{1/2} = 0.02$ s) and ^{215}At ($t_{1/2} = 0.10$ ms) which are in secular equilibrium with ^{223}Ac. The combined alpha spectra of ^{223}Ac, ^{219}Fr, and ^{215}At in coincidence with all gammas are given in Fig. 1. By studying the gamma rays in coincidence with the alpha particles of ^{219}Fr which are well separated from ^{223}Ac alpha particles (Fig. 1), we are able to deduce the level structure of ^{215}At which up to now has not been well studied.

The level structure of ^{215}At is of considerable interest. With just 3 protons and 4 neutrons beyond the double closed shell in ^{208}Pb, ^{215}At might be described by the shell model, or alternatively, like ^{219}Fr [1], with 2 more protons and 2 more neutrons, it might be described in terms of a reflection asymmetric model. It is of interest to learn where the border is between nuclei described by the shell model and nuclei described by the quadrupole-octupole deformed model.

The level structure of ^{215}At was studied by observing the alpha decay of ^{219}Fr in secular equilibrium with mass separated $^{223}AcF_2^+$ and the accompanying gamma transitions. A 10 g Th-Ce alloy target (40–60 % by weight) was heated to 1100 °C and bombarded with ~1 μA of 200-MeV protons. While passing CF_4 vapor over the target [2] during the bombardment, $^{223}AcF_2^+$ ions of mass 261 were separated using the Orsay ISOCELE separator. A tape transported the ^{223}Ac and ^{219}Fr activities between alpha and gamma detectors in 180° close geometry. The alpha detector had a resolution of ~15 keV for ^{223}Ac and 18 keV for ^{219}Fr alpha particles while the gamma detector had a resolution of ~ 600 eV at 100 keV. Measurement cycles were 2 min, in accordance with the 2.2 min half-life of the ^{223}Ac parent. Singles alpha and gamma spectra and 4096 by 4096 channel alpha-gamma coincidence measurements were recorded simultaneously.

The alpha spectra of ^{223}Ac, ^{219}Fr, and ^{211}Bi in coincidence with all gamma rays observed in the experiment are shown in Fig. 1. The alpha energies used to label the

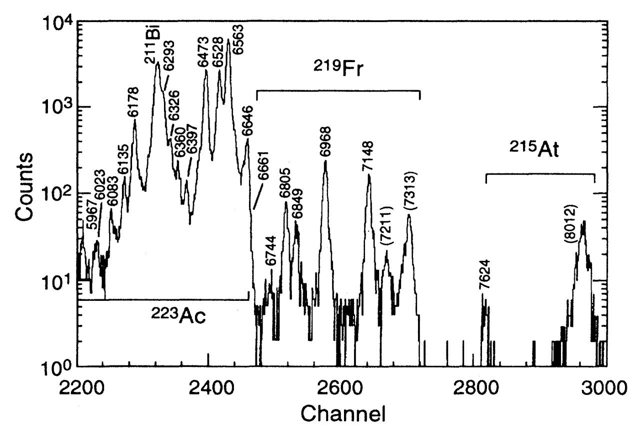

FIG. 1. Alpha spectrum of ^{223}Ac and daughters ^{219}Fr and ^{215}At in coincidence with all gammas. Energies of the major alpha groups are given in keV and taken from Leang [3]. The 7313 and 8012 keV alpha groups are random coincidences (ground state $\xrightarrow{\alpha}$ ground state transitions). The 7211 keV alpha group is a sum group (7148 keV alpha group + electron conversion K of 169 keV transition) due to the very close geometry and high K conversion of the 169.9 keV transition.

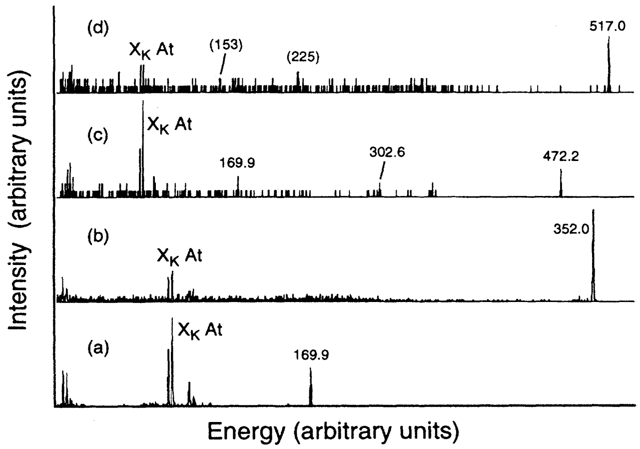

FIG. 2. Gamma spectra in coincidence with particular alpha groups: (a) with the 7148 keV alpha feeding the 169.9 keV level, (b) with the 6968 keV alpha feeding the 352.0 keV level, (c) with the 6849 keV alpha feeding the 472.2 keV level, and (d) with the 6805 keV alpha feeding the 517.0 keV level.

peaks in Fig. 1 are the more accurate values of Leang [3] who employed a magnetic alpha spectrograph.

The clearly separated alphas of ^{219}Fr from 6697 to 7190 keV were used as coincidence gates to give the gamma spectra shown in Fig. 2. Gamma rays in ^{215}At are labeled by their energies in keV while x rays are specifically labeled. The gamma-ray spectra of Fig. 2 are relatively simple with a total of only 7 transitions which can be assigned to the ^{215}At level structure. This simplicity has made possible the use of K x-ray to gamma intensity ratios from specific states populated in alpha decay in coincidence experiments (Fig. 2) to derive the internal conversion coefficients and therefore the multipolarities of 4 of these 7 transitions. Table I lists the gamma rays observed, together with their energies, intensities, and multipolarities when they could be determined. The assignments in the level scheme are also indicated.

Using the results from Fig. 2 and Table I the level scheme of Fig. 3 is proposed for ^{215}At. It represents more than 99.7% of the alpha decay of ^{219}Fr. The level structure including the transitions between states is quite firm. However, except for the ground state the spins (but not most of the parities) are listed in parentheses because of uncertainties. The ground state of ^{215}At has previously been assigned [1] as $9/2^-$ based on the alpha decay hindrance factor of 1.2 between the ^{219}Fr $9/2^-$ ground state and the ground state of ^{215}At. This assignment is confirmed by the hindrance factor of 2.7 between the ^{215}At ground state and the known $9/2^-$ state of ^{211}Bi [4]. Presumably the $9/2^-$ ground state results from the coupling of three $h_{9/2}$ protons to a partial J^π of $9/2^-$ and the coupling of the four $g_{9/2}$ neutrons to a partial J^π of 0^+. Thus the ground state configuration of ^{215}At is $\{\pi(h_{9/2})^3\ \nu(g_{9/2})^4\}_{9/2^-}$.

We expect to see evidence of the $f_{7/2}$ and $i_{13/2}$ shell model states in that order based on the level ordering in ^{209}Bi and the theoretical shell model. These are the states assigned at 169.9 and 363 keV to the right in Fig. 3 with the complete configurations $\{\pi(h_{9/2})^2\ f_{7/2}\ \nu(g_{9/2})^4\}_{7/2^-}$ and $\{\pi(h_{9/2})^2 i_{13/2}\ \nu(g_{9/2})^4\}_{13/2^+}$, respectively. We also expect to see the rest of the low lying part of the $\pi(h_{9/2})^3$ configuration at about the level of the 2^+ states in the neighboring even-even nuclei. The nuclei ^{214}Po and ^{216}Rn, with one less proton and one more proton than ^{215}At, have 2^+ states at 609 and 465 keV, respectively [5, 6], or an average of 537 keV (to the right in Fig. 3). This is near, but somewhat above, the average position of the rest of the observed states in ^{215}At (in the middle of Fig. 3). Unfortunately the spin sequence of the seniority three $\pi(h_{9/2})^3$ configuration is incomplete and uncertain in the experimental spectra of ^{211}At and ^{213}At. We therefore used the experimental spin sequences in the $\pi(g_{9/2})^3$ configuration in ^{93}Tc [7], ^{95}Tc [8], and ^{97}Tc [9] for guidance. They suggest the following spin sequence: $9/2^+$(g.s.) followed by $7/2^+$, $5/2^+$, $13/2^+$, $11/2^+$, $3/2^+$ in that order. The $11/2^+$, $3/2^+$ spins are reversed in one case and the $5/2^+$ state is missing in one case, but the trend of spins is clear. In addition, the experimental level structures in ^{211}At and ^{213}At are consistent with these sequences, but not nearly so well determined [4, 10]. Therefore, the sequence of spins assigned to ^{215}At for the partial $\pi(h_{9/2})^3$ configuration is $9/2^-$(g.s.), $5/2^-$, $7/2^-$, $13/2^-$, and $3/2^-$. This is very similar to the sequence of spins observed in the $\pi(g_{9/2})^3$ configuration except that the $5/2^-$ and $7/2^-$ states are reversed and the $11/2^-$ state is missing. It is quite clear why the $7/2^-$ state is above its expected position. Presumably it mixes with the $f_{7/2}$ shell model state at 169.9

TABLE I. Energies, intensities, multipolarities, and assignments in ^{215}At.

E_γ(keV)	(ΔE_γ)	$I_\gamma(\Delta I_\gamma)/10^3\alpha$	Multipolarity[a]	Levels Initial → Final	Calculated electron conversion coefficients
(153)		~0.06		517 → 363[b]	
169.9	(0.1)	1.0 (0.1)	$M1 + (E2)$ α_K=1.5±0.2	167 → 0	$\alpha_K(M1)$ 2.3; $(E2)$ 0.23
(225)		~0.1			
302.6	(0.3)	~0.06		472 → 169	
352.0	(0.1)	5.6 (0.5)	$E2$ α_K=0.06±0.01	352 → 0	$\alpha_K(M1)$ 0.30; $(E2)$ 0.05
472.2	(0.2)	0.50 (0.15)	$(M1)$ $\alpha_K \sim 0.1$	472 → 0	$\alpha_K(M1)$ 0.14; $(E2)$ 0.03
517.0	(0.2)	1.9 (0.4)	$E2$ α_K=0.03±0.01	517 → 0	$\alpha_K(M1)$ 0.11; $(E2)$ 0.02
$X_K(\alpha+\beta)$		2.2(0.3)			

[a] The α_K values are deduced from X_K/I_γ intensity ratios in coincidence with the alpha feeding groups.

[b] The 363 keV level was observed in the magnetic alpha spectrum [3].

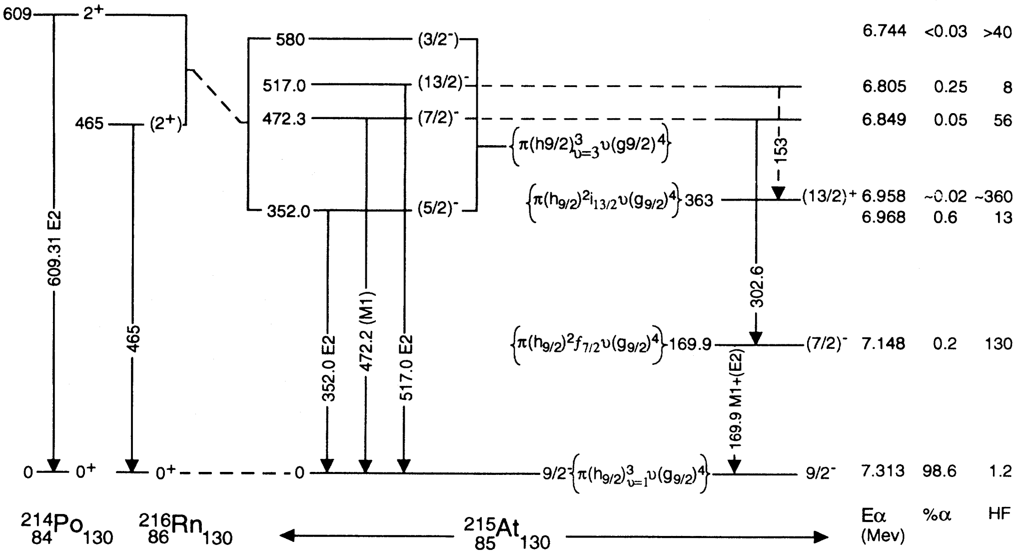

FIG. 3. The level structure of $^{215}_{85}At_{130}$ compared with the low lying level structures of $^{214}_{84}Po_{130}$ and $^{216}_{86}Rn_{130}$ with one less proton and one more proton, respectively. Shell model configurations are indicated. To the far right the energies, percentage populations, and hindrance factors for the ^{219}Fr alphas which populate the levels in ^{215}At are given.

keV. This results in the observed larger alpha hindrance in populating this state when compared with the other members of the $\pi(h_{9/2})^3$ configuration and an increase in energy of the state, lifting it above the $5/2^-$ state. It is also to be noted that calculations [11] of the level structure of the neutron closed shell nucleus ^{211}At give the same sequence of states as that observed in ^{215}At except that the order of the $5/2^-$ and $7/2^-$ states is reversed. Presumably the greater mixing between the two $7/2^-$ states in ^{215}At is responsible.

All of the rationale for the level scheme is presented in Fig. 3. It must be noted however that, although no other spin sequence is as satisfactory either experimentally or theoretically as that in Fig. 3, the spins except for the ground state are uncertain.

Assuming the correctness of the level scheme of Fig. 3 it is interesting to note that it fits well with all concepts of the shell model, but has very little in common with reflection asymmetric models. There are no parity doublet bands and no observed enhanced $E1$ transitions. The only possible indication of reflection asymmetry is the presence of $13/2^-$ and $13/2^+$ states $\sim$150 keV apart.

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