Decays of ^{211}At, ^{211}Po, and ^{207}Bi

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The energies and intensities of γ rays and internal-conversion electrons from the electron-capture decay of ^{211}At and from the α decays of ^{211}At and ^{211}Po have been measured. A new first-forbidden electron-capture branch of ^{211}At is reported. First-forbidden electron-capture transition rates are discussed with reference to the $2g_{9/2}$ and $1i_{11/2}$ neutron states in ^{211}Po. γ rays corresponding to the l-forbidden $M1$ transitions $\nu(3p_{3/2})^{-1} \to \nu(2f_{5/2})^{-1}$ in ^{207}Pb and $\nu(1i_{11/2}) \to \nu(2g_{9/2})$ in ^{211}Po have been observed. The α spectra of ^{211}At and ^{211}Po and the energies and relative intensities of γ rays from the electron-capture decay of ^{207}Bi have been remeasured. A level scheme incorporating all of these decays is given.

[RADIOACTIVITY ^{211}At [from ^{209}Bi(α, 2n)]; measured E_γ, I_γ, I_{ce}, I_α; deduced logft, EC branching, α branching. ^{211}Po, ^{207}Bi, ^{207}Pb deduced levels, J, π, ICC, γ multipolarity, γ branching. Ge(Li), Si(Li), Au-Si detectors.]

I. INTRODUCTION

Daughter nuclei produced from the electron-capture and α-decay branches of ^{211}At (7.2 h)[1] both decay directly to the same stable granddaughter (^{207}Pb), but at quite different rates. The ^{211}Po daughter from the electron-capture branch has a short half-life[2] (0.56 sec); for sources of ^{211}At it is in transient equilibrium and decays by α emission to ^{207}Pb with the half-life of ^{211}At. The ^{207}Bi daughter from the ^{211}At α branch has a longer half-life[1,3] (38 yr) so that its electron-capture decay to ^{207}Pb is much slower. In the decay chain of ^{211}At, excited states of ^{211}Po, ^{207}Bi, and ^{207}Pb are populated. Since these nuclei are near the doubly closed shell of ^{208}Pb, theoretical wave functions exist for many of their levels, and measurements of decay properties can be compared with theoretical first-forbidden electron-capture decay rates, electromagnetic transition rates, and α-decay rates. ^{211}At also has a potential for applied use in radiobiological studies[4,27] since astatine, like iodine, selectively concentrates in the thyroid gland but emits primarily α particles rather than longer range β particles. Thus it is also of some practical interest to study ^{211}At.

In this paper measurements of γ rays, internal-conversion electrons, and α particles in the ^{211}At decay chain are reported. Six γ rays were found to follow the ^{211}At half-life and have been given definite assignments in the decay chain. Energies and intensities of three of the weaker γ rays and multipolarities of two of the stronger transitions have not been reported in previous studies.[5,6] From these results a new electron-capture branch of ^{211}At is deduced. First-forbidden β-decay transitions to states in ^{211}Po are discussed and two γ-ray transitions in ^{211}Po and ^{207}Pb of the l-forbidden $M1$ type[7,8] are identified. In addition, the energies and intensities of γ rays in the electron-capture decay of ^{207}Bi were remeasured.

II. EXPERIMENTAL

^{211}At was prepared via the ^{209}Bi(α, 2n) reaction by bombarding bismuth metal targets with 27 MeV α particles. At this energy none of the radiations[9] of ^{210}At, produced from an (α, 3n) reaction, were observed. Sources produced for the study[9] of ^{210}At contained appreciable amounts of ^{211}At and these were also used for some of the present measurements. Chemical separation was achieved by a volatilization procedure previously described.[9,10] Sources for γ-ray, internal-conversion electron, and α measurements were prepared on aluminum backings, either by evaporation of aqueous solutions, or by evaporation of astatine vapor from a heated target onto a cooled backing. A thin layer ($\approx$4 μg/cm^2) of aluminum was vacuum-sublimed from a tungsten filament onto sources for electron and α counting. This reduced the migration of the astatine in the vacuum chambers of these spectrometers. A ^{207}Bi source was prepared (by evaporation) for γ-ray counting from a commercial material.

γ-ray spectra were measured with a 10-cm^3 Ge(Li) planer detector and a 35-cm^3 Ge(Li) coaxial detector (system resolutions were 2.3 and 2.5 keV full width at half-maximum (FWHM) at 1332 keV, respectively) coupled with a PDP-7 4096-channel data acquisition system.[9,10] Energy and relative efficiency calibrations were made using

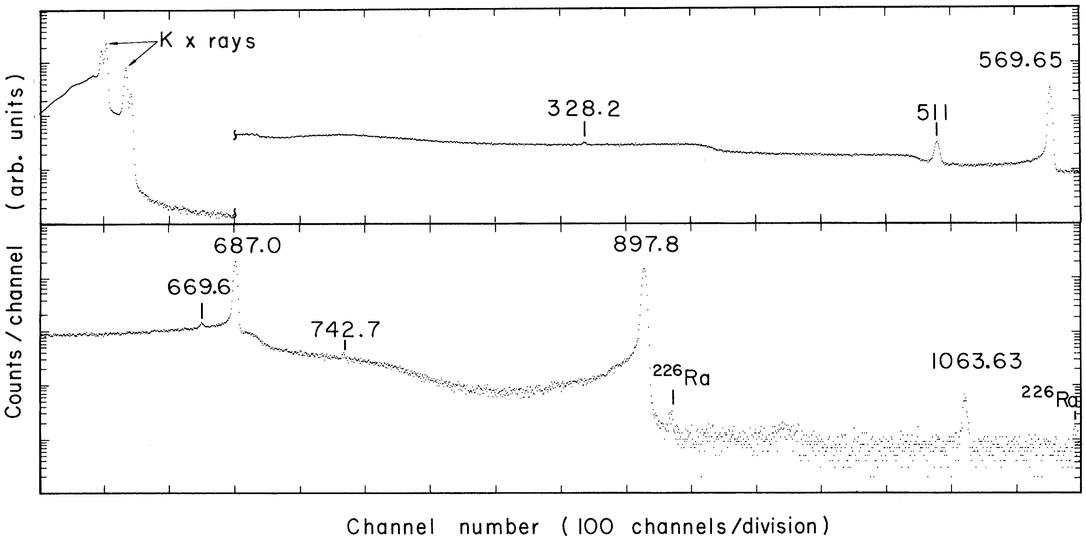

FIG. 1. γ-ray spectrum of a ^{211}At source with ^{211}Po in equilibrium. Weak peaks at 511 and 1063.63 keV are due to ^{18}F (impurity) and ^{207}Bi, respectively.

standard techniques previously described.[11, 12]

Conversion-electron spectra were measured with a 5-mm thick $\times$1-cm^2 Si(Li) detector whose resolution was 2.2 keV (FWHM) at 975 keV. The relative efficiency of the electron detector was calibrated by measurement of standard sources.[13]

Spectra of α particles were measured with a 6-mm diameter Au-Si surface-barrier detector [system resolution 16 keV (FWHM) at 4.8 MeV]. All spectra were analyzed with the shape-fitting program SAMPO on CDC-6600 computers.[14]

III. RESULTS

A γ-ray spectrum representation of the data collected for a source of ^{211}At is shown in Fig. 1. The measured energies and relative intensities of γ rays originating from the electron-capture and α-decay branches of ^{211}At, and from the decay of ^{211}Po in equilibrium, summarized from all our data, are given in Table I. The results for the three strongest transitions in Table I agree with the scintillation measurements of Mihelich, Schart, and Segrè[5] while the remaining transitions are reported for the first time in this decay. The measured energy for the 687.0-keV transition does not agree with the value of 668 keV reported by Ref. 6. The intensity of the 569.65-keV transition from the decay of ^{211}Po $\to$ ^{207}Pb has been corrected for a small contribution from the decay of ^{207}Bi, which grows in slowly. The correction is

TABLE I. Measured energies, intensities, and internal-conversion coefficients of transitions from a source of ^{211}At with ^{211}Po in equilibrium. Transitions from the decay of ^{207}Bi (daughter) are not included.

Transition energy (keV)	Nuclide [a]	Relative [b] photon intensity	Relative conversion-electron intensity	*K*-conversion coefficient Experimental [c]	Theoretical [d] *M*1	*M*2	*E*1	*E*2	*E*3
328.2 ± 0.2	^{207}Pb	0.6 ± 0.2							
569.65 ± 0.10	^{207}Pb	100	100	assumed 0.016	0.065	0.174	0.0061	0.016	0.039
669.6 ± 0.2	^{207}Bi	1.1 ± 0.2							
687.0 ± 0.1	^{211}Po	79 ± 4	213 ± 20	0.043 ± 0.006	0.047	0.117	0.0045	0.012	0.028
742.7 ± 0.5	^{207}Bi	0.3 ± 0.1							
897.8 ± 0.1	^{207}Pb	97 ± 5	97 ± 10	0.016 ± 0.003	0.020	0.048	0.0025	0.0065	0.0145

[a] This refers to the nuclide *in which* the transition occurs.

[b] A renormalization to absolute intensities can be made since the 569.65-keV transition has an absolute intensity of 0.31 ± 0.02 photons per 100 decays of ^{211}At (see text).

[c] These conversion coefficients were measured relative to the 569.65-keV *E*2 transition in ^{207}Pb.

[d] Theoretical values were obtained by computer interpolation from the tables of Hager and Seltzer (Ref. 15).

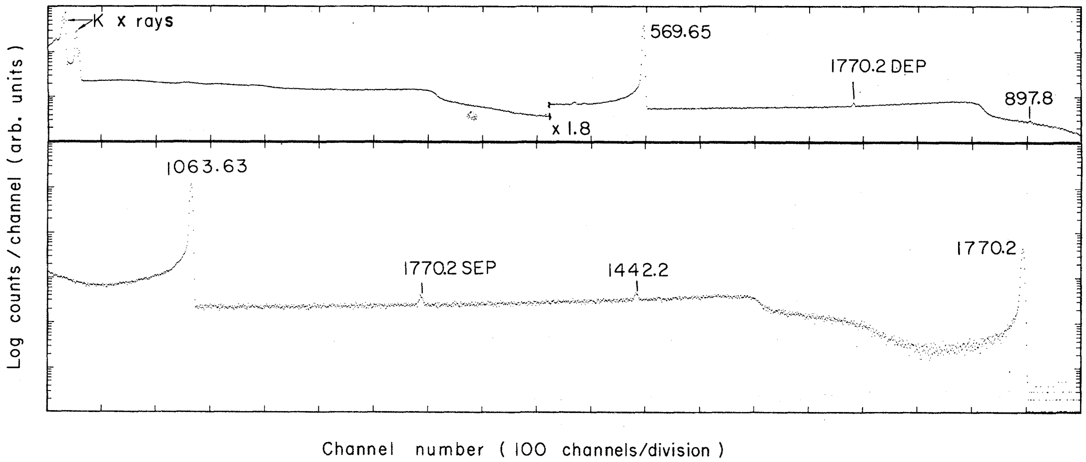

FIG. 2. γ-ray spectrum of a pure ^{207}Bi source.

based on the observed intensity of the 1063.63-keV transition, which occurs only in the decay of ^{207}Bi.

Figure 2 shows a γ-ray spectrum of a pure ^{207}Bi source; the measured energies and relative γ-ray intensities from the electron-capture decay of ^{207}Bi are given in Table II.

Figure 3 shows a typical conversion-electron spectrum obtained with a ^{211}At source. Tailing of the peaks due to the intense α particles of ^{211}At and ^{211}Po are the cause of the high flat background observed. Column 4 of Table I contains the measured relative K-conversion electron intensities; column 5 contains the experimental K-conversion coefficients. In order to obtain these conversion coefficients, the electron and γ spectra were normalized by the theoretical[15] K-conversion coefficient of the 569.65-keV $E2$ transition in ^{207}Pb. On the basis of the conversion coefficients, $M1$ multipolarities are assigned to the 897.8- and 687.0-keV transitions. The separation between K and L lines of the 687.0-keV transition is consistent only with the binding energies in polonium, which supports the assignment of this γ ray to the electron-capture decay of ^{211}At.

Finally, we show in Fig. 4 an α-particle spectrum taken with a source containing ^{210}At as well as ^{211}At. The measured relative α intensities of ^{211}At and ^{211}Po are shown in column 4 of Table III. (These intensities are for a source of ^{211}At with ^{211}Po in equilibrium and are based on a common relative scale normalized to the ^{211}At ground-state group.) Energies of the α particles given in Table III were taken from the high-resolution work of Ref. 16. α groups from ^{211}At populating excited states of ^{207}Bi are known[16] to be approximately four orders of magnitude weaker than those populating the ground state so that the branching ratio of α decay to electron capture for ^{211}At can be determined from the measured ratio of the ground-state ^{211}At group to the sum of the three ^{211}Po α groups. This ratio was found to be 0.7223 ± 0.0144 which implies an α branching for ^{211}At of $41.94 \pm 0.50\%$ α, in good agreement with the value $41.8 \pm 0.2\%$ α (Ref. 16). Column six of Table III gives the intensities of the ^{211}Po α groups renormalized to α particles per 100 decays of ^{211}Po.

TABLE II. γ rays observed in decay of ^{207}Bi.

Transition energy (keV)	Relative photon [a] intensity
(328.2)	... [b]
569.65 ± 0.10	100
897.8 ± 0.1	0.14 ± 0.02
1063.63 ± 0.10	75.5 ± 2.3
1442.2 ± 0.2	0.15 ± 0.02
1770.27 ± 0.10	6.95 ± 0.20

[a] A renormalization to absolute intensities can be made since the 569.65-keV transition has an absolute intensity of 97.7 photons per 100 decays of ^{207}Bi (see text).

[b] This extremely weak transition was only observed in the alpha decay of ^{211}Po. It has a calculated relative photon intensity of ≈ 0.00087 (relative to 100 for the 569.65-keV transition) based on the branching ratio of the 897.8- and 328.2-keV γ rays given in Table I.

IV. DECAY CHAIN OF ^{211}At

The decay chain (or scheme) of ^{211}At shown in Fig. 5 was constructed from energy sums, intensity balances and previous results[5,7,16-20]; it can

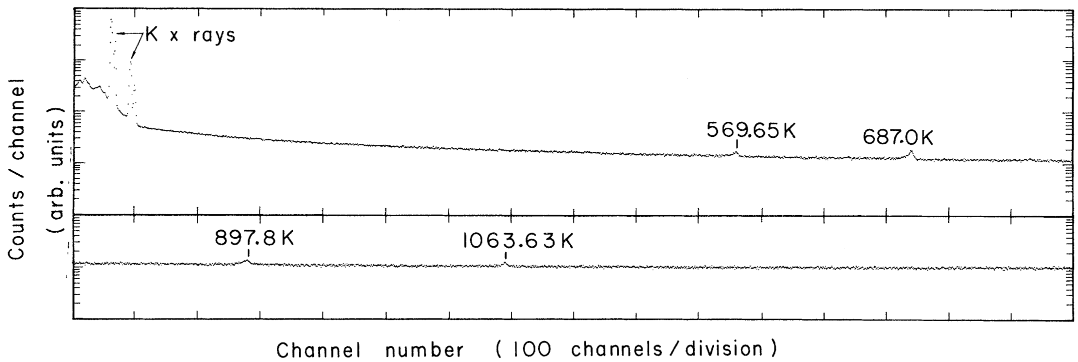

FIG. 3. Internal-conversion electron spectrum of a ^{211}At source with ^{211}Po in equilibrium. The 1063.63 K line of the $M4$ transition from ^{207}Bi, that has grown in, also appears.

be divided into two different parts with half-lives[1,3] of 7.2 h and 38 yr. The 7.2 h half-life includes the electron-capture and α-decay branches of ^{211}At as well as the subsequent α decay of the short-lived ^{211}Po to ^{207}Pb. The electron-capture decay of the 38 yr ^{207}Bi to ^{207}Pb, shown separately in the lower-right portion of Fig. 5, is in agreement with previous studies.[17]

Placements of the six transitions reported in Table I in various isotopes of the 7.2 h decay chain are shown in Fig. 5. Based on the measured α-group intensities for ^{211}Po, the absolute intensity of the 569.65-keV γ ray is calculated to be 0.534 ± 0.019 photons per 100 decays of ^{211}Po (or 0.31 ± 0.02 photons per 100 decays of ^{211}At). The absolute intensities of the other γ rays, and thus of the electron-capture and α transitions in the decay of ^{211}At, follow from this normalization.

The intensity of the electron-capture transition to the 687.0-keV state in ^{211}Po is $0.26 \pm 0.02\%$. Based on the Q value[21] 793 ± 8 keV, $\log ft$ values for decay to the ground and 687-keV states are calculated to be 6.0 and 5.9, respectively.

The 669.6- and 742.7-keV transitions in ^{207}Bi are known[18,19] from studies of the electron-capture decay of ^{207}Po to be $M1$ transitions. The intensities of the two weak α groups of ^{211}At, calculated from the intensities of these transitions, are given in column 4 of Table III. These values are only marginally consistent with the direct measurements[16] of the α-group intensities.

The absolute intensities of electron-capture transitions in the decay of ^{207}Bi (Fig. 5) are in generally good agreement with values compiled by Schmorak and Auble[17] from numerous studies of this decay scheme. The calculated absolute intensity of the 569.65-keV γ ray is 97.7 photons per 100 decays of ^{207}Bi. A Q value[21] of 2.405 ± 8 MeV was used to calculate the $\log ft$ values shown in Fig. 5.

V. DISCUSSION

The ground-state spin of $^{211}_{85}$At^{126} has been measured[22] as $\frac{9}{2}$. Shell-model ground-state configurations of ^{211}At and ^{211}Po are $(\pi(h_{9/2})^3\nu(g_{9/2})^0)_{9/2^-}$ and $(\pi(h_{9/2})^2\nu(g_{9/2})^1)_{9/2^+}$, respectively. A $\frac{9}{2}^+$ as-

TABLE III. α particle energies and intensities for a source of ^{211}At with ^{211}Po in equilibrium.

Parent Nuclide	E_α [a] (keV)	Daughter level energy (keV)	α intensity per 100 decays of ^{211}At: This work [b]	per 100 decays of ^{211}At: Ref. 16	per 100 decays of ^{211}Po: This work	per 100 decays of ^{211}Po: Ref. 16
^{211}At	5866 ± 2	0	41.93	41.93		
	5210.0 ± 1.5	669.6	0.0036 ± 0.0008 [c]	0.0054 ± 0.0009		
	5141 ± 2	742.7	0.00097 ± 0.00033 [c]	0.0017 ± 0.0009		
^{211}Po	7450 ± 3	0	57.4 ± 1.1		98.917	98.917
	6892.5 ± 2.5	569.65	0.317 ± 0.010		0.546 ± 0.019	0.56 ± 0.05
	6570.0 ± 2.5	897.8	0.312 ± 0.010		0.537 ± 0.019	0.58 ± 0.05

[a] Energies measured by Ref. 16.
[b] These intensities were arbitrarily normalized to the ^{211}At ground state group.
[c] Not measured directly, but calculated from relative γ-ray intensities as described in text.

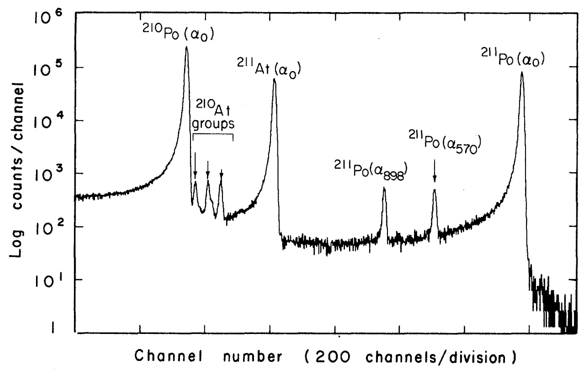

FIG. 4. α-particle spectrum of a source containing ^{211}At and ^{210}At. The ^{211}Po is in equilibrium with the ^{211}At.

signment for the ^{211}Po ground state also derives from a study[20] of the ^{210}Po$(d, p)^{211}$Po reaction where only two states below 1 MeV were populated, both intensely. These were the ground state and a state at 685 ± 5 keV with measured[20] (tentative) l transfers of four and six, respectively. The state at 685 keV is believed to correspond to the 687.0-keV state populated in the electron-capture decay of ^{211}At and can be assigned the shell-model configuration $(\pi(h_{9/2})^2\nu(i_{11/2})^1)_{11/2^+}$ from these data and by analogy with the ^{208}Pb(d, p)-^{209}Pb reaction.[23] [^{209}Pb has a $\frac{9}{2}^+$ ground state and a $\frac{11}{2}^+$ first-excited state at 778 keV which are due to the neutron single-particle orbitals $2g_{9/2}$ and $1i_{11/2}$ (Ref. 23).] Electron-capture decay of ^{211}At to these two states of ^{211}Po can take place by the

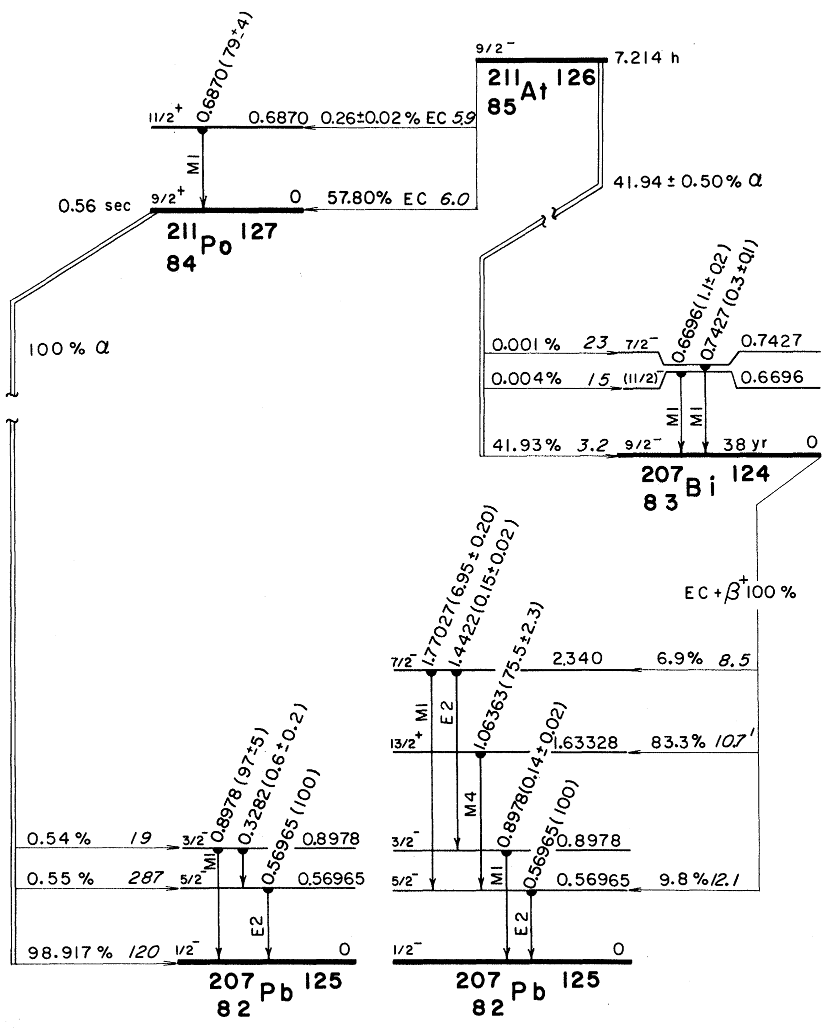

FIG. 5. Decay chain of ^{211}At. Photon intensities from the electron-capture decay of ^{211}At and the α decays of ^{211}At and ^{211}Po are shown on the same relative scale, whereas those shown for the ^{207}Bi electron-capture decay are on a different scale. Calculated (Ref. 25) logft values and α-hindrance factors are shown in italics next to the absolute feedings.

first-forbidden single-particle transitions $\pi(1h_{9/2}) \overset{EC}{\rightarrow} \nu(2g_{9/2})$ and $\pi(1h_{9/2}) \overset{EC}{\rightarrow} \nu(1i_{11/2})$. The $\log ft$ values of 6.0 and 5.9 ± 0.1, in addition to the $M1$ multipolarity assignment for the 687.0-keV transition, are consistent with these assignments. This value of the $\log ft$ is also comparable to that observed[9, 24] for the same transition $(\pi(1h_{9/2}) \rightarrow \nu(2g_{9/2}))$ seen in the electron-capture decays of ^{210}At and ^{209}At. It is also of interest to note that for these pure shell-model configurations the 687.0-keV $M1$ transition is another of the l-forbidden $(1i_{11/2} \rightarrow 2g_{9/2})$ type recently summarized for the lead region by Häusser *et al.*[8]

The Q value[21] for the electron-capture decay of ^{211}At is 793 ± 8 keV. The energy of the capture transition to the 687.0-keV state of ^{211}Po is only 106 ± 8 keV, which implies a value of $8.5^{+40.3}_{-4.7}$ for the ratio of L to K capture.[25] This low K-capture probability explains the fact that the 687-keV γ ray was not observed[5] in coincidence with polonium K x rays. (If K capture is energetically allowed, as the present Q value indicates, this sensitivity of the theoretical L/K electron-capture ratio might be used to determine the ^{211}At electron-capture Q value more accurately through x-ray/γ-ray coincidence measurements. Such measurements would also determine a more accurate value for the ^{207}Bi electron-capture Q value.)

The three states of ^{207}Pb populated by the α decay of ^{211}Po have been assigned[17] the single-neutron hole configurations $3p_{1/2}$, $2f_{5/2}$, and $3p_{3/2}$. The lower hindrance factor for α decay to the $\nu(3p_{3/2})^{-1}$ state is due to the fact that the spin of the odd particle does not change directions (no "spin-flip"), which results in a larger contribution from partial waves of minimum allowed orbital angular momentum. This α-decay selection rule has been reviewed in more detail by Rasmussen.[26]

The predominant γ-ray decay of the 897.8-keV state in ^{207}Pb is to the ground state by the $M1$ single-particle transition $\nu(3p_{3/2})^{-1} \rightarrow \nu(3p_{1/2})^{-1}$. A less intense 328.2-keV γ ray was recently observed to compete with the 897.8-keV transition in a Coulomb-excitation experiment.[7] This weaker transition involves the l-forbidden $M1$ single-particle transition $\nu(3p_{3/2})^{-1} \rightarrow \nu(2f_{5/2})^{-1}$. We have also observed this transition in our γ spectra from the α decay of ^{211}Po. Our γ-ray branching ratio is less accurate, but consistent with the Coulomb excitation value. Häusser *et al.*[7] have given a detailed discussion of the significance of the disagreement of present theoretical calculations with the experimental $B(M1, 3p_{3/2} \rightarrow 2f_{5/2})$ calculated from this branching ratio.

The electron-capture decay of ^{207}Bi has been the subject of numerous studies and discussions, as summarized in Ref. 17.

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