^{211}At - Comments on evaluation of decay data

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Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate.

Decay Scheme

A reasonably simple decay scheme was constructed from the α-particle and γ-ray measurements of Hoff (1953Ho49), Gray (1956Gr11), Golovkov *et al.* (1969Go23), Jardine (1975Ja04), and Chumin *et al.* (2001Ch66), and studies of the α branching fraction by Neumann and Perlman (1951Ne02), Golovkov *et al.* (1969Go23), Afanasiev *et al.* (1970AfZZ), Jardine (1975Ja04), Yanokura *et al.* (1978Ya04), and Lambrecht and Mirzadeh (1985La17).

Nuclear Data

^{211}At is an important α-emitting radionuclide in therapeutic nuclear medicine, along with daughter ^{211}Po.

Half-life

The recommended half-life of 7.216 (7) hours has been adopted from five sets of measurements (1956Gr11, 1959Ra08, 1961Ap01, 1962Th08, 1978Ya04).

Half-life measurements

Reference	Half-life (hours)
1956Gr11	7.20 ± 0.05
1959Ra08	7.23 ± 0.04
1961Ap01	7.214 ± 0.007
1962Th08	7.17 ± 0.09
1978Ya04	7.23 ± 0.02
Recommended value	7.216 ± 0.007

A half-life of 0.516 (3) second was adopted for ^{211}Po from the DDEP evaluation of Luca (July-November 2009), while the ^{207}Bi half-life of 32.9 (14) years was taken from the DDEP evaluation of Bé and Chisté (December 2009). More recently, a further re-evaluation of the half-life of ^{207}Bi by Kondev and Lalkovski resulted in a recommended value of 31.55 (4) years (2011Ko04).

Branching fractions

Neumann and Perlman (1951Ne02), Golovkov *et al.* (1969Go23), Afanasiev *et al.* (1970AfZZ), Jardine (1975Ja04), Yanokura *et al.* (1978Ya04), and Lambrecht and Mirzadeh (1985La17) have determined the α branching fraction for ^{211}At. These data were used to derive an alpha branch of 41.78 (8) %, along with a matching electron-capture branch of 58.22 (8) %.

Reference	BF_α
1951Ne02	0.409 ± 0.005
1969Go23	0.418 ± 0.002
1970AfZZ	0.413 ± 0.013
1975Ja04	0.419 ± 0.005
1978Ya04	0.4174 ± 0.0010
1985La17	0.4194 ± 0.0016
Recommended value	0.4178 ± 0.0008
α branch	(41.78 ± 0.08) %

Q values

Q_{EC} of 785.4 (25) keV and Q_α of 5982.4 (13) keV were adopted from the evaluated tabulations of Audi *et al.* (2003Au03).

Alpha Particles

Alpha-particle measurements reveal a relatively simple α-decay mode (1969Go23, 1975Ja04, 1991Ry01, 2001Ch66). The Q_α of 5982.4 (13) keV (2003Au03) and nuclear level energies as defined by Kondev and Lalkovski (2011Ko04) were used to calculated the alpha-particle energies, while the alpha-particle emission probabilities were primarily adopted from the measurements of Golovkov *et al.* (1969Go23), Afanasiev *et al.* (1970AfZZ), Jardine (1975Ja04) and Chumin *et al.* (2001Ch66).

Alpha-particle emission probabilities per 100 disintegrations of ^{211}At, and hindrance factors.

E_α(keV)	P_α					HF
	1969Go23*	1970AfZZ†	1975Ja04#	2001Ch66#	Recommended value	
4895.4 (13)	–	–	–	< 0.000 04	< 0.000 04	> 9.6
4993.4 (13)	–	~ 0.000 4 ?	–	–	~ 0.000 4	~ 3.8
5140.3 (13)	0.001 7 (9)	0.001 5	0.001 0 (3)	0.001 1 (2)	0.001 1 (2)	10.1
5211.9 (13)	0.005 4 (8)	0.006 7	0.003 6 (8)	0.003 9 (3)	0.003 9 (3)	7.3
5869.0 (13)	41.8 (2)	[41.78]	41.93	41.80	41.78 (8)	1.59

* Calculated from measurements of the relative alpha-particle emission probabilities.

† Calculated from measurements of the relative alpha-particle emission probabilities, but no uncertainties listed; absolute emission probability of 41.78 % was adopted for the 5869.0-keV α particle to convert other data in this study to comparable absolute values.

\# Calculated from measurements of the relative gamma-ray emission probabilities.

An unweighted mean value of 1.422 (13) was adopted for the radius parameter $r_0(^{207}Bi)$ as derived from the equivalent data for neighboring nuclei (1998Ak04), and used in the calculation of α-hindrance factors (HF):

$$r_0(^{207}Bi) = [r_0(^{206}Pb) + r_0(^{208}Po)] / 2$$

$$= [1.40882(10) + 1.4343(34)] / 2$$

$$= 1.422\ (13)$$

Gamma Rays

Energies

All gamma-ray transition energies and uncertainties were calculated from the structural details of the proposed decay scheme. Nuclear level energies were adopted from Browne for ^{211}Po and from Kondev and Lalkovski for ^{207}Bi (2004Br45, 2011Ko04).

Emission Probabilities

The absolute emission probabilities of the 149.72-, 222.69-, 669.77-, 742.74- and 892.46-keV gamma rays from the α-decay branch were derived from a combination of the alpha-particle emission probabilities populating the ground state and 669.77-, 742.74-, 892.46- and 992.43-keV nuclear levels of ^{207}Bi (1969Go23, 1970AfZZ), relevant relative emission probabilities for these gamma rays (1975Ja04, 1985La17), theoretical internal conversion coefficients of Band *et al.* (2002Ba85, 2008Ki07), and depopulating ratios of the 149.72-, 222.69- and 892.46-keV gamma transitions as quantified by Kondev and Lalkovski (2011Ko04). A weighted mean value of 0.245 (12) was adopted for the absolute emission probability of the 687.7-keV gamma ray from the EC-decay branch, based on the gamma-ray spectroscopy studies of Jardine (1975Ja04) and Lambrecht and Mirzadeh (1985La17).

Gamma-ray emission probabilities relative to 100 % for the 569.7-keV gamma ray of daughter ^{211}Po.

E_γ (keV)	P_γ^{rel}		
	1975Ja04	**1985La17**	**Recommended value**
[569.70]	100	100.0 (14)	–
669.77 (7)	1.1 (2)	–	–
687.2 (7)	79 (4)	83.0 (20)	82 (2)
742.74 (7)	0.3 (1)	–	–

Absolute gamma-ray emission probabilities per 100 disintegrations of ^{211}At.

	E_γ (keV)	P_γ^{abs}		
		1975Ja04*	**1985La17**	**Recommended value**
$\gamma_{3,2}$ (Bi)	149.72 (10)	–	–	~ 0.000 05
$\gamma_{3,1}$ (Bi)	222.69 (10)	–	–	~ 0.000 04
$\gamma_{1,0}$ (Bi)	669.77 (7)	0.003 4 (6)	–	0.003 8 (3)
$\gamma_{1,0}$ (Po)	687.2 (7)	0.245 (12)	0.247 (26)	0.245 (12)
$\gamma_{2,0}$ (Bi)	742.74 (7)	0.000 9 (3)	–	0.001 25 (19)
$\gamma_{3,0}$ (Bi)	892.46 (7)	–	–	~ 0.000 14

* Derived from an absolute emission probability of 0.31 (2) per 100 decay of ^{211}At for the 569.70-keV gamma transition within the α decay of daughter ^{211}Po.

Multipolarities and Internal Conversion Coefficients

The nuclear level schemes specified by Browne for ^{211}Po and Kondev and Lalkovski for ^{207}Bi have been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2004Br45, 2011Ko04). All known gammas are (M1 + E2) transitions, and their mixing ratios have been derived on the basis of the studies of Astner and Alpsten (1970As07), Schmidt-Ott and Dincklage (1978Sc12), and Herzog *et al.* (1983He09). Recommended internal conversion coefficients have been determined from the frozen orbital approximation of Kibédi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45).

Gamma-ray emissions: recommended energies, emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

	E_γ (keV)	P_γ^{abs}	Multipolarity	α_K	α_L	α_{M+}	α_{tot}	
$\gamma_{3,2}$ (Bi)	149.72 (10)	~ 0.000 05	86.2 % M1 + 13.8 % E2 δ = 0.40 (20)	2.3 (3)	0.50 (4)	0.2	3.0 (3)	α
$\gamma_{3,1}$ (Bi)	222.69 (10)	~ 0.000 04	86.2 % M1 + 13.8 % E2 δ = 0.40 (10)	0.76 (5)	0.147 (2)	0.043	0.95 (5)	α
$\gamma_{1,0}$ (Bi)	669.77 (7)	0.003 8 (3)	94.1 % M1 + 5.9 % E2 δ = 0.25 (3)	0.042 6 (8)	0.007 25 (12)	0.002 15	0.052 0 (9)	α
$\gamma_{1,0}$ (Po)	687.2 (7)	0.245 (12)	96.15 % M1 + 3.85 % E2 δ = -0.20 (2)	0.043 7 (7)	0.007 52 (12)	0.002 38	0.053 6 (9)	E C
$\gamma_{2,0}$ (Bi)	742.74 (7)	0.001 25 (19)	91.7 % M1 + 8.3 % E2 δ = 0.30 (3)	0.032 0 (6)	0.005 44 (10)	0.001 66	0.039 1 (7)	α
$\gamma_{3,0}$ (Bi)	892.46 (7)	~ 0.000 14	33.8 % M1 + 66.2 % E2 δ = 1.4 (2)	0.011 7 (11)	0.002 15 (16)	0.000 65	0.014 5 (13)	α

Electron-capture Transitions

Energies

Electron-capture energies were calculated from the nuclear level energies of Browne (2004Br45) and a Q_{EC} value of 785.4 ± 2.5 keV taken from Audi *et al.* (2003Au03).

Transition probabilities

The EC transition probabilities were calculated from BF_{EC} of 0.5822 (8) and the absolute emission probability and theoretical internal conversion coefficients of the 687.2-keV gamma ray.

EC transition probabilities per 100 disintegrations of ^{211}At.

	E_{EC} (keV)	P_{EC}	Transition type	log *ft*	P_K	P_L	P_M
$EC_{0,1}$	98.2 ± 2.6	0.258 ± 0.013	1st forbidden non-unique	5.77	0.015 (17)	0.684 (10)	0.301 (7)
$EC_{0,0}$	785.4 ± 2.5	57.96 ± 0.08	1st forbidden non-unique	5.97	0.773 1 (2)	0.169 3 (1)	0.057 58 (4)

Atomic Data

The x-ray and Auger-electron data have been calculated using the evaluated gamma-ray data, and atomic data from 1996Sc06, 1998ScZM and 1999ScZX. Both the x-ray and Auger-electron emission probabilities were determined by means of the EMISSION computer program (version 4.01, 28 January 2003). This program incorporates atomic data from 1996Sc06 and the evaluated gamma-ray data.

K and L X-ray emission probabilities per 100 disintegrations of ^{211}At.

			Energy (keV)	Photons per 100 disint.
XL		(Bi)	9.420 – 15.709	0.000 136 (14)
	XL_l	(Bi)	9.420	0.000 003 3 (4)
	XL_α	(Bi)	10.731 – 10.839	0.000 063 (7)
	XL_η	(Bi)	11.712	0.000 001 03 (15)
	XL_β	(Bi)	12.480 – 13.393	0.000 057 (6)
	XL_γ	(Bi)	15.248 – 15.709	0.000 011 0 (12)
XK_α	$XK_{\alpha 2}$	(Bi)	74.8157 (9)	0.000 098 (15)
	$XK_{\alpha 1}$	(Bi)	77.1088 (10)	0.000 164 (25)
$XK'_{\beta 1}$	$XK_{\beta 3}$	(Bi)	86.835	)
	$XK_{\beta 1}$	(Bi)	87.344	) 0.000 056 (9)
	$XK_{\beta 5}''$	(Bi)	87.862	)
$XK'_{\beta 2}$	$XK_{\beta 2}$	(Bi)	89.732	)
	$XK_{\beta 4}$	(Bi)	90.074	) 0.000 017 (3)
	$XKO_{2,3}$	(Bi)	90.421	)
XL		(Po)	9.658 – 16.213	18.6 (8)
	XL_l	(Po)	9.658	0.465 (12)
	XL_α	(Po)	11.016 – 11.130	8.53 (20)
	XL_η	(Po)	12.085	0.134 (4)
	XL_β	(Po)	12.823 – 13.778	7.76 (14)
	XL_γ	(Po)	15.742 – 16.213	1.53 (3)
XK_α	$XK_{\alpha 2}$	(Po)	76.864 (4)	12.66 (9)
	$XK_{\alpha 1}$	(Po)	79.293 (5)	21.08 (12)
$XK'_{\beta 1}$	$XK_{\beta 3}$	(Po)	89.256	)
	$XK_{\beta 1}$	(Po)	89.807	) 7.26 (12)
	$XK_{\beta 5}''$	(Po)	90.363	)
$XK'_{\beta 2}$	$XK_{\beta 2}$	(Po)	92.263	)
	$XK_{\beta 4}$	(Po)	92.618	) 2.26 (5)
	$XKO_{2,3}$	(Po)	92.983	)

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

Data Consistency

An effective Q-value of 2956.7 (16) keV has been adopted from the atomic mass evaluation of Audi *et al*. (2003Au03) while in the course of formulating the decay scheme of ^{211}At. This value has subsequently been compared with the Q-value calculated by summing the

contributions of the individual emissions to the ^{211}At alpha- and EC-decay processes (i.e. α, γ, conversion electrons, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 2957\ (5)\ \text{keV}$$

Percentage deviation from the effective Q-value of Audi *et al*. is – (0.01 ± 0.17) %, which supports the derivation of a highly consistent decay scheme.

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