^{212}Pb – Comments on evaluation of decay data

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Evaluation Procedures

Limitation of Relative Statistical Weight Method (LWM) was applied to average numbers throughout the evaluation. The uncertainty assigned to the average value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

Decay Scheme

A reasonably simple and consistent decay scheme has been constructed from the gamma-ray measurements of 1960Ro16, 1961Gi02, 1972DaZA (1973Da38), 1978Av01, 1982Sa36, 1983Sc13, 1983Va22, 1984Ge07 and 1992Li05. Only five distinct gamma-ray emissions were identified with ^{212}Pb decay in all of these studies. A further gamma ray has been added in the evolution of the decay scheme (energy of 123.449 keV) to achieve the necessary population-depopulation balance of the 115.183-keV nuclear level of ^{212}Bi.

Low-energy gamma transitions have been postulated to exist in the decay scheme of ^{212}Pb (with energies between 40 and 60 keV). However, this possibility was rejected on the basis of insufficient experimental evidence in the open literature. Further studies are required to resolve this issue, and confirm the correctness of the proposed decay scheme.

Nuclear Data

^{228}Th decay chain is important in quantifying the environmental impact of the decay of naturally-occurring ^{232}Th. Specific radionuclides in this decay chain are noteworthy because of their decay characteristics (^{224}Ra alpha decay to ^{220}Rn; ^{212}Bi and ^{208}Tl gamma-ray emissions).

Half-life

The recommended half-life is the weighted mean of three elderly measurements (1952Bu72, 1953Ma26 and 1955To11). Further studies are merited to determine this value with greater confidence.

Reference	Half-life (h)
1952Bu72	10.67 (5)
1953Ma26	10.64 (3)
1955To11	10.643 (12)
Recommended value	10.64 (1)

Beta Particles

Energies

All beta-particle energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of 2005Br03 and Q-value of 569.9 keV (2003Au03) were used to determine the energies and uncertainties of the beta-particle transitions to the various levels.

Emission Probabilities

The beta-particle emission probabilities were calculated from gamma-ray energy balances, using the recommended internal conversion coefficients determined from the frozen orbital approximation of Kibédi *et al.* (2008Ki07) based on the theoretical model of Band *et al.* (2002Ba85, 2002Ra45):

415.272 keV nuclear level:

[$\Sigma P_{\gamma i} (1 + \alpha_i)$ depopulating 415.272-keV level]·NF was calculated to be 11.44 (45)·NF; since NF = 0.004 36 (3), populating beta-particle emission probability is calculated to be 4.99 (21) % (0.0499 (21));

238.632 keV nuclear level:

{[$\Sigma P_{\gamma i} (1 + \alpha_i)$ depopulating 238.63-keV level] - P_γ(176.640 keV)(1 + α(176.640 keV))}·NF was calculated to be 187.3 (23)·NF; since NF = 0.004 36 (3), populating beta-particle emission probability is calculated to be 81.7 (11) % (0.817 (11));

115.183 keV nuclear level:

spin and parity considerations support no direct beta decay to this level;

population and depopulation by gamma transitions requires balance of the form

$\Sigma P_{\gamma i} (1 + \alpha_i)$ populating 115.183-keV level should equal P_γ(115.183 keV)(1 + α(115.183 keV)); hence TP_γ(123.449 keV) = 0.46 (4)·NF, and P_γ(123.449 keV) = 0.12 (1)·NF;

ground state (0.0 keV):

(i) through population of ground state: [$\Sigma P_{\gamma i} (1 + \alpha_i)$ populating ground state]·NF + $P_{\beta_{0,0}}$ = 100 and NF = 0.004 36 (3) to give $P_{\beta_{0,0}}$ = 13.3 (11) % (0.133 (11))

(ii) through summation of beta decay and NF = 0.004 36 (3)

$$P_{\beta_{0,0}} = 13.3\ (11)\ \%\ (0.133\ (11)).$$

Beta-particle emission probabilities per 100 disintegrations of ^{212}Pb, transition type and log *ft*.

E_β(keV)	P_β		transition type	log *ft*
	1948Ma30	Recommended value*		
154.6 (19)	-	4.99 (21)	(1st forbidden non-unique)	5.35
331.3 (19)	-	81.7 (11)	(1st forbidden non-unique)	5.18
569.9 (19)	12 (2)	13.3 (11)	(1st forbidden non-unique)	6.74

* Recommended emission probabilities derived from evaluated gamma-ray emission probabilities and theoretical internal conversion coefficients.

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of 2005Br03 were adopted, and used to determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels.

Emission Probabilities

Weighted mean relative emission probabilities were determined for the 115.183-, 176.640-, 238.632- and 300.089-keV gamma rays, using the relevant data from the measurements of 1960Ro16, 1961Gi02, 1972DaZA (1973Da38), 1978Av01, 1982Sa36, 1983Sc13, 1983Va22, 1984Ge07 and 1992Li05. The relative emission probability of the 415.272-keV gamma ray was adopted from the studies of 1961Gi02, while a further gamma ray has been added in the evolution of the decay scheme (energy of 123.449 keV) to achieve the necessary population-depopulation balance of the 115.183-keV nuclear level of ^{212}Bi.

Gamma-ray emission probabilities: relative to P_γ(238.632 keV) of 100.

E_γ (keV)	P_γ^{rel}				
	1960Ro16	1961Gi02	1972DaZA	1978Av01	1982Sa36
115.183 (5)	[observed]	1.4 (3)	1.3 (3)	1.4 (1)	1.65 (12)
123.449 (5)	-	-	-	-	-
176.640 (11)	~ 0.5	0.50 (10)	0.10 (3)	-	-
238.632 (2)	100	100	100	100 (3)	100 (5)
300.089 (12)	7.7 4)	6.9 (4)	7.7 (15)	6.3 (2)	6.7 (5)
415.272 (11)	~ 0.3	0.33 (5)	-	-	-

E_γ (keV)	P_γ^{rel} (cont.)				
	1983Sc13	1983Va22	1984Ge07	1992Li05	Recommended value*
115.183 (5)	-	-	1.37 (2)	-	1.43 (5)
123.449 (5)	-	-	-	-	0.12 (1)‡
176.640 (11)	-	-	0.12 (1)	-	0.12 (1)
238.632 (2)	100 (3)	100 (1)	100 (1)	100 (2)	100 (1)
300.089 (12)	7.5 (2)	7.3 (1)	7.6 (1)	7.6 (3)	7.3 (3)
415.272 (11)	-	-	-	-	0.33 (5)

* Weighted mean values adopted when appropriate using LWEIGHT.

‡ Derived from proposed decay scheme – balance of gamma transitions that populate-depopulate 115.183-keV nuclear level.

A weighted mean normalisation factor of 0.004 36 (3) was calculated for the emission probabilities from the measurements of 1982Sa36, 1983Sc13, 1983Va22, 1984Ge07 and 1992Li05.

Absolute gamma-ray emission probabilities: normalisation factor.

E_γ (keV)	P_γ^{abs}					
	1982Sa36	1983Sc13	1983Va22	1984Ge07	1992Li05	Recommended value*
238.632 (2)	0.430 (20)	0.435 (12)	0.440 (6)	0.433 (4)	0.441 (10)	0.436 (3)

* Weighted mean value adopted from LWEIGHT.

<u>Multipolarities and Internal Conversion Coefficients</u>

The nuclear level scheme specified by 2005Br03 has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities. Limited studies of the internal conversion coefficients support the proposed transition types: 100 % M1 for the 115.183-, 238.632- and 300.089-keV gamma rays (1957Ni11, 1957Kr49, 1959Se59, 1960Ro16, 1963Da11, 1969Kr06 and 1978Av01); the 176.640- and 415.272-keV gamma rays were also assigned 100 % M1 multipolarity, while the 123.45-keV gamma transition was defined as E2. 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).

Multipolarity assignments.

Reference	E_γ (keV)	Multipolarity
1957Ni11	115.183 (5)	M1 [K/L = 5 (1)]
1957Kr49	115.183 (5)	M1
	176.640 (11)	E0 [K/L = 1 : 0.18 (2)]
	238.632 (2)	M1
	300.089 (12)	M1
1959Se59	115.183 (5)	M1
		[L_I:L_{II}:L_{III} → 100 : 10.4 (3) : 0.88 (10)]
	238.632 (2)	M1
		[L_I:L_{II}:L_{III} → 100 : 10.4 (2) : 0.74 (5)]
1960Ro16	115.183 (5)	M1 [α_K = 5.8 (9)]
	238.632 (2)	M1 [α_K = 0.74 (7)]
1963Da11	238.632 (2)	M1
	415.272 (11)	M1 [α_K ~ 0.35]
1969Kr06	238.632 (2)	M1
1978Av01	115.183 (5)	E2
	238.632 (2)	M1 (+ E2)
	300.089 (12)	M1 + E2

Gamma-ray emissions: multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_γ (keV)	Multipolarity	α_K	α_L	α_{M+}	α_{total}
115.183 (5)	(M1)	5.53 (8)	0.972 (14)	0.298 (5)	6.80 (10)
123.449 (5)	(E2)	0.421 (6)	1.766 (25)	0.613 (9)	2.80 (4)
176.640 (11)	(M1)	1.646 (23)	0.287 (4)	0.087 (1)	2.02 (3)
238.632 (2)	(M1)	0.710 (10)	0.1232 (18)	0.0388 (5)	0.872 (13)
300.089 (12)	(M1)	0.378 (6)	0.0653 (10)	0.0207 (3)	0.464 (7)
415.272 (11)	(M1)	0.1571 (22)	0.0269 (4)	0.0080 (1)	0.192 (3)

Atomic Data

The x-ray data have been calculated using the evaluated gamma-ray data, and the 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 ^{212}Pb.

			Energy (keV)	Photons per 100 disint.
XL		(Bi)	9.420 – 15.709	13.8 (6)
	XL_l	(Bi)	9.420	0.340 (9)
	XL_α	(Bi)	10.731 – 10.839	6.36 (16)
	XL_η	(Bi)	11.712	0.103 (3)
	XL_β	(Bi)	12.480 – 13.393	5.76 (12)
	XL_γ	(Bi)	15.248 – 15.709	1.111 (23)
XK_α	$XK_{\alpha2}$	(Bi)	74.8157	10.07 (18)
	$XK_{\alpha1}$	(Bi)	77.1088	16.8 (3)

$XK'_{\beta1}$	$XK_{\beta3}$	(Bi)	86.835 }	
	$XK_{\beta1}$	(Bi)	87.344 }	5.77 (13)
	$XK''_{\beta5}$	(Bi)	87.862 }	
$XK'_{\beta2}$	$XK_{\beta2}$	(Bi)	89.732 }	
	$XK_{\beta4}$	(Bi)	90.074 }	1.77 (5)
	$XKO_{2,3}$	(Bi)	90.421 }	

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

A Q_β-value of 569.9 (19) keV has been adopted from the atomic mass evaluation of Audi *et al.* (2003Au03) while in the course of formulating the decay scheme of ^{212}Pb. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{212}Pb beta-decay process (i.e. β^-, conversion electrons, γ, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 569\ (7)\ \text{keV}$$

Percentage deviation from the Q-value of Audi *et al.* is (0.158 ± 0.013) %, which supports the derivation of a highly consistent decay scheme.

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