^{211}Pb - Comments on evaluation of Decay Data

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1. Decay Scheme

The nuclide ^{211}Pb (J^π=9/2$^+$) disintegrates 100 % by β^- emissions. The strongest β^--decay branch of 91.28 (12) % populates the J^π=9/2$^-$ ground state of the daughter nuclide ^{211}Bi. The level schemes of ^{211}Pb and ^{211}Bi, including J^π values, are based on the ENSDF evaluation of Browne (2004Br45).

2. Nuclear Data

Adopted Q(β^-) value of 1367 (6) keV is taken from the evaluation of Audi *et al.* (2003Au03).

The experimental data for the half-life of the ^{211}Pb ground state are very scarce. The value of 36.1 (2) min that is included in ENSDF (2004Br45) originates from the work of Sargent (1939Sa11) and Nurmia (1965Nu03). This value is adopted in the present evaluation, but new measurements are certainly required to confirm this value.

2.1. β^- Transitions

The values for the maximum β^--decay energies ($E_{\beta-,max,}$ presented in Table 1) were derived from Q(β^-) = 1367 (6) keV (2003Au03) and the level energies deduced in the present evaluation, as detailed in section 2.2. The β^--decay transition probabilities (P_β) were deduced from the decay scheme and the corresponding absolute γ–ray transition probabilities. Log *ft* values were calculated using the *LOGFT* program from the ENSDF evaluation package, based on the work of Gove and Martin (1971Go40).

2.2. Gamma Transitions and Electron Internal Conversion Coefficients

The γ–ray transition energy data are presented in Table 2. Statistical analysis using the *LWEIGHT* program has been performed, and the resulting gamma-ray energies are listed in column 13 of Table 2. With those energies, the level scheme was fitted using the *GTOL* program from the ENSDF analysis package, and new level energies were obtained (shown in Table 1). Then adopted gamma-ray energies were determined from the corresponding level energies.

The γ–ray transition multipolarities and mixing ratios were taken from the ENSDF evaluation of Browne (2004Br45). The electron conversion coefficients were calculated using the *BrIcc* code (2008Ki07).

Table 1. Level energies, quantum numbers, $E_{\beta0,t\ max}$, P_β and log *ft* values in the β^- decay of ^{211}Pb (J^π=9/2$^+$).

Level energy (keV)	J^π	$E_{\beta-\ max}$ (keV)	P_β (%)	Nature	log *ft*
1270.75 (6)	(7/2,9/2,11/2)-	96 (6)	0.0172 (15)	first forbidden non-unique	5.93
1234.3 (4)		133 (6)	0.0009 (3)	-	-
1196.33 (5)		171 (6)	0.019 (4)	-	-
1109.509 (23)	9/2-	257 (6)	1.06 (4)	first forbidden non-unique	5.58
1103.52 (20)		263 (6)	0.0047 (7)	-	-
1080.64 (4)		286 (6)	0.0570 (24)	-	-
1014.38 (4)	(7/2,9/2,11/2)-	-	-	-	-
831.984 (12)	9/2-	535 (6)	6.32 (9)	first forbidden non-unique	5.73

Level energy (keV)	**J$^{\pi}$**	**E$_{\beta- max}$ (keV)**	**P$_{\beta}$ (%)**	**Nature**	**log *ft***
766.680 (13)	(9/2,11/2)-	600 (6)	< 0.09	first forbidden non-unique	> 7.7
404.834 (9)	7/2-	962 (6)	1.57 (9)	first forbidden non-unique	7.21
0.0	9/2-	1367 (6)	91.28 (12)	first forbidden non-unique	5.99

The gamma-ray emission probability data are presented in Table 3. The reported values were determined relative to $I_\gamma(351.07_\gamma) = 100$ %, where the 351.07 keV transition depopulates the first $3/2^+$ level of the ^{207}Tl nuclide fed in the α decay of ^{211}Bi. The statistical analysis using the *LWEIGHT* program has been performed and *deduced* intensities were obtained (column 14 of Table 3). Using the absolute emission probability of $I_\gamma(351.07_\gamma) = 13.06$ (12) % (2011Ko04) and %α (^{211}Bi) = 99.724 (4) % (2004Br45), a normalization factor of 0.1302 (12) was obtained. This value was used to determine the *adopted* gamma-ray emission probabilities, which are shown in the last column of Table 3.

A number of weak transitions, summarized in Table 4, have been assigned to the β^- decay of ^{211}Pb by 1988Hi14 (five gamma rays), 1971Da34 (nine gamma rays), 1968Ha21 (three gamma rays) and 1968Br17 (one gamma ray). However, the experimental information presented in those articles is insufficient to assign these gamma rays unambiguously to the decay of ^{211}Pb, and hence they were not placed in the proposed decay scheme. None of the above publications reported the same unplaced gamma rays, which facilitated the conclusion made in this evaluation to exclude them from the proposed decay scheme. Further work, including gamma-ray coincidence studies, is merited to obtain a more complete decay scheme for ^{211}Pb.

3. Atomic Data

The atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electrons energies and relative probabilities) were provided by the SAISINUC software (2008DuZX). Details regarding the origin of these data can be found in 1996Sc06, 1998ScZM, 1999ScZX, 2000Sc47 and 2003De44.

4. Data Consistency

The adopted Q_β-value of 1367 (6) keV (2003Au03) has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{211}Pb beta-decay process (i.e. β^-, conversion electrons, γ, etc.):

$$Q_{\beta-}(\text{calc}) \quad = \quad \sum (E_i \times P_i) \quad = \quad 1368\ (6)\ \text{keV}$$

Percentage deviation from the Q-value of Audi *et al.* is 0.0731 (5) %, which supports the derivation of a highly consistent decay scheme.

Table 2. Measured, deduced and adopted gamma-ray energies in β^{-}–decay of ^{211}Pb.

1988Hi14	1976Bl13	1971Da34	1968Br17	1968Go15	1968Ha21	1967Da20	1967Da10	1965Co06	1965Me07	1963Va05	1962Gi03	deduced, keV	adopted, keV
	65.420 (14)		65.5 (2)	65.4 (2)		65.7 (10)	65.5 (5)		65.502 (8) g)			65.420 (14)	65.304 (18)
		95.0 (2)		95.0 (6)		94.5 (5)						95.0 (2)	95.13 (5)
313.64 (12)	313.58 (9)	313.8 (2)	313.6 (3)	313.6 (5)		313.5 (10)	313 (1)	290 (10)	310 (3)			313.59 (9)	313.96 (4)
342.02 (12)	342.90 (4)*	342.7 (2)		342.7 (3)			342.5 (10)		340 (3)			342.91 (4)	342.829 (26)
	362.062 (17)*		362.9 (5) ?									362.072 (17)	361.846 (16)
404.89 (12)	404.843 (10)	404.84 (4)	404.8 (1)	404.8 (1)	405	404.8 (5)	404.7 (3)	400 (7)	404.84 (4) g)	404	405 (5)	404.853 (10)	404.834 (9)
427.14 (12)	427.078 (10)	426.99 (4)	427.0 (1)	426.9 (1)	427	427.1 (5)	427.0 (3)	430 (7)	426.99 (4) g)	426	425 (5)	427.088 (10)	427.150 (15)
				429.1 (5)								429.1 (5)	429.65 (6)
504.12 (12)		503.3 (4)		503.6 (7)								504.12 (12)	504.07 (6)
	609.33 (4)*	609.5 (2)	609.1 (2)	609.3 (5)		610 (2)			612 (5) f)		615 (5)	609.38 (4)	609.55 (4)
	676.65 (7)*		676.6 (3)	675.2 (3)				650 (10)				676.69 (7)	675.81 (4)
704.66 (12)	704.59 (3)	704.5 (1)	704.5 (2)	704.3 (2)	702	703.3 (8)	703.8 (3)	706 (7)	702 (3)	700	700 (5)	704.64 (3)	704.675 (25)
766.45 (12)	766.47 (3)	766.34 (7)	766.3 (2)	766.4 (1)	766	766.2 (8)	766.2 (3)	758 (7)	766.34 (7) g)		755 (10)	766.51 (3)	766.680 (13)
832.02 (12)	831.96 (3)	831.83 (4)	831.8 (1)	831.8 (1)	832	831.8 (5)	831.7 (5)	830 (7)	831.83 (4) g)	830	830 (2)	832.01 (3)	831.984 (12)
865.87 (24)	865.88 (14)	865.6 (3)	865.5 (3)	865.2 (2)		866 (2)	864 (1)		860 (10)			865.93 (14)	865.92 (6)
1014.71 (12)	1014.59 (5)	1014.7 (2)	1014.4 (3)	1014.1 (5)		1014.8 (10)	1014 (1)		1020 (3)		1020 (10)	1014.64 (5)	1014.38 (4)
1080.10 (13)	1080.11 (6)	1080.2 (1)	1080.0 (3)	1080.0 (5)	1076	1080.9 (10)	1079 (1)	1060 (15)	1076 (3)			1080.16 (6)	1080.64 (4)
1103.52 (20)	1103.7 (8)	1103.4 (4)	1103.0 (6) ?									1103.52 (20)	1103.52 (20)
1109.48 (13)	1109.43 (5)	1109.5 (2)	1109.8 (3)	1109.1 (1)	1106	1109.6 (8)	1108.5 (10)	1100 (15)	1104 (2)	1104	1100 (5)	1109.48 (5)	1109.509 (23)
1196.15 (14)	1196.28 (5)	1196.6 (2)	1196.1 (3)	1195.5 (5)		1196.6 (10)	1194 (1)		1188 (2)			1196.33 (5)	1196.33 (5)
		1234.3 (4)	1234.6 (10)									1234.3 (4)	1234.3 (4)
1270.79 (18)	1270.66 (8)	1270.8 (2)	1270.3 (3)	1270.0 (5)	1265	1271.2 (10)	1269 (1)		1265 (2)			1270.71 (8)	1270.75 (6)

*) value omitted from the statistical data analysis.
g) value reported in 1965Me07, but measured by A. Green, PhD thesis, University of California at Davis with Ge detector (unpublished).

Table 3. Measured, deduced and adopted gamma-ray emissions probabilities for gamma-transitions in β^-–decay of ^{211}Pb.

Eg, keV	1988Hi14	1976Bl13	1971Da34	1968Br17	1968Go15	1968Ha21	1967Da20	1967Da10	1965Co06	1965Me07	1963Va05	1962Gi03	deduced, rel	adopted, %
65		0.57 (6)	0.60 (4)	0.58 (11)			0.10 (5) *	~0.35 *		0.5 (2)			0.59 (3)	0.077 (4)
95			0.14 (2)					~0.10					0.14 (2)	0.018 (3)
314		0.20 (3)	0.24 (3)	0.19 (4)	0.10 (5)		0.26 (5)	0.21 (7)	0.90 (21) *	~0.2 *			0.206 (16)	0.0268 (21)
343		1.63 (13) *	0.27 (4)		0.15 (5)					~0.3 *			0.22 (3)	0.029 (4)
362		0.326 (24)		0.30 (8)									0.324 (23)	0.042 (3)
405	29.3 (9)	30.2 (14)	30.0 (9)	30.8 (15)	29.6 (20)	28.6 (11)	28.0 (28)	29.9 (35)	30.6 (28)	27.4 (12)	26 (5)	34(4)	29.4 (4)	3.83 (6)
427	13.9 (4)	14.2 (7)	13.5 (6)	14.3 (8)	13.7 (10)	11.6 (7)	14.0 (14)	13.9 (17)	21.5 (21) *	14.5 (14)	12.5 (25)	22 (3) *	13.9 (3)	1.81 (4)
429					0.065 (25)								0.065 (25)	0.008 (3)
504	0.045 (6)		0.12 (2) *		~ 0.006 *								0.045 (6)	0.0059 (8)
610		0.407 (24) *	0.18 (3)	0.38 (4)	0.25 (5)		0.30 (6)	0.21 (7)		0.9 (2) *		0.76 (13) *	0.25 (7)	0.033 (9)
676		0.130 (8)		0.173 (15)	0.10 (5)				1.3 (3) *				0.139 (7)	0.0181 (9)
705	3.6 (1)	3.6 (3)	3.77 (19)	3.68 (23)	3.7 (3)	2.9 (1) *	3.0 (3)	3.3 (4)	5.3 (6) *	3.7 (2)	3.8 (11)	5.5 (4) *	3.61 (7)	0.47 (1)
767	4.94 (16)	5.1 (4)	5.55 (28)	5.04 (30)	4.9 (3)	4.5 (1)	4.0 (4)	5.1 (6)	6.3 (6)	5.2 (2)		6.1 (4)	4.8 (3)	0.62 (4)
832	26.7 (8)	25.4 (20)	29.8 (7) *	25.6 (23)	24.1 (17)	27.4 (4)	23.0 (23)	26.4 (35)	26.4 (28)	27.4 (12)	24.8 (25)	34.2 (13) *	26.9 (3)	3.50 (5)
866	0.042 (6)	0.033 (4)	0.050 (8)	0.053 (15)	0.07 (2)		0.03 (1)	0.0347 (14)		0.04 (2)			0.0354 (13)	0.0046 (2)
1014	0.129 (8)	0.122 (8)	0.14 (1)	0.128 (15)	0.15 (1)		0.13 (2)	0.125 (21)		0.14 (2)		0.38 (19) *	0.133 (4)	0.0173 (5)
1081	0.095 (6)	0.090 (7)	0.120 (12)	0.083 (10)	0.08 (1)	0.0025 (1) *	0.08 (2)	0.104 (14)	0.49 (7) *	0.13 (12) *			0.093 (4)	0.0121 (5)
1104	0.033 (4)	0.049 (5)	0.040 (6)	0.023 (5)									0.036 (5)	0.0047 (7)
1110	0.90 (3)	0.82 (6)	1.15 (8)	0.79 (8)	0.81 (6)	0.0105 (7) *	0.70 (15)	0.87 (10)	0.83 (14)	1.03 (10)	1.07 (16)	1.46 (19) *	0.891 (21)	0.116 (3)
1196	0.072 (5)	0.081 (6)	0.10 (1)	0.079 (15)	0.08 (1)		0.08 (2)	0.076 (14)		0.11 (3)			0.079 (3)	0.0103 (4)
1234			0.010 (2)	0.0053 (15)									0.0070 (23)	0.0009 (3)
1271	0.043 (4)	0.057 (5)	0.070 (7)	0.048 (8)	0.08 (1)	0.0006 (1) *	0.05 (1)	0.042 (7)		0.06 (2)			0.052 (9)	0.0068 (12)

*) value omitted in the statistical data analysis.

Table 4. Gamma-ray energies and emission probabilities (relative to I_γ(351.07γ) = 100) for transitions that were not placed in the proposed decay scheme of ^{211}Pb.

Eγ, keV	1988Hi14	1971Da34	1968Ha21	1968Br17
81.0 (2)		0.35 (9)		
83.8 (1)		0.45 (7)		
88.2 (2)		0.13 (3)		
94.3 (3)		0.09 (2)		
97.3 (2)		0.09 (1)		
244			0.003 (1)	
275			0.004 (1)	
478.0 (4)		0.10 (2)		
479.6 (2)	0.04 (1)			
481.1 (4)		0.20 (4)		
481.92 (12)	0.08 (1)			
491.82 (12)	0.032 (6)			
494.2 (3)	0.013 (5)			
500.4 (5)		0.09 (2)		
502.0 (2)	0.028 (6)			
951			0.0017 (1)	
1090.5 (5)		0.020 (5)		
1120 (1)				0.0019 (11)

5. References

1939Sa11 B.W. Sargent. Can. J. Res. 17A (1939) 103.
(Half-life)

1962Gi03 M. Giannini, D. Prosperi, S. Sciuti. Nuovo Cimento 25 (1962) 1227.
(Gamma-ray emission energies and probabilities)

1963Va05 S.E. Vandenbosch, C.V.K. Baba, P.R. Christensen, O.B. Nielsen, H. Nordby. Nucl. Phys. 41 (1963) 482.
(Gamma-ray emission energies and probabilities)

1965Co06 C.R. Cothern, R.D. Connor. Can. J. Phys. 43 (1965) 383.
(Gamma-ray emission energies and probabilities)

1965Me07 R.O. Mead, J.E. Draper. Phys. Rev. 139 (1965) B9.
(Gamma-ray emission energies and probabilities)

1965Nu03 M. Nurmia, D. Giessing, W. Sievers, L. Varga. Ann. Acad. Sci. Fennicae Ser. A VI (1965) No. 167.
(Half-life)

1967Da10 W.F. Davidson, C.R. Cothern, R.D. Connor. Can. J. Phys. 45 (1967) 2295.
(Gamma-ray emission energies and probabilities)

1967Da20 J. Dalmasso, H. Maria. C.R. Acad. Sci. (Paris) 265B (1967) 822.
(Gamma-ray emission energies and probabilities)

1968Br17 C. Briançon, C.F. Leang, R. Walen. C.R. Acad. Sci. (Paris) 266B (1968) 1533.
(Gamma-ray emission energies and probabilities)

1968G015 S. Gorodetzky, F.A. Beck, T. Byrski, A. Knipper. Nucl. Phys. A117 (1968) 208.
(Gamma-ray emission energies and probabilities)

1968Ha21 W.D. Hamilton, K.E. Davies. Nucl. Phys. A114 (1968) 577.
(Gamma-ray emission energies and probabilities)

1971Da34 E.F. da Silveira, A.G. de Pinho, C.V. de Barros. An. Acad. Brasil. Cienc. 43 (1971) 97.
(Gamma-ray emission energies and probabilities)

1971Go40 N.B. Gove, M.J. Martin. Nucl. Data Tables A10 (1971) 205.
(Log ft)

1976Bl13 K. Blaton-Albicka, B. Kotlinska-Filipek, M. Matul, K. Stryczniewicz, M. Nowicki, E. Ruchowska-Lukasiak. Nukleonika 21 (1976) 935.
(Gamma-ray emission energies and probabilities)

1988Hi14 M.M. Hindi, E.G. Adelberger, S.E. Kellogg, T. Murakami. Phys. Rev. C38 (1988) 1370.
(Gamma-ray emission energies and probabilities)

1996Sc06 E. Schönfeld, H. Janssen. Nucl. Instrum. Methods Phys. Res. A369 (1996) 527.
(K-shell fluorescence yields)

1998ScZM E. Schönfeld, G. Rodloff. Report PTB-6.11-98-1 Braunschweig (1998).
(K Auger electron energies)

1999ScZX E. Schönfeld, G. Rodloff. Report PTB-6.11-1999-1 Braunschweig (1999).
(K X-ray energies and relative emission probabilities)

2000Sc47 E. Schönfeld, H. Janssen. Appl. Radiat. Isot. 52 (2000) 595.
(X-ray and Auger electron emission probabilities and energies)

2003Au03 G. Audi, A.H. Wapstra, C. Thibault. Nucl. Phys. A729 (2003) 337.
(Q value)

2003De44 R.D. Deslattes, E.G. Kessler Jr., P. Indelicato, L. de Billy, E. Lindroth, J. Anton. Rev. Mod. Phys. 75 (2003) 35.
(K and L X-ray energies)

2004Br45 E. Browne. Nucl. Data Sheets 103 (2004) 183
(Nuclear levels, multipolarities and mixing ratios)

2008DuZX C. Dulieu, M.M. Bé, V. Chisté. Proc. Int. Conf. on Nuclear Data for Science and Technology, Nice, France, 22-27 April 2007 (2008) 97.
(SAISINUC software)

2008Ki07 T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor Jr. Nucl. Instrum. Methods Phys. Res. A589 (2008) 202.
(Theoretical ICCs)

2011Ko04 F.G. Kondev, S. Lalkovski. Nucl. Data Sheets 112 (2011) 707.
(Nuclear levels)