^{208}Tl – Comments on evaluation of decay data

by A. L. Nichols

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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

The ground state of ^{208}Tl ($J^{\pi} = 5^{+}$) decays by beta minus emission to various excited levels of ^{208}Pb. A consistent decay scheme has been derived, assuming no direct beta decay to both the 2614.55-keV nuclear level and ground state of ^{208}Pb (based on spin-parity considerations). This decay scheme is primarily based on the gamma-ray measurements of 1960Em01, 1960Sc07, 1961Si11, 1969Au10, 1969La23, 1969Pa02, 1972DaZA/1973Da38, 1972Ja25, 1975Ko02, 1977Ge12, 1978Av01, 1982Sa36, 1983Sc13, 1983Va22, 1984Ge07, 1992Li05 and 1993El08.

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 half-life is the weighted mean of the measurements of 1957Ba05, 1967La20, 1970Mu21 and 1971Ac02, with the uncertainty increased artificially to encompass the most precise study.

Reference	Half-life (min)
1957Ba05	3.100 (15)
1967La20	3.055 (6)
1970Mu21	3.17 (5)
1971Ac02	3.0527 (33)*
Recommended value	3.058 (6)$^{\#}$

* Uncertainty adjusted to ± 0.0055 to reduce weighting to no more than 0.50.
$^{\#}$ Weighted mean adopted, with uncertainty increased to include most precise value.

Gamma Rays

Energies

Both the 583.187 (2)- and 2614.511 (10)-keV gamma-ray energies were taken from 2000He14. All other gamma-ray transition energies were calculated from the structural details of the proposed decay scheme; the nuclear level energies of 2007Ma45 were adopted, and used to determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels.

Adopted nuclear levels of ^{208}Pb: Energy, J^{π} and origins (2007Ma45).

Nuclear level	Nuclear level energy (keV)*	J^{π}	Origins
0	0.0	0 +	^{208}Bi EC decay, **^{208}Tl β⁻ decay**, ^{212}Po α decay, ^{206}Pb(t,x), ^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(γ, x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), ^{209}Bi(t,x), Coulomb excitation, etc.
1	2614.552 ± 0.010	3 –	^{208}Bi EC decay, **^{208}Tl β⁻ decay**, ^{212}Po α decay, ^{206}Pb(t,x), ^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), ^{209}Bi(t,x), Coulomb excitation, etc.
2	3197.711 ± 0.010	5 –	**^{208}Tl β⁻ decay**, ^{212}Po α decay, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), ^{209}Bi(t,x), Coulomb excitation, etc.
3	3475.078 ± 0.011	4 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
4	3708.451 ± 0.012	5 –	**^{208}Tl β⁻ decay**, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{209}Bi(d,x), ^{209}Bi(t,x), etc.
5	3919.966 ± 0.013	6 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), etc.
6	3946.578 ± 0.014	4 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
7	3961.162 ± 0.013	5 –	**^{208}Tl β⁻ decay**, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), ^{209}Bi(t,x), etc.
8	3995.438 ± 0.013	4 –	**^{208}Tl β⁻ decay**, ^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
9	4037.443 ± 0.014	7 –	^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), etc.
10	4051.134 ± 0.013	3 –	^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{209}Bi(d,x), etc.
11	4085.52 ± 0.04	2 +	^{206}Pb(t,x), ^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(γ, x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), Coulomb excitation, etc.
12	4125.347 ± 0.012	5 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{209}Bi(d,x), ^{209}Bi(t,x), etc.
13	4180.414 ± 0.014	5 –	**^{208}Tl β⁻ decay**, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), etc.
14	4206.277 ± 0.004	6 –	^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
15	4229.590 ± 0.017	2 –	^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x)
16	4254.795 ± 0.017	3 –	^{206}Pb(t,x), ^{207}Pb(n,γ), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x)
17	4261.871 ± 0.013	4 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
18	4296.560 ± 0.013	5 –	**^{208}Tl β⁻ decay**, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), etc.
19	4323.946 ± 0.014	4 +	**^{208}Tl β⁻ decay**, ^{206}Pb(t,x), ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), etc.
20	4358.670 ± 0.013	4 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
21	4383.285 ± 0.017	6 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{209}Bi(d,x), etc.
22	4423.647 ± 0.015	6 +	^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{210}Pb(p,x), ^{209}Bi(d,x), etc.
23	4480.746 ± 0.016	6 –	**^{208}Tl β⁻ decay**, ^{207}Pb(d,x), ^{208}Pb(e,x), ^{208}Pb(n,n′γ), ^{208}Pb(p,x), ^{208}Pb(d,x), ^{208}Pb(α,x), ^{209}Bi(d,x), etc.

* Nuclear levels at 4144 (5) and 4447 (5) keV not included, although proposed in studies of the ^{209}Bi(d,^{3}He) reaction.

Placements of gamma-ray transitions (2007Ma45).

	Adopted E_γ* (keV)	Proposed location in decay scheme (^{208}Pb nuclear levels)		Adopted E_γ* (keV)	Proposed location in decay scheme (^{208}Pb nuclear levels)
$\gamma_{5,4}$	211.52 (2)	3919.966 (13) – 3708.451 (12)	–	835.90 (11)	not placed in decay scheme
$\gamma_{4,3}$	233.37 (2)	3708.451 (12) – 3475.078 (11)	$\gamma_{3,1}$	860.53 (2)	3475.078 (11) – 2614.552 (10)
$\gamma_{7,4}$	252.71 (2)	3961.162 (13) – 3708.451 (12)	$\gamma_{20,3}$	883.59 (2)	4358.670 (13) – 3475.078 (11)
$\gamma_{3,2}$	277.37 (2)	3475.078 (11) – 3197.711 (10)	$\gamma_{12,2}$	927.64 (2)	4125.347 (12) – 3197.711 (10)
$\gamma_{7,3}$	486.08 (2)	3961.162 (13) – 3475.078 (11)	$\gamma_{13,2}$	982.70 (2)	4180.414 (14) – 3197.711 (10)
$\gamma_{4,2}$	510.74 (2)	3708.451 (12) – 3197.711 (10)	$\gamma_{4,1}$	1093.90 (2)	3708.451 (12) – 2614.552 (10)
$\gamma_{2,1}$	583.187 (2)	3197.711 (10) – 2614.552 (10)	$\gamma_{19,2}$	1126.24 (2)	4323.946 (14) – 3197.711 (10)
$\gamma_{18,4}$	588.11 (2)	4296.560 (13) – 3708.451 (12)	$\gamma_{20,2}$	1160.96 (2)	4358.670 (13) – 3197.711 (10)
$\gamma_{12,3}$	650.27 (2)	4125.347 (12) – 3475.078 (11)	$\gamma_{21,2}$	1185.57 (2)	4383.285 (17) – 3197.711 (10)
$\gamma_{13,3}$	705.34 (2)	4180.414 (14) – 3475.078 (11)	$\gamma_{23,2}$	1283.04 (2)	4480.746 (16) – 3197.711 (10)
$\gamma_{5,2}$	722.26 (2)	3919.966 (13) – 3197.711 (10)	$\gamma_{8,1}$	1380.89 (2)	3995.438 (13) – 2614.552 (10)
$\gamma_{6,2}$	748.87 (2)	3946.578 (14) – 3197.711 (10)	$\gamma_{17,1}$	1647.32 (2)	4261.871 (13) – 2614.552 (10)
$\gamma_{7,2}$	763.45 (2)	3961.162 (13) – 3197.711 (10)	$\gamma_{20,1}$	1744.12 (2)	4358.670 (13) – 2614.552 (10)
–	808.32 (13)	not placed in decay scheme	$\gamma_{1,0}$	2614.511 (10)	2614.552 (10) – 0
$\gamma_{18,3}$	821.48 (2)	4296.560 (13) – 3475.078 (11)			

* Values derived from the adopted energies of the ^{208}Pb nuclear levels as specified in columns 3 and 6, with the uncertainties rounded upwards on the basis of the recommended uncertainties of the nuclear level energies (2007Ma45).

Emission Probabilities

A consistent decay scheme has been constructed from the gamma-ray measurements of 1960Em01, 1960Sc07, 1961Si11, 1969Au10, 1969Pa02, 1969La23, 1972Ja25, 1972DaZA/1973Da38, 1975Ko02, 1977Ge12, 1978Av01, 1982Sa36, 1983Sc13, 1983Va22, 1984Ge07, 1992Li05 and 1993El08. The study of 1975Ko02 is particularly comprehensive, along with the gamma-ray measurements of 1993El08 below 1000 keV. Gamma-ray emission probabilities have been expressed relative to the 2614.511-keV transition, and specific sets of data were adjusted accordingly (some of the original measurements were quantified relative to the 583.187-keV gamma ray or as absolute emission probabilities, while minor modifications were made to the relevant emission probabilities for the partially resolved 277.37-, 510.74- and 583.187-keV gamma rays as reported by 1983Sc13). 1993El08 observed additional gamma rays (808.32 and 835.90 keV) that have not been successfully placed in the proposed decay scheme – all nuclear levels of ^{208}Pb below an energy of 4611 keV have been assessed in terms of shell-model calculations and particle-gamma coincidence measurements by 1997Sc21, arguing against the possible existence of additional nuclear levels below this energy that might accommodate either of these two gamma transitions.

Experimental studies have been made of weak crossover gamma transitions by Vasil'ev et al. (2006Va23) to provide upper limits for the emission probabilities of three such emissions:

E_γ (keV)	P_γ (%), expressed per 100 decays of ^{208}Tl
3197.7	≤ 0.0007
3475.0	≤ 0.0003
3708.5	≤ 0.0004

Other high-energy gamma emissions were identified as summation peaks. These crossover gamma transitions have not been included in the proposed decay scheme because of their somewhat ill-defined, low emission probabilities and tentative nature.

Published gamma-ray emission probabilities.

E_γ (keV)	P_γ						
	1960Em01	**1960Sc07**	**1961Si11**		**1969Au10***	**1969La23**	**1969Pa02**
211.52 (2)	-	-	-	-	-	0.20 (5)	0.17 (8)
233.37 (2)	-	0.3	-	-	-	0.30 (5)	0.33 (17)
252.71 (2)	1.5 (7)	1.1	-	-		0.8 (1)	0.70 (11)
277.37 (2)	6.9 (8)	8.6	-	7.2 (7)	-	6.9 (5)	6.5 (4)
486.08 (2)	-	0.1 (1)	-	-	-	0.07 (4)	0.05 (2)
510.74 (2)	23 (2)	25.3 (12)	24 (3)	22.5 (25)	-	23 (1)	22.5 (12)
583.187 (2)	86.4 (56)	85.1 (40)	81 (5)	84 (5)	100	85 (4)	86 (4)
588.11 (2)	-	-	-	-	-	-	-
650.27 (2)	-	-	-	-	-	-	-
705.34 (2)	-	-	-	-	-	-	-
722.26 (2)	-	-	)	-	-	0.3 (1)	0.27 (8)
748.87 (2)	-	-	) 22.5 (20)	-	-	-	-
763.45 (2)	1.9 (5)	3.4 (2)	)	3.6 (7)	-	2.0 (2)	1.68 (8)
808.32 (13)	-	-	-	-	-	-	-
821.48 (2)	-	-	-	-	-	-	0.09 (4)
835.90 (11)	-	-	-	-	-	-	-
860.53 (2)	11.4 (12)	14.2 (6)	15.3 (20)	15.2 (15)	-	13 (1)	12.0 (8)
883.59 (2)	-	-	-	-	-	-	-
927.64 (2)	-	-	-	-	-	0.15 (5)	0.13 (3)
982.70 (2)	-	-	-	-	-	0.20 (5)	0.20 (3)
1004 (2)	-	-	-	-	-	-	~ 0.01
1093.90 (2)	-	0.7 (1)	~ 2	-	-	0.5 (1)	0.38 (5)
1126.24 (2)	-	-	-	-	-	-	-
1160.96 (2)	-	-	-	-	-	-	-
1185.57 (2)	-	-	-	-	-	-	-
1283.04 (2)	-	-	-	-	-	-	0.05 (2)
1380.89 (2)	-	-	-	-	-	-	0.02 (1)
1647.32 (2)	-	-	~ 3	-	-	-	~ 0.01
1744.12 (2)	-	-	-	-	-	-	-
2614.511 (10)	100	(100)	100	100	116.7 (24)	100	100

Published gamma-ray emission probabilities (cont.).

E$_\gamma$ (keV)	**P$_\gamma$** (cont.)					
	1973Da38	**1972Ja25**	**1975Ko02**	**1977Ge12***	**1978Av01**	**1982Sa36†**
211.52 (2)	0.16 (4)	-	0.17 (2)	-	-	-
233.37 (2)	~ 0.2	-	0.31 (3)	-	-	-
252.71 (2)	0.8 (2)	-	0.80 (5)	-	0.62 (4)	0.28 (3)
277.37 (2)	6.6 (13)	6.2 (7)	6.8 (3)	-	6.1 (2)	2.4 (1)
486.08 (2)	0.04 (1)	-	0.050 (5)	-	-	-
510.74 (2)	22.9 (23)	21.9 (7)	21.6 (9)	-	22.8 (7)	7.8 (4)
583.187 (2)	85.0 (85)	86.0 (4)	86 (3)	100	85	30.0 (14)
588.11 (2)	~ 0.04	-	0.04 (2)	-	-	-
650.27 (2)	-	-	0.036 (5)	-	-	-
705.34 (2)	~ 0.02	-	0.022 (4)	-	-	-
722.26 (2)	0.21 (6)	-	0.203 (14)	-	0.27 (2)	-
748.87 (2)	0.05 (1)	-	0.043 (4)	-	-	-
763.45 (2)	1.7 (3)	-	1.64 (9)	-	1.82 (9)	0.7 (1)
808.32 (13)	-	-	-	-	-	-
821.48 (2)	0.04 (1)	-	0.040 (4)	-	-	-
835.90 (11)	-	-	-	-	-	-
860.53 (2)	11.8 (12)	11.5 (10)	12.0 (4)	14.79 (15)	13.9 (6)	4.2 (2)
883.59 (2)	~ 0.025	-	0.031 (3)	-	-	-
927.64 (2)	0.13 (4)	-	0.125 (11)	-	-	-
982.70 (2)	0.20 (6)	-	0.197 (15)	-	-	-
1004 (2)	-	-	< 0.005	-	-	-
1093.90 (2)	0.37 (7)	-	0.37 (4)	-	-	-
1126.24 (2)	-	-	0.005 (2)	-	-	-
1160.96 (2)	-	-	0.011 (3)	-	-	-
1185.57 (2)	-	-	0.017 (5)	-	-	-
1283.04 (2)	~ 0.05	-	0.052 (5)	-	-	-
1380.89 (2)	-	-	0.007 (3)	-	-	-
1647.32 (2)	-	-	0.002 (1)	-	-	-
1744.12 (2)	-	-	0.002 (1)	-	-	-
2614.511 (10)	100	(100)	100	118.5 (16)	(100)	-

Published gamma-ray emission probabilities (cont.).

Eγ (keV)	**Pγ** (cont.)				
	1983Sc13‡	**1983Va22#**	**1984Ge07***	**1992Li05**	**1993El08¶**
211.52 (2)	-	-	0.228 (20)	-	0.18 (1)
233.37 (2)	-	-	0.31 (4)	-	0.30 (1)
252.71 (2)	-	-	0.955 (13)	-	0.77 (2)
277.37 (2)	2.33 (7)	2.29 (4)	7.55 (6)	2.54 (7)§	6.88 (12)
486.08 (2)	-	-	-	-	0.055 (11)
510.74 (2)	7.90 (23)	8.31 (14)	26.9 (9)	-	22 (1)
583.187 (2)	30.7 (8)	30.8 (6)	100.0 (6)	29.4 (7)§	86 (3)
588.11 (2)	-	-	-	-	0.07 (1)
650.27 (2)	-	-	-	-	0.065 (11)
705.34 (2)	-	-	-	-	-
722.26 (2)	-	-	0.31 (6)	-	0.27 (2)
748.87 (2)	-	-	-	-	0.054 (9)
763.45 (2)	0.73 (5)	-	2.15 (2)	0.651 (40)	1.72 (8)
808.32 (13)	-	-	-	-	0.029 (7)
821.48 (2)	-	-	-	-	0.041 (17)
835.90 (11)	-	-	-	-	0.075 (11)
860.53 (2)	4.55 (12)	-	14.78 (9)	4.32 (15)	12.6 (7)
883.59 (2)	-	-	-	-	-
927.64 (2)	-	-	-	-	0.13 (1)
982.70 (2)	-	-	-	-	0.21 (1)
1004 (2)	-	-	-	-	-
1093.90 (2)	-	-	0.525 (8)	-	0.47 (4)
1126.24 (2)	-	-	-	-	-
1160.96 (2)	-	-	-	-	-
1185.57 (2)	-	-	-	-	-
1283.04 (2)	-	-	-	-	0.049 (13)
1380.89 (2)	-	-	-	-	-
1647.32 (2)	-	-	-	-	-
1744.12 (2)	-	-	-	-	-
2614.511 (10)	35.6 (11)	-	119.1 (21)	-	98.1 (13)

* Emission probabilities relative to Pγ(583.187 keV) of 100.
† Emission probabilities relative to Pγ(583.187 keV) of 30.0.
‡ Emission probabilities relative to Pγ(583.187 keV) of 30.7.
# Emission probabilities relative to Pγ(583.187 keV) of 30.8.
¶ Absolute emission probabilities.
§ Unresolved overlap with another gamma-ray emission.

Equivalent measurements of specific emission probabilities deviate significantly between laboratories:

252.71-keV gamma ray: 1960Em01 and 1978Av01;
486.08-keV gamma ray: 1960Sc07;
510.74-keV gamma ray: 1960Sc07;
583.187-keV gamma ray: 1961Si11;
763.45-keV gamma ray: 1960Sc07 and 1961Si11;
860.53-keV gamma ray: 1960Sc07, 1961Si11 and 1978Av01;
927.64-keV gamma ray: 1969La23;
1093.90-keV gamma ray: 1960Sc07.

These particular values were judged to be outliers, and were not included in the weighted-mean analyses. Other gamma-ray emission probabilities were not reported with uncertainties within 1960Sc07, along with the 583.187-keV gamma-ray emission in 1978Av01; these data were also not included in the weighted-mean analyses. 1982Sa36, 1983Va22 and 1992Li05 reported measurements that did not include the main 2614.511-keV gamma-ray transition: the evaluated relative emission probability of the 583.187-keV gamma ray was adopted to create data sets comparable with the other studies, and therefore the assumed Pγ(583.187 keV) in these particular calculations were not included in the subsequent analysis.

While an uncertainty of 0.8 % can be derived for the relative emission probability of the 2614.511-keV gamma ray from the emission probabilities and uncertainties determined experimentally by 1969Au10, 1977Ge12, 1983Sc13, 1984Ge07 and 1993El08, the precise nature of this transition in such a welldefined area of the decay scheme permits the establishment of a recommended value of 100 % with no assigned uncertainty:

Reference	**P_γ(2614.511 keV)**
1969Au10	100 (2)
1977Ge12	100.0 (14)
1983Sc13	100 (3)
1984Ge07	100 (2)
1993El08	100.0 (13)
Weighted-mean value (LRSW)	100.0 (8) → 100 (1)
Recommended value	100

Gamma-ray emission probabilities: Relative to P_γ(2614.511 keV) of 100 %.

E_γ (keV)	**P_γ^{rel}**						
	1960Em01	**1960Sc07**	**1961Si11**		**1969Au10**	**1969La23**	**1969Pa02**
211.52 (2)	-	-	-	-	-	0.20 (5)	0.17 (8)
233.37 (2)	-	0.3[§]	-	-	-	0.30 (5)	0.33 (17)
252.71 (2)	1.5 (7)[†]	1.1[§]	-	-		0.8 (1)	0.70 (11)
277.37 (2)	6.9 (8)	8.6[§]	-	7.2 (7)	-	6.9 (5)	6.5 (4)
486.08 (2)	-	0.1 (1)[†]	-	-	-	0.07 (4)	0.05 (2)
510.74 (2)	23 (2)	25.3 (12)[†]	24 (3)	22.5 (25)	-	23 (1)	22.5 (12)
583.187 (2)	86.4 (56)	85.1 (40)	81 (5)[†]	84 (5)	85.7 (18)	85 (4)	86 (4)
588.11 (2)	-	-	-	-	-	-	-
650.27 (2)	-	-	-	-	-	-	-
705.34 (2)	-	-	-	-	-	-	-
722.26 (2)	-	-	)	-	-	0.3 (1)	0.27 (8)
748.87 (2)	-	-	) 22.5 (20)[‡]	-	-	-	-
763.45 (2)	1.9 (5)	3.4 (2)[†]	)	3.6 (7)[†]	-	2.0 (2)	1.68 (8)
808.32 (13)	-	-	-	-	-	-	-
821.48 (2)	-	-	-	-	-	-	0.09 (4)
835.90 (11)	-	-	-	-	-	-	-
860.53 (2)	11.4 (12)	14.2 (6)[†]	15.3 (20)[†]	15.2 (15)[†]	-	13 (1)	12.0 (8)
883.59 (2)	-	-	-	-	-	-	-
927.64 (2)	-	-	-	-	-	0.15 (5)[†]	0.13 (3)
982.70 (2)	-	-	-	-	-	0.20 (5)	0.20 (3)
1004 (2)	-	-	-	-	-	-	~ 0.01
1093.90 (2)	-	0.7 (1)[†]	~ 2	-	-	0.5 (1)	0.38 (5)
1126.24 (2)	-	-	-	-	-	-	-
1160.96 (2)	-	-	-	-	-	-	-
1185.57 (2)	-	-	-	-	-	-	-
1283.04 (2)	-	-	-	-	-	-	0.05 (2)
1380.89 (2)	-	-	-	-	-	-	0.02 (1)
1647.32 (2)	-	-	~ 3	-	-	-	~ 0.01
1744.12 (2)	-	-	-	-	-	-	-
2614.511 (10)	100	(100)	100	100	100 (2)	100	100

Gamma-ray emission probabilities: Relative to P$_\gamma$(2614.511 keV) of 100 % (cont.).

E$_\gamma$ (keV)	P$_\gamma^{rel}$ (cont.)					
	1973Da38	**1972Ja25**	**1975Ko02**	**1977Ge12**	**1978Av01**	**1982Sa36**
211.52 (2)	0.16 (4)	-	0.17 (2)	-	-	-
233.37 (2)	~ 0.2	-	0.31 (3)	-	-	-
252.71 (2)	0.8 (2)	-	0.80 (5)	-	0.62 (4)†	0.80 (9)
277.37 (2)	6.6 (13)	6.2 (7)	6.8 (3)	-	6.1 (2)	6.8 (3)
486.08 (2)	0.04 (1)	-	0.050 (5)	-	-	-
510.74 (2)	22.9 (23)	21.9 (7)	21.6 (9)	-	22.8 (7)	22.2 (11)
583.187 (2)	85.0 (85)	86.0 (4)	86 (3)	84.4 (11)	85§	[85.2 (3)]$^#$
588.11 (2)	~ 0.04	-	0.04 (2)	-	-	-
650.27 (2)	-	-	0.036 (5)	-	-	-
705.34 (2)	~ 0.02	-	0.022 (4)	-	-	-
722.26 (2)	0.21 (6)	-	0.203 (14)	-	0.27 (2)	-
748.87 (2)	0.05 (1)	-	0.043 (4)	-	-	-
763.45 (2)	1.7 (3)	-	1.64 (9)	-	1.82 (9)	2.0 (3)
808.32 (13)	-	-	-	-	-	-
821.48 (2)	0.04 (1)	-	0.040 (4)	-	-	-
835.90 (11)	-	-	-	-	-	-
860.53 (2)	11.8 (12)	11.5 (10)	12.0 (4)	12.48 (13)	13.9 (6)†	11.9 (6)
883.59 (2)	~ 0.025	-	0.031 (3)	-	-	-
927.64 (2)	0.13 (4)	-	0.125 (11)	-	-	-
982.70 (2)	0.20 (6)	-	0.197 (15)	-	-	-
1004 (2)	-	-	< 0.005	-	-	-
1093.90 (2)	0.37 (7)	-	0.37 (4)	-	-	-
1126.24 (2)	-	-	0.005 (2)	-	-	-
1160.96 (2)	-	-	0.011 (3)	-	-	-
1185.57 (2)	-	-	0.017 (5)	-	-	-
1283.04 (2)	~ 0.05	-	0.052 (5)	-	-	-
1380.89 (2)	-	-	0.007 (3)	-	-	-
1647.32 (2)	-	-	0.002 (1)	-	-	-
1744.12 (2)	-	-	0.002 (1)	-	-	-
2614.511 (10)	100	(100)	100	100.0 (14)	(100)	-

Gamma-ray emission probabilities: Relative to P_γ(2614.511 keV) of 100 % (cont.).

E_γ (keV)	P_γ^{rel} (cont.)					
	1983Sc13	1983Va22	1984Ge07	1992Li05	1993El08	Recommended value*
211.52 (2)	-	-	0.19 (2)	-	0.18 (1)	0.18 (1)
233.37 (2)	-	-	0.26 (3)	-	0.31 (1)	0.31 (1)
252.71 (2)	-	-	0.80 (1)	-	0.78 (2)	0.78 (2)
277.37 (2)	6.5 (2)	6.3 (1)	6.34 (5)	7.36 (20)$^\psi$	7.01 (12)	6.6 (3)
486.08 (2)	-	-	-	-	0.056 (11)	0.049 (4)
510.74 (2)	22.2 (6)	23.0 (4)	22.6 (8)	-	22 (1)	22.6 (2)
583.187 (2)	85.8 (22)	[85.2 (3)]#	84.0 (5)	[85.2 (3)]$^\psi$	88 (3)	85.2 (3)
588.11 (2)	-	-	-	-	0.07 (1)	0.06 (1)
650.27 (2)	-	-	-	-	0.066 (11)	0.041 (5)
705.34 (2)	-	-	-	-	-	0.022 (4)
722.26 (2)	-	-	0.26 (5)	-	0.28 (2)	0.24 (4)
748.87 (2)	-	-	-	-	0.055 (9)	0.046 (3)
763.45 (2)	2.05 (14)	-	1.81 (2)	1.89 (12)	1.75 (8)	1.80 (2)
808.32 (13)	-	-	-	-	0.030 (7)	0.030 (7)
821.48 (2)	-	-	-	-	0.042 (17)	0.041 (4)
835.90 (11)	-	-	-	-	0.076 (11)	0.076 (11)
860.53 (2)	12.8 (3)	-	12.41 (8)	12.5 (4)	12.8 (7)	12.4 (1)
883.59 (2)	-	-	-	-	-	0.031 (3)
927.64 (2)	-	-	-	-	0.13 (1)	0.128 (7)
982.70 (2)	-	-	-	-	0.21 (1)	0.205 (8)
1004 (2)	-	-	-	-	-	-
1093.90 (2)	-	-	0.441 (7)	-	0.48 (4)	0.44 (1)
1126.24 (2)	-	-	-	-	-	0.005 (2)
1160.96 (2)	-	-	-	-	-	0.011 (3)
1185.57 (2)	-	-	-	-	-	0.017 (5)
1283.04 (2)	-	-	-	-	0.050 (13)	0.052 (5)
1380.89 (2)	-	-	-	-	-	0.007 (3)
1647.32 (2)	-	-	-	-	-	0.002 (1)
1744.12 (2)	-	-	-	-	-	0.002 (1)
2614.511 (10)	100 (3)	-	100 (2)	-	100.0 (13)	100

* Weighted mean values adopted when appropriate; remainder derived from proposed decay scheme; normalisation factor of 0.997 55 (4) calculated from total theoretical internal conversion coefficient of 2614.511-keV (0.002 46 (4)) gamma transition and transition probability of 100 % (1.00), with no direct β^- decay to the 2614.552-keV nuclear level and ground state of ^{208}Pb.

† Rejected as outlier, and not included in weighted-mean analysis.

§ No uncertainty quoted; data not included in the weighted-mean analysis.

‡ Unresolved data not included in the weighted-mean analysis.

\# Measurements did not include determination of the 2614.511-keV gamma ray; therefore, relative emission probability of 85.2 (3) for the 583.187-keV gamma ray was used to convert all other data in this study to comparable relative values – under these circumstances, P_γ(583.187 keV) was not included in the weighted-mean analysis.

$^\psi$ unresolved overlap with another gamma-ray emission, and measurement did not include 2614.511-keV γ ray; therefore relative emission probability of 85.2 (3) was used for the 583.187-keV γ ray to convert other data in this study to comparable relative values – under these circumstances, P_γ(277.37 keV) and P_γ(583.187 keV) were not included in the weighted-mean analyses.

Multipolarities and Internal Conversion Coefficients

The major 583.187- and 2614.511-keV gamma rays were identified as E2 and E3 transitions, respectively. Many other gamma rays have mixed M1 + E2 multipolarities; these transitions were generally assumed to be 100 % M1, although estimated mixing ratios derived from the studies of 1954El07, 1957Kr56, 1957Vo22, 1963Da11, 1972Ja25, 1976Av03, 1978Av01 and 1990Go33 were used to determine specific multipolarities and theoretical internal conversion coefficients: ((97 % M1 + 3 % E2) for the 211.52-keV gamma transition, (67 % M1 + 33 % E2) for the 233.37-keV gamma transition, (86 % M1 + 14 % E2) for the 252.71-keV gamma transition, (99.96 % M1 + 0.04 % E2) for the 277.37-keV gamma transition, (99.75 % M1 + 0.25 % E2) for the 510.74-keV gamma transition, (91.2 % M1 + 8.8 % E2) for the 722.26-keV gamma transition, (99.0 % M1 + 1.0 % E2) for the 763.45-keV gamma transition, and (99.98 % M1 + 0.02 % E2) for the 860.53-keV gamma transition). The assigned multipolarity of the 860.53-keV gamma ray is particularly important in achieving the desired population-depopulation balance for the 2614.552-keV nuclear level. 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). Ion-pair formation coefficients were calculated by means of the methodology described by Kibédi *et al.* (2008Ki07). Uncertainties of ± 1.5 % were adopted for the E1 and E2 gamma transitions.

A normalisation factor (NF) of 0.997 55 (4) was calculated for the relative emission probabilities of the gamma rays, assuming no direct beta decay to the ground state of ^{208}Pb:

absolute transition probability of 2614.511-keV gamma ray = 100 %,
relative emission probability of 2614.511-keV gamma ray = 100 %, and
total theoretical internal conversion coefficient (2614.511-keV E3 transition) = 0.002 46 (4) (2002Ba85, 2002Ra45, 2008Ki07) →

$$P_\gamma^{abs} = P_\gamma^{rel} \ x \ NF = \frac{TP_\gamma^{abs}}{[1 + \alpha_{total}]}$$

and, therefore:

$$NF = \frac{TP_\gamma^{abs}}{[1 + \alpha_{total}] \ x \ P_\gamma^{rel}} = \frac{100}{[1 + 0.00246(4)] \ x \ 100}$$

$$NF = 0.99755(4)$$

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

E_γ (keV)	Multipolarity	α_K	α_L	α_{M+}	α_{IPF}	α_{total}
211.52 (2)	97%M1 + 3%E2 δ = 0.18(2) 1957Kr56, 1957Vo22	0.890 (14)	0.1570 (22)	0.049	–	1.096 (17)
233.37 (2)	67%M1 + 33%E2 δ = 0.70(7) 1957Kr56, 1957Vo22	0.51 (3)	0.1136 (18)	0.0364	–	0.66 (3)
252.71 (2)	86%M1 + 14%E2 δ = -0.40(4) 1957Vo22, 1963Da11, 1978Av01	0.495 (14)	0.0926 (14)	0.0284	–	0.616 (15)
277.37 (2)	99.96%M1 + 0.04%E2 δ = 0.02(1) 1957Vo22, 1963Da11, 1976Av03, 1978Av01, 1990Go33	0.432 (6)	0.0739 (11)	0.0231	–	0.529 (8)
486.08 (2)	[M1] 1957Vo22	0.0954 (14)	0.01608 (23)	0.00492	–	0.1164 (17)
510.74 (2)	99.75%M1 + 0.25%E2 δ = -0.05(5) 1957Vo22, 1963Da11, 1976Av03, 1978Av01	0.0835 (13)	0.01406 (21)	0.00434	–	0.1019 (16)
583.187 (2)	E2 1954El07, 1957Kr56, 1963Da11, 1972Ja25, 1978Av01	0.01509 (22)	0.00410 (6)	0.00131	–	0.0205 (3)
588.11 (2)	[M1]	0.0577 (8)	0.00968 (14)	0.00302	–	0.0704 (10)
650.27 (2)	[M1]	0.0444 (7)	0.00742 (11)	0.00228	–	0.0541 (8)
705.34 (2)	[M1]	0.0360 (5)	0.00599 (9)	0.00181	–	0.0438 (7)
722.26 (2)	91.2%M1 + 8.8%E2 δ = 0.31(3) 1976Av03, 1978Av01	0.0317 (6)	0.00534 (10)	0.00166	–	0.0387 (7)
748.87 (2)	[M1]	0.0308 (5)	0.00512 (8)	0.00158	–	0.0375 (6)
763.45 (2)	99.0%M1 + 1.0%E2 δ = -0.10(1) 1957Vo22, 1963Da11, 1978Av01, 1990Go33	0.0291 (4)	0.00484 (7)	0.00146	–	0.0354 (5)
808.32 (13)	–	–	–	–	–	–
821.48 (2)	[M1]	0.0242 (4)	0.00402 (6)	0.00128	–	0.0295(5)
835.90 (11)	–	–	–	–	–	–
860.53 (2)	99.98%M1 + 0.02%E2 δ = 0.015 1957Vo22, 1963Da11, 1972Ja25, 1976Av03, 1978Av01, 1990Go33	0.0215 (3)	0.00356 (5)	0.00114	–	0.0262 (4)
883.59 (2)	[M1]	0.0201 (3)	0.00333 (5)	0.00097	–	0.0244 (4)
927.64 (2)	[M1]	0.01774 (25)	0.00293 (5)	0.00093	–	0.0216 (3)
982.70 (2)	[M1]	0.01530 (22)	0.00253 (4)	0.00077	–	0.0186 (3)
1093.90 (2)	E2	0.00449 (7)	0.000844 (12)	0.000266	–	0.00560 (8)
1126.24 (2)	E1	0.001691 (24)	0.000256 (4)	0.000081	0.00000206 (3)	0.00203 (3)
1160.96 (2)	[M1]	0.01000 (14)	0.001641 (23)	0.000496	0.00000259 (4)	0.01214 (17)
1185.57 (2)	[M1]	0.00947 (14)	0.001555 (22)	0.000480	0.00000501 (7)	0.01151 (17)
1283.04 (2)	[M1]	0.00775 (11)	0.001269 (18)	0.000388	0.0000232 (4)	0.00943 (14)
1380.89 (2)	[M1]	0.00643 (9)	0.001050 (15)	0.000315	0.0000546 (8)	0.00785 (11)
1647.32 (2)	[M1]	0.00411 (6)	0.000669 (10)	0.000207	0.000194 (3)	0.00518 (8)
1744.12 (2)	[M1]	0.00356 (5)	0.000578 (8)	0.000177	0.000255 (4)	0.00457 (7)
2614.511 (10)	E3	0.001708 (24)	0.000292 (4)	0.000089	0.000371 (6)	0.00246 (4)

Beta Particles

Energies

All beta-particle energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of 2007Ma45 and the $Q_{\beta-}$ value of 4999.0 (17) keV adopted from 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 probability balances, through the recommended gamma-ray emission intensities, and adopted multipolarities and theoretical internal conversion coefficients. A significant majority of the beta-particle transitions were defined as first forbidden non-unique.

Beta-particle emission probabilities per 100 disintegrations of ^{208}Tl.

	E_β(keV)	P_β				Transition type	log ft
		1960Em01	1960Sc07	1967Os01	Recommended value*		
$\beta_{0,23}$	518.3 (17)	–	–	–	0.052 (5)	1st forbidden non-unique	6.67
$\beta_{0,21}$	615.7 (17)	–	–	–	0.017 (5)	1st forbidden non-unique	7.41
$\beta_{0,20}$	640.3 (17)	–	–	4.15 (15)	0.045 (4)	1st forbidden non-unique	7.04
$\beta_{0,19}$	675.1 (17)	–	–	–	0.005 (2)	allowed	8.1
$\beta_{0,18}$	702.4 (17)	–	–	–	0.102 11)	1st forbidden non-unique	6.82
$\beta_{0,17}$	737.1(17)	–	–	–	0.002 (1)	1st forbidden non-unique	8.6
$\beta_{0,13}$	818.6 (17)	–	–	–	0.231 (9)	1st forbidden non-unique	6.70
$\beta_{0,12}$	873.7 (17)	–	–	–	0.174 (9)	1st forbidden non-unique	6.92
$\beta_{0,8}$	1003.6 (17)	–	–	–	0.007 (3)	1st forbidden non-unique	8.5
$\beta_{0,7}$	1037.8 (17)	3.6	4.6 (2)	< 0.6	3.17 (4)	1st forbidden non-unique	5.92
$\beta_{0,6}$	1052.4 (17)	–	–	–	0.048 (3)	1st forbidden non-unique	7.76
$\beta_{0,5}$	1079.0 (17)	–	–	–	0.63 (4)	1st forbidden non-unique	6.68
$\beta_{0,4}$	1290.5 (17)	24.3	23.9 (8)	21 (2)	24.1 (2)	1st forbidden non-unique	5.38
$\beta_{0,3}$	1523.9 (17)	20.6	22.7 (7)	22 (2)	22.1 (5)	1st forbidden non-unique	5.69
$\beta_{0,2}$	1801.3 (17)	51.3	48.8 (27)	52 (1)	49.2 (6)	1st forbidden non-unique	5.61
					Σ 99.9 (8)		

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

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 ^{208}Tl.

			Energy (keV)	**Photons per 100 disint.**
XL		(Pb)	9.184 – 15.216	2.75 (12)
	XL_l	(Pb)	9.184	0.0671 (19)
	XL_α	(Pb)	10.450 – 10.551	1.27 (4)
	XL_η	(Pb)	11.349	0.0209 (7)
	XL_β	(Pb)	12.142 – 13.015	1.155 (25)
	XL_γ	(Pb)	14.765 – 15.216	0.220 (5)
XK_α	$XK_{\alpha 2}$	(Pb)	72.8049 (8)	2.03 (5)
	$XK_{\alpha 1}$	(Pb)	74.9700 (9)	3.42 (7)
$XK'_{\beta 1}$	$XK_{\beta 3}$	(Pb)	84.451	)
	$XK_{\beta 1}$	(Pb)	84.937	) 1.17 (3)
	$XK''_{\beta 5}$	(Pb)	85.470	)
$XK'_{\beta 2}$	$XK_{\beta 2}$	(Pb)	87.238	)
	$XK_{\beta 4}$	(Pb)	87.580	) 0.353 (11)
	$XKO_{2,3}$	(Pb)	87.911	)

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 4999.0 (17) keV has been adopted from the atomic mass evaluation of Audi *et al.* (2003Au03) while in the course of formulating the decay scheme of ^{208}Tl. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{208}Tl beta-decay process (i.e. β^-, conversion electrons, γ, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 4989\ (14)\ \text{keV}$$

Percentage deviation from the Q-value of Audi *et al.* is (0.2 ± 0.3) %, which supports the derivation of a highly consistent decay scheme.

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