^{226}Ra - Comments on evaluation of decay data
by V. Chisté and M. M. Bé

This evaluation was completed in 2006. This updated version was done in January 2007. The literature available by this date is included.

1 Decay Scheme

^{226}Ra disintegrates by alpha emissions mainly to the 186 keV level and to the ground state level of ^{222}Rn. Spin and parity are from the mass-chain evaluation of Y. A. Akovali (1996El01 and 1996Ak02).
A certain number of measurements of the 186-keV gamma intensity were carried out and the adopted data set is consistent, so the deduced intensity can be considered having a good level of confidence. Therefore, the decay scheme here was built from the gamma-ray intensity measurements.
A good agreement was found between the effective Q value (4870.5 (27) keV) calculated from the decay scheme data and the adopted and recommended value from Audi.

2 Nuclear Data

The Q value is from the atomic mass evaluation of Audi *et al.* (2003Au03).

Experimental ^{226}Ra half-life values (in years) are given in Table 1:

Table 1: Experimental values of ^{226}Ra half-life.

Reference	Experimental value (a)	Comments
S. W. Watson (1928Wa**)	1608	Not used: no uncertainty. Calorimetry.
H. J. J. Braddick (1928Br**)	1603	Not used: no uncertainty. α current.
I. Curie (1928Cu**)	1590	Not used: no uncertainty. Ion current.
F. A. B. Ward (1929Wa**)	1599	Not used: no uncertainty. Number α's emitted.
L. Meitner (1930Me**)	1590	Not used: no uncertainty. Calorimetry.
E. Gleditsch (1935Gl02)	1691	Not used: no uncertainty. Growth rate.
P. Günther (1939Gü**)	1603	Not used: no uncertainty. He production.
T. P. Kohman (1949Ko01)	1622 (13)	Number α's emitted.
W. Sebaoun (1956Se10)	1617 (12)	Number α's emitted.
G. V. Gorshkov (1959Go80)	1577 (9)	Calorimetry.
G. Martin (1959Ma12)	1602 (8)	Calorimetry.
H. Ramthun (1966Ra13)	1599 (7)	Calorimetry.
Recommended value	**1600 (7)**	χ^2 = 2.87

The weighted average was calculated with LWEIGHT computer program (version 3).

The evaluators have chosen to take into account the only five experimental values with uncertainty found in the literature: 1949Ko01, 1956Se10, 1959Go80, 1959Ma12 and 1966Ra13. With this data set, the largest contribution to the weighted average comes from the value of Ramthun amounting to 33 %. The weighted average of **1600 a** and the external uncertainty of **7 a** is the half-life adopted value. The reduced-χ^2 value is 2.87.

2.1 a Transitions

The transition energies of the α-particles given in Section 2.1 were calculated from Q_α (2003Au03) and level energies.

2.2 g Transitions

The transitions probabilities were calculated using the γ-ray emission intensities and the relevant internal conversion coefficients (see **6.2 Gamma Emissions**).

Multipolarities of these γ-ray transitions are from 1996El01.

186-keV γ-ray : E2
262-keV γ-ray : [E2]
414-keV γ-ray : [E1]
449-keV γ-ray : [E1]
600-keV γ-ray : [E1]

The internal conversion coefficients (ICC's) for these γ-ray transitions have been interpolated from theoretical values of I. M. Band (2002Ba85) using the BrIcc computer program (calculation for 'hole'). Theoretical values are compared with measured values below:

	De Pinho (1973De50)	Band (Icc99v3a computer program, no hole)[a]	BrIcc program (recommended values)
α_K	0.200 (9)	0.186 (6)	0.190 (3)
α_{L1}	0.031 (6)	0.0319 (10)	0.0321 (5)
α_{L2}	0.226 (16)	0.208 (6)	0.208 (3)
α_{L3}	0.124 (8)	0.1196 (36)	0.1196 (17)
α_L	0.380 (20)	0.360 (11)	0.360 (5)

[a] The evaluators have used a fractional uncertainty of 3 % for all Band conversion coefficients.

The results of De Pinho (1973De50) and the theoretical values calculated with two different programs (Icc99v3a (calculation for 'no hole') and BrIcc) are consistent to each other. The recommended values are the BrIcc values for the all conversion coefficients.

3 Atomic Data

Atomic values, ω_K, ϖ_L and n_{KL} and the X-ray and Auger electron relative probabilities are from Schönfeld and Janβen (1996Sc06).

4 a Emissions

The α-particle energies for the $\alpha_{0,2}$, $\alpha_{0,3}$ and $\alpha_{0,4}$ are from G. Bastin-Scoffier (1963Ba62), with uncertainties given by A. Rytz (1991Ry01). For the $\alpha_{0,0}$ and $\alpha_{0,1}$ emissions, the energies are from A. Rytz (1991Ry01).

The emission intensities of the α-particles have been deduced from the P(γ + ce) decay scheme balance at each level. In Table 2, the calculated and recommended values of the emission intensities are compared with the experimental results. For the two most important lines a slight agreement was found between the experimental results given by 2001La14 and the recommended values deduced from the decay scheme balance. For the three weak lines the calculated alpha emission intensities deduced from γ ray measurements are in good agreement with the measured values of Bastin-Scoffier.

Table 2: Experimental and recommended (deduced) values of the α-particles emission intensities.

Energy (keV)	G. Bastin-Scoffier (1963Ba62)	S. LaMont (2001La14)	Recommended values
4784.34 (25)	94.45 (5)[a]	93.84 (11)	94.038 (40)
4601 (1)	5.55 (5)[a]	6.16 (3)	5.950 (40)
4340 (1)	0.0065 (3)		0.0066 (22)
4191 (2)	0.0010 (1)		0.0008
4160 (2)	0.00027 (5)		0.0002

[a] uncertainties as given by Rytz.

5 Electron Emissions

The conversion electrons emission intensities have been calculated from γ-ray data using the EMISSION computer program.

6 Photon emissions

6.1 X-rays

The X-ray absolute intensities have been calculated from γ-ray data and ICC using the EMISSION computer program. In Table 3, the recommended values of ^{222}Rn X-ray emission intensities are compared with the experimental results.

Table 3: Experimental and recommended values of X-ray emission intensities.

	Delgado (2002De03)	Schötzig (1983Sc13)	De Pinho (1973De50)[a]	Recommended values
$K\alpha_1$	0.215 (3)			0.317 (6)
$K\alpha_2$	0.156 (39)			0.192 (4)
Kα	0.371 (39)	0.418 (21)		0.509 (7)
$K\beta_1$	0.079 (5)			0.1098 (25)
$K\beta_2$	0.020 (4)			0.0351 (10)
Kβ	0.099 (6)	0.145 (9)		0.1449 (27)
XK	0.47 (4)	0.563 (23)	0.693 (26)	0.654 (8)
XL1			0.0181 (25)	0.0147 (4)
XL2			0.420 (28)	0.427 (10)
XL3			0.401 (14)	0.365 (9)
XL			0.839 (43)	0.807 (13)

[a] Calculated with I_γ (186) = 3.555 (19)

The calculated recommended values and 1973De50 values, based on the assumption that I_γ (186) = 3.555 (19), are significantly greater than those measured by Delgado (2002De03) or Schötzig (1983Sc13).

The recommended data are in agreement, within the uncertainty values, with the experimental ones of 1973De50, who used a ^{226}Ra source from which the descendants were removed, since Schötzig and Delgado carried out measurements with sources in equilibrium with their daughters.

6.2 g-ray Emissions

The energies of the γ-ray emissions given in Section 6.2 are from Y. A. Akovali (1996El01).

The experimental relative γ emission intensities in ^{222}Rn are based on all available relative and absolute measurements of gamma-rays for the ^{226}Ra decay chain. The normalization factor to convert the relative emission intensities to absolute intensities is the weighted average of the measured absolute gamma-ray emission intensities (Table 4) of the most intense line in ^{226}Ra decay chain, presents in the ^{214}Bi disintegration namely the 609.3-keV line.

Table 4: Experimental 609.3 keV absolute gamma-ray emission intensities.

References	Experimental values (%)	Comments
E. W. A. Lingeman (1969Li10)	42.8 (40)	
D. G. Olson (1983Ol01)	45.0 (7)	
U. Schötzig (1983Sc13)	44.6 (5)	
W. –J. Lin (1991Li11)	46.1 (5)	
J. Morel (1998Mo14)	44.8 (6)	Superseded by 2004Mo07
J. Morel (2004Mo07)	45.57 (18)	
Recommended value	**45.49 (19)**	χ^2 = 1.45

The recommended normalization factor is the weighted average of the five experimental values: 45.49 with an external uncertainty of 0.19.

The experimental relative γ emission intensities of 186- and 262-keV given in Table 5 are relative to the ^{214}Bi 609-keV γ-ray.

Table 5: Experimental data set of the 186- and 262- keV relative γ emission intensities.

References	186-keV γ-ray	262-keV γ-ray	Comments
K. Ya. Gromov (1969Gr33)	9.5 (10)		Not used by the evaluators.
G. Wallace (1969Wa27)	9.91 (31)		Not used by the evaluators.
R.S. Mowatt (1970Mo28)	8.20 (12)		outlier
V. S. Aleksandrov (1974AlZT)	8.87 (30)		outlier
V. Zobel (1977Zo01)	9.00 (10)		Not used by the evaluators.
M. A. Farouk (1982Fa10)	9.07 (14)		Not used by the evaluators.
D. G. Olson (1983Ol01)	7.69 (11)		
U. Schötzig (1983Sc13)	7.72 (14)		
G. Mouze (1990MoZP)	8.58 (5)	0.012 (4)	outlier
W. –J. Lin (1991Li11)	7.89 (14)		
D. Sardari (2000Sa32)	7.6 (8)	0.012 (4)	
J. U. Delgado (2002De03)	7.812 (31)		
G. L. Molnar (2002MoZP)	7.85 (5)		
J. Morel (2004Mo07)	7.812 (31)		Not used by the evaluators.
Recommended values	**7.815 (25)**	**0.012 (4)**	
χ^2	0.52		

Were omitted from analysis:

a) four values: A. Hachem (1975Ha31), G. Mouze (1981Mo28), H. Akcay (1982Ak03) and O. Diallo (1993Di09), because these values comes from the same laboratory of G. Mouze (1990MoZP).
b) the sets of values from K. Ya. Gromov (1969Gr33), G. Wallace (1969Wa27) and M. A. Farouk (1982Fa10), because of lack in the articles concerning their experimental measurements.
c) the set of values from V. Zobel (1977Zo01), because these values have changed the consistency of the data set when they were introduced in the preliminary calculation with Lweight program and produced inconsistent weighted average for gamma emission intensity.

For the 186-keV γ-ray, the evaluators have chosen to take into account the nine values with associated uncertainty for the calculation. The relative γ emission intensity value given by 2004Mo07 is the same one that those measured by J. U. Delgado (2002De03). In 2004Mo07 article, the author measured the 609.3 keV absolute emission probability (Table 4) and normalized the 2002De03 data set with this value of 45.57 (18), so the value given in 2004Mo07 was omitted. The weighted average of the remaining values above was calculated using LWEIGHT computer program (version 3). Based on the Chauvenet's criterion, Mowatt (1970Mo28), Aleksandrov (1974AlZT) and Mouze (1990MoZP) were shown outlier values by the Lweight program, then they have been omitted.

The adopted relative value is the weighted mean of the six remaining values: *7.815*, with an internal uncertainty of *0.025* and a reduced χ^2 of 0.52, so this data set is consistent. The largest contribution comes from the value of Delgado (2002De03), amounting to 63 %.

For the 414-, 449- and 600-keV γ-rays, the evaluators used the measured ratios of Lourens (1971Lo19): I_{414}/I_{186} = 0,00086 ; I_{449}/I_{186} = 5,5 $\times 10^{-5}$; I_{600}/I_{186} =0,00014 and the absolute value I_γ(186) = 3.555 (19) %, to determine their absolute emission intensities.

The evaluated relative and absolute γ-ray emission intensities are given in Table 6.

Table 6: Evaluated relative and absolute γ-ray emission intensities.

Energy (keV)	Relative emission intensity (%)	Absolute emission intensity (%)
186.211 (13)	7.815 (25)	3.555 (19)
262.27 (5)	0.012 (4)	0.0055 (18)
414.60 (5)		0.0003
449.37 (10)		0.0002
600.66 (5)		0.0005

6 References

1928Wa** S. W. Watson, M. C. Henderson, Proc. Roy. Soc. A118(1928)318 [Half-life].
1928Br** H. J. J. Braddick, H. M. Cave, Proc. Roy. Soc. A121(1928)367 [Half-life].
1928Cu** I. Curie, F. Joliot, Compt. Rend. (Paris) 187(1928)43 [Half-life].
1929Wa** F. A. B. Ward, C. E. Wynn-Williams, H. M. Cave, Proc. Roy. Soc. A125(1929)713 [Half-life].
1930Me** L. Meitner, W. Ortmann, Z. Phys. 60(1930)143 [Half-life].
1935Gl02 E. Gleditsch, E. Foeyn, Am. J. Sci. 29(1935)253 [Half-life].
1939Gü** P. Günther, Z. Phys. Chem. A185(1939)367 [Half-life].
1949Ko01 T. P. Kohman, D. P. Ames, J. Sedet, NNES 14B(1949)1675 [Half-life].
1956Se10 W. Sebaoun, Ann. Phys. (Paris) 1(1956)680 [Half-life].
1959Ma12 G. R. Martin, D. C. Tuck, Int. J. Appl. Radiat. Isot. 5(1959)141 [Half-life].
1959Go80 G. V. Gorshkov, Z. G. Gretchenko, A. T. Il'inskaya, B. S. Kuznetsov, N. S. Shimanskaya, At. Energ. (USSR) 7(1959)912 [Half-life].
1960St20 F. S. Stephens, F. Asaro, I. Perlman, Phys. Rev. 119(1960)796 [I_γ].
1963Ba62 G. Bastin-Scoffier, C. F. Leang, R. J. Walen, J. Phys. 24(1963)854 [I_α].
1966Ra13 H. Ramthun, Nucleonik 8(1966)244 [Half-life].
1969Gr33 K. Ya. Gromov, B. M. Sabirov, J. J. Urbanets, Bull. Acad. Sci. USSR, Phys. Ser. 33(1970)1510 [I_γ].
1969Li10 E. W. A. Lingeman, J. Konijn, P. Polak, A. H. Wapstra, Nucl. Phys. A133(1969)630 [I_γ].
1969Wa27 G. Wallace, G. E. Coote, Nucl. Instrum. Meth. 74(1969)353 [I_γ].
1970Mo28 R. S. Mowatt, Can. J. Phys. 48(1970)2606 [I_γ].
1971Lo19 W. Lourens, A. H. Wapstra, Z . Phys. 247(1971)147 [I_γ].
1974AlZT V. S. Aleksandrov, JINR – PL 7308(1973) [I_γ].
1973De50 A. G. de Pinho, M. Weskler, Z. Naturforsch. 28a(1973)1635 [X-ray emission intensities].
1975Ha31 A. Hachem, Compt. Rend. (Paris) 281B(1975)45 [I_γ].
1977Zo01 V. Zobel, J. Eberth, U. Eberth, E. Eube, Nucl. Instrum. Meth. 141(1977)329 [I_γ].
1981Mo28 G. Mouze, Compt. Rend. (Paris) 292(1981)1243 [I_γ].
1982Ak03 H. Akcay, G. Mouze, D. Maillard, Ch. Ythier, Radiochem. Radioanal. Lett. 51(1982)1 [I_γ].
1982Fa10 M. A. Farouk, A. M. Al-Soraya, Nucl. Instrum. Meth. 200(1982)593 [I_γ].
1983Ol01 D. G. Olson, Nucl. Instrum. Meth. 206(1983)313 [I_γ].
1983Sc13 U. Schötzig, K. Debertin, Int. J. Appl. Radiat. Isot. 34(1983)533 [I_γ].
1990Ho28 N. E. Holden, Pure Appl. Chem. 62(1990)941 [Half-life].

1990MoZP G. Mouze, C. Ythier, J. F. Comanducci, Rev. Roumaine Phys. 35(1990)337 [I_γ].
1991Li11 W. –J. Lin, G. Harbottle, J. Radioanal. Nucl. Chem. Lett. 153(1991)137 [I_γ].
1991Ry01 A. Rytz, At. Data and Nucl. Data Tables 47(1991)205 [E_α, I_α].
1993Di09 O. Diallo, G. Mouze, C. Ythier, J. F. Comanducci, Nuovo Cimento 106A(1993)1321 [I_γ].
1996Ak02 Y. A. Akovali, Nucl. Data Sheets 77(1996)433 [Spin, parity and multipolarity].
1996El01 Y. A. Akovali, Nucl. Data Sheets 77(1996)271 [Spin, parity and multipolarity].
1996Sc06 E. Schönfeld, H. Janβen, Nucl. Instrum. Meth. Phys. Res. A369(1996)527 [Atomic data].
1998Mo14 J. Morel, M. Etcheverry, J. L. Picolo, Appl. Radiat. Isot. 49(1998)1387 [I_γ].
2000Sa32 D. Sardari, T. D. MacMahon, J. Radioanal. Nucl. Chem. 244(2000)463 [I_γ].
2001La14 S. P. LaMont, R. J. Gehrke, S. E. Glover, R. H. Filby, J. Radioanal. Nucl. Chem. 248(2001)247 [I_α].
2002De03 J. U. Delgado, J. Morel, M. Etcheverry, Appl. Radiat. Isot. 56(2002)137 [I_γ].
2002MoZP G. L. Molnar, Z. S. Révay, T. Belgya, 11th Int. Symp. on capture gamma-ray spectroscopy, 2-6 Sep. 2002, Pruhonice (2003)522 [I_γ].
2002Ba85 I. M. Band, M. B.Trzhaskovskaya, C. W. Nestor, Jr., P. O. Tikkanen, S. Raman, At. Data Nucl. Data Tables 81(2002)1 [Theoretical ICC].
2003Au03 G. Audi, A. H. Wapstra, C. Thibault, Nucl. Phys. A729(2003)129 [Q].
2004He** R. G. Helmer, IAEA – CRP Report to be published (2004) [I_γ].
2004Mo07 J. Morel, S. Speman, M. Rasko, E. Terechtchenko, J. U. Delgado, Appl. Radiat. Isot. 60(2004)341 [I_γ].