^{177}Lu - Comments on Evaluation of Decay Data for b^{-} Decay

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Evaluation Procedures

The *Limitation of Relative Statistical Weight* (LWM) [1] method for averaging numbers has been applied throughout this evaluation.

1. Decay Scheme

The decay scheme for ^{177}Lu is taken from the recent evaluations of Kondev (2002KoXX) and Browne (1993Br06). The ground state has been assigned $J^{\pi} = 7/2^{+}$ and the $7/2^{+}[404]$ ($g_{7/2}$) Nilsson configuration. It decays via β^{-} emission ($P_{\beta-}$= 100%) to levels of the stable ^{177}Hf daughter isotope. While the decay branches to the ^{177}Hf ground state ($J^{\pi} = 7/2^{-}$) and to the 112.9499 keV ($J^{\pi} = 9/2^{-}$), and 321.3162 keV ($J^{\pi} = 9/2^{+}$) levels are well established, there is some ambiguity in the literature regarding the direct β^{-}-decay feeding into the $J^{\pi} = 11/2^{-}$ level at 249.6744 keV.

2. Nuclear Data

Half-life

The half-life of the ^{177}Lu ground state has been measured by several authors and the results are summarized in Table 1. In all cases the source was prepared using the ^{176}Lu(n,γ) reaction, where a three-quasiparticle isomer ($K^{\pi} = 23/2^{-}$ and excitation energy of 970 keV), with a half-life that is significantly longer ($T_{1/2}$ = 160.44(6) d), when compared to that for the ^{177}Lu ground state, is also produced. Since the isomer de-excites partially via gamma emission (P_{γ}= 21.4%(8)), its half-life and relative population should be taken into account when determining the $T_{1/2}$ for the ground state. The recommended value for the ^{177}Lu ground state half-life is $T_{1/2}$ = 6.647(4) d. It is the weighted average of the 6.645(30) d (1982La25), 6.65(1) d (2001Zi01) and 6.646(5) d (2001Sc23) values. The half-lives reported by 1958Be41, 1960Sc19, 1972Em01 and 1990Ab02 were excluded from this analysis since authors did not consider the effect of the ^{177}Lu^{m} isomer ($T_{1/2}$ = 160.44 d) was not taken into account. Although the relative statistical weight of the 2001Sc23 value was 78.3%, its uncertainty was not increased since the set is consistent. It should be noted that there are may be a systematic uncertainty in the recommended $T_{1/2}$ value for the ^{177}Lu ground state, due to possible differences in the half-life values of ^{177}Lu^{m} and its population intensity that were used in 1982La25, 2001Zi01 and 2001Sc23.

Table 1 Measured and recommended values for the ^{177}Lu ground state half-life.

Reference	$T_{1/2}$, d	Comment
1958Be41	6.75 (5) #	
1960Sc19	6.74 (4) #	
1972Em01	6.71 (1) #	
1990Ab02	6.7479 (7) #	
1982La25	6.645 (30)	$T_{1/2}$(^{177m}Lu) = 159.5 d (7) was used in the fitting procedure.
2001Zi01	6.65 (1)	Corrections for $T_{1/2}$(^{177m}Lu) have been applied, but the value has not been reported.
2001Sc23	6.646 (5)	$T_{1/2}$(^{177m}Lu) = 160.4 d was used in the fitting procedure.
Adopted	**6.647 (4)**	c2/(N-1) = **0.07**

Contributions from the decay of the $^{177}Lu^{m}$ ($T_{1/2}$ = 160.44 d) isomer have not been taken into account. The value is not used in the analysis.

Q value

The Q(β^-) = 498.3(8) keV is from 1995Au04. It is in agreement with that of 496.8(17) keV (1962El02), deduced from the β^-–decay endpoint energy to the ^{177}Hf ground state. The total average decay energy released in the β^--decay of the ^{177}Lu ground state is calculated using RADLST [2] as 497.4(25) keV. It agrees very well with the Q(β^-) value that is reported by Audi (1995Au04), thus suggesting that the decay scheme is complete.

2.1 b - **Decay Transitions**

The β^- transition endpoint energies were determined from Q(β^-) = 498.3(8) keV (1995Au04) and the individual level energies. The latter were deduced from a least-squares fit to the adopted gamma-ray energies that are given in Table 3. The β^- transition endpoint energies are in agreement with values measured by 1962El02 and 1955Ma12. The adopted values for the β^- transition probabilities per 100 disintegrations were determined from the total (photons + conversion electrons) transition probability balances at each level. In general, values deduced in the present evaluation are consistent with those from 2001Sc23, 1975El07 and 1993Br06, albeit in 2001Sc23 there is no report on a direct β^- -decay feeding into the $J^\pi = 11/2^-$ level.

Table 2 Measured and adopted values for the ^{177}Lu b$^-$-decay transition probabilities

Reference	$P_{\beta-}$ to $J^\pi = 7/2^-$	$P_{\beta-}$ to $J^\pi = 9/2^-$	$P_{\beta-}$ to $J^\pi = 11/2^-$	$P_{\beta-}$ to $J^\pi = 9/2^+$
2001Sc23	79.3 (5)	9.1 (5)		11.58 (12)
1975El07 1993Br06	78.6 (10)	9.1 (10)	0.05 (2)	12.2 (7)
1967Ha09	87.2 (11)	6.0 (8)	0.07 (2)	6.7 (3)
1964Al04	86.3 (13)	7 (1)	0.03 (3)	6.7 (3)
1962El02	90 (4)	2.95 (3)	0.31 (6)	6.72 (25)
1956Wi39	96	1.3	0.2	2.6
1955Ma12	90	3		7
1949Do05	65	17		
Adopted	**79.3 (5)**	**9.1 (5)**	**0.012 (8)**	**11.64 (10)**

There are, however, significant differences with the 1967Ha09, 1964Al04, 1962El02, 1956Wi39, 1955Ma12 and 1949Do05 work, as summarized in Table 2. The log *ft* values were calculated using the program LOGFT [3] using the adopted β^- transition probabilities.

2.2 Gamma Transitions and Internal Conversion Coefficients

The measured values for gamma-ray transition energies that follow the decay of the ^{177}Lu ground state are presented in Table 3. The gamma-ray energies reported by Matsui et al. (1989Ma56) were adopted in the present evaluation. These were measured with a high precision using a germanium spectrometer. The total (photon + conversion electrons) transition probabilities were deduced by multiplying the adopted values for the relative gamma-ray intensities (Table 10) by a normalization factor that was deduced from the values for the absolute intensity per 100 disintegrations of the 208.3662 keV gamma ray (Table 11). The total electron conversion coefficients were interpolated from the tables of Rösel (1978Ro22). Transition multipolarities are taken from 2002KoXX and 1996Br06. They are based on comparisons between the measured electron conversion coefficients with theoretical values (1978Ro22), as well as on available angular correlation data.

Table 3 Measured and adopted values for gamma ray transition energies following b⁻ decay of ^{177}Lu

Reference	$\gamma_{1,0}$	$\gamma_{2,1}$	$\gamma_{2,0}$	$\gamma_{3,2}$	$\gamma_{3,1}$	$\gamma_{3,0}$
1989Ma56	112.9498 (4)	136.7245 (5)	249.6742 (6)	71.6418 (6)	208.3662 (4)	321.3159 (6)
1981Hn03	112.95 (2)	136.72 (2)	249.7 (5)	71.646	208.35 (2)	321.27 (5)
1967Ha09	112.95 (2)	136.72 (5)	249.65 (6)	71.66 (6)	208.34 (6)	321.32 (12)
1965Ma18	112.952 (2)	136.730 (6)	249.868 (25)	71.646 (2)	208.359 (10)	321.330 (40)
1964Al04	112.97 (2)	136.68 (2)	249.69 (10)	71.64 (2)	208.36 (6)	321.36 (20)
1961We11	112.97 (2)	136.70 (10)	249.70 (10)	71.60 (10)	208.38 (2)	321.34 (3)
1955Ma12	112.965 (20)		250.0 (5)	71.644 (20)	208.362 (20)	321.36 (10)
Adopted	**112.9498 (4)**	**136.7245 (5)**	**249.6742 (6)**	**71.6418 (6)**	**208.3662 (4)**	**321.3159 (6)**

Details about the mixing ratios values for E1+M2 and M1+E2 transitions are given below. The electron conversion coefficients are interpolated values from the tables of Rösel (1978Ro22). The quoted uncertainties reflect the corresponding uncertainties in the mixing ratios values. Adopted α_K, α_{L1}, α_{L2}, α_{L3}, and α_M values were also used as an input for the RADLST [2] and EMISSION (2001Sc08) programs.

2.2.1 112.9498 keV (g$_{1,0}$)

Values used in the analysis of the mixing ratios are summarized in Table 4. The unweighted average value is adopted, but its uncertainty was increased to 0.4, so that the range includes the most precise value of $\delta(\gamma_{1,0})$ = –4.85(5) (1992De53). During the analysis, the uncertainty of the 1992De53 value was also increased to 0.056, so that its relative statistical weight is scaled down from 55.8% to 50%.

Table 4 Measured and adopted mixing ratios values for the 112.9498 keV transition

Reference	$\delta(\gamma_{1,0})$	Comment
1974Kr12	-4.7 (2)	From $\gamma(\theta)$ in ^{177m}Lu ($T_{1/2}$ = 160.44 d) decay.
1974Ag01	-3.99 (25)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1970Hr01	-3.7 (3)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1961We11	-4.0 (2)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1972Ho54	-4.75 (7)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1972Ho39	-4.5 (3)	From ICC ratios in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1977Ke12	-4.8 (2)	From $\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
1992De53	-4.85 (5)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay.
Adopted	**-4.4 (4)**	c**2/(N-1) = 5.61**

2.2.2 136.7245 keV (g$_{2,1}$)

The adopted mixing ratios values of $\delta(\gamma_{2,1})$ = –3.0 (7) is from 1974Kr12.

2.2.3 321.3159 keV (g$_{3,0}$)

Values used in the analysis of the mixing ratios are summarized in Table 5. The unweighted average value is adopted, but the uncertainty was expanded so that the range includes the most precise value of $\delta(\gamma_{1,0})$ = + 0.17(1) (1974Kr12). The sign of $\delta(\gamma_{3,0})$ was determined to be positive by 1974Kr12.

Table 5 Measured and adopted mixing ratios values for the 321.3159 keV transition

Reference	$\lvert\delta(\gamma_{3,0})\rvert$	Comment
1974Kr12	0.17 (1)	From $\gamma(\theta)$ in ^{177m}Lu ($T_{1/2}$ = 160.44 d) decay
	0.42 (1)	From comparison between experimental α_K = 0.087(3), weighted average from values reported by 1972Gr35, 1974Ag01, 1974Je02 and 1961We11, and theoretical α_K(E1), and α_K(M2) values from 1978Ro22.
	0.42 (1)	From comparison between experimental α_L = 0.0169(8), weighted average from values reported by 1972Gr35, 1974Ag01, 1974Je02 and 1961We11, and theoretical α_L(E1), and α_L(M2) values from 1978Ro22.
Adopted	**0.34 (17)**	$c^2/(N-1)$ = **208.33**

2.2.4 208.3662 keV ($g_{3,1}$)

Values used in the analysis of the mixing ratios are given in Table 6. The weighted average and the internal uncertainty were adopted. The sign of $\delta(\gamma_{3,1})$ is uncertain. It has been reported to be positive by 1974Kr12, but negative by 1977Ke12 and 1961We11.

Table 6 Measured and adopted mixing ratios values for the 208.3662 keV transition

Reference	$\lvert\delta(\gamma_{3,1})\rvert$	Comment
1974Kr12	0.07 (2)	From $\gamma(\theta)$ in ^{177m}Lu ($T_{1/2}$ =160.44 d) decay
1977Ke12	0.08 (2)	From $\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay
1961We11	0.07 (3)	From $\gamma\gamma(\theta)$ in ^{177}Lu ($T_{1/2}$ = 6.647 d) β^- decay
Adopted	**0.074 (13)**	$c^2/(N-1)$ = **0.07**

2.2.5 71.6418 keV ($g_{3,2}$)

Values used in the analysis of the mixing ratios are shown in Table 7. None of them has a relative statistical weight greater than 50%, and hence the weighted average value was adopted. The sign of $\delta(\gamma_{3,2})$ is negative as determined by 1974Kr12 and 1970Hr01.

Table 7 Measured and adopted mixing ratios values for the 71.6418 keV transition

Reference	$\lvert\delta(\gamma_{3,2})\rvert$	Comment
1974Kr12	0.051(37)	From $\gamma(\theta)$ in ^{177m}Lu ($T_{1/2}$ = 160.44 d) decay.
1974Ag01	0.049 (15)	From comparison between experimental α_K = 0.90(11) from 1974Ag01 and theoretical α_K(E1), and α_K(M2) values from 1978Ro22.
1970Hr01	0.017 (7)	From $\gamma\gamma(\theta)$.
	0.016 (6)	From comparison between experimental α_{L1} = 0.076(5), weighted average from values reported by 1972Gr35 and 1974Ag01, and theoretical α_{L1}(E1), and α_{L1}(M2) values from 1978Ro22.
	0.034 (14)	From comparison between experimental α_{L2} = 0.029(3), weighted average from values reported by 1972Gr35 and 1974Ag01, and theoretical α_{L2}(E1), and α_{L2}(M2) values from 1978Ro22.
Adopted	**0.018 (4)**	$c^2/(N-1)$ = **0.37**

3. Atomic Data

3.1 Hf

The data are from Schönfeld and Janssen (1996Sc06).

3.1.1 X Radiation

While the energies for XKα_2 (Hf) and XKα_1 (Hf) are from Schönfeld and Rodloff (1999ScZX), the X-Kβ and XL energies are from Firestone (1996FiZX). Relative emission probabilities were calculated using the program EMISSION (2001Sc08).

3.1.2 Auger Electrons

The energies for KLL (Hf), KLX (Hf) and KXY (Hf) are from Schönfeld and Rodloff (1998ScZM). Relative emission probabilities were calculated using the program EMISSION (2001Sc08).

4.Photon Emission

4.1 X-Ray Emission

While the energies for X-Kα2 (Hf) and X-Kα1 (Hf) are from Schönfeld and Rodloff (1999ScZX), the X-Kβ and XL energies are from Firestone (1996FiZX). The adopted absolute intensities per 100 disintegrations were calculated using the program EMISSION (2001Sc08). Comparisons between calculated values and the experimental data in 2001Sc23 and 1987Me17, as well as values calculated using the program RADLST [2], are presented in Table 8. In general the agreement between various entries is fairly good, thus suggesting that the ^{177}Lu ground state decay scheme is complete.

Table 8 comparison between various X-ray emission intensities per 100 disintegration

	Energy KeV	2001Sc23	1987Me17	RADLST	EMISSION
XLl (Hf)	6.960	0.0735 (25)	0.087 (5)		0.0613 (16)
XLα2 (Hf)	7.844	}	}		0.137 (4)
XLα1 (Hf)	7.899	} 1.51 (3) }	1.59 (6)		1.21 (3)
XLη (Hf)	8.139	}	}		0.0313 (9)
XLβ4 (Hf)	8.905	}	}		0.0335 (12)
XLβ1 (Hf)	9.023	} 1.34 (3) }	}		1.15 (4)
XLβ6 (Hf)	9.023	}	} 1.76 (7)		0.0147 (4)
XLβ3 (Hf)	9.163	}	}		0.0435 (15)
XLβ2,15 (Hf)	9.342	0.274 (7)	}		0.248 (7)
XLγ1 (Hf)	10.516	} 0.231 (6)	}		0.222 (6)
XLγ6 (Hf)	10.733	}	}		0
			} 0.292 (12)		
XLγ2 (Hf)	10.834	} 0.0223 (14)	}		0.00835 (19)
XLγ3 (Hf)	10.890	}	}		0.0115 (4)
XL				3.08 (7)	3.18 (6)
XKα2 (Hf)	54.6120 (7)	1.55 (3)	1.65 (3)	1.59 (5)	1.59 (3)
XKα1 (Hf)	55.7909 (8)	2.73 (6)	2.84 (5)	2.78 (9)	2.78 (6)
XK'β1 (Hf)	62.985-63.662	0.885 (15)	0.919 (16)		0.917 (23)
XK'β2 (Hf)	64.942-65.316	0.238 (5)	0.252 (5)		0.245 (8)
XKβ (Hf)				1.16 (4)	1.16 (3)

4.2 Gamma Emission

The measured relative intensities for transitions following the β– decay of ^{177}Lu and their adopted values are presented in Table 9. The original values were normalized to I_γ = 100.0 for the 208.3662 keV ($\gamma_{3,1}$) gamma ray. The uncertainty in I_γ for the 321.3159 keV ($\gamma_{3,0}$) gamma ray was increased 1.86 times so that its statistical weight was lowered from 77.6% to 50%.

The measured absolute intensities for the 208.3662 keV ($\gamma_{3,1}$) gamma ray and its corresponding adopted value are presented in Table 10. The latter was used to normalize the relative intensities (Table 9) to absolute values per 100 disintegrations.

Table 9 - Relative gamma-ray intensities for transitions following b^- decay of ^{177}Lu

	$\gamma_{1,0}$	$\gamma_{2,1}$	$\gamma_{2,0}$	$\gamma_{3,2}$	$\gamma_{3,1}$	$\gamma_{3,0}$
2001Sc23	59.6 (6)	0.448 (8)	1.918 (17)	1.674 (21)	100.0	2.002 (19) *
1987Me17	59.6 (11)	0.457 (8)	2.00 (3)	1.71 (5)	100.0	2.17 (4)
1974Ag01	60 (5)	0.52 (5)	1.90 (20)	1.50 (10)	100.0	2.00 (20)
1964Al04	58 (4)	0.43 (3)	1.93 (14)	1.40 (10)	100.0	1.99 (14)
1961We11	62 (2)	0.47 (15)	2.00 (20)	0.30 (10) #	100.0	2.28 (10)
1955Ma12	45.5 #		1.36 #	0.91 #	100.0	1.45 (29) #
Adopted	**59.7 (5)**	**0.453 (6)**	**1.938 (15)**	**1.663 (19)**	**100.0**	**2.08 (8)**
$c^2/(N-1)$	**0.38**	**0.76**	**1.45**	**3.58**		**3.62**

* The uncertainty was increased 1.86 times in order to reduce its statistical weight from 77.6% to 50%.
# Value not used in the analysis.

Table 10 - Absolute emission probabilities per 100 disintegrations for the 208.3662 keV gamma ray

	Absolute Intensity for $\gamma_{3,1}$ per 100 disintegrations, %
2001Sc23	10.36 (7)
1964Cr02	10.7 (5)
1961We11	11.4 (6)
Adopted	**10.38 (7)**
$c^2/(N-1)$	**1.69**

5. Electron Emission

The electron energies and emission probabilities were calculated using the RADLST [2] program. The average β^- energies were calculated using the LOGFT [3] program. The β^- transition endpoint energies were determined using $Q(\beta^-)$ = 498.3(8) keV (1995Au04) and the individual level energies that were deduced from a least-squares fit to the recommended gamma-ray energies. The adopted values for the β^- transition emission probabilities were determined from the total (photons + electrons) gamma-ray emission probability balances at each level.

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