^{64}Cu - Comments on evaluation of decay data
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This evaluation was completed in September 2010. To compare with the previous evaluation of R.G. Helmer in 2002, it includes several results published since this date (2002We02, 2007Qa02, 2010Wanke) and others obtained in the context of an Euramet exercise (2012Bé).
Several procedures can be followed to determine the decay scheme of ^{64}Cu. In this evaluation we tried to introduce results coming from methods other than ionizing radiation measurements, in order to minimize the inherent correlation of the results.

1 Decay Scheme

The only levels in ^{64}Zn and ^{64}Ni below the decay energies are those populated in this decay, so the decay scheme is complete.

The J^{π} values and half-lives for the excited levels are from Adopted Levels in Nuclear Data Sheets (2007Si04).

2 Nuclear Data

Q values from 2003Au03 are 579.4 (7) keV for β^- decay and 1675.03 (20) keV for $\varepsilon\beta^+$ decay.

The change in the half-life as a function of the chemical form or electron environment has been studied by several authors. These results are tallied after those used for the half-live evaluation.

The results of half-life measurements are listed below, in hours.

Not included in the evaluation			
	$T_{1/2}$	u_c	
(1935Am01)	10		omitted, no uncertainty
(1937He05)	12.5		omitted, no uncertainty
(1944Hu05)	11.9	1	omitted, same data as 1943Hu03
(1957Wr37)	12.87	0.05	superseded by 1972Em01
(1965He08)	13.9		omitted, no uncertainty
(1967Vi08)	12.8		omitted, no uncertainty
(1972WyZZ)	12.72	0.04	superseded by 1972Em01

The half-life values considered are, in hours:

	$T_{1/2}$	u_c	
(1936Va02)	12.8	0.1	
(1938Ri)	12.8	0.3	as cited in 1968Ke12
(1939Sa02)	12.8	0.3	as cited in 1968Ke12
(1943Hu03)	11.9	1	

	$T_{1/2}$	u_c	
(1950Ra62)	12.8	0.04	as cited in 1968Ke12
(1951Sc56)	12.74	0.07	
(1951Si91)	12.88	0.03	
(1955To07)	12.80	0.03	as cited in 1968Ke12
Rudstam	12.90	0.06	as cited in 1968Ke12
(1959Po64)	12.85	0.05	
(1965Pa18)	12.86	0.03	
(1966Fu14)	12.70	0.03	
(1966Li09)	12.86	0.03	
*(1968He20)	12.701	0.011	as cited in 1973De56
(1968Ke12)	12.80	0.04	
(1969Bo11)	12.65	0.17	
*(1972Em01)	12.715	0.007	
*(1972MeZM)	12.701	0.007	as cited in 1996Si12
(1973ArZI)	12.6	1	
*(1973De56)	12.699	0.002	
(1973Ne02)	12.82	0.04	
*(1974Ry01)	12.704	0.006	
*(1980RuZY, 1982RuZV)	12.701	0.003	
*(1989Ab22)	12.700	0.003	
*(2010Wanke)	12.704	0.005	
*(2012Bé - IFIN)	12.696	0.012	
*(2012Bé - NPL)	12.702	0.008	

The set of 26 unsuperseded values with uncertainties is inconsistent. The unweighted average is 12.76 (2) hours and the weighted average is 12.7024 with an internal uncertainty of 0.0013, a reduced-χ^2 of 6, and an external uncertainty of 0.0031. It has been suggested that many of the older measurements give longer half-lives due to the presence of unidentified impurities. The value of 12.699 (2) used here for 1973De56 is the simple mean of their 22 measured values. The input value of 12.715 (7) is the evaluator's weighted average of the three values given in the paper of 1972Em01. The uncertainty given by 1989Ab22 has been increased to 0,003 to include systematic uncertainty components, but due to the very brief description of the process given in this paper, it is very difficult to assess them.

From the original set of 26 values, the most accurate ones (*) with uncertainties less than 0.012 hour have been accepted for statistical processing. In this set of nine values (1968He20, 1972Em01, 1972MeZM, 1973De56, 1974Ry01, 1980RuZY, 1989Ab22, 2010Wanke, 2012Bé – IFIN, and 2012Bé - NPL), the value of 1972Em01 was found outlier by the Chauvenet's criterion.

The adopted half-life is then the weighted average of the 9 remaining values. This average is 12.7004 with an internal uncertainty of 0.0013; an external uncertainty of 0.0006 and a reduced-χ^2 of 0.24.

As noted below, changes in this half-life of the order of 1 part in 10^4 have been reported depending on the chemical form. Since these changes are comparable to the calculated uncertainty, the adopted uncertainty has been increased to 0.0020.

This half-life has been measured, and reported, many times primarily to identify the radionuclide observed, for example, in the process of cross section measurements. Some of these values, which are not included above are: 13 (1948Mi12); 12.8 (1950Ho26); and 13.8 (14), 13.6 (7), and 12.4 (17) (1972Cr02).

Since ^{64}Cu decays, in part, by electron capture, there have been several measurements of the variation in the decay constant with the chemical form or atomic environment. The results from 1968 to 1975 are tallied in 1976Ha66 and given in the following table.

Reference and first author	Forms compared		$\Delta\lambda/\lambda\cdot 10^4$
1972Au Auric	Cu phtalocyanine in two forms		10.0 (16)
1972Em01 Emery	Cu metal	$Cu(NO_3)_2$	15 (15)
1973Ha60 Harbottle	Cu metal	CuO	0 (3)
1973De56 Dema	Cu phtalocyanine in two forms		0.4 (20)
1974Je Jenschke	Cu metal	$Cu(H_2O)_6SO_4$	.12 (9)
	Cu metal	$Cu(H_2O)_4(NO_3)_2$	0.81 (10)
	Cu metal	Cu(2)	2.94
	Cu metal	Cu(3)	1.86
1974Jo17 Johnson	Cu phtalocyanine in two forms		1.4 (23)
	Cu phtalocyanine in two forms		3.7(58)
	Cu metal	CuO	0.0 (23)
1975MaXN	Cu metal	Cu_2S	2.3 (10)
	Cu metal	$CuInS_2$	1.5 (10)
	Cu metal	Cu_2SnS_3	1.5 (10)
	$CuInS_2$	Cu_2SnS_3	0 (1)
1979Eh01 Ehrhart	Cu metal	atom % Cu in Ag	
		2	1.7 (3)
		5	1.6 (4)
		25	0.9 (4)
		50	0.7 (5)
		75	0.2 (4)
1979Ko31 Koran	Cu metal	atom % Cu in Au	
		2	3.1 (4)
		5	3.0 (4)
		25	1.4 (4)
		50	0.7 (5)
		75	-0.2 (9)

The earliest measurements gave larger values of $\Delta\lambda/\lambda$, but the values beginning in 1973 range from 0 to 0.000 37 (6). These values are similar in magnitude to the uncertainty of 1.5 parts in 10^4 assigned to the adopted value. A set of measurements is also given in 1968Ke12, but the units of the results are not clear.

No dependence of the half-life with the temperature has been observed (2008Fa12).

2.1 β^-, β^+ and Electron Capture Transitions

The probabilities of the β^-, β^+, and ε branches were determined by a series of separate, but partially correlated, measurements by 1983Ch47, 1986Ka03 and 2007Qa02. These measurements included the β^- spectrum, β^+ spectrum, 4πβ-γ coincidences, liquid scintillation counting, and X- , γ- ray spectrum. Then, in 1983Ch47 their analysis contained a least-squares fit to the various measured quantities and ratios of quantities, taking the covariances into account.

Another kind of investigation made by mass spectrometry measurements of the number of atoms of ^{64}Ni and ^{64}Zn produced in the decay of a ^{64}Cu sample (2002We02) led to the determination of the $P_{\beta-}$ branching ratio.

- **β^- Transition**

The published measured probabilities of the β^- transition are:

References	$P_{\beta-}$ (%)	uc (%)	Comments
1983Ch47	39.04	0.33	$4\pi\beta$(LS)–γ coincidence counting
1986Ka03	38.34	0.56	deduced
2002We02	38.06	0.3	Mass spectrometry
2007Qa02	38.4	1.2	2π PC – anti coincidence counting
χ^2 /n – crit χ^2	1.6	3.8	
UWM	38.46	0.21	
WM	**38.48**	**0.26**	**Adopted**

From P_{β}^- = 38.48 (26) %, then **$P(_{\beta}^+$ +ec) = 61.52 (26) %.**

- **β^+ Transition**

Two methods are possible to derive the $P(_{\beta}^+)$ value:

➢ From published measured probabilities of the β^+ transition:

References	$P_{\beta+}$ (%)	uc (%)	Comments
1983Ch47	17.86	0.14	Ge(Li) spectrometry
1986Ka03	17.93	0.20	HPGe γ spectrometry
2007Qa02	17.8	0.4	γ–γ coincidence counting
2010Wanke	17.56	0.11	HPGe γ spectrometry
2010Bé - CMI	17.69	0.19	HPGe γ spectrometry
2010Bé - LNHB	17.55	0.15	HPGe γ spectrometry
2010Bé – IFIN	17.65	0.60	HPGe γ spectrometry
χ^2 /n – crit χ^2	0.9	2.8	
UWM	17.72	0.06	
WM	17.68	0.06	

➢ From theoretical calculations, using the LOGFT program, the ratio Pec/ $P(_{\beta}^+)$ is: 2.485 (25), from the $P(_{\beta}^+ +ec_{0,0})$ = 61.05 (26) % below, the $P(_{\beta}^+)$ value is derived being $P(_{\beta}^+)$ = 17.52 (15) %.

The latter value has been obtained by an independent method and it is less correlated than the results of direct measurements. Moreover, it can be noted that the weighted mean of the four 2010 values, listed in the above table, of 17.58 (8) is very close to 17.52 (15). Thus, **$P(_{\beta}^+)$ = 17.52 (15) %** has been adopted in this evaluation.

- **Electron Capture Transitions**

The adopted $P_{ec0,1}$ value is deduced:

From P_{g1345} = 0.4749 (34) % (§ 2.4), then **$P_{ec0,1}$ = 0.4749 (34) %,**

and with $P(_{\beta}^+ +ec_{0,0} + ec_{0,1})$ = 61.52 (26) %, **$P(_{\beta}^+ +ec_{0,0})$ = 61.05 (26)%.**

From the two values of $P(\beta^+)$ as determined above two $P_{ec0,0}$ can be derived:

- With $P(\beta^+)$ = 17.71 (7), $P(ec_{0,0})$ = 43.34 (27) %,
- With $P(\beta^+)$ = 17.52 (15), $P(ec_{0,0})$ = 43.53 (20) %.

These values can be compared with the three experimental results obtained for the total P_{ec} (1983Ch47, 1986Ka03, 2007Qa02):

References	Total P_{ec}	uc (%)	Comments
1983Ch47	43.10	0.46	4πβ(LS)–γ coincidence counting
1986Ka03	43.73	0.52	4πβ(PC)–γ coincidence counting + HPGe γ spectrometry + 4πβ–γ coincidence counting
2007Qa02	43.8	1.4	Si(Li) X-ray spectrometry
χ^2 /n – crit χ^2	0.5	4.6	
UWM	43.54	0.22	$P(ec_{0,0})$ = 43.07 (33)
WM	43.40	0.33	$P(ec_{0,0})$ = 42.93 (33)

The unweighted and the weighted means above are consistent, within the uncertainty limits, with $P(ec_{0,0})$ = 43.34 (27) % calculated from experimental $P_{\beta+}$ values. This was expected since they were derived from the same sets of measurements.

The set of two values: **$P(\beta^+)$ = 17.52 (15) % and $P(ec_{0,0})$ = 43.53 (20) %** has been adopted in this evaluation because it was derived from another different method (using theoretical Pec/ $P(\beta^+)$ ratio).

The average particle energies to the ^{64}Ni and ^{64}Zn ground states are 278.2 (9) and 190.7 (3) keV, respectively, and are from the LOGFT code. The log ft values to the ^{64}Ni ground state and level of 1345 keV are 4.973 (3) and 5.501 (6), respectively, and to the ^{64}Zn ground state - 5.302 (3), all of which are consistent with allowed transitions from the 1^+ parent state.

2.2 Gamma Transitions

The J^π assignments are from the Adopted Levels in the Nuclear Data Sheets (2007Si04) and these imply the γ-ray has E2 multipolarity.

The internal-conversion coefficients (ICC) were interpolated from the tables of Band *et al.* (2002Ba85) by using the computer code BrIcc (2008Ki07) with the so called “Frozen orbital” approximation.

The internal-pair-formation coefficient was interpolated from the theoretical values and it is IPFC(1345) = 0.000 039.

From the ICC values and gamma ray emission intensity I_{g1345} = 0.4748 (34) % (§ 4.2), the 1345 keV gamma transition probability and electron capture probability to the first excited level in ^{64}Ni are deduced being: $P_{g1345} = P_{ec0,1}$ = 0.4749 (34) %.

3 Atomic Data

The data are from 1996Sc06.

4 Radiation Emissions

4.1 Electron Emissions

Auger electron emission intensities are deduced from the evaluated data set.

4.2 Photon Emissions

X-ray emission intensities are deduced from the evaluated data set.

The γ-ray energy is 1345.77 (6) keV from 1974HeYW.

The intensity of the 1345 keV gamma ray is deduced from the measured values:

Reference	$I_{\gamma 1345}$ (%)	uc (%)	Comments
1983Ch47	0.471	0.011	HPGe γ spectrometry
1986Ka03	0.487	0.020	HPGe γ spectrometry
2007Qa02	0.54	0.03	HPGe γ spectrometry - Outlier
2010Wanke	0.474	0.005	HPGe γ spectrometry
2012Bé - CMI	0.476	0.006	HPGe γ spectrometry
2012Bé - LNHB	0.472	0.012	HPGe γ spectrometry
2012Bé- IFIN	0.481	0.017	HPGe γ spectrometry
χ^2 /n – crit χ^2	0.15	3.	
UWM	0.476	0.0029	
WM	0.4748	0.0034	Adopted

4.3 X-ray emissions

Experimental results (2012Amiot) are compared below with those derived from the decay scheme data. They are in good agreement.

	Experimental (%)	Calculated (%)
Kα	14.22 (24)	14.46 (13)
Kβ	2.00 (4)	1.99 (3)

5 Various comparisons

The following tables summarize values of some ratios measured or deduced in the publications compared with those derived from the present data set. Both are in agreement within the uncertainty limits.

- P_{β}^{-} / P_{β}^{+} ratio

Reference	P_{β}^{-} / P_{β}^{+}	uc	Remark
1946Br03	2.1		
1949Bo16	2.00	0.15	
1983Ch47	2.187	0.007	
1986Ka03	2.138	0.032	
χ^2 /n – crit χ^2	2.2	6.6	
UWM	2.163	0.025	Value deduced from the present adopted data set: 2.196 (24)
WM	2.185	0.010	

- I_{g1345} / P($_{\beta}^{+}$) ratio

Reference	I_{g1345} / P($_{\beta}^{+}$)	uc	Remark
1956Dz26	0.0207		
1952Vl03	0.023	0.004	Omitted, outlier
1959Sc71	0.0280	0.0024	Omitted, outlier
1983Ch47	0.0264	0.0006	

1986Ka03	0.0272	0.0012	
2007Qa02	0.0303	0.0018	Omitted, outlier
2010Wanke	0.02699	0.00038	
2010Bé - CMI	0.02691	0.00045	
2010Bé - LNHB	0.0266	0.0007	
χ^2 /n – crit χ^2	0.23	3.3	
UWM	0.02682	0.00014	Value deduced from the present adopted data set: 0.02706 (30)
WM	0.02684	0.00024	

6 Main production modes

They are taken from: Table de Radionucléides, F; Lagoutine, N. Coursol, J. Legrand. ISBN 2 7272 0078-1

7 Other earlier publications not used in the evaluation

- H. von Bradt (1946Br03)
$P_{\beta}^{-} / P_{\beta}^{+} = 2.1$

- R. Bouchez (1949Bo16)
$P_{\beta}^{-} / P_{\beta}^{+} = 2.00$ (15)

- Reynolds (1950Re51)
$P(\beta^{+} + ec) / P_{\beta}^{-} = 1.62$ (11)
$P(ecK) / P(\beta^{+}) = 2.32$ (28)

- Vlaar (1952Vl03)
$I_{g1345} / P(\beta^{+}) = 0.023$ (4)

- Dzelepov *et al.* (1956Dz26)
$I_{g1345} / P(\beta^{+}) = 0.0207$

- Schmidt-Ott (1959Sc71)
$I_{g1345} / P(\beta^{+}) = 0.0280$ (24)

8 References

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