^{61}Cu – Comments on evaluation
by M.-M. Bé

This evaluation was completed in August 2013. Literature published to this date are included.

Decay Scheme

^{61}Cu ($T_{1/2}$ = 3,366 h) decays 100 % by electron capture and β^+ disintegrations to various excited levels and to the ground state of ^{61}Ni.
Q^{EC} value for ^{61}Cu decay was adopted from Wang *et al.* (2012Wa38).
The spins, parities and level energies are based on the mass-chain evaluation of Bhat (1999Bh04).

Half-life

The experimental half-life values used to calculate the recommended value are listed in the following table:

Reference	**h**	**uc (h)**	**Comments**
1969Ri04	3,408	0,012	Smallest of uncertainty measurement
1972Du09	3,26	0,05	
1973Ne02	3,39	0,04	
1982Gr10	3,333	0,01	Original uncertainty: 0,005
Crit (χ^2)	3,8		
χ^2 /(n-1)	8,6		
UWM	3,348		
LWM	3,366		
uc(WM)int. :	0,008		
uc(WM)ext. :	0,023		
Adopted:	**3,366**	**0,033**	**EXPANDED**

The original uncertainty of 0,005 h given by Grütter (1982Gr10) was defined, in the article, as the statistical uncertainty only, at the 1σ level. It has been increased to 0,01 h, even if it is difficult to appreciate the real systematic component due to a lack of information in the publication.

The data set is discrepant, the adopted value is the weighted mean of the four values with an expanded uncertainty to cover the most precise value of 1982Gr10.

Values given by Berman (1954Be84), Martins *et al.* (1982Ma41) and Crisler *et al.* (1972Cr02) have not been taken into account because they were obtained as a mean to control another experiment and not as a specific study.

Electron Capture and β^+ transitions

All EC and β^+ energies were derived from the level energies and the Q value.
The shell and sub shells capture probabilities were calculated by mean of the EC-Capture program (1998Sc28).

To the ground state

In this decay scheme the ground state is fed by a transition where electron capture and β^+ emission are in competition, the determination of its probability is crucial to establish the decay scheme. Some attempts have been made to determine the β+ probability mainly from the measurement of the 511 keV photon emission in coincidence with other gamma emission. It must be noted that these results depend of other quantities and some of them were given without uncertainty. However, due to the importance of such a value, all the available results have been taken into consideration.

Nussbaum *et al.* (1956Nu02) investigated the Cu-61 decay by using coincidence techniques and obtained a β+ probability to the ground state of 51 (5) %. They also measured the K conversion coefficients of the 67,4 and 282,8 keV transitions.
Bolotin *et al.* (1967Bo01) studied the decay scheme by using coincidence techniques and obtained a β+ probability to the ground state of 50,7 %. Absolute γ ray intensities were given with an uncertainty of 5 %.
Schöneberg *et al.* (1967Sc02) determined the decay scheme from their measurement results and using the K conversion coefficients of the 67,4 and the 282,8 keV transitions measured by Nussbaum. Finally, they found a β+ probability to the ground state of 51,7 % and a total 511 keV intensity of 126,1 (40) %. The other absolute γ ray intensities were given with an uncertainty of 3 – 4 %.
Béraud *et al.* (1967Be12) measured the β+ in coincidence with other gamma rays, they adopted the probability of the 67,4 keV transition of Nussbaum *et al.* (1956Nu02). Finally, they obtained a β+ probability to the ground state of 53,1 %. They determined the γ intensities with an uncertainty of 10 %.

Since three data have no uncertainty stated by the authors, the simple mean of the four values is adopted. An uncertainty which covers all values would lead to 51,6 (15) %, however considering the uncertainties on the various experimental results, an uncertainty of 5 % is adopted here. That is: β+ to g.s. = 51,6 (25) %.

The theoretical ratios EC/β+ have been calculated by the Logft program from the theoretical tables of Gove *et al.* (1971Go40). The ratio for transitions to the ground state level is 0,3155 (33), then the total capture probability to the g.s. is 16,3 (8) %.
The total EC + β+ to the g.s. is 67,9 (26) %.

To excited levels
The total EC + β+ to each level of the decay scheme were derived from the P(ce+ γ) probability balance, then each component was obtained from the EC/β+ ratio.

Level	Energy (keV)	Spin	EC/β+	uc
0	0	3/2⁻	0,3155	0,0033
1	67,412	5/2⁻	0,3791	0,00394
2	282,9568	1/2⁻	0,7471	0,0079
3	656,012	1/2⁻	4,25	0,05
4	908,62	5/2⁻	38	0,06
5	1014,8	7/2⁻	199	5
6	1099,622	3/2⁻		
7	1132,332	5/2⁻		
8	1185,236	3/2⁻		
9	1609,639	5/2⁻		
10	1729,471	3/2⁻		
11	1997,7	5/2⁻		
12	2124	1/2⁻		

Other

The total β+ emissions, as determined above, lead to a 511 keV photon emission of 123 (5) % which is in good agreement with the experimental value of Schöneberg *et al.* (1967Sc02) of 126,1 (40) %.

Relative gamma emission intensities, Iγ

Meyer (1978Me10) and Satyanarayana (1988Sa26) carried out relative measurements, the 282 keV gamma ray being the reference ray.
Nussbaum *et al.* (1956Nu02), Ritter (1969Ri04), Schöneberg (1967Sc02), Bolotin (1967), Béraud *et al.* (1967Be12) studied the decay scheme, they made use of coincidences techniques to determine the population of the various levels in Ni-61 and they published results for the gamma intensities. The absolute γ intensities and the intensities of the β^+ they obtained are correlated. The values of the β^+ intensities have already been used in this evaluation to obtain the branching ratio to the ground state, so, they have not been included in the determination of the relative gamma intensities.
The adopted relative gamma intensities are the mean of the values of Meyer (1978Me10) and Satyanarayana (1988Sa26). The adopted uncertainty is the standard deviation, but is never lower than the lowest experimental uncertainty.

Levels	Energy (keV)		Meyer 1978		Satyan. 1988		UWM	uc ext.	Adopted relative Iγ	
(i,f)	Eγ	Eγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)
(1,0)	**67,412**	0,003	31,5	1	34,7	1,1	33,1	1,6	33,1	1,6
(7,5)	**117,5**				0,086	0,046	0,086	0,046	0,086	0,046
	190,79	0,12	0,04	0,008					omitted	
(2,1)	**215,55**	0,18	0,036	0,009	0,176	0,058	0,106	0,021	0,106	0,058
	276,688	0,053	0,21	0,02					omitted	
(2,0)	**282,956**	0,002	100		100	2,4	100		100	2,4
(3,2)	**373,05**	0,005	17,2	0,5	17,6	0,4	17,4	0,195	17,4	0,4
	443,5	0,1	0,03	0,01					omitted	
(8,3)	**529,169**	0,022	3,3	0,6	3,08	0,07	3,19	0,025	3,19	0,070
	544,8				0,048	0,03	0,048	0,030	0,048(*)	0,030
(3,1)	**588,605**	0,009	9,6	0,1	9,57	0,17	9,585	0,013	9,585	0,1
(4,2)	**625,605**	0,024	0,4	0,03	0,33	0,037	0,365	0,034	0,365	0,034
	629,9	0,25	0,05	0,02					omitted	
(3,0)	**656,008**	0,004	85,3	2	88,34	1,52	86,82	1,465	86,82	1,520
(9,4)	**701,1**	0,3	0,09	0,02					0,09(w)	0,020
(6,2)	**816,692**	0,013	2,89	0,06	2,52	0,06	2,705	0,185	2,705	0,185
(10,4)	**820,89**	0,17	0,18	0,02					0,18(w)	0,020
(4,1)	**841,211**	0,017	1,98	0,08	1,755	0,054	1,8675	0,104	1,8675	0,104
(8,2)	**902,294**	0,02	0,72	0,02	0,68	0,04	0,7	0,016	0,7	0,020
(4,0)	**908,631**	0,017	9,7	0,3	9,03	0,168	9,365	0,286	9,365	0,286
(5,1)	**947,4**	0,4	0,02	0,01	0,08	0,04	0,05	0,014	0,05	0,014
(5,0)	**1014,8**	0,4	< 0,01		0,086	0,03	0,048		0,086	0,03
(6,1)	**1032,162**	0,027	0,53	0,09	0,346	0,03	0,438	0,055	0,438	0,055
(7,1)	**1064,896**	0,02	0,48	0,04	0,395	0,03	0,4375	0,041	0,4375	0,041
(10,3)	**1073,465**	0,025	0,43	0,03	0,267	0,025	0,3485	0,080	0,3485	0,080
(11,4)	**1089,11**		≤ 0,005						0,005(w)	
(6,0)	**1099,56**	0,019	2,27	0,08	2,01	0,05	2,14	0,117	2,14	0,117
(8,1)	**1117,822**	0,043	0,39	0,03	0,265	0,034	0,3275	0,062	0,3275	0,062
(7,0)	**1132,351**	0,032	0,79	0,03	0,737	0,034	0,7635	0,026	0,7635	0,030
(8,0)	**1185,234**	0,015	29,5	0,6	30,71	0,57	30,105	0,604	30,105	0,604
(10,2)	**1446,492**	0,019	0,4	0,02	0,369	0,024	0,3845	0,015	0,3845	0,020
(9,1)	**1542,204**	0,023	0,27	0,01	0,21	0,018	0,24	0,025	0,24	0,025
(9,0)	**1609,625**	0,048	0,22	0,02	0,174	0,017	0,197	0,023	0,197	0,023

Levels	Energy (keV)		Meyer 1978		Satyan. 1988		UWM	uc ext.	Adopted relative Iγ	
(i,f)	Eγ	Eγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)	Iγ	Iγ(uc)
(10,1)	**1662**	0,019	0,42	0,02	0,433	0,024	0,4265	0,006	0,4265	0,020
(10,0)	**1729,473**	0,018	0,64	0,04	0,442	0,024	0,541	0,087	0,541	0,087
	1840,7	0,2	0,014	0,004					omitted	
(11,0)	**1997,73**	0,85	0,03	0,01	0,032	0,01	0,031	0,001	0,031	0,010
	2120				0,08		0,08		0,08(*)	
(13,0)	**2123,432**	0,035	0,32	0,01	0,339	0,024	0,3295	0,007	0,3295	0,010

Some rays were observed only by Meyer (1978Me10) and not confirmed by Satyanarayana (1988Sa26), they were omitted. Similarly, some rays questionable (*) are not placed as well. But some rays (w) observed by Meyer were also observed by Wadsworth *et al.* (1977Wa03), they were adopted in this decay scheme.

Internal conversion coefficients

The adopted ICC are the theoretical values calculated by the BrIcc program (2008Ki07).
Most of the transitions are of M1+E2 type. The adopted mixing ratios are from the experimental study of Wadsworth *et al.* (1977Wa03) who carried out an extensive spectroscopy of the nucleus ^{61}Ni.
For the 67 and 282 keV transitions, the K internal conversion coefficients were measured by Nussbaum *et al.* (1956Nu02) to be 0,11 and 0,004 respectively. These experimental values are in good agreement with the theoretical ones obtained by the BrIcc program for transitions of M1 character.

Normalisation Factor

For 100 % of ^{61}Cu decays, 100 % of the transitions (β^+, γ , EC) must populate the ground state of the daughter:

$$\sum_i I_{\gamma i}\,[1+\alpha_{Ti}] \;=\; \frac{100\% - \left(P_{\beta +} + P_{EC}\right)}{N}$$

Where:
The sum $\sum_i I_{\gamma i}\,[1+\alpha_{Ti}]$ is over the γ transitions feeding the ground state; $I_{\gamma i}$ is the relative emission intensity of the i^{th} gamma-ray, α_{Ti} is its total internal conversion coefficient and, $P_{\beta +} + P_{EC}$ is the sum of β^+ and EC – transitions populating the ground state. N is a normalisation factor between the relative γ intensities and the absolute values.

From above, the total EC + β^+ to the g.s. is 67,9 (33) %, then the sum of the γ gamma transition probabilities to the g.s. must be equal to 32,1 (33) %. Therefore, a normalization factor of 12,0 (17) % is deduced.

Atomic Data

The fluorescence yield data, the relative K x-ray emission probabilities, the ratios P(KLX)/P(KLL) and P(KXY)/P(KLL) are from Schönfeld *et al.* (1996Sc06).

The Auger electrons and X-ray absolute intensities were calculated by the EMISSION program (2000Sc47) from the related decay data (γ intensities, ICC, P_{EC} probabilities, etc.) as determined above.

Data Consistency

The sum of all the energies involved in a decay (EC, γ , etc.) is 2238 (46) keV which can be compared with the value of 2237,5 (10) as adopted for the Q value.

References

1954Be84 A.I.Berman, K.L.Brown. Phys.Rev. 96, (1954) 83. Half-life
1956Nu02 R.H.Nussbaum, A.H.Wapstra, W.A.Bruil, M.J.Sterk, G.J.Nijgh, N.Grobben. Phys. Rev. 101 (1956) 905. Beta plus emission probabilities
1967Bo01 H.H.Bolotin, H.J.Fischbeck. Phys. Rev. 158 (1967) 1069. Beta plus emission probabilities
1967Sc02 R.Schöneberg, A.Flammersfeld. Z. Physik 200 (1967) 205. Beta plus emission probabilities
1967Be12 R.Béraud, I.Berkes, J.Daniere, M.Levy, G.Marest, R.Rougny. Nucl. Phys. A99 (1967) 577. Beta plus emission probabilities
1969Ri04 J.C.Ritter, R.E.Larson. Nucl. Phys. A127 (1969) 399. Half-life
1971Go40 N.B. Gove, M.J. Martin. Nucl. Data Tables 10 (1971) 205. EC/positron ratios
1972Du09 G.H.Dulfer, B.O.ten Brink, T.J.Ketel, A.W.B.Kalshoven, H.Verheul. Z. Physik 251 (1972) 416. Half-life
1972Cr02 D.F.Crisler, H.B.Eldridge, R.Kunselman, C.S.Zaidins. Phys. Rev. C5 (1972) 419. Half-life
1973Ne02 D.A.Newton, S.Sarkar, L.Yaffe, R.B.Moore. J. Inorg. Nucl. Chem. 35 (1973) 361. Half-life
1977Wa03 R.Wadsworth, A.Kogan, P.R.G.Lornie, M.R.Nixon, H.G.Price, P.J.Twin. J. Phys. (London) G3 (1977) 35. Gamma rays
1978Me10 R.A.Meyer, A.L.Prindle, W.A.Myers, P.K.Hopke, D.Dieterly, J.E.Koops. Phys. Rev. C17 (1978) 1822. Half-life, gamma-ray energies and emission intensities
1982Ma41 M.N.Martins, E.Wolynec, M.C.A.Campos. Phys. Rev. C26 (1982) 1936. Half-life
1982Gr10 A.Grutter, . Int. J. Appl. Radiat. Isotop. 33 (1982) 533. Half-life
1988Sa26 G.Satyanarayana, N.Venkateswara Rao, G.S.Sri Krishna, M.V.S.Chandrasekhar Rao, S.Bhuloka Reddy, D.L.Sastry, S.N.Chintalapudi, V.V.Rao. Nuovo Cim. 99A (1988) 309. Gamma-ray emission intensities
1996Sc06 E. Schönfeld, H. Janssen. Nucl. Instrum. Methods Phys. Res. A369 (1996) 527. Atomic Data
1998Sc28 E. Schönfeld, .Appl. Radiat. Isot. 49 (1998) 1353. Fractional EC probabilities
1999Bh04 M.R.Bhat, .Nucl. Data Sheets 88 (1999) 3. Spin and Parity, level energies
2000Sc47 E. Schönfeld, H. Janssen. Appl. Radiat. Isot. 52 (2000) 595. P(X), P(Ae)
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 ICC
2012Wa38 M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer. Chin. Phys. C36 (2012) 1603. Q-value