^{109}Cd - Comments on evaluation of decay data by M.M. Bé, E. Schönfeld

This evaluation was first completed by E. Schönfeld in 1996, and was completely reviewed by M.M. Bé in November 2014. New half-life and γ intensity measurement results and improved calculations of the internal conversion coefficients were included.

1 Decay Scheme

The observed transition in the decay of ^{109}Cd is an allowed EC transition $\varepsilon_{0,1}$ to the 88 keV level in ^{109}Ag. If there is an EC branch to the ground state of ^{109}Ag, it would have ΔJ = 2 with no change of parity (2006Bl02), so it would be 2nd forbidden. From the paper of S. Raman et al. (1973Ra10) it is then expected to have a lg *ft* greater than 11 and this corresponds to an EC branch of less than 0,005%.

Below the decay energy of ^{109}Cd there is a level at 132,74 (11) keV in ^{109}Ag, $J^{\pi} = 9/2^{+}$, $T_{1/2}$ = 2,60 (12) ns. This level has been observed in the decay of ^{109}Pd but not in the decay of ^{109}Cd. If this EC branch exists, it is 2nd forbidden with an expected lg *ft* greater than 11 and an emission probability of less than 0,0003%.

2 Nuclear Data

The Q_{EC} value of **215,5 (18) keV** is taken from the atomic mass evaluation of Wang *et al.* (2012Wa38).

In the past, some discrepancies in the Q_{EC} values were observed: 183,9 keV was derived from internal bremsstrahlung measurements (Gopinathan *et al.* (1968Go25)); 201 (3) keV from P(L)/P(K) = 0,193 (3) (Goedbloed (1968GoZY), Goedbloed *et al.* (1970Go39)) measured experimentally; 220 (3) keV from P(L, M, N)/P(K) = 0,227 (2) (average from Leutz *et al.* (1965Le06), Goedbloed (1968GoZY), Goedbloed *et al.* (1970Go39)) measured experimentally.
From the present accepted Q_{EC} value of 215,5 (18) keV, the P_K, P_L, etc. have been derived (§2.1) and used to calculate (with the atomic data) the X-ray intensities. The ratio of the X-ray over the γ ray intensity was found to be consistent with the experimental values (§5), that support the adopted Q_{EC} value.

The following values of the half-life have been considered ($T_{1/2}$, in days):

Reference	$T_{1/2}$ (d)	Comments
Gum and Pool (1950Gu54)	470 (8)	Omitted
Leutz *et al.* (1965Le06)	453 (2)	Omitted
East and Murphy (1968Ea01)	459 (6)	Omitted
Reynolds *et al.* (1968Re04)	450 (5)	Omitted
Vaninbroukx *et al.* (1981Va11)	461,9 (3)	
Lagoutine and Legrand (1982La25)	463,1 (4)	Original uncertainty 3σ divided by 2
Hoppes *et al.* (1982HoZJ)	463,2 (6)	Superseded by 1992Un01
Unterweger *et al.* (1992Un01)	463,26 (63)	Superseded by 2002Un02
Martin *et al.* (1997Ma75)	460,2 (4)	Original uncertainty multiplied by 2
Unterweger (2002Un02)	463,26 (63)	Same value as in 1992Un01, Superseded by 2012Fi12
Schrader (2004Sc04)	459,6 (17)	
Van Ammel *et al.* (2011Va02)	462,29 (30)	Weighted mean of two results
Fitzgerald (2012Fi12)	462,6 (7)	Superseded by 2014Un01

Unterweger and Fitzgerald (2014Un01)	462,3 (8)	
Fenwick	*462,40 (20)*	*Not yet published, measurement in progress – not included*
Chi2 crit.:	3,0	
Chi2 :	6,2	
UWM	461,57	
WM	461,93	
uc(WM)int. :	0,17	
uc(WM)ext. :	0,41	
Adopted	**461,9 (4)**	

The uncertainty given by Lagoutine and Legrand (1982La25) was calculated as the sum of the systematic components and three times the statistical component, thus it cannot be simply divided by three. It was divided by two only, that gives it a weight comparable to the other values published at the same period of time.
With the original uncertainty of 0,2 d given by Martin (1997Ma75) the set of the six accepted data is strongly not consistent with a reduced χ^2 of 13,6 and this value weighs for 45%, thus it has been multiplied by two. Then, the values of 1981Va11 and 2011Va02 amounts for 37% and those of 1982La25 and 1997Ma75 for 17%.
In spite of, the set of the six data is not consistent, the three most recent values ranging from 459,6 d (2004Sc04) to 462,3 d (2014Un01).
The LWEIGHT program has used the weighted mean and external uncertainty.

Makaryunas and Makaryunene (1984Ma**) searched for a chemical alteration of the probability of EC by the ^{109}Cd nucleus. Metallic Cd, CdS and CdTe were measured. No significant change ($\Delta\lambda/\lambda < 1 \cdot 10^{-4}$) has been found from a 1000 d measurement with a NaI(Tl) detector equipped with a Be window and collimation.

Half-life (^{109m}Ag)

The recommended half-life has been determined from the measurements of Alvarez (1940Al01), Wiedenbeck (1945Wi11), Bradt *et al.* (1947Br05), Wolicki *et al.* (1951Wo15), Middelboe (1967Mi11), Abrams and Pelekis (1967Ab07), Cottrell (1973Co10) and Yoshida *et al.* (2000Yo07).
The values of 1973Co10 and 2000Yo07 have been omitted as outliers due to Chauvenet's criterion. The adopted value is the weighted mean of the six remaining values, *i.e.* 39,7 (2) seconds.

Half-life measurements (^{109m}Ag)

Reference	Half-life (*s*)	Comments
1940Al01	40 (2)	
1941He01	40	Same as 1940Al01
1945Wi11	40,4 (2)	
1947Br05	39,2 (2)	
1951Wo15	40 (1)	
1967Mi11	39,80 (18)	
1967Ab07	39,3 (3)	
1973Co10	35 (5)	Outlier
2000Yo07	38,0 (12)	Outlier
Recommended value	**39,7 (2)**	

2.1 Electron Capture Transitions

Available experimental values of P_K, P_L, P_M are listed below. They are compared with the theoretical values calculated by the EC-CAPTURE program (1998Sc28) for an allowed transition and Q = 215,5 (18) keV; the resulting values are in good agreement with the measured ones.

P_K	P_L	P_{M+}	P_L/P_K	P_{LMN}/P_K	Reference
			0,28 (3)		Der Mateosian (1953De26)
			0,32 (4)		Bertolini et al. (1954Be41)
0,805 (27)				0,24 (4)	Wapstra and van der Eijk (1957Wa05)
0,814 (2)	0,159	0,027	0,195 (5)	0,228 (3)	Leutz et al. (1965Le06)
0,778 (25)	0,184	0,038	0,237 (15)	0,332 (15) (O)	Moler and Fink (1965Mo06)
0,794 (25)	-	-	-	0,26 (4)	Durosinmi-Etti *et al.* (1966Du01)
0,816 (2)	0,157 (5)	0,027	0,193 (3) (LW)	0,226 (3)	Goedbloed *et al.* (1970Go39)
0,780 (15)	-	-	-	0,282	Plch *et al.* (1979Pl04)
0,815 (2)			0,199 (8)	0,227 (2)	Weighted mean
0,812 (3)	0,150 (3)	0,0385 (10)	0,183 (9)	0,231 (10)	Theory

(O) outlier; (LW) limited weight

2.2 Gamma Transitions

The conversion coefficients of this E3 transition have been extensively measured. The main studies are summarized below.

Experimentally and theoretically determined conversion coefficients are compiled in the following tables:

	α_K	α_T	α_K/α_L	$\alpha_K/(\alpha_L+\alpha_M+\alpha_N)$	**Reference**
1	12,4 (10)	-		0,85 (2)	Brunner *et al.* (1953Br73)
2	10,3 (5)	-	-	-	Wapstra and van der Eijk (1957Wa05)
3	-	-	0,95 (3)	-	Boyd *et al.* (1964Bo12)
4	11,0 (3)	24,7 (5)	-	-	Leutz *et al.* (1965Le06)
5	11,3 (4)	24,2 (14)	-	-	Sen and Durosinmi-Etti (1965Se08)
6	12,7 (9)	29,4 (25)	0,94	0,76 (2)	Foin *et al.* (1968Fo03)
7	-	-	-	0,76 (2)	Planskoy (1969Pl08)
8	10,6 (5)	-	-	-	Bashandy (1970Ba37)
9	-	25,4 (5)	-	-	Legrand *et al.* (1973Le29)
10	11,4 (3)	26,4 (4)	0,933	0,760	Dragoun *et al.* (1976Dr07)
11	9,6 (2)	-	-	-	Prochazka *et al.* (1978Pr**)
12	11,4 (3)	26,4 (3)	-	-	Plch *et al.* (1979Pl04)
13	-	26,21 (14)	-	-	Ballaux *et al.* (1988Ba60)
14	-	26,67 (9)	-	-	Ratel (1994Ra37)

15		26,30 (25)			Kossert *et al.* (2006Ko27)
	11,28 (12)	26,62 (9)	0,913	0,736	Weighted mean of experimental values
16		26,46 (8)			The α_t value corresponds to the I_γ as determined in §4.2
17	11,41 (16)	26,3 (4)	0,946 (19)	0,765 (14)	BRICC Frozen Orbital approximation

	Brenner and Perlman (1972Br02)	Davidonis *et al.* (1980Da23)	Dragoun *et al.* (1976Dr07)	Shevelev *et al.* (1978Sh08)		Theory: BRICC Frozen Orbital approximation
α_{L1}			0,63 (13)			0,891 (13)
α_{L2}			5,48 (18)			5,16 (8)
α_{L3}			6,11 (20)			6,02 (9)
α_M			2,40 (8)			2,47 (4)
L_1 / L_2 / L_3	0,132 (8) / 0,830 (20) / 1	0,148 (7) / 0,86 (2) / 1	0,103 (22) / 0,897(42) / 1	0,159 (13) / 0,860 (20) / 1		0,148 (3) / 0,857 (18) / 1
K/L/M/N				0,98 (5) / 1 / 0,20 (1) / 0,050 (5)		0,946 (19) / 1 / 0,205 (4) / 0,032 (1)

The most recent values, from 1976 to 2006, of α_T and α_K are generally in agreement with the theoretical values within the uncertainty limits. Also, the experimental and theoretical ratios L_1 / L_2 / L_3 and K/L/M/N are most often in agreement, which supports the improvements made in the theoretical calculations (Band and Trzhaskovskaya (2002Ba85)) for such E3 transitions since the previous evaluation.

As α_T and I_γ are closely connected, further experimental values can be found in papers which are dealing with the determination of I_γ (§4.2).

Double K-shell vacancy creation in the decay of ^{109}Cd has been measured by van Eijk and Wijnhorst (1977Va05): P_{KK} (IC) = 2,8 (7) · 10^{-5} per K internal conversion. In a later paper, van Eijk *et al.* (1979Va04), determined the probability P_{KK} (IC) of double K-shell vacancy creation per K internal conversion of the 88 keV E3 transition in the decay of ^{109m}Ag, by means of a K_α-X-ray-K-X-ray coincidence experiment on ^{109}Pd, to be 13,0 (11) · 10^{-5}. From a similar experiment on ^{109}Cd, the probability P_{KK} (EC) of double K-shell vacancy production per K-electron capture decay of ^{109}Cd has been determined to be 1,02 (36) · 10^{-5}. Nagy *et al.* (1975Na01) found the probability that a double K-shell vacancy is formed per K-shell internal conversion to be 1,53 (24) · 10^{-4}. Horvat and Ilakovac (1985Ho06) measured the decay of the double-K-shell vacancy state in ^{109m}Ag, the probability of creation of double K-shell vacancies per ^{109}Cd decay was determined to be 6,07 (12) · 10^{-5}.

The energy shift of the hyper satellite Ag $K_{\alpha1}^{H}$-X-ray line was found to be 532 (6) eV.

Martin *et al.* (1975Ma32) measured ratios of L subshell conversion electrons.

Ilakovac *et al.* (1988Il01) searched for double photon decay of the ^{109}Ag metastable state at 88 keV and found an experimental upper limit of the relative transition probability $P_{\gamma\gamma} / P_\gamma < 6 \cdot 10^{-7}$ using a pair of Ge detectors and a fast-slow coincidence system.

3 Atomic data

The atomic data, $P(K_\beta)/P(K_\alpha)$ and $P(K_{\alpha_2})/P(K_{\alpha_1})$, P(KLX)/P(KLL) and P(KXY)/P(KLL), etc. have been taken from Schönfeld and Janßen (1996Sc06).

4 Electron Emissions

The conversion electron energies were calculated from the transition energy and the binding energies of the electrons of the corresponding shells. The number of conversion and Auger electrons per 100 disintegrations is based on the decay scheme parameters as given in Section 2.1 and 2.2 and on the atomic data as given in Section 3.

5. Photon Emissions

5.1 X-ray Emissions

The total KX- ray emission intensity is (assuming there is no EC transition to the ground state):

$$I_{KX} = \omega_K \{P_K + [\alpha_K/(1 + \alpha_t)]\} \times 100\ \% = 102{,}2\ (9)\ \%.$$

The measured values of the ratio I_{KX} / I_γ are summarized below and compared with the value deduced from the decay scheme parameters.

	I_{KX} / I_γ	**Reference**
1	33,8 (7) $^{(O)}$	Wapstra and van der Eijk (1957Wa05) - outlier
2	26,2 (6)	Leutz *et al.* (1965Le06)
3	22,2 (6) $^{(O)}$	Jansen and Wapstra (1966Ja01) - outlier
4	29,1 (10)	Freedman *et al.* (1966Fr12)
5	30 (4)	Foin *et al.* (1968Fo03)
6	26,2 (5)	Campbell and McNelles (1972Ca16)
7	27,0 (3)	Dragoun *et al.* (1976Dr07) – superseded by 1979Pl04
8	27,3 (6)	Plch *et al.* (1979Pl04)
9	27,34 (27)	Hoppes and Schima (1982HoZF)
10	27,9 (4)	Egorov *et al.* (1989Eg**)
11	27,7 (5)	Unweighted mean
12	27,25 (29)	Weighted mean; reduced-χ^2 = 2,4 ; Crit. χ^2 = 2,8
13	**27,92 (45)**	Present evaluation using the above equation together with the adopted values of ω_K, P_K, α_K, α_T and $I\gamma$

In the set of data above, the results 1 and 2 are outliers due to Chauvenet's criterion. The value 7 is superseded by 8. The remaining set of seven results is consistent with a reduced χ^2 of 2,4. The unweighted and weighted means (values 11 and 12, respectively) are in agreement within the uncertainty limits with the value 13 obtained in this evaluation.

5.2 Gamma Emissions

	E_γ **(keV)**	**Reference**
1	88,008 (42)	Freedman *et al.* (1966Fr12)
2	88,041 (87)	Schima and Hutchinson (1967Sc22)
3	88,05 (5)	Libert (1967Li10)
4	88,033 (42)	Pierson and Marsh (1967Pi05)
5	88,09 (3)	Foin *et al.* (1968Fo03)

6	88,21 (3)	Furuta and Rhodes (1968Fu05)
7	88,036 (8)	Heath (1969HeZY)
8	88,036 (8)	Greenwood *et al.* (1970Gr13)
9	88,035 (6)	Raeside (1970Ra37)
10	88,035 (4)	Morii (1978Mo22)
11	**88,0336 (10)**	Helmer and van der Leun (2000He14), adopted here.

The γ ray energy is taken from Helmer and van der Leun (2000He14).
The number of X photons per 100 disintegrations is based on P_K, P_L, P_M as given in Section 2.1, α_K, α_L as given in Section 2.2 and the atomic data as given in Section 3.

The following values for the number of γ photons per 100 disintegrations have been taken into account:

	I_γ (%)	correspond. α_t	Comments on I_γ results
1	3,65 (4)	26,4 (3)	Plch *et al.* (1979Pl04) – superseded by [2]
2	3,62 (2)	26,82 (14)	Plch (UVVVR, 1988) – simple mean of two values deduced from activity measurements
4	3,65 (3)	26,40 (23)	Gostely (IER, 1988)
5	3,59 (11)		Konstantinov (IMM, 1988)
6	3,70 (6)	26,0 (5)	Park *et al.* (KSRI, 1988)
7	3,60 (2)	26,78 (8)	Chauvenet (LMRI, 1988) – original uncertainty × 2
8	3,57 (10)	27,0 (8)	Woods and Smith (NPL, 1988)
9	3,65 (8)	26,4 (6)	Szörenyi *et al.* (OMH, 1988)
10	3,675 (18)	26,21 (15)	Ballaux (NBS, 1988) and 1988Ba60
11	3,66 (5)	26,3 (4)	Hino and Kawada (ETL, 1988) and 1989Hi01
12	3,68 (4)	26,2 (5)	Funck and Schötzig (PTB, 1989), Schötzig *et al.* (1992ScZZ) – superseded by [14]
13	3,65 (2)	26,4 (4)	Nedovesov (1989Ne**) based on Plch measurements - omitted
14	3,663 (33)	26,30 (25)	Kossert *et al.* (2006Ko27)
A	3,641 (11)		Weighted mean of values 2–11 and 14 Reduced χ^2 = 1,2 ; crit. χ^2 = 2,4
15	3,89 (7)	24,7 (5)	Leutz *et al.* (1965Le06) from α_t
16	3,97 (21)	24,2 (14)	Sen and Durosinmi-Etti (1965Se08); from α_t
17	3,29 (25)	29,4 (25)	Foin *et al.* (1968Fo03); from α_t
18	3,79 (7)	25,4 (5)	Legrand *et al.* (1973Le29) ; from α_t
19	3,65 (5)	26,4 (4)	Dragoun *et al.* (1976Dr07); from α_t
B	3,74 (6)		Weighted mean of values 15–19; Reduced χ^2 = 3,2 ; crit. χ^2 = 3,3
C	3,641 (10)	26,46 (8)	Weighted mean of 2–11, 14 and 19 Reduced χ^2 = 1,1 ; crit. χ^2 = 2,3.
D	**3,66 (5)**	**26,3 (4)**	From theoretical ICC - Adopted

The first set of data (1 - 14) lists the I_γ results obtained by direct measurements of the total activity of a ^{109}Cd solution by means of absolute methods and the photon emission rate by gamma spectrometry counting. All these results, except the value 14, were obtained in the framework of an international comparison of activity measurements (1994Ra37), some of them (10, 11, 12) were also published elsewhere. When two results were given (Plch, 1988) the simple mean was adopted. The original uncertainty of the value 7 has been multiplied by two; this value then has a weight comparable to the others. The weighted mean of values 2–11 and 14 is given on line A of the above table.

The second set of data (15 – 19) lists the I_γ results derived from measurements of the internal conversion coefficients. The set of five values is just consistent with a reduced χ^2 of 3,2. The weighted mean is listed on line B.

When processing all the available data (1 – 19) the values (15 -18) were found to be outliers due to Chauvenet's criterion. The set of the eleven remaining values is consistent with a reduced χ^2 of 1,1; the weighted mean is given on line C.

An I_γ value has been derived on line D, from the theoretical value of the total internal coefficient for an E3 transition interpolated from Band *et al.* tables (2002Ba85) using the BRICC program with the "frozen orbital approximation" (Kibédi *et al.* 2008Ki07). The I_γ and ICC values listed on line D are in good agreement with the experimental values obtained on line C.

It is noteworthy that the I_γ determined in various studies are dependent on the efficiency of the γ detector at 88 keV, but there are only a few γ rays available to establish an efficiency curve in this energy region. For this reason, and in order to propose an independent value, the I_γ derived from the theoretical ICC is adopted here, that is: I_γ = 3,66 (5) %.

6 Main Production Modes

Taken from the "Table de Radionucléides", LMRI, 1982:

Cd-108(n,γ)Cd-109, σ: 1,1 (3) barns
Possible impurities: Ag-110m

Ag-109(p,n)Cd-109
Possible impurities: none

7 References

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