^{109}Cd - Comments on evaluation of decay data
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1 Decay Scheme

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

Below the decay energy of ^{109}Cd there is beside the 88 keV level in ^{109}Ag a level at 132.74(11), 9/2+ or 7/2+, 2.60(12) ns. This level has been observed in the decay of ^{109}Pd but not in the decay of ^{109}Cd. This level is much more of a problem. If it has $J^{\pi} = 7/2+$, the decay to it would be allowed; then if the lg *ft* were the same as that to the 88-keV level, the branch to it would be about 30 % or smaller. Since the total conversion coefficient of the resulting 44-keV gamma would be much less than that of the 88-keV gamma, the 44-keV photons should be observed along with the conversion electrons. If the 132-keV level has $J^{\pi} = 9/2+$, the EC branch is 2nd forbidden with an expected lg *ft* greater than 11,0 and an emission probability of less than 0,0003 %. This assignment is more probable than the first assumption as up to now no 44-keV photons have been observed. The J^{π} data and $T_{1/2}$ = 39,6(2) s (88 keV) are taken from Blachot (1984).

2 Nuclear Data

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

1	470(8)	Gum and Pool (1950)
2	453(2)	Leutz et al. (1965)
3	459(6)	East and Murphy (1968)
4	450(5)	Reynolds et al. (1968)
5	461,9(3)	Vaninbroukx et al. (1981)
6	463,1(8)	Lagoutine and Legrand (1982); uncertainty 3 σ
7	463,2(6)	Hoppes et al. (1982)
8	460,2(2)	Martin and Taylor (1996)
9	462,6(7)	IAEA-TECDOC-619 (1991) derived from values 4 - 7
10	461,4(12)	adopted value, present evaluation

The uncertainty of the value No. 6 is related to 3 σ. For the calculation of the weighted mean it has been reduced to 0,3 d. For the weighted mean only the values 5 - 8 have been used. No. 8 contributes just 50 % to the mean. The internal uncertainty for the average of the values 5 - 8 is 0,14 days with the reduced-χ^2 is 26,6. It should be noted that the adopted value does not fall within the 1-σ range of any of the four values. Also, the values 8 and 6 differ by 2,9(4) d or about 7 σ. From the reduced-χ^2 and these statements it must be concluded that the 4 values are very discrepant although they are all from metrology laboratories. There is need to clarify this situation by new measurements. According to the agreed rules LWM has used the weighted average and expanded the uncertainty so that the uncertainty of the adopted value 10 includes the most precise value 8.

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

The Q_{EC} value 213,8(27) is taken from Audi and Wapstra (1995). There are some discrepancies in the Q_{EC} value: 183,9 keV is derived from internal bremsstrahlung measurements (Gopinathan et al. (1968)); 201(3) keV from $P(L)/P(K)$ = 0,193(3) (Goedbloed (1968), Goedbloed et al. (1970)) exp. measured;

220(3) keV from P(L, M, N)/P(K) = 0,227(2) (average from Leutz et al. (1965), Goedbloed (1968), Goedbloed et al. (1970) exp. measured). Kozub and Hindi (1994) have attempted (but so far failed) to resolve this discrepancy by remeasuring the internal bremsstrahlung endpoint. The most probable value extracted from the measurements is 201,8(1,3) keV. This situation is not satisfying.

In the present evaluation P(L)/P(K) = 0,184(3) and P(L, M, N)/P(K) = 0,232(4) was derived starting from the Audi and Wapstra Q-value whereas in the Table de Radionucléides (1982) for this ratio 0,218 and Q_{EC} = 182(3) keV is given.

2.1 Electron Capture Transitions

The transition energy of the allowed transition to the 88 keV level in ^{109}Ag is calculated from the Q_{EC} value (Audi and Wapstra, 1995) and the level energy. P_K, P_L, P_M are calculated using this transition energy and the report of Schönfeld (1995).

For comparison:

	P_K	P_L	P_{M+}	P_L/P_K	P_{LMN}/P_K	
1	-	-	-	0,28(3)		Der Mateosian (1953)
2	-	-	-	0,32(4)		Bertolini et al. (1954)
3	0,805(27)	-	-	-	0,24(4)	Wapstra and van der Eijk (1957)
4	0,814(2)	0,159	0,027	0,195(5)	0,228(3)	Leutz et al. (1965)
5	0,778(25)	0,184	0,038	0,237(15)	0,332(15)	Moler and Fink (1965)
6	0,794(25)	-	-	-	0,26(4)	Durosinmi-Etti (1966)
7	0,816(2)	0,157(5)	0,027	0,193(3)	0,226(3)	Goedbloed et al.(1970) Goedbloed (1968)
8	0,780(15)	-	-	-	0,282	Plch et al. (1979)
9	0,815(2)					weighted mean 3-8 reduced-χ^2 = 1,8
10	0,788(10)	0,172(5)	0,040(4)	0,218	0,269	Table de Radionucléides (1982)
11	0,812(3)	0,150(3)	0,038(1)	0,185(3)	0,232	Present evaluation (Theory)

Theoretical values other than value 11 are not given because they depend critically on the transition energy Q_{EC} - E_γ and are based on very different values for Q_{EC}. The present value for P_K is in good agreement with the values 4 and 7, i. e. the most confident values, and also with the weighted mean which is dominated by these two values. The values of item 10 are significantly different from those of 11 because they are based on a much lower Q_{EC} value of 184 keV.

Vatai (1970) discussed the measurements of Moler and Fink (1965) and pointed out that the values for P_L/P_M measured with multi-wire proportional counter (MWPC) are not so reliable, as was thought. Fink (1969) revised the original value measured by Moler and Fink (1965), P_M/P_L = 0,232(20) using gaseous sources in a MWPC to give the new value P_L/P_M = 0,202(20).

2.2 Gamma Transitions

The level difference is calculated from the gamma ray energy (4.2) and the recoil energy. The total conversion coefficient is calculated from the experimental determined gamma-ray emission probability (4.2). a_K and a_L are calculated from the ratios $a_K/a_L/a_t$ = 11,35 / 12,43 / 26,78 as given by the theory (Rösel et al., 1978), interpolated by cubic spline method.

The value of a_t = 26,58(20) of the present evaluation is between the theoretical value 26,78 and the experimental value 26,4(4) of Dragoun et al. (1976). The evaluated value is by 0,8 % lower than the theoretical value. This tendency is qualitatively in agreement with that found by Nemeth and Veres (1990) for E3 and M3 transitions.

3 Atomic data

The atomic data are taken from Schönfeld and Janßen (1996).

3.1 X Radiation

The energy values are calculated from the wavelengths in Å* as given by Bearden (1967). The relative emission probabilities $P(K_\beta)/P(K_\alpha)$ and $P(K_{a_2})/P(K_{a_1})$ are taken from Schönfeld and Janßen. The ratio for $P(K_{b'_2})/P(K_{b'_1})$ is taken from the calculation of Scofield (1974). The ratio $P(X_L)/P(K_{a_1})$ is calculated from the absolute emission probabilities (Section 4.2). The total K-X ray emission probability is (assumed that there is no EC transition to the ground state)

$$P(KX) = w_K \{P_K + [a_K/(1 + a_t)]\}$$

$P(KX)$ is calculated from $P(KX)/P_g$ with the here adopted value of P_γ.

	$P(KX)$	$P(KX)/P_\gamma$	
1	1,225(25)	33,8(7)	Wapstra and van der Eijk (1957)
2	0,950(22)	26,2(6)	Leutz et al. (1965)
3	0,805(22)	22,2(6)	Jansen and Wapstra (1966)
4	1,055(36)	29,1(10)	Freedman et al. (1966)
5	1,088(145)	30(4)	Foin (1968)
6	0,928(33)	25,6(9)	Campbell and Mc Nelles (1972)
7	0,979(11)	27,0(3)	Dragoun et al. (1976)
8	0,990(22)	27,3(6)	Plch et al. (1979)
9	0,991(10)	27,34(27)	Hoppes and Schima (1982)
10	1,026(30)	28,3(9)	Geidelman et al. (1988)
11	1,012(14)	27,9(4)	Yegorov et al. (1989)
12	1,002(17)		Unweighted mean without values 1 and 3
13	0,990(8)		Weighted mean without values 1 and 3; reduced-χ^2 = 1,9
14	0,994(10)		Rec. by Bambynek in IAEA-TECDOC-619 (1991)
15	1,014(7)	29,0(2)	Present evaluation using the above equation together with the adopted values of ω_K, P_K, α_K, α_t

Value 15 is larger than values 12 to 14. Values 1 and 3 have been rejected from statistical considerations. These values differ by a factor 1,52, both claiming an uncertainty of less than 3 %. The unweighted mean (value 12) avoids an unjustified influence of single values with possibly overestimated accuracies. The more up-to-date values 7 to 11 are in reasonable agreement with the adopted value 15.

3.2 Auger Electrons

The energy values are taken from Larkins (1977) (KLL) and the Table de Radionucléides (1982; LMRI).

The ratios $P(KLX)/P(KLL)$ and $P(KXY)/P(KLL)$ are taken from Schönfeld and Janßen (1996).
The ratio $P(e_{AL})/P(KLL)$ is calculated from the absolute emission probabilities (Section 4.1).
A precise measurement of the Ag KLL Auger spectrum has been carried out by Kawakami et al. (1986).

4 Radiation Emission

4.1 Electron Emission

The Auger electron energies are the same as above. The conversion electron energies are calculated from the transition energy and the binding energies of the electrons of the corresponding shells. The number of electrons per disintegration are based on P_K, P_L, P_M as given in Section 2.1, a_K, a_L as given in Section 2.2 and the atomic data as given in Section 3.

4.2 Photon Emission

	E_γ in keV	
1	88,008(42)	Freedman et al. (1966)
2	88,041(87)	Schima and Hutchinson (1967)
3	88,05(5)	Libert (1967)
4	88,033(42)	Pierson and Marsh (1967)
5	88,09(3)	Foin et al. (1968)
6	88,21(3)	Furuta and Rhodes (1968)
7	88,036(8)	Heath (1969)
8	88,036(8)	Greenwood et al. (1970)
9	88,035(6)	Raeside (1970)
10	88,035(4)	Morii (1978)
11	88,0341(11)	Helmer et al. (1978)
12	88,0336(1)	R. G. Helmer and C. van der Leun (2000), here adopted

The X-ray energies are the same as above. The γ ray energy is taken from Helmer and van der Leun (1996). The number of X ray photons per disintegration are based on P_K, P_L, P_M as given in Section 2.1, a_K, a_L as given in Section 2.2 and the atomic data as given in Section 3.
The following values for the number of γ ray photons per disintegration have been taken into account:

	P_γ	correspond. a_t	
1	0,0365(4)	26,4(3)	Plch et al. (1979)
2	0,03594(19)	26,82(14)	Plch and Suran (1988)
3	0,0367(7)	26,2(6)	Martin (AECL, 1988)
4	0,0365(3)	26,40(23)	Gostely (IER, 1988)
5	0,0370(6)	26,0(5)	Park et al. (KSRI, 1988)
6	0,03600(10)	26,78(8)	Chauvenet (LMRI, 1988)
7	0,0357(10)	27,0(8)	Woods and Smith (NPL, 1988)
8	0,0365(8)	26,4(6)	Szörenyi et al. (OMH, 1988)
9	0,03675(18)	26,21(15)	Ballaux et al. (1988)
10	0,0366(5)	26,3(4)	Hino and Kawada (1989)
11	0,0368(7)	26,2(5)	Funck and Schötzig (1989), Schötzig et al. (1991)
12	0,0365(5)	26,4(4)	Chechev (1989)
13	0,03614(12)	26,67(12)	Ratel (1994) based on measurements in the framework of a BIPM intercomparison including the results measured b by the others of values 2 to 8
14	0,0389(7)	24,7(5)	Leutz et al. (1965); from a_t
15	0,0397(21)	24,2(14)	Sen and Durosinmi-Etti (1965); from a_t
16	0,0329(25)	29,4(25)	Foin et al. (1968); from a_t
17	0,0379(7)	25,4(5)	Legrand et al. (1973) ; from a_t
18	0,0360	26,8	Rysavy (1976); from theoretical a_t
19	0,0365(5)	26,4(4)	Dragoun et al. (1976); from a_t
20	0,03600	26,78	Rösel et al. (1978); from theoretical a_t
21	0,0365(3)	26,4(5)	Table de Radionucléides (1982); evaluation
22	0,0365(7)	26,0(3)	Hansen (1985); evaluation
23	0,03632(12)	26,53(9)	IAEA-TECDOC-619 (1991)
24	0,03626(26)	26,58(20)	present evaluation, weighted mean direct exp. values 1 - 12 and 14 - 17, 19

The weighted mean is calculated from all experimentally determined valus. Value 2 does not supersede value 1; it is an independent measurement. Value 2 through 8 were determined in the frame of an BIPM intercomparison, summarized by Ratel (value 13). When calculating the weighted mean (value 24) the largest weights come from values 2, 6 and 9. Whereas 2, 6 and also 13 are in excellent agreement, the value 9 is somewhat larger than these. [Values 21 to 23 are given only for comparison. In contrast to the above, for the calculation of value 23 the uncertainties of the values 9 and 6 has been increased by a factor of 2 on the basis of statistical considerations.] Value 6 agrees well with values 2 and 13 and value 9 is to be considered as a result of a careful work. For the present purpose the originally given uncertainties have not been changed. The weighted mean is 0,03626(7), but LWM has expanded the uncertainty so as to include the most precise value 6. The adopted value (line 24) is in agreement with values 13 (BIPM intercomparison), 18, 20 (from theoretical conversion coefficient) and the results of other evaluations (21 - 23).

Davidonis et al. (1988), compared measured ratios (88 keV) $L_1 : L_2$, $L_1 : L_3$, $L_2 : L_3$, $M_{4+5} : M_{1+2+3}$, N : M with the corresponding theoretical values, interpolated from the Tables of Hager-Seltzer, Rösel et al. and Band and Trzhazkovskaya (Dirac-Fock-Slater and Dirac-Fock approximation). Generally there is agreement within the uncertainties.

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

	a_K	a_t	a_K/a_L	$a_K/(a_L+a_M+a_N)$	
1	12,4(10)	-	-	0,85(2)	Brunner et al. (1953)
2	10,3(5)	-	-	-	Wapstra and van der Eijk (1957)
3	-	-	0,95(3)	-	Boyd et al. (1964)
4	11,0(3)	24,7(5)	-	-	Leutz et al. (1965)
5	11,3(4)	24,2(14)	-	-	Sen and Durosinmi-Etti (1965)
6	12,7(9)	29,4(25)	0,94	0,76(2)	Foin et al. (1968)
7	-	-	-	0,76(2)	Planskoy (1969)
8	10,6(5)	-	-	-	Bashandy (1970)
9	-	25,4(5)	-	-	Legrand et al. (1973)
10	11,4(3)	26,4(4)	0,933	0,760	Dragoun et al. (1976)
11	9,6(2)	-	-	-	Prochazka et al. (1978)
12	11,4(3)	26,4(3)	-	-	Plch et al. (1979)
13	-	26,21(14)	-	-	Ballaux et al. (1988)
14	-	26,67(9)	-	-	Ratel (1994)
15	11,28(12)	26,62(9)	0,913	0,736	weighted mean of experimental values
16	11,4	26,8	0,91	0,740	Rysavy (1976), theory
17	11,35	26,78	0,913	0,736	Rösel et al. (1978), theory
18	11,1(2)	26,0(3)	-	-	Hansen (1985), evaluation
19	11,3(2)	26,4(5)	0,904	0,748	Table de Radionucléides (1982)
20	11,28(12)	26,58(20)	0,913(9)	0,736(7)	present evaluation; the value for α_t corresponds to the evaluated value of P_γ

As a_t and P_γ are closely connected, further experimental values can be found in papers which are dealing with the determination of P_γ (above table). The most confident experimental values of conversion coefficients have been measured by Dragoun et al. (1976) (Entry 10). They have measured also a_{L_1} = 0,63(13), a_{L_2} = 5,48(18), a_{L_3} = 6,11(20), a_M = 2,40(8), and a_{NO} = 0,405(21). In order to obtain finally adopted values of the conversion coefficients, we follow here the procedure of Hansen (1985), who took into consideration only the values 4, 5, 9, 10 and 12 where the first two have been recalculated. The recommended values derived from this set are given under line 18.Values 16 and 17 are from theory, the latter is taken as cited in the IAEA-TECDOC-619 (1991). Shevelev et al. (1978) have measured the following ratios for the conversion coefficients of the 88 keV transition in ^{109}Ag: K / L / M / N = 0,98(5) / 1 / 0,20(1) / 0,050(5) and L_1 / L_2 / L_3 = 0,185(15) / 1 / 1,163(27). The ratios found by Shevelev et al. are in poor agreement with those of Dragoun. Davidonis et al. (1980) determined the ratios L_1 / L_2 / L_3 in sources containing Cd, CdTe and CdSe to be 0,148(7) / 0,86(2) / 1 and (N+O):M = 0,178(3) in good agreement with the corresponding theoretical values of Dragoun et al. (1976) and Rösel et al. (1978). A former measurement of Brenner and Perlman (1972) gave L_1 / L_2 / L_3 = 0,132(8) / 0,830(20) / 1. Martin et al. (1975) measured also the L_1 / L_2 / L_3-ratio for the 88 keV E3 transition in $^{109}Ag^m$ and found no significant departures from theory.

Nemeth and Veres (1973) pointed out that the internal conversion coefficients calculated by Hager and Seltzer are considered to be systematically 2 - 3 % higher for high multipol electromagnetic transitions than the experimental value. This was found already by Raman et al. (1973). Again, Nemeth and Veres (1990) compare theoretical conversion coefficient interpolated from the tables of Rösel et al. (1978) and came to the conclusion that for third and fourth order the theoretical values give better agreement with experimental values when they are multiplied by 0,975. For the 88 keV transition in ^{109}Ag the ratio between the adopted value and the Rösel value is 0,993. Band and Trzhaskovskaya (1993) have calculated ICCs for some high-multipole-order transitions using Dirac-Fock electron wave functions in different approximations. For the 88 keV E3 transition they found a_K values between 11,1 and 11,6 in reasonable agreement with value 18.

Double K-shell vacancy creation in the decay of ^{109}Cd has been measured by van Eijk and Wijnhorst (1977): P_{KK} (IC) = $2{,}8(7) \cdot 10^{-5}$ per K internal conversion. In a later paper van Eijk et al. (1979) determined the probability P_{KK}(IC) of double K-shell vacancy creation per K internal conversion of the 88 keV E 3 transition in the decay of $^{109}Ag^m$ by means of a K_α-X-ray-K-X-ray coincidence experiment on ^{109}Pd to be
$(13{,}0 \pm 1{,}1) \cdot 10^{-5}$. 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 $(1{,}02 \pm 0{,}36) \cdot 10^{-5}$. The energy shift of the hypersatellite Ag $K_{\alpha 1}^H$-X-ray line was found to be (532 ± 6) eV. Martin et al. (1975) measured ratios of L subshell conversion electrons. By Nagy et al. (1975) the probability that a double K-shell vacancy is formed per K-shell internal conversion was found to be $1{,}53(24) \cdot 10^{-4}$. Horvath and Ilakovac (1985) measured the decay of the double-K-shell vacancy state in $^{109}Ag^m$ the probability of creation of double K-shell vacancies per ^{109}Cd decay was determined to be $6{,}07(12) \cdot 10^{-5}$. Probability ratios of several hypersatellite peakes of K_α and K_β are determined. Inteman (1985) calculated the total probability per K-capture event for the ionization of the remaining K electron for a dozen nuclides of interest using a semirelativistic theory and compared them with experimental values. Ilakovac et al. (1988) 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.

5 Main Production Modes

Taken from the „Table de Radionucléides“, LMRI, 1982.

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