^{54}Mn - Comments on evaluation of decay data by V.P. Chechev and N.K. Kuzmenko

The first DDEP evaluation of ^{54}Mn decay data was undertaken in 2001 by R.G. Helmer and E. Schönfeld, with correction of the specification of the β^+-branch in 2004 (2004BeZR). Corrected from (0,1) to (0,0). The current evaluation was completed in March 2014 with a literature cut-off of the same date.

1. DECAY SCHEME

The structure of the adopted scheme of ^{54}Mn is based on the ENSDF evaluation by Huo and Huo (2006Hu08). ^{54}Mn disintegrates by electron capture (99.9997 (3) %) directly to the 834.855-keV excited level (2+) of ^{54}Cr, and by very weak electron capture and β+ transitions to the ground state (0+) of ^{54}Cr. The decay scheme of ^{54}Mn is judged to be complete since these are the only two levels populated in ^{54}Cr below the decay energy. The β^- decay branch is negligible and has not been included in this evaluation. The spin, parity and half-life of the ^{54}Cr excited level were adopted from the evaluation by 2006Hu08.

2. NUCLEAR DATA

Q_{EC} value is taken from the 2012 mass evaluation by Wang *et al.* (2012Wa38).

The recommended half-life of ^{54}Mn is based on the experimental results given in Table 1.

Table 1. Experimental values of the ^{54}Mn half-life (in days).

No.	Author(s) and year	Reference	$T_{1/2}$	Method and comments
1	Backofen and Herber (1955)	1955Ba10	291 (1)	Ionization chamber; *omitted*
2	Kafalas and Irvine (1956)	1956Ka33	290 (6)	Ionization chamber; *omitted*
3	Schuman *et al*. (1956)	1956Sc87	278 (5)	Ionization chamber; *omitted*
4	Wyatt *et al*. (1961)	1961Wy01	313.5 (7)	Ionization chamber; *omitted* as outlier
5	Ben-David (1964)	1964Be26	300	Ionization chamber; *omitted* – no uncertainty
6	Marin and Clare (1964)	1964Ma14	303 (1)	Ionization chamber; *omitted* as outlier
7	Anspach *et al*. (1965)	1965An07	311.9 (2)	Ionization chamber, sample 1; *omitted* (superseded by 23)
8	Anspach *et al*. (1965)	1965An07	311.9 (2)	4πγ ionization chamber, sample 2; *omitted* (superseded by 23)
9	Anspach *et al*. (1965)	1965An07	312.6 (4)	4πγ ionization chamber, sample 3; *omitted* (superseded by 23)

10	Salisbury and Chalmers (1965)	1965Sa09	314	4πγ ionization chamber; *omitted* - no uncertainty
11	Hammer (1968)	1968Ha47	312 (5)	Ionization chamber
12	Lagoutine *et al*. (1968)	1968La10	312.2 (3)	Ionization chamber; quoted σ of 0.9 divided by 3
13	Zimmer and Dahl (1968)	1968Zi01	312.99 (5)	Ionization chamber, quoted σ of 0.10 divided by 2; *omitted* as outlier
14	Bock *et al*. (1969)	1969BoZX	312.2 (9)	Ionization chamber
15	Merritt, Taylor (1973)	1973MeYE	312.16 (11)	Ionization chamber; *omitted* (superseded by 18)
16	Visser *et al*. (1973)	1973Vi13	315.40 (3)	4πγ ionization chamber; *omitted* as outlier
17	Cressy (1974)	1974Cr05	312.6 (8)	Ge(Li) detector
18	Merritt *et al*. (1979)	1979MeZY	312.21 (5)	NaI(Tl) detector; *omitted* (superseded by 19)
19	Rutledge *et al*. (1980)	1980RuZV	312.21 (3)	NaI(Tl) detector; *omitted* (superseded by 20)
20	Rutledge *et al*. (1982)	1982RuZV	312.21 (3)	NaI(Tl) detector
21	Rytz (1982)	1982RyZX	312.19 (13)	4πγ ionization chamber
22	Rytz (1982)	1982RyZX	312.15 (23)	4πγ ionization chamber
23	Hoppes *et al*. (1982)	1982HoZJ	312.02 (4)	4πγ ionization chamber; γ counting; *omitted* (superseded by 24)
24	Unterweger *et al*. (1992)	1992Un01	312.028 (34)	4πγ ionization chamber; *omitted* (superseded by 27)
25	Martin *et al*. (1997)	1997Ma75	312.11 (5)	4πγ ionization chamber
26	Huh and Liu (2000)	2000Hu20	312.6 (5)	4πγ ionization chamber
27	Unterweger *et al*. (2002)	2002Un01	311.97 (5)	4πγ ionization chamber; *omitted* (superseded by 32)
28	Da Silva *et al*. (2006)	2006Da20	312.1 (9)	HPGe detector
29	Van Ammel *et al*. (2010)	2010Va13	312.32 (9)	Ionization chamber
30	Van Ammel *et al*. (2010)	2010Va13	311.9 (5)	HPGe detector
31	Van Ammel *et al*. (2010)	2010Va13	311.9 (6)	NaI detector
32	Fitzgerald (2012)	2012Fi12	312.03 (3)	4πγ ionization chamber; *omitted* (superseded by 33)
33	Unterweger and Fitzgerald (2014)	2014Un01	311.94 (17)	4πγ ionization chamber
Recommended value		**312.19 (3) days**		**LWM**

Values 1→3 obtained before 1960 were omitted because of the difficulty in determining the presence of impurities in the samples by means of the spectrometry methods available at that time. Both values 5, 10 are without uncertainties, and were also omitted. The quoted uncertainty for the value of 1968La10 was divided by 3 to convert to the 1σ confidence level. Values 7, 8, 9, 15, 18, 19, 23, 24, 27, 32 were not used because they have been subsequently replaced by later results from the same laboratory.

Values 4, 6, 13, 16 have been rejected by the LWEIGHT computer program based on the Chauvenet's criterion to give a weighted average of the remaining fourteen values of 312.19 d. The LWEIGHT program includes the limitation of relative statistical weight method (LWM), and this procedure was used to determine the weighted average with an internal uncertainty of 0.024 d and an external uncertainty of 0.020 d. The largest contributions to the weighted average give values of 20 (63%) and 25 (23%), while the ratio of the reduced $\chi^2 / (\chi^2)_{crit}$ is 0.7/2.0. The smallest experimental uncertainty is 0.03 d.

The recommended value for the ^{54}Mn half-life is **312.19 (3) days**.

2.1 Electron-Capture and β^+ Transitions

As discussed by Helmer and Schönfeld (2004BeZR), the unique 2nd forbidden ($\varepsilon + \beta^+$) - transition to the ^{54}Cr ground state has not been observed, but an upper limit can be determined from the log *ft* systematics (1998Si17) as well as from searches for positron emissions. From log *ft* systematics, log $f_{2u}t$ > 13.9 which corresponds to an ($\varepsilon + \beta^+$)-branch of < 0.0007%. Experimental limits on the β^+ intensity come from searches for the 511-keV annihilation radiation, and are $\leq 8\times10^{-5}$ % (1968Be01), $\leq 4.4\times10^{-6}$ % (1989Su08), and $\leq 5.7\times10^{-7}$ % (1993Da20). The latter value and theoretical ε/β^+ ratio of 638 (11) gives an electron capture probability of ≤ 0.00036 %. Since this limit is lower than that from the log *ft* systematics, this value was adopted, and the evaluators recommend a value of 0.0003 (3) % for the probability of the ε-transition to the ^{54}Cr ground state. Thus, P_ε (^{54}Cr excited state, 834.9 keV) = 100 % – 0.0003 (3) % = 99.9997 (3) % assuming that the β^- decay of ^{54}Mn is negligible (Table 2).

Table 2. ^{54}Cr levels populated in decay of ^{54}Mn.

Level	Energy (keV)	Multipolarity	Half-life	P_ε (%)	$P_{\beta+}$ (%)
0	0	0+	Stable	0.0003 (3)	< 5.7×10^{-7}
1	834.855 (3)	2+	7.9 (3) ps	99.9997 (3)	-

2.2 β⁻ transition

A unique 2nd forbidden β^- transition to the ^{54}Fe ground state was not observed. As calculated from log *ft* systematics (1998Si17), log $f_{2u}\ t \geq 13.9$, and this corresponds to $P_{\beta^-} \leq 0.0005\%$ (2004BeZR).

From cosmic-ray data and a model of galactic transport of cosmic rays, the authors of 1996Du15 deduce the partial half-life for β^- decay to be between 1×10^6 and 2×10^6 years, which corresponds to a β^- branch intensity between 0.00004% and 0.00009%. Owing to the lack of information, no data for this negligible branch have been included in this evaluation.

2.3 Gamma Transition and Internal Conversion Coefficients

The gamma-ray transition probability is equal to the adopted probability of (ε + β^+)-transition to the ^{54}Cr 834.9 keV excited level (99.9997 (3) %). Adopted ICC(s) are theoretical values interpolated by the BrIcc computer program (2008Ki07) from the tables of Band et al. (2002Ba85), based on BrIccNH approximation. Multipolarity has been taken from 2006Hu08.

3. ATOMIC DATA

SAISINUC software has been used to determine the atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electrons energies and relative probabilities).

4. ELECTRON EMISSIONS

The energies of the conversion electrons have been obtained from the gamma-ray transition energy and the electron binding energies. Absolute emission probabilities of the conversion electrons have been deduced using recommended Pγ and ICC values.

The absolute emission probabilities of K- and L-Auger electrons have been calculated using the EMISSION computer program.

5. PHOTON EMISSIONS

5.1. X-ray Emissions

The absolute emission probabilities of Cr KX- and LX- rays have been calculated using the EMISSION computer program. Calculated values were compared to the experimental data listed in Table 3.

Table 3. Experimental and adopted values of the total XK - ray emission probability (%) in the decay of ^{54}Mn.

P(XK)	Reference
25.7 (4)	1963Ta19
24.3 (12)	1965Le21

25.14 (17)	1967Ba50
24.90 (53)	1967PeZZ
24.92 (17)	1968Ha47
24.4 (3)	1973KoAA
24.7 (9)	1973MuAA
25.93 (14)	1978Ma06
25.1 (7)	1980Co22
25.7 (5)	**Adopted (calculated)**

5.2. Gamma ray emissions

The energy of the 834.9 keV gamma ray has been adopted from 2006Hu08, and the emission probability has been computed from the adopted γ-ray transition probability (99.9997 (3) %) and ICC α_T.

6. ENERGY CONSERVATION

A total average energy of 1377.1 (10) keV for one disintegration has been calculated from the current evaluated data. This value corresponds very well to an energy of 1377.2 (10) keV (Q_{EC}) obtained from the mass tables (2012Wa38), and confirms the consistency of the decay scheme and reliability of this evaluation.

7. REFERENCES

1955Ba10 E. W. Backofen, R. H. Herber, Phys. Rev. 97 (1955) 743. [$T_{1/2}$]

1956Ka33 P. Kafalas, J. W. Irvine, Jr., Phys. Rev. 104 (1956) 703. [$T_{1/2}$]

1956Sc87 R. P. Schuman, M. E. Jones, A. C. McWherter, J. Inorg. Nucl. Chem. 3 (1956) 160. [$T_{1/2}$]

1961Wy01 E. I. Wyatt, S. A. Reynolds, T. H. Handley, W. S. Lyons, H. A. Parker, Nucl. Sci. Eng. 11 (1961) 74. [$T_{1/2}$]

1963Ta19 J. G. V. Taylor, J. S. Merritt, Proc. Int. Conf. Role of Atomic Electrons in Nuclear Transformations, Warsaw, vol. III (1963) p. 465. [P_X]

1964Be26 G. Ben-David, Nucl. Sci. Eng. 20 (1964) 281. [$T_{1/2}$]

1964Ma14 W. H. Marin, D. M. Clare, Nucl. Sci. Eng. 19 (1964) 465. [$T_{1/2}$]

1965An07 S. C. Anspach, L. M. Cavallo, S. B. Garfinkel, J. M. R. Hutchinson, C. N. Smith, Non-Project Report NP-15663, available from DOE Technical Information Center, Oak Ridge, Tennessee (1965). [$T_{1/2}$]

1965Le21 K. F. Leistner, Atomkernenergie 10 (1965) 311. [P_X]

1965Sa09 S. R. Salisbury, R. A. Chalmers, Phys. Rev. 140 (1965) B305 [$T_{1/2}$]

1967Ba50 W. Bambynek, Z. Phys. 206 (1967) 66. [P_X]

1967PeZZ M. Petel, H. Houtermans, "Standardization of Radionuclides", (IAEA, Vienna, 1967) 301. [P_X]

1968Be01 D. Berenyi, D. Varga, B. Vasvari, E. Brucher, Nucl. Phys. A106 (1968) 248. [$I_{\beta+}$]

1968Ha47 J. W. Hammer, Z. Phys. 216 (1968) 355. [P_X]

1968La10 F. Lagoutine, Y. le Gallic, J. Legrand, Int. J. Appl. Radiat. Isot. 19 (1968) 475. [$T_{1/2}$]

1968Zi01 W. H. Zimmer, R. E. Dahl, Nucl. Sci. Eng. 32 (1968) 132. [$T_{1/2}$]

1969BoZX P. Bock, Gesellschaft fuer Kernforschung mbH, Karlsruhe report KFK-1116 10/14/71 (1969). [$T_{1/2}$]

1973MeYE J. S. Merritt, J. G. V. Taylor, Atomic Energy of Canada Ltd. report AECL-4657 (1974) 30. [$T_{1/2}$]

1973Ko** A. A. Konstantinov, T. E. Sazonova, A. Konstantinov, Proc. Int. Conf. Inner-Shell Ionization Phenomena and Future Applications, April 1972 (1973) p. 144. [P_X]

1973Mu** A. Mukerji, Chin Lee, Proc. Int. Conf. Inner-Shell Ionization Phenomena and Future Applications, April 1972 (1973) p. 164. [P_X]

1973Vi13 C. J. Visser, J. H. M. Karsten, F. J. Haasbroek, P. G. Marias, Agrochemophysica 5 (1973) 15. [$T_{1/2}$]

1974Cr05 P. J. Cressy, Jr., Nucl. Sci. Eng. 55 (1974) 450. [$T_{1/2}$]

1978Ma06 P. Magnier, J. Bouchard, M. Blondel, J. Legrand, J.-P. Perolat, R. Vatin, Z. Phys. A284 (1978) 389. [P_X]

1979MeZY J. S. Merritt, A. R. Rutledge, L. V. Smith, F. H. Gibson, NEANDC report NEANDC(CAN)-51/L (1979) 12. [$T_{1/2}$]

1980Co22 D. D. Cohen, Nucl. Instrum. Methods 178 (1980) 481. [P_X]

1980RuZV A. R. Rutledge, L. V. Smith, J. S. Merritt, Atomic Energy of Canada Ltd. report AECL-6692 (1980). [$T_{1/2}$]

1982HoZJ D. D. Hoppes, J. M. R. Hutchinson, F. J. Schima, M. P. Unterweger, National Bureau of Standards report NBS-SP-626 (1982) 85. [$T_{1/2}$]

1982RuZV A. R. Rutledge, L. V. Smith, J. S. Merritt, National Bureau of Standards report NBS-SP-626 (1982) 5. [$T_{1/2}$]

1982RyZX A. Rytz, National Bureau of Standards report NBS-SP-626 (1982) 32. [$T_{1/2}$]

1989Su08 B. Sur, K. R. Vogel, E. B. Norman, K. T. Lesko, R.-M. Larimer, E. Browne, Phys. Rev. C39 (1989) 1511. [$T_{1/2}$]

1992Un01 M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Methods Phys. Res. A312 (1992) 349. [$T_{1/2}$]

1993Da20 M. T. F. da Cruz, Y. Chan, A. Garcia, M. M. Hindi, G. Kenchian, R.-M. Larimer, K. T. Lesko, E. B. Norman, R. G. Stokstad, F. E. Wietfeldt, I. Zlimen, Phys. Rev. C48 (1993) 3110. [ε, β^+]

1996Du15 M. A. DuVernois, Phys. Rev. C54 (1996) R2134. [$T_{1/2}$]

1997Ma75 R. H. Martin, K. I. W. Burns, J. V. G. Taylor, Nucl. Instrum. Methods Phys. Res. A390 (1997) 267. [$T_{1/2}$]

1998Si17 B. Singh, J. L. Rodriguez, S. S. M. Wong, J. K. Tuli, Nucl. Data Sheets 84 (1998) 487. [log ft systematics]

2000Hu20 C.A. Huh, L.F. Liu, J. Radioanal. Nucl. Chem. 246 (2000) 229. [$T_{1/2}$]

2002Un02 M.P. Unterweger, Appl. Radiat. Isot. 56 (2002) 125. [$T_{1/2}$]

2002Ba85 I.M. Band, M.B. Trzhaskovskaya, C.W. Nestor, Jr., P.O. Tikkanen, S. Raman, At. Data Nucl. Data Tables 81 (2002) 1. [Theoretical ICC]

2004BeZR M.-M. Be, V. Chiste, C. Dulieu, E. Browne, V. Chechev, N. Kuzmenko, R. Helmer, A. Nichols, E. Shönfeld, R. Dersch. *Table of Radionuclides (Vol. 1 – A = 1 to 150).* Bureau International des Poids et Mesures, 2004. ^{54}Mn, p. 71. [Previous ^{54}Mn decay data evaluation]

2006Hu08 J. Huo, S. Huo, Nucl. Data Sheets 107 (2006) 1393. [Decay Scheme, ^{54}Cr adopted levels and gammas].

2006Da20 M.A.L. da Silva, R. Poledna, A. Iwahara, C.J. da Silva, J.U. Delgado, R.T. Lopes. Appl. Radiat. Isot. 64 (2006) 1440. [$T_{1/2}$]

2008Ki07 T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Jr. Nucl. Instrum. Methods Phys. Res. A589 (2008) 202. [BrIcc computer program]

2010Va13 R. Van Ammel, J. Paepen, S. Pommé, G. Sibbens, Appl. Radiat. Isot. 68 (2010) 2387. [$T_{1/2}$]

2012Wa38 M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer. Chin. Phys. C36 (2012) 1603. [Q]

2012Fi12 R. Fitzgerald, J. Res. Natl. Inst. Stand. Technol. 117 (2012) 80. [$T_{1/2}$]

2014Un01 M.P. Unterweger, R. Fitzgerald. Appl. Radiat. Isot. 87 (2014) 92. [$T_{1/2}$]