^{46}Sc - Comments on evaluation of decay data

by R.G. Helmer and N.K. Kuzmenko

This evaluation was originally completed by R.G. Helmer in 2001 (2004BeZR) and was updated by N.K. Kuzmenko in June 2014 to include new references on the ^{46}Sc half-life and decay energy and new internal conversion coefficients and thus to re-evaluate the half-life and to correct nuclear transition energies and gamma ray emission probabilities.

1. DECAY SCHEME

The only levels in ^{46}Ti below the decay energy are those populated in this ^{46}Sc β^- decay, so that portion of the decay scheme is complete. However, ^{46}Sc can also electron-capture decay to levels in ^{46}Ca with a decay energy of 1378 keV (2012Wa38). The available levels are 0^+ at 0 keV and 2^+ at 1346 keV with 4th forbidden and 2nd forbidden EC-branches, respectively. From systematics (1998Si17), the corresponding log *ft* limits are ≥ 22.5 and ≥ 10.6, and the deduced $P_{\varepsilon + \beta+}$ limits are $\leq 1.0\times10^{-12}$ % and $\leq 2.5\times10^{-6}$ %, respectively. Therefore, these EC- branches are negligible.

2. NUCLEAR DATA

Q value is from the 2012 mass evaluation by Wang *et al.* (2012Wa38).

The recommended half-life of ^{46}Sc is based on the experimental results given in Table 1.

Table 1. Experimental values of the ^{46}Sc half-life (in days)

N	Author(s) and year	Reference	$T_{1/2}$	Method and comments
1	Walke (1940)	1940Wa01	85 (1)	*omitted* according to Chauvenet's criterion
2	Schuman *et al.* (1956)	1956Sc87	84.1 (3)	Proportional counter; *omitted* according to Chauvenet's criterion
3	Geiger (1957)	1957Ge07	83.89 (6)	Ionization chamber; *omitted* according to Chauvenet's criterion
4	Wright *et al.* (1957)	1957Wr37	84.2 (2)	Ionization chamber; *omitted* according to Chauvenet's criterion
5	Hontzeas, Yaffe (1963)	1963Ho17	84.0 (9)	*omitted* according to Chauvenet's criterion
6	Anspach *et al.* (1965)	1965An07	83.80 (3)	4πγ ionization chamber; *omitted* as superseded by 14

7	Walker, Easterday (1967)	1967Wa29	84.3 (4)	Ionization chamber; *omitted* on Chauvenet's criterion
8	Bambynek *et al.* (1972)	1972BaWG	83.69 (9)	
9	Cressy (1974)	1974Cr05	84.34 (13)	NaI *omitted* according to Chauvenet's criterion
10	Merritt, Gibson (1977)	1977MeZP	83.75 (3)	*omitted* as superseded by 13
11	Houtermans *et al.* (1980)	1980Ho17	83.819 (6)	Ge(Li) detector
12	Olomo, MacMahon (1980)	1980Ol03	83.79 (6)	4π βγ coincidence
13	Rutledge *et al.* (1980)	1980RuZY	83.752 (15)	NaI(Tl) detector
14	Hoppes *et al.* (1982)	1982HoZJ	83.79 (6)	4πγ ionization chamber; *omitted* as superseded by 17
15	Rutledge *et al.* (1982)	1982RuZV	83.752 (15)	*omitted* as reported the measurement result 13
16	Walz *et al.* (1983)	1983Wa26	83.73 (12)	4πγ pressurized ionization chamber
17	Unterweger *et al.* (1992)	1992Un01	83.83 (7)	4πγ ionization chamber; *omitted* as superseded by 18
18	Fitzgerald (2012)	2012Fi12	83.828 (66)	4πγ ionization chamber; *omitted* as superseded by 19
19	Unterweger and Fitzgerald (2014)	2014Un01	83.84 (8)	4πγ ionization chamber
Recommended value			**83.787 (16)**	**LWM**

The values 1-5, 7, 9 have been rejected by the LWEIGHT computer program based on Chauvenet's criterion.

The values 6, 10, 14, 17, 18 were not used because they were replaced ultimately by later results of the same laboratories. The value 15 was omitted as 1982RuZV reported the measured value from 1980RuZY.

For 6 values (8, 11, 12, 13, 16, 19) included, the LWEIGHT computer program using the limitation of relative statistical weight method (LWM) increased the uncertainty of the value of 1980Ho17 from 0.006 d to 0.014 d in order to reduce its relative weight from 85 % to 50 %. Thereafter the relative weight of the value 15 was increased from 14 % to 44 %.

For the final weighted average of 83.787 d, the internal uncertainty is 0.010, the reduced- χ^2 / $(\chi^2)_{crit}$ value is 2.5/3.0, and the external uncertainty is 0.016. The LWEIGHT program has chosen the weighted average with the external uncertainty.

Thus, the recommended value of ^{46}Sc half-life is **83.787 (16) days**.

2.1. Beta Transitions

The energies of β^{-} transitions have been obtained using the Q^{-} value and the ^{46}Ti level energies calculated from the gamma-ray energies (Table 2). The J$^{\pi}$ values and half-lives for the excited levels ^{46}Ti are from Adopted Levels in Nuclear Data Sheets (2000Wu08).

Table 2. ^{46}Ti levels populated in ^{46}Sc β^{-}-decay

Level	**Energy (keV)**	**Spin, parity**	**Half-life**	**$P_{\beta-}$ (%)**
0	0	0+	Stable	0
1	889.280 (2)	2+	5.32 (15) ps	0.02 (2)
2	2009.832 (4)	4+	1.62 (10) ps	99.98 (2)

The β^{-} branch to the ground state of ^{46}Ti is 4th forbidden with an expected log *ft* ≥ 22.5 (1998Si17) and a corresponding $P_{\beta-}$(2367 keV) ≤ 1×10^{-11} %, the measured limit is ≤ 1×10^{-4} % (1954Ke04).

Similarly, for the 2nd forbidden decay to the 889 keV level, the expected log *ft* ≥ 10.6 which corresponds to $P_{\beta-}$ (1477 keV) ≤ 0.8 %. The measured $P_{\beta-}$ to this level are 0.096 (10) % (1954Ke04), 0.0036 (7) % (1956Wo09), ≤ 0.06 % (1950Mo62), and ≤ 0.05 % (1950So57). Some previous evaluators (e.g., 1986Al19) have assigned $P_{\beta-}$ (1477 keV) = 0.0036 (7) % because it is consistent with the limits of 1950Mo62 and 1950So57. However, R.G. Helmer (2004BeZR) had some reservations about the resulting precision for $P_{\beta-}$ (357.5 keV) and, therefore, expanded the uncertainty for $P_{\beta-}$ (1477 keV) to 0.004 (+36-4) %, which is consistent with the two limits and the value of 1956Wo09, and thus $P_{\beta-}$(356.7 keV) = 99.996 (+4-36) %.

As symmetric uncertainties are required for these quantities, $P_{\beta-}$ (1477 keV) = 0.02 (2) % and $P_{\beta-}$(356.7 keV) = 99.98 (2) % are adopted values in this evaluation.

The β^{-} average energies and log *ft* values are from LOGFT code.

2.2. Gamma Transitions and Internal Conversion Coefficients

Gamma-ray transition probabilities have been deduced from their gamma-ray emission intensities, the total conversion coefficients ICC(s), and the adopted internal pair creation coefficient (IPC). The adopted ICC(s) are the theoretical values interpolated by the BrIcc computer program (2008Ki07) from the tables of Band et al. (2002Ba85), accepting the “frozen orbital (no hole)” approximation. The multipolarities and mixing ratio δ have been taken from 2000Wu08. The adopted internal pair creation coefficient, α_{π}, have been calculated with the BrIcc computer program.

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 energies and the electron binding energies.

The absolute emission probabilities of the conversion electrons have been deduced using recommended $P\gamma$ and ICC values.

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

β^- average energies have been calculated using the LOGFT computer program.

5. PHOTON EMISSIONS

5.1. X-ray Emissions

The absolute emission probabilities of Ti KX- and LX- rays have been calculated using the EMISSION computer program.

5.2. Gamma ray emissions

The γ-ray energies are from 2000He14 for the 889 keV and 1120 keV lines and the 2009 keV energy is the sum of these values corrected for nuclear recoil.

The γ-ray emission intensity of the 2009-keV γ-ray, $I\gamma_{2,0}$, is from 1980Fu07.

The emission intensity of the 889-keV γ-ray $I\gamma_{1,0} = [100.0\ \% - I\gamma_{2,0}\ (1 + \alpha_T(\gamma_{2,0})] / [1 + \alpha_T(\gamma_{1,0})] = 99.999987\ (10)\ \% / 1.0001625\ (23) = 99.98374\ (25)\ \%$.

That of the 1120-keV γ-ray $I\gamma_{2,1} = \{P_{\beta-}\ (356.7\ \text{keV}) - P\gamma_{2,0}\} / [1 + \alpha_T\ (\gamma_{2,1}) + \alpha_\pi(\gamma_{2,1})] = [99.98\ (2) - 0.000013\ (10)] / 1.0000941\ (12) = 99.97\ (2)\ \%$

$I\gamma\pm = 2 \times I\gamma_{2,1} \times \alpha_\pi(\gamma_{2,1})$.

6. ENERGY CONSERVATION

The total average energy of 2366.7 (9) keV, for one disintegration, calculated from the current evaluated data corresponds well to the available energy of 2366.5 (7) keV (Q^-) from the mass tables (2012Wa38) confirming the consistency of the decay scheme and the reliability of this evaluation.

7. REFERENCES

1940Wa01 H. Walke, Phys. Rev. 57 (1940) 163.
[T1/2]

1950Mo62 M. L. Moon, M. A. Waggoner, A. Roberts, Phys. Rev. 79 (1950) 905.
[$P_{\beta-}$]

1950So57 B. N. Sorensen, B. M. Dale, J. D. Kurbatov, Phys. Rev. 79 (1950) 1007.
[$P_{\beta-}$]

1954Ke04 G. L. Keister, F. H. Schmidt, Phys. Rev. 93 (1954) 140.
[$P_{\beta-}$]

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

1956Wo09 J. L. Wolfson, Can. J. Phys. 34 (1956) 256.
[$P_{\beta-}$]

1957Ge07 K. W. Geiger, Phys. Rev. 105 (1957) 1539.
[T1/2]

1957Wr37 H.W. Wright, E.I. Wyatt, S.A. Reynolds, W.S. Lyon, T.H. Handley, Nucl. Sci. Eng. 2 (1957) 427.
[$T_{1/2}$]

1963Ho17 S. Hontzeas, L. Yaffe, Can. J. Chem. 41 (1963) 2194
[$T_{1/2}$]

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, Tenn. (1965).
[$T_{1/2}$]

1967Wa29 D.A. Walker, H.T. Easterday, Nucl.Instr.Methods 48 (1967) 277
[$T_{1/2}$]

1972BaWG W. Bambynek, G. Bortels, D. Reher, EANDC(E) 150 U, p.144 (1972)
[$T_{1/2}$]

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

1977MeZP J. S. Merritt, F. H. Gibson, AECL-5696 (1977) 40.
[T1/2]

1979Sc31 P. Schluter, G. Soff, At. Data Nucl. Data Tables 24 (1979) 509.
[α_{π}]

1980Fu07 M. Fujishiro, Y. Satoh, K. Okamoto, T. Tsujimoto, Can. J. Phys. 58 (1980) 1712 .
[Pγ]

1980Ho17 H. Houtermans, O. Milosevic, F. Reichel, Intern. J. Appl. Radiat. Isotop. 31 (1980) 153.
[$T_{1/2}$]

1980Ol03 J.B. Olomo, T.D. MacMahon, J. Phys.(London), G6 (1980) 367.
[T1/2]

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

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

1982RuZV A. R. Rutledge, L. V. Smith, J. S. Merritt, National Bureau of Standards, Washington, D.C., Report NBS-SP-626 (1982) 5.

[$T_{1/2}$]

1983Wa26 K.F. Walz, K. Debertin, H. Schrader, Intern. J. Appl. Radiat. Isot. 34 (1983) 1191.
[$T_{1/2}$]

1986Al19 D. E. Alburger, Nucl. Data Sheets 49 (1986) 237.
[evaluation]

1992Un01 M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instr. Meth. Phys. Res. A312 (1992) 349.
[T1/2]

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

2000He14 R. G. Helmer, C. van der Leun, Nucl. Instr. Meth. A450 (2000) 35.
[Eγ]

2000Wu08 S.-C. Wu, Nucl. Data Sheets 91 (2000) 1.
[J^{π}, multipolarities]

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

2004BeZR M.-M. Bé, V. Chisté, C. Dulieu, E. Browne, V. Chechev, N. Kuzmenko, R. Helmer, A. Nichols, E. Schönfeld, R. Dersch. *Table of Radionuclides (Vol. 1 – A = 1 to 150).* Bureau International des Poids et Mesures, 2004. ^{46}Sc.
[Previous ^{18}F decay data evaluation]

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

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

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

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