^{47}Sc - Comments on evaluation of decay data by X. Mougeot

This evaluation was completed in 2013, taking into account the available literature by November 2013. This radionuclide was first identified correctly by 1945HI04 who associated to ^{47}Sc the correct half-life and beta electron energies.

The study of the β^- decay of ^{47}Sc by 1986RE12 is the most precise and complete one. Notice also that it comes from a collaborative work of three metrological laboratories (CBNM, NPL, LNHB). Therefore, the final evaluated values adopted here are very similar to their results.

1 Decay Scheme

The decay scheme is complete for this β^- decay. The ground state of ^{47}Sc is 7/2$^-$ (2007BU08). From Q^- = 600,8 (19) keV (2012WA38), two levels of ^{47}Ti are reachable (2007BU08): the ground state, 5/2$^-$ and, the first excited state at 159 keV, 7/2$^-$. The two beta transitions populating them are allowed.

Consistency of the decay scheme was checked in Section 4.2.2. The effective Q value resulting from total energy balance considerations is: Q_{eff} = 601 (35) keV, consistent with Q^- = 600,8 (19) keV from 2012WA38 adopted in this evaluation.

2 Nuclear Data

The Q value adopted in this evaluation, Q^- = 600,8 (19) keV, is from Wang *et al.* 2012 (2012WA38).

2.1 ^{47}Sc Half-life

A full list of the half-life values available by November 2013 is summarized in Table 1, including the experimental methods used. Values reported without uncertainty were not taken into account in the present evaluation.

The original value from 1968ME07 is 3,345 (3) d. In their paper, the authors gave all the measured values they obtained, reproduced in Table 2, from which they calculated a weighted average. The LWEIGHT program excludes the value 3,332 (3) d by Chauvenet's criterion and gives 3,3476 (17) d. The value 3,332 (3) d is therefore excluded of this evaluation. Dispersion of data was used by the evaluator to determine a systematic uncertainty, which was included to give: 3,348 (5) d. Nevertheless, the adopted value is provided by the arithmetical mean because the values are from the same authors using the same method. Including a systematic uncertainty, it was found 3,347 (5) d, consistent with the value provided by LWEIGHT.

The original value from 1969RA16 is 82,12 (9) h. It was just converted into days by the evaluator: 3,4217 (38) d.

The original value from 1986RE12 is 3,3492 (6) d, which comes from a weighted mean of six half-life measurements, given in Table 3: three from NPL using a ionization chamber, two from CBNM using Ge(HP), and one from CBNM using NaI(Tl) integral counting. An arithmetical mean was performed with the NPL values and the minimum uncertainty was chosen: 3,3484 (6) d. Identically, an arithmetical mean was determined from the measurements from CBNM: 3,3502 (13) d. The uncertainty was chosen to be the one from the arithmetical mean because CBNM used two different techniques.

Considering the values of Table 1 with uncertainties, the data set is discrepant. LWEIGHT recommends an unweighted average and expands the uncertainty so range includes the most precise value from 1986RE12: 3,3484 (6) d. Actually, there are two groups of consistent measurements: the ones obtained from beta measurements only, and the ones obtained using gamma measurements (including sometimes also beta measurements). This fact was highlighted by 1980MO26 but without giving an explanation. The evaluated half-life from the first group is 3,4219 (37) d. LWEIGHT excludes the value from 1956LI38 by Chauvenet's criterion, and adopts a weighted average with internal uncertainty. The evaluated half-life from the second group is 3,3485 (9) d. LWEIGHT excludes the values from 1955LY34, 1963HO17 and 1968BA33 by

Chauvenet's criterion, and uses a weighted average with external uncertainty. The latter evaluated value was preferred by the evaluator because it includes the value from 1986RE12.

To conclude, the recommended half-life for the β^- decay of ^{47}Sc is: **$T_{1/2}$ = 3,3485 (9) d**.

Table 1: ^{47}Sc half-life measurements

Reference	$T_{1/2}$ (d)	Method	Comments
1945HI04	3,40	β	Rejected: no uncertainty
1949KR12	3,43 (3)	β	
1953CH16	3,4	β+γ	Rejected: no uncertainty
1953CO44	3,40 (5)	β	
1953DU22	3,44	β	Rejected: no uncertainty
1953MA64	3,44 (5)	β	
1955LY34	3,45 (10)	β + γ	
1956LI38	3,3 (1)	β	
1959PO64	3,45 (6)	β	
1963HO17	3,38 (9)	γ	
1964MI07	3,40	γ	Rejected: no uncertainty
1968BA33	3,3 (1)	γ	
1968ME07	3,347 (5)	β + γ	Re-evaluated from 3,345 (3) d
1969RA16	3,4217 (38)	β	Calculated from 82,12 (9) h
1980MO26	3,341 (3)	γ	
1986RE12	3,3502 (13)	γ	Evaluated from the CBNM measurements
1986RE12	3,3484 (6)	β + γ	Evaluated from the NPL measurements
Evaluated	**3,3485 (9)**		**From γ and β + γ measurements**

Table 2: ^{47}Sc half-life measurements from 1968ME07

Comments	$T_{1/2}$ (d)
	3,344 (3)
	3,347 (3)
	3,352 (3)
Excluded by Chauvenet's criterion	3,332 (3)
	3,343 (6)
	3,351 (6)
Weighted average	3,345 (3)
Re-evaluated	**3,347 (5)**

Table 3: ^{47}Sc half-life measurements from 1986RE12

Comments	$T_{1/2}$ (d)
CBNM NaI(Tl) integral counting	3,3500 (6)
CBNM Ge(HP)	3,3480 (31)
CBNM Ge(HP)	3,3525 (15)
Evaluated	**3,3502 (13)**
NPL Ionization Chamber	3,3478 (10)
NPL Ionization Chamber	3,3491 (19)
NPL Ionization Chamber	3,3483 (6)
Evaluated	**3,3484 (6)**

2.2 Half-life of the first excited state of ^{47}Ti

The half-life of the first excited state of ^{47}Ti does not come from the β^- decay of ^{47}Sc. It was taken in 2007BU08: **$T_{1/2}$(159 keV) = 210 (6) ps**.

2.3 Beta Transitions

Probabilities of the two beta transitions involved in the ^{47}Sc decay were determined by two methods in the literature: from direct β-electron measurements, or deduced from the absolute gamma-ray probability P_γ.

The β-electron measurements are given in Table 4. $P_{\beta 1}$ is associated with the ^{47}Sc ground state to the ^{47}Ti ground state transition, and $P_{\beta 2}$ is associated with the ^{47}Sc ground state to the 159 keV ^{47}Ti excited state transition. Using only the consistent values with uncertainties, LWEIGHT calculated a weighted average with internal uncertainty and a found a reduced-χ^2 of 0,8 in both cases ($P_{\beta 1}$ and $P_{\beta 2}$ are correlated values). The resulting values are given in Table 4.

Table 4: ^{47}Sc beta transition probabilities from direct β-electron measurements. $P_{\beta 1}$ is for the g.s. to g.s. transition, and $P_{\beta 2}$ is for the g.s. to 159 keV state transition.

Reference	$P_{\beta 1}$	$P_{\beta 2}$
1953CH16	0,34 (4)	0,66 (4)
1955LY34	0,34 (3)	0,66 (3)
1955NI15	0,36	0,64
1956GR12	0,4	0,6
1956LI38	0,26	0,74
1964MI07	0,27 (4)	0,73 (4)
1986RE12	0,326 (14)	0,674 (14)
Evaluated	**0,325 (12)**	**0,675 (12)**

The absolute gamma-ray intensity was evaluated in Section 4.2.2: I_γ(159 keV) = 0,681 (5). With the total internal conversion coefficient calculated in Section 2.4.2, it is found: $P_{\beta 2} = P_\gamma = I_\gamma (1 + \alpha_T)$ = 0,685 (5). Thus: $P_{\beta 1}$ = 0,315 (5). Notice that the measured α_T =0,0045 (3) from 1986RE12 leads to $P_{\beta 2}$ = 0,684 (5) which is consistent and very close despite a discrepancy of about 30 % between the measured and calculated α_T.

The $P_{\beta 1}$ and $P_{\beta 2}$ values evaluated from direct β-electron measurements, or deduced from the absolute gamma-ray probability I_γ are consistent. In order to obtain a consistent decay scheme, the most precise values that come from I_γ were preferred. Therefore, the recommended values are:

$P_{\beta 2}$ = 0,685 (5) and **$P_{\beta 1}$ = 0,315 (5)**.

These two beta transitions are allowed. Average energies and log *ft* values are from the LOGFT program.

2.4 Gamma Transition

The evaluated energy of the gamma transition is from 2007BU08 (see Section 4.2.1).

2.4.1 Mixing ratio and multipolarity

The mixing ratio of the first excited state of ^{47}Ti was taken from 2007BU08. It was evaluated using the half-life, B(E2) and the angular distribution of the emitted gamma-ray. The recommended mixing ratio is then: **δ = -0,099 (9)**. The corresponding multipolarity of the gamma transition is thus: **M1 + 0,97 (17) % E2**.

2.4.2 Internal conversion coefficients

The internal conversion coefficients of the gamma transition in ^{47}Ti were calculated with the BrIcc program (2008KI07) within the Frozen Orbitals approximation, using the mixing ratio from 2007BU08 given previously.

Notice the following measurement results: α_T = 0,0036 (9) from 1953CH16 ; $\alpha_K/\alpha_L \sim 10$ from 1953CO44 ; P_{eK} = 0,00277 (14), α_K = 0,00406 (21), $\alpha_K/\alpha_L \sim 10$, α_{L+} = 0,00041 (10) and α_T =0,0045 (3) from 1986RE12.

3 Atomic Data

3.1 Fluorescence yields

The fluorescence yields are taken from 1996SC06.

3.2 X Radiations and Auger electrons

The X-ray and Auger electron data intensities are from Schönfeld and Janßen (1996SC06).

4 Gamma Emissions

4.2.1 Gamma-ray energies

The adopted energy of the first excited state of ^{47}Ti is from 2007BU08. Independent evaluation, described below, was carried out by the evaluator. Results agree very well. The one from 2007BU08 was preferred because of the completeness of their evaluation.

The gamma-ray energy measurements are given in Table 5. Values without uncertainty were not taken into account. The values from 1953CH16, 1955LY34 and 1955NI15 were excluded by the LWEIGHT program during the statistical process. The resulting data set is consistent and a weighted average was used with the internal uncertainty. The reduced-χ^2 is 0,05. The evaluated value of 159,382 (14) is very close to the value from 2007BU08.

Table 5: E_γ measurements of the levels of ^{47}Ti.
Final adopted value in red is from 2007BU08.

Reference	Energy (keV)
1953CH16	185 (7)
1953CO44	159,5
1955LY34	157 (7)
1955NI15	167 (2)
1956GR12	159 (2)
1956LI38	160 (5)
1964MI07	163
1967KO01	159,2 (5)
1969WO02	159,39 (5)
1972GEZG	159,381 (15)
Evaluated	159,382 (14)
2007BU08	**159,373 (12)**

4.2.2 Gamma-ray emission intensities

The measurement of the absolute intensity of the γ ray occurring in the ^{47}Sc decay requires the determination of the source activity. This was done only twice, in 1968BA33 and in 1986RE12, using a 4π β-γ coincidence method.

The value from 1968BA33 is I_γ = 0,685 (27).

The original value from 1986RE12 is I_γ = 0,683 (4), which comes from a weighted mean of four measurements, given in Table 6. An arithmetical mean was performed with the CBNM values and the minimum uncertainty was chosen: 0,6745 (40). Identically, the LNHB values led to: 0,6880 (40).

Then, LWEIGHT was used for these three values. From this consistent data set, LWEIGHT used a weighted average with its external uncertainty and found a reduced-χ^2 of 2,6. This evaluation leads to:

$$\mathbf{I_\gamma(159\ keV) = 0,681\ (5).}$$

Table 6: ^{47}Sc I_γ measurements.

<table>
<tr><th>Comments</th><th>I_γ</th><th></th></tr>
<tr><td>CBNM Ge(HP)</td><td>0,678 (5)</td><td rowspan="2">Arithmetical mean: 0,6745 (40)</td></tr>
<tr><td>CBNM Ge(HP)</td><td>0,671 (8)</td></tr>
<tr><td>LNHB NaI(Tl)</td><td>0,687 (4)</td><td rowspan="2">Arithmetical mean: 0,6880 (40)</td></tr>
<tr><td>LNHB Ge(HP)</td><td>0,689 (7)</td></tr>
<tr><td>1968BA33</td><td>0,685 (27)</td><td>0,685 (27)</td></tr>
<tr><td>Evaluated</td><td></td><td>0,681 (5)</td></tr>
</table>

5. Electron Emissions

The β^- intensities were evaluated as described above in Section 2.3.

The energies of the conversion electrons were calculated from the gamma-transition energy given in Section 4.2.1 and the electron binding energies.

The emission intensities of the conversion electrons were calculated using the internal conversion coefficients (see Section 2.4.2). The emission intensities of K-Auger electrons were calculated using the transition probabilities given in Sections 2.3 and 2.4, the atomic data given in Section 3, and the internal conversion coefficients.

Consistency of the decay scheme was tested from total energy balance considerations. The resulting effective Q value, Q_{eff} = 600,8 (41) keV, is consistent with Q^- = 600,8 (19) keV from 2012WA38 adopted in this evaluation.

6. References

1945HI04 C.T. Hibdon, M.L. Pool, Phys. Rev. 67, 313 (1945) [First correct identification]

1949KR12 N.L. Krisberg, M.L. Pool, Phys. Rev. 75, 1693 (1949) [$T_{1/2}$]

1953CH16 L.S. Cheng, M.L. Pool, Phys. Rev. 90, 886 (1953) [$T_{1/2}$, P_β, ICC, E_γ]

1953CO44 J.M. Cork, J.M. LeBlanc, M.K. Brice, W.H. Nester, Phys. Rev. 92, 367 (1953) [$T_{1/2}$, ICC, E_γ]

1953DU22 J.E. Duval, M.H. Kurbatov, J. Am. Chem. Soc. 75, 2246 (1953) [$T_{1/2}$]

1953MA64 L. Marquez, Phys. Rev. 92, 1511 (1953) [$T_{1/2}$]

1955LY34 W.S. Lyon, B. Kahn, Phys. Rev. 99, 728 (1955) [$T_{1/2}$, P_β, E_γ]

1955NI15 R.T. Nichols, E.N. Jensen, Phys. Rev. 100, 1407 (1955) [P_β, E_γ]

1956GR12 W.E. Graves, S.K. Suri, Phys. Rev. 101, 1368 (1956) [P_β, E_γ]

1956LI38 L.J. Lidofsky, V.K. Fischer, Phys. Rev. 104, 759 (1956) [$T_{1/2}$, P_β]

1959PO64 A. Poularikas, R.W. Fink, Phys. Rev. 115, 989 (1959) [$T_{1/2}$]

1963HO17 S. Hontzeas, L. Yaffe, Can. J. Chem. 41, 2194 (1963) [$T_{1/2}$]

1964MI07 S.C. Misra, U.C. Gupta, N.P.S. Sidhu, Nucl. Phys. 51, 174 (1964) [$T_{1/2}$, P_β, E_γ]

1967KO01 J. Konijn, E.W.A. Lingeman, S.A. De Wit, Nucl. Phys. A 90, 558 (1967) [E_γ]

1968BA33 Z.T. Bak, P. Rieh, Int. J. Appl. Radiat. Isot. 19, 593 (1968) [$T_{1/2}$, P_γ]

1968ME07 J.W.T. Meadows, V.A. Mode, J. Inorg. Nucl. Chem. 30, 361 (1968) [$T_{1/2}$]

1969RA16 H. Ravn, J. Inorg. Nucl. Chem. 31, 1883 (1969) [$T_{1/2}$]

1969WO02 R.E. Wood, J.M. Palms, P. Venugopala Rao, Nucl. Phys. A 126, 300 (1969) [E_γ]

1972GEZG R.J. Gehrke, ANCR-1088, p. 392 (1972) [E_γ]

1980MO26 H. Mommsen, I. Perlman, J. Yellin, Nucl. Instrum. Methods 177, 545 (1980) [$T_{1/2}$]

1986RE12 D. Reher, H.H. Hansen, R. Vaninbroukx, M.J. Woods, C.E. Grant, S.E.M. Lucas, J. Bouchard, J. Morel, R. Vatin, Int. J. Appl. Radiat. Isot. 37, 973 (1986) [$T_{1/2}$, P_β, ICC, P_γ]

1996SC06 E. Schönfeld, H. Janßen, Nucl. Instrum. Meth. A 369 (1996) 527 [ω_K, K x ray ratios, Auger e- ratios, atomic data]

2007BU08 T.W. Burrows, Nucl. Data Sheets 108, 923 (2007) [ENSDF evaluation, mixing ratio, E_γ, J^π]

2008KI07 T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Jr. Nucl. Instrum. Meth. A 589 (2008) 202-229 [BrIcc]

2012WA38 M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer, Chin. Phys.C 36, 1603 (2012) [Q-value]