# $^{44}$Ti – Comments on evaluation of decay data
# by E. Browne

## Evaluation Procedures

The *Limitation of Relative Statistical Weights* [1] (LWM) method, used for averaging numbers throughout this evaluation, provided a uniform approach for the analysis of discrepant data. The uncertainty assigned to the recommended value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

## Decay Scheme

$^{44}$Ti ($T_{1/2}$= 60.0 y) decays 100% by electron capture (Q(EC)=267.5 (19) keV) to excited levels at 67.9- and 146.2 keV only in $^{44}$Sc ($T_{1/2}$=3.93 h), which subsequently decays by EC+$\beta^+$ to $^{44}$Ca (stable).

90Sc08 measured the relative emission probabilities of the 1157-, 67.9- and 78.4-keV gamma rays from a $^{44}$Ti - $^{44}$Sc equilibrium source. Since the absolute emission probability of the 1157-keV gamma ray from $^{44}$Sc is well known (0.999)[2], this measurement provided values for the absolute emission probabilities of the 67.9- and 78.4 keV gamma rays as well, thus normalizing the decay scheme of $^{44}$Ti.

## Nuclear Data

$^{44}$Ti is of considerable interest in astrophysics, since it is one of the few long-lived gamma-ray-emitting nuclides expected to be substantially produced during a supernova explosion. Moreover, the solar system abundance of $^{44}$Ca is believed to have originated from the nucleosynthesis of $^{44}$Ti and the subsequent decays. The characteristic 1157-keV gamma ray from $^{44}$Sc, which was observed from the young supernova remnant Cassiopeia A [3], opened the possibility of deducing the mass of $^{44}$Ti that was ejected in the explosion. For this calculation, however, it was needed (among other quantities) a reasonably precise knowledge of the $^{44}$Ti half-life.

The recommended half-life of $^{44}$Ti, 60.0 (11) y, is a weighted average (LWM, $\sigma_{int}$=0.5, $\chi^2/\nu$= 5.6) of:
- 60.7 (12) y [4] (method: decay of count rate),
- 59.0 (6) y (98Ah03[5], method: decay of count rate),
- 60.3 (13) y (98Go05[6], method: specific activity with beam fragmentation),
- 62 (2) y (98No06[7], method: decay of count rate),
- 66.6 (16) y (90Al11[8], method: decay of count rate), and
- 54.2 (21) y (83Fr27[9], method: specific activity with accelerator mass spectroscopy).

The following results have not been included in the averaging:

- Preliminary results: 58 (10) y [10] (method: specific activity with beam fragmentation), 39.0 (18) y [11] (method: specific activity with beam fragmentation), and 63 (3) y (97No06[12], method: decay of count rate).
- Older measurements: 48.2 (9) y (65Mo07[13], method: specific activity), and 46.4 (17) y (65Wi05[14], method: specific activity). These values significantly deviate from recent results, probably because of systematic errors.

Woosley and Diehl [15] have recommended a half-life of 60 (1) y for $^{44}$Ti, based on the 1998 values.

## Gamma Rays

Energies

$^{44}$Ti emits gamma rays of 67.9-, 78.4-, and a very weak one of 146.2 keV. The precise gamma-ray energies for the 67.9- and 78.4-keV transitions given in Table 4.2 (and the values corrected for nuclear recoil, in Table 2.2) are weighted averages (LWM) of results from 63Kl06[16], 67Ri06[17], and 91We08[18] (See Table I). Other: 88Al27[19] (superseded by 91We08[18]). The energy of 146.22 (3) keV for the 146-keV is from level-energy differences. A measured value is: 147.0 (15) keV (67Ri06[17]).

Table I - $^{44}$Ti Gamma-ray Energies

| | 67.9 keV | 78.4 keV |
|---|---|---|
| 91We08[18] | 67.8679 (14) | 78.3234 (10)* |
| 67Ri06[17] | 67.85 (4) | 78.38 (4) |
| 63Kl06[16] | 67.85 (7) | 78.44 (7) |
| Average | 67.8679 (14) | 78.36 (3) |
| $\chi^2/\nu$ | 0.13 | 1.3 |

∗ The uncertainty of 0.0010 was increased to 0.035 to reduce the statistical weight of this measurement from 99.9% to 50%. Original $\chi^2/\nu$ = 2.4.

Emission Probabilities

The relative emission probabilities are average values (LWM) from 88Al27[19], 90Sc08[20], and 67Ri06[17], as given in Table II below.

Table II - $^{44}$Ti Relative Emission Probabilities

| Energy keV | 67Ri06[17] $P_\gamma$(rel.) | 88Al27[19] $P_\gamma$(rel.) | 90Sc08[20] $P_\gamma$(rel.) | W. Average (LWM) $P_\gamma$(rel.) | $\chi^2/\nu$ |
|---|---|---|---|---|---|
| 67.8679 (14) | 0.942 (15)* | 0.981 (11) | 0.960 (15) | 0.965 (16)@ | 2.3 |
| 78.36 (3) | 1.000 (11)* | 1.000 (11) | 1.000 (13) | 1.000 (11)& | |
| 146.22 (3) | 0.0010 (3) | 0.00093 (6) | 0.00095 (3) | 0.00095 (3) | 0.05 |

* Original uncertainties of 0.005 seemed unrealistically low. Evaluator has increased these values.
& Uncertainty is the smallest of the individual values.
@ Internal uncertainty $\sigma_{int}$=0.011

A factor to normalize relative to absolute emission probabilities was deduced as follows:

- N= 0.955 (15), from the average relative emission probabilities given in Table III column 2, the theoretical conversion coefficients from Section 2.2, and the condition that the total transition intensity to the ground state is 100%, as shown below.

  $[P_\gamma\,(67.8)(1 + \alpha_{68}) + P_\gamma\,(146)(1 + \alpha_{146})]\ N = 100\%$

- N=0.974 (13), from the emission probability of the 78-keV gamma ray (0.974 (13)) relative to an absolute probability of 0.999 (1) for the 1157-keV gamma ray in the decay of $^{44}$Sc in equilibrium with $^{44}$Ti (90Sc08).

The (unweighted) average of these normalization factors is $N_{avg}$=0.964 (13) (smallest uncertainty from input values).

Table III gives recommended relative and absolute gamma-ray emission probabilities.

Table III - Recommended Relative and Absolute Gamma-Ray Emission Probabilities

| $E_\gamma$ ( keV) | $P_\gamma$ (rel.)* | $P_\gamma$ (abs.) & |
|---|---|---|
| 67.9 | 0.965 (16) | 0.930 (15) |
| 78.36 (3) | 1.000 (11) | 0.964 (11) |
| 146.22 (3) | 0.00095 (3) | 0.00092 (3) |

* From Table II, column 5.
& Values from column 2 multiplied by $N_{avg}$ (=0.964 (13))

<u>Multipolarities and Conversion Coefficients</u>

The following experimental conversion coefficients: $\alpha_K$ = 0.123 (23) (67Ri06[17]), $\alpha$= 0.10 (5) (63Kl06[16]) for the 67.9-keV gamma ray, and $\alpha_K$ = 0.031 (5) (67Ri06[17]), $\alpha$ = 0.017 (8) (63Kl06[16]) for the 78.4-keV gamma ray, suggest E1 and M1 multipolarities for the 67.9- and 78.4-keV transitions, respectively. Spins of 0- (for the 146-keV level) and 1- (for the 67.9-keV level) require M1 multipolarity for the 78.4-keV gamma ray. The evaluator has assigned from decay scheme (0- to 2+)[M2] multipolarity to the 146-keV gamma ray.

Total conversion coefficients also may be deduced from the measured absolute gamma-ray emission probabilities of 90Sc08, by using 0.7 (3)% (88Al27, delayed-coincidence experiment) for the electron-capture feeding to the 67-keV level, and neglecting the very weak 146-keV transition. These calculations are:
$\alpha$(67.9) = [1.0/0.935 (15)]-1.0 = 0.069 (17); $\alpha$(78.4) = [(1.0 - 0.007 (3))/0.974 (13)]-1.0 = 0.019 (14), which agree with the measured values. Where 0.935 (15) and 0.974 (13) (90Sc08) are the experimental absolute emission probabilities of the 67.9- and 78.4-keV gamma rays, respectively. The absolute adopted emission probabilities were not used in this calculation because they are partially based on decay scheme considerations (that include the conversion coefficient of the 67.9-keV gamma ray.)
Table IV shows experimental and theoretical conversion coefficients for the 67.9-, 78.4-, and 146-keV gamma rays.

Table IV - Conversion Coefficients

| $E_\gamma$ keV | $\alpha_T$@ From $P_\gamma$(%) | $\alpha_T$ Exp. | $\alpha_T$* Theory | $\alpha_K$ Exp | $\alpha_K$* Theory | Mult. |
|---|---|---|---|---|---|---|
| 67.8679 (14) | 0.069 (17) | 0.10 (5)# | 0.0845 (25) | 0.123 (23)& | 0.0766 (23) | E1 |
| 78.36 (3) | 0.019 (14) | 0.017 (8)# | 0.032 (1) | 0.031 (5)& | 0.0273 (8) | M1 |
| 146.22 (3) | | | 0.046 (1) | | 0.0414 (12) | M2 |

* Interpolated from 76Ba63[21]
\# From 63Kl06[16]
& From 67Ri06[17]
@ See text

The experimental conversion coefficients in Table IV are quite imprecise, therefore, the evaluator has adopted interpolated theoretical values as the recommended conversion coefficients. The interpolation was done with the computer program ICC[22].

## Electron-Capture Transitions

The EC probability to the 146-keV level is given by:

$\varepsilon(146) = [P_\gamma(78.4)+e(78.4) + P_\gamma(146)+e(146)] \times 100 = 99.5\ (11)\% + 0.096\ (3)\% = 99.6\ (11)\%$.

For the EC probability to the 0+ ground state of $^{44}$Sc (0+ to 2+, second forbidden) a log ft >10.6 is expected from the systematic trend for second forbidden transitions (98Si17), which corresponds to $\varepsilon(0) < 0.04\%$. Using $\varepsilon(0)$=0.04% and $\varepsilon(146)$ = 99.6 (11)% gives $\varepsilon(67.4)$ = 0.4 (11)%. Experimental values for this quantity are 0.7 (3)% (88Al27[19]), and 1.9 (15)% (67Ri06[17]), both measured in γ-x ray coincidence experiments.

Electron-capture probabilities to the various atomic sub-shells, ie. $P_K$, $P_L$, $P_{M+}$ in Table 2.1, are theoretical values (98Sc28[23]) calculated with the computer program EC-CAPTURE[24].

<u>Levels half-life</u>

Table V shows the experimental half-life values for the 67.3- and 78.4 keV levels, as well as their respective recommended (i.e., average) values.

Table V - $^{44}$Sc Levels half-life

| 67.9 keV | | 78.4 keV | |
|---|---|---|---|
| 153 (2 ) ns | (67Ri06[17]) | 50 (3) µs | (63Kl06[16]) |
| 153 (1) ns | (62Th12[25]) | 49.5 (10) µs | (64Br27[27]) |
| 180 (20) ns | (59Cy90[26]) | 51.2 (9)* µs | (88Al27[19]) |
| 166 (5) ns | (63Kl06[16]) | | |
| 155 (2) ns | (75Gu24[28]) | | |
| 154.8 (8) ns | (88Al27[19]) | | |
| Avg.(LWM) = 154.2 (8) ns | | Avg. (LWM) = 50.4 (7) µs | |
| $\chi^2/\nu$ = 1.95 | | $\chi^2/\nu$ = 0.77 | |

* The uncertainty was increased from 0.3 ($\chi^2/\nu$ = 1.4) to 0.9 to reduce its statistical weight from 91% to 50%.

## Atomic Data

The X-ray and Auger-electron probabilities in Section 4 have been calculated using the gamma-ray and electron-capture data that are presented in Section 2, and using atomic data from 96Sc06[29].

Total Average Radiation Energy

Our calculated (RADLST[30]) total average radiation energy of 268 (3) keV (which includes all the radiations emitted by $^{44}$Ti), agrees very well with Q(EC) = 267.5 (19) keV (95Au04[31]) and confirms the quality and completeness of the $^{44}$Ti decay scheme.

## References

1. M.J. Woods and A.S. Munster, *Evaluation of Half-Life Data*, National Physical Laboratory, Teddington, UK, Rep. RS(EXT) 95, (1988) - 88WoZO
2. Richard B. Firestone, Table of Isotopes, eighth edition, John Wiley & Sons, Inc., 1996.
   [$^{44}$Sc $\varepsilon+\beta^{+}$ decay, $E_\gamma$, $I_\gamma$]
3. A.F. Iyudin et al., Astron. Astrophys. **284**, L1 (1994)
4. F.E. Wietfeldt et al., Phys. Rev. **C59**, 528 (1999)
   [$T_{1/2}$]
5. I. Ahmad et al., Phys. Rev. Lett. **80**, 2550 (1998) - 98Ah03
   [$T_{1/2}$]
6. J. Gorres et al., Phys. Rev. Lett. **80**, 2554 (1998) - 98Go05
   [$T_{1/2}$]
7. E.B. Norman et al., Phys. Rev. **C57**, 2010 (1998) - 98No06
   [$T_{1/2}$]
8. D.E. Alburger and G. Harbottle, Phys. Rev. **C41**, 2320 (1990) - 90Al11
   [$T_{1/2}$]
9. D. Frekers et al., Phys. Rev. **C28**, 1756 (1983) - 83Fr27
   [$T_{1/2}$]
10. J. Meissner et al., in *Nuclei in the Cosmos III*, edited by Maurizio Busso and Claudia M. Raiteri, AIP Conf. Proc. No. 327 (AIP, New York, 1995), p. 303.
   [$T_{1/2}$]
11. J. Meissner, Ph. D. thesis, University of Notre Dame, 1996.
   [$T_{1/2}$]
12. E.B. Norman et al., in Proceedings of the International Conference on *Nuclei in the Cosmos IV*, Nucl. Phys. **A621**, 92c (1997) - 97No06
   [$T_{1/2}$]
13. P.E. Moreland and D. Heymann, J. Inorg. Nucl. Chem. **27**, 493 (1965) - 65Mo07
   [$T_{1/2}$]
14. J. Wing et al., J. Inorg. Nucl. Chem. 27, 487 (1965) - 65Wi05
   [$T_{1/2}$]
15. Stan Woosley and Roland Diehl, Physics World **11**, No. 7, 22 (1998)
   [$T_{1/2}$]
16. J.K. Kliwer et al., Nucl. Phys. **49**, 328 (1963) - 63Kl06
   [$E_\gamma$]
17. R.A. Ristinen and A.W. Sunyar, Phys. Rev. **153**, 1209 (1967) - 67Ri06
   [$E_\gamma$, $I_\gamma$]
18. C. Wesselborg and D.E. Alburger, Nuc. Instrum. Meth. **A302**, 89 (1991) - 91We08
   [$E_\gamma$]
19. D.E. Alburger and E.K. Warburton, Phys. Rev. **C38**, 1843 (1988) - 88Al27
   [$I_\gamma$]

20. U. Schötzig, Nucl. Instrum. Meth. **A286**, 523 (1990) - 90Sc08
[$I_\gamma$]
21. I.M. Band et al., At. Data Nucl. Data Tables **18**, 433 (1976) - 76Ba63
[Theoretical internal conversion coefficients]
22. E. Yakusev and N. Coursol, ICC, a computer program to interpolate internal conversion coefficients, 1998.
23. E. Schönfeld, App. Rad. Isot. **49**, 1353 (1998) - 98Sc28
[$P_K$, $P_L$, $P_M$]
24. E. Schönfeld, F.Y. Chu, and E. Browne, EC-CAPTURE, a computer program to calculate electron capture probabilities to atomic sub-shells, 1998.
25. P. Thieberger, Arkiv Fysik **22**, 127 (1962) - 62Th12
[Level $T_{1/2}$]
26. E.W. Cybulska and L. Marquez, Nuovo Cimento **14**, 479 (1959) - 59Cy90
[Level $T_{1/2}$]
27. K. Bandi et al., Nucl . Phys. **59**, 33 (1964) - 64Br27
[Level $T_{1/2}$]
28. V.P. Gupta and D.K. Gupta, Indian J. Pure Appl. Phys. **13**, 334 (1975) - 75Gu24
[Level $T_{1/2}$]
29. E. Schönfeld and H. Janβen, Nucl. Instrum. Meth. Phys. Res. **A369**, 527 (1996) - 96Sc06
[X rays, $\omega_K$]
30. *The Program RADLST*, Thomas W. Burrows, report BNL-NCS-52142, February 29, 1988.
31. G. Audi and A.H. Wapstra, Nucl. Phys. **A595**, 409 (1995) - 95Au04
[Q-value]
32. B. Singh, J.L. Rodriguez, S.S.M. Wong, and J.K. Tuli, Nucl. Data Sheets 84, 487 (1998) - 98Si17
[Systematics of log *ft*]