^{99}Tc - Comments on evaluation of the decay data

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This evaluation is an update of a former evaluation done in 2010 (2011BeZW), including the available literature by early November 2025.

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate with the LWEIGHT program.

1. Decay Scheme

The decay scheme is complete since all of the levels in ^{99}Ru below the decay energies are populated. The total angular momenta and parities of the levels are from 2017Br15.

The evaluation of the ^{99}Tc half-life is based on a limited dataset and is dominated by the value from 1984Co30 which was only reported as “suggested”. **New measurements of ^{99}Tc half-life are recommended.**

The β-decay of ^{99}Tc from its $9/2^+$ ground state to the $5/2^+$ ground state of ^{99}Ru is almost 100%. A β-decay with a very small intensity to the $3/2^+$ first excited state of ^{99}Ru was observed in 1973Le10 and 1974En02. Its energy, half-life and the multipolarity of the de-exciting γ-ray have been evaluated, and the β^- branching ratio has been deduced. The Q-value, log *ft* and average energy of the β spectrum, the latter being important for decay heat analysis of spent nuclear fuel (2022Do06), have been significantly improved with the study of 2024Pa41.

2. Nuclear Data

The adopted Q-value is from 2024Pa41, determined from a high-precision measurement of the β spectrum: **Q_β = 295,82 (16) keV**. The recommended AME2020 value is not consistent. AME values have exhibited significant variation over the last two decades: Q_β = 293,8 (14) keV in 2003Au03; Q_β = 295,1 (11) keV in 2012Wa38; Q_β = 297,5 (9) keV in 2021Wa16. This is due to the precision of the measured values in the dataset, which are given in Table 1.

Table 1 – Measured end-points of the main β transition.

Reference	E_{max} (keV)	Comments
1947Mo15	320	
1950Ke02	300 (10)	
1951Ta05	292 (3)	
1952Fe16	290 (4)	
1960Bo08	290 (10)	
1966Sn02	294 (4)	
1974Re11	293 (2)	
1980Al02	292,1 (26)	From ^{99m}Tc Q-value and metastable energy of 2017Br15
2024Pa41	295,82 (16)	
Adopted	**295,82 (16)**	From 2024Pa41

2.1. ^{99}Tc half-life

The measured half-life values of ^{99}Tc are given in Table 2 together with the experimental methods employed. The value from 1947Mo15 has not been considered because no uncertainty was reported. In addition, the values from 1947Mo15 and 1960Bo08 are from the same authors.

The resulting dataset is consistent (χ^2 = 0,29 and $\chi^2_{crit.}$ = 3,79) and the weighted average has been adopted. The value from 1984Co30 weighs 82%, and is the most recent and precise measurement. However, it should be underlined that the authors mainly focused on ^{99}Tc standardisation and reported their half-life value as "suggested". Consequently, their reported uncertainty, which is higher than both the internal and external uncertainties, has been adopted. Finally, the adopted value is **$T_{1/2}$ = 2,115 (12) × 10^5 a**. New measurements of ^{99}Tc half-life are recommended.

Table 2 – ^{99}Tc half-life measurements.

Reference	$T_{1/2}$ (x10^5 a)	Method	Comments
1947Mo15	9,4	Aluminium absorption	Not used: no uncertainty.
1951Fr05	2,12 (4)	Aluminium absorption	
1960Bo08	2,15 (5)	Aluminium absorption	Same authors as 1947Mo15.
1966Go10	2,14 (5)	Liquid Scintillation Counting	
1984Co30	2,111 (12)	Liquid Scintillation Counting	Suggested half-life.
Adopted	**2,115 (12)**	Weighted average with minimum experimental uncertainty	

2.2. Gamma transition

2.2.1. Energy of the first excited state of ^{99}Ru

The measured energies of the γ-ray emission between the first excited state and the ground state of ^{99}Ru are given in Table 3, together with the experimental methods employed. Two additional values, 89 (2) keV and 89 (5) keV, are reported in an XUNDL compilation of the data from 2017Fr08. These values are not present in the publication and come from private communication with the authors. Only the most precise value has been considered, which is excluded by Chauvenet criterion. The resulting dataset is consistent (χ^2 = 0,10 and $\chi^2_{crit.}$ = 3,32) and the weighted average with internal uncertainty has been adopted: **E_γ (^{99}Ru) = 89,52 (15) keV**. The value from 1974En02 weighs 59%.

Table 3 – Measurements of the $\gamma_{1,0}$ emission energy in ^{99}Ru.

Reference	$E_{\gamma\ 1,0}$ (keV)	Method
1967Mo20	89,36 (40)	^{99}Rh decay, γ Ge(Li)
1970An12	89,6 (5)	^{99}Rh, γ Ge(Li)
1971Le20	89,4 (10)	$^{98}Mo(\alpha,3n)^{99}Ru$, γ Ge(Li)
1973Le10	89,7 (4)	^{99}Tc decay, β Si(Li)
1974En02	89,5 (2)	^{99}Tc decay, γ Si(Li)
2017Fr08	89 (2)	From XUNDL compilation
Adopted	**89,52 (15)**	Weighted average with internal uncertainty

The nuclear mass of ^{99}Ru has been determined from its atomic mass corrected for the contribution of the atomic electrons, adopting the method and the recommended values from 2021Wa16. The recoil energy of the γ transition has been deduced to be **E_{recoil} = 0,04311 (15) eV**.

Consequently, the adopted energy of the ^{99}Ru first excited state is **E_{level} = 89,52 (15) keV**.

2.2.2. $T_{1/2}$(^{99}Ru, 89 keV)

The measured half-life values of the first excited state of ^{99}Ru are given in Table 4 together with the experimental methods employed. The original uncertainty of 1972Gu01 was not detailed in the publication and seems to be only that from the data fitting. The authors of 1973Be72 used the same method with similar statistics and reported an uncertainty of 0,6. Consequently, the uncertainty from 1972Gu01 has been increased from 0,1 to 0,6. In addition, the value from 1974En02 has been excluded by Chauvenet criterion.

The resulting dataset is consistent (χ^2 = 1,08 and $\chi^2_{crit.}$ = 3,02) and the weighted average with internal uncertainty has been adopted. The value from 1965Ma27 weighs 41%. The authors detailed their estimation of the uncertainty, and there is no reason to believe it was underestimated. The adopted value is **$T_{1/2}$(^{99}Ru, 89 keV) = 20,43 (19) ns**.

Table 4 – Measurements of the half-life of the first excited state of ^{99}Ru.

Reference	$T_{1/2}$ (ns)	Method	Comments
1964Bo28	19,7 (4)	^{99}Rh, γ spectro.	
1965Ki01	20,0 (10)	^{99}Rh, γ spectro.	
1965Ma27	20,7 (3)	^{99}Rh, γ spectro.	
1972Gu01	20,5 (1)	^{99}Rh, γ Ge(Li)	Uncertainty increased from 0,1 to 0,6.
1973Be72	21,04 (60)	^{99}Rh, γ Ge(Li)	
1974En02	18,9 (10)	^{99}Tc decay, γ Si(Li)	Excluded by Chauvenet criterion.
2015Ki14	20,5 (6)	^{99}Rh, $\gamma\gamma$ coinc.	
Adopted	**20,43 (19)**	Weighted average with internal uncertainty	

2.2.3. Multipolarity

The γ transition from the 3/2$^+$ first excited state to the 5/2$^+$ ground state of ^{99}Ru is a mixture of M1+E2. The available measurements of the mixing ratio δ^2 = E2/M1 are summarized in Table 5, together with the experimental methods employed. Only two measurements have been used for the evaluation because most of the publications are from the same author. Only the most recent one, which is also the most precise, has been considered. The value from 1973Be72 has been rejected in the absence of reported uncertainty.

Table 5 – Measurements of the multipolarity mixing ratio of the first excited state of ^{99}Ru.

Reference	δ^2 = E2/M1	Method	Comments
1964Ki01	~2	^{99}Ru Mössbauer γ transition	Same author as 1976Ki02
1965Ki01	2,4 (9)	^{99}Ru Mössbauer γ transition	Value from 1964Ki01, same author
1966Ki02	2,7 (6)	^{99}Ru Mössbauer γ transition	δ<0, same author as 1976Ki02
1972Wa*	2,7 (6)	^{99}Ru Mössbauer γ transition	Refers to 1966Ki02
1973Be72	2,57	^{99}Rh, γ Ge(Li)	Not used: no uncertainty
1973Gi11	2,72 (17)	^{99}Ru Mössbauer γ transition	
1976Ki02	2,43 (6)	^{99}Ru Mössbauer γ transition	Reported as δ = -1,56 (2)
Adopted	**2,46 (6)**	Weighted average and minimum experimental uncertainty	

The weighted average of the consistent dataset (χ^2 = 2,59 and $\chi^2_{crit.}$ = 6,63) has been adopted, with minimum experimental uncertainty. The value from 1976Ki02 weighs 89%. The adopted value is δ^2 = 2,46 (6). This corresponds to the mixing ratio **δ(^{99}Ru, 89 keV) = -1,568 (19)** and to the γ transition multipolarity **M1 + 71,1(5)% E2**.

2.2.4. Branching ratios

The authors of 1973Le10 and 1974En02 inferred a small β^- transition from the $9/2^+$ ground state of ^{99}Tc to the $3/2^+$ 89-keV level of ^{99}Ru, by detecting a de-exciting γ-ray. This β transition is second forbidden unique, whereas the main transition is second forbidden non-unique.

The authors reported the number of photons detected per decay: 6,5 (15) $\times$ 10^{-6} for 1973Le10 and 4,9 (17) $\times$ 10^{-6} for 1974En02. Next, they used the total internal conversion coefficient α_T = 1,5 calculated in 1968Ha52 to determine the corresponding total γ-ray transition probability, which corresponds to the β^- branching in the decay scheme of ^{99}Tc.

The absolute γ-ray intensity has been evaluated as the weighted average of this consistent dataset (χ^2 = 0,50 and $\chi^2_{crit.}$ = 6,63). The value of 1973Le10 weighs 56%. The adopted value is **I_{abs}(^{99}Ru, 89 keV) = 0,00058 (15) %**, with minimum experimental uncertainty.

The total conversion coefficient has been calculated using the BrIcc program (2008Ki07) with the γ-ray energy and the mixing ratio established above: α_T = 1,498 (24). The β^- branching is equal to the γ transition probability $P_\gamma = I_{abs}(1+\alpha_T)$. The adopted value is **$P_{\beta 0,1}$ = 0,00145 (37) %**. The β^- branching to the ground state of ^{99}Ru is then: **$P_{\beta 0,0}$ = 99,99855 (37) %**.

2.3. Beta transitions

The branching ratio of the main β^- transition is 99,99855 (37) %, as deduced in Section 2.2.4. This second forbidden non-unique transition was measured in the past with different techniques. These studies showed that the β spectrum can be well described in the measured energy range with the shape factor of a first forbidden unique transition: $C(W) = q^2 + \lambda p^2$. Table 6 summarizes these results, where the λ parameter was fitted on the data. In the case of a real first forbidden unique transition, this parameter is not adjusted but calculated from the relativistic electron wave functions. Evaluating form factors is a difficult task because the authors of the published data did not describe in detail all the possible sources of distortion of the measured spectra and their contributions.

Table 6 – Measurements of the form factor of the main β transition.

Reference	λ	E_{max} (keV)	Energy range (keV)	Method	Comments
1951Ta05	~1	290 (4)	150 – end-point	Mag. spectro.	
1952Fe16	0,50 (13)	292 (3)	60 – end-point	Mag. spectro	Recalc. by 1966Li*
1966Sn02	0,49 (4)	294 (4)	50 - 280	Plastic scint.	Recalc. by 1976Be*
1974Re11	0,54 (2)	293 (2)	55 - 250	Si(Li)	

The most accurate measurement of the β spectrum is from the recent study of 2024Pa41, where the authors realized two independent cryogenic measurements with metallic magnetic calorimeters, confirmed by an independent silicon measurement. The results are all in agreement in the common energy range and the spectrum shape was found to significantly disagree with past studies below 100 keV, in particular with 1974Re11 – a conclusion suggested in 1990Ga13. The reference spectrum, measured from 0,75 keV to the end-point, was analysed to extract the transition energy E_{max} = 295,82 (16) keV. The spectrum shape was calculated in detail including nuclear structure and was found to be sensitive to the axial-vector coupling constant of the weak interaction, which aligns with other theoretical studies (2017Ko12, 2017Ko29, 2024De17, 2024Ra14, 2024Ra27). The authors of 2024Pa41 also established the average energy of the β spectrum **E_{av} (^{99}Tc→^{99}Ru^{gs}) = 98,51 (23) keV**, adopted in this evaluation. In addition, they determined the corresponding value log *f* = -0.47660 (22), which has been combined with the half-life and the branching ratio to establish the adopted **log *ft* (^{99}Tc→^{99}Ru^{gs}) = 12,3478 (25)**.

A second transition to the first excited state of ^{99}Ru exists, which branching has been deduced in Section 2.2.4 as 0,00145 (37) **%**. This transition is second forbidden unique and is calculated correctly by the BetaShape program (2023Mo21), which provides the average spectrum energy E_{av}(^{99}Tc→^{99}Ru*) = 82,20 (9) keV and log *ft* (^{99}Tc→^{99}Ru*) = 15,86 (11).

3. Atomic Data (Ru, Z=44)

The atomic vacancies have been determined from the internal conversion process.

The fluorescence yield data, the relative K X-ray emission probabilities and the ratios P(KLX)/P(KLL) and P(KXY)/P(KLL) have been taken from Schönfeld *et al.* (1996Sc06).

The Auger electron and X-ray absolute probabilities have been determined with the EMISSION program (2000Sc47) from the related decay data.

4. Radiation Emissions

4.1. Electron Emission

The β^- intensities have been evaluated as described in Section 2.

The emitted β particle can ionize the electron cloud of the ^{99}Ru daughter nucleus, distorting the β energy spectrum. The available measurements of the K-shell auto-ionization probability accompanying the ^{99}Tc decay are given in Table 7. The experimental dataset is discrepant due to the value from 1967St36 (χ^2 = 4,20 and $\chi^2_{crit.}$ = 3,79). After its removal, the dataset is consistent (χ^2 = 1,16 and $\chi^2_{crit.}$ = 4,61) and the weighted average with minimum experimental uncertainty is **P_K = 0,0377 (16) % per emitted β particle**. Theoretical values are given in Table 8. The most precise calculations from 1975La20 are in good agreement. With such a low probability, this phenomenon is negligible in almost all applications.

4.2. Photon Emission

The details of the photon emission evaluation are given in Section 2. ^{99}Ru decays from its first excited state at 89,52 (15) keV, with a half-life of 20,43 (19) ns, and a γ-ray multipolarity of M1 + 71,1(5)% E2. The absolute γ-ray emission probability is 5,8 (15) x 10^{-4} %. Measurement of the photon spectrum from internal bremsstrahlung process was reported in 1983Gu07, 1984El11 and 2000Ke02.

5. Consistency

Consistency of the recommended data has been verified by calculating the total average emission energy per decay, E_{rel}, for all the emissions involved in ^{99}Tc decay using RADLST (1988Bu*) and Saisinuc (2008DuZX). The total average energy has been calculated by Saisinuc to be $E_{rel}(\beta^-)$ = 295,82 (16) keV, in perfect agreement with the expected value Q_β = 295,82 (16) keV. The value calculated by RADLST is $E_{rel}(\beta^-)$ = 295,8 (14) keV, in good agreement with the expected value.

Table 7 – Measured K-shell auto-ionization probabilities accompanying the ^{99}Tc decay.

Reference	P_K (x 10^{-2} %)	Comments
1967St36	4,8 (3)	Not used.
1972Wa36	3,89 (16)	
1974Ha12	3,9 (3)	
1980La02	3,52 (20)	
Adopted	**3,77 (16)**	Weighted average and minimum experimental uncertainty

Table 8 – Theoretical K-shell auto-ionization probabilities accompanying the ^{99}Tc decay.

Reference	P_K (x 10^{-2} %)	Comments
1965Fe*	4,08	With experimental shape
1967St36	2,03	With experimental shape
	2,49	Assuming allowed shape
1968Ca29	5,17	With experimental shape
1972Mo26	3,08	Assuming allowed shape
1975La20	3,26	With experimental shape
	3,70	Assuming allowed shape
	3,54	With experimental shape and direct collision correction
	3,98	Assuming allowed shape and direct collision correction
1977Is05	1,69	Assuming allowed shape

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