# $^{103m}$Rh – Comments on evaluation of decay data

**by A. L. Nichols[1], T. Kibédi[2]**

[1] Department of Physics, University of Surrey, Guildford GU2 7XH, UK

[2] Department of Nuclear Physics, The Australian National University (ANU), Canberra ACT, Australia

**Reviewer: S. Leblond**

Université Paris-Saclay, CEA, Laboratoire National Henri Becquerel, 91120 Palaiseau, France

**Evaluated: May 2013, January 2015, March/April 2021, April 2023, June 2024**

## $^{103m}$Rh IT decay separated from $^{103}$Pd (100% EC decay)

### Decay Scheme

$^{103m}$Rh undergoes 100% IT decay ($T_{½}$ = 56.115 minutes) to the ground state of $^{103}$Rh ($Q_{IT}$ = 39.753 (6) keV). A simple decay scheme can be proposed on the basis of the depopulation of the metastable state by means of the single 39.753-keV gamma ray to the ground state of $^{103}$Rh.

### Nuclear Data

There is a strong interest in the nuclear structure of $^{103}$Rh and the IT decay of $^{103m}$Rh because of the adoption of $^{103m}$Rh as a neutron flux monitor.

### Half-life of $^{103m}$Rh

The measurements of 1967VuZZ, 1969KoZW, 1973Gu06, 1974Sa15, 1978La21 and 1981Va11 were adopted to give a weighted mean half-life of 56.115 (16) min based on LWM-NRM-Rajeval analyses (Avetools code, version 3.0, and V.AveLib 06-22 code, both ENSDF utility programs).

| Reference | Half-life (min) | Selected detail, issues and uncertainties |
|---|---|---|
| 1944Fl01 | 48 ± 5 | $^{103}$Rh($n_f$,n') reaction – outlier (Chauvenet criterion), and therefore not included in analytical procedures |
| 1945Wi03/1945Wi12 | 45 ± 1 | $^{103}$Rh(X,γ) reaction – outlier (Chauvenet criterion), and therefore not included in analytical procedures |
| 1947Fl03 | 52 ± 2 | $^{103}$Rh(d,d') reaction – outlier (Chauvenet criterion), and therefore not included in analytical procedures |
| 1950Me26 | 56 | separation of Pd target and $^{103m}$Rh – uncertainty not specified, and therefore not included in analytical procedures |
| 1957Jo19 | 57.5 ± 0.5 | $^{103}$Rh(n,n') reaction – outlier (Chauvenet criterion), and therefore not included in analytical procedures |
| 1967VuZZ | **56.6 ± 0.4** | $^{103}$Rh(n,n') reaction; 4π proportional counter and thin NaI crystal |
| 1969KoZW | **56.6 ± 0.6** | $^{102}$Ru(n,γ)$^{103}$Ru($β^-$)$^{103m}$Rh; radiochemical separation, NaI(Tl) scintillation counter |
| 1972Pa10 | 57.5 | $^{103}$Rh($n_{14.7keV}$,n') reaction, Si(Li) detector – uncertainty not specified, and therefore not included in analytical procedures |
| 1973Gu06 | **56.116 ± 0.009** | $^{nat}$Pd(n,xn')$^{103}$Pd(EC)$^{103m}$Rh; three counting techniques: liquid scintillation counter, 2π-methane flow counter, and NaI(Tl) crystal – weighted mean of three sets of measurements is 56.116 (7), compared with a value of 56.116 (9) quoted by 1973Gu06; uncertainty adjusted to ± 0.016 to reduce weighting to ~ 0.50 |
| 1974Sa15 | **56.3 ± 0.6** | $^{103}$Rh(n,n') reaction; decay curve followed over many half-lives, NaI(Tl) X-ray detector |
| 1978La21 | **56.112 ± 0.028** | ion exchange of $^{103m}$Rh from $^{103}$Pd solutions; decay curves involving 15 sources followed over three half-lives by means of an ill-defined photon spectrometer |
| 1979VaZE | 56.1 ± 0.1 | preliminary measurement - replaced by half-life determined by 1981Va11 |
| 1981Va11 | **56.114 ± 0.020** | ion exchange of $^{103m}$Rh from $^{103}$Pd solutions; decay curves followed over two and three half-lives, NaI(Tl) detector – weighted mean of two sets of measurements is 56.114 (12), compared with a value of 56.114 (20) quoted by 1981Va11 |
| **Recommended value** | **56.115 ± 0.016** | recommended uncertainty adjusted from ± 0.011 to ± 0.016, to align with smallest uncertainty of the values used to calculate weighted-mean value |

Limitation of relative statistical weight method (LWM), normalized residual method (NRM), Rajeval technique, expected value method (EVM), bootstrap method and Mandel-Paule approach were considered in the analysis of the data set.

| Analytical method | Half-life (min) | $\chi^2$/(N-1) | $\chi^2/(N-1)_{critical}$ |
|---|---|---|---|
| UWM | 56.31 ± 0.16 | – | – |
| LWM | 56.115 ± 0.011 | 0.45 | 2.21 for rejection at 95.0% confidence level |
| NRM | 56.115 ± 0.011 | 0.45 | 2.21 for rejection at 95.0% confidence level |
| Rajeval | 56.115 ± 0.011 | 0.45 | 2.21 for rejection at 95.0% confidence level |
| EVM | 56.13 ± 0.08 | – | 97.0% confidence level |
| Bootstrap | 56.22 ± 0.17 | 15.8 | – |
| Mandel-Paule | 56.115 ± 0.011 | 0.45 | – |

Half-life of (56.115 ± 0.016) minutes recommended for $^{103m}$Rh, as quantified by LWM-NRM analytical procedures (1973Gu06 uncertainty increased to ± 0.016 in order to adjust weighting to ~ 0.50).

### Q value

A $Q_{IT}$ value for $^{103m}$Rh of 39.753 (6) keV has been adopted (2021Ko07).

## Gamma-ray energies and emission probabilities

Energies

The well-defined nuclear level energy for the first-excited metastable state was adopted from the $Q_{IT}$ value, along with the recommended energy and associated uncertainty of the gamma-ray emission to the ground state of $^{103}$Rh (2021Ko07).

**Adopted energies, spins and parities for the relevant nuclear levels of $^{103}$Rh (see also 2009De29, 2000KoZT).**

| Nuclear level number | Nuclear level energy (keV) | Spin and parity | Half-life | |
|---|---|---|---|---|
| 0 | 0.0 | 1/2 – | stable | $^{103}$Rh |
| 1 | 39.753 ± 0.006 | 7/2 + | 56.115 (16) min | $^{103m}$Rh |

Emission Probabilities

A simple decay scheme has been assembled for the IT decay of $^{103m}$Rh. The 39.753-keV gamma transition depopulates the $^{103m}$Rh nuclear level 100%, and is defined as (99.935%E3 + 0.065%M4) from spin and parity considerations ($7/2^+ \rightarrow 1/2^-$), internal conversion coefficients, and shell and subshell ratios (1950Ko10, 1952Co16, 1955Av11, 1955Dr43, 1967Br04, 1967VuZZ, 1968Ma08, 1969Gr13, 1969Le17, 1970NiZV, 1970Pe04, 1972Br02, 1972Pa10, 1974CzZY, 1975Cz03, 1975Ma32, 1976Ma37, 1979VaZE, 1999Sa78, 2018Ni14). Recommended internal conversion coefficients have been determined by means of the BrIcc code (frozen orbital approximation) of Kibédi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45).

**Gamma-ray emission from 100% IT decay of $^{103m}$Rh: multipolarity and theoretical internal-conversion coefficients (frozen orbital approximation).**

| $E_\gamma$ (keV) | Multipolarity | $\alpha_K$ | $\alpha_L$ | $\alpha_{L1}$ | $\alpha_{L2}$ | $\alpha_{L3}$ | $\alpha_M$ | $\alpha_N$ | $\alpha_O$ | $\alpha_{total}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 39.753 (6) | 99.935%E3 + 0.065%M4 $\delta = 0.025^{+10}_{-15}$ | 142 (7) | 1051 (30) | 13 (5) | 423 (6) | 615 (18) | 214 (6) | 31.4 (9) | 0.024 (11) | 1440 (40) |

**Recommended gamma-ray energy, absolute emission probability, and transition probability from 100% IT decay of $^{103m}$Rh.**

| | $E_\gamma$ (keV) | $P_\gamma^{abs}$ (%) | Transition probability (%) | Δ (TP − $P_\gamma^{abs}$) (%) |
|---|---|---|---|---|
| $\gamma_{1,0}$ | 39.753 (6) | 0.0694 (15) | 100.0 | 99.9306 (15) |

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

**Energies and emission probabilities of internal conversion electrons from 100% IT decay of $^{103m}$Rh.**

| | | Energy (keV) | Electrons per 100 disint. |
|---|---|---|---|
| $ec_{1,0\ T}$ | (Rh) | 16.533 – 39.751 | 99.9306 (15) |
| $ec_{1,0\ K}$ | (Rh) | 16.533 (6) | 9.85 (+50-40) → 9.85 (45) |
| $ec_{1,0\ L}$ | (Rh) | 36.341 – 36.749 | 73 (3) |
| $ec_{1,0\ M}$ | (Rh) | 39.126 – 39.446 | 14.9 (5) |
| $ec_{1,0\ N+}$ | (Rh) | 39.672 – 39.751 | 2.18 (8) |

## Atomic Data

X-ray decay data and related parameters for $^{103m}$Rh have been measured experimentally over many years (e.g., 1973In07, 1974Sa15, 1975Cz03, 1981Va22, 1994Sc43), and most recently by Riffaud *et al.* (2017Ri10, 2018Ri01, 2021Ri01). The $^{103}$Rh(n,n')$^{103m}$Rh reaction is important for reactor dosimetry studies because of the generation of suitable data traceable to reactor operations. This radionuclide emits only X-rays for which emission probabilities can be determined by means of the single gamma-ray transition probability and fluorescence yields. While these $\omega_K$, $\omega_L$, etc. have been measured as well as calculated by means of semi-empirical and theoretical models, available experimental data are rather limited as implied in the following table (1936Ba01, 1937St02, 1954Ro45, 1957Ro58, 1990Si19, 1992Ga24, 2017Ri10). Both the X-ray and Auger-electron data have been subsequently calculated on the basis of the evaluated gamma-ray data, along with atomic data from 1996Sc06, 1998ScZM, 1999ScZX, 2000Sc47 (Rh: $\omega_K$ = 0.809 (4); $\varpi_L$ = 0.0494 (12); $n_{KL}$ = 0.987 (4)).

### Fluorescence yields for Rh.

| Reference | $\omega_K$ | $\varpi_L$ | $\varpi_M$ | Comments |
|---|---|---|---|---|
| 1936Ba01 | 0.801[a] | – | – | experimental measurements |
| 1937St02 | 0.77[a] | – | – | experimental measurements |
| 1954Ro45 | 0.779[a] | – | – | experimental measurements |
| 1957Ro58 | 0.786 ± 0.015[b] | – | – | experimental measurements |
| 1990Si19/1994Hu23 | 0.829 ± 0.058 | – | – | based upon 1990Si19 measurements of $\sigma_K$ |
| 1992Ga24/1994Hu23 | – | 0.051 ±0.005 | – | based upon 1992Ga24 measurements of $\varpi_L$ |
| 2017Ri10 | 0.814 ± 0.041 | – | – | experimental measurements |
| **Mean or only value** | 0.803 ± 0.024 | 0.050 ± 0.002[c] | 0.00135[d] | |
| 1972Bb16 | 0.807 ± 0.031 | – | – | assessment/evaluation of $\omega_K$ models |
| 1994Hu23 | 0.792<br>0.8086 | 0.0499<br>0.0459 | 0.00135<br>0.00135 | assessment/evaluation of $\omega_K$, $\varpi_L$ and $\varpi_M$ models<br>development of existing fitted functions |
| 1996Sc06 | 0.809 ± 0.004 | 0.0494 ± 0.0012 | – | assessment/evaluation of $\omega_K$ and $\varpi_L$ models |
| 2011Ka49 | 0.80205 | – | – | assessment/evaluation of $\omega_K$ models |

[a] Unspecified uncertainty – not included in weighted-mean analyses of experimental data set.
[b] Uncertainty adjusted from ± 0.015 to ± 0.034 to reduce weighting to no more than 0.50.
[c] Estimation, as guided by a single measurement (1992Ga24) and assessments/evaluations (1994Hu23, 1996Sc06).
[d] Estimation, as proposed by assessment/evaluation (1994Hu23).

### Measured LX-ray decay data: $^{103m}$Rh.

| | Levels | Energy (keV) | Relative $P_{LX}$ |
|---|---|---|---|
| **2021Ri01** | L3-M1 | 2.370 | 2.67 (14) |
| | L2-M1 | 2.513 | 1.73 (9) |
| | L3-M4,5 | 2.695 | 100 (5) |
| | L2-M4 | 2.891 | 48.5 (24) |
| | L1-M2 | 2.891 | 8.23 (41) |
| | L1-M3 | 2.915 | – |
| | L3-N1 | 2.934 | – |
| | L3-N4,5 | 3.012 | 8.00 (40) |
| | L1-M4,5 | 3.101 | 4.94 (25) |
| | L2-N4 | 3.154 | 0.841 (43) |
| | L1-N2,3 | 3.373 | 0.848 (44) |

X-ray and Auger-electron spectra for the IT decay of $^{103m}$Rh were determined by means of BrIccEmis calculations within the NS_RadList program, as described in 2012Le09, 2013LeZX, 2016Le19, 2020TeZY and 2023Texx. Transition energies within each propagation step were derived from the atomic binding energies determined by adopting the relativistic Dirac-Fock approach employed in the RAINE code (2002Ba85), along with the application of a semi-empirical correction procedure that aligns these energies more fully with known spectral data. Fixed transition rates were obtained from the EADL database (1991PeZY, 1993Cu08). Resulting X-ray and Auger-electron energies and emission probabilities are listed below for $^{103m}$Rh probabilities (both sets of energies are listed as mean energies and ranges of energies at the 95% confidence level, with additional extensions of these energy ranges in italics for specific X-ray and Auger electron emissions). The number of simulated nuclear events is $10^6$, and the intensity cut-offs for both the X-ray and Auger-electron listings are 0.01 per 100 decays. As defined by 1991PeZY, uncertainties in these theoretical X-ray emission probabilities are ~ 10% for the K and L shells and 30% for the outer shells, whereas uncertainties in the theoretical Auger-electron emission probabilities are < 15% for the K and L shells (except for Coster-Kronig and super Coster-Kronig transitions) and 30% for the outer shells.

### X-ray energies and emission probabilities from IT decay of $^{103m}$Rh (BrIccEmis/NS_RadList).

| | | Mean energy (keV) | Energy (keV) 95% confidence range/extension | Photons per 100 decays[a] |
|---|---|---|---|---|
| $X_{tot}$ | (Rh) | 14.255 | 2.378 – 22.725 | 12.5 (4) |
| $XK_{tot}$ | (Rh) | 20.599 | 20.073 –23.167/*23.173* | 8.1 (4) |
| XKL2 | (Rh) | 20.073 | 20.073 | 2.33 (10) |
| XKL3 | (Rh) | 20.215 | 20.215 | 4.41 (20) |
| XKM | (Rh) | 22.717 | 22.699 – 22.725 | 1.11 (5) |
| XKM2 | (Rh) | 22.699 | 22.699 | 0.375 (17) |
| XKM3 | (Rh) | 22.725 | 22.725 | 0.730 (33) |
| XKN | (Rh) | 23.171 | 23.167 – 23.173 | 0.219 (10) |
| XKN2 | (Rh) | 23.167 | 23.167 | 0.0746 (34) |
| XKN3 | (Rh) | 23.173 | 23.173 | 0.144 (6) |
| $XL_{tot}$ | (Rh) | 2.743 | 2.378 – 3.067 | 4.27 (10) |
| $XM_{tot}$ | (Rh) | 0.321 | 0.189 – 0.546 | 0.1184 (23) |

[a] Quoted uncertainties include direct contributions from only the internal-conversion electrons (2023Texx) – these data do not include significant uncertainties from the more complex but less well-defined atomic radiation probabilities as considered semi-quantitatively in EADL, whereby uncertainties in the theoretical X-ray radiative rates are ~ 10% for the K and L shells, and can be of the order of 30% for the outer shells (1991PeZY).

**Auger-electron energies and emission probabilities from IT decay of $^{103m}$Rh (BrIccEmis/NS_RadList).**

| | | Mean Energy (keV) | Energy (keV) 95% confidence range/extension | Electrons per 100 decays[a] |
|---|---|---|---|---|
| Auger total | (Rh) | 0.461 | 0.002 – 2.490 | 582 (12) |
| Auger $K_{tot}$ | (Rh) | 17.708 | 16.281 –21.922/*22.838* | 1.92 (9) |
| Auger KLL | (Rh) | 16.811 | 16.281 – 17.083 | 1.34 (6) |
| Auger KLX | (Rh) | 19.574 | 19.133 – 20.146 | 0.525 (24) |
| Auger KXY | (Rh) | 22.275 | 21.922 – 22.838 | 0.0495 (22) |
| Auger $L_{tot}$ | (Rh) | 2.139 | *0.004*/0.064 –2.768/*3.133* | 85.4 (19) |
| Auger Coster-Kronig LLM | (Rh) | 0.038 | 0.004 – 0.051 | 0.94 (+22-17) |
| Auger Coster-Kronig LLX | (Rh) | 0.098 | 0.031 – 0.313 | 5.36 (15) |
| Auger LMM | (Rh) | 2.239 | 1.842 – 2.490 | 66.2 (15) |
| Auger LMX | (Rh) | 2.600 | 2.383 – 2.824 | 12.25 (28) |
| Auger LXY | (Rh) | 2.969 | 2.851 – 3.133 | 0.620 (14) |
| Auger $M_{tot}$ | (Rh) | 0.200 | *0.021*/0.054 – 0.368/*0.390* | 235 (5) |
| Auger Coster-Kronig MMX | (Rh) | 0.103 | 0.021 – 0.178 | 69.0 (13) |
| Auger MXY | (Rh) | 0.240 | 0.141 – 0.390 | 166.1 (34) |
| Auger $N_{tot}$ | (Rh) | 0.019 | 0.001 –0.034/*0.064* | 259 (5) |
| Auger super Coster-Kronig NNN | (Rh) | 0.019 | 0.001 – 0.034 | 249 (5) |
| Auger Coster-Kronig NNX | (Rh) | 0.020 | 0.002 – 0.064 | 9.94 (21) |

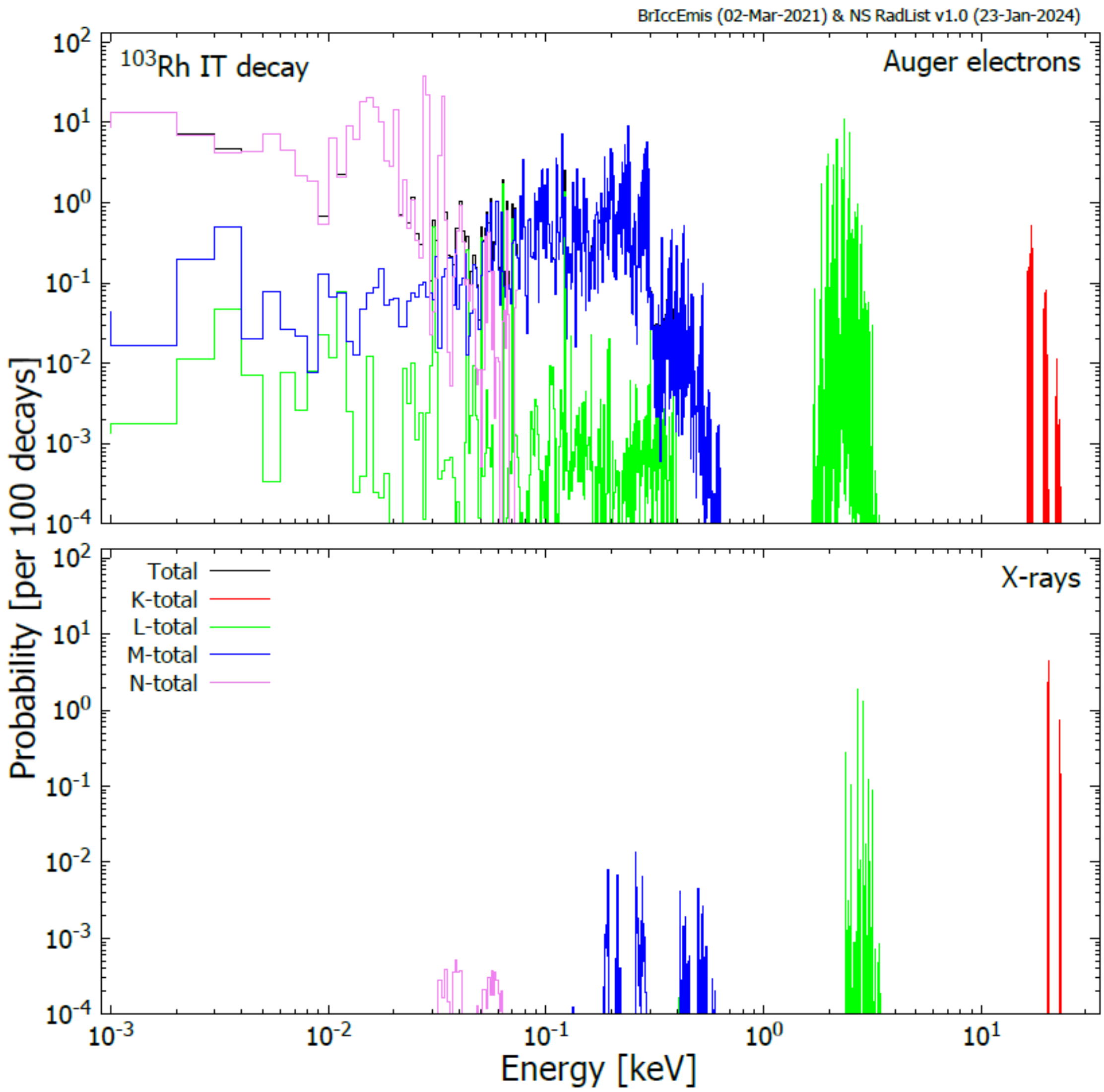
[a] Quoted uncertainties include direct contributions from only the internal-conversion electrons (2023Texx) – these data do not include significant uncertainties from the more complex but less well-defined atomic radiation probabilities as considered semi-quantitatively in EADL, whereby uncertainties in the theoretical Auger-electron radiative rates are < 15% for the K and L shells (except for Coster-Kronig and super Coster-Kronig transitions), and can be of the order of 30% or more for Coster-Kronig and super Coster-Kronig transitions and the outer shells (1991PeZY).

Total energy release per decay as determined from the BrIccEmis/NS_RadList studies:

| Radiation | Total energy (keV per decay) | Total intensity (%) |
|---|---|---|
| Gamma rays | 0.0276 (8) | 0.0694 (19) |
| Conversion electrons | 35.3 (12) | 100.3 (35) |
| Auger electrons | 2.67 (6) | 582 (12) |
| X-rays | 1.77 (6) | 12.5 (4) |
| Summed total | 39.8 (12) | |
| Q(IT) | 39.753 (6) | |

The final X-ray and Auger-electron spectra were effectively evaluated from one million simulated nuclear decay events. Both component spectra of the Auger-electron and X-ray emissions as calculated by the BrIccEmis code for the IT decay of $^{103m}$Rh are shown in the following figure.

**Auger-electron (upper panel) and X-ray (lower panel) spectra of $^{103m}$Rh IT decay:**




## Main Production Modes for $^{103}$Pd and $^{103m}$Rh

$^{103m}$Rh: $^{103}$Rh(n,n')$^{103m}$Rh, $^{103}$Rh(d,d')$^{103m}$Rh, $^{103}$Rh(α,α')$^{103m}$Rh, $^{103}$Rh(γ,γ')$^{103m}$Rh
parent $^{103}$Pd(EC)$^{103m}$Rh
parent $^{103}$Ru(β$^-$)$^{103m}$Rh: $^{102}$Ru(n,γ)$^{103}$Ru, $^{102}$Ru(d,p)$^{103}$Ru, $^{104}$Ru(d,t)$^{103}$Ru, $^{100}$Mo(α,n)$^{103}$Ru

## Data Consistency

**$^{103m}$Rh**

A $Q_{IT}$-value of 39.753 (6) keV for the IT decay of $^{103m}$Rh from NUBASE2020/AME2020 (2021Ko07, 2021Wa16) has been similarly compared with a calculated Q-value of 39.8 (6) keV to give a percentage deviation of – (0.1 ± 1.5)%, which supports the derivation of a consistent decay scheme with a modest variant.

## References


1936Ba01 I. Backhurst, LVIII The X-ray K-fluorescence Yield, London Edinburgh Dublin Phil. Mag. J. Sci. **22** (1936) 737-752. [Rh $\omega_K$]

1937St02 R.J. Stephenson, X-ray Fluorescence Yields, Phys. Rev. **51** (1937) 637-642. [Rh $\omega_K$]

1944Fl01 A. Flammersfeld, Kernanregung durch Schnelle Neutronen bei Rhodium und Silber, Naturwissenschaften **32** (1944) 36-37. [$^{103m}$Rh half-life]

1945Wi03 M.L. Wiedenbeck, The Nuclear Excitation of Krypton and Rhodium, Phys. Rev. **68** (1945) 237-239. [$^{103m}$Rh half-life]

1945Wi12 M.L. Wiedenbeck, The Nuclear Excitation of Rhodium, Phys. Rev. **67** (1945) 267-268. [$^{103m}$Rh half-life]

1947Fl03 A. Flammersfeld, O. Bruna, Die Anregungsenergie der Isomeren Zustände des Rhodiums 103 und 104, Z. Naturforsch. **2a** (1947) 241-244. [$^{103m}$Rh half-life]

1950Ko10 E. Kondaiah, Disintegration of Ru$^{103}$, Phys. Rev. **79** (1950) 891-892. [K/(L+M) ratio (40 keV)]

1950Me26 J.Y. Mei, C.M. Huddleston, A.C.G. Mitchell, The Disintegration of Ruthenium-103 and Palladium-103, Phys. Rev. **79** (1950) 429-432. [$^{103m}$Rh half-life]

1952Co16 J.M. Cork, J.M. LeBlanc, F.B. Stumpf, W.H. Nestor, The Radioactive Decay of Ruthenium 103, Phys. Rev. **86** (1952) 575-576. [K/L ratios]

1954Ro45 C.E. Roos, A New Method for Measuring Auger Transitions, Phys. Rev. **93** (1954) 401-405. [Rh $\omega_K$]

1955Av11 P. Avignon, A. Michalowicz, R. Bouchez, Étude de la Désintégration du $^{103}$Pd, J. Phys. Radium **16** (1955) 404-410. [$E_\gamma$, $P_\gamma$, $\alpha_K$, $\alpha_L$, K/L ratio]

1955Dr43 G.M. Drabkin, V.I. Orlov, L.I. Rusinov, Investigation of the Nuclear Isomerism of Zn$^{69}$, Se$^{79}$, Se$^{81}$, Rh$^{103}$ and Ba$^{137}$, Izvest. Akad. Nauk SSSR, Ser. Fiz., Columbia Tech. Transl. **19** (1956) 294-304. [$\alpha_K$, K/L and L/M ratios]

1957Jo19 G.A. Jones, W.R. Phillips, Electrical Octupole Coulomb Excitation in Rhodium, Proc. Royal Soc. (London) **239A** (1957) 487-493. [$^{103m}$Rh half-life]

1957Ro58 C.E. Roos, K Fluorescence Yield of Several Metals, Phys. Rev. **105** (1957) 931-935. [Rh $\omega_K$]

1967Br04 A.M. Bresesti, M. Bresesti, H. Neumann, Measurement of K X-ray Emission in the Decay of $^{103m}$Rh, J. Inorg. Nucl. Chem. **29** (1967) 15-20. [$^{103}$Ru $\beta^-$ decay: $P_{KX}$, K/(L+M+N) ratio of 39.75-keV gamma transition]

1967VuZZ A. Vuorinen, Calibration of $^{103m}$Rh by the Coincidence Method, pp. 257-263, Proc. Symp. Standardization of Radionuclides, IAEA, Vienna, Austria (1967). [$^{103m}$Rh half-life, K/(K + L + M) ratio, $P_{KX}$ of 39.75-keV gamma transition]

1968Ma08 J.C. Manthuruthil, H.J. Hennecke, C.R. Cothern, Internal-Conversion-Electron Study of the Decay of Ru$^{103}$, Phys. Rev. **165** (1968) 1363-1370. [ICC, multipolarities, mixing ratios]

1969Gr13 Y. Grunditz, S. Antman, H. Pettersson, M. Saraceno, Studies in the Decay of $^{103}$Pd, Nucl. Phys. **A133** (1969) 369-384. [$^{103}$Pd half-life, $E_\gamma$, $P_\gamma$, $\alpha_K$, subshell ratios, $P_{KX}$ and P(357 keV)/$P_{KX}$ ratio of $^{103}$Pd-$^{103m}$Rh]

1969KoZW Y. Kobayashi, Half-lives of Rhodium-106, -105 and -103m, JAERI report JAERI-1178 (1969) 21-22. [$^{103m}$Rh half-life]

1969Le17 M.A. Lepri, W.S. Lyon, Decay of $^{103}$Pd–$^{103m}$Rh, Int. J. Appl. Radiat. Isot. **20** (1969) 297-298. [$K_{\alpha}/K_{\beta}$ $^{103}$Pd-$^{103}$Rh, 39.75-keV $\alpha_K$]

1970NiZV E.B. Nieschmidt, D.A. Pearson, Nuclear Levels of $^{103}$Rh, IN-1317 (1970) 122-126. [$E_{\gamma}$, $P_{\gamma}$, $\alpha_K$, L subshell ratios]

1970Pe04 H. Pettersson, S. Antman, Y. Grunditz, Studies in the Decay of $^{103}$Ru, Z. Phys. **233** (1970) 260-274; Erratum, Z. Phys. **235** (1970) 485. [$E_{\gamma}$, $L_1/L_2$, $L_1/L_3$, $L_2/L_3$ ratios, $\alpha_K$]

1972Bb16 W. Bambynek, B. Crasemann, R.W. Fink, H.-U. Freund, H. Mark, C.D. Swift, R.E. Price, P. Venugopala Rao, X-Ray Fluorescence Yields, Auger, and Coster-Kronig Transition Probabilities, Rev. Mod. Phys. **44** (1972) 716-813; Erratum, Rev. Mod. Phys. **46** (1974) 853. [K-shell fluorescence yield]

1972Br02 D.S. Brenner, M.L. Perlman, Subshell Conversion-line Intensity Ratios for Some Pure Transitions, Nucl. Phys. **A181** (1972) 207-216. [39.75-keV $L_1/L_3$, $L_2/L_3$ ratios]

1972Pa10 A. Pazsit, J. Csikai, Cross Sections of the Reactions In$^{113}$(n,n')In$^{113m}$ and Rh$^{103}$(n,n')Rh$^{103m}$, Sov. J. Nucl. Phys. **35** (1972) 232-233. [$^{103m}$Rh half-life, $\alpha_K$(39.75 keV)]

1973Gu06 E. Günther, K. Knauf, K.F. Walz, The Half-life of $^{103m}$Rh, Int. J. Appl. Radiat. Isot. **24** (1973) 87-89. [$^{103m}$Rh half-life]

1973In07 H. Ing, W.G. Cross, Absolute Counting of K X-rays from $^{103m}$Rh in Thick Foils, Int. J. Appl. Radiat. Isot. **24** (1973) 437-450. [$^{103}$Ru $\beta^-$ decay: $P_{KX}$ of $^{103}$Ru-$^{103m}$Rh]

1974CzZY K.H. Czock, N. Haselberger, F. Reichel, The Disintegration of $^{103m}$Rh, IAEA report IAEA/RL/26 (1974). [$\alpha_{total}$, $\alpha_K$, K/(L + M + …..) ratio]

1974Sa15 D.C. Santry, J.P. Butler, Cross Section Measurements for the $^{103}$Rh(n,n')$^{103m}$Rh Reaction from 0.122 to 14.74 MeV, Can. J. Phys. **52** (1974) 1421-1428. [$^{103m}$Rh half-life, $P_{KX}$ of $^{103m}$Rh]

1975Cz03 K.H. Czock, N. Haselberger, F. Reichel, The Disintegration of $^{103m}$Rh, Int. J. Appl. Radiat. Isot. **26** (1975) 417-421. [$\alpha_{total}$, $\alpha_K$, $P_{KX}$ of $^{103m}$Rh]

1975Ma32 B. Martin, D. Merkert, J.L. Campbell, Intensity Ratios of L, M, N, O Subshell Conversion Electrons in M3 and E4 Transitions, Z. Phys. **A274** (1975) 15-21. [39.75-keV $L_1/L_2$, $L_1/L_3$, $L_2/L_3$, M, N, O ratios]

1976Ma37 E.S. Macias, M.E. Phelps, D.G. Sarantites, R.A. Meyer, Decay of 39-day $^{103}$Ru and 17-day $^{103}$Pd to the Levels of $^{103}$Rh, Phys. Rev. **C14** (1976) 639-644. [$E_{\gamma}$, $P_{\gamma}$, $\alpha_K$, $\alpha_L$, $P_{KX}$ and P(357 keV)/$P_{KX}$ ratio of $^{103}$Pd-$^{103m}$Rh]

1977La19 F.P. Larkins, Semiempirical Auger-electron Energies for Elements $10 \leq Z \leq 100$, At. Data Nucl. Data Tables **20** (1977) 311-387. [Auger-electron energies]

1978La21 F. Lagoutine, J. Legrand, C. Bac, Périodes de Quelques Radionucléides, Int. J. Appl. Radiat. Isot. **29** (1978) 269-272. [$^{103m}$Rh half-life]

1979VaZE R. Vaninbroukx, G. Grosse, W. Zehner, Studies of the Decay of $^{103m}$Rh, NEA report NEANDC(E)-202U, Vol. III (1979) 28-30. [$P_{\gamma}$, $P_{KX}$, $\alpha_{total}$, $\alpha_K$ of $^{103m}$Rh]

1981Va11 R. Vaninbroukx, G. Grosse, W. Zehner, New Determinations of the Half-lives of $^{57}$Co, $^{103}$Ru, $^{103m}$Rh, $^{103}$Pd and $^{109}$Cd, Int. J. Appl. Radiat. Isot. **32** (1981) 589-591. [$^{103}$Pd and $^{103m}$Rh half-lives]

1981Va22 R. Vaninbroukx, W. Zehner, Determination of the K X-ray Emission Probability in the Decay of $^{103m}$Rh, Int. J. Appl. Radiat. Isot. **32** (1981) 850. [$^{103m}$Rh $P_{KX}$]

1990Si19 S. Singh, R. Rani, D. Mehta, N. Singh, P.C. Mangal, P.N. Trehan, K X-ray Fluorescence Cross-section Measurements of Some Elements in the Energy Range 8-47 keV, X-ray Spectrom. **19** (1990) 155-158. [Rh $\omega_K$]

1991PeZY S.T. Perkins, D.E. Cullen, M.H. Chen, J.H. Hubbell, J. Rathkopf, J. Scofield, Tables and Graphs of Atomic Subshell and Relaxation Data Derived from the LLNL Evaluated Atomic Data Library (EADL), Z = 1–100, Lawrence Livermore National Laboratory report UCRL-50400, **30** (1991). [atomic database]

1992Ga24 R.R. Garg, S. Puri, S. Singh, D. Mehta, J.S. Shahi, M.L. Garg, N. Singh, P.C. Mangal, P.N. Trehan, Measurements of L X-ray Fluorescence Cross Sections and Yields for Elements in the Atomic Range $41 \leq Z \leq 52$ at 5.96 keV, Nucl. Instrum. Methods Phys. Res. **B72** (1992) 147-152. [Rh $\varpi_L$]

1993Cu08 D.E. Cullen, S.T. Perkins, S.M. Seltzer, Photon and Electron Databases and Their Use in Radiation Transport Calculations, Appl. Radiat. Isot. **44** (1993) 1343-1347. [atomic database]

1994Hu23 J.H. Hubbell, P.N. Trehan, N. Singh, B. Chand, D. Mehta, M.L. Garg, R.R. Garg, S. Singh, S. Puri, J. Phys. Chem. Ref. Data **23** (1994) 339-364; Erratum, J. Phys. Chem. Ref. Data, **33** (2004) 621. [Rh $\omega_K$, $\varpi_L$, $\varpi_M$]

1994Sc43 U. Schötzig, Photon Emission Probabilities in the Decay of $^{103}$Ru/$^{103m}$Rh, Appl. Radiat. Isot. **45** (1994) 641-644. [$^{103m}$Rh $P_{KX}$]

1996Sc06 E. Schönfeld, H. Janβen, Evaluation of Atomic Shell Data, Nucl. Instrum. Methods Phys. Res. **A369** (1996) 527-533. [$\omega_K$, $\varpi_L$, $K_\beta/K_\alpha$, $K_{\alpha2}/K_{\alpha1}$, KLX/KLL, KXY/KLL]

1998ScZM E. Schönfeld, G. Rodloff, Tables of the Energies of K-Auger Electrons for Elements with Atomic Numbers in the Range from Z = 11 to Z = 100, PTB Report PTB-6.11-98-1, October 1998. [Auger electrons]

1999Sa78 M. Sainath, K. Venkataramaniah, Measurement of $\alpha_K$, $\alpha_L$, $\alpha_M$ of the Hindered E3 Transition in $^{103}$Rh, Indian J. Pure Appl. Phys. **37** (1999) 87-91. [39.75-keV $\alpha_K$, $\alpha_L$, $\alpha_M$]

1999ScZX E. Schönfeld, G. Rodloff, Energies and Relative Emission Probabilities of K X-rays for Elements with Atomic Numbers in the Range from Z = 5 to Z = 100, PTB Report PTB-6.11-1999-1, February 1999. [$X_K$]

2000KoZT A. Kovalík, E.A. Yakushev, D.V. Filosofov, V.M. Gorozhankin, V.G. Kalinnikov, Energies of the 39.7 keV E3 Transition in $^{103}$Rh, the 25.6 keV E1 Transition in $^{161}$Dy, the 74.6 keV and 76.2 keV M1 Transitions in $^{161}$Ho, and 67.2 keV E3 and 71.9 keV M1 + E2 Transitions in $^{158}$Ho, Program and Thesis, Proc. 50$^{th}$ Ann. Conf. Nucl. Spectrosc. Struct. At. Nuclei, St. Petersburg, Russia (2000) 175. [39.7537(21)-keV γ-ray energy $^{103m}$Rh]

2000Sc47 E. Schönfeld, H. Janβen, Calculation of Emission Probabilities of X-rays and Auger Electrons Emitted in Radioactive Disintegration Processes, Appl. Radiat. Isot. **52** (2000) 595-600. [$P_X$, $P_{Ae}$]

2002Ba85 I.M. Band, M.B. Trzhaskovskaya, C.W. Nestor, Jr., P.O. Tikkanen, S. Raman, Dirac–Fock Internal Conversion Coefficients, At. Data Nucl. Data Tables **81** (2002) 1-334. [Theoretical ICC]

2002Ra45 S. Raman, C.W. Nestor, Jr., A. Ichihara, M.B. Trzhaskovskaya, How Good are the Internal Conversion Coefficients Now? Phys. Rev. **C66** (2002) 044312, 1-23. [Theoretical ICC]

2008Ki07 T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Jr., Evaluation of Theoretical Conversion Coefficients using BrIcc, Nucl. Instrum. Methods Phys. Res. **A589** (2008) 202-229. [Theoretical ICC]

2009De29 D. De Frenne, Nuclear Data Sheets for A = 103, Nucl. Data Sheets **110** (2009) 2081-2256. [Nuclear levels]

2011Ka49 A. Kahoul, A. Abassi, B. Deghfel, M. Nekkab, K-shell Fluorescence Yields for Elements with $6 \le Z \le 99$, Radiat. Phys. Chem. **80** (2011) 369-377. [Rh $\omega_K$]

2012Le09 B.Q. Lee, T. Kibédi, A.E. Stuchbery, K.A. Robertson, Atomic Radiations in the Decay of Medical Radioisotopes – A Physics Perspective, Comput. Math. Methods Med. Article ID 651475 (2012) 1-14, doi:10.1155/2012/651475. [Atomic radiation]

2013LeZX B.Q. Lee, T. Kibédi, A.E. Stuchbery, K.A. Robertson, F.G. Kondev, A Model to Realize the Potential of Auger Electrons for Radiotherapy, Proc. Heavy Ion Accelerator Symposium (HIAS2013), 8-12 April 2013, Canberra, Australia, EPJ Web of Conferences, **63** (2013) 01002, 1-5, editors: C. Simenel, M. Evers, T. Kibédi, D. Huy Luong, M. Reed, M. Srncik, A. Wallner; doi.org/10.1051/epjconf/20136301002. [Auger electrons]

2016Le19 B.Q. Lee, Hooshang Nikjoo, J. Ekman, P. Jönsson, A.E. Stuchbery, T. Kibédi, A Stochastic Cascade Model for Auger-electron Emitting Radionuclides, Int. J. Radiat. Biol. **92** (2016) 641-653; doi: 10.3109/09553002.2016.1153810. [Atomic radiation]

2017Ri10 J. Riffaud, M.-C. Lépy, Y. Ménesguen, A. Novikova, Measurement of K Fluorescence Yields of Niobium and Rhodium Using Monochromatic Radiation, X-ray Spectrom. **46** (2017) 341-346. [Rh $\omega_K$]

2018Ni14 N. Nica, J.C. Hardy, V.E. Iacob, V. Horvat, H.I. Park, T.A. Werke, K.J. Glennon, C.M. Folden III, V.I. Sabla, J.B. Bryant, X.K. James, M.B. Trzhaskovskaya, Precise Measurement of $\alpha_K$ and $\alpha_T$ for the 39.8-keV E3 transition in $^{103}$Rh: Test of Internal-conversion Theory, Phys. Rev. **C98** (2018) 054321, 1-11. [$\alpha_K$, $\alpha_T$, $\delta$ (39.75-keV $\gamma$-ray transition)]

2018Ri01 J. Riffaud, P. Cassette, D. Lacour, V. Lourenço, I. Tartès, M.A. Kellett, M. Corbel, M.-C. Lépy, C. Domergue, C. Destouches, H. Carcreff, O. Vigneau, Measurement of Absolute K X-ray Emission Intensities in the Decay of $^{103m}$Rh, Appl. Radiat. Isot. **134** (2018) 399-405. [$^{103m}$Rh IT decay: absolute $P_{KX}$, absolute $P_\gamma$]

2020TeZY B.P.E. Tee, T. Kibédi, B.Q. Lee, M. Vos, R. du Rietz, A.E. Stuchbery, Development of a New Database for Auger-electron and X-ray Spectra, Proc. Heavy Ion Accelerator Symposium (HIAS2019), 9-13 September 2019, Canberra, Australia, EPJ Web of Conferences, **232** (2020) 01006, 1-4, editors: A.J. Mitchell, S. Pavetich, D. Koll; doi.org/10.1051/epjconf/202023201006. [Atomic radiation]

2021Ko07 F.G. Kondev, Meng Wang, W.J. Huang, S. Naimi, G. Audi, The NUBASE2020 Evaluation of Nuclear Physics Properties, Chin. Phys. **C45** (2021) 030001, 1-180; doi: 10.1088/1674-1137/abddae [$Q_{IT}$($^{103m}$Rh)]

2021Ri01 J. Riffaud, M.-C. Lépy, P. Cassette, M. Corbel, M.A. Kellett, V. Lourenço, Measurement of the Absolute Gamma-ray Emission Intensities from the Decay of $^{103}$Pd, Appl. Radiat. Isot. **167** (2021) 109298, 1-9. [$^{103}$Pd half-life, absolute $P_{KX}$, relative $P_{LX}$, absolute $P_\gamma$]

2021Wa16 Meng Wang, W.J. Huang, F.G. Kondev, G. Audi, S. Naimi, The AME2020 Atomic Mass Evaluation (II): Tables, Graphs and References, Chin. Phys. **C45** (2021) 030003, 1-512; doi: 10.1088/1674-1137/abddaf [Q-values]

2023Texx B.P.E. Tee, T. Kibédi, B.Q. Lee, A.E. Stuchbery, BrIccEmisDB Database and Computational Tool to Evaluate Atomic Relaxation Radiations, in preparation for submission to At. Data Nucl. Data Tables (2023-2024). [Atomic radiation]

65 references and three errata – 68 items

**ENSDF Analysis Programs:**
BrIcc, version 2.3b, 16 December 2014
BrIccEmis, 2 March 2021
NS_RadList, version 1.0, 7 December 2023
BrIccMixing, version 2.3d, 28 September 2019

**ENSDF Utility Programs:**
Avetools, version 3.0, 11 December 2014
V.AveLib, version 06-22, 19 March 2024
FMTCHK, version 10.4d, 29 November 2018

The above codes have undergone and will continue to undergo various forms of modification and improvement, which will be reflected in changes to the version number and date of issue into the public domain. Assistance from Tibor Kibédi (ANU, Australia – particularly BrIccEmis and NS_RadList) concerning improved operational features of some of the above codes is gratefully acknowledged by ALN.