^{151}Sm - Comments on evaluation of decay data

by X. Mougeot
Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), 91120 Palaiseau, France

This evaluation was completed including the literature available by end of July 2023. It is an update of the previous DDEP evaluation performed in 2014 [2016BEZX].

Only a single relevant new publication was found, by Kossert *et al.* [2022KO10]. In this study, a high-precision measurement of the β spectra was carried out with a metallic magnetic calorimeter, establishing new Q-value and branching ratios. The branching ratio to the first excited state of ^{151}Eu was found to be significantly lower than past measurements.

New measurement of the half-life is suggested, as the recommended value is vastly dominated by 2015BE23. New measurements of the branching ratios (via the β particles or the γ emission) are also recommended.

1. Decay Scheme

^{151}Sm decays by β^- disintegrations to the first excited level and to the ground state of ^{151}Eu. Level energy, spin and parities were taken from [2009SI01].

The available energy for the decay is **$Q_{\beta-}$ = 76.43 (7) keV**, taken from [2022KO10]. The latest recommended value from the Atomic Mass Evaluation (AME) 2020 [2021WA16] is consistent yet less precise, with $Q_{\beta-}$ = 76.6 (5) keV.

2. Nuclear Data

2.1. Half-life

The experimental half-lives used to calculate the recommended value are listed in Table 1. Only the two latest values have been considered, as their relative uncertainty is less than 5%. The small dataset is consistent, with critical χ^2 = 6.63 and reduced χ^2 = 0.65. The weighted mean is adopted with the smallest experimental uncertainty.

Table 1 – Measured ^{151}Sm half-lives and recommended value.

References	$T_{1/2}$ (a)	Uncertainty (a)	Comments
1950IN01	122		No uncertainty; omitted
1952RU10	> 20		
1952KA26	73	33	$^{+25}_{-14}$; omitted
1955ME52	93		No uncertainty; omitted
1965FL02	87	10	Too large uncertainty; omitted
1968RE04	93	8.6	Too large uncertainty; omitted
2009HE22	96.6	2.4	
2015BE23	94.6	0.6	
Adopted	**94.7**	**0.6**	

2.2. Beta minus transitions

Two β emissions were measured by Achor [1959AC28] with maximum energies of 75.9 keV and 54.2 keV, and respective intensities of 98.3 (3) % and 1.7 (3) %. From spins and parities of the initial and final nuclear states, both transitions are first forbidden non-unique. In [1959AC28], they were found either first forbidden non-unique shape, or allowed. In [2015BE12], the measured spectra were found to be close to an allowed shape. In [2022KO10], deviation from the allowed shape was quantified by calculations that included nuclear structure: maximum 2.4% in the dominant transition, and maximum 4% in the secondary transition.

The measured branching ratio in [1959AC28] was re-calculated in [1975FR01] with an approximate graphical scaling to be 0.9 (3) %. It was not considered in the present evaluation because of a too large uncertainty and a lack of confidence in the robustness of this value.

In [1975FR01], the branching ratio was measured with two different sources. Their final result takes also into account another measurement that depends on the total conversion coefficient (not given), and their recalculated value of [1959AC28]. Only the simple mean of the first two measurements was considered, with the uncertainty quoted in [1975FR01].

In [1980LA02], a branching ratio of 0.94 (6) % was deduced from the measured absolute gamma emission intensity and a total conversion coefficient α_T = 28.1 (5). Using the adopted multipolarity of the transition (see Section 2.3), the BrIcc program [2008KI07] provides a value of α_T = 27.6 (5). The branching ratio was then re-calculated to be 0.92 (6) %.

The absolute gamma emission intensity was also measured to be I_γ = 0.0324 (13) % in [2011SH37]. With α_T from the BrIcc program [2008KI07], the corresponding branching ratio of 0.927 (41) % was obtained.

Finally, the branching ratios were determined from the beta spectra measurement in [2022KO10].

The dataset, given in Table 2, is consistent (χ^2 = 1.6 vs critical-χ^2 = 3.8). The value from [2011SH37] has a dominant weight of 48%. The minimum experimental uncertainty was taken for the adopted weighted average because of the small size of the dataset. The adopted branching ratio to the first excited state of ^{151}Eu was then established to be **$I_{\beta0,1}$ = 0.89 (4) %**.

Then, the intensity of the transition that populates the ground state is **$I_{\beta0,0}$ = 99.11 (4) %**.

Table 2 – Measured branching ratio to the 54 keV level and recommended value.

Reference	$I_{\beta0,1}$ (%)	Uncertainty	Comments
1959AC28	0.9	0.3	Re-calculated by [1975FR01]; omitted
1975FR01	0.85	0.06	Mean of 0.86 and 0.84; uncertainty from [1975FR01]
1980LA02	0.92	0.06	Re-calculated with α_T from BrIcc
2011SH37	0.927	0.041	Deduced from absolute I_γ and α_T from BrIcc
2022KO10	0.69	0.11	
Adopted	**0.89**	**0.04**	Weighted mean; minimum uncertainty of dataset rounded to one digit

The average energy of the beta spectra and the log *ft* values were determined using the BetaShape program, version 2.3. This version includes precise atomic corrections (screening, exchange and overlap) that are of importance for such low-energy transitions [2014MOU0, 2019MO35].

2.3. Gamma transition

The energy is from the first excited state energy at 21.541 (3) keV [2009SI01]. This level has a half-life of $T_{1/2}$(^{151}Eu, 21.5 keV) = 9.6 (3) ns [2009SI01]. Measured multipolarities and conversion coefficients of this transition are given in Table 3.

The adopted multipolarity is the weighted mean of the values from [1966AV05, 1968GR25], [1970AN17] and [1981AR17] associated with the lowest experimental uncertainty.

The corresponding internal conversion coefficients are the theoretical values provided by the BrIcc program v2.2 [2008KI07] assuming the “frozen orbital (no hole)” approximation. It is noteworthy that the decay energy is not sufficient to allow for a conversion process of the K electrons.

The theoretical, adopted α_T is in good agreement with the experimental result of [1977VE01] and the α_L theoretical value of 21.7 (4) is in agreement, within the uncertainty limits, with the results of [1959AC28], [1968GR25], [1970FO02] and [1981AR17].

Table 3 – Measured multipolarities and conversion coefficients from the gamma transition that follows ^{151}Sm decay. Adopted values are also given.

Reference	Quantity	Uncertainty	Multipolarity
1959AC28	α_L = 20	4	M1
1966AV05, 1968GR25	δ = 0.035	0.007	M1 + 0.12(3)% E2
1968GR25	α_L = 20	5	
1970AN17	δ = 0.0297(24)	0.00007	M1 + 0.088(7)% E2
1970FO02	α_L = 24.7(40)	4	M1 + <6% E2
1975FR01	$\delta \leq 0.022$		M1 + $\leq$ 0.05% E2
1977VE01	α_T = 27.5	1.5	
1981AR17	α_L = 23.9	5.0	M1+0.083(5) %E2
Adopted	**δ = 0.029(2)**		**M1+0.085(5)%E2**
BrIcc theory FO	α_T = 25.9	0.4	M1
BrIcc theory FO	α_T = 27.6	0.5	M1 + 0.085(5)% E2
Adopted	**α_T = 27.6**	**0.5**	**M1 + 0.085(5)%E2**

The gamma-ray intensity was then deduced from the branching ratio and the total internal conversion coefficient: **I_γ = 0.0311 (15) %**. This adopted value is in agreement with the measurements from [1980LA02] and [2011SH37], I_γ = 0.0323 (21) % and I_γ = 0.0324 (13) % respectively.

3. Atomic Data

Several studies were conducted in order to measure the internal ionisation probabilities in the K and L shells following the ^{151}Sm beta decay. The Auger electron and X-ray absolute emission probabilities were computed with the EMISSION program [2000SC47] from the related decay data (γ-ray emission intensities, ICCs, etc.).

The measured relative intensities of the X photons emitted in the ^{151}Sm beta decay are listed in Table 4 and compared with the values obtained considering I_γ = 0.0311 (15) % and α_T = 27.6 (5).

Table 5 gives the measured intensity per 100 β decays of L X-rays due to internal ionisation. The recommended value was calculated with the EMISSION program, consistently with all the quantities from this evaluation. This recommended value is about twice the measured values from [1975FR01] and [1981UN02]. However, an inconsistency is noteworthy in the measurements because a close value I_{Lx} = 0.052% can only be obtained with EMISSION considering $I_{\beta 0,1}$ = 0.4%, $I_{\beta 0,0}$ = 99.6% and I_γ = 0.014%, which values are too far from the direct measurement of these probabilities.

Table 6 gives the measured internal ionisation probabilities. For the K shell, the recommended value is the weighted average of all the values, except [1971CA44] rejected by Chauvenet's criterion, with the external uncertainty. For the L shell, the value from [1981UN02] dominates the weighted mean and its experimental uncertainty is kept.

Table 4 – Relative intensities of the X photons emitted in ^{151}Sm decay.

X-rays	**1971CA44**	**1981UN02**	**Calculated with EMISSION**
$L\ell$		0.073 (4)	0.0434 (31)
$L\alpha$, η		1.73 (9)	1.08 (7)
$L\beta$		2.65 (13)	2.15 (12)
$L\gamma$		0.636 (32)	0.476 (28)
γ 21.5 keV	1	1	1
$K\alpha$	5.8 (2) 10^{-3}	4.0 (2) 10^{-3}	
$K\beta$		1.0 (2) 10^{-3}	

Table 5 – Absolute intensity of L X-rays due to internal ionisation in ^{151}Sm decay.

Reference	**I_{Lx} (%)**
1975FR01	5.4 (10) 10^{-2}
1981UN02	4.7 (5) 10^{-2}
Calculated with EMISSION	**11.6 (4) 10^{-2}**

Table 6 – Internal ionisation probabilities in ^{151}Sm decay.

Reference	**P_K (%)**	**P_L (%)**
1971CA44	0.041 (6) 10^{-4}	
1975FR01	2.4 (3) 10^{-4}	
1975LA20	2.3 (3) 10^{-4}	30 (6) 10^{-2}
1980LA02	2.4 (3) 10^{-4}	
1981UN02	1.59 (13) 10^{-4}	31 (3) 10^{-2}
Recommended	**1.98 (23) 10^{-4}**	**30.8 (30) 10^{-2}**

4. Consistency of recommended data

The total average emission energy per decay for all emissions involved in the ^{151}Sm decay process (γ-rays, X-rays, etc.) is 76.43 (8) keV. This value is in excellent agreement with the adopted Q value of 76.43 (7) keV from [2022KO10], with no surprise for such a simple decay scheme.

5. References

1950IN01 M.G. Inghram, R.J. Hayden, D.C. Hess, Phys. Rev. 79, 271 (1950) [Half-life]

1952KA26 D.G. Karraker, R.J. Hayden, M.G. Inghram, Phys. Rev. 87, 901 (1952) [Half-life]

1952RU10 W.C. Rutledge, J.M. Cork, S.B. Burson, Phys. Rev. 86, 775 (1952) [Half-life]

1955ME52 E.A. Melaika et al., Can. J. Chem. 33, 830 (1955) [Half-life]

1959AC28 W.T. Achor et al., Phys. Rev. 114, 137 (1959) [I_β, ICC]

1965FL02 K.F. Flynn, L.E. Glendenin, E.P. Steinberg, Nucl. Sci. Eng. 22, 416 (1965) [Half-life]

1966AV05 M.P. Avotina et al., Izv. Akad. Nauk SSSR, Ser. Fiz. 30, 1304 (1966); Bull. Acad. Sci. USSR, Phys.Ser. 30, 1362 (1967) [Mixing ratio]

1968RE04 S.A. Reynolds, J.F. Emery, E.I. Wyatt, Nucl. Sci. Eng. 32, 46 (1968) [Half-life]

1968GR25 E.P. Grigorev et al., Izv. Akad. Nauk SSSR, Ser. Fiz. 32, 786 (1968); Bull. Acad. Sci. USSR, Phys. Ser. 32, 723 (1969) [Mixing ratio, ICC]

1970AN17 S. Antman, H. Pettersson, Z. Zehlev, I. Adam, Z. Phys. 237, 285 (1970) [Mixing ratio]

1970FO02 J.W. Ford, A.V. Ramayya, J.J. Pinajian, Nucl.Phys. A146 (1970) 397 [ICC]

1971CA44 J.L. Campbell, L.A. McNelles, J. Law, Can. J. Phys. 49, 3142 (1971) [Internal ionisation]

1975FR01 M.S. Freedman, D.A. Beery, Phys. Rev. Lett. 34, 406 (1975) [I_β, Mixing ratio, Internal ionisation]

1975LA20 J. Law, J.L. Campbell, Phys. Rev. C12, 984 (1975); Err. Phys. Rev. C14, 2347 (1976) [Internal ionisation]

1977VE01 V.R. Veluri, P. Venugopala Rao, Z. Phys. A280 (1977) 317 [ICC]

1980LA02 C.E. Laird, P.C. Hummel, H.C. Liu, Phys. Rev. C21, 723 (1980) [I_γ, Internal ionisation]

1981AR17 K.P. Artamonova et al., Bull. Acad. Sci. USSR, Phys. Ser. 45,1 (1981) 93 [Mixing ratio, ICC]

1981UN02 I.J. Unus, P.A. Indira, P. Venugopala Rao, J. Phys. (London) G7, 1683 (1981) [Internal ionisation]

2000SC47 E. Schönfeld, H. Janssen. Appl. Radiat. Isot. 52 (2000) 595 [P_X, P_{Ae}]

2008KI07 T. Kibédi et al., Nucl. Instrum. Methods Phys. Res. A589 (2008) 202 [BrIcc code]

2009HE22 M. He et al., Phys. Rev. C 80, 064305 (2009) [Half-life]

2009SI01 B. Singh, Nucl. Data Sheets 110, 1 (2009) [^{151}Eu levels, Evaluation]

2011SH37 H. Shen et al., Phys. Rev. C 84, 054307 (2011) [I_γ]

2014MOU0 X. Mougeot, C. Bisch, Phys. Rev. A 90, 012501 (2014) [BetaShape code]

2015BE23 M.M. Bé et al., RadioChimica Acta 103 (9), 619-626 (2015) [Half-life]

2016BEZX M.M. Bé et al., Monographie BIPM-5, vol.8., Bureau International des Poids et Mesures (2016) [Evaluation]

2019MO35 X. Mougeot, Appl. Rad. Isotopes 154 (2019), 108884 [BetaShape code]

2021WA16 M. Wang et al., Chin. Phys. C 45 (2021), 030003 [Q-value]

2022KO10 K. Kossert et al., App. Radiat. Isot. 185 (2022), 110237 [Q-value, I_β]