EVALUATION OF THE ^{89m}Y HALF-LIFE DATA

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Precise determination of the ^{89m}Y isomeric half-life is critical for nuclear structure models and activation analysis. However, historical measurements exhibit a long-standing, unresolved scatter. With the present work, we aim to resolve this statistical tension by introducing a high-resolution low-background half-life measurement and evaluating historical dataset. The ^{89m}Y half-life was measured by using the high-energy resolution HPGe detectors of RoSphere. Statistical analysis was performed on the $909\gamma(t)$ data, obtained in 11 independent measurements. This dataset is highly consistent, displaying a near-ideal reduced chi-squared (χ^2/n.d.f.) of 0.91. Conversely, the statistical analysis, performed on the historical data, reveals some extreme statistical discrepancies. Grouping the measurements by detection methodology confirms a systematic 188 ms bias between the NaI(Tl) and HPGe data. The new measurement and statistical analysis performed in the present study do not disagree with the most precise measurement of 15.663 (5) s for the ^{89m}Y half-life previously measured in 1995. Half-life of 15.61 (4) s was evaluated by applying the Rajeval technique on all available HPGe data.

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1. Introduction

The semi-magic ${}^{89}_{39}\mathrm{Y}_{50}$ is the sole stable isotope of yttrium. It has a metastable state at 909 keV [1] that was discovered by Schure and Deutsch in 1951 [2]. To populate the excited state, the authors used a ${}^{89}\mathrm{Y}(d,d')$ reaction, performed at the Massachusetts Institute of Technology cyclotron, where they observed an electron conversion line with an energy of 909 keV and decay half-life considerably longer than the electron spectrometer resolving time, which was approximately 10^{-7} s. Given that several channels were open in this experiment, the authors could not identify unambiguously which nucleus emits the delayed radiation, but suggested that it may be associated with either Sr or Y isotopes. Later the same year, Goldhaber and collaborators [3] identified a 0.92 MeV γ-line from a ${}^{89}\mathrm{Y}(n,n'\gamma)$ experiment, decaying with a half-life of 13 (2) s. Also, in the same work, the authors quote a different number for the half-life for the same metastable state, that is 16 (3) s, which was obtained from a deuteron inelastic scattering. Based on conversion electron measurements, X-ray spectroscopy and γ-ray analysis, Goldhaber and co-authors deduced that it is indeed an $M4$ isomeric transition belonging to ^{89}Y. Further in the 60s, the half-life was measured in several other works on inelastic neutron scattering [4–9] and photo-excitation [10] reactions. In 1995, a half-life measurement of the ^{89m}Y state was performed [11] with unprecedented precision of 0.03%, which indeed is the presently adopted [1] by NSDD network [12] half-life of this state. Again, it was populated in inelastic neutron scattering, but this time the isomeric transition was detected with one then state-of-the-art HPGe detector. Because of the high yield such experiments provide, the authors used a fast spectroscopy amplifier capable of operating at high counting rates. However, results from this measurement were only reported in Ref. [11], but never published in a reviewed journal. More recently, $T_{1/2} = 15.28$ (17) s was obtained from inelastic neutron scattering [13] by using one semi-conductor HPGe detector, but the measurement is statistically different from the 1995 value at a 5% significance level. All historic data is summarized in Table 1.

To evaluate the data set in Table 1 for consistency, we calculate and analyze the standardized residuals, *i.e.* the σ-pull value [15, 16], defined as

$$\sigma\text{-pull}_i = \frac{x_i - \bar{x}_{\neq i}}{\sqrt{\sigma_i^2 + \sigma_{\neq i}^2}}\,, \tag{1}$$

where, for each measurement i of the set in Table 1, a sample not containing the i^{th} measurement is drawn. The $\bar{x}_{\neq i}$ and $\sigma^2_{\neq i}$ are the average and the dispersion for each of thus-constructed samples, respectively. The σ-pull statistics is standardized, where variations greater than 3σ are highly suspicious and those greater than 4σ are mathematically impossible. σ-pull

Table 1. ^{89m}Y half-life historical data in order of appearance. From left to right, the columns show: measurement ID assigned by the authors, the NSR key number [14], bibliography reference (Ref.), reaction and detectors used in the respective work, the half-life $T_{1/2}$ in seconds, as provided by the authors, and the σ-pull values for the subset containing ID2 to ID13 data.

ID	Keynumber	Ref.	Reaction	Detectors	$T_{1/2}$, s	σ-pull
1	1951Sh24	[2]	$Y(d, d')$	e-detector	$> 10^{-7}$	
2	1951Go42	[3]	$Y_2O_3(d, d'\gamma)$	scint.	16 (3)	+0.11
3	1951Go42	[3]	$^{89}Y(n, n'\gamma)$	one NaI(Tl)	13 (2)	−1.33
4	1955Sw92	[4]	$Y_2O_3(n, n'\gamma)$	one NaI(Tl)	16.1 (3)	+1.44
5	1962Br42	[5]	$^{93}Nb(n, n'\alpha)$	one NaI(Tl)	16.3 (13)	+0.49
6	1963Ka34	[10]	$^{89}Y(\gamma, \gamma')$	scint.	15.0 (2)	−3.35
7	1966Du07	[6]	$^{89}Y(n, n'\gamma)$	scint.	15.91 (17)	+1.42
8	1967Yu01	[7]	$^{89}Y(n, n'\gamma)$	one NaI(Tl)	16.06 (4)	+9.85
9	1968Bo28	[8]	$^{89}Y(n, n'\gamma)$	scint.	15.9 (6)	+0.39
10	1968Bo28	[8]	$^{89}Y(n, n'\gamma)$	scint.	16.4 (8)	+0.91
11	1968Bo52	[9]	$^{89}Y(n, n'\gamma)$	NaI(Tl)	15.78 (11)	+1.01
12	1995ItZY	[11]	$^{89}Y(n, n'\gamma)$	HPGe	15.663 (5)	−8.41
13	1998Do17	[13]	$^{89}Y(n, n'\gamma)$	HPGe	15.28 (17)	−2.29

values were calculated for all 12 historical points listed in Table 1, without the lower limit given in 1951Sh24. From this analysis, we can conclude that the data set contains some severely discrepant measurements. There is one significant outlier, the 1963Ka34 15.0 (2) s measurement, exerting a statistical pull of -3.35σ, and two extreme outliers, the 1967Yu01 16.06 (4) s and the ultra-precise 1995ItZY 15.663 (5) s values, with σ-pulls of $+9.85\sigma$ and -8.41σ, respectively. A way to cure the discrepancy is to eliminate some or all outliers. Excluding only the ultra-precise 15.663 s value does not solve the problem, since still there are remaining outliers in the new sample. By removing all three outliers, the discrepancy is resolved and the weighted average of thus-filtered sample is 15.73 (8) s. The unweighted mean of the same sample is statistically similar — 15.63 (35) s. Interestingly enough, these values do not indeed disagree with the 1995ItZY value. The weighted and unweighted averages are compared to the historical data in Fig. 1.

Filtering procedures, like the one described above, are often used in statistical data analysis. They clean the data by eliminating some of the most precise values on the basis of χ^2 criterion only, without taking into account the experimental techniques and methodology used in the respective

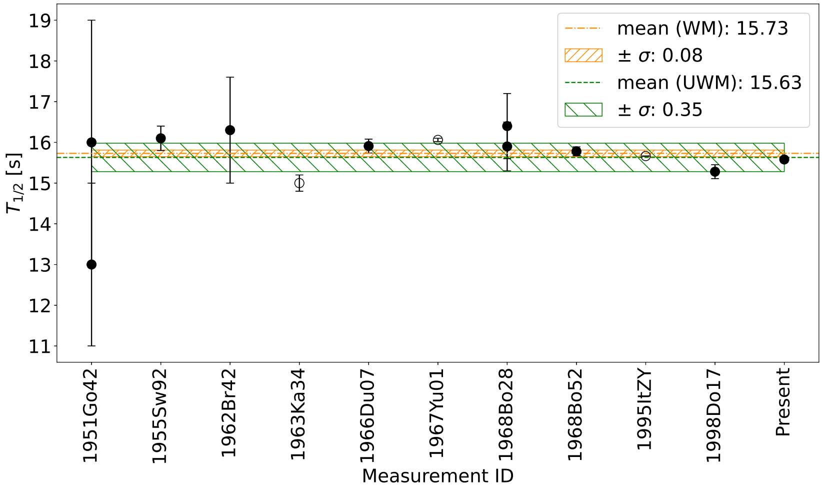

Fig. 1. Historical data in the order of appearance as given in Table 1, compared to the weighted and unweighted means. Last point is from the present measurement as described in Section 2.

work. Indeed, in our case, we just removed the 1995ItZY value, only because it does not reconcile with the rest of the data. This decision can be justified by the lack of experimental detail in this secondary source, but its removal may still be a mistake. Eliminating outliers creates false sense for precision. Inflating the uncertainties may hide real physical effects and false impression for a clean data, while the real world data is messy. The experiments in general are difficult and prone to variations. Alternatively, by exploring the data as-it-is, we can learn more about the nature of the measurements.

In this work, we present new data, obtained in a low-counting rate experiment (Section 2) as well as in-depth statistical analysis of all available data (Section 3). In Section 4, we provide conclusions and a recommended value for the ^{89m}Y half-life.

2. Experimental set up and the new data analysis

In the present work, we exploit an approach different to these used in the past, where high-counting rate experiments were performed with light particles and bremsstrahlung. Here, the yttrium meta-stable state was populated in the ^{11}B+^{82}Se heavy-ion reaction and the isomeric transition observed in several off-beam periods, when the data is considerably cleaner as shown in Fig. 2.

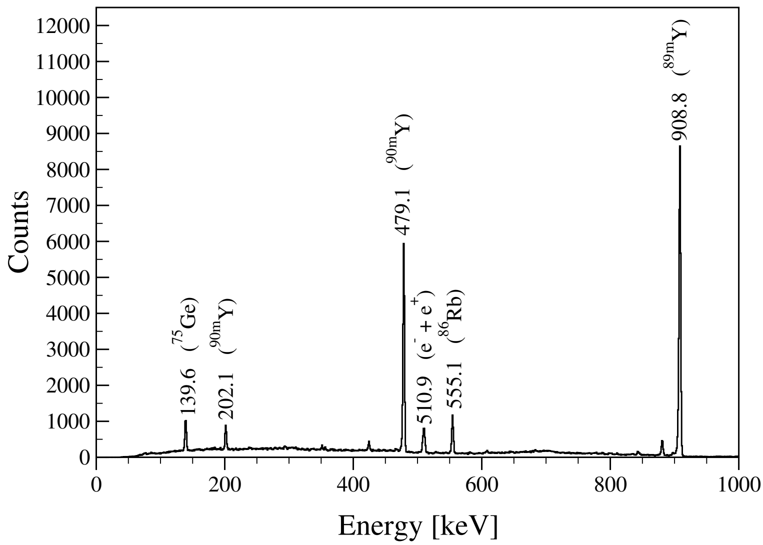

Fig. 2. Sample off-beam γ-ray spectrum, obtained in the present work, with the ^{89m}Y isomeric transition and impurities denoted, respectively. γ-ray energies are as observed in the present experiment, where $\Delta E_\gamma = 1$ keV.

The beam was accelerated to 40 MeV by the IFIN-HH 9 MV Tandem accelerator and was then delivered to a 5 mg/cm^2 thick ^{82}Se target, stacked between two Au foils. The beam current was $I \approx 1.5$ pnA. Emitted γ-rays were detected by the RoSphere spectrometer, comprising 14 HPGe detectors and 11 $LaBr_3Ce$ scintillators. The data, presented here, is from the high-resolution HPGe detectors only. The output signals were digitized and stored into eleven files, each of which taken in one of the 11 off-beam periods. The off-beam data were sorted in singles. The maximum counting rate, observed in the first few seconds after the beam was stopped, was ≈ 1000 counts per second, *i.e.* less than one event per millisecond. The average time between two consecutive events is much slower than the digitiser's shaping time of approximately 1.5 μs. The software packages GASPware [17], RADware [18, 19], GNUPLOT [20], and PYTHON [21] were used for data analysis. The spectrum in Fig. 3 presents the time distribution of 909 keV γ-ray for one of the eleven measurements, performed in the present study.

First, we estimate the ^{89m}Y half-life for each of the eleven time spectra using a least-squares fit to the respective time spectrum gated on the 909 keV transition. The resulting half-lives are listed in Table 2. A sample time spectrum obtained from one measurement and the corresponding least-square fit curve are presented in Fig. 3. The time spectrum presents the number of counts/sec for time intervals of one second, *i.e.* the i^{th} point on the graph shows the number of counts, registered in the i^{th} second after

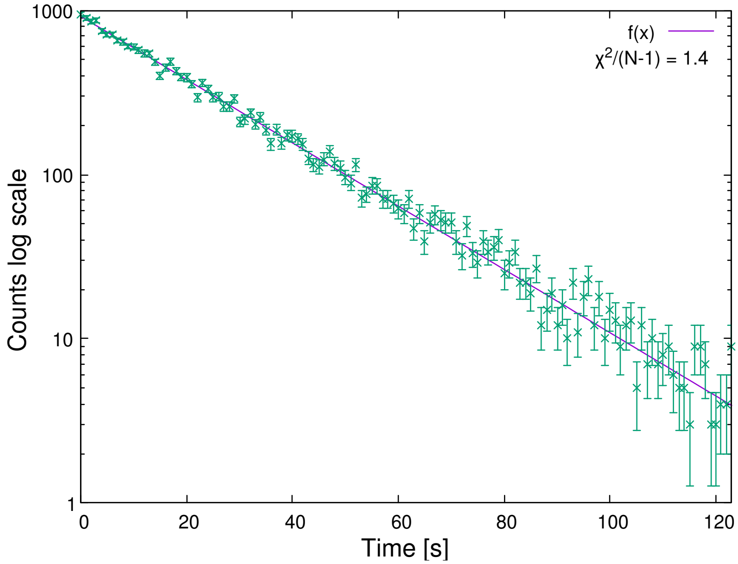

Fig. 3. A sample ^{89m}Y time spectrum observed in one of the off-beam measurements together with the curve obtained from a least-square fit to the data.

the acquisition start. The adopted uncertainties are taken as the square root of the number of counts observed in the i^{th} second. Because the data were recorded for a variable off-beam duration ranging from $4 \times T_{1/2}$ to $11 \times T_{1/2}$ seconds, we treat these measurements as independent rather than combining all data into one spectrum. The set in Table 2 statistically consistent with χ^2 is 0.91, where all σ-pulls are below 3σ.

The data presented in Table 2 were then analyzed by using various statistical methods including the Weighted Mean (WM) and Unweighted Mean (UWM) methods, Limitation of relative statistical weights (LRSW), Normalised residuals (NR), Rajeval Technique (RT), and Bootstrap method (BS). All these methods were previously used to test half-life data sets for consistency in Ref. [22] and references therein. We should note here that the LRSW, NRM, and MP methods give 15.58 (4) s, while the RT and BS return slightly different but statistically similar values of 15.59 (4) and 15.59 (3) s, respectively, as given in Table 3. Indeed, all methods return statistically similar $T_{1/2}$ with $\chi^2 < \chi^2_{\text{cr}}$. For the purpose of the present work, we adopt the RT value of 15.59 (4) s as the half-life obtained in the present study. Given our new result on $T_{1/2}$, we cannot reject the null hypothesis H_0 (our mean value is the same as the 1995 value) at a 5% significance level. It is also consistent with the UWM of the historical data, that is 15.63 (35) s and is compatible with the historical data WM value of 15.73 (8) s, as obtained in the introduction section.

Table 2. The ^{89m}Y half-life data as obtained in the present experiment.

Off-beam period	$T_{1/2}$ [s]
1	15.58 (17)
2	15.62 (11)
3	15.62 (13)
4	15.73 (10)
5	15.64 (11)
6	15.58 (11)
7	15.40 (13)
8	15.52 (16)
9	15.23 (17)
10	15.59 (13)
11	15.59 (11)

Table 3. Results from the statistical analysis of the eleven ^{89m}Y half-lives from Table 2.

Method	$T_{1/2}$ [s]	χ^2_{cr}	$\frac{\chi^2}{N-1}$
LRSW	15.58(4)	2.32	0.9
NRM	15.58(4)	1.83	0.9
RT	15.59(4)	1.83	0.8
BS	15.59(3)		0.8
MP	15.58(4)		0.9

3. Data analysis and evaluation

A statistical analysis was carried out for all available data to test the following two hypotheses:

(1) the means of the ordered subsets drawn from the set of historical data converge with the sample size;

(2) the half-lives obtained with HPGe detectors are statistically similar to the ones determined from NaI(Tl) measurements.

To explore the first assumption, we consider the ordered historical data set, given in Table 1 including our value of 15.59 (4) s and excluding the 1951Sh24 estimations, since it is a lower limit only. Twelve ordered subsets were then drawn from that sample with sample sizes ranging from 2 to 13, where Sample 2 contains the measurements {ID2, ID3}, Sample 3 the measurement {ID2, ID3, ID4}, *etc.* Sample 12 contains all historical data except ID1. Sample 13 is extended from Sample 12 by appending our measurement. Sample sizes vary from 2 to 13 and are embedded in the samples names. For each of these sub-samples, averaging procedures were carried out by using various approaches such as the LRSW, NR, RT, BS, and Mandle–Paule (MP) approaches. In Fig. 4, the average values are presented as a function of the sample size. The data in colors, obtained from LRSW, MP, NRM, and RT analysis, are more sensitive to larger data variations. In this particular case, these methods lead to smaller relative uncertainties, but converge slower to the mean value with the sample size. In contrast, the BS and UWM methods converge quicker, but at the price of larger uncertainties. Finally, the averaging procedures applied to the entire data set including all historical data points return the results presented in Table 4. The average values, calculated for the full data set, including our measurement, are presented in Table 5.

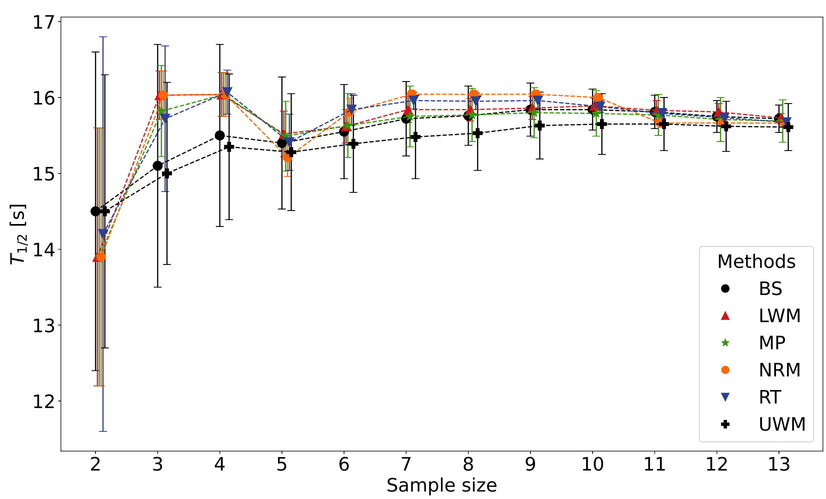

Fig. 4. Average ^{89m}Y half-life data as a function of the subset volume. The abscissa shows the number of points taken into account in the averaging procedure, starting from the 2$^{\rm nd}$ and 3$^{\rm rd}$ points from the ordered set in Table 1.

All methods converge at larger sample sizes (Fig. 4), resulting in statistically similar half-lives (Table 5). This is an interesting result, given the fundamental difference in some of the methods. The LRSW method searches for data with relative weight larger than 50% and reduces it to 50%. By applying this method, we assume that some uncertainties may be overestimated while the rest are correct. In general, uncertainties estimations are

Table 4. Results from the statistical analysis of Sample 12 containing all historical data without ID1 data.

Method	$T_{1/2}$ [s]	χ^2_{cr}	$\frac{\chi^2}{N-1}$
LRSW	15.81 (15)	2.25	7.9
NRM	15.664 (8)	1.79	2.5
RT	15.73 (6)	1.79	1.46
BS	15.88 (16)		172
MP	15.7 (3)		16.5

Table 5. Results from the statistical analysis of all available data, including our measurement (Sample 13).

Method	$T_{1/2}$ [s]	χ^2_{cr}	$\frac{\chi^2}{N-1}$
LRSW	15.73 (6)	1.79	10.1
UWM	15.61 (31)		
NRM	15.662 (8)	1.75	2.6
RT	15.68 (5)	1.75	1.6
BS	15.73 (18)		22.8
MP	15.7 (3)		12.2

independent of the procedures used to determine the mean value, and while the mean value might be correctly measured, the uncertainty could indeed be overestimated. This method is considered by some to be a brutal data manipulation. The unweighted average goes even further, by implying that all uncertainties should not be trusted. In contrast, the classical weighted average uses the uncertainties as they are provided by the authors empowering the most precise measurements which might be overestimated. When considering Sample 12, which contains the historic data only, all methods return statistically similar results, as given in Table 4. Given the better χ^2_{cr} value, the RT output of 15.73 (6) s is adopted as the historical average (Sample 12). It agrees well with the 1995ItZY data, as well as with our measurement at 5% significance level. The value is also statistically similar to the WM and UWM values, 15.63 (35) s and 15.73 (8) s, respectively, of the filtered data as discussed in the introduction section. Thus, the first conclusion that can be drawn from the present study is that the advanced averaging procedures, and RT in particular, return similar result for ^{89m}Y half-life as the WM and UWM on the filtered sample, where the outliers are excluded.

It is interesting to note that the data in Table 1 tend to gravitate around two different values. It seems that the scintillation detector measurement pull the average towards a larger value at approximately 16.0 s, while the semiconductor detector measurements gravitate around 15.6 s. To test the hypothesis for statistical equality of the weighted average of these sub-set, we now draw two data sets. Set 1 (measurement's IDs 2 to 11), containing only data obtained with scintillation detectors, and Set 2 (measurement's ID 12, 13, and the value from the present experiment) representing data taken only with HPGe detectors. Set 1 still contains one extreme outlier, that is the 1963Ka34 value of 15.0 (2) s, and one significant outlier, that is the 16.06 (4) s published in 1967Yu01. By excluding the two values, the weighted mean of the remaining set is 15.85 (9). The weighted mean of Set 2 is 15.662 (10). These values are not statistically the same at the 5% level of significance. Hence, the second conclusion is that the scintillation detector's data systematically overestimate the ^{89m}Y half-life by 188 ms. Finally, we should note that while the present study shows a systematic deviation and larger discrepancies in the scintillation measurements, the source of these discrepancies remains unclear. One possible explanation could be the poorer energy resolution of the NaI detectors and the high counting rate, which the experimentalist had to tackle. At a first glance, the HPGe data look more consistent. It is thus not surprising that all methods applied to the Set 2 data give statistically similar results.

In summary, given the larger discrepancies observed in the NaI data (Table 6) and the better consistency of the HPGe data (Table 7), we adopt the half-life of the metastable state as $T_{1/2} = 15.61(4)$ from the RT analysis ($\chi^2/N-1 = 0.85$) of the Set 2 data, comprising three independent HPGe measurements, namely IDs 12, 13, and our measurement $T_{1/2} = 15.59$ (4) s. This result is not statistically different from the 1995 measurement which

Table 6. Statistical analysis of NaI data (Sample 10, containing data points ID2 to ID11).

Method	$T_{1/2}$ [s]	χ^2_{cr}	$\frac{\chi^2}{N-1}$
LRSW	15.89 (17)	2.41	3.16
UWM	15.65 (32)		
NRM	16.00 (4)	1.88	1.67
RT	15.90 (8)	1.88	0.92
BS	15.95 (16)		3.94
MP	15.8 (3)		7.1

we would have eliminated if we had decided to use the filtering procedure described in the introduction. Even though the experimental details in the publication are incomplete, the new measurement reported here and the statistical analysis performed in the present work suggest that the Japanese team may have got it right after all [11].

Table 7. Statistical analysis of HPGe data (ID12, ID13 and our measurement).

Method	$T_{1/2}$ [s]	χ^2_{cr}	$\frac{\chi^2}{N-1}$
LRSW	15.62 (5)	3.0	2.9
UWM	15.51 (12)		
NRM	15.65 (3)	3.0	3.75
RT	15.61 (4)	3.0	0.85
BS	15.55 (14)		262
MP	15.56 (15)		203

4. Conclusion

In the past, the ^{89m}Y isomeric decay half-life was measured in several experiments. The historic data show some discrepancies which were addressed via statistical data analysis and new measurements. The statistical analysis clearly points out several outliers. By filtering the data and performing analysis on the entire set, we extract statistically similar results for the half-life of the metastable state. Further, new experimental data are presented, which are consistent with the historical data average. It also fits better with the HPGe group of data. Indeed, when divided into two sub-sets by detectors used, the scintillation detector measurements clearly deviate from the HPGe measurements in average by 188 ms. Because of possible unaccounted systematical uncertainties in the first group, we adopt the HPGe average value of 15.61 (4) s, obtained via the RT method.

5. Statistical evaluation software

Data evaluation is completed using ENSDF Analysis and Utility Codes: AveTools 3.0 and V.AveLib [2024-03]. Both codes are developed in the framework of the NSDD network [12], an international team of experts providing recommended nuclear structure, and decay data for basic and applied research.

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