^{212}Pb – Comments on evaluation of nuclear data

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This evaluation was completed in May 2025 with a literature cutoff date of the end of that month.

The Limitation of Relative Statistical Weights Method (LWM) was applied to average the decay data when appropriate using the LWEIGHT Excel add-in (Helmer, 1999), with adjustments to the final uncertainties made if necessary. Any such adjustments are described below in their appropriate context. All uncertainties are given as the combined uncertainty to one standard deviation.

Prior to this work, Aurenen and McCutchan (2020) performed the most recent decay data evaluation for ^{212}Pb for the Evaluated Nuclear Structure Data File (ENSDF). Nichols (2011) performed a previous evaluation for the Decay Data Evaluation Project (DDEP) in 2011, updating a previous evaluation carried out by the same author in 2004 (Bé *et al.*, 2004).

1 Decay scheme

Lead-212 decays by β^- emission to three excited levels in ^{212}Bi. The ground state of ^{212}Bi decays via β^- and α emission with a half-life of 60.54 (6) min to excited states in ^{212}Po and ^{208}Tl, respectively. Those progeny, in turn, decay via beta-particle emission (^{208}Tl) and alpha-particle emission (^{212}Po) to stable ^{208}Pb. Level energies, half-lives (except for the ^{212}Pb ground state), spins, and parities were taken from Auranen and McCutchan (2020) and are identical to those of the previous DDEP evaluation. Transition multipolarities are also taken from the Adopted Levels and Gammas Tables from Auranen and McCutchan (2020).

The placement of gamma rays is based primarily on the original assignments by Roetling *et al.* (1960), Giannini *et al.* (1961), and Dalmasso (1972). As discussed below in Section 2.2, there is considerable uncertainty concerning the inclusion of a gamma ray at 415.273 keV that depopulates the level at 415.272 keV to the ground state. This is because very few investigations report observing that transition, and of those that do, there is only one reliably measured intensity for the gamma ray. There is sufficient evidence that this transition exists, particularly the measurement of the K-conversion coefficient, so this transition has been included in this evaluation. It is hoped that the information provided herein encourages further measurements to assign a more definitive gamma-ray intensity value.

In the ENSDF evaluation of Auranen and McCutchan (2020) and its predecessors, on which the previous DDEP evaluation was also based, a 123.449 keV transition was added to de-excite the level at 238.632 keV based on energy sums and intensity balance. This transition has not been directly observed in the literature and its existence is questionable. One particular piece of evidence against the placement of this transition lies in the intensity imbalance that already exists in the previous ENSDF and DDEP level schemes, where the level at 115.183 keV has more intensity going into it than de-exciting it. In the previously evaluated level scheme, the level at 115.183 keV is fed by the 300.089 keV and 123.449 keV gamma rays; the sole de-exciting gamma ray is the 115.183 keV transition. Even neglecting the 123.449 keV gamma ray, the total intensity going into that level ($I_{Tot}(300)$ = 4.83 (6) per 100 decays) is greater than that going out (I_{Tot}(115) = 4.65 (7) per 100 decays). The additional intensity introduced by including the 123.449 keV gamma ray only worsens this imbalance. The present evaluated data set does not include the 123.449 keV gamma ray. Moreover, the newly evaluated gamma-ray and conversion electron-emission probabilities reduce the imbalance so that the feeding and de-exciting intensities now overlap within their respective uncertainties.

The resulting level scheme is complete and consistent as presented. This is demonstrated by the agreement between Q_{calc} = 569 (9) keV determined by SAISINUC (Dulieu *et al.*, 2017) from the sum of the products of the decay energies and probabilities of all the transitions that feed into the levels and depopulate them and Q_{tot} = 569.0 (18) keV from the most recent atomic mass evaluation of (Wang *et al.*, 2021). The difference between the summation of all decay out of the levels and the feeding into them by beta decay is 0.0145%. It should be noted that the *Q*-value given in an earlier version of these comments (Zimmerman, 2025) was, in fact, the value from the 2016 mass evaluation, and not the updated 2020 evaluation as indicated in that reference. This error required a recalculation of the beta decay energies and log *ft* values as discussed below in Section 2.3.

2 Nuclear data

2.1 Half-life

Only published experimental half-life values with associated uncertainties were considered in this evaluation. The results from the National Physical Laboratory (NPL) and the National Institute of Standards and Technology (NIST) reported in Pibida, *et al.* (2024) were treated as independent measurements since they were performed using solutions of different origins using different techniques undertaken by different personnel at different times. The set of half-life measurements used in this evaluation is presented in Table 1. For the NIST measurements, the adopted value was calculated from the weighted mean of the results of 4 measurement methods, and the uncertainty was calculated as the quadratic combination of the relative standard deviation of the weighted mean (0.037%) and the average relative standard uncertainty of the 4 measurements (0.061%) to give a single value of 10.634 (8) h. These data form a consistent dataset, as evidenced by the χ^2 value of 0.491 and a critical χ^2 value of 2.511 for 8 degrees of freedom and a significance level of α = 0.05.

From the data in Table 1, a weighted average of 10.630 (4) h is obtained. Recognizing, however, that this uncertainty is lower than any of the values that went into the calculation of the weighted mean, the minimum uncertainty in the data set (that of Kossert (2017)) was adopted as a more realistic uncertainty for the recommended value. Therefore, the recommended half-life becomes 10.630 (7) h. This supersedes the recommendation of 10.628 (5) h that was proposed by Pibida, *et al.* (2024) as part of an informal evaluation in that work.

This new recommended half-life value maintains the same level of precision as the current ENSDF recommendation of 10.622 (7) h but increases the value by 0.08%. However, the present ENSDF recommendation is based on only a single value (Kossert, 2017), while our new recommended value is based on nine measurements, five of which were published after Kossert (2017). Compared to the previous DDEP evaluation, which was based on only three published values, the new recommendation changes the half-life by -0.09% but improves the uncertainty from 0.094% to 0.066%.

Table 1. Experimental half-life determinations of ^{212}Pb considered in this evaluation.

Reference	Year	$T_{1/2}$ (h)	Uncertainty (h)
Buttlar, 1952	1952	10.67	0.05
Marin, *et al.*	1953	10.64	0.03
Tobailem and Robert	1955	10.643	0.012
Kossert	2017	10.622	0.007
Fränkel, *et al.*	2022	10.66	0.16
Bergmann and Jelínek	2022	10.620	0.018
Pibida, *et al.* NIST	2024	10.634	0.008
Pibida, *et al.* NPL	2024	10.628	0.010
Bobin, *et al.*	2025	10.6314	0.0074
Recommended		**10.630**	**0.007**
LWEIGHT χ^2 = 0.497 and χ^2 critical = 2.511			

2.2 Gamma-ray transitions

Gamma-ray energies and intensities

High-resolution gamma-ray spectrometry data were considered from 8 primary sources: Pibida, *et al.* (2024), which reported two independent sets of measurements from two different laboratories; Lin and Harbottle (1992); Gehrke, *et al.* (1984); Vaninbroukx and Hansen (1983); Schötzig and Debertin (1983); Sadasivan and Raghunath (1982); Avignone and Schmidt (1978); and Dalmasso, *et al.* (1973), for a total of 9 independent data sets. Earlier published data based on gamma-ray spectrometry performed with NaI(Tl) detectors by Roetling, *et al.* (1960) and Giannini, *et al.* (1961) were reviewed but were not included in the calculation of photon emission probabilities because of the availability of a large set of data acquired with high-resolution detectors. Data from Dalmasso (1972) were considered but are superseded by Dalmasso *et al.* (1973).

Energies of the $\gamma_{1,0}$- and $\gamma_{2,0}$-rays were taken from the ENSDF Adopted Levels and Gammas (Auranen and McCutchan, 2020). The 415 keV $\gamma_{3,0}$-ray does not have an uncertainty in the ENSDF evaluation. For this case, the weighted average of the sum of the energies of the two cascades that depopulate that level was taken as the adopted energy of the ground state transition. From the energies of the transitions in the 300 keV $\rightarrow$ 115 keV cascade, we obtain an energy sum of 415.270 (11) keV; from the 177 keV $\rightarrow$ 239 keV cascade, the energy sum is 415.312 (50) keV. From these values, a weighted average of 415.272 (9) keV is calculated and is taken as the adopted value. The energies of the $\gamma_{3,1}$- and $\gamma_{3,2}$-rays were then deduced from the level energy differences.

As discussed in Section 1, there is uncertainty regarding the existence of a 415 keV gamma-ray that depopulates the level at 415.272 keV to the ground state. This transition was first proposed by Roetling, *et al.* (1960), who assigned an absolute intensity of “about 2×10^{-3}” with no uncertainty. This was confirmed a year later by Giannini, *et al.* (1961), who reported an absolute intensity of 1.6 (4) x 10^{-3}. In both cases, measurements were performed with NaI(Tl) detectors. Although the transition was included in the original thesis by Dalmasso (1972), a subsequent set of measurements by that group using high-resolution Ge(Li) detectors did not report its existence (Dalmasso *et al.*, 1973). The only subsequent publication that provides a measured intensity for this gamma ray is a conference report by Veremeva, *et al.* (1990) that cites a ratio of its intensity relative to that of the 300.1 keV gamma-ray of $I_\gamma(415)/I_\gamma(300)$ = 3.9 (6) x 10^{-3}. Both groups that conducted the measurements reported in Pibida, *et al.* (2024) explicitly indicate that their data did not support the existence of either the 415 keV or 123 keV gamma-rays. It was also not observed in the recent work by (Bobin *et al.*, 2025). However, a subsequent review of the spectra indicated at least qualitatively that it was possible that the 415 keV gamma-ray was present in the spectrum, but also indicated that there were insufficient data to provide an estimate of its intensity (Pibida, 2024).

The weighted average of the relative emission intensity for each gamma ray, with the exception of the 415.272 keV gamma-ray, was calculated using LWEIGHT with the data from all 9 sources that were included in the evaluation.

Within their respective uncertainties, all the data sets used in the evaluation are internally consistent, as indicated by inspection of the respective χ^2 and critical χ^2 values. In each case, the uncertainty on the weighted average calculated by LWEIGHT was smaller than the smallest uncertainty on any of the constituent values. Therefore, the smallest uncertainty in each set was adopted as the uncertainty on each relative emission intensity.

In the calculation for the 300.089 keV gamma ray, the relative emission intensities reported by Avignone and Schmidt (1978) and Sadasivan and Raghunath (1982) were excluded as outliers by the Chauvenet criteria. For the 115.183 keV gamma ray, the value of Sadasivan and Raghunath (1982) was excluded for the same reason.

For the 115.183 keV, 238.632 keV, and 300.089 keV gamma rays, the NIST uncertainties from Pibida, *et al.* (2024) were adopted since they were the minima of each data set, while the uncertainty on the NPL value was adopted for the 176.640 keV gamma ray.

For this evaluation, the intensity of the 415.272 keV gamma ray was calculated from the intensity ratio of $I_\gamma(415)/I_\gamma(300\text{ keV})$ = 3.9 (6) x 10^{-3} given by Veremeva, *et al.* (1990) and applied to the relative intensity of the 300.089 keV gamma ray calculated BY LWEIGHT.

The normalization factor to convert relative gamma-ray emission intensities to absolute emission per decay was calculated as the weighted average of the absolute intensities of the 238.632 keV gamma ray reported by the National Physical Laboratory (NPL) and the National Institute of Standards and Technology (NIST) in Pibida, *et al.* (2024), Bobin *et al.* (2025), Lin and Harbottle (1992), Gehrke, *et al.* (1984), Vaninbroukx and Hansen (1983), Schötzig and Debertin (1983), and Sadasivan and Raghunath (1982). From these data, seen in Table 2, a weighted average of 0.4329 (17) gamma rays per decay was calculated by LWEIGHT. As with the calculation of the average relative emission intensities, the uncertainty calculated by LWEIGHT was smaller than any member of the data set. Therefore, the uncertainty on the recommended value was increased to match the smallest uncertainty in the data set (from the NIST data in Pibida, *et al.* 2004), leading to a recommended value of 0.4329 (24) gamma rays per decay.

Absolute emission probabilities were calculated by multiplying the LWEIGHT-calculated relative emission intensities for each gamma-ray by the conversion factor to determine new recommended values of the absolute emission probabilities. The data that comprised the evaluated set, along with the evaluated relative and absolute emission probabilities, are presented in Tables 3a and 3b.

Table 2. Values considered in the evaluation of the conversion factor to convert relative gamma-ray intensities to absolute gamma-ray probabilities.

	Conversion factor
Sadasivan and Raghunath (1982)	0.43 (2)
Schötzig and Debertin (1983)	0.435 (12)
Vaninbroukx and Hansen (1983)	0.440 (6)
Gehrke, *et al.* (1984)	0.433 (7)
Lin and Harbottle (1992)	0.441 (10)
Pibida, *et al.* (NIST) (2004)	0.4316 (24)
Pibida, *et al.* (NPL) (2004)	0.4321 (34)
Bobin, *et al.* (2025)	0.4315 (33)
Recommended	**0.4326 (24)**

Multipolarities and internal conversion coefficients

Gamma-ray multipolarities were taken from the ENSDF Adopted Gammas table (Auranen and McCutchan, 2020). Internal conversion coefficients were calculated using BrIcc (Kibédi *et al.*, 2008) and assumed to be pure M1 transitions.

Measurements of K/L and L_1:L_2:L_3 ratios for the strongest transitions were performed by Krisyouk, *et al.* (1957), Sergeyev, *et al.* (1958), Högberg, *et al.* (1967), Krpic *et al.*, (1969), and Gelletly and Geiger (1969); K-conversion coefficients for the 238.632 keV and 115.182 keV transitions were measured by Roetling, *et al.* (1960), and for the 115.182 keV transition by Nielsen, *et al.* (1957), while measured conversion coefficients are reported for the 238.632 keV, 300.089 keV, and 415.272 keV gamma rays by Vorobev, *et al.* (1957). Agreement between the measured and theoretical internal conversion coefficients confirmed the assignment of M1 for the multipolarity of the transitions in each. Comparisons of the measured and theoretical K/L and L_1:L_2:L_3 ratios are given in Table 4 are given as demonstration of agreement between experiment and present theoretical values. The recommended internal conversion coefficients and corresponding electron emission rates are given in the full set of tables on the DDEP website.

Table 3a. List of evaluated relative gamma-ray probabilities (per 100 decays) in the decay of ^{212}Pb, normalized to the intensity of the 238.632 keV gamma ray.

	P_γ per 100 decays											
Energy (keV)	**Dalmasso, *et al.* (1973)**	**Avignone, *et al.* (1978)**	**Sadasivan and Raghunath (1982)**	**Schötzig and Debertin (1983)**	**Vaninbroukx and Hansen (1983)**	**Gehrke, *et al.* (1984)**	**Veremeva, *et al.* (1992)**	**Lin and Harbottle (1992)**	**Pibida, *et al.* (NIST) (2004)**	**Pibida, *et al.* (NPL) (2004)**	**Bobin, *et al.* (2025)**	**Recommended**
115.183 (5)	1.27 (28)	1.37 (15)	1.65 (14)	-	-	1.37 (2)	-	-	1.374 (12)	1.327 (16)	1.316 (28)	**1.355 (12)**
176.640 (9)	0.102 (27)	-	-	-	-	0.120 (14)	-	-	0.137 (9)	0.122 (5)	-	**0.124 (5)**
238.632 (2)	100 (14)	100 (4)	100 (7)	100 (4)	100 (2)	100 (2)	-	100 (3)	100.0 (8)	100 (1)	100.0 (8)	**100.0 (8)**
300.089 (10)	7.7 (17)	6.33 (28)	6.74 (56)	7.52 (29)	7.32 (17)	7.56 (9)	-	7.57 (32)	7.419 (59)	7.545 (84)	7.55 (11)	**7.484 (59)**
415.272 (9)	-	-	-	-	-	-	0.029 (6)*	-			-	**0.029 (6)**

*Calculated from reported ratio of intensity with 300.089 keV gamma-ray. See text for details.

Table 3b. List of evaluated absolute gamma-ray probabilities (per 100 decays) in the decay of ^{212}Pb, calculated from the relative gamma-ray intensities given in Table 3a and the evaluated conversion factor given in Table 2.

Energy (keV)	**Recommended P_γ (per 100 decays)**
115.183 (5)	**0.5862 (61)**
176.640 (9)	**0.0537 (21)**
238.632 (2)	**43.26 (42)**
300.089 (10)	**3.238 (31)**
415.272 (9)	**0.013 (3)**

Table 4. Comparison of experimentally-determined K/L and L subshell conversion coefficient ratios for the gamma-rays in the decay of ^{212}Pb. The recommended values from this evaluation are taken from the BrIcc calculations (Frozen Orbital Approximation, assuming M1 multipolarity).

	Krisyouk, *et al.* (1957)	Nielsen, *et al.* (1957)	Sergeev, *et al.* (1958)	Högberg, *et al.* (1967)	Gelletley and Geiger (1969)	This evaluation
α_K/α_L (115 keV)	4.02[*]	5 (1)	-	-	-	5.69 (12)
α_K/α_L (177 keV)	5.55 (62)	-	-	-	-	5.74 (8)
α_K/α_L (239 keV)	5.91[*]	-	-	-	-	5.76 (12)
α_K/α_L (300 keV)	5.88 (34)	-	-	-	-	5.79 (13)
L_1:L_2:L_3 (115 keV)	1:0.12 (1):< 0.02	-	1:0.104 (3):0.0088 (10)	-	-	1.00 (2):0.107 (2):0.0082 (2)
L_1:L_2:L_3 (239 keV)	-	-	1:0.104 (2):0.0074 (5)	1:0.1055 (5):0.0076 (1)	1:0.1068 (15):0.0075 (3)	1.00 (2):0.106 (2):0.0075 (1)

[a] No uncertainty provided.

2.3 Beta-particle transitions

Maximum beta-decay energies were calculated from the adopted *Q*-value and the level energies in the ^{212}Bi decay daughter. Transition probabilities were deduced from the imbalance in total intensities of the gamma rays feeding into and out of each level. Log *ft* values and average beta decay energies for each level were calculated with the BetaShape program within SAISINUC (Mougeot 2023, 2017).

As discussed in Section 1, the beta decay *Q*-value was not properly updated in the original version of these Comments (Zimmerman, 2025), which resulted in incorrect values for the beta transitions appearing in the original Table 5 of that reference. The calculated beta-particle spectrum endpoint energies and emission rates resulting from the recalculation with the updated *Q*-value are presented in Table 5 below. Updating the *Q*-value resulted in an increase in the values of $E_{\beta,max}$ of between 0.24% and 0.52% compared to the values in Table 5 of (Zimmerman, 2025).

As discussed in Section 1, the 123.449 keV transition proposed in previous evaluations was excluded from the present evaluation. With the scheme as currently recommended, the intensities are balanced within uncertainties.

Table 5. Comparison of recommended and experimental beta-particle endpoint energies and emission probabilities.

		Martin and Richardson (1948)	**This evaluation**	
Transition	**Level (keV)**	I_{β^-} **(%)**	$E_{\beta^-,max}$ **(keV)**	I_{β^-} **(%)**
$\beta^-_{0,3}$	415.272 (11)	-	153.7 (18)	4.92 (8)
$\beta^-_{0,2}$	238.632 (2)	-	330.4 (18)	80.8 (14)
$\beta^-_{0,1}$	115.183 (5)	-	453.8 (18)	-
$\beta^-_{0,0}$	0.0	12 (2)	569.0 (18)	14.4 (1.4)

There has only been a single direct measurement of the beta-particle spectrum reported in the literature, which is that of Martin and Richardson (1948). They report an intensity I_β value of 12 (2) per 100 decays for the transition to the ground state, which is consistent with the recommended value.

3 Atomic data

Fluorescence yields were calculated within the SAISINUC program (Dulieu, *et al.* 2017) using the data of Schönfeld and Janßen (1996) and give values of ω_k = 0.964 (4), average ω_L = 0.391 (16), and η_{KL} = 0.809 (5). Auger-electron and x-ray energies were calculated within the SAISINUC program using the data from Schönfeld and Rodloff (1999, 1998), respectively.

The x-ray and Auger-electron emission intensities were calculated using the 2013 version of the EMISSION code, as described in Schönfeld and Janßen (2000) and implemented in SAISINUC. Recommended values are presented in Tables 6a and 6b.

Table 6a. Recommended values for absolute x-ray emission probabilities.

Radiation	Energy (keV)	Photons (per 100 decays)
$K_{\alpha 2}$	74.8157	9.94 (17)
$K_{\alpha 1}$	77.1088	16.63 (27)
$K'_{\beta 1}$	86.835, 87.344, 87.862	5.69 (13)
$K'_{\beta 2}$	89.732, 90.074, 90.421	1.74 (5)
L_l	9.4207	0.335 (9)
L_α	10.7308 to 10.8387	6.26 (15)
L_η	11.7127	0.1012 (28)
L_β	12.4814 to 13.8066	5.66 (11)
L_γ	14.7735 to 15.7084	1.092 (23)

Table 6b. Recommended values for absolute Auger-electron emission probabilities.

Radiation	Energy (keV)	Photons (per 100 decays)
Auger K		1.27 (15)
KLL	57.491 to 63.419	
KLX	70.025 to 77.105	
KLY	82.53 to 90.52	
Auger L	5.4204 to 16.3366	21.20 (26)

4 Conclusion

A new evaluation of the decay data for ^{212}Pb has been performed for the Decay Data Evaluation Project (DDEP) based on the publication of several new measurements of gamma-ray emission probabilities and half-lives. The new recommended half-life improves on both the previous DDEP and ENSDF values by the inclusion of 5 new published experimental measurements. The addition of 3 new sets of measurements of gamma-ray emission probabilities has also resulted in improvements in the recommended values for those quantities. Moreover, a more detailed consideration of the intensities and placements of the 123.449 keV and 415.272 keV gamma rays resulted in a more balanced level scheme. However, improved measurements of these two weak transitions are still greatly needed.

5 References

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