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PAPER

Critically Evaluated Half-Life for ^{222}Rn Radioactive Decay and Associated Uncertainties

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A critical review and evaluation of 17 independent determinations of the half-life for ^{222}Rn decay made over the past 90 years (c. 1902-1994) indicates that a five-significant figure value of the half-life with a relative uncertainty of approximately 10^{-4} is justified, but not for the reasoning usually invoked. Although the commonly adopted and tabulated high-precision value of $T = 3.8235 \pm 0.0003$ d, which is based almost exclusively on the 1972 measurements of Butt and Wilson, is consistent and virtually indistinct; a value of $T = 3.8232 \pm 0.0004$ d, obtained by considering the entire available data base, is more supportable. Even in the extreme of a very conservative evaluation, the half-life is certainly known to a relative uncertainty interval of ±0.03 percent which contradicts some other extant data compilations that contend that no adopted half-life value for any radionuclide has a relative uncertainty of less than ±0.1 percent. Resulting propagated uncertainty contributions for either ^{222}Rn radioactive decay or ^{222}Rn growth accumulations from ^{226}Ra decay due to the uncertainty in the ^{222}Rn half-life is thereby clearly negligible in nearly all ^{222}Rn measurement applications.

The radionuclide ^{222}Rn, and hence a precise—if not an accurate—and uniformly accepted value of its half-life, is important and of interest in a variety of disciplines ranging from esoteric studies in global atmospheric modelling and the geophysical sciences to the more prosaical domains of indoor air quality and concern over its potential human health hazards.

Many compilations and tabulations of nuclear and radioactive data, for example,[1-3] provide a ^{222}Rn half-life of $T = 3.8235 \pm 0.0003$ days. This value appears and is sometimes cited to be entirely based on the reportedly precise determination of Butt and Wilson in 1972,[4] and seemingly ignores a substantial data base of other determinations. Considerations that few determinations of a radionuclidic half-life to a precision of five significant figures can withstand critical scrutiny, and that compiled data sets are often at the mercy of experimental optimists have been commented on in a companion paper[5] and by others.[6,7] Occasionally, to somewhat minimize the dominance of a single datum in a data set, some data evaluations use methods of limitation on the relative weights, such as by not allowing a relative maximum statistical weight of greater than 50 percent for any one value within an inconsistent data set.[8-10] Such critical treatments, however, are uncommon, particularly for half-life determinations.

At an almost opposite pole, other data compilations are inherently conservative—virtually contending that no half-life for radioactive decay is known to a relative uncertainty of better than 0.1 percent. For example, a recent critical evaluation by an International Union of Pure and Applied Chemistry (IUPAC) commission gives a ^{222}Rn half-life of $T = 3.823 \pm 0.004$ d.[6] In this IUPAC study, the mean value (3.823) was obtained from a weighted combination of seven independent determinations after "revising" the uncertainties for six of the seven determinations. Even then, the resulting combined uncertainty was further increased to satisfy a general "≥0.1 percent uncertainty rule." In effect, the assigned uncertainty is independent of the data. Another tabulation[11] providing a ^{222}Rn half-life of $T = 3.825 \pm 0.004$ d has a comparable result.

This author is generally sympathetic to the justified revision of reported uncertainties when they are clearly underestimated, particularly when applied to a single measurement result or even to a few determinations. However, a universal "≥0.1 percent uncertainty rule" is less supportable when applied to many independent measurements, particularly if, as in this case, they

are made at many different times by many different experimentalists with many different sources and with considerably different instruments and measurement methodologies. It is probably true that few radionuclidic half-lives have been determined to a relative uncertainty of better than 0.1 percent. Yet, the half-life of ^{222}Rn may be one of the exceptions that proves the generalization as to the obtainable precision in half-life determinations. This is, of course, only stated as an adagy. Nevertheless, based on the critical evaluation that follows, the reported five-significant figure value for the ^{222}Rn half-life with a relative precision of approximately 0.01 percent appears justifiable but for reasons other than relying exclusively on the determination of Butt and Wilson.[4] Prior to this evaluation, the author frankly was skeptical that this reported precision could be supported, and this skepticism led to the initiation of this study and the companion work.[5]

A historical review and critique of all previously reported determinations of the ^{222}Rn half-life has recently been completed by Collé and Maroufi-Collé.[12] Table 1 contains a capsulized chronological summary of these determinations dating back to 1902. The values tabulated here are taken directly from the above cited review.[12] In some cases, the tabulated means were revised from that originally reported, in part to resolve some obvious discrepancies in the reported means, and moreover to place them all on as nearly a comparable basis as possible. For comparative purposes, all values originally reported in terms of other decay parameters, such as a decay constant $\lambda = \ln 2/T$ or average lifetime $\tau = 1/\lambda$, were uniformly transformed into a common half-life parameter T. All reported half-life or transformed half-life values in other time units were converted to units of days. To avoid possible rounding errors, one additional significant figure was included here in all citations, tabulations, and calculational analyses whenever parameter transformations or time unit conversions were made. Similarly, every effort was made to place all of the reported precision estimators on the common basis of a standard deviation (square root of the variance), such as in converting "standard errors" (standard deviations of the mean) or "probable errors" into standard deviations. The original meaning of the precision estimators were not always explicitly stated or clear in the reported literature. In these cases, the reported estimators were assumed to correspond to standard deviations. Precision estimators for the mean values of the entire data set in Table 1 are not given here in order to avoid confusions and numerous justifications of underlying conversion assumptions and provisoes. They are discussed and treated at length elsewhere.[12] The uncertainties associated with more restrictive subsets of the data are summarized later.

Figure 1 illustrates all of these previously reported determinations as a function of time. The chronological record is interesting. Even before the determination by P. Curie,[13] the first measurement with some clearly recognizable precision, the ^{222}Rn half-life was generally considered to be "about 4 days" based on earlier semi-quantitative determinations (Cf., ref. 12). Within a decade, mainly based on the work of M. Curie[18,19] and Rutherford,[20,21] the half-life was "known" and accepted to be $T = 3.85$ d with a relative uncertainty of about 1 percent. In 1921, Bothe and Lechner[22] obtained a value of $T = 3.811$ d with a reported relative precision improved by an order of magnitude. By 1930, following the studies of Bothe[23] and I. Curie and Chamié,[24] the half-life was routinely compiled[29] with a relative uncertainty of less than 0.1 percent: either $T = 3.825 \pm 0.003$ d[23] or $T = 3.823 \pm 0.002$ d,[24] noting that the a foregoing "agree within the limits of experimental error."[29] All of these determi-

Reference	T (days)[a]	Year	n[b]	$\overline{T}$ (days)[c]
P. Curie[13]	3.987	1902	1	4.0
Rutherford and Soddy[14]	3.7_1	1903	2	3.85 ± 0.14
Bumstead and Wheeler[15]	3.89_6	1904	3	3.864 ± 0.081
Sackur[16]	3.86_3	1905	4	3.864 ± 0.057
Rümelin[17]	3.74_7	1907	5	3.841 ± 0.051
Bronson[17]	3.72	1907	6	3.821 ± 0.046
M. Curie[18,19]	3.85	1910	7	3.825 ± 0.039
Rutherford[20,21]	3.84_7	1911	8	3.828 ± 0.034
Bothe and Lechner[22]	3.81_1	1921	9	3.826 ± 0.030
Bothe[23]	3.824	1923	10	3.825 ± 0.027
I. Curie and Chamié[24]	3.823	1924	11	3.825 ± 0.024
Tobailem[25]	3.823_5	1955	12	3.825 ± 0.022
Marin[26]	3.823_1	1956	13	3.825 ± 0.020
Robert[27]	3.825	1956	14	3.825 ± 0.019
Shimanskaia[28]	3.83	1956	15	3.825 ± 0.018
Butt and Wilson[4]	3.8235_1	1972	16	3.825 ± 0.016
Collé[5]	3.8224	1994	17	3.825 ± 0.015

[a] Reported mean value. Refer to preceding footnote in text regarding parameter transformations and unit conversions.

[b] Cumulative number of reported determinations.

[c] Cumulative unweighted mean of the reported T values. The uncertainty corresponds to the standard deviation of the mean $\overline{T}$ for n determinations of T.

Table 1 Reported determinations of the half-life for ^{222}Rn radioactive decay and the cumulative mean half-life as a function of time.

nations[13-24] were based on ionization chamber, including early electroscope, measurements. Subsequent ionization chamber measurements were reported by Tobailem[25] and Marin[26] in 1955-56. These were followed by the two microcalorimetry measurements of Robert[27] and Shimanskaia,[28] by the NaI(Tl)-detector scintillation measurements of Butt and Wilson[4] in 1972; and, most recently, by the 4π-$\alpha\beta$ liquid scintillation measurements of Collé.[5]

The methods used to derive the determined T values also varied considerably over the years. In most of the early works, the half-lives were determined by nonredundant two-datum point solutions of the exponential decay law using pairs of decay measurements at two times, or various combinations of these nonredundant solutions with more time pairs or with one or more ^{222}Rn samples. Somewhat later, others (for example, ref. 18) used graphical techniques in which T was obtained from the slope of a linear logarithmic transformation of the decay law. Later determinations[25-27] made in the mid-1950s were obtained from linear least-squares regressions of the logarithmic transformation fitted to the decay data. Butt and Wilson[4] and Collé,[5] using more modern computer-based calculational methods based on matrix manipulations for the simultaneous solution of multiple nonlinear equations, performed more rigorous χ^2-minimization regressions with the exponential form itself.

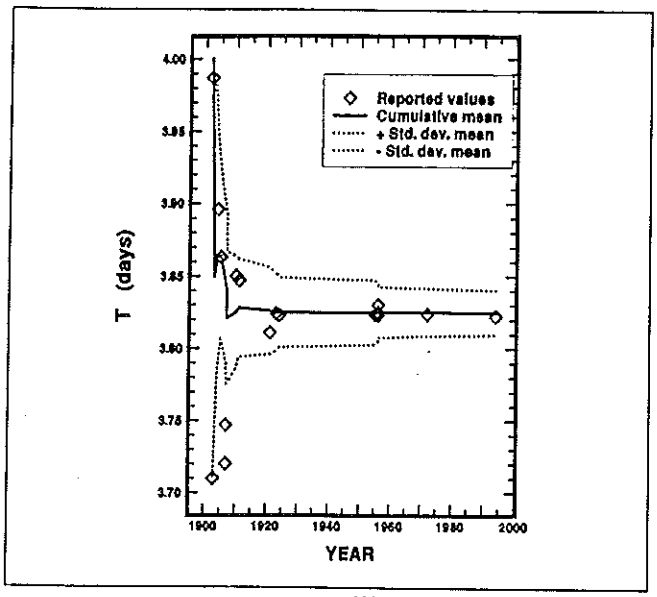

Figure 1 Determinations of the ^{222}Rn half-life as a function of time that the values were reported. The solid line corresponds to a calculated cumulative unweighted mean of the reported values as a function of time. The dotted lines are the corresponding limits of a cumulative standard deviation of the mean uncertainty interval.

Reference	Code	Instrument/technique	n_T[a]	L_T[b]	Comments
Bothe[23]	B23	gamma-ray ionization chamber	4	3-15	comparative measurement of 2 sources quantitatively divided with volumetric gas pipette, with one source decayed over long time interval; T from replicate nonredundant 2-point solutions; reported estimated uncertainty ±0.01%.
I. Curie and Chamié[24]	CC24	gamma-ray ionization chamber (well type)	4	2	compensation method with paired sources; T from combinations of nonredundant 2-point solutions (graphical analyses); reported estimated uncertainty ±0.05%.
Tobailem[25]	T55	dual gamma-ray ionization chambers operating differentially	2	0.5	T from unweighted linear least-squares fit with log transformations; reported uncertainties include only fitting precision.
Marin[26]	M56	gamma-ray ionization chamber	3	5	T from unweighted linear least-squares fit with log transformations; reported uncertainties include only fitting precision.
Robert[27]	R56	adiabatic microcalorimetry	1	4	T from unweighted linear least-squares fit with log transformations; uncertainty is only fitting precision.
Shimanskaia[28]	S56	differential microcalorimetry (dual calorimeters)	1	10	T from nonredundant 2-point solution.
Butt and Wilson[4]	BW72	gamma-ray scintillation; NaI(Tl) well detector	2	20	T from weighted exponential regression; reported uncertainties include only fitting precision.
Collé[5]	C94	4π-$\alpha\beta$ liquid scintillation	6	4	T from weighted and unweighted exponential regressions; reported estimated uncertainties ±0.05% based on complete uncertainty analysis.

[a] Number of independent determinations or number of sources measured.
[b] Approximate time duration of the measurements in units of half-life T.

Table 2 Comparative summary of the measurement techniques employed for the ^{222}Rn half-life determinations.

Considering the great diversity in these measurements made over 90 years, even a simplistic analysis of the results of all 17 reported T values in Table 1 is revealing. The unweighted mean of these T values calculated cumulatively as a function of time is illustrated in Figure 1 along with the standard deviation of the mean uncertainty interval on the cumulative means (see also Table 1). The unweighted mean $\overline{T}$ as a function of time generally decreases, rapidly dropping from an initial value of about 4 d to around 3.85 d, and then begins to converge. The results from 1923 onwards are identical to four significant figures with a mean of $\overline{T}$ = 3.825 d. The initial progressive decrease in the mean $\overline{T}$ is perhaps unsurprising since almost any type of activity-level dependent nonlinearity in instrument response, e.g., that due to ion-pair recombination effects, ionization current saturation, dead-time or pulse pileup losses, has the effect of lengthening the apparent half-life. From 1923 to the present with a constant mean $\overline{T}$ = 3.825 d, the corresponding standard deviation of the mean gradually, but progressively, decreased from 0.7 percent to 0.4 percent as also illustrated in Figure 1. Hence, an unweighted mean of all of the reported T values provides a result of $\overline{T} = 3.825 \pm 0.015$ d even without any statistical weighting or critical considerations. The above associated uncertainty for this wealth of diverse measurements made over 90 years is within a factor of 4 of the more conservative critically-evaluated compilations that are extant.[6,11]

The last eight determinations listed in Table 1 were selected to perform a more critical evaluation. The selection criteria were based on the companion historical review and critique of these studies[12] as well as on the factors that these 8 determinations comprised the set of values in which the above mentioned cumulative mean remained unchanged at $\overline{T}$ = 3.825 d, and that they comprised all reported values that fell within the interval 3.82 d $\leq T \leq$ 3.83 d.

Each of the half-life measurement techniques employed for these eight determinations were based on different analytical approaches. The main characteristics for each are summarized in Table 2, and were discussed and comparatively critiqued at greater length elsewhere.[12] A complete tabulation of all of the determinations is provided in Table 3. It contains every independent determination of T originally reported, and unweighted mean $\overline{T}_u$ and weighted mean $\overline{T}_w$ values. All of the uncertainties on individual T values reflect fitting (regression) precisions only, obviously excepting the B23, CC24, and S56 results (references 23, 24, and 28). The uncertainties on the means reflect only replication precisions. For B23 and CC24, the two means are, of necessity, equal since their reported T values have no individually associated uncertainties. For the single determinations of R56 and S56, the uncertainties used here were that originally reported. In the original C94 work, an adopted value of $T = 3.8224 \pm 0.0018$ d was based on averaged combinations of the results from both weighted and unweighted exponential regressions and a detailed uncertainty analysis. The determinations of C94 used here included only the results obtained from weighted exponential regressions and the fitting uncertainties obtained from them. This was done to place the C94 results on a more comparable uncertainty basis with the other reported high-pre-

Reference Code[a]	T (days)	Unweighted mean $\overline{T}_u$[b]	Weighted mean $\overline{T}_w$[c]
B23	3.827_4	$3.824_8 \pm 0.001_3$	$3.824_8 \pm 0.001_3$
	3.821_3		
	3.825_5		
	3.825_1		
CC24	3.825	$3.823 \pm 0.0008_2$	$3.823 \pm 0.0008_2$
	3.821		
	3.823		
	3.823		
T55	3.826 ± 0.006	$3.823_5 \pm 0.0025$	$3.824_7 \pm 0.005_1$
	3.821 ± 0.010		
M56	$3.8239_2 \pm 0.0005$	$3.8231 \pm 0.0005_3$	$3.8232_9 \pm 0.0004_3$
	$3.8221_3 \pm 0.0007_1$		
	$3.8232_5 \pm 0.0004_2$		
R56	3.825 ± 0.004	3.825 ± 0.004	3.825 ± 0.004
S56	3.83 ± 0.03	3.83 ± 0.03	3.83 ± 0.03
BW72	3.82325 ± 0.00047	$3.8235_1 \pm 0.0002_6$	$3.8235_1 \pm 0.0003_3$
	3.82378 ± 0.00048		
C94	$3.8222_6 \pm 0.0018_9$	$3.8225_2 \pm 0.0010_1$	$3.8224_8 \pm 0.0008_6$
	$3.8199_5 \pm 0.0020_5$		
	$3.8206_6 \pm 0.0021_7$		
	$3.8259_1 \pm 0.0021_8$		
	$3.8211_6 \pm 0.0022_8$		
	$3.8251_9 \pm 0.0021_5$		

[a] Refer to Table 2.

[b] The uncertainties given here for the unweighted means $\overline{T}_u$ are standard deviations of the mean s_{um}, except for the single determinations of R56 and S56. The corresponding standard deviations are $\sqrt{n_T}\, s_{um}$ where n_T is the number of determinations in each data set.

[c] The weighted means $\overline{T}_w$ were obtained using weights of $w_i = 1/u_i^2$ where u_i is the reported uncertainty (col. 2) on each of the n_T independent T_i values. The associated weighted uncertainty is $s_{wm} = 1/\Sigma\ w_i$.

Table 3 Reported ^{222}Rn half-life determinations used in the critical evaluation.

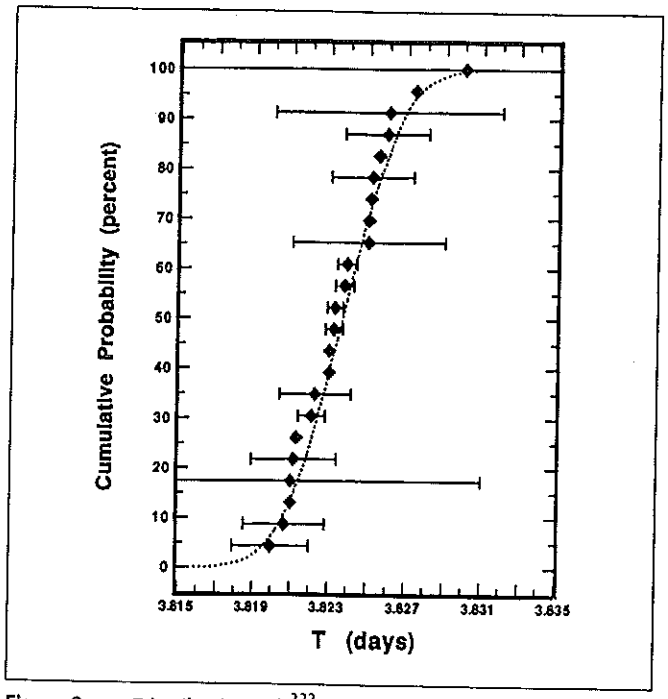

Figure 2 Distribution of ^{222}Rn half-life measurements for the data of Table 3. The dotted line is for a normal (Gaussian) distribution with a mean and variance calculated from the data set: $\mu = 3.824$ and $\sigma = 0.0024$.

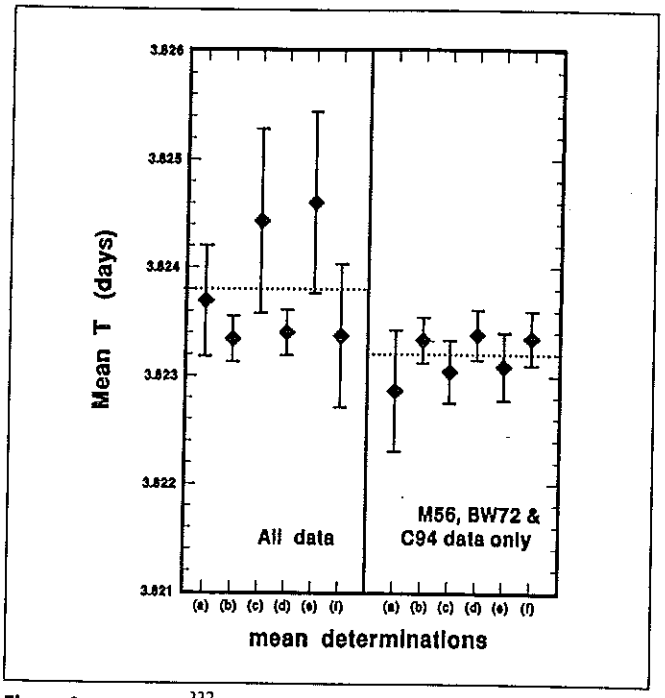

Figure 3 Mean ^{222}Rn half-life values and associated uncertainties for six types of mean values. Refer to text for details.

cision values. It reasonably could be argued that the S56 result should be excluded from the data set because of its large uncertainty. The precision of this determination was more typical of that obtained in the 1910-1920 era (Table 1). It was nevertheless included in the evaluation for completeness; and any bias error that might be introduced by its inclusion would only affect unweighted means.

The 23 independent T determinations presented in Table 3 are a consistent randomly distributed data set as demonstrated in Figure 2. The unweighted mean is $\overline{T} = 3.824$ d with a standard deviation of 0.0024 d. Comparison of the cumulative probability distribution of the data compared to that for a normal (Gaussian) distribution defined by the above two parameters has a reduced χ^2 of $\chi^2_\nu = 0.975$. This χ^2_ν corresponds to a probability of about 0.46 that χ^2 would be exceeded in a normally distributed random set of data, and may be compared to an expected probability of exactly 0.5 for any random set of normally distributed data. Hence, one may conclude that the fit of the normal distribution to the data is reasonable and that the data set is consistent.

The independent T values of Table 3 may be averaged in several ways, viz., (a) by taking the unweighted mean of the 23 values in column 2; (b) by taking the weighted mean of the 23 values in column 2 using weighting factors of $w_i = 1/u_i^2$ where u_i is the reported uncertainty on each of the independent T_i values, and assuming $u_i = 0.01$ d for the B23 and CC24 data; (c) by taking the unweighted grand mean of the eight unweighted means in column 3; (d) by taking the weighted grand mean of the eight unweighted means using weighting factors of $1/s^2_{um}$; (e) by taking the unweighted grand mean of the eight weighted means in column 4, and (f) by taking the weighted grand mean of the eight weighted means of column 4 using weighting factors of $1/s^2_{wm}$. These six means, illustrated in the left-hand side of Figure 3, range from $\overline{T} = 3.8233$ d to 3.8246 d with s_{um} and s_{wm} uncertainties ranging from 0.0002 d to 0.0008 d (corresponding to uncertainties of ±0.0055 percent to 0.022 percent on a relative basis). In terms of relative standard deviations, taken as $\sqrt{23}\,s_{um}$ and $\sqrt{8}\,s_{wm}$, the uncertainties range from 0.016 percent to 0.049 percent. All six means are statistically equivalent as evidenced by the results of t-tests for differences between means. The six means are centralized around a value of $\overline{T} = 3.8238$ d (Figure 3). The influence of the S56 determination is quite evident. The effect, of course, is only on the unweighted means (a), (c), and (d), and even more so on the two latter grand means where the S56 means carry 1/8 of the statistical weight. Excluding these two means, the remaining four means centralize around a value of $T = 3.8234$ d with an appreciably smaller range of relative uncertainties. Given the above, and considering the number and diversity of the determinations comprising these mean values, it should be apparent that the half-life is known with a relative uncertainty substantially less than 0.1 percent. Careful and critical examination of the left-hand side of Figure 3 indicates that an evaluated value of $T = 3.8234$ d is justified and supportable. The relative standard deviation may be taken to be about 0.03 percent since the relative standard deviations for the three grand means s_{wm} are 0.026 percent, 0.016 percent, and 0.049 percent for means (b), (d), and (f), respectively. Therefore, even conservatively, the evaluated half-life is $T = 3.823 \pm 0.001$ d. If only one of the above weighted averaging rules had been selectively used, and

if the uncertainty was taken to be just s_{wm}, then an evaluated half-life of $T = 3.8234 \pm 0.0002$ d could equally be justified.

A further critical evaluation may be obtained by considering a smaller subset of the data in Table 3 using only the M56, BW72, and C94 determinations. The criteria for selecting these three were (1) that they represented determinations based on three uniquely different measurement methodologies, (2) that they comprised the most reportedly precise determinations, and (3) that their precision estimators were all comparable within a factor of 5 or so. Admittedly, the choices and selection criteria are somewhat arbitrary. One could endlessly argue. For example, that the Tobailem[25] (T55) results are probably comparable to those of Marin[26] (M56), and are nearly in the same precision range as that for Collé[5] (C94); that the calorimetry result of Robert[27] (R56) should be included for completeness in the covered measurement methodologies; that the uncertainty analyses of the much earlier Curie and Chamié[24] (CC24) work are clearly superior to the later, but superficial treatment of Butt and Wilson[4] (BW74); or that the Collé[5] work (which interestingly yielded the smallest T values) should be exclusively considered since it was the only study that explicitly addressed and accounted for the uncertainties in instrument nonlinearities and temporal variations over the course of the half-life determinations.

The results for an analysis identical to that above for the determination of the six means using only the M56, BW72, and C94 data are given in the right-hand side of Figure 3. As before, the first two means, the unweighted (a) and weighted (b), are derived using all 11 independent T values. The four grand means (c), (d), (e), and (f) are derived from the three unweighted and weighted mean results. From Figure 3, it is clear that the means centralize around a value of $T = 3.8232$ d. The uncertainties, excepting the slightly larger value for mean (a), in terms of relative standard deviations are all typically 0.01 percent. Therefore, a recommended evaluated half-life value is $T = 3.8232 \pm 0.0004$ d which comports excellently with that given above. And as before, it must be mentioned that the use of any one of the means or just s_{wm} uncertainty values would result in an evaluated T that is substantially more precise.

The uncertainty in the evaluated ^{222}Rn half-life value is such that resulting propagated uncertainty contributions for either ^{222}Rn radioactive decay or growth accumulations of ^{222}Rn from ^{226}Ra decay is negligible in nearly all ^{222}Rn measurement applications. Figure 4 illustrates the relative uncertainty contributions as a function of either decay time or growth time obtained using a ^{222}Rn half-life value of $T = 3.823 \pm 0.001$ d. Using even this conservative uncertainty value, the uncertainty in a decay correction approaches ±0.1 percent only after nearly six half-lives (22 d). The magnitude of this uncertainty contribution would be significant in only high-precision ^{222}Rn metrology applications such as those performed at calibration or standards laboratories. As shown in Figure 4, the relative uncertainty contributions for growth accumulations generally (for accumulation times greater than 5 d) are even less than that for decay. As a practical matter, the uncertainty in the $(1 - e^{-\lambda t})$ accumulation factor due to the timing uncertainty in a typical growth accumulation would be substantially larger than that

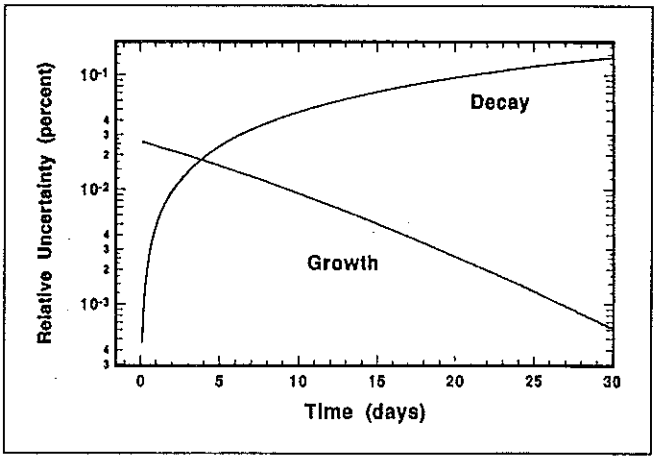

Figure 4 Propagated relative uncertainty for ^{222}Rn radioactive decay and for growth accumulations of ^{222}Rn from ^{226}Ra decay due to the uncertainty in the ^{222}Rn half-life having a value of $T = 3.823 \pm 0.001$ d.

due to the uncertainty in the ^{222}Rn half-life. The timing itself can be done quite precisely, perhaps within seconds, but the typical transfer of an accumulated sample requires a finite time interval that has appreciable timing variability in defining the end of the accumulation.

An example of decay-corrected counting data may vividly demonstrate the measurement precision necessary to distinguish between different ^{222}Rn half-life values; and hence illustrate the practical consequences of the underlying uncertainty on the half-life. Table 4 contains the summarized results of 120 liquid scintillation measurements performed on each of 6 ^{222}Rn samples over approximately 15 days (about 4 half-lives). These counting results are from Collé;[5] and were, in fact, those used to obtain the fitted half-lives for that study (Table 3). For this example, each of the 720 counting results (120 for each sample) were decay corrected to a common t = 0 reference time using three different ^{222}Rn half-life values: $T = 3.821$ d; $T = 3.823$ d; and $T = 3.825$ d. The values conservatively represent at least 2s limits in T around a central value of 3.823 d. As indicated in Table 4, the mean decay-corrected activity concentration for each sample is virtually indistinct (to four significant figures), independent of the T value used to perform the decay corrections. The uncertainties provided in the table for each sample are standard deviations of the mean s_{um} averaged over the respective 120 measurements. Although a more detailed analysis of the results of the calculations using the different T values reveal slight systematic irregularities in the residuals at long time intervals, all s_{um} values are invariant.

In conclusion, it may be of interest to briefly recapitulate the historical course of the "known" and accepted ^{222}Rn half-life. Initially (c. 1902), T was "about 4 d" even following the first quantitative determinations of P. Curie.[13] Shortly thereafter (1905-1907), T began to decrease; the half-life was still routinely tabulated as $T = 4$ d, but was known to be somewhat shorter. Values of 3.8 d and 3.9 d began to appear in the literature.[12] By 1910-1911, following the work of M. Curie[18,19] and Rutherford,[20,21] the half-life was firmly established as

Sample Identity	Corrected ^{222}Rn Activity Concentration (Bq · g^{-1})[a]		
	Using $T = 3.821$	Using $T = 3.823$	Using $T = 3.825$
P3	10.6789 ± 0.0038	10.6712 ± 0.0037	10.6636 ± 0.0037
P4	10.6774 ± 0.0038	10.6698 ± 0.0038	10.6621 ± 0.0038
P5	10.6753 ± 0.0040	10.6677 ± 0.0040	10.6600 ± 0.0041
P7	10.6853 ± 0.0040	10.6777 ± 0.0040	10.6700 ± 0.0040
P8	10.6781 ± 0.0042	10.6704 ± 0.0040	10.6628 ± 0.0040
P9	10.6641 ± 0.0039	10.6564 ± 0.0039	10.6488 ± 0.0039
Unweighted grand mean	10.6765 ± 0.0028	10.6689 ± 0.0028	10.6612 ± 0.0028
Weighted grand mean	10.6764 ± 0.0016	10.6688 ± 0.0016	10.6611 ± 0.0016

[a] Calculated mean and standard deviation of the mean for 120 measurements (on each sample) decay corrected to a common $t = 0$ reference time.

Table 4 Decay correction using three ^{222}Rn half-life values: an example.

$T = 3.85$ d with an estimated uncertainty of about ±0.04 d (i.e., approximately ±1%). This T value prevailed over more than the following decade. By the mid-1920s, following Bothe[23] and I. Curie and Chamié,[24] T typically became either 3.823 d or 3.825 d with the estimated uncertainty improved by an order of magnitude to about 0.1 percent.[29] For the next 20 years, either of these values were accepted. The confirmatory studies of the mid-1950s[25-28] firmly placed the value at $T = 3.825$ d with associated uncertainties ranging from about ±0.001 d to ±0.003 d. The reportedly high-precision result of Butt and Wilson[4] in 1972, $T = 3.82351 \pm 0.00033$ d, became nearly definitive, or at least often has been considered to be so.[1-3] The evaluated result recommended here

$$T = 3.8232 \pm 0.0004 \text{ d}$$

is entirely consistent, but more justifiable; particularly with due consideration to the recent precise measurements of Collé[5] and to the companion historical review and critique.[12] It is believed that this value can withstand critical scrutiny and will survive the proverbial test of time.

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