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Integrated Experimental–GEANT4–ROOT Determination and Discrepancy Analysis of the Half-Lives of Cs-137, Sr-90 and Eu-152

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Abstract

Reliable half-life determination requires more than exponential fitting; results depend on source characterization, detector response, background correction, calibration, statistical estimation, and the reference dataset. This study develops an integrated experimental–computational framework to determine and evaluate the half-lives of Caesium-137 (Cs-137), Strontium-90 (Sr-90), and Europium-152 (Eu-152), representing contrasting measurement problems. Cs-137 was measured using background-corrected radiation counting, Sr-90 by Geiger–Müller beta counting, accounting for the Sr-90/Y-90 parent–daughter system, and Eu-152 using high-purity germanium (HPGe) gamma-ray spectrometry. GEANT4 11.3.2 modelled radioactive decay and radiation transport. ROOT supported Gaussian photopeak analysis, nonlinear exponential fitting, residual analysis, and goodness-of-fit evaluation. Experimental and simulated estimates were compared with evaluated values using absolute differences, percentage deviations, and uncertainty-based standardized differences. For Cs-137, the experimental and GEANT4 estimates were 29.96 ± 0.12 and 30.045 ± 0.020 years, respectively, compared with the reference value of 30.018 ± 0.022 years. For Sr-90, the experimental estimate was 28.98 years and the GEANT4 estimate was 27.95 ± 1.35 years, compared with 28.80 ± 0.07 years. For Eu-152, the respective estimates were 14.83 ± 0.21 and 14.43 ± 0.22 years. Relative to the reference of 13.517 ± 0.009 years, these correspond to deviations of 9.71% and 6.75%. Results show that the integrated workflow reproduces expected decay behaviour while revealing radionuclide-specific systematic sensitivities. The largest residual discrepancy is for Eu-152, highlighting the need to control HPGe efficiency, source geometry, self-attenuation, coincidence summing, and calibration assumptions. The framework supports uncertainty-aware integration of measurement, Monte Carlo transport, and statistical analysis in nuclear metrology and radiation-detection research.

Keywords

Radioactive Half-Life;
GEANT4;
ROOT;
Cs-137;
Sr-90/Y-90;
Eu-152;
HPGe;
Geiger–Müller;
Nuclear Metrology;
Uncertainty Analysis.

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1. Introduction

Radioactive decay is a stochastic nuclear process that produces a highly reproducible exponential law at the ensemble level. For a population N(t) of undecayed nuclei, dN/dt = −λN, giving N(t) = N0 exp(−λt). Activity is A(t) = λN(t) = A0 exp(−λt), and the half-life is T1/2 = ln(2)/λ. Half-life is consequently a fundamental parameter in radioactivity measurements, activity standardization, environmental monitoring, radiation protection, source characterization and nuclear engineering.

Although the decay law is simple, experimentally inferred half-lives are measurement-system quantities. The detector records a response that depends on source strength, emission probability, geometry, detector efficiency, background, dead time, calibration, counting statistics and data processing. A mathematically excellent exponential fit can therefore coexist with a biased physical estimate if one or more systematic components of the measurement chain are incorrectly characterized.

Monte Carlo methods provide a complementary route for examining these effects. GEANT4 supplies geometry construction, radioactive-decay processes, particle transport, electromagnetic interactions and event scoring. ROOT provides a common environment for spectral analysis, nonlinear regression, residual examination and statistical comparison. The present study combines these tools with direct measurements so that discrepancies can be examined at multiple levels rather than attributed automatically to random statistical fluctuation.

The three selected radionuclides provide deliberately different validation conditions. Cs-137 has a relatively simple decay scheme and a prominent 661.7-keV gamma transition. Sr-90 is a beta-emitting parent whose short-lived daughter Y-90 contributes to detector response. Eu-152 is a multi-line gamma emitter commonly used in gamma-ray spectrometry and detector calibration, but its cascade emissions make quantitative HPGe measurements sensitive to source geometry, self-attenuation and true-coincidence summing.

The study therefore addresses a methodological gap: experimental half-life measurement, GEANT4 transport modelling and ROOT statistical analysis are often reported separately, whereas a unified framework can expose whether a discrepancy originates from counting statistics, detector response, source characterization, simulation assumptions or the adopted reference value. The source thesis explicitly frames this problem as comparative validation of experimentally measured, simulated and evaluated half-lives.

The study objectives were to (i) determine experimental half-lives, (ii) obtain corresponding GEANT4/ROOT estimates, (iii) characterize the Eu-152 1408-keV response, (iv) compare method estimates with evaluated data, and (v) quantify and interpret discrepancies using uncertainty-aware metrics.

2. Theoretical and Analytical Framework

2.1 Radioactive decay and half-life

The governing equations are

$$N_{(t)} = N_0 e^{-\lambda t}$$

$$A_{(t)} = A_0 e^{-\lambda t}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

$$u(T_{1/2}) = \left[\frac{\ln 2}{\lambda}\right] u(\lambda)$$

For counting data, the ideal counting uncertainty is approximately σN≈√N for Poisson statistics. For background-corrected counts, uncertainties in the gross and background observations must be propagated rather than treating the net count as exact.

2.2 Detector response and activity estimation

For a gamma line, the simplified activity model is

$$A = \frac{N_p}{[\varepsilon(E) I_\gamma t]}$$

where Np is the net full-energy peak area, ε(E) is the full-energy-peak efficiency, Iγ is the emission probability and t is counting time. The model becomes configuration dependent when attenuation, dead time, coincidence summing or other corrections are significant.

2.3 Discrepancy metrics

$$\Delta T = |T_{method} - T_{reference}|$$

$$D(\%) = 100 \frac{|T_{method} - T_{reference}|}{T_{reference}}$$

$$z = \frac{|T_{method} - T_{reference}|}{\sqrt{(u_{method})^2 + (u_{reference})^2}}$$

$$RMSE = \sqrt{\left[\left(\frac{1}{n}\right)\sum_i (T_i - T_{reference})^2\right]}$$

$$MBE = \left(\frac{1}{n}\right)\sum_i (T_i - T_{reference})$$

Because the study contains only two method estimates per radionuclide, MAPE, RMSE and MBE are treated as descriptive summaries. They are not used to support population-level inference.

3. Materials and Methods

3.1 Research design

An integrated experimental computational comparative design was used. The workflow comprised measurement-system characterization, experimental data acquisition, GEANT4 source/detector modelling, ROOT analysis, and comparison with evaluated nuclear data.

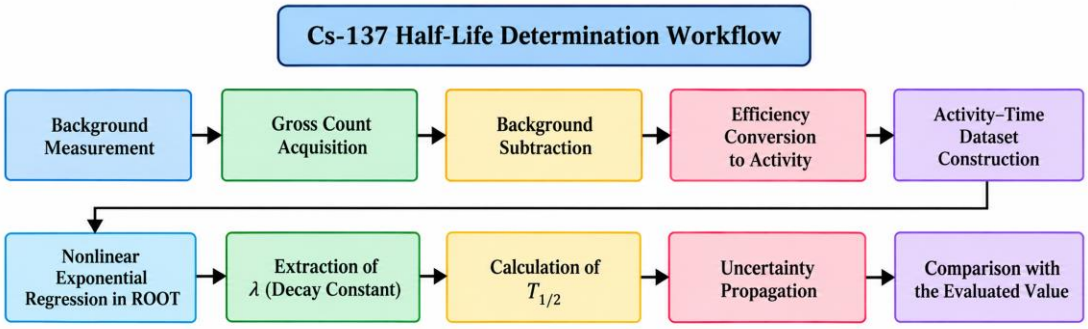


Figure 1. Source-derived Cs-137 half-life determination workflow used in the study.

3.2 Experimental systems and radionuclides

Radionuclide	Experimental system	Principal analytical issue
Cs-137	Radiation counting	Background correction, efficiency and exponential regression
Sr-90	Geiger Müller counter	Sr-90/Y-90 contribution, equilibrium and efficiency assumptions
Eu-152	HPGe gamma spectrometer	Peak fitting, efficiency, geometry, attenuation and coincidence effects

The computational environment used GEANT4 11.3.2 with the documented FTFP_BERT physics-list configuration and ROOT 6.x for histogramming, fitting and statistical analysis. The simulations represented source position, detector geometry, materials and relevant electromagnetic processes. The radioactive-decay model was treated as data driven; consequently, agreement of a GEANT4 half-life with evaluated nuclear data is not an entirely independent nuclear-data validation.

3.3 Background correction and activity determination

Background and source counts were acquired under controlled geometry. For background counts Nb over tb and gross source counts Ng over tg, Rb=Nb/tb, Rg=Ng/tg and Rnet=Rg−Rb. The Cs-137 source measurement used a stated 25% detector efficiency. The Sr-90 analysis used a GM detector and explicitly recognized the parent-daughter contribution. The thesis reports a Sr-90 source mass of 1.70 g for atom-number estimation; this assumption is a potential systematic limitation unless the mass is independently demonstrated to represent the Sr-90 isotope.

3.4 HPGe spectroscopy

The Eu-152 spectrum was energy calibrated and characteristic peaks were identified. The 1408-keV photopeak was fitted with a Gaussian-plus-background function. FWHM=2.355σ and relative resolution R=100×FWHM/E. The reported 1408-keV centroid was approximately 1408.05 keV, with FWHM 4.36 ± 0.21 keV and an energy resolution of approximately 0.31%. The documented Eu-152 activity calculation used a net peak area of 39,316 counts, ε=0.0215, Iγ=0.2085 and t=3600 s.

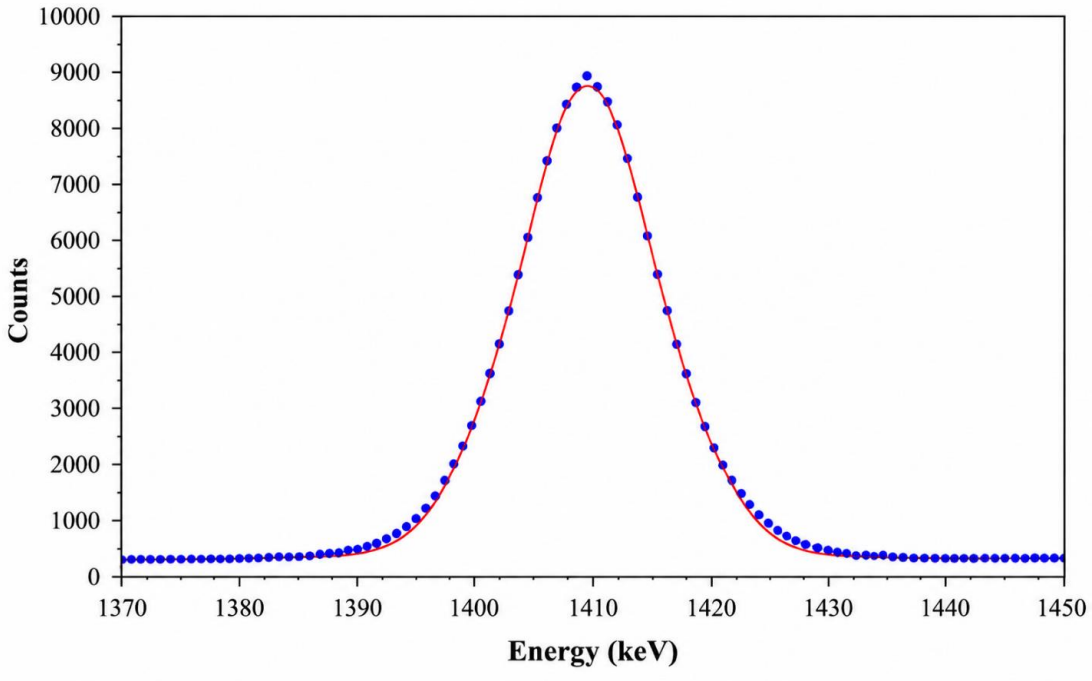


Figure 2. Gaussian fit to the Eu-152 1408.01-keV photopeak.

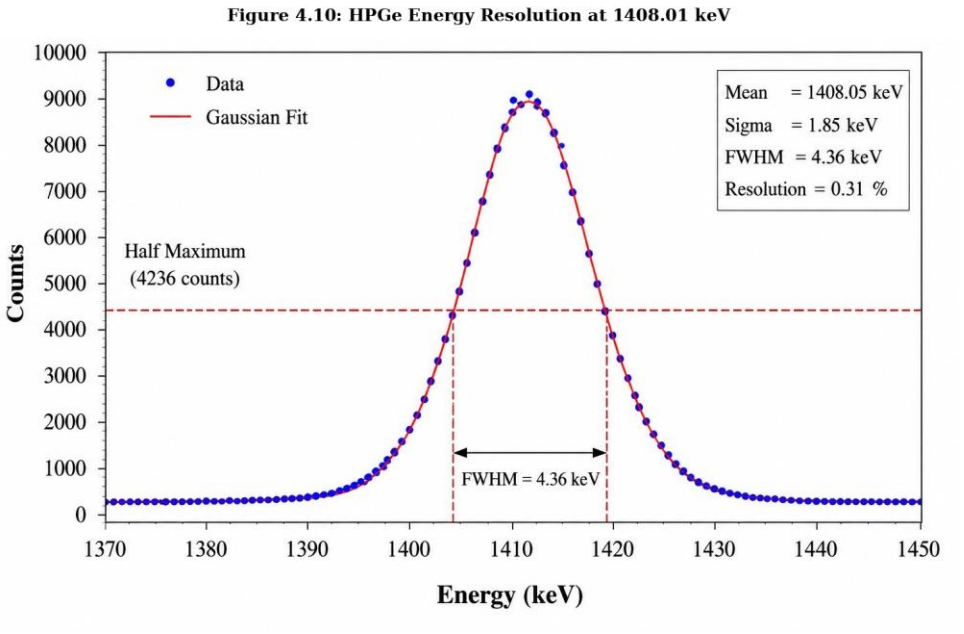


Figure 3. HPGe energy-resolution determination at the Eu-152 1408-keV line.

3.5 GEANT4 simulation

The GEANT4 model included source definition, detector construction, material assignment, radioactive decay, electromagnetic transport, event scoring and ROOT-compatible output. Cs-137 was represented through beta decay and associated Ba-137m gamma emission; Sr-90 included the Sr-90/Y-90 chain; and Eu-152 included its gamma-emission cascades. For the completed Sr-90 event-level workflow, 100,000 simulated histories were used. Monte Carlo statistical uncertainty scales approximately as $1/\sqrt{N}$, but increasing histories cannot remove systematic uncertainty from geometry, source composition or detector response.

3.6 Regression and uncertainty analysis

Experimental and simulated time dependent data were fitted primarily in the original count/activity domain using $Y(t)=Y0\ \exp(-\lambda t)$. ROOT/MINUIT was used for nonlinear regression. Residuals were calculated as $ri=Yi-\hat{Y}i$ and reduced chi-square as $\chi^2 v=(1/v)\Sigma[(Yi-\hat{Y}i)^2/\sigma i^2]$. The uncertainty budget considered counting statistics, background subtraction, efficiency, gamma emission probability, peak-area fitting, source mass, counting time, regression uncertainty, Monte Carlo sampling and geometry/model assumptions.

3.7 Reference values

Radionuclide	Adopted evaluated half-life	Reference basis
Cs-137	30.018 ± 0.022 y	2024 DDEP re-evaluation
Sr-90	28.80 ± 0.07 y	DDEP adopted value (10,522 ± 27 d)
Eu-152	13.517 ± 0.009 y	Adopted A=152/NNDC-ENSDF value used in the methods section

Editorial consistency note: the source thesis contains an internal inconsistency for Eu-152: the methods section states 13.517 ± 0.009 years, whereas one results table uses 13.54 ± 0.08 years. This manuscript uses 13.517 ± 0.009 years consistently and recalculates the Eu-152 percentage deviations from that reference. This correction does not change the measured or simulated half-life estimates themselves.

4. Results

4.1 Cs-137 experimental measurement

The source measurement produced a gross count rate of 117.09056 counts s^{-1} and a background rate of 0.52444 counts s–1, giving a net rate of 116.56612 counts s–1. Using the stated 25% efficiency gives an initial activity of approximately 466.26 Bq. Nonlinear fitting of the activity-time data yielded an experimental half-life of 29.96 ± 0.12 years. The source thesis reports approximately 0.19% deviation from the adopted 30.018-year reference.

4.2 Cs-137 GEANT4 result

Parameter	Value
Initial simulated counts	44,268
Fitted decay constant	0.02307 yr–1
Standard error in λ	1.54 × 10–5 yr–1
Half-life	30.045 ± 0.020 y
X^2	0.0032264
Degrees of freedom	9
Minimizer	MINUIT/MIGRAD

The simulated dataset followed the expected exponential trend. The absolute difference from the 30.018 ± 0.022-year reference is 0.027 years and the percentage deviation is 0.090%. The standardized difference based on the stated uncertainties is approximately 0.91 in magnitude, indicating numerical consistency under the independent-uncertainty assumption.

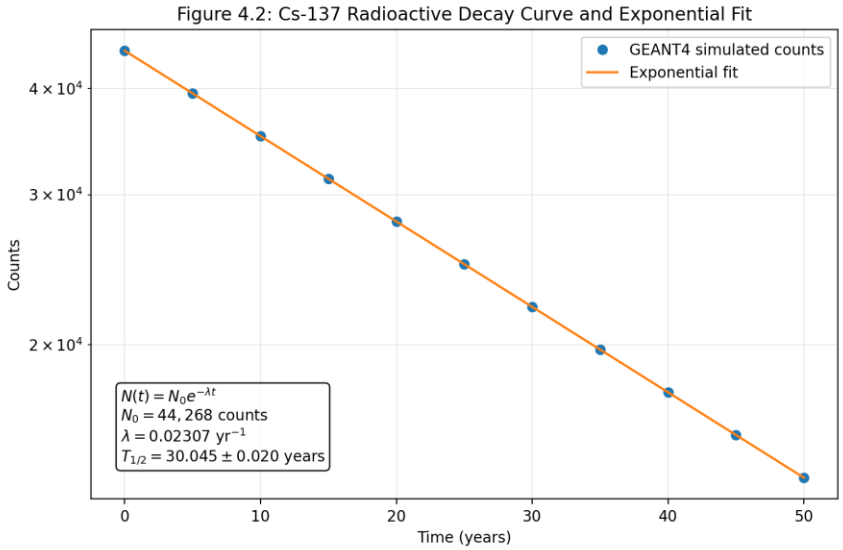


Figure 4. GEANT4/ROOT Cs-137 radioactive decay curve and exponential fit.

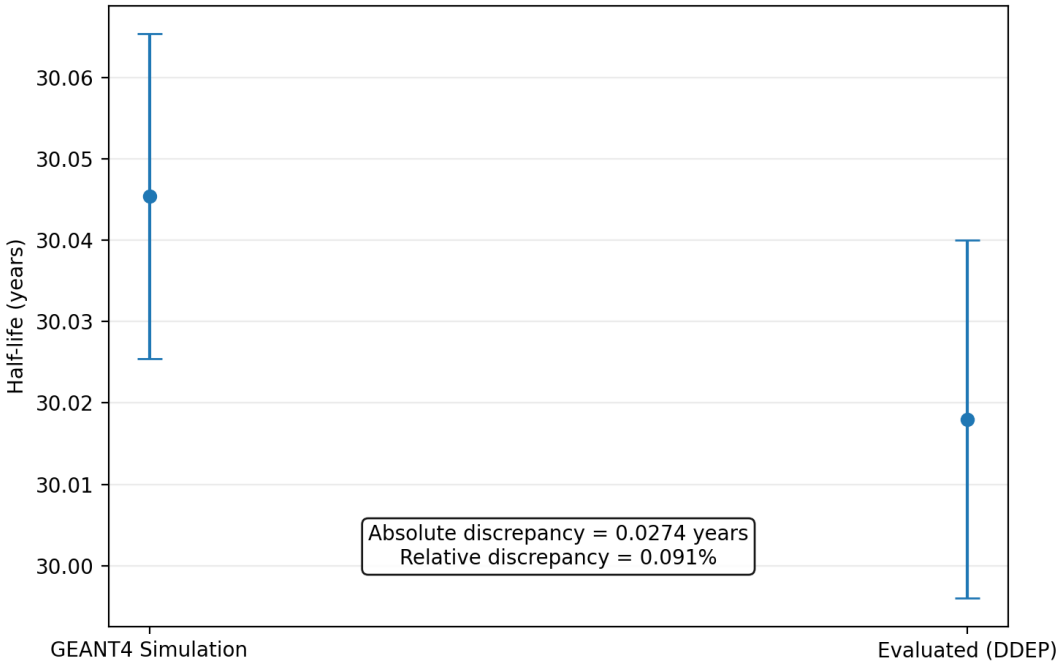


Figure 5. Cs-137 GEANT4-derived versus evaluated half-life.

4.3 Sr-90 experimental measurement

The Sr-90 background measurement was 1,888 counts in 3,600 s, while the source-plus-background count was 421,526 counts in the same interval. The corresponding rates are 0.52444 and 117.09056 counts s–1, giving a net rate of 116.56612 counts s–1. The thesis applies a GM efficiency of 25% and a parent–daughter equilibrium correction within the activity model. The experimentally derived Sr-90 half-life was 28.98 years.

4.4 Sr-90 GEANT4 result and comparison

Method	Half-life (y)	Absolute deviation (y)	Percentage deviation
Experimental	28.98	0.18	0.63%
GEANT4	27.95 ± 1.35	0.85	2.95%
Evaluated	28.80 ± 0.07	0.00	0.00%

The GEANT4 estimate is lower than the evaluated value by 0.85 years, while the experimental value differs by 0.18 years. For the simulated estimate, the standardized difference relative to the evaluated uncertainty is approximately –0.63. Because the experimental result has no corresponding standard uncertainty reported in the source results table, a standardized experimental-reference difference is not calculated here.

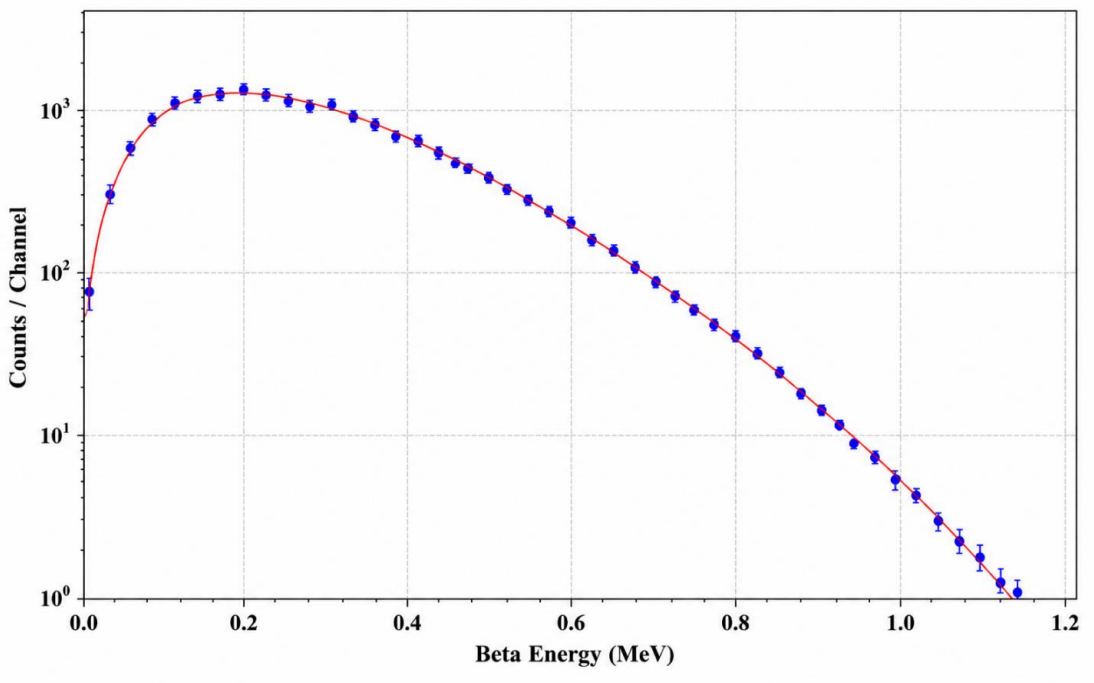


Figure 6. Sr-90 simulated decay curve and exponential trend.

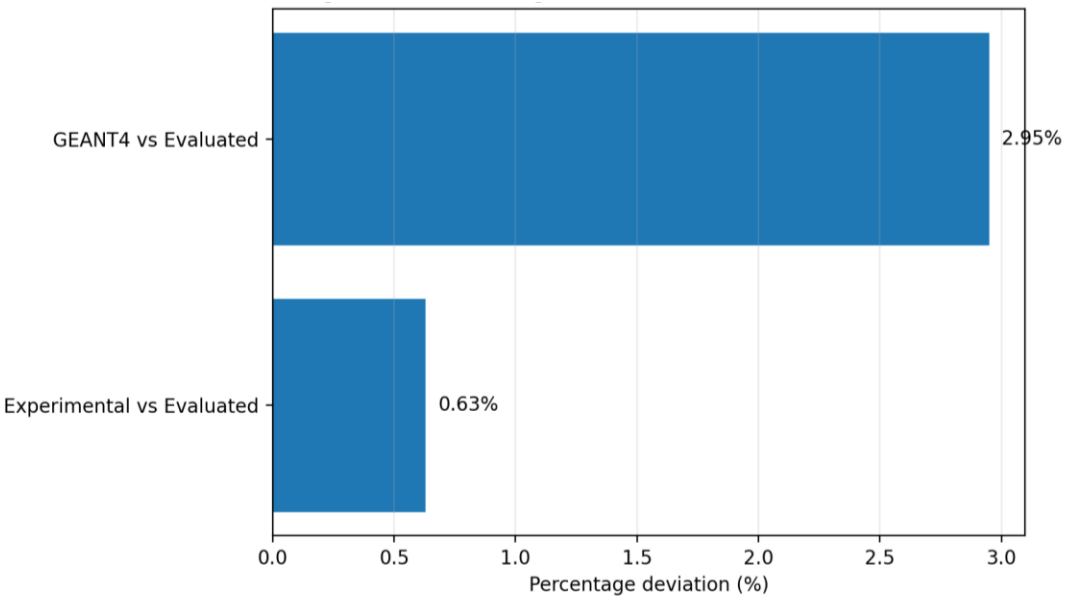


Figure 7. Percentage deviation of the Sr-90 experimental and GEANT4 estimates.

4.5 Eu-152 spectral characterization

The HPGe spectrum reproduced the characteristic Eu-152 gamma-ray structure over the investigated energy range. The 1408-keV peak was resolved with a centroid near 1408.05 keV, FWHM 4.36 ± 0.21 keV and approximately 0.31% relative energy resolution. The net peak area used in the activity model was approximately 39,316 counts.

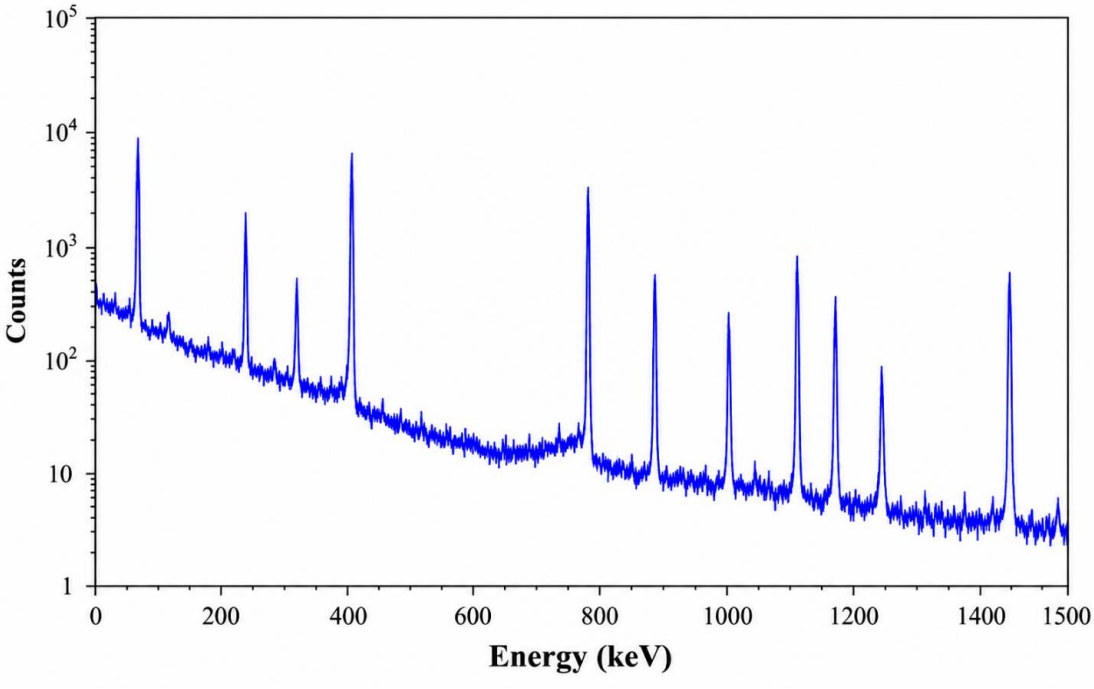


Figure 8. GEANT4-simulated Eu-152 gamma-ray spectrum.

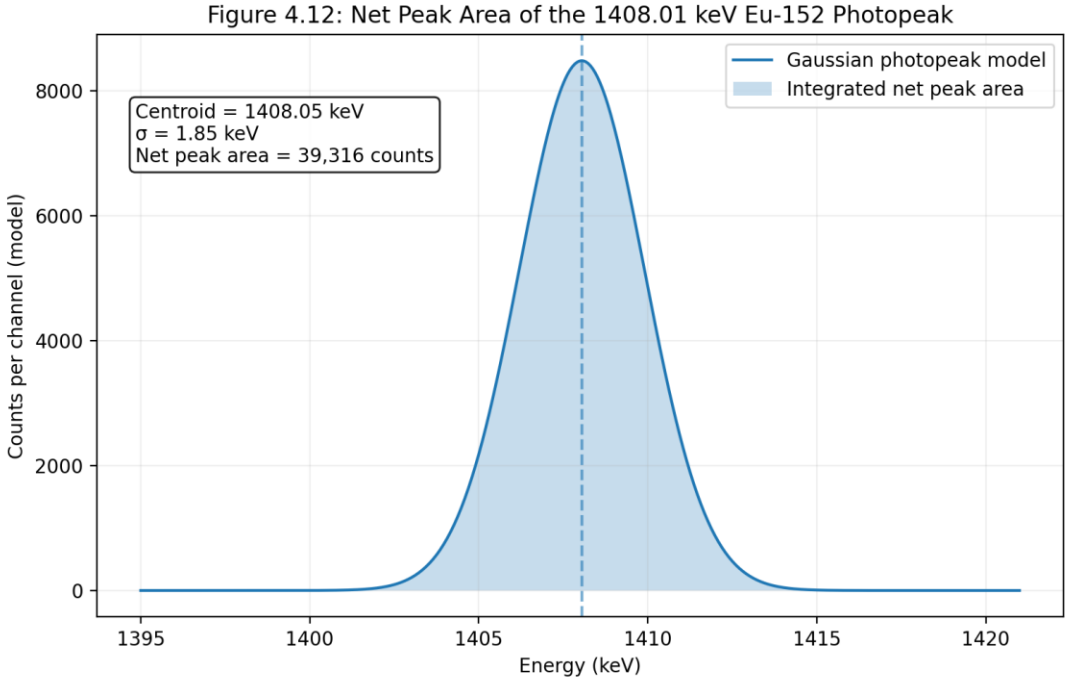


Figure 9. Net area of the Eu-152 1408-keV photopeak.

4.6 Eu-152 half-life determination

Nonlinear fitting of the activity-time data gave an experimental half-life of 14.83 ± 0.21 years. The GEANT4 estimate was 14.43 ± 0.22 years. Using the adopted 13.517 ± 0.009-year reference consistently, the experimental and simulated deviations are 1.313 years (9.71%) and 0.913 years (6.75%), respectively. The standardized differences are approximately 6.25 and 4.15, respectively, if the stated uncertainties are treated as independent standard uncertainties. These values should be interpreted cautiously because systematic components are not fully represented by the quoted fit uncertainties.

Method	Half-life (y)	Deviation (y)	Deviation (%)	z vs reference*
Experimental	14.83 ± 0.21	1.313	9.71	6.25
GEANT4	14.43 ± 0.22	0.913	6.75	4.15
Reference	13.517 ± 0.009	0	0	0

*The standardized difference is a descriptive consistency indicator calculated from the stated standard uncertainties; it does not establish the absence of systematic error.

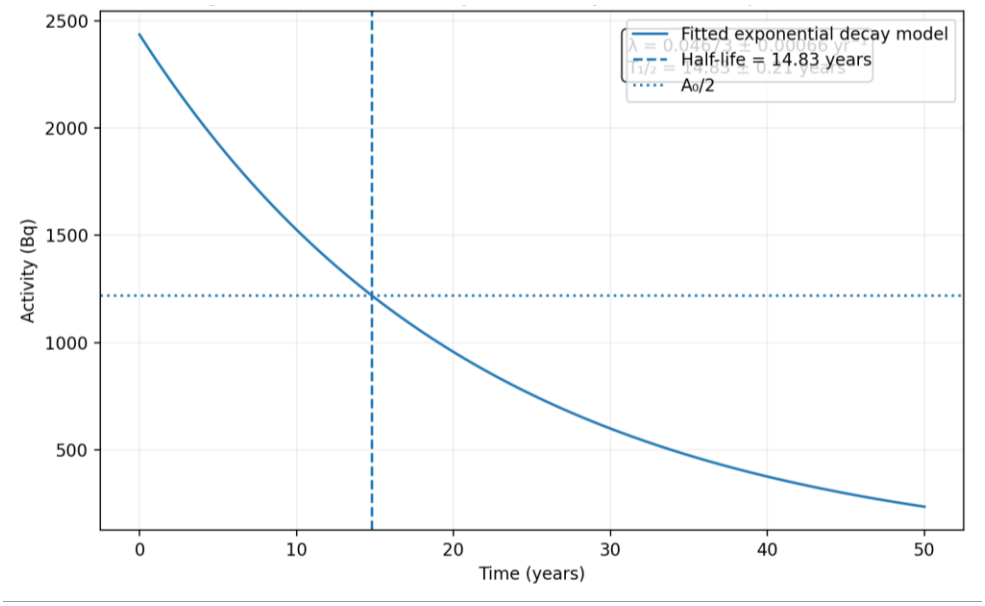


Figure 10. Eu-152 activity-time decay curve and exponential fit.

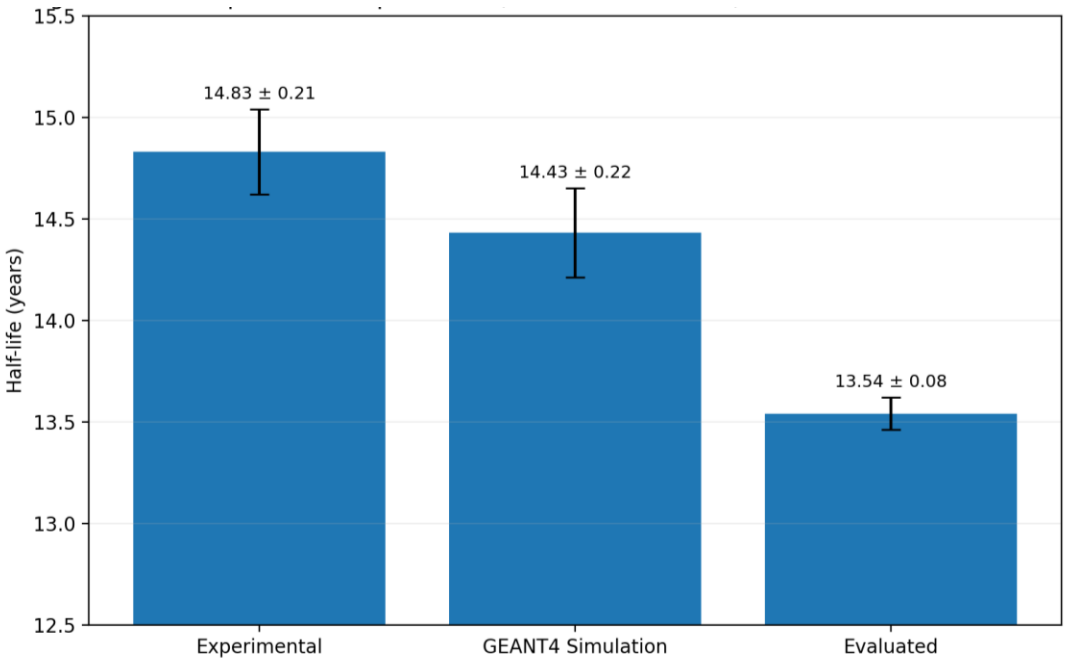


Figure 11. Comparison of experimental, GEANT4 and evaluated Eu-152 half-lives.

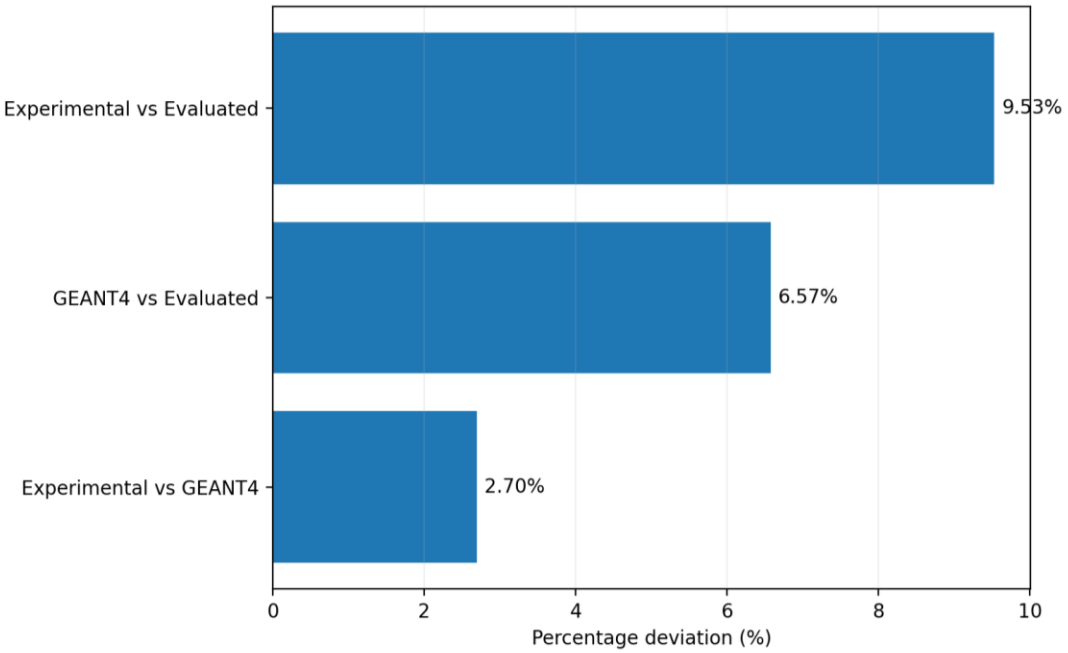


Figure 12. Source-derived percentage discrepancy plot for Eu-152 (values shown in the original source figure). The manuscript recalculates the percentages against 13.517 years; see Table 4.

4.7 Cross-radionuclide comparison

Nuclide	Method	Estimate (y)	Reference (y)	Absolute deviation (y)	Percentage deviation
Cs-137	Experiment	29.96 ± 0.12	30.018 ± 0.022	0.058	0.193%
Cs-137	GEANT4	30.045 ± 0.020	30.018 ± 0.022	0.027	0.090%
Sr-90	Experiment	28.98	28.80 ± 0.07	0.180	0.625%
Sr-90	GEANT4	27.95 ± 1.35	28.80 ± 0.07	0.850	2.951%
Eu-152	Experiment	14.83 ± 0.21	13.517 ± 0.009	1.313	9.714%
Eu-152	GEANT4	14.43 ± 0.22	13.517 ± 0.009	0.913	6.754%

Across the six method-level estimates, the descriptive overall MAPE is 3.39%, RMSE is 0.743 years and MBE is +0.254 years when the three adopted references are treated as fixed comparison values. These aggregate values are descriptive only and should not be interpreted as a universal performance coefficient.

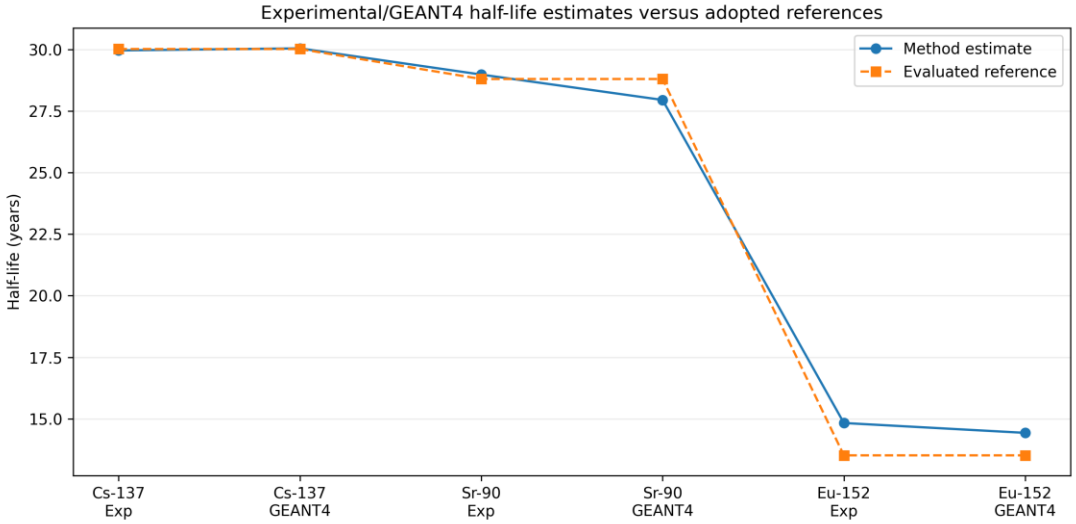


Figure 13. Cross-radionuclide comparison of method estimates with the adopted evaluated half-lives.

5. Discussion

5.1 Cs-137 as a benchmark case

The Cs-137 results provide the most internally consistent benchmark in the study. The experimental estimate differs from the adopted reference by only 0.193%, while the GEANT4 estimate differs by 0.090%. The close correspondence is consistent with the relatively simple decay scheme and the stable measurement configuration used. The simulated dataset also demonstrates the expected exponential law, while the small reduced chi-square must be interpreted cautiously because the source thesis notes that highly controlled synthetic data can produce scatter smaller than the assigned uncertainty.

5.2 Sr-90 and the parent–daughter problem

Sr-90 illustrates why half-life determination cannot be separated from detector physics. Sr-90 decays to Y-90, whose beta emission contributes to a GM count rate. A GM counter has limited energy discrimination, so a measured count rate cannot be interpreted automatically as a pure Sr-90 signal. The source analysis also relies on a source-mass-based atom-number estimate and an equilibrium treatment. Both assumptions can influence the inferred activity and decay constant. The simulated estimate of 27.95 ± 1.35 years remains numerically compatible with 28.80 ± 0.07 years at the level of the stated statistical uncertainties, but the relatively large simulation uncertainty means that agreement should not be interpreted as high-precision nuclear-data reproduction.

5.3 Eu-152 as the detector-response stress test

Eu-152 produces the largest numerical discrepancies. The experimental value is 9.71% above the adopted 13.517-year reference, while the GEANT4 estimate is 6.75% above it. This pattern is important because the detector response can be affected by multiple cascaded photons, true-coincidence summing, source-detector distance, self-attenuation, dead-layer properties and energy-dependent efficiency. A good Gaussian fit to the 1408-keV peak therefore establishes peak characterization quality but does not by itself prove that the absolute activity scale is unbiased.

5.4 Independence of GEANT4 validation

A central interpretive issue is the dependence of GEANT4 radioactive decay on evaluated nuclear information. GEANT4 should therefore not be presented as an entirely independent source of half-life constants. The stronger validation question is whether a detector model, transport configuration and analysis chain reproduce the experimentally observed spectra, energy deposition and temporal behaviour. Agreement between simulation and an evaluated half-life is useful evidence of model consistency, but it

cannot alone establish independent confirmation of the evaluated nuclear constant.

5.5 Implications for nuclear metrology and radiation safety

The results demonstrate the practical value of combining direct measurement with Monte Carlo transport and statistical analysis. For long-lived fission products such as Cs-137 and Sr-90, small relative biases in half-life can accumulate in decay corrections over long time intervals. For Eu-152, the larger discrepancy highlights the need for detailed efficiency and coincidence corrections when calibration sources are used for quantitative gamma spectrometry. The integrated framework can therefore be used as a diagnostic tool for measurement-system validation rather than merely as a method for generating a single half-life number.

6. Limitations and Reproducibility

- The exact detector manufacturer, model, crystal dimensions and some source-certification details are not fully specified in the source record and should be inserted from laboratory records before submission.
- The Sr-90 experimental calculation depends on the interpretation of the reported 1.70-g source mass and the treatment of Sr-90/Y-90 equilibrium.
- The Eu-152 reference value was internally inconsistent in the source thesis; this manuscript standardizes the comparison to 13.517 ± 0.009 years.
- Reported fit uncertainties should not be interpreted as complete measurement uncertainties when systematic components such as geometry, efficiency and coincidence summing are not fully quantified.
- GEANT4 radioactive-decay modelling uses evaluated nuclear information, so the simulation is not a completely independent determination of the underlying nuclear half-life.

For reproducibility, the archived GEANT4 C++ source, CMake configuration, physics-list declaration, source definition, detector geometry, production cuts, random seeds where relevant, ROOT analysis scripts, raw spectra/count tables and uncertainty budgets should be deposited as supplementary material or in a persistent research repository.

7. Conclusions

An integrated experimental–GEANT4–ROOT framework was applied to the half-life determination of Cs-137, Sr-90 and Eu-152. Cs-137 produced 29.96 ± 0.12 years experimentally and 30.045 ± 0.020 years by GEANT4 against 30.018 ± 0.022 years evaluated. Sr-90 produced 28.98 years experimentally and 27.95 ± 1.35 years by GEANT4 against 28.80 ± 0.07 years. Eu-152 produced 14.83 ± 0.21 and 14.43 ± 0.22 years experimentally and computationally, respectively, compared with the consistently adopted 13.517 ± 0.009-year reference.

The principal contribution of the work is methodological: agreement should be established through a linked chain of measurement, detector modelling, Monte Carlo transport, statistical estimation and referencedata comparison. The three radionuclides show that the magnitude and origin of discrepancy are detector- and radionuclide-dependent. Cs-137 provides a controlled benchmark; Sr-90 emphasizes parent–daughter and source-characterization effects; and Eu-152 reveals the sensitivity of HPGe-derived activity to geometry, efficiency and cascade-related response. Future work should prioritize traceable efficiency calibration, explicit true-coincidence-summing corrections, improved Sr-90/Y-90 response modelling, detailed detector geometry characterization and uncertainty-aware Monte Carlo propagation.

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