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Characterization of Neutron Emission Rates of Commercial ^{252}Cf Sources

October 2025

Changing the World's Energy Future

Jeffrey Smith Burggraf, David L Chichester



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Jeffrey Smith Burggraf, David L Chichester

October 2025

**Idaho National Laboratory
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

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Characterization of Neutron Emission Rates of Commercial ^{252}Cf Sources

Accurate Determination of Emission Rates and Uncertainties for Use in Modeling and Fast-Neutron Experiments

OCTOBER 2025

Jeffrey Burggraf
David Chichester

Idaho National Laboratory



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ABSTRACT

Accurate knowledge of ^{252}Cf neutron emission rates is critical for modeling and fast-neutron experiments, yet commercial sources are often supplied without traceable calibration or uncertainty estimates. This report describes a method to characterize ^{252}Cf sources using a pulse-shape-discrimination (PSD) scintillator. The scintillator was efficiency-calibrated against a time-tagged ^{252}Cf fission chamber manufactured at ORNL over 40 years ago. Isotopic evolution of the calibration source was modeled using Bateman equations to account for changes in the effective average neutrons per fission at the time of measurement. The calibrated scintillator was then used to measure absolute emission rates of several commercial ^{252}Cf sources, revealing deviations of up to 12% from nominal manufacturer values. This methodology provides a practical approach for establishing uncertainty-quantified ^{252}Cf neutron emission rates, improving fidelity in simulations and supporting the accurate interpretation of measurements.

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ACRONYMS

PSD	Pulse Shape Discrimination
HPGe	High Purity Germanium (Detector)
PGNAA	Prompt Gamma Neutron Activation Analysis
MCNP	Monte Carlo N-Particle (Transport Code)
NIST	National Institute of Standards and Technology
EGAF	Evaluated Gamma-ray Activation File
S/N	Signal-to-Noise (Ratio)
S/N	Material Type (in MCNP cross-section libraries)
GEF	GEneral Fission (code)
LSB	Least Significant Bit
VCC	Voltage-to-Charge Conversion
DPP	Digital Pulse Processing

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Characterization of Neutron Emission Rates of Commercial ^{252}Cf

Accurate Determination of Emission Rates and Uncertainties for Use in Modeling and Fast-Neutron Experiments

1. INTRODUCTION

Commercial suppliers of ^{252}Cf neutron sources typically provide only nominal neutron emission rates without accompanying uncertainty estimates, uncertainty analysis, or NIST traceable calibration data. This lack of rigor limits the precision and accuracy of neutron source terms used in high-fidelity modeling for applications such as prompt gamma-ray neutron activation analysis (PGNAA) and other neutron-based measurements. It also impedes the validation of Monte Carlo simulations for such applications.

To address this issue, a detailed method was developed and used to characterize ^{252}Cf neutron sources used for validation studies as a part PGNAA related research. This was accomplished by measuring the neutron emission rates using a pulse-shape discrimination (PSD)-capable stilbene scintillator with a well-characterized efficiency to ^{252}Cf fission neutrons. The efficiency of the scintillator was determined using a time-tagged ^{252}Cf fission chamber, which consists of an ionization chamber containing a thin electroplated layer of Cf, enabling coincident detection of fission events and associated neutrons. The fission chamber allows for the measurement of absolute neutron detection efficiency and, subsequently, the measurement of the absolute neutron emission rate of the commercial ^{252}Cf sources.

A unique aspect of this work is its consideration of several complicating factors, including the advanced age (over 40 years) of the Cf fission chamber, which significantly alters the isotopic composition and neutron emission characteristics. Over time, the increasing contribution of the ^{250}Cf contaminant (introduced during ^{252}Cf production) and the decay of ^{252}Cf with the buildup of the ^{248}Cm daughter product both affect the mean number of neutrons emitted per fission, denoted $\bar{\nu}$. These changes also affect the energy distribution of the emitted neutrons, although this can be neglected. The associated uncertainties due to these effects are propagated through the analysis. The methods, analysis, and results of the commercial ^{252}Cf source characterization campaign are presented herein.

2. ELECTRONICS

The fission chamber (described in (Mihalcz, 2021)) operates by detecting energetic fission fragments emitted from a thin electroplated layer of ^{252}Cf . As these fragments pass through a chamber filled with inert gas, they produce an electron avalanche, similar to the operation of a proportional counter. The resulting electrical pulses are time-correlated with neutron events detected by a stilbene scintillator positioned 129 cm from the fission chamber. The average number of neutrons emitted per fission is determined by measuring the ratio of coincident neutron detections in the scintillator to the total number of fission events recorded by the chamber. This ratio, combined with the known geometry and timing, allows for the calculation of the absolute neutron detection efficiency of the scintillator.

A positive 220 V bias is applied to the fission chamber using a Cividec CxL0195 amplifier. Signal acquisition and pulse shape analysis are performed using a CAEN 5730 digitizer equipped with DPP-PSD firmware. The digitizer settings, including gate widths and thresholds, are summarized in Table 1. Pulse-shape discrimination (PSD) is achieved using both short- and long-integration gates. The short gate captures the prompt portion of the pulse, while the long gate integrates the full signal. The ratio of these integrals (tail-to-total) is used to distinguish neutron events from gamma-ray interactions.

Table 1: Acquisition settings used to measure the efficiency of the stilbene scintillator. The “Long gate” is the width used for pulse integral. Short gate is used for determining the tail-to-total pulse ratio for PSD.

	Polarity	Threshold [lsb/mV]	Pre Gat	Short gate	Long gate	Pre trig	High Voltage	Charge per lsb
Fission	+	100/12.2	234	N/A	450	296	+220	40
Scintillator	-	160/19.5	54	28	350	48	-1400	10

	Input dynamic [V]	CFD fraction [%]	CFD delay [ns]	Coincidence window [μ s]
Fission	2	50	120	6
Scintillator	2	50	6	6

3. FISSION CHAMBER

3.1. Effective Neutrons Per Fission

An important consideration regarding the fission chamber used in this study is its age of 43.3 years (see section 0). Aging is considered in the determination of absolute neutron detection efficiency due to changes in the effective number of neutrons emitted per fission (denoted ν). Over time, most of the original ^{252}Cf decays, and neutron emissions from isotopic contaminants ^{250}Cf (introduced during production) and ^{248}Cm (a daughter product of ^{252}Cf) become the majority neutron emitters. This change alters the ν of the fission chamber.

The ν for ^{250}Cf and ^{248}Cm are assumed to be 3.52 ± 0.22 and 3.11 ± 0.07 , respectively, taken from the ENDF database. While the exact quantities of these isotopes are not known, they are estimated using the $^{250}\text{Cf}/^{252}\text{Cf}$ ratios from production batches manufactured at Oak Ridge National Laboratory in the 1980s (as reported in (Feldman, 2014)). The initial $^{250}\text{Cf}/^{252}\text{Cf}$ fraction used in this analysis is $8.9 \pm 1\%$, where the nominal value and uncertainty is taken to be the mean and standard deviation of those historical batches. Interestingly, the calculated ν is relatively insensitive to the initial ^{250}Cf fraction. This is due in part to a compensating effect: at the current age of the source, an increase in the initial ^{250}Cf fraction is largely offset by a corresponding decrease in ^{252}Cf and an increase in its daughter product, ^{248}Cm .

The relative fractions of $^{250}/^{252}\text{Cf}$, and the daughter products ^{246}Cm and ^{248}Cm over time are calculated by solving the Bateman equations using the initial $^{250}\text{Cf}/^{252}\text{Cf}$ ratio described above, with uncertainties propagated accordingly. The resulting time-dependent ν as well as the neutron emission contributions from each isotope over the life of the fission chamber are shown Figure 1.

Based on this analysis, ν of the fission chamber at the time of this work is determined to be 3.48 ± 0.13 , representing a significant deviation from the ν of 3.76 for pure ^{252}Cf . The uncertainty in ν is carried through to the characterization of commercial ^{252}Cf sources, where it constitutes the largest component of the total uncertainty. The dominant contributor to uncertainty in the calculated ν is the ν of ^{250}Cf , with a smaller but non-negligible contribution from ^{248}Cm . The relatively high uncertainty in the ν of ^{250}Cf stems from the fact that only a single measurement exists in the literature (Orth, 1971).

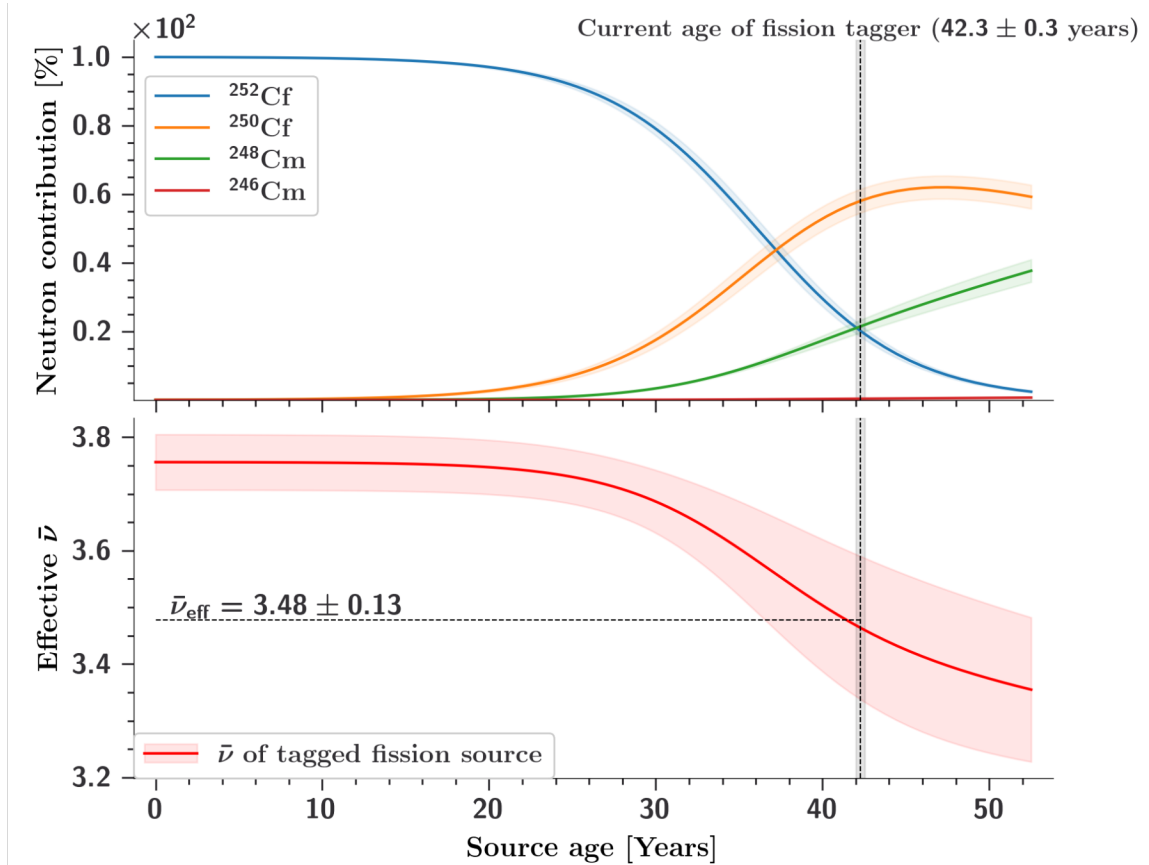


Figure 1: The tagged ^{252}Cf fission source used to measure detector neutron efficiency is so old that ^{250}Cf is the majority (65%) contributor to total neutron emission. However, this effect on the mean neutrons emitted per fission is relatively small (about a 6% reduction). Age of source and uncertainty are indicated by vertical dotted-line and shaded region, respectively.

3.2. Age

The age of the fission chamber is determined by the measurement of fission product decays via gamma-ray spectrometry. To improve the S/N ratio, the HPGe detector is operated in anti-coincidence with the fission chamber signal, suppressing gamma-ray emissions from alpha decay and prompt fission events. Fission product pairs used for age determination must meet the following criteria: a short-lived product that quickly reaches equilibrium with the decay of ^{252}Cf , and a long-lived product that accumulates over time on the order of 5 or more years. This dynamic results in a time-dependent change in the ratio of their decay rates, which can be used to estimate the age of the ^{252}Cf source.

Among long-lived fission products, the most viable candidate for age determination is ^{137}Cs (30-year half-life). Another potential candidate is ^{155}Eu ; however, its gamma-ray emission peaks were observed to suffer from poor signal-to-noise ratios due to spectral interference, limiting its usefulness. Five short-lived fission products were used to determine the age of the fission chamber: ^{132}I (667 keV), ^{140}La (1596 keV), ^{144}La (397 keV), ^{138}Cs (1436 keV), and ^{103}Ru (497 keV). The ratios over time in the case of ^{140}La are shown in Figure 2. For the source age at the time of measurement (2009, approximately 16 years prior to this writing), ^{103}Ru provides low uncertainty due its high gamma-ray emission and relatively high detection efficiency at 497 keV. ^{144}La also performs well, benefiting from a favorable signal-to-noise ratio at 1596 keV (see Figure 3). The ages determined using all five fission products are shown in Table 2.

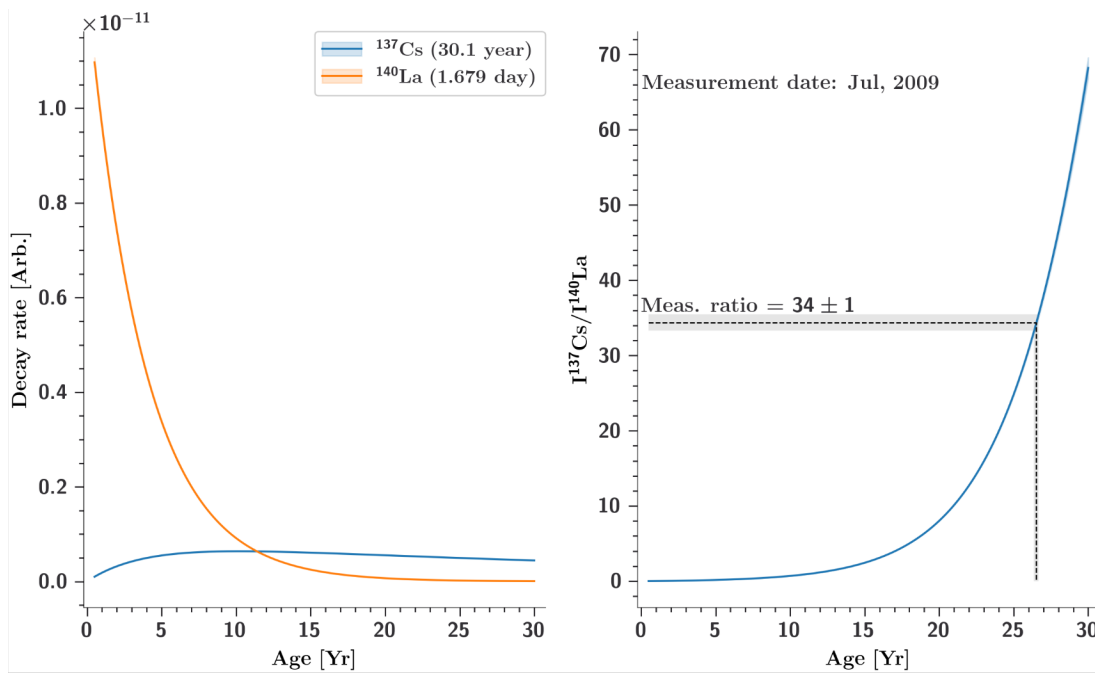


Figure 2: Illustration of the ^{252}Cf fission chamber age determination using the ratio of ^{137}Cs and ^{140}La gamma-ray emissions.

Table 2: Each of the fission products listed here are used to determine ^{252}Cf age by comparing their gamma-ray emission rates to that of $^{137\text{m}}\text{Ba}$.

Isotope	Determined age [year]
^{132}I	41.20 ± 0.75
^{140}La	42.80 ± 0.30
^{144}La	42.33 ± 0.58
^{103}Ru	42.68 ± 0.33
^{138}Cs	41.45 ± 0.58
Average	42.11 ± 0.24

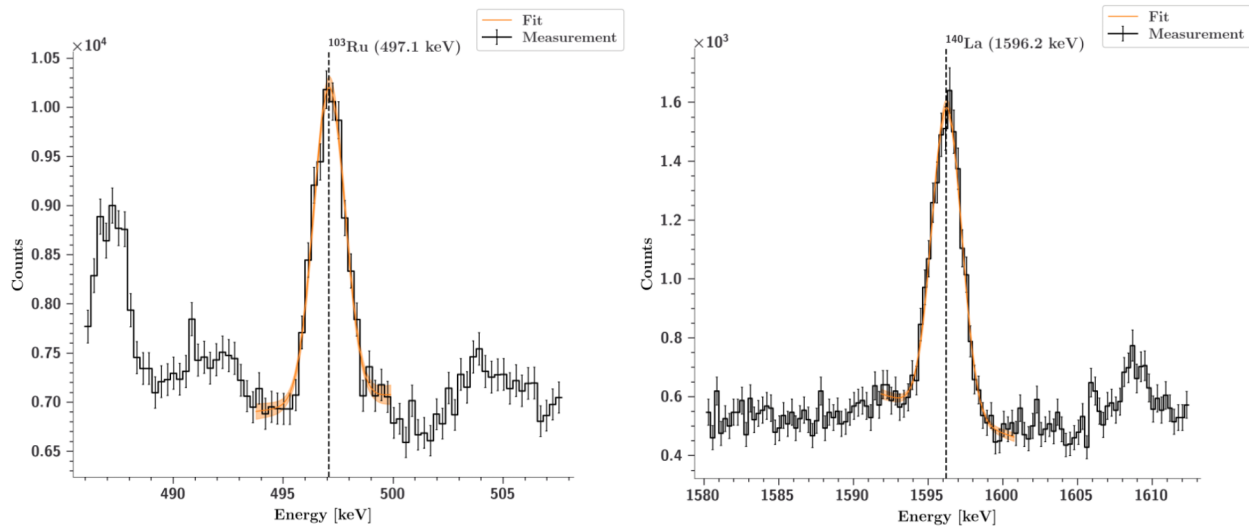


Figure 3: ^{140}La produces the lowest uncertainty in ^{252}Cf source age, due to good S/N around 1600 keV. ^{103}Ru at 497.1 keV also does well due to high gamma detection rates.

3.3. Efficiency Determination

3.3.1. Fission Event Tagging

Each correctly identified fission pulse from the fission chamber corresponds to a known average number of neutrons emitted, allowing the accurate determination of absolute neutron detection efficiency. Pulses misidentified as fission will cause a systematic underestimation in absolute neutron detection efficiency. It is important to note that charged particles from other decay modes, particularly alpha decay but also beta-minus (β^-) decay, can produce detectable signals in the fission chamber. Discrimination of fission events is possible because fission fragments tend to deposit significantly more energy in the chamber than the most energetic alpha or β^- particles. Fission products tend to be emitted with $>10\times$ more energy than alpha particles and $>70\times$ that of β^- particles. This substantial difference in energy deposition enables effective identification of fission events using a minimum pulse amplitude threshold.

The need to perform fission event discrimination leads to another consequence of the fission chamber's age: a dramatic increase in the alpha-to-spontaneous-fission decay ratio, from approximately 30:1 in a new source to about 700:1 in the current aged source. Furthermore, the source is now much weaker than when it was new (by a factor of $\sim 13,000$), now emitting only about 500 neutrons/second, and thus measurement times can be reduced by precisely setting the fission chamber pulse amplitude threshold so that as many fission events as possible are accepted without including false positives from alpha decay.

Two distinct peaks in the pulse amplitude distribution from the fission chamber are shown in Figure 4. The lower-amplitude peak is attributed mostly to alpha and β^- decays, while the higher-amplitude peak consists primarily of fission events, with some overlap from alpha particles. Although fission fragments deposit significantly more energy than alpha particles, there is still some overlap in pulse amplitudes between the two decay modes. Several factors contribute to this overlap, in order of decreasing importance: (1) the depth at which fission fragments are emitted within the electroplated source material, (2) whether the lighter or heavier fission fragment is detected, and (3) the total kinetic energy of the fission fragments.

At a sufficiently high pulse amplitude threshold, all non-fission events are excluded (fission events are tagged). Beyond this point, the probability of detecting a coincident neutron in the scintillator (per fission chamber pulse above threshold) becomes constant. As the threshold increases, a plateau emerges in the neutron detection probability, indicating that non-fission events have been effectively filtered out. This interpretation is supported by a simple MCNP model. In the model, representative fission products, ^{142}Ba and ^{106}Mo , as well as alpha particles are emitted uniformly throughout a $2\ \mu\text{m}$ thick disk composed of pure ^{250}Cf at a density of $15\ \text{g}/\text{cm}^3$. The initial energies of the heavy and light fission fragments are modeled as Gaussian distributions with means of 80 MeV and 102 MeV, and standard deviations of 7 MeV and 5 MeV, respectively. Alpha particles are emitted at a fixed energy of 6 MeV. The particle energies are tallied as they exit the cylinder, creating the histogram shown in Figure 5.

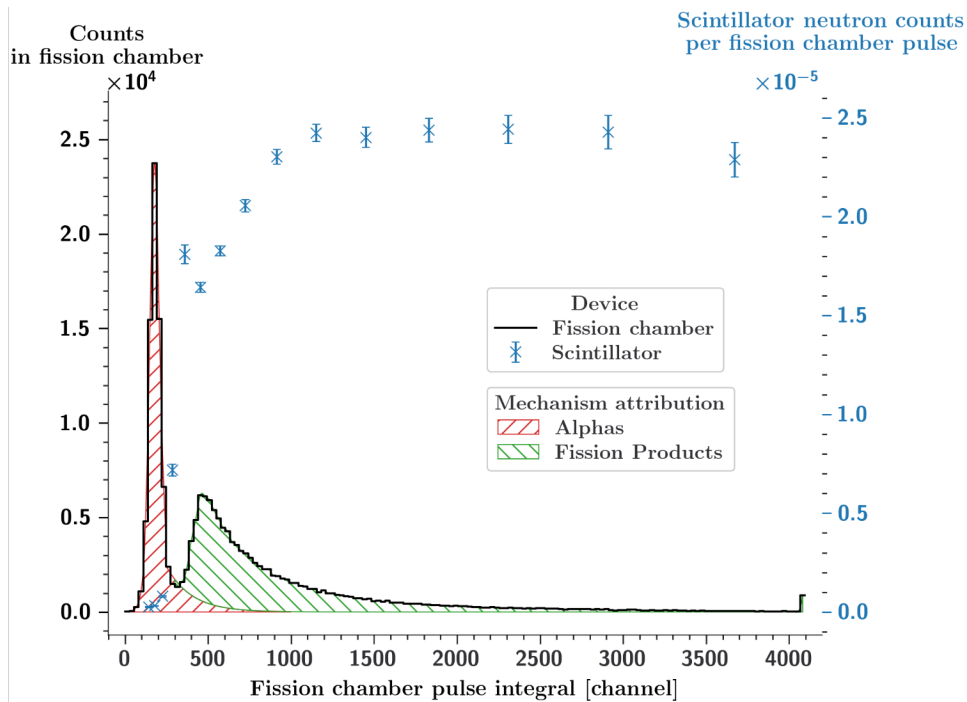


Figure 4: Pulses generated by the fission chamber include contributions from fission products as well as lower-energy alpha and potentially beta decays. To exclude non-fission events, an appropriate pulse integral threshold must be applied.

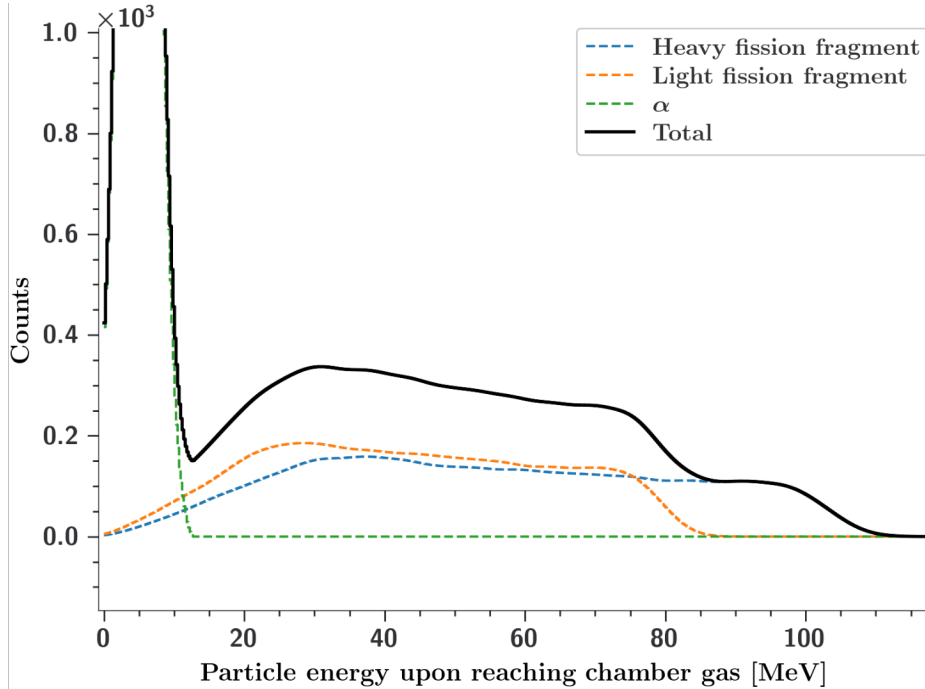


Figure 5: Simulated energy spectra of fission fragments and alpha particles emerging from a 3.5 μm thick electroplated ^{252}Cf layer, based on a simplified MCNP model.

3.3.2. Scintillator Absolute Neutron Detection Efficiency

By tagging on fission events and using the determined , the absolute neutron detection efficiency can be determined. The effect of fission chamber pulse amplitude threshold on calculated efficiency is shown in Figure 6. A threshold of channel 1100 was selected based on the rationale described in Section 3.3.1. With the ability to tag exclusively on fission events, the absolute neutron detection efficiency of a 2x2-inch stilbene scintillator to ^{252}Cf neutrons at a distance of 129 cm is measured to be $(2.52 \pm 0.1) \times 10^{-3} \%$, corresponding to an intrinsic neutron detection efficiency of $17.1 \pm 0.5 \%$ for fission-spectrum neutrons.

Because this efficiency is used to determine the emission rates of commercial ^{252}Cf sources, a potential concern is the difference in neutron energy spectra due to contributions from ^{250}Cf and ^{248}Cm in the aged fission chamber, which are not present in significant quantities in newer commercial sources. To assess whether these isotopic contributions significantly alter the fission neutron energy spectrum, simulations were performed using the GEF (Schmidt, Jurado, Schmitt, & Amouroux, 2016) code. As shown in Figure 7, the resulting spectral differences are negligible within experimental uncertainties. Therefore, the neutron efficiency determined using the fission chamber is valid for characterizing commercial ^{252}Cf sources.

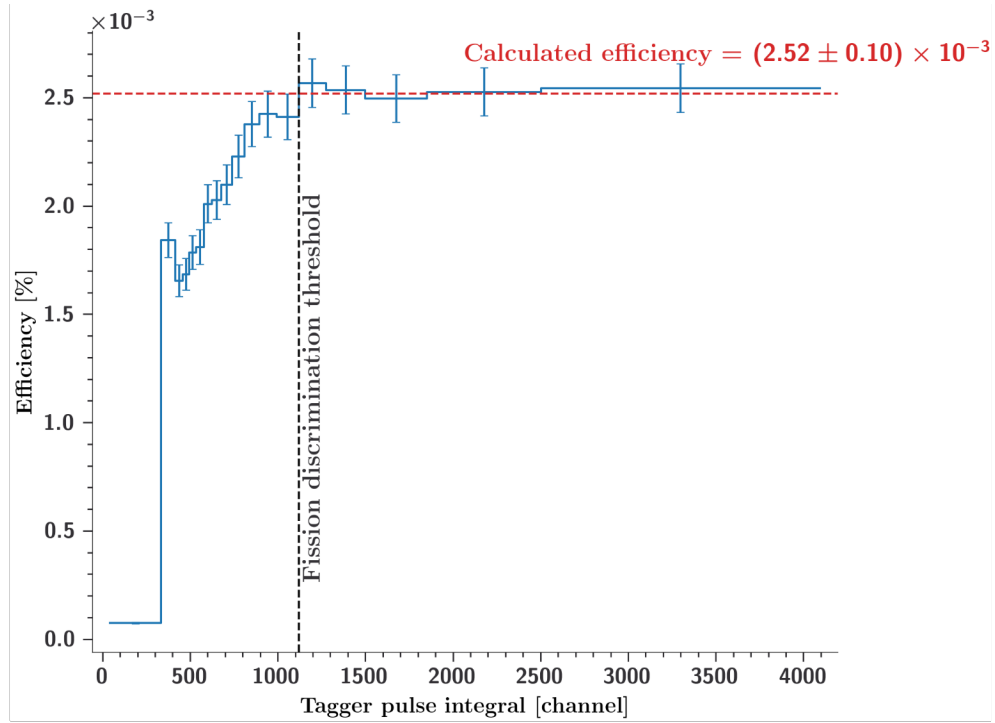


Figure 6: The appropriate pulse integral discrimination threshold excludes all non-fission events occurring within the fission chamber.

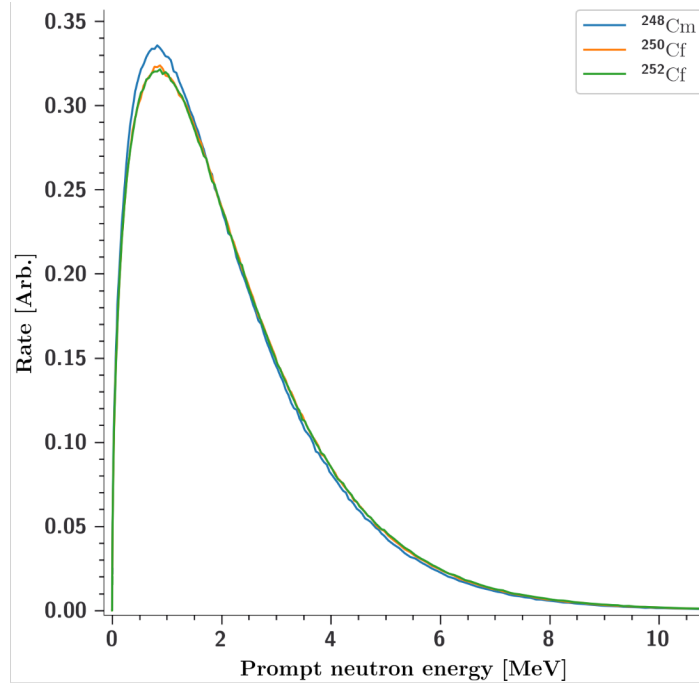


Figure 7: Prompt neutron energy distributions of isotopes that significantly contribute to the fission chamber's neutron rate, according to the GEF code. Spectral differences are minimal, supporting the use of the aged ^{252}Cf fission chamber as reference for the calibration of newer ^{252}Cf source.

4. COMMERCIAL ^{252}Cf SOURCE NEUTRON RATE MEASUREMENT

The stilbene scintillator, now with a calibrated absolute neutron detection efficiency for ^{252}Cf fission-spectrum neutrons, was used to measure the absolute neutron emission rates of three commercial ^{252}Cf sources. During these measurements, background counts were subtracted, and the same detector-to-source distance and PSD cuts were used for efficiency measurements, as shown in Figures 8 and 9. The measured neutron emission rates are generally 12 % greater than the decay-corrected value reported by the manufacturer. Measured emission rates for several ^{252}Cf sources are reported in Table 3. The calculation is summarized by the following equation:

where R_c is the rate of fission pulses in the chamber, R_{sc} is the rate of neutron detections in the scintillator in coincidence with fission pulses from chamber, R_{sc}^c is the rate of neutron detections in the scintillator while measuring commercial ^{252}Cf source emission rate, R_{sc}^0 is the rate of neutron detections with no source present, and ν_{eff} is the effective number of neutrons emitted per fission by the chamber.

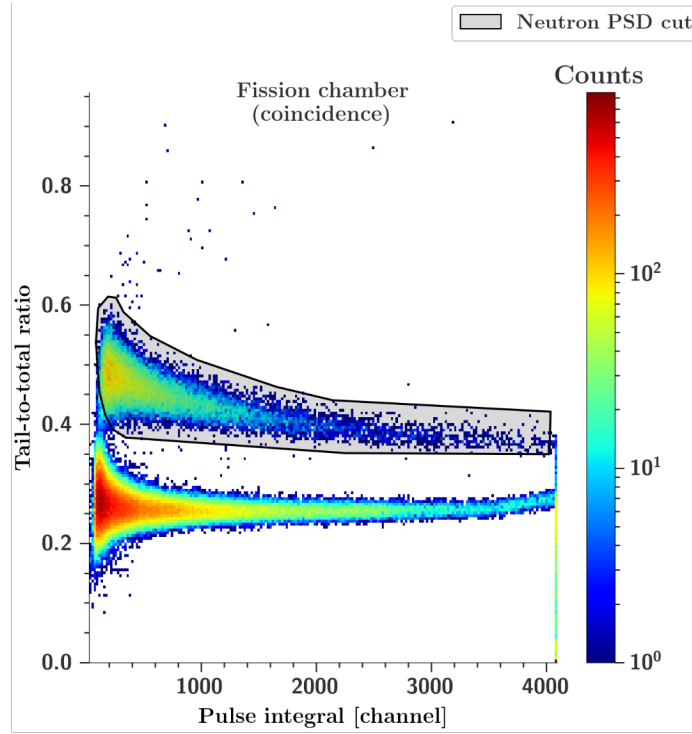


Figure 8: PSD histogram the fission chamber in coincidence with neutron detector.

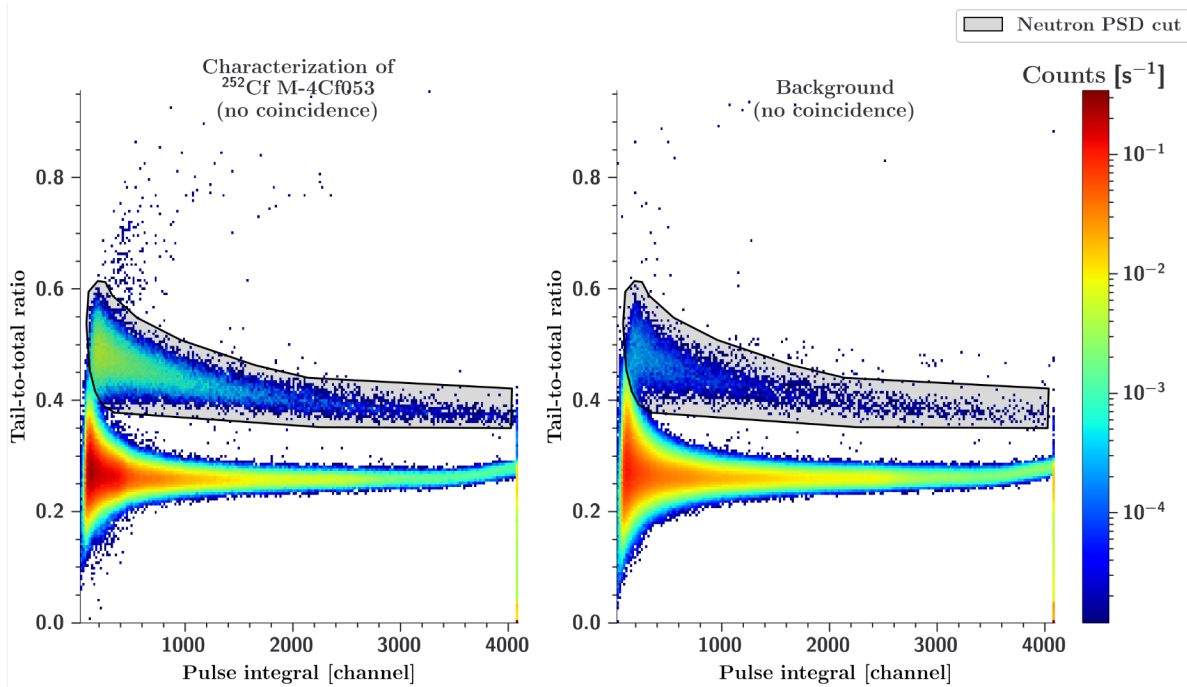


Figure 9: PSD histogram produced during the ^{252}Cf source characterization. The scintillator neutron detection efficiency determined using the tagged fission source is used to determine neutron emission rate.

Table 3: Measured neutron emission rates of commercial ^{252}Cf sources.

Source serial number	Date of measurement	Measured neutron rate []	Manufacturer reported neutron rate [1/s]
M-4Cf052	2024-07-15		
M-4Cf053	2024-10-14		
M-4Cf054	2024-07-10		

4.1. Consistency Checks

Several consistency checks were performed to validate the methodology and ensure the robustness of the measured emission rates. First, the detector efficiency was recalculated using a more stringent neutron PSD cut (Figure 10) and then applied during the measurement of the commercial ^{252}Cf sources. If significant gamma-ray contamination were present, tightening the PSD cut would have altered the measured rate. The results remained unchanged within statistical uncertainties, confirming that gamma-ray leakage into the neutron PSD window is negligible.

As a second check, the pulse integral distribution of neutrons from the untagged commercial ^{252}Cf sources was compared to that obtained from the fission chamber under coincidence (Figure 11). The distributions exhibit the same shape within uncertainties, confirming that the efficiency determined using the tagged source is applicable to untagged commercial sources. These consistency checks collectively support the validity of the calibration procedure and the resulting absolute neutron emission rate measurements.

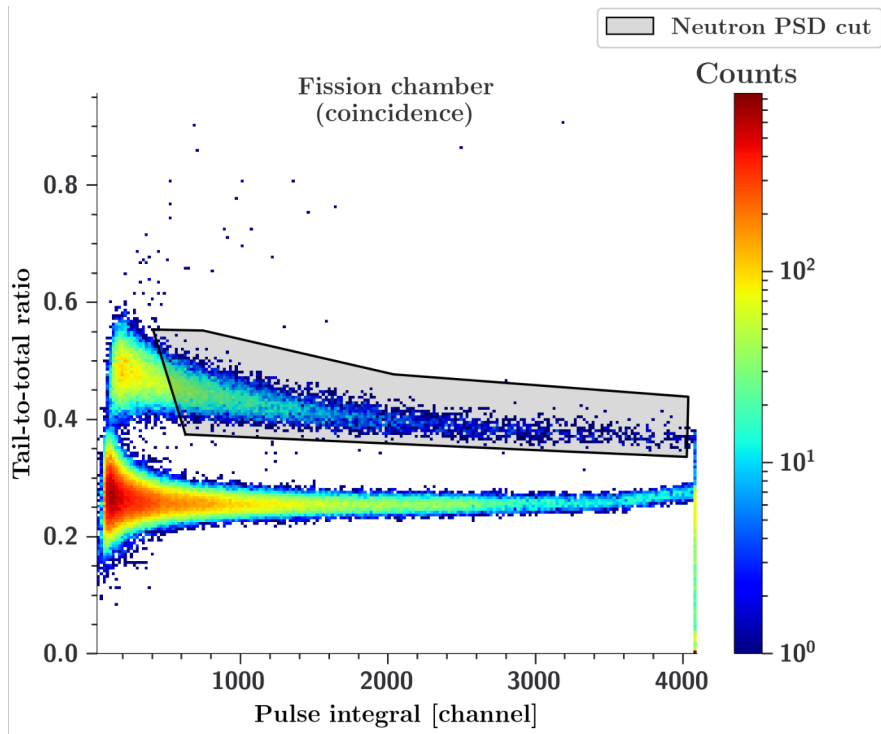


Figure 10: Applying a “stricter” neutron PSD cut does not alter the nominal neutron detection efficiency, (though it increases the associated uncertainties). The independence of the calculated efficiency from the specific PSD cut serves as a useful consistency check.

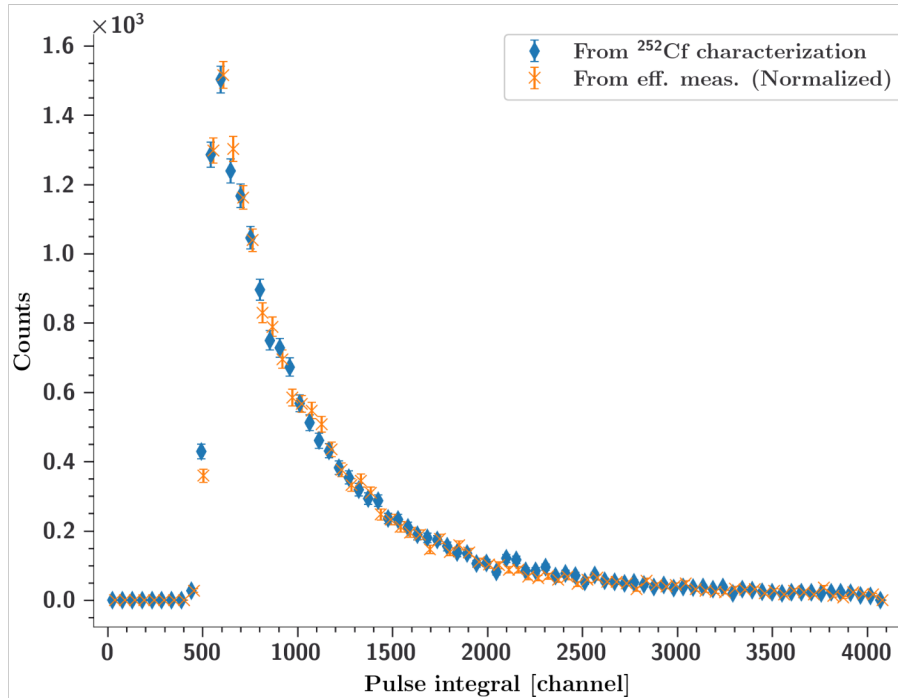


Figure 11: An additional consistency check is provided by comparing the neutron pulse integral distributions obtained using the fission chamber in coincidence with the scintillator during the efficiency measurement (blue \blacklozenge), and without coincidence during the measurement of a ^{252}Cf source neutron rate (orange \times).

5. CONCLUSION

This work presents a robust and practical methodology for establishing uncertainty-quantified neutron emission rates of commercial ^{252}Cf sources. By using a PSD-capable stilbene scintillator calibrated against a time-tagged ^{252}Cf fission chamber, uncertainty quantified measurements of absolute neutron emission rates is achieved. The calibration process accounted for the isotopic evolution of an over 40-year-old fission chamber, enabling accurate determination of the effective average number of neutrons per fission ($\bar{\nu}$) and its associated uncertainty. Looking forward, this approach can be extended to characterize other neutron-emitting isotopes and support the development of traceable neutron standards. Improved precision in the ^{250}Cf and ^{248}Cm could reduce uncertainty of the method.

This approach provides a self-consistent framework for characterizing ^{252}Cf sources without reliance on manufacturer-supplied data. This enables improved fidelity in neutron transport modeling, benchmark experiments, and other applications requiring a well-defined neutron source term, supporting long-term reproducibility and comparability of experimental data.

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