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Evaluation of Neutron Dose Rate Generated from Cf-252 Source Based on Theoretical Calculation Model

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Abstract

Californium-252 (Cf-252) is a spontaneous fission radioactive source that is utilized in both scientific and industrial fields due to its strong neutron emission. The MCNP code is widely used for simulating dose rates and designing radiation shielding to protect against radiation emitted by various radioactive sources, including Cf-252. This method, however, requires some knowledge of MCNP simulation techniques and detailed data about the radioactive source and shielding materials. Therefore, in this study, we propose a theoretical calculation method to rapidly estimate the neutron dose rate along the central axis of the Cf-252 source. At the same time, a TPS-451c neutron dose meter was used to evaluate the theoretical model's calculated values. The results show strong agreement between the experimental measurements and the theoretical calculations.

Keywords: Neutron dose rate; Cf-252; TPS-451c; Theoretical calculation model

1. Introduction

Assessing neutron dose rates is crucial for applications involving radiation protection, medical physics, and nuclear engineering. Californium-252 (Cf-252) is a widely used spontaneous-fission neutron source, notable for its intense neutron emission and broad applications, including calibration of neutron detection instruments, radiation therapy, and research [1]. Accurate knowledge of neutron dose rates from Cf-252 is essential to ensure safety and optimize experimental procedures. Theoretical neutron dose rate calculations for Cf-252 often use Monte Carlo simulation techniques to model neutron transport and interactions within specified geometries, such as water phantoms [2]. These simulations determine dosimetric parameters, including air kerma strength and dose rate constants, by considering neutron energy spectra, angular distributions, and source properties.

Experimental measurements typically utilize instruments calibrated to detect neutron flux and dose rates, supplying empirical data for dose rate verification. For example, Ngoc-Thiem et al. (2017) used the Aloka TPS-451c neutron meter [2], which features a ^{3}He detector and is widely valued for its reliable response across a broad neutron energy range (thermal to 15 MeV) and low photon sensitivity, making it suitable for neutron dose rate measurements in diverse radiation fields [2-3].

This study compares neutron dose rates from a Cf-252 source measured experimentally with a TPS-451c neutron meter to those derived from theoretical calculations. The objective is to verify the theoretical model's accuracy using empirical data and to assess uncertainties stemming from practical measurement conditions. These evaluations are essential for improving neutron dosimetry techniques, ensuring radiological safety, and enhancing the application of Cf-252 sources.

2. Materials and Methods

2.1. Materials

This study, which was conducted at the Training Center of the Nuclear Research Institute in Vietnam, used a cylindrical Californium-252 (Cf-252) radioactive source with an initial activity of 11.6 mCi, manufactured on May 19, 2011 [4]. The source's active core measures 3.4 mm in diameter and 3 mm in length, while the entire source has overall dimensions of 7 mm in diameter and 15 mm in length. Over time, the activity has significantly decreased due to radioactive decay, reaching the current level (23/5/2025) of 0.294 mCi, corresponding to a neutron emission strength of 1.27×106 n/s.

Figure 1. Experimental setup for determining neutron dose rate of Cf-252 source

To detect and assess the neutron dose rate in this work, a TPS-451c neutron dosimeter has been employed, which is a neutron survey meter designed mainly for neutron safety assessment and radiation protection. It utilizes a ^{3}He detector capable of measuring neutron energies from thermal levels up to 15 MeV. The device exhibits negligible sensitivity to photons, which ensures high specificity for neutron detection [3].

2.2. Methods

The neutron dose rate in air at a distance from the radioactive source is calculated by the formula [5]:

$$\dot{H}_0 = \frac{S \times q}{4\pi d^2} \quad (1)$$

In this formula, S represents the radioactive source strength (n/s), q denotes the ratio of equivalent dose rate to neutron flux ((mSv/h)/(n/cm^2/s)), and d indicates the distance between the radioactive source and the reference point (cm).

3. Results and Discussion

3.1. Ratio of equivalent dose rate to neutron flux

The ratio of the equivalent dose rate to the neutron flux depends on the neutron energy [6] and is usually calculated at a reference point 100 cm from the radioactive source. As is known, the neutron spectrum emitted by the Cf-252 source is continuous and follows the Watt distribution [7] in the range of 0 to 14 MeV [2]. It is similar to the continuous spectra of bremsstrahlung radiation from X-ray generators or beta particles emitted by radioactive isotopes; therefore, it is necessary to determine the average energy of these spectra. The integral ratio method, as described in our previous work [8], is employed for this calculation. Using this method, the average energy of the Cf-252 neutron spectrum was found to be 2.13 MeV, with numerator and denominator values of 3.33506 and 1.56713, respectively.

Using Origin software, we fitted the data from reference [6] in the 0.1–5 MeV energy range to 4 energy levels (0.1, 0.5, 1, and 5 MeV) to calculate the q value for the neutron energy of 2.13 MeV obtained earlier. Figure 2 presents the fitting curve and the model's correlation coefficient. Based on this fit, the q value at 2.13 MeV was determined to be 17.13, approximately 5% lower than the value of 18 reported in reference [5].

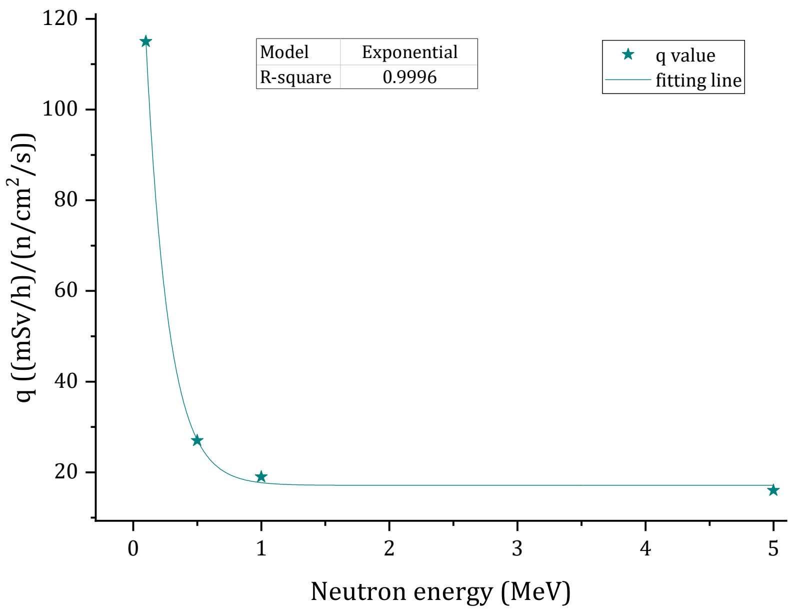

Figure 2. Ratio of equivalent dose rate to neutron flux versus neutron energy at 100 cm from the radioactive source

3.2. Evaluate neutron dose rate

After determining the q value for the 2.13 MeV average energy of the Cf-252 neutron spectrum, we employed Eq. (1) to calculate neutron dose rates at five reference points along the central axis of the source, positioned at distances of 90, 100, 120, 150, and 200 cm. The experimental neutron dose rate was obtained by first measuring the laboratory radiation background, followed by measurements with a Cf-252 radioactive source present. Each measurement type/location was repeated three times to calculate the average value and the associated uncertainty. Each background measurement duration was approximately 10 minutes, while measurements with the radioactive source ranged from 2 to 3 minutes, depending on the value of the neutron dose rate. After recording the measurements, a correction factor of 1.12 specific to the instrument was applied to the results. Finally, the processed data yielded the experimental results. The theoretical calculation values and experimental measurement results for the neutron dose rate of Cf-252 are presented in Table 1.

Table 1. Comparison of neutron dose rates between experimental measurement and theoretical calculation

Distance from Cf-252 source [cm]	Neutron dose rate [μSv/h]	
	Theoretical calculation	Experimental measurement
90	18.21	18.13 ± 0.31
100	14.75	15.00 ± 0.17
120	10.24	10.41 ± 0.17
150	6.55	6.91 ± 0.15
200	3.69	4.04 ± 0.11

As shown in Table 1 and Fig. 3, the experimental measurements of neutron dose rates at varying distances from the radioactive source follow the inverse square law function of distance and agree well with the theoretical calculation values. At all distances, the experimental means deviate only slightly from theoretical predictions, with the differences well within the reported uncertainties. For example, at 90 cm, the experimental dose rate is 18.13 ± 0.31 μSv/h, compared with a theoretical value of 18.21 μSv/h, demonstrating excellent agreement. At larger distances, such as 200 cm, the values of 4.04 ± 0.11 μSv/h (experimental) and 3.69 μSv/h (theoretical) remain in close alignment. This consistent agreement across the measured range indicates the theoretical model accurately predicts neutron dose rates and validates the reliability of the experimental procedures and instrumentation used.

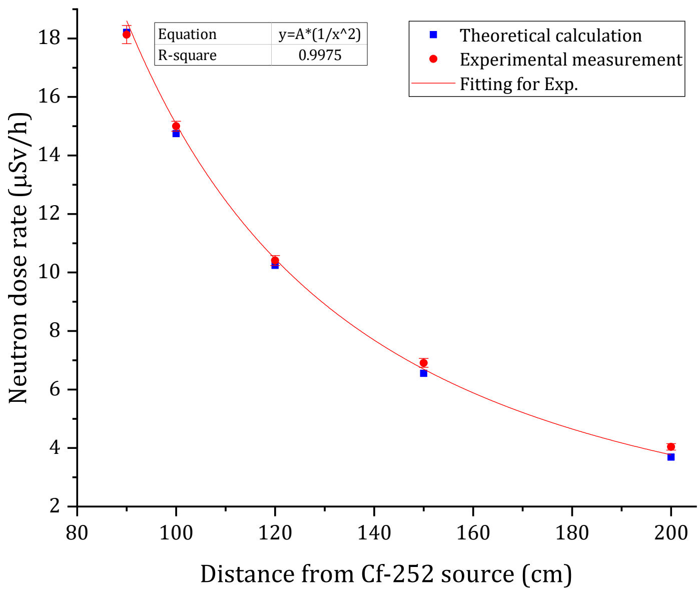

Figure 3. Comparison of experimental and calculated data

4. Conclusion

The experimental results for the neutron dose rate from Cf-252 show very good agreement with the theoretical calculations, confirming the accuracy of the computational models used. The theoretical calculation model for the neutron dose rate of the Cf-252 source offers several advantages. It provides a quick, efficient way to estimate neutron dose rates at varying distances without complex simulations, making it ideal for educational purposes and preliminary assessments. The model simplifies the process, allowing students and researchers to quickly assess radiation doses, saving time while maintaining sufficient accuracy for many practical applications. Overall, it serves as a valuable tool for both teaching and preliminary safety assessments involving Cf-252 neutron sources.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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