Development of a spherical tissue equivalent proportional counter for neutron monitoring Postprint

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Abstract

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Full Text

Development of a Spherical Tissue Equivalent Proportional Counter for Neutron Monitoring

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Abstract

A spherical tissue equivalent proportional counter (TEPC) for neutron monitoring has been developed. The detector was properly designed to produce uniform electric field intensity around the anode wire. An internal ^{241}Am alpha source was adopted for lineal energy calibration. The TEPC was characterized in terms of dose equivalent response in a standard ^{252}Cf neutron field and tested with 2.45 MeV neutrons. Microdosimetric spectra, frequency-mean lineal energy, and dose-average mean lineal energy of 2.45 MeV neutrons were obtained and compared with FLUKA Monte Carlo simulation results. The measurement and simulation results agreed well. The mean quality factor and dose equivalent values evaluated from the 2.45 MeV neutron measurement were in good agreement with the recommended effective quality factor and ambient dose equivalent H*(10), respectively. Preliminary results have proved the availability of the developed TEPC for neutron monitoring.

Keywords: Neutron monitoring, Tissue-equivalent proportional counters, Dose equivalent response, FLUKA simulation, Microdosimetric spectra, Mean quality factor
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INTRODUCTION

Tissue-equivalent proportional counters (TEPCs) are widely used in radiation protection and radiation biology. In neutron monitoring, real-time dosimeters are vital for radiation protection. Most conventional instruments employ a thermal neutron detector inside a large polyethylene sphere. These moderator-based devices convert their response to dose equivalent through simple calibration in a reference neutron spectrum, assuming this calibration remains valid for other fields. Obviously, such neutron dosimeters are applicable only to limited situations and may produce large errors in some cases. Additionally, these instruments are usually too heavy to handle.

Unlike traditional dosimeters, low-pressure TEPCs for neutron radiation protection are based on simultaneous measurement of absorbed dose D and mean quality factor Q. The dose equivalent H is calculated using Eqs. (1)-(3):

$$H = D \times \bar{Q}$$

where y is lineal energy defined as the quotient of energy imparted   to matter in a volume from a single energy deposition event divided by the mean chord length $\bar{l}$ in that volume ($\bar{l}$ = 2/3 µm for a spherical cavity equivalent to a tissue cell of 1 µm); d (in µm) is the inner diameter of the TEPC; n(y_i) is the number of counts within interval y_i; Q(y) is the quality factor defined as a function of linear energy transfer (LET) recommended in International Commission on Radiological Protection Publication 60; and f(y) is the probability density function of lineal energy y.

Consequently, TEPCs are promising candidates for neutron radiation protection. In this work, a spherical TEPC was developed. The prototype detector was characterized using a built-in ^{241}Am alpha source and a standard ^{252}Cf field. The TEPC was further characterized with 2.45 MeV neutrons, and its performance was satisfactory.

II. EXPERIMENTS

A. Detector Configuration

The Benjamin design was employed in the spherical TEPC to maintain a spatially uniform multiplication process around the anode wire. Figure 1 [Figure 1: see original paper] shows a sketch and photograph of the TEPC. With an inner diameter of 44.8 mm, the TEPC is constructed of A-150 (Shonka) plastic with a wall thickness of 3.0 mm. A single tungsten wire (25 µm diameter, gold-coated) serves as the anode. An outer stainless steel shell of 3.0 mm thickness ensures airtightness. A sealed mode, rather than gas-flow system, was employed for portability. The system leak rate was measured at $< 10^{-13}$ Pa$\cdot$m^3/s, ensuring stable operation of the TEPC. A ^{241}Am alpha source is attached to the outside wall for energy calibration. Most alpha particles can enter the cavity through a 1 mm diameter hole in the cathode wall. In this work, the TEPC was temporarily flushed with methane-based tissue equivalent (MTE) gas (64.4% CH_4, 32.4% CO_2, 3.2% N_2) at 2.12 kPa to simulate 1 µm soft tissue, meaning the energy deposited by a charged particle along the TEPC diameter is equivalent to the energy absorbed in 1 µm soft tissue. An absolute barometer measured the MTE gas pressure from 0 to 100 kPa with a precision of 0.01 kPa.

B. Experiments in Reference ^{252}Cf Field

Dose equivalent response R__H is defined as the ratio of the dose equivalent reading of a TEPC to the ambient dose equivalent H*(10) at the same point. R__H of the TEPC was measured in a standard bare ^{252}Cf neutron radiation field. The neutron emission rate of the ^{252}Cf source is approximately 4.86×10^6 s^{-1}. In this measurement, the TEPC was tested with the electronic system shown in Figure 2 [Figure 2: see original paper]. The detector pre-amplifier (ORTEC 142PC) was placed in the irradiation room, and the TEPC was positioned 30 cm from the ^{252}Cf source. A 40-m signal cable connecting the pre-amplifier and amplifier introduced significant noise to the measuring system. This noise was measured after the experiment and subtracted from the measured neutron pulse height distribution.

C. Measurements in Mono-Energetic Neutron Field

The TEPC was tested with 2.45 MeV neutrons generated by the d(d, n)p reaction. A schematic layout of the experimental arrangement is shown in Figure 3 [Figure 3: see original paper]. Deuterium ions were accelerated to bombard a deuterium target, producing 2.45 MeV neutrons. The TEPC detector was placed 20 cm from the target. A Si(Au) surface barrier detector (SBD) monitored total neutron yields by recording protons at 135° to the beam incidence and 1 m from the target. Photo event contamination for an accelerator-based neutron source was assumed negligible.

III. RESULTS AND DISCUSSION

A. Characterization of the TEPC with Built-In ^{241}Am Alpha Source

Calibration of the TEPC was performed using the ^{241}Am alpha source. Due to the extremely low pressure of MTE gas in the TEPC, alpha particles lose only a fraction of their kinetic energy in the gas cavity. A typical pre-amplifier output signal (142-PC) for the ^{241}Am alpha source is shown in Figure 4 [Figure 4: see original paper].

Energy deposition of 5.48 MeV alpha particles from ^{241}Am in the gas cavity was simulated using FLUKA codes. In the simulation, sampling alpha particles were directed into the TEPC along the cavity diameter. The resulting energy deposition distribution is plotted in Figure 5 [Figure 5: see original paper]. It can be seen that an average alpha particle traversing 44.8 mm in the TEPC cavity deposits 85.11 keV. Consequently, the lineal energy is y_α = energy deposited/mean chord length = 85.11 keV/(2/3) µm = 127.67 keV/µm. The lineal energy calibration y_I with channel I in the MTE-filled TEPC is thus given by:

$$y = \frac{127.67\ \mathrm{keV/\mu m}}{I_\alpha} \times I$$

where I_α is the channel number corresponding to the ^{241}Am alpha peak. In calibration, the TEPC counting rate for the built-in ^{241}Am alpha source is about 1.2 cps. For an accurate I_α value, data collection time should be no less than 20 minutes. At a bias of 730 V, the lineal energy per channel using Eq. (4) was 0.152 keV/µm. With an MCA of 2048 channels, the measured lineal energy can be extended from 0.2 keV/µm to 300.0 keV/µm in a single measurement. The measured alpha peak with the TEPC biased at 730 V is shown in Figure 6 [Figure 6: see original paper].

B. Dose Equivalent Response of the TEPC in ^{252}Cf Neutron Field

The direct output of TEPC measurement is pulse height distribution, also known as energy deposition spectra. The TEPC measurement of a ^{252}Cf source is shown in Figure 7 [Figure 7: see original paper]. After subtracting photo components from the ^{252}Cf source and electronic noise, the lineal energy y_i and counts n_i for each channel were calculated using Eq. (4). Absorbed dose D, mean quality factor Q, and dose equivalent rate were derived using Eqs. (1)-(3). From the ^{252}Cf source measurement, we obtained H_{TEPC} rate = 19.2 µSv/h and H*(10) rate = 17.6 µSv/h.

It should be noted that the reference H*(10) rate for* ^{252}*Cf neutrons at the same point was 17.6 μSv/h, giving a dose response of the TEPC to* ^{252}*Cf neutrons of R_H = 1.1. This indicates good approximation of the TEPC dose equivalent rate reading to the* $H(10)$ rate in ^{252}Cf reference neutron fields.

C. Characterization of TEPC in Mono-Energetic Neutron Field

1. Microdosimetric Spectra and Mean Lineal Energy Figure 8 [Figure 8: see original paper] shows the measured pulse height distribution of 2.45 MeV neutrons. Frequency-mean lineal energy ȳ_f and dose-average lineal energy ȳ_d were estimated from the measurement using Eqs. (5) and (6):

$$\bar{y}_f = \frac{\sum_{i=1}^{N} y_i \times f(y_i)}{\sum_{i=1}^{N} f(y_i)}$$

$$\bar{y}_d = \frac{\sum_{i=1}^{N} y_i \times d(y_i)}{\sum_{i=1}^{N} d(y_i)}$$

where f(y) is the probability density function of lineal energy:

$$f(y_i) = \frac{n_i}{\sum_{i=1}^{N} n_i}$$

and d(y) is the dose distribution:

$$d(y) = y \times f(y)$$

The measured and simulated mean lineal energies are given in Table 1 . In general, the measurement results agree well with simulation, being just 8.8% less than the simulated ȳ_f and 6.9% larger than the simulated ȳ_d. The measured and simulated microdosimetric spectra are shown in Figure 9 [Figure 9: see original paper]. The two spectra fit well for the region > 40 keV/µm, though they differ relatively large in the region < 10 keV/µm, probably due to photo events which were omitted in the FLUKA simulation. The falling slope near 100 keV/µm, referred to as the proton edge, is attributed to recoil protons generated in the A-150 plastic that stop exactly at the border between A-150 and MTE gas after traversing a random diameter of the cavity. Due to the Bragg effect, these recoil protons deposit maximum energy. According to energy-range relations for protons in MTE gas, the proton energy was 72.6 keV for the TEPC simulating 1 µm tissue. The corresponding lineal energy was 108.9 keV/µm, which agrees well with both experimental and simulation results.

2. Mean Quality Factor and Dose Equivalent Absorbed dose D of 2.45 MeV neutrons to the TEPC was estimated at 1.9 mGy using Eq. (2). The mean quality factor was evaluated using Eq. (3) and compared with the effective quality factor Q_{eff}. The measured dose equivalent was obtained using Eq. (1). Ambient dose equivalent H*(10) estimated using fluence-to-H*(10) conversion coefficients was used for comparison. All results are listed in Table 2 . For mean quality factor, the evaluated value from measurement underestimated Q_{eff} by 21.8%, mainly attributed to the approximation of LET by y. Operating the TEPC at lower pressure with a simulated size of 0.5 μm or less may alleviate this problem. For dose equivalent values, the difference between results was 1.66%.

IV. CONCLUSION

We have developed a spherical TEPC for use as a neutron dosimeter for radiation protection purposes. The Benjamin design was employed to improve the energy resolution of the TEPC. The measured lineal energy can be extended from 0.2 keV/μm to 300 keV/μm in a single measurement when biased at 730 V. The dose equivalent response of the TEPC was found to be 1.1 in the ^{252}Cf reference field. Microdosimetric spectra, frequency-mean lineal energy, and dose-average lineal energy of 2.45 MeV neutrons have been evaluated and show good agreement with FLUKA simulation results. Mean quality factor and dose equivalent H estimated from measurement agreed well with reference data.

Preliminary results indicate that the developed TEPC has sufficient accuracy to measure lineal energy distribution for absorbed dose and mean quality factor estimation. The evaluated dose equivalent can be used to approximate H*(10) for neutron radiation protection. Further characterization of the TEPC in low neutron fields around nuclear reactors is in progress.

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Note: Figure translations are in progress. See original paper for figures.