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Article title: DEVELOPMENT OF A HIGH-EFFICIENCY PROTON RECOIL TELESCOPE FOR D-T NEUTRON FLUENCE MEASUREMENT
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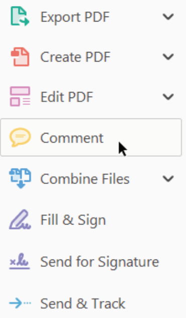

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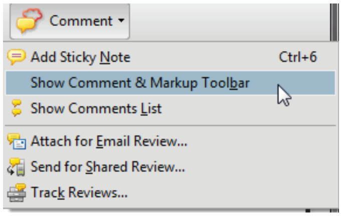

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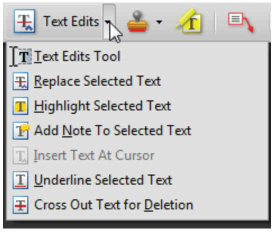

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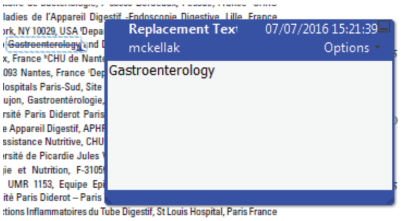

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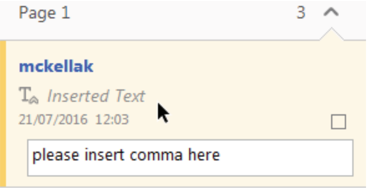

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Radiation Protection Dosimetry (2017), pp. 1–5 doi:10.1093/rpd/ncx278

DEVELOPMENT OF A HIGH-EFFICIENCY PROTON RECOIL TELESCOPE FOR D-T NEUTRON FLUENCE MEASUREMENT

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A high-efficiency proton recoil telescope was developed to determine neutron fluences in neutron fields using the ^{3}H(d,n)^{4}He reaction. A 2-mm thick plastic scintillation detector was employed as a radiator to increase the detection efficiency and compensate for the energy loss of the recoil proton within. Two silicon detectors were employed as the Δ*E* and *E* detectors. The distance between the radiator and the E detector was varied between 50 and 150 mm. The telescope had detection efficiencies of 3.5×10^{-3} and 7.1×10^{-4} cm^2 for distances of 50 and 100 mm, respectively, which were high enough to determine the neutron fluence in 14.8-MeV neutron fields, with a few thousand cm^{-2} s^{-1} fluence rate, within a few hours.

INTRODUCTION

Mono-energetic neutron calibration fields have been developed between 8 keV and 19 MeV using a 4-MV Pelletron accelerator at the Facility of Radiation Standards (FRS) of the Japan Atomic Energy Agency (JAEA) according to ISO 8529-1(1–4). The 14.8- and 19-MeV neutrons are produced by the ^{3}H (d,n)^{4}He reaction (D-T reaction). Neutron fluence is the reference quantity for the calibration of neutron measurement instruments and should be precisely experimentally determined in calibration fields. The proton recoil telescope (PRT) has been widely used to determine the fluence of mono- or quasi-mono-energetic neutrons above a few MeV, and the typical PRT consists of a radiator to generate recoil protons, a Δ*E* detector to separate the signals of recoil protons from those of other charged particles and an *E* detector to measure the recoil proton energy(5).

A typical PRT employs a thin radiator to minimize the proton energy loss in the radiator, which degrades the energy resolution. However, a thin radiator decreases the detection efficiency (typically 10^{-5} cm^2) of PRTs(5). Recently, a high efficient PRT was developed by enlarging the detection solid angle of the recoil proton using pixel sensors, but the efficiency is still up to 10^{-4} cm^2(6). The low detection efficiency hinders the achievement of enough detection counts to determine the neutron fluence within a practical time. A detection efficiency of ~5×10^{-4} cm^2 is necessary to obtain more than 10 000 counts (corresponding to a statistical uncertainty of 1% error) within a few hours in a neutron fluence rate of a few thousand cm^{-2} s^{-1}. To improve the detection efficiency, a thick hydrogenous detector such as a plastic scintillator (PS) or methane-filled proportional counter can be used as a radiator, and the proton energy loss is compensated by using the output of the detector(7–9). A PRT called COTETRA, developed by Osakabe, achieved a detection efficiency of 1.3×10^{-4} cm^2(10). However, this was low for our purposes. Moreover, the COTETRA, which consists of a PS as a radiator and a silicon detector as an *E* detector, requires another background measurement to eliminate the random coincidence events, through the insertion of a Ta recoil proton stopper between the detectors.

Therefore, we developed a high-efficiency PRT (HEPRT) for the fluence measurement of the D-T neutrons in the range from 14 to 19 MeV. The radiator is a thick PS to make the detection efficiency higher than that of the COTETRA. A Δ*E* detector is used instead of a Ta stopper to easily discriminate the signals of the recoil protons produced in the radiator. No more background measurement is therefore required allowing more time to perform foreground measurements. This study describes the design of the HEPRT and its performance examined in the 14.8-MeV mono-energetic neutron calibration field at the FRS/JAEA.

DETECTOR DESIGN

A schematic drawing of the HEPRT is shown in Figure 1. All components, except the photomultiplier tubes (PMTs), are placed in a vacuum to reduce the energy loss of the recoil protons in the air between each detector. The vacuum chamber has an outer diameter of 11.5 cm and a length of 26.4 cm. The 2-mm thick radiator with dimensions of 52 mm in width and length is made of a BC-408 plastic scintillator. The thicknesses of the PS was determined by considering the stopping power of the initial 14.8-MeV proton. For accurate determination of neutron fluence, materials between the neutron source and the

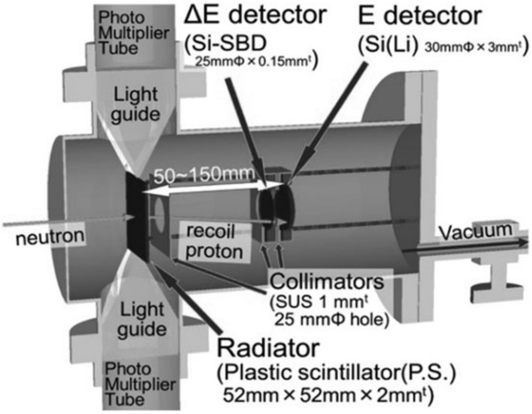

Figure 1. Schematic drawing of the HEPRT.

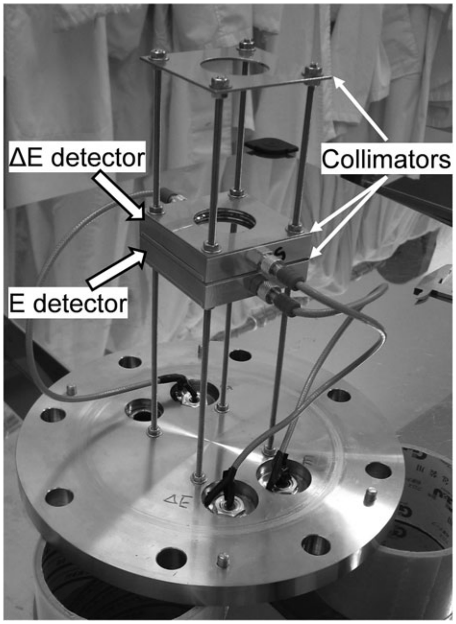

Figure 2. Photograph of the collimators and ΔE and E detectors.

radiator should be avoided as most as possible because they could scatter the neutrons before they enter the radiator and increase the uncertainty. Therefore, the entrance window of the vacuum chamber made of stainless steel was minimized down to 1 mm. Two light guides are settled on both sides of the PS, to lead the light signal of the recoil protons to the PMTs connected to the light guides. The ΔE detector is a transmission type silicon surface barrier detector with a sensitive area of 490 mm^2 and a depletion layer depth of 150 μm. The E detector is a lithium-drifted silicon detector, with a sensitive area of 700 mm^2 and a depletion layer of 3 mm which is thick enough to stop a 20-MeV proton. Three collimators are placed between the radiator and the E detector to precisely determine the solid angle of the recoil protons which directly affects the detection efficiency. The 1-mm thick collimators are made of stainless steel with a 25-mm diameter hole. The first collimator is placed ~25 mm from the radiator exit, the second is set on the entrance of the ΔE detector, and the third is placed between the ΔE and E detectors.

The collimators and ΔE and E detectors are fixed by four long bolts used as their guide rails and 16 nuts and flat washers as shown in Figure 2. The distance from the radiator to the E detector can be varied from 50 to 150 mm by adjusting the nut positions.

EXPERIMENTAL PROCEDURE

The detection efficiency of the HEPRT was calibrated at the 14.8-MeV mono-energetic neutron calibration field of the FRS/JAEA. The 14.8-MeV neutrons were produced by bombarding a deuteron beam onto a tritium target made of tritium absorbed in a titanium layer. The HEPRT was set at a calibration point ~900 mm away from the tritium target at an angle of 45° to the beam line as shown in Figure 3. Measurements were made with a deuteron beam current of 5 μA and irradiation time of ~8000 s. The neutron fluences at the HEPRT during the experiments were determined using the neutron monitor installed in the irradiation room as shown in Figure 3(3, 11). The relationship of the monitor counts to the neutron fluence at the calibration point was determined by the fluence measurement using the Bonner sphere whose fluence response was calibrated at the Japanese primary standard laboratory.

A block diagram of the HEPRT measurement system is shown in Figure 4. The amplifier gains of both PMTs were adjusted identically by matching the pulse heights of the Compton edge of the ^{137}Cs gamma ray measured using each PMT(10). The output signals from both PMTs were summed and delayed to synchronize the signal of the PS with those of the ΔE and E detectors using the sum and delay module. The pulse height of the signals from the PS, ΔE and E detectors were digitized by three analog-to-digital converters. The digitized pulse-height data from each detector for each event was recorded in a list mode with the multiparameter multichannel analyser system (FAST ComTec MPA-3). The recoil proton energy was obtained by summing the pulse heights of both PMTs connected to the PS and the ΔE and E detectors.

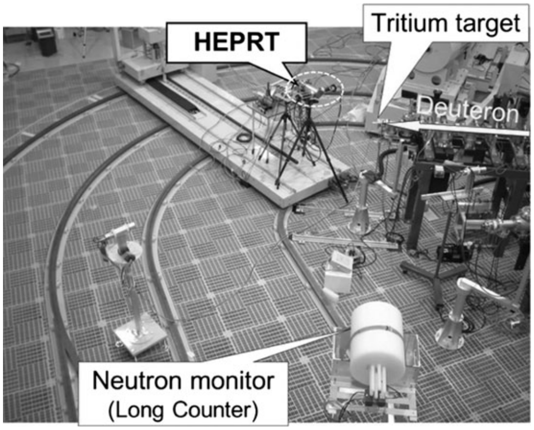

Figure 3. Experimental set-up for the performance test of the HEPRT in the 14.8-MeV mono-energetic neutron calibration field at the FRS/JAEA.

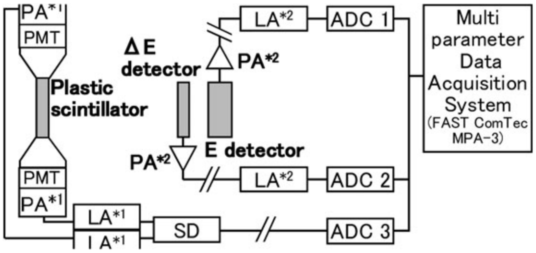

Figure 4. Block diagram of the HEPRT measurement system. The labels shown in this figure are as follows: PA^{*1}, photomultiplier base with preamplifier (ORTEC 276); PA^{*2}, preamplifier (CANBERRA 2003BT); LA^{*1}, dual amplifier (ORTEC 855); LA^{*2}, linear amplifier (ORTEC 572); SD, sum and delay amplifier (OKEN 719-1); ADC1 and ADC2, dual analog to digital converters (Fast ComTec 7072) and ADC3, analog to digital converter (CANBERRA 8715).

DETECTION EFFICIENCY CALCULATION

The detection efficiency of the HEPRT was calculated using the NRESP-ANT code(12–15). The NRESP-ANT code is a modified version of the NRESP code and can calculate the energy deposition of charged particles produced by neutron reactions in gas, liquid and solid detectors. It is practically used to determine the neutron fluence at the primary standard institute in Japan and is highly reliable in calculating detection efficiency(14).

RESULTS AND DISCUSSIONS

Figure 5 shows the measured pulse-height spectra of the PS, Δ*E* and *E* detectors compared to those calculated for a distance from the radiator to the *E* detector of 50 mm. The measured and calculated spectra are consistent for each detector. This provides that the recoil protons generated in the radiator were successfully measured by the HEPRT.

Figure 6 shows the recoil proton spectra obtained by summing the measured pulse heights of the PS, Δ*E* and *E* detectors. The vertical axis was normalized to the 14.8-MeV mono-energetic neutron fluence at the calibration point of the HEPRT. Distances between the radiator and the *E* detector were 50, 100 and 150 mm. The calibrated and calculated detection efficiencies and the measured energy resolutions are summarized in Table 1 for each distance. The measured detection efficiencies are consistent with those calculated by NRESP-ANT code. The energy resolution improves with distance due to the decrease of the solid angle of the recoil proton. In the 14.8-MeV neutron calibration field, nuclear reactions in a target such as ^{48}Ti(d,n)^{49}V and ^{2}H(d, n)^{3}He can produce unwanted neutrons(16). As the energies of these neutrons are below 10 MeV, an energy resolution of a few MeV is required to distinguish 14.8-MeV neutrons from these unwanted neutrons. This can be achieved by the HEPRT if the

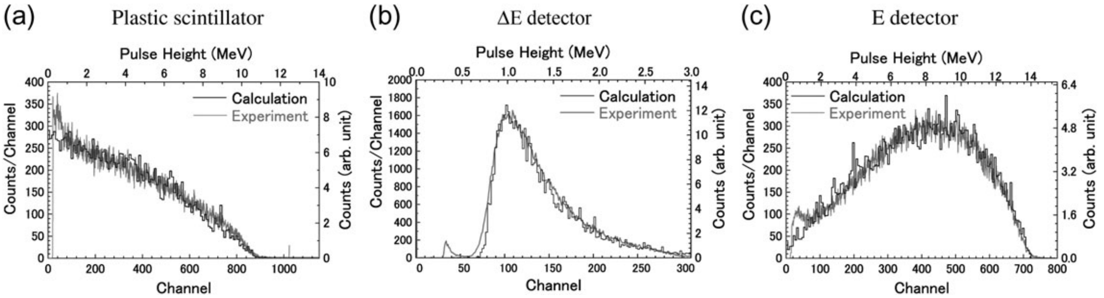

Figure 5. Pulse-height spectra of plastic scintillator, Δ*E* detector and *E* detector measured in the 14.8-MeV mono-energetic neutron calibration field and calculated using NRESP-ANT code. The distance between the radiator (plastic scintillator) and *E* detector was set to 50 mm. (**a**) Plastic scintillator, (**b**) Δ*E* detector and (**c**) *E* detector.

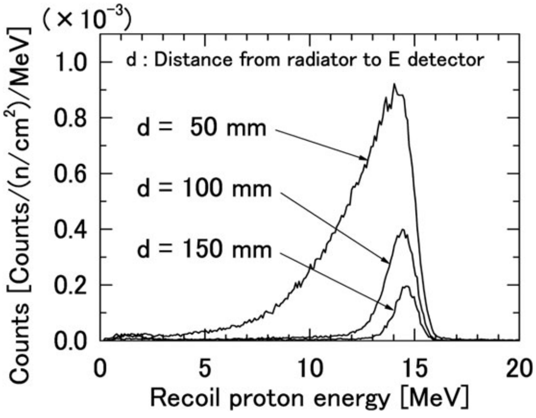

Figure 6. Recoil proton spectra measured in the 14.8-MeV mono-energetic neutron calibration field at the FRS in the JAEA.

Table 1. Detection efficiency and energy resolution of the HEPRT for 14.8-MeV mono-energetic neutrons.

Radiator to *E* detector distance (mm)	Detection efficiency (cm^2)		Energy resolution (MeV)
	Calibrated	Calculated	
50	$(3.5 \pm 0.2) \times 10^{-3}$	3.7×10^{-3}	4.43 (30%)
100	$(7.1 \pm 0.4) \times 10^{-4}$	6.9×10^{-4}	1.86 (13%)
150	$(2.8 \pm 0.2) \times 10^{-4}$	2.7×10^{-4}	1.16 (7.8%)

distance from the radiator to the *E* detector is >100 mm. However, the detection efficiency decreases with this distance down to 2.7×10^{-4} at 150 mm. This is due to lower number of recoil protons entering the *E* detector. At a distance of 100 mm, the detection efficiency is 7.1×10^{-4} and is sufficient to determine the neutron fluence at 14.8 MeV-neutron fields with fluence rates of a few thousand cm^{-2} s^{-1} within a few hours. As a compromise, the distance of 100 mm is the best option for the HEPRT at 14.8 MeV allowing both acceptable energy resolution and detection efficiency which is a few orders of magnitude higher than for most of PRTs.

SUMMARY

A HEPRT has been developed for accurate determination of neutron fluences in neutron fields using the ^{3}H(d,n)^{4}He reaction in the energy range from 14 to 19 MeV. A 2-mm thick plastic scintillation detector (BC-408) is used as a radiator to increase the detection efficiency and compensate for the energy loss of the recoil proton. Two silicon detectors with depletion layers of 150 μm and 3 mm thick are used as ΔE and E detectors, respectively. The distance between the radiator and the E detector is variable from 50 to 150 mm. The performance tests of the HEPRT were studied at the 14.8-MeV mono-energetic neutron calibration field of the FRS/JAEA, showing a good agreement between experimental data and simulations with the NRESP-ANT code. The energy resolution of the HEPRT was high enough to distinguish the 14.8-MeV neutrons from the unwanted neutrons whose energies were below 10 MeV when the distance was >100 mm. The HEPRT had detection efficiencies of 3.5×10^{-3} and 7.1×10^{-4} for the distances of 50 and 100 mm, respectively, and were high enough to precisely determine the neutron fluence in 14.8-MeV neutron fields with fluence rates of a few thousand cm^{-2} s^{-1} within a few hours. The distance of 100 mm is most suitable for the HEPRT to determine the neutron fluence at 14.8-MeV field of the FRS/JAEA considering both the energy resolution and the detection efficiency. The neutron fluence measurement at 19-MeV field is planned using the developed HEPRT in further studies.

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