Radiation Measurements 119 (2018) 16–21

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Experimental characterization of a long counter for neutron fluence measurement

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ARTICLE INFO

Keywords:
Long counter
Calibration
Response function
Effective center

ABSTRACT

A De Pangher-type long counter was constructed at Peking University for neutron fluence measurement. The responses and effective centers of the long counter were calculated using the Monte Carlo method. The variations with neutron energy of the position of the effective center, calculated by the Monte Carlo code, was experimentally validated with a ^{241}AmBe neutron source and several mono-energetic neutron sources ranging from 100 keV to 6 MeV. Long counter calibration was performed using a radionuclide source from Peking University, and neutron fluence measured by the calibrated long counter was successfully compared to values determined with reference instruments (two recoil proton counters and a ^{238}U fission chamber). The relative deviations were lower than 6% along the whole energy range. The calibrated long counter was thus successfully applied in the calibration of a Bonner sphere spectrometer.

1. Introduction

Experimental validation of the response function of a Bonner sphere spectrometer was performed in the experimental hall of Peking University at six mono-energetic neutron fields ranging from 100 keV to 20 MeV provided by a 4.5-MV Van de Graaff accelerator (Hu et al., 2014b, 2017) at the State Key Laboratory of Nuclear Physics and Technology. Neutron fluence measurement devices should be employed to determine the neutron fluence value at the measurement position of the Bonner sphere spectrometer (Alevra and Thomas, 2003; Birattari et al., 2010; Klein and Thomas, 2003; Lacoste et al., 2004). Two types of reference devices, namely two recoil proton proportional counters and one ^{238}U fission chamber (Hu et al., 2017; Zhang et al., 2011), were used to measure neutron fluence within energy ranges from 100 keV to 1 MeV and from 2 MeV to 20 MeV, respectively. They were designed by China Institute of Nuclear Energy and the two counters were traceable to international standards (Ryves, 1987). The uncertainty on the neutron fluence is approximately 2% with the counters (Chen et al., 2007) and 3% with the fission chamber. This chamber is made of a 2-cm diameter ^{238}U sample attached to the inner face of a copper cylinder box. The ^{238}U sample has a mass of (547.2 ± 1.3%) μg with enrichment greater than 99.997% (Zhang et al., 2011). To provide reference fluence values between 1 MeV and 2 MeV, a calibrated long counter was selected, and the range of use varied from a few eVs/keVs to 20 MeV.

The long counter has been widely applied in neutron fluence measurement due to characteristics such as a relatively flat response in a wide neutron energy range between a few eVs or keVs and a few MeVs; insensitivity to gamma rays with an appropriate threshold; and good stability (Tagziria and Thomas, 2000). The Hanson and McKibben (1947) and De Pangher (De Pangher and Nichols, 1966) types of long counters have been employed as standard instruments in many laboratories (Gressier et al., 2014; Nolte and Thomas, 2011; Roberts et al., 2010; Tagziria and Thomas, 2000). They are based on a cylindrical moderator, usually made of paraffin or polythene materials with a thermal neutron tube in the center. The moderator is embedded in an additional shield to reduce sensitivity to room-scattered neutrons and endow the counter with high efficiency to neutron incidents from the front face along the axis. The response of long counters can be roughly independent of energy, up to 3 MeV–5 MeV depending on type. Recently, some newly developed long counters have also been reported in the literature (Gressier and Lacoste, 2014; Harano et al., 2011; Hu et al., 2014a; Kim et al., 2012; Lacoste, 2010; Lacoste and Gressier, 2010; Mazunga et al., 2017; Tanimura et al., 2014), using Monte Carlo simulations to either optimize the geometry or employ new materials.

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https://doi.org/10.1016/j.radmeas.2018.08.017
Received 4 November 2017; Received in revised form 24 August 2018; Accepted 28 August 2018
Available online 29 August 2018

A long counter based on the De Pangher design was constructed at Peking University to calibrate a Bonner sphere spectrometer and for other applications. This long counter, which generally does not have a perfectly flat response over a wide energy range, needed to be experimentally calibrated because its efficiency cannot be derived from first principles like recoil proton telescopes (Roberts et al., 2010). For any feasible fluence measurement, the effective center of the long counter, depending on the counter design and neutron energy, should also be accurately determined by combining measurements and detailed Monte Carlo simulations (Roberts et al., 2010; Tagziria and Thomas, 2000). In this paper, Monte Carlo simulations were performed to determine the fluence responses and effective centers as a function of neutron energy. Simulations were then validated by measurements at eight mono-energetic neutron fields between 100 keV and 14.0 MeV as well as in front of a ^{241}AmBe radioactive source. Good agreement was obtained between the experimental and simulated values.

2. Materials and methods

2.1. Construction of long counter

The schematic geometry and image of the De Pangher-type long counter are presented in Fig. 1. The cylindrical long counter measures 43 cm in length and 39 cm in diameter and consists mainly of a thermal neutron counter, two annular moderators, an outer annular shield, and three thermal neutron absorbers. The thermal neutron counter, manufactured by CENTRONIC Ltd., is a proportional tube with a diameter of 3.8 cm and a length of 45 cm, filled with ^{3}He gas at a pressure of 6 atm. The moderators and shield are made of polyethylene with a mass density of 0.93 g/cm^3. Boron loaded plastic, measuring 1 cm thick, is installed between the moderators and outer shield. A 0.6-mm thick rear cadmium sheet is inserted between the front and rear polyethylene moderators, and another cadmium sheet is mounted on the front face of the long counter. An annular trough is dredged in the front moderator. All parts of the long counter are supported and fixed with aluminum materials.

2.2. Monte Carlo simulations

Monte Carlo simulations were performed using the MCNP5 code (X-5 Monte Carlo Team, 2003). Detailed geometric parameters, including the dimensions and density of the materials, were described based on the design values. The standard cross-section data for most elements were taken from the ENDF/B-VII.1 library (Chadwick et al., 2011). All calculations were performed in a vacuum environment.

The response to neutron fluence was defined as the ratio of the detector reading (number of ^{3}He (n, p)^{3}H reactions) to the incident neutron fluence. In response function calculations, a parallel neutron beam starting from a disk with a 40-cm diameter irradiated the front face of the long counter along its axis, and the F4 and FM4 tally cards of MCNP5 were combined to derive the response values (Hu et al., 2014b, 2017).

The effective center, r_0, is defined as the position of the calibration point. The long counter is regarded as a point detector in the fluence measurements from a point neutron source, such that the count rate varies as $(r + r_0)^{-2}$, where r is typically the distance from the point source to the front face of the long counter (Lacoste and Gressier, 2010; Roberts et al., 2004; Tagziria and Thomas, 2000). In calculating effective centers, the inverse of the square root of the count rate against distance r was linearly fitted to yield the effective centers. The counts of the long counter at 51 distances were simulated. The pseudorandom number for each distance was different and randomly generated as in reference (Roberts et al., 2004). This method can overcome correlations between calculations at each distance by using the same pseudorandom number. At each distance, the calculation was separated into six runs with different initial random numbers.

2.3. Experimental setup

The experimental determination of the response and effective center values, which aimed to verify the calculated values, was carried out using a ^{241}AmBe source and eight mono-energetic neutron sources ranging from 100 keV to 14.0 MeV in the experimental hall (20 m long, 12 m wide, and 8 m high) at Peking University (Hu et al., 2017).

The neutron emission rate of the ^{241}AmBe source was determined to be $(6.94 \pm 0.75\%) \times 10^6$ s^{-1} on July 21, 2006 based on manganese bath equipment from China Institute of Atomic Energy (Roberts et al., 2011). The manganese bath equipment was applied in neutron emission rate comparisons in 1984 (Axton, 1987) and 2005. The neutron spectrum and anisotropy factor were calculated using the Monte Carlo method (Li et al., 2013; Liu et al., 2007).

The charged particle beams accelerated by a 4.5-MV Van de Graaff accelerator were sent to various solid targets to produce mono-energetic neutron fields of 0.144 MeV, 0.565 MeV, 1.2 MeV, 2.5 MeV, 4.0 MeV, 5.0 MeV, 6.0 MeV, and 14.0 MeV through the ^{7}Li (p, n)^{7}Be, T (p, n)^{3}He, D (d, n)^{3}He, and T (d, n)^{4}He reactions (Hu et al., 2017; Zhang et al., 2011). The targets were positioned near the center of the hall and 1.8 m above the ground. A cylindrical hole, 3 m in diameter and 2 m in depth, was dug in the ground just below the target to decrease the scattered neutrons near the target. The energies and angle distributions of mono-energetic neutrons emitted from the targets were calculated by the PTB Monte Carlo code TARGET (Schlegel, 2005).

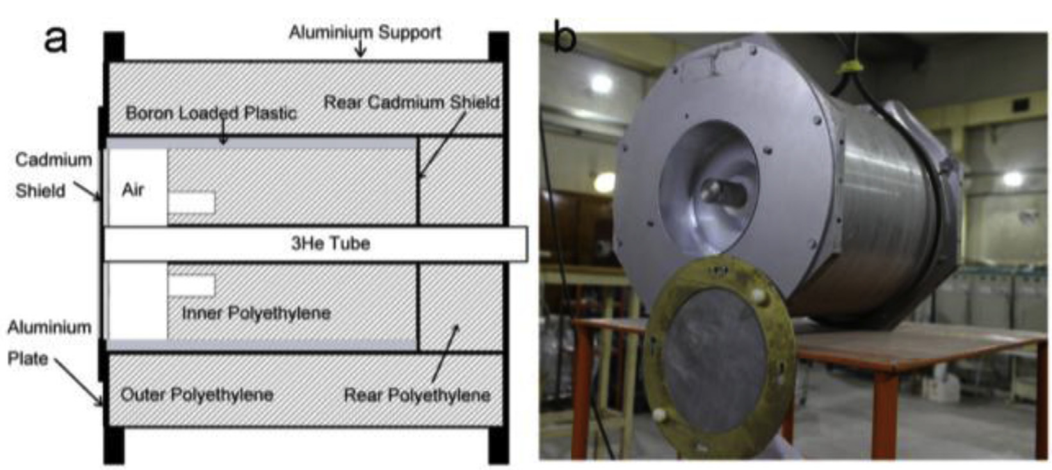

Fig. 1. (a) Schematic geometry and (b) image of the long counter.