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Optimizing the design of a moderator-based neutron detector for a flat response curve in the 2–14 MeV energy range

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ABSTRACT

The efficiency of a neutron detector with boron trifluoride proportional tubes embedded in a polyethylene moderator was simulated with a Monte Carlo program. A moderator structure where the detector had uniform sensitivity for neutrons from 2 to 14 MeV was determined by simulation. A counter was built based on the simulation results. The counter's efficiencies were calibrated with an Am–Be source and an accelerator that served as a D–D and D–T neutron source. Experimental neutron efficiencies of these sources are approximately uniform. The simulated model was validated by the consistent results between the calculated and experimental data.

1. Introduction

Long counters are widely used in measuring neutron fluence because they are largely insensitive to γ-rays and usually have relatively uniform sensitivity over a wide energy range. The response of the long counter, first introduced by Hanson and Mckibben [1], was flat from 10 keV to 3 MeV. Though there has been considerable research done on long counters previously [1–3], most of the existing counters have only a flat response below 5 MeV; above 5 MeV the sensitivity falls rapidly.

In our laboratory, fluence of pulse neutron tubes needs to be measured. Neutrons emitted from the tubes may be D–D neutrons, D–T neutrons, or mixed together. A detector with constant efficiencies for D–D and D–T neutrons is especially necessary when the neutron types are mixed, and the detector should have a high sensitivity. The detector is made with BF_3 proportional counter tube(s) and a carefully designed moderator. The influence of the moderator to the detector's efficiency was simulated to determine if it would meet our requirements. Based on the simulation, we found that the detector could have a flat response curve over a wide energy range of 2–14 MeV. This detector will be better suited to measure the yield of various (α, n) sources (e.g., Am–Be, Pu–Be) than the traditional long counter since the energy spectra of these sources extend beyond 10 MeV.

2. Simulation of the moderator

The neutron tube produces neutron pulses by manual operation, and the width of the pulse is only several microseconds. After the moderator has expanded the pulse, the distribution of thermal neutrons is a sharply rising peak with a long tail, full width of which expands by dozens of times at half maximum (similar to the experimental results of Dinter and Tesch [4]). The typical dead time of a proportional counter tube is about 10 μs [5,6], so a single proportional counter tube cannot collect enough counts due to this dead time. To achieve high efficiency in the detector and be able to collect a large number of counts, nine 27 mm diameter, 34 cm long, 1 atm, BF_3 proportional tubes are embedded parallel to each other in a polyethylene moderator cube in a 3×3 array. Each of the tubes has a separate amplifier and scalar system, which minimizes the counter's overall dead time. The horizontal and vertical separation of adjacent tubes is 5 cm. Dimensions of the cube and depth of the tubes were determined with Monte Carlo simulation. The design of the detector configuration is shown in Fig. 1.

The Monte Carlo program MCNP is used to simulate sensitivities of the detector for different moderator sizes and tube depths. Tube depth refers to the distance from the front face of the moderator to the front face of the boron trifluoride proportional tube. The simulation process is as follows: neutrons entered the polyethylene moderator; they are slowed down primarily by the hydrogen atoms to thermal energies; some neutrons are captured by the proportional tubes when the nuclear reaction ^{10}B (n,α) ^{7}Li occurs; then a count is recorded.

To simplify the simulation process, we first observed an arrangement with only one tube in a rectangular moderator,

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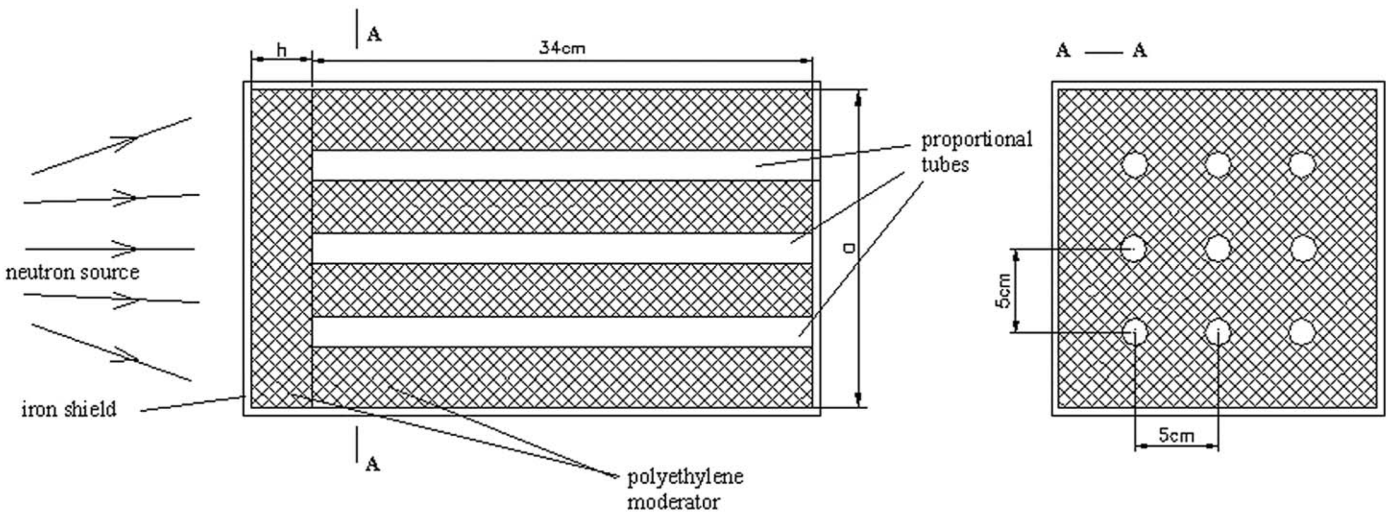

Fig. 1. Structural design of the detector.

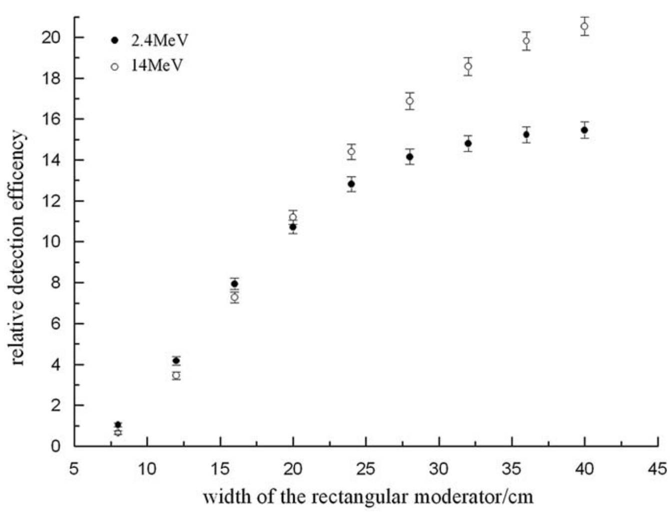

Fig. 2. Relationship between the neutron efficiency and the width of the moderator when the depth is fixed (12 cm).

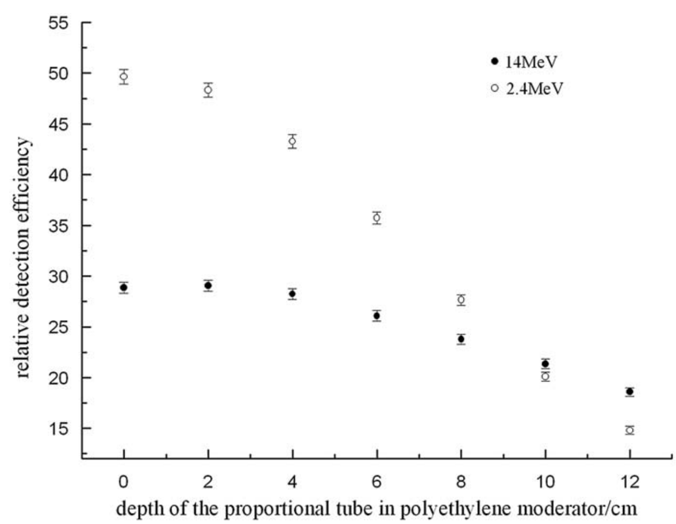

Fig. 3. Relationship between the neutron efficiency and the depth of tube when the width of moderator is fixed (36 cm).

where the width and depth of the tube was varied. The simulation results are shown in Figs. 2 and 3. Uncertainties are from the statistical fluctuations of measured counts. It can be seen that when the depth is fixed (12 cm), the detection efficiency for the neutrons increases with an increasing width. Here, detection efficiency means the number of particles detected per the total number of particles emitted by source. For 14.1 MeV neutrons, increase in efficiency with increase in width is more apparent, but when the width is larger than 30 cm, the rate of increase slows, especially for 2.4 MeV neutrons. When the width of the moderator is fixed (36 cm), efficiency for neutrons decreases with the increasing depth.

From these single-tube results, we approximate a detector configuration that has high and consistent sensitivities for both D–D and D–T neutrons; the nine-tube arrangement is then considered. Based on previous results and by carefully adjusting the polyethylene size and tube depths, the optimized moderator dimension is $32 \times 32 \times 42$ cm, and the depth is 8 cm. For this configuration, the simulated efficiencies for neutrons of different energies are shown in Fig. 4. The efficiencies at 2.4 and 14 MeV are consistent, but the efficiency is 30% higher at 6 MeV than at 2.4 MeV.

3. Experimental observations

The detector was built according to the optimized simulation results. Signals from the boron trifluoride proportional tubes are amplified with nine linear, pulse-shaping amplifiers. Then, the pulses are recorded separately by scalars. Efficiencies were calibrated using an (α, n) source and an accelerator served as D–D and D–T neutron source. Am–Be was the (α, n) source with an average energy of 4.2 MeV. The source was placed in front of the detector along the central axis. Efficiencies were measured at several distances, where distance was measured from the source to the front surface of the detector.

When the accelerator was used, the detector's central axis was normal to the incident beam, and the target was in front of the detector along the central axis. The beam intensity was adjusted to reduce dead time. Influence of scattered neutrons was observed using a 100-cm-long polyethylene cone, the last 20 cm of which was mixed with boron.

The measured efficiencies of the detector on these sources are shown in Fig. 4. The uncertainties of the efficiencies are mainly caused by scattered neutrons and Poisson noise in the measurement's statistics. As can be seen, the energy response for these neutron