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A modular large-area lithium foil multi-wire proportional counter neutron detector

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HIGHLIGHTS

- The modular system had an efficiency of 13.9 ± 0.03% for a bare ^{252}Cf source.
- The system was able to record a transient source approaching and exiting.
- The angular response varied 15% from 0° to 360° in 15° increments.
- GRRs of 1.0×10^{-6} or better were achieved at exposure rates up to 1000 mR hr^{-1}.

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ABSTRACT

Several Li foil multi-wire proportional counters were constructed with five layers of 75 μm thick ^{6}Li foils spaced 1.63 cm apart. Each detector had 1250 cm^2 of active area and was backfilled with 1.0 atm of P-10 gas. Two of these detectors were positioned back-to-front with 5.0 cm of high-density polyethylene (HDPE) positioned between the two detectors and on the front and back. Additional 2.54 cm thick HDPE sheets were added to the remaining sides. The detectors were operated with a single electronics unit and were delivered to a test facility where multiple neutron and gamma-ray sensitivity experiments were completed. First, a ^{252}Cf neutron source was positioned at various distances from the front of the detector and the absolute detection efficiency (cps ng^{-1}) was recorded at each distance. Second, a transient test was completed by moving the neutron source in front of the detector at a constant rate while recording the change in count rate (cps). Third, the lateral sensitivity and symmetry of the detection system was investigated by positioning a ^{252}Cf source up to 5.0 m away from the centerline of the arrayed detectors in 1.0 m increments in both outward directions. The angular response was investigated by positioning the ^{252}Cf source 2.0 m from the center of the device and recording the count rate at each stationary position in 15° increments from 0° to 360°. The count rate varied 15% from minimum to maximum during the angular response test. Additionally, the arrayed system was modeled in MCNP6 and had an intrinsic neutron detection efficiency of 12.6% for a bare ^{252}Cf source, less than the experimentally determined efficiency of 13.9 ± 0.03%, as expected. The gamma-ray sensitivity of the detection system was also investigated and pulse-height spectra were collected and plotted against a neutron response spectrum for comparison.

1. Introduction

Recently, the Kansas State University (KSU) Semiconductor Materials And Radiological Technologies Laboratory (S.M.A.R.T. Lab) has developed neutron detectors based on a large-area, high-efficiency, low-cost, ^{6}Li foil multi-wire proportional counter (MWPC) (Bellinger et al., 2013a, 2013b; Nelson et al., 2011, 2012, 2014). The ^{6}Li foil MWPC suspends ^{6}Li metal foils (95% enrichment) between banks of anode wires. Suspending the foils dramatically increases the neutron detection efficiency compared to coating the walls because reaction products from the ^{6}Li(n,α)^{3}H reaction are able to escape both sides of the foil and enter a proportional gas volume. Several Li foil MWPCs have been constructed to date, including a backpack neutron detector that was

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accepted as a viable ^{3}He replacement at a government sponsored test campaign (Nelson et al., 2014). Intrinsic advantages of suspending the Li foils over alternative coated designs results in a higher neutron detection efficiency per Li foil and is explained in greater detail by Nelson et alli (Nelson et al., 2011, 2012, 2014).

The microscopic thermal-neutron (0.0259 eV) absorption cross-sections for ^{6}Li is 940 b and has a natural abundance of 7.59%. Enriched ^{6}Li has a density of 0.463 g cm^{-3} and a macroscopic thermal neutron absorption cross-section of 43.56 cm^{-1} (Tsoulfanidis, 1995; Knoll, 2000; McGregor et al., 2003). The ^{6}Li(n,t)^{4}He reaction leads to the following products, with a reaction Q-value of 4.78 MeV (Tsoulfanidis, 1995; Knoll, 2000; McGregor et al., 2003),

$$^{6}\text{Li} + {}^{1}_{0}\text{n} \rightarrow {}^{3}\text{H}(2.73\text{MeV}) + \alpha(2.05\text{MeV}). \quad (1)$$

The results reported herein are for a neutron detection system constructed from two of these detectors one behind the other interspersed and surrounded with HDPE moderator. The intent is to maximize intrinsic neutron detection efficiency. The detection system was optimized for an unmoderated (bare) ^{252}Cf source. To set performance expectations and optimize the design, the system was modeled using MCNP6. Several neutron and gamma-ray sensitivity experiments reported here were completed at a government sponsored test conducted by government personnel at their facility using protocols they established without comment from the authors. One of the neutron tests was repeated at KSU and the results are compared. Additionally, gamma-ray sensitivity tests were completed at KSU using a ^{137}Cs source.

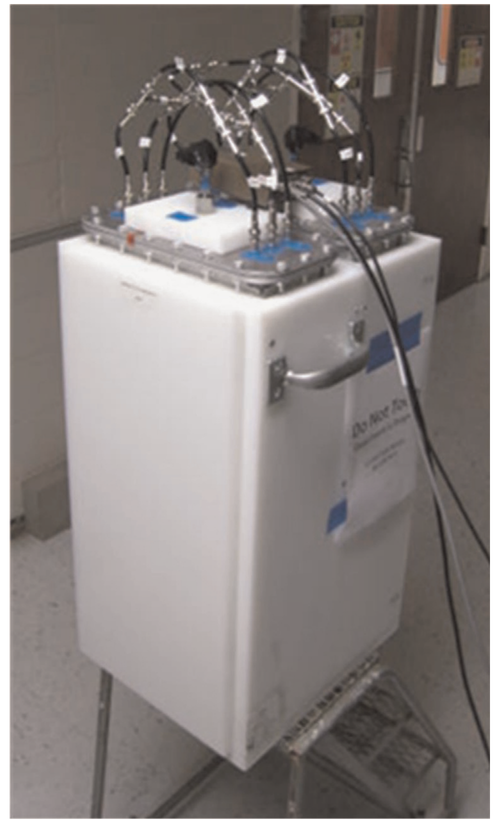

Fig. 1. The arrayed detection system containing the two Li foil MWPCs and HDPE neutron moderator. The “Front” is to the left; the handle is on one “Side”.

2. Experimental procedure

Four large-area Li foil MWPCs were constructed each containing five layers of 25 × 50 cm (1250 cm^{2}) 75 μm thick ^{6}Li foil (95% enrichment) sheets spaced 1.63 cm apart. Six anode wire banks enclosed the five foil layers and collected the ionization generated in the P-10 gas volume by the triton and alpha particle reaction products. Assembly of Li foil MWPC neutron detectors of this type are outlined in more detail elsewhere (Nelson et al., 2011, 2012, 2014).

Operating voltage was determined for each detector without moderator by exposing the unit to thermal neutrons from the diffracted thermal neutron beam at the KSU TRIGA Mark II nuclear reactor and recording pulse-height spectra and counting curves. The counting curve, counts versus voltage, exhibited a plateau consistent with stable operation at 900 V, the voltage used thereafter. The intrinsic thermal neutron detection efficiency, neutrons detected per incident neutron, was approximately 55% for each detector. The expected intrinsic thermal neutron detection of each 5-layer Li foil MWPC was 55% as has also been reported elsewhere (Nelson et al., 2012, 2014).

For the government tests, two large-area Li foil MWPCs were positioned back-to-front with 5.0 cm of high-density polyethylene (HDPE) positioned between the two detectors and on the front and back of the assembly. Additionally, 2.54 cm thick sheets of HDPE were attached to the sides, top, and bottom of the arrayed system. A picture of the detection system is shown in Fig. 1. In total, including HDPE and both detectors, the unit weighed approximately 250 lbs. (113 kg); each detector weighed approximately 25 lbs (11.3 kg). Four of these detectors (two spares) were driven more than 1500 miles (2414 km) to and from the test facility and still functioned properly. Before delivery a detection system functionality test was completed with a ^{252}Cf source to ensure the system was operating properly.

At the test facility, four neutron sensitivity experiments were completed by government personnel. For the first measurement, a 73 μCi (117 ng) ^{252}Cf neutron source was positioned at 1, 2, 4, 6, 8, and 10 m from the front face of the detection system. Measurement methodology performed by the scientists at the test facility involved collecting three one-minute measurements at each distance and source shielding thickness.

The second neutron measurement investigated the response of the detection system to a source in motion, referred to as a transient test. The same source that was used in the first measurement was used here and passed in front of the detection system at a constant rate (not reported to the authors). The data collection system was operated in multichannel-scaler mode, recording the total counts from the detection system every second as the source passed in front of the detection system. The transient test was repeated 10 times at a closest distance of 2.0 m, and repeated again with the closest distance set to 4.0 m.

Third, a field-of-view (FOV) test was carried out by placing the same ^{252}Cf neutron source on the centerline in front of the detector at a distance of 25.5, 125.5 or 225.5 cm then moving it perpendicularly away from the centerline in steps of one meter up to five meters on each side of the centerline. The intention of the experiment was to measure the symmetry of the detector response. The FOV test was repeated with the 2.0 and 8.0 cm source moderators. However, only the bare source results are reported herein, but the moderated source results had similar symmetrical responses. Finally, a background measurement was collected to determine the baseline for comparing the count rates in the experiment.

The last neutron test investigated the angular response of the detection system and was completed by positioning the bare ^{252}Cf neutron source 2.0 m from the center of the detection system and rotating the source 360° around detection system in 15° increments. The count rates at each position were recorded and plotted.

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