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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.

In addition to the government tests, when the detection system was returned to KSU, a stationary test with the source on center at various distances from the front of the detector was repeated to confirm system functionality. Additionally, a gamma-ray sensitivity test was completed with a 65 mCi ^{137}Cs gamma-ray source. Count rates and pulse-height spectra were recorded with the source at distances to provide gamma ray exposure rates of 10, 50, 100, and 1000 mR h^{-1}. The government sponsored tests performed did not report measurements of this sort. A pulse-height spectrum was also collected when a bare 17 ng ^{252}Cf was positioned 2.0 m from the front face of the detection system for comparison.

Additionally, the static test was repeated at KSU. The measurements were conducted in a long and relatively narrow basement hallway surrounded by cinderblock walls. The source was shielded with a five sided box made of borated HDPE. The open face of the shielding box was pointing towards the center of the system. This shielding significantly reduced wall and ground scattering.

3. Calculated response

To calculate detector response using MCNP6 the detector geometry was approximated as 5 parallel sheets of 75 μm thick ^{6}Li foils spaced 1.63 cm apart. P-10 proportional gas (90% Ar, 10% CH_4) surrounded the ^{6}Li sheets and was contained within a 0.3175 cm (1/8 in.) thick Al housing sized to match the actual detectors. Anode wires and charge collection were not modeled; rather the simulation was used to obtain only efficiency values. HDPE moderator was included to match the build with the 5.0 and 2.5 cm thicknesses described in the prior section.

In addition, to simulate a likely environment for the government test whose actual geometry was not known in advance, a bare ^{252}Cf source was positioned 2.0 m away from the front face of the detection system. The source and detectors were positioned 1.5 m above a simulated $10 \times 10 \times 1$ m^3 concrete slab to replicate the floor of the test facility. The simulated intrinsic neutron detection efficiency, counts per incident neutron on the moderator, was 12.6%. It is expected the experimental response will be higher because of air scatter and scatter off the walls, ceiling, and other structures near the facility.

4. Experimental results

The neutron response pulse-height spectrum collected at KSU is shown in Fig. 2 along with the four gamma-ray pulse-height spectra at several exposure rates. The results of the four neutron experiments completed at the test facility are shown in Figs. 3–6. The intrinsic neutron detection efficiency measured at KSU with a bare ^{252}Cf source positioned 2.0 m from the front face of the detection system was 13.9 ± 0.03%.

5. Discussion

Gamma-ray sensitivity of the detection system was investigated at the test facility, but the results were not shared with KSU which led to the separate measurements described earlier and reported in Fig. 2. Gamma ray rejection ratios measured at all exposure rates for a 1.0 MeV lower level discriminator (LLD) were 1.0×10^{-6} or better. For each gamma ray measurement the count rate in the front detector was 10–15 times higher than in the back detector. Clearly gamma rays scatter and are absorbed in the front detector which reduces intensity in the back one and in addition average gamma ray energy is reduced so that many events occurred below the LLD.

Comparison of the test facility and KSU neutron sensitivity results at 1.0 m in Fig. 3 shows reasonable agreement with absolute efficiencies of 6.12 and 6.05 cps/ng, respectively, thus it was concluded that the detector was operating correctly for all tests even though the authors were not in attendance. The curve fit in the figure shows a dependence on distance at about $1/R^{2/3}$. Static

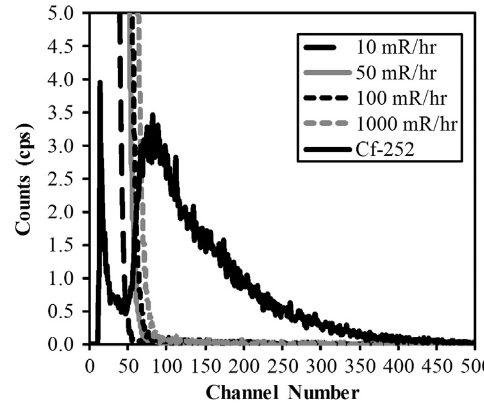

Fig. 2. Pulse-height spectra obtained by the detection system from exposure to a ^{252}Cf neutron source and ^{137}Cs gamma-ray source at various exposure rates without neutrons.

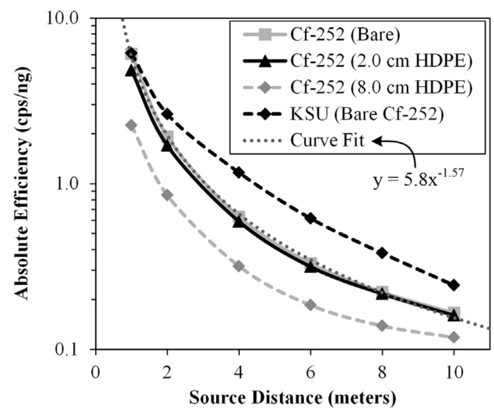

Fig. 3. The static detection system results, which show the absolute neutron detection efficiency as a function of ^{252}Cf source distance. This measurement was completed first with a bare source followed by source moderator thicknesses of 2.0 and 8.0 cm. The same test completed at KSU is also shown and a curve fit line for the bare results obtained at the test facility.

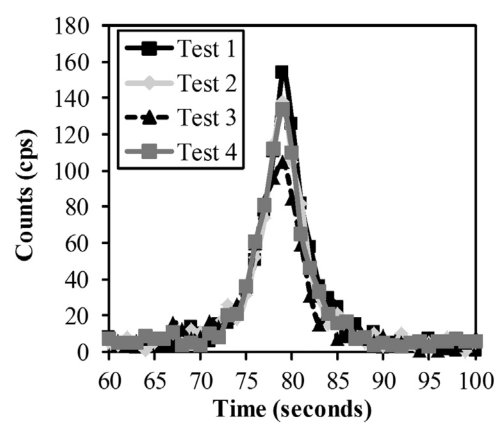

Fig. 4. Transient test results plotted the recorded counts per second every second as the source moved in front of the detection system at a constant rate (rate was not reported to the authors).

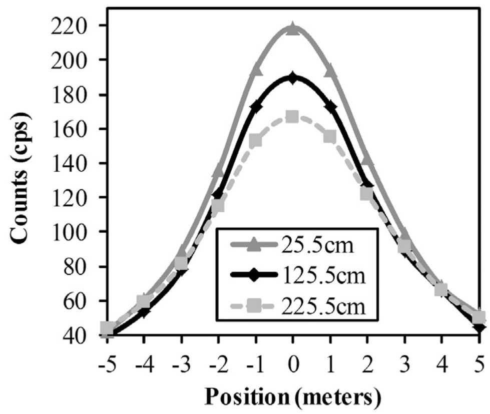

Fig. 5. Field-of-View (FOV) results, which show relatively even symmetry about the 0 m centerline distance. At lateral distances of 5.0 m away, the count rates was almost 8x background. Centerline distances shown are the values reported by the test facility.

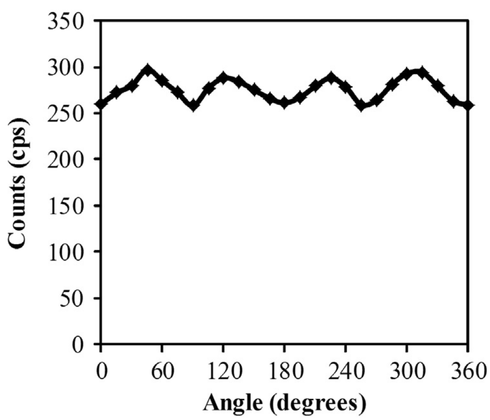

Fig. 6. The recorded counts per second by the detection system from a bare ^{252}Cf source positioned 2.0 m from the center of the system and rotated from 0° to 360° in 15° increments.

test results did not follow the ideal $1/R^2$ trend, which was expected because the $1/R^2$ response is only found in idealized scenarios. Scattering of neutrons in air and scattering of neutrons off the ground/floor and surrounding structure add to the count rate expected from $1/R^2$ alone. The additional scattering from the hallway walls in the KSU setup resulted in a response that falls off more slowly than at the test facility. Error bars are not included in the plot because the error was < 1.0–3.5% for all measurements, thus the lines fell within the symbol representing the data point.

Further evidence that the detector was operating properly during the tests comes from comparison of the measured intrinsic neutron detection efficiency and the value calculated with the MCNP6 model. The measured result was 13.9 ± 0.03%, which is slightly higher than the simulated result of 12.6%. The difference is expected since the measurement has more scattering elements (walls, ceiling, air, etc.) than the simulation, which only had a concrete floor.

Transient test results, Fig. 4, show relatively good count rate symmetry when the source is approaching compared to when the source is moving away from the detector. Source speed or rate information was not provided, thus, it is difficult to predict the sensitivity of the device in this test. At each closest distance setting, 2.0 and 4.0 m, each test was repeated 10 times and very similar results were obtained for each measurement. In Fig. 4, only four of the 10 are shown for the 2.0 m setting as to not crowd the plot with too much data.

FOV results also show relatively even count rate symmetry about the 0.0 m centerline distance (25.5, 125.5, and 225.5 cm) for each lateral distance setting, which was the intention of the experiment. The rates on centerline at the three distances do not match the values that would be expected from the stationary test in Fig. 3. The authors do not know if the distance used was different than reported, if data sets were mislabeled, or if different source(s) were used for different curves. However, what can easily be concluded is there is good symmetry in the system about the centerline as mentioned previously. Lastly, the background count rate was approximately 7.5 cps, which makes the count rates at 5.0 m away approximately five times greater than the background count rates.

Angular response count rates varied 15% between the lowest and highest count rates. The peaks occur when the source is at 45 degrees from the faces of the detector. More precisely, the faces of the detector are at 0°, 90°, 180°, and 270° and the maximum count rates occurred on the diagonals at 45°, 135°, 225°, ad 315°, while the minimum count rates repeated perpendicular to the faces. The highest rates occur on the diagonals because the detector presents a larger solid angle to the source in this position. At 0° the fractional solid angle, defined by the HDPE dimensions with an effective area of 2620 cm^2 and the source distance of 2.0 m, is 0.0051. At the diagonal setting (45° off normal), the fractional solid angle intercepted by the perimeter of the HDPE increases to 0.0072 due to an effective area of 3705 cm^2. At 45° more neutrons strike the moderator and scatter into the active region of the detector and produce the higher count rates.

Given that the lithium foils are all parallel to the front and back faces of the detectors, one might expect that the count rates at 0° and 180° would be higher than the count rates at 90° and 270°, but in fact these were almost the same, a result of the symmetry of the detector and repeated scattering in the moderator before capture by the foil. This symmetry virtually eliminates sensitivity to orientation of the foils.

6. Conclusions

The recently developed large-area Li foil MWPCs were shown to function properly when arrayed together in the fashion described above. This demonstrated the modularity of the devices and other arrangements should be investigated, including those for multiplicity counting. The arrayed system showed good sensitivity for stationary and transient neutron sources along with good symmetry and angular sensitivity. Repeating neutron tests at KSU and simulating the system confirmed the detectors were functioning properly during the tests. Improvements to the detectors should be considered to increase the sensitive area of the Li foil MWPCs and reduce the weight.

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