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# Characterization of a mid-sized Li foil multi-wire proportional counter neutron detector

Kyle A. Nelson [a,*], Michael R. Kusner [b], Benjamin W. Montag [a], Michael R. Mayhugh [b], Aaron J. Schmidt [a], Clayton D. Wayant [a], J. Kenneth Shultis [a], Philip B. Ugorowski [a], Douglas S. McGregor [a]

[a] S.M.A.R.T. Laboratory, Mechanical and Nuclear Engineering, Kansas State University, Manhattan, KS 66506, USA
[b] Saint-Gobain Crystals, Hiram, OH 44234, USA



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ABSTRACT

A 550 $cm^2$ thermal neutron detector was constructed with five parallel sheets of 75 μm thick $^6$Li foils (95% enrichment) spaced 1.63 cm apart. Anode wire banks containing a plurality of anode wires were strung on both sides of each foil, six banks in total. The chamber was backfilled with *P*-10 proportional gas and over-pressured to 1.1, 1.5, 2.0, and 2.8 atm (111, 151, 202, and 284 kPa). The design was tailored to allow the products from the $^6$Li(n,t)$^4$He reaction to escape both sides of the Li foil simultaneously, thereby, allowing for concurrent measurement in the proportional gas. The measured intrinsic thermal neutron detection efficiency of the detector with normal incident thermal neutrons to the foil sheets was $53.8 \pm 0.20\%$. When the detector was angled (55° from normal) such that a 0.5 cm diameter thermal neutron beam intersected all of the foil layers, the intrinsic thermal neutron detection efficiency increased to $58.6 \pm 0.21\%$. A $^{252}$Cf neutron source positioned at a distance of 2.0 m yielded an absolute neutron detection efficiency of 0.73 cps $ng^{-1}$. The gamma-ray rejection ratio (GRR) was $7.67 \times 10^{-9}$ as measured from a $^{60}$Co source for an exposure rate of 40 mR $hr^{-1}$. Theoretical pulse-height spectra obtained with MCNP6 agreed well with experimental data and allowed pulse-height spectra and discriminator settings to be energy-calibrated. These results demonstrate the potential for the Li foil multi-wire proportional counter (MWPC) as a viable $^3$He neutron detector replacement.



## 1. Introduction

The relatively recent shortage of $^3$He gas has raised interest in alternative neutron detection technologies. Recently, a new category of gas-filled detectors has been introduced that utilizes solid $^6$Li neutron absorbers configured to allow all $^6$Li(n,t)$^4$He reaction products to escape the absorber concurrently into a proportional gas [1,2]. The Kansas State University (KSU) Semiconductor Materials And Radiological Technologies Laboratory (S.M.A.R.T. Lab) has developed a large-area, high-efficiency, low-cost, $^6$Li foil multi-wire proportional counter (MWPC) that successfully demonstrates an acceptable alternative to $^3$He-based neutron detector technology. A Li foil MWPC with dimensions and effective areas described here can also be used as backpack neutron detectors. Increasing the effective area of the device will allow the technology to be used in radiation portal monitors (RPMs)

Commercially available neutron detectors based on coated surfaces are restricted to the measurement of only one reaction product per neutron absorption because the other reaction product, moving in the opposite direction, deposits its energy in the device wall. An obvious example of this is the $^{10}$B-lined counter, whose pulse-height spectrum is dominated by the 'wall-effect'. The consequences of the wall-effect result in lower neutron detection efficiency and poor gamma-ray discrimination [3,4]. Adequate gamma-ray discrimination can be achieved with these devices, but a large percentage of the neutron counts must be sacrificed in order to achieve acceptable gamma-ray rejection ratios (GRR). Neutron detectors filled with a neutron absorbing gas can measure both reaction products simultaneously which enhances the detection efficiency and gamma-ray discrimination properties, but $^3$He gas is in short supply and $^{10}BF_3$ gas is considered hazardous. Single-crystal scintillator materials can have high neutron detection efficiency, but suffer from both limited size and limited gamma-ray discrimination capability [3,4]. Gamma-ray rejection can be improved for some of these materials with the use of pulse shape discrimination (PSD) [5]. This PSD approach extends also to powdered scintillator sheets

* Corresponding author.
*E-mail address:* knelson1@ksu.edu (K.A. Nelson).

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that are read out by adjacent wavelength-shifting fibers. However, the necessary electronics for PSD is an additional cost.

The general design approach of the MWPC neutron detector is to suspend thin Li foils between anode wire banks, thus allowing for measurement of reaction products on both sides of the Li foil. This method takes advantage of the immediate availability of thin lithium foils, a fortuitous consequence of advancements in Li-ion battery manufacturing. Other neutron reactive materials can be used in place of $^6$Li, but all result in lower neutron detection efficiency and reduced effective areas. 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$^{-1}$ [3,4,8]. The $^6$Li(n,t)$^4$He reaction leads to the following products, with a reaction *Q*-value of 4.78 MeV [3,4,8],

$$^6\mathrm{Li} + {}^1_0n \rightarrow {}^3\mathrm{H}(2.73\ \mathrm{MeV}) + \alpha(2.05\ \mathrm{MeV}). \quad (1)$$

Herein, layout and performance are reported of a 550 cm$^2$ $^6$Li foil MWPC neutron detector containing 5 layers of 75 μm thick foils interspersed with anode wire banks. Results are compared to simulated outcomes obtained using MCNP6 simulation software for this same geometry under various backfill gas pressures.

## 2. Theoretical considerations

To predict detector response, MCNP6 was used with detector geometries approximated as 5 parallel sheets of 75 μm thick $^6$Li foils spaced 1.63 cm apart. *P*-10 proportional gas (90% Ar, 10% $CH_4$) was modeled as surrounding the $^6$Li sheets and was contained within a 1/8 in. thick Al housing. The *P*-10 pressure was varied to match experimental conditions. A 1.5 cm diameter thermal neutron beam was modeled as normally incident through the center of the MWPC. When a neutron was absorbed, the randomized paths of the reaction products were tracked through the $^6$Li foil material and the gas. The signal generated by the MWPC was approximated as equal to the energy deposited in the gas by the reaction product(s) as calculated by MCNP6. Electric fields, charge collection, and gas avalanche gain were not modeled.

Because the Li foil thickness (75 μm) is less than the summed range of the triton and alpha particle reaction products (156 μm) several distinct energy depositions characteristic to this type of MWPC can occur, all of which were tracked and calculated. To illustrate the cases, consider Fig. 1, a simple cross-sectional diagram of three Li foils suspended in *P*-10 gas. There are three situations that allow the reaction products to deposit energy in the gas and produce a measurable event (*i.e.* a pulse). The first such case occurs when both reaction products escape into the gas simultaneously and are measured. A pulse is also produced when only the triton is measured and the alpha particle does not escape the $^6$Li foil. The probability only the triton is measured is highest among all three events resulting in a measurable electronic pulse and is a result of the long range of the triton (133 μm) compared to the alpha particle range (23.2 μm) in pure $^6$Li foil [9]. The third characteristic deposition is generated when only the alpha particle is measured, which has the lowest event probability of the three cases for 75 μm thick foils. In the latter two cases, only one reaction product enters in the gas volume, while the other is absorbed in the Li foil. Finally, also illustrated in Fig. 1, both reaction products may be entirely absorbed in the Li foil, thereby, not producing a measurable event. The probability of this last outcome decreases as foil thickness decreases.

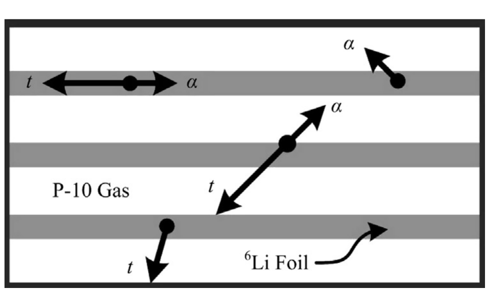


**Fig. 1.** A cross-sectional diagram of three Li foils suspended in a detector, each separated by *P*-10 gas. Shown are four basic trajectories for the alpha particle and triton reaction products. Signals are generated from the three basic trajectories that allow reaction products to deposit energy in the *P*-10 gas.

At 1.0 atm of *P*-10 gas, the ranges of the 2.73 MeV triton and 2.05 MeV alpha particle are 7.26 cm and 1.25 cm, respectively [9]. In principle the largest pulse will result if all reaction product energy that escapes the foil is deposited in the gas. However, this design for maximum energy deposition would require spacing the lithium foils 7.3 cm apart, a design that is neither practicable nor necessary. As a practical matter, the electronic output pulses need only exceed signal background from electronic white noise and gamma rays. Particles depositing approximately 500 keV of energy or more meet this criterion; hence the detector was designed with foil spacing of 1.63 cm, a distance that allows for the absorption of at least 500 keV from the triton in the gas. Therefore, a 500 keV lower level discriminator (LLD) setting or lower allows for most triton depositions to be counted.

Shown in Fig. 2 are theoretical neutron response pulse-height spectra calculated with MCNP6 for the detector configuration previously described. The pulse-height spectra were calculated for *P*-10 gas pressures of 1.1, 1.5, 2.0, and 2.8 atm (111, 151, 202, and 284 kPa), revealing the expected spectral changes. The fraction of reaction products measured does not change with gas pressure, but the ranges and energy deposited by each particle and its associated event does vary with pressure. For example, the increase in *P*-10 gas pressure increases the amount of energy deposited by the triton in the gas region, thereby, resulting in larger pulses. Note that the amount of energy deposited by the alpha particle in the gas volume does not change with increasing *P*-10 pressure because, at 1.0 atm (101 kPa), the range of alpha particle in the gas is already less than the distance between the $^6$Li foils. Thus, increasing the pressure only shortens the range of the alpha particle in the gas region and does not increase the energy deposited. Further, the range of the reaction products in *P*-10 gas changes linearly with pressure. If the pressure is doubled from 1.0 atm to 2.0 atm (101–202 kPa), then the maximum ranges of the reaction products are reduced by approximately 50%.

In the four pulse-height spectra shown in Fig. 2 at the various *P*-10 gas pressures all have a sharp decrease in count rate at

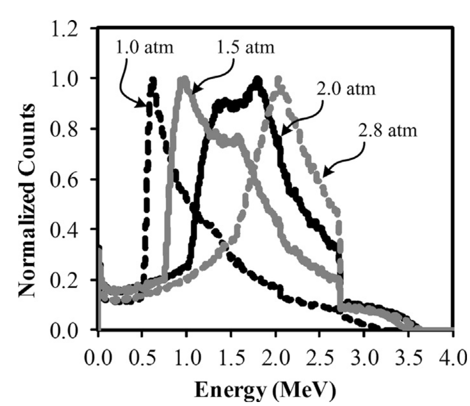


**Fig. 2.** The simulated thermal neutron pulse-height spectra from a MWPC with five layers of 75 μm thick $^6$Li foils separated 1.63 cm apart as obtained for *P*-10 gas pressures of 1.0, 1.5, 2.0, and 2.8 atm (101, 151, 202, and 284 kPa).