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Investigation of a lithium foil multi-wire proportional counter for potential ^{3}He replacement

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ABSTRACT

The recent shortage in the supply of ^{3}He for neutron detection has caused a large surge in research for a viable replacement. ^{6}Li has a large cross section for the absorption of thermal neutrons and emits two relatively short-ranged interaction products. Li foil can now be manufactured thin enough to allow both reaction products to escape the foil. Ten layers of natural Li foil were placed in a multi-wire continuous flow gas chamber with a single anode wire between each foil. Four different thicknesses, 30, 50, 75 and 120 μm, were tested in a thermalized neutron beam. The intrinsic thermal neutron detection efficiencies of 10 layers of 30, 50, and 75 μm thick Li foil were measured to be 8.1, 11.1, and 15.7 percent. The n/γ ratio was found to be 1.25×10^7 using a ^{137}Cs gamma-ray source. Additionally, neutron response pulse-height spectra of the four foil thicknesses are presented and compare well to simulated response spectra. Theoretical calculations show that thermal neutron detection efficiencies above 70 percent are achievable using enriched ^{6}Li foils for the same detector geometries.

1. Introduction

^{3}He proportional counters are commonly used for neutron detection and are critical to nuclear safeguards, homeland security, and oil well exploration and logging. In recent years, ^{3}He has reached a supply crisis and a significant amount of research has been initiated to find and/or develop a realistic alternative. The requirements for the replacement of ^{3}He neutron detectors are high thermal neutron detection efficiency, large area, and high gamma-ray discrimination. Current commercially available alternatives, such as boron-lined counters and BF_3 proportional counters, have limitations and fail many of the requirements to replace established ^{3}He proportional counting systems. These limitations include poor efficiency, low gamma-ray discrimination, and some of the newer designs would require a complete replacement of the electronics and structure already in place at certain facilities and locations. Several neutron reactive materials, such as ^{6}Li, ^{10}B, ^{113}Cd, and ^{157}Gd, and have been used as neutron detectors [1–13]. However, the focus can be narrowed to ^{6}Li and ^{10}B materials due to the large reaction *Q*-value and short ranges of their reaction products. In the present work, natural Li foils are being investigated, which only contain 7.5 percent ^{6}Li, due to its commercial availability. The thermal neutron (0.0259 eV) microscopic cross section for ^{6}Li is 940 b and the ^{6}Li(n,t)^{4}He reaction leads to the following products, with a reaction *Q*-value of 4.78 MeV,

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

For slow neutron absorptions, the reaction products are emitted in opposite directions (180°).

Thin-film coated devices, such as boron-coated semiconductor diodes and boron-lined proportional counters, are limited to low efficiency due to reaction product self-absorption [14]. Further, because the reaction products are emitted in opposite directions, one may enter the detecting medium, be it gas, scintillator or semiconductor, but the other reaction product will not. For a gas-filled detector, the other reaction product will enter the wall onto which the coating was applied. This "wall effect" causes the loss of substantial energy, and therefore, a reduced signal-to-noise ratio and reduced gamma-ray discrimination.

Therefore, using a device where both reaction products can be measured simultaneously becomes critical. One adaptation to the coated diode devices is to add microstructures to the surface, which has been researched extensively [15,16]. The microstructures allow both reaction products to be measured simultanesouly, thereby, increasing the detection efficiency by an order of magnitude as compared to common thin-film coated planar diodes.

New ultra-thin Li foil fabrication technology has matured in the Li battery industry. The Li foils ranging in thickness from 30–120 μm are routinely manufactured. Note that the range

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of 2.73 MeV ^{6}Li(n,t)^{4}He reaction tritons is 134 μm in pure Li metal, and the range of 2.05 MeV alpha particle reaction products is 23.3 μm [14]. Hence, Li foils can be acquired with thickness of the order or less than the ^{6}Li(n,t)^{4}He reaction product ranges. Suspending ultra thin Li foil in a gas-filled chamber and positioning an anode wire on either side of the foil will allow the device to measure both reaction products simultaneously. By stacking several ultra-thin foils with alternating anode wires positioned between the foils, a large area high-efficiency neutron detector can be realized, without the use of ^{3}He gas. Additionally, if the foils were produced from enriched ^{6}Li metal, the intrinsic thermal neutron detection efficiency could match or exceed that of ^{3}He proportional counters, depending on the number of foils used and the thickness of the foils. Furthermore, Li is a low-Z material and a relatively low density solid, which reduces the probability of absorbing gamma-rays.

In the present work, theoretical calculations are compared to experimental results. Measured intrinsic thermal neutron detection efficiency results of 30, 50, and 75 μm thick foils corroborate the theoretical efficiency plots. The Li foil multi-wire proportional counter also has high gamma-ray discrimination with insignificant loss of thermal neutron detection efficiency. Experimentally obtained ^{6}Li(n,t)^{4}He reaction pulse-height spectra of 30, 50, 75, and 120 μm thick Li foil samples are compared to simulated results of the same thicknesses.

2. Theoretical considerations

The calculated efficiencies expected from a multi-wire Li foil detector design are discussed in the following section. Also included is a short discussion on thermal neutron detection efficiency calibration and pulse height spectra modeling.

2.1. Operation and efficiency calculations

Shown in Fig. 1 is a conceptual arrangement for a multi-foil multi-wire proportional counter with an inset of a single foil [17]. Because the range of the triton reaction product is longer than the thicknesses of the Li foil, the triton has a high probability of escaping the foil. There is a minute chance that neither reaction product will escape the foil, and that probability will increase with foil thickness. Because the summed range of the interaction products is much longer than the thickness of the Li foil, there is a chance that the reaction products will escape both sides of the Li foil, thereby, leaving more energy in the chamber than a conventional coated proportional counter. As the interaction products travel through the gas medium, they deposit their energy and generate free electron-ion pairs. The electrons travel to the central anode wire where the device operates as a conventional proportional counter by creating a Townsend avalanche [3,4]. The ions travel to the cathode of the chamber, which can be either the metal casing or the grounded Li foil, because both are conductive metals.

The theoretical calculations performed to obtain the intrinsic thermal neutron detection efficiency of the natural Li foils have been developed elsewhere and are well understood [14]. The analytical approach, using a system of equations, allows for calculations of neutron detection efficiencies for thin-film coated diode devices having various neutron absorber layers and layer thicknesses [14]. Although originally developed for coated semiconductor diodes, the same equations can be used for gas-filled detectors.

Using the method in the literature, and allowing for attenuation of neutrons through each foil, efficiency calculations were performed using the density of natural Li, 0.531 g/cm^3, and an energy threshold or lower level discriminator (LLD) setting of 300 keV. The macroscopic thermal neutron absorption cross section is 3.25 cm^{-1} for natural Li. Eventually, the detector will be designed with enriched ^{6}Li foils, in which case the density of enriched ^{6}Li metal is 0.460 g/cm^3, although and the range of the triton and alpha particles are nearly unchanged at 134 μm and 23.3 μm, respectively. The macroscopic thermal neutron absorption cross section is 43.56 cm^{-1} for pure ^{6}Li. Shown in Figs. 2 and 3 are the results of the theoretical calculations for 1–5, 10, 15, and 20 foils, ranging in thickness from 1–180 μm for natural and enriched Li foils. The plots show that for a particular number foils there is an optimum thickness of the foils that maximizes the intrinsic thermal neutron detection efficiency. Note also that the calculations assume the incident neutrons are perpendicular to the faces of the foils as shown in the conceptual arrangement in Fig. 1.

The experimental neutron detection efficiency of the multi-wire proportional counter was calculated using three measurements. The first measurement, a, was obtained using just the multi-wire proportional counter placed in a collimated neutron beam. The second measurement, b, was collected from a ^{3}He proportional counter positioned behind the multi-wire detector, but still in the neutron beam. The last measurement, c, was again collected from the ^{3}He proportional counter, but the multi-wire

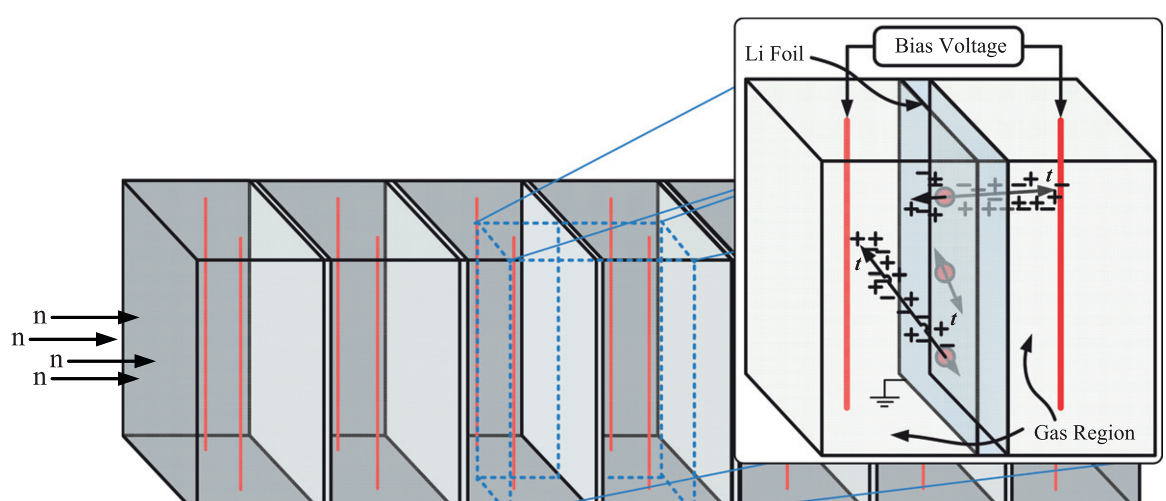

Fig. 1. A cross-sectional illustration of a portion of the conceptual arrangement of the Li foil multi-wire proportional chamber.