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^{6}Li Foil Scintillation Sandwich Thermal Neutron Detector

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Abstract.

Increasing needs for neutron detection and limited supply of ^{3}He lead to the need for replacement neutron detection technology. This paper presents the design and initial results for a neutron detector (^{6}Li foil scintillator sandwich) that uses lithium metal foil to detect thermal neutrons. The reaction products, primarily the triton, deposit most of their energy in thin scintillator films and create light pulses. Gamma rays can only deposit a small amount of energy in the thin films and so produce only very small light pulses. Lithium is preferable to boron in this application because the triton escapes from the lithium more easily than does the alpha particle from boron, allowing the use of thicker films and hence greater efficiency. In addition, the triton has a higher light output in the scintillator than the boron alpha particle. Lithium metal is preferable to a lithium compound, such as LiF, because the number of tritons that escape from the metal is greater for the same amount of lithium. Monte Carlo simulations show that good efficiency values can be achieved with reasonable size detectors, greater than comparable ^{3}He systems for portal monitors. In addition, simulations of a neutron coincidence counting concept show high counting efficiency and short die-away time (16μs) that imply better performance than the HCLNC-II standard neutron coincidence detector. Initial experimental measurements on a prototype detector using alpha particles (having similar light output to the expected tritons), show good light collection and transport properties.

Keywords: neutron detection, scintillation detectors, ^{3}He proportional counter, nuclear safeguards, ^{6}Li foil.

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1. Introduction.

Neutron measurements are commonly used in nuclear safeguards, and ^{3}He detectors are the backbone technology of these measurements. The increasing needs for neutron detection and the current shortage of ^{3}He gas have led to rigorous research-and-development efforts in alternative neutron detection technology. The unique combination of ^{3}He properties [near 100% efficiency for thermal neutrons, inherent insensitivity to gain and high-voltage (HV) variations, and reasonable tolerance to gamma radiation] present a real challenge to candidate replacement technologies. This challenge is especially severe for neutron coincidence counting applications, where high detection efficiency, low dead time, short die-away time, and high stability are essential.

Two of the most common thermal neutron-capturing materials (^{10}B and ^{6}Li) have become a major object of research for detector technology. In order to create a signal, the reaction products need to escape the layer of material. The maximum calculated thermal neutron efficiency for single-sided readout is ~4% with a ^{10}B film thickness of ~2 μm whereas for pure ^{6}Li metal films, the maximum thermal neutron detection efficiency of 11.6% is obtained for a film thickness of ~95 μm [1]. However, because of lithium metal's chemical reactivity, the compound lithium fluoride (LiF) is commonly used for detector development and this lowers the intrinsic efficiency to 4.3% with a ^{6}LiF film thickness of ~25 μm [1]. In the case of scintillation detectors, ^{6}Li is the preferred choice because of the higher light yield of the secondary particle produced. The emerging technology of ^{10}B-lined proportional counters [2,3] obtains reasonable efficiency but the neutron pulse height spectrum is high at low pulse heights and falls dramatically as the pulse height increases. Also the gamma pulse height distribution can overlap at low pulse heights. This creates signal-processing electronics challenges stemming from the lack of a true plateau and the higher capacitance of multiwire anode configurations. For scintillation applications, the most common use has been neutron-sensitive ZnS(Ag)/^{6}LiF scintillation sheets sandwiched with wavelength shifters [4]. When ZnS(Ag)/^{6}LiF is used, there is severe charge absorption in the LiF, light self-absorption in the ZnS scintillator and poor light transfer to the non-scintillating fiber, and only a small fraction of an incident particle's energy is converted and transported to the photomultiplier tubes (PMTs) as a light signal. [5] The recent status of this technology has been reported at the 2010 Symposium on radiation Measurements and Applications (SORMA) conference [6,]. A step forward in using ZnS/LiF is sandwiching it between light-guide strips instead of non-scintillating fibers [7]. This approach eliminates additional distortion of the neutron pulse height spectrum in the wavelength-shifting fibers.

In all of these technologies, the intrinsic efficiency and quality of neutron and gamma pulse-height distribution are limited by the short range (due to self-absorption) of charged particles in the neutron-capturing film. The use of pure ^{6}Li foil as a neutron-capturing film could substantially improve the pulse height distribution while maintaining reasonable efficiency

because of the longer range of charged particles in lithium metal. There are several developments using 6Li foil neutron converters: a large area thermal neutron detector based on a proportional counter with parallel 6Li sheets and double sided readout with multi-wire anode [8]; a thermal neutron imaging detector with composite 6Li foil convertor and gaseous electron multiplier [9]; a thermal neutron detector based on 6Li ionization chamber with integrated body/moderator from HDPE [10,11]. Calculations and experimental measurements of an eight-cell prototype of the latter show an intrinsic efficiency of up to 12% for a Cf-252 source. These developments have shown that lithium metal is a practical material for detector use. Based on this work, we have developed a new approach for the design of a neutron detector. As in these later examples, the detection medium is lithium metal, but the detection of the charged particles (primarily the triton) is done with thin scintillation films. The thickness of these films is such that most of the triton energy is deposited in them, but the energy deposited by a gamma (electron) is very limited. The light produced by the scintillating films is transferred to photomultipliers by non-scintillating light guides. These light guides have very little attenuation and so can be made quite long. This basic detection module can be combined as a building block to make large volume, in which the hydrogen content of the light guide acts as a moderator so that the overall package is an effective detector for fast neutrons.

2. Detection concept.

Multiple layers of reactive film and light guide are stacked in a sandwich configuration for improved moderation and efficiency. The ends of the light-guide strips are interfaced to the PMTs using a fishtail light guide. This detector concept relies on a good longitudinal light transport to the PMT's photocathodes. The double-sided readout of charged particles escaping the ^{6}Li reactive layer doubles the intrinsic efficiency per layer while preserving a good pulse height distribution. Gamma discrimination is improved by the low-energy deposition in the thin scintillator film. The very close refraction indexes [1.58 for the physical vapor deposition (PVD) scintillator and 1.502 for the polymethyl methacrylate (PMMA) light guide] allow for low-light losses during light transfer between the scintillator sheets and light-guide strip.

3. Light transport measurements.

The light transport from the place of light generation in scintillation film to PMMA light-guide strips and the longitudinal light transport to the ends of light-guide strips and PMT photocathodes are critical elements of detector design. We constructed an experimental detector consisting of 20–in.-long-×-2-in.-wide-×-0.25-in.-thick strips of PMMA light guide laminated with 200-μm plastic scintillator film coupled to Hamamatsu PMTs (model R6232). This detector was tested with a ^{239}Pu alpha source (the alpha particles with 5.15-MeV energy have a light yield that is similar to the 2.7-MeV tritons [17]) for light transport properties. The accumulated

spectrum, taken in different positions of the ^{239}Pu source in the presence of constant exposure to gamma radiation from a ^{137}Cs source, is shown in Fig. 2.

This experiment shows good pulse height distribution from alpha particles with a light yield equivalent to 2.7-MeV tritons. A gap exists between the gamma source response and alpha particle distribution, which is similar to that of ^{3}He detectors. In final application, we will use ~30-μm-thick scintillation films [the triton range in the plastic scintillator is ~60 μm, as calculated by the stopping and range of ions in matter (SRIM) code [13]. These thin scintillator films will significantly reduce the sensitivity to gamma radiation.

4. Pulse height spectrum and intrinsic efficiency

To evaluate the performance of the sandwich detector, a set of Monte Carlo simulations has been performed using the MCNPX code [14]; this code allows the alpha and triton particles to be followed subsequent to a $^{6}Li(n,\alpha)^{3}H$ nuclear reaction. For these simulations we have assumed that the lithium is enriched at 95% in ^{6}Li. Figure XXX shows the results obtained from these calculations: the neutron reaction rate into the lithium film and the intrinsic efficiency for various event thresholds. It is worth mentioning the high tolerance of detection efficiency to variations of event threshold. For example, at a 40-μm thickness, increasing the event threshold from 1 MeV to 2 MeV leads to a reduction of the intrinsic efficiency from ~29% to ~23%. Besides the tolerance to instability of the detector and electronics, this feature allows operation to occur at very high gamma fields without a significant loss of efficiency.

If we take a conservative approach, even if both the alpha and triton particles deposit energy in the scintillator film, we ignore the alpha's contribution to the light pulse and use the triton's energy deposition as an estimate for light pulse height distribution. Figure 6 shows the calculated pulse-height spectrum for tritons. The gamma sensitivity is naturally limited by the 30- to 50-μm thickness of the plastic scintillator film.

5. Efficiency modeling of neutron detector assembly.

The ^{6}Li foil sandwich detector features described in the previous paragraphs (high efficiency and a well-defined gap in the distribution of gamma rays and charged particles) show potential for developing neutron detectors for homeland security and nuclear safeguards. To this end, a side-by-side MCNPX modeling of drop-in detector assemblies was performed for two typical applications employing ^{3}He proportional counter: neutron detector for Radiation Portal Monitor (RPM) used for homeland security application and HLNCC-II neutron coincidence counter used in the nuclear safeguards applications. The equivalent RPM detector was modeled in MCNPX code as consisting of 9 Li films (having a thickness of 30μm) sandwiched between 10 strips of light guide. The dimensions are 150 cm by 50 cm by 1 cm (shorter than the 182 cm of the standard RPM because of the space for the PMT's) and the sandwich is surrounded by 1 cm of polyethylene. The detector efficiency was computed assuming a ^{252}Cf source located 2 m from the detector. For safeguards applications, we modeled an equivalent of the high-level neutron

coincidence counter HLNCC-II [15], a typical neutron coincidence counter, by substituting ^{6}Li sandwich detectors for the ^{3}He proportional counters. The detector system of the HLNCC-II is composed of a cylindrical polyethylene body with 18 ^{3}He proportional counters. The equivalent detector was modeled in MCNPX as a polygon of 10 sides with 12 layers of ^{6}Li (having a thickness of 50 μm) and 13 light-guide strips in each side. The overall dimensions are identical to the standard HLNCC-II made with ^{3}He proportional counters. The results of the simulation of both the detectors are reported in Table 1. In both cases, the efficiency is greater than the standard arrangement using the ^{3}He counters. Moreover the HLNCC equivalent with ^{6}Li has a die-away time of ~16μs; about 1/3 of that seen in the standard HLNCC-II counter. Monte Carlo calculations are in progress to optimize the arrangement for both configurations presented.

6. Conclusion

We have designed a thermal neutron detector based on lithium foil sandwiched between light-guide strips laminated with thin film of plastic scintillator. *The double side readout of the lithium foil provides intrinsic efficiency per layer between ~ 20-35% depending of event threshold setting and the foil thickness.* The pulse height spectrum measured with ^{239}Pu and ^{137}Cs sources shows good separation between gamma and charged particles responses and inherent insensitivity to instability of detector and changes in electronics gain.The MCNPX comparison model of the portal monitor and neutron coincidence well counter based on ^{6}Li shows higher efficiency than the standard detector using ^{3}He proportional counters, up to three times shorter die-away time. The combination of these properties with the inherent insensitivity to detector and electronics instability makes this detector a good alternative of ^{3}He technology.

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FIGURE AND TABLE CAPTATIONS

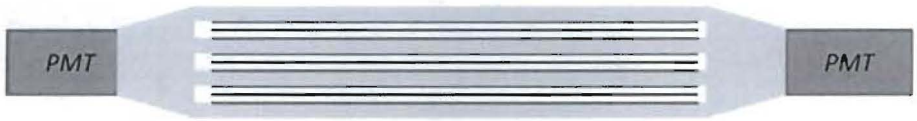
Figure 1. Lithium foil sandwich detector concept. The ^{6}Li sheets are shown in red, the PVD scintillator film is shown in blue, and the PMMA light-guide strips and fishtail light guide are shown in yellow.

Figure 2. Measured gamma and charged particles—pulse height distribution. The bottom picture shows the 20-in.-×-2-in.-thick prototype slab with ^{238}Pu sources at different positions.

Figure. 3. Neutron reaction rate and intrinsic efficiency results as obtained by MCNPX modeling.

Figure. 4. Triton pulse height spectrum as a function of the lithium foil scintillator film. The intrinsic efficiency of the detector is also reported.

Table 1. Comparison of RPM and HLNCC-II with ^{3}He detector with the equivalent with 6Li sandwich detector.



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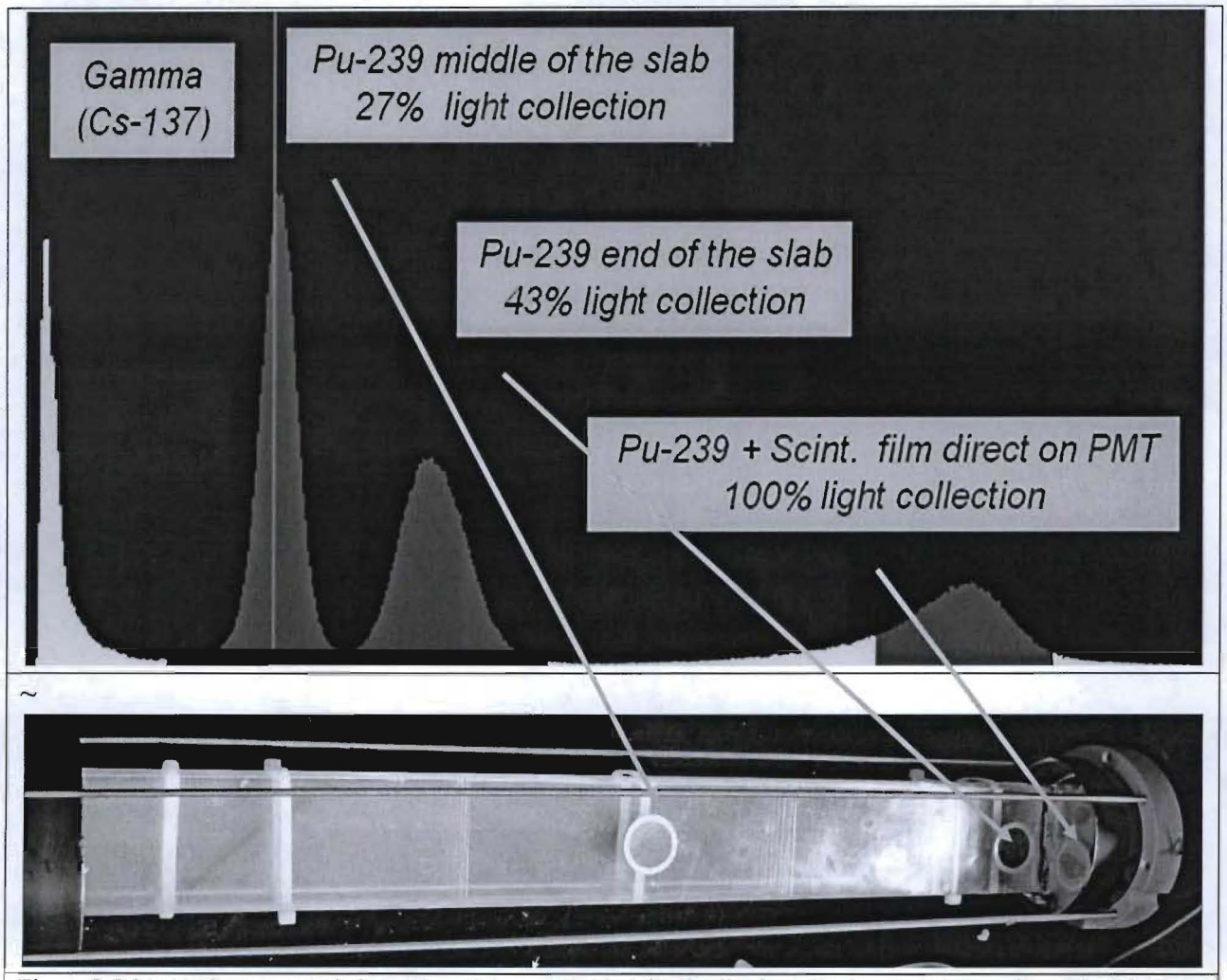

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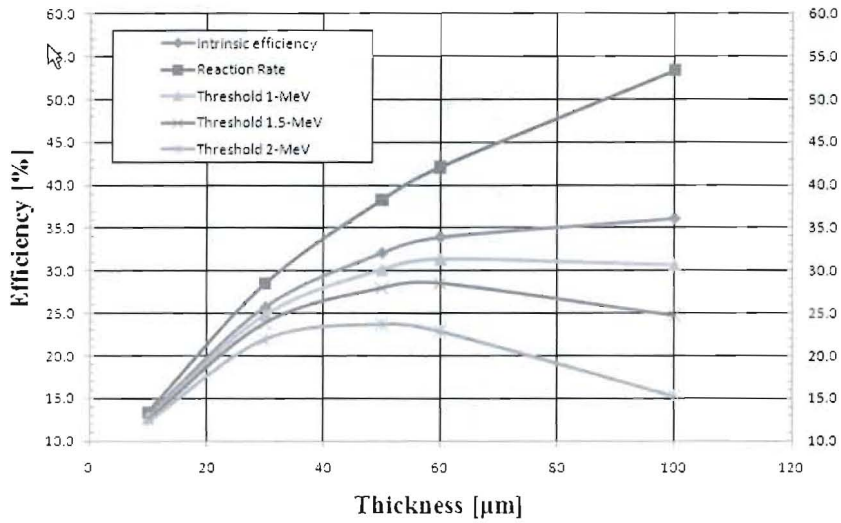

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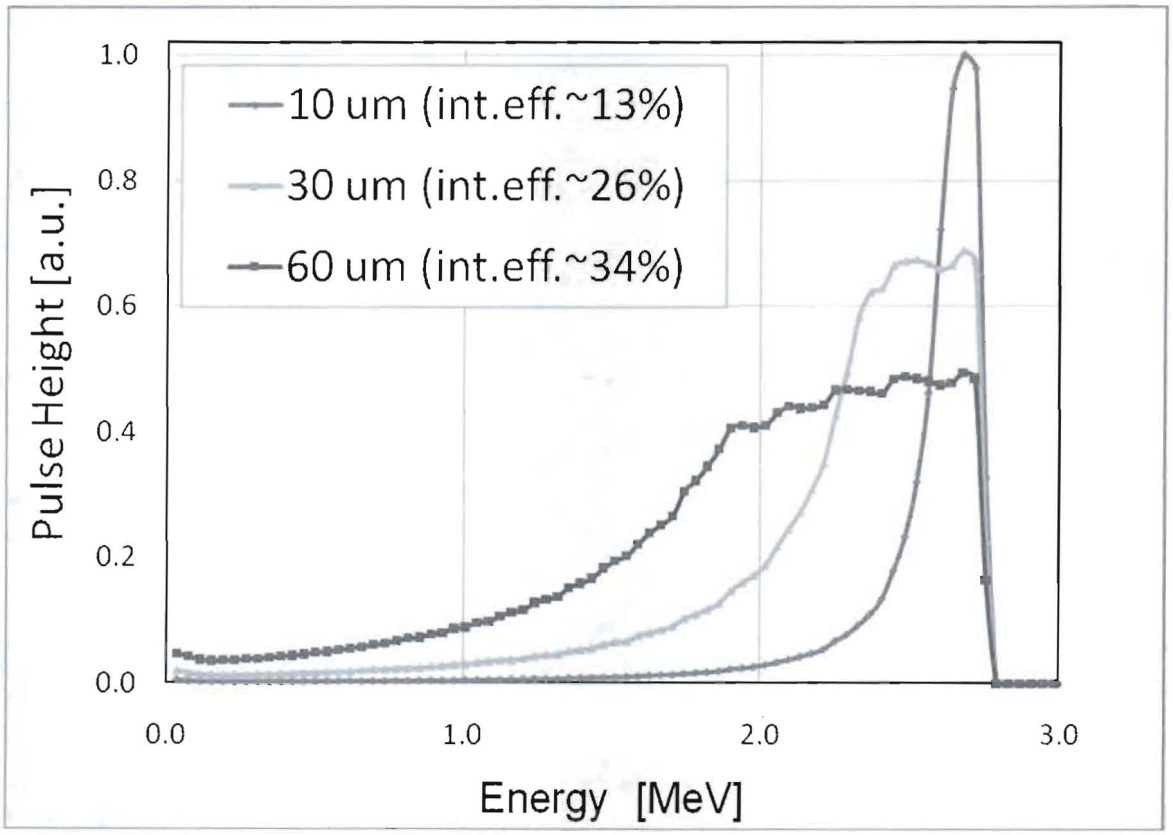

Figure. 4. Triton pulse height spectrum as a function of the lithium foil scintillator film. The intrinsic efficiency of the detector is also reported.

Table 2. Comparison of RPM and HLNCC-II with ^{3}He detector with the equivalent with 6Li sandwich detector.

Application	^{3}He tube efficiency (%)	^{6}Li Film efficiency (%)
RPM ($1^{3}He$)	0.12 [16]	0.49 (30μm foil)
HLNCC-II	17.5 [15]	34 (50μm foil)