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A suspended boron foil multi-wire proportional counter neutron detector

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ABSTRACT

Three natural boron foils, approximately 1.0 cm in diameter and 1.0 μm thick, were obtained from The Lebow Company and suspended in a multi-wire proportional counter. Suspending the B foils allowed the alpha particle and Li ion reaction products to escape simultaneously, one on each side of the foil, and be measured concurrently in the gas volume. The thermal neutron response pulse-height spectrum was obtained and two obvious peaks appear from the 94% and 6% branches of the $^{10}B(n,\alpha)^{7}Li$ neutron reaction. Scanning electron microscope images were collected to obtain the exact B foil thicknesses and MCNP6 simulations were completed for those same B thicknesses. Pulse-height spectra obtained from the simulations were compared to experimental data and matched well. The theoretical intrinsic thermal–neutron detection efficiency for enriched ^{10}B foils was calculated and is presented. Additionally, the intrinsic thermal neutron detection efficiency of the three natural B foils was calculated to be $3.2 \pm 0.2\%$.

1. Introduction

Since the ^{3}He gas crisis was recognized, a plethora of experiments have been completed by many different organizations in attempts to identify a viable alternative. These alternative concepts have been restricted to specific isotopes and compounds that readily absorb neutrons and have reaction products that are relatively easy to measure. One such element is B, or more specifically ^{10}B, which has a natural abundance of 19.9% [1,2]. Commercially available neutron detectors using ^{10}B, or compounds containing ^{10}B, typically use the material as a coating layer, such as B-coated diodes and B-lined proportional counters. Another similar neutron absorbing isotope commonly used in neutron detectors is ^{6}Li whose natural abundance is 7.59% [1,2]. Recently, ^{6}Li foils have been suspended in a multi-wire proportional counter (MWPC), which exhibit improved intrinsic thermal neutron detection efficiency and gamma-ray rejection over conventional Li or LiF coated devices [3–7]. Benefits of suspended Li foils arise from the ability to measure more than one reaction product per neutron absorption, and measure reaction products escaping both sides of the suspended neutron absorber sheet. The same advantages shown with suspended Li foils over coated devices should also apply to suspended B foil neutron detectors. The Kansas State University (KSU) Semiconductor Materials And Radiological Technologies (SMART) laboratory completed experiments using suspended B foils with thicknesses less than the summed range of the reaction products, thus, allowing for more than one reaction product to escape the B foil per neutron absorption.

^{10}B is a widely used neutron absorber material due to the relatively high thermal neutron absorption cross-section, large reaction *Q*-value, and short reaction product ranges. ^{10}B has a microscopic thermal neutron (0.0259 eV) absorption cross-section of 3840 b [1,2]. The $^{10}B(n,\alpha)^{7}Li$ reaction has a total *Q*-value of 2.79 MeV and has two branches

$$^{10}B + {}^{1}_{0}n \rightarrow {}^{7}Li(1.015\ \text{MeV}) + \alpha(1.777\ \text{MeV}), \quad 6\%$$

$$^{10}B + {}^{1}_{0}n \rightarrow {}^{7}Li(0.840\ \text{MeV}) + \alpha(1.470\ \text{MeV}) + \gamma(0.480\ \text{MeV}). \quad 94\%$$

Most neutron detectors utilizing ^{10}B as the absorber material are designed to be insensitive to gamma rays, thus, the 480 keV gamma ray emitted in the 94% branch is typically not measured.

In ^{10}B-lined proportional counters, only one reaction product can be measured per neutron absorption, which escapes the ^{10}B coating and enters the gas region of the detector, while the other reaction product is emitted in the opposite direction depositing its energy in the coating material and/or cathode wall. Additionally, the reaction product entering the gas volume deposits only a fraction of its total energy due to energy self-absorption in the ^{10}B coating. The average amount of energy self-absorption increases as the coating thickness increases. If the coating thickness is greater than or equal to the

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longest range reaction product, then full energy self-absorption of the combined reaction products is possible. Thus, the resulting pulse-height spectrum contains two shoulders each appearing at approximately the characteristic energy of each reaction product. The two shoulders give the appearance of a stair-step pulse-height spectrum blending into the electronic noise, a result commonly referred to as the 'wall effect' [1,2].

Because the reaction product ranges of the $^{10}B(n,\alpha)^{7}Li$ reaction are short (<5.0 μm) in solid materials, fabricating a suspended material with any ^{10}B material is difficult. For example, ^{10}B could be coated onto thin (≤ 2.0 μm) Mylar substrates, but the coating thickness would be less than 1.0 μm in order to optimize neutron detection efficiency for a multiple layered device. Mylar would occupy 1/3–2/3 of the total absorber sheet thickness, which would cause self-absorption of the reaction products and, consequently, impair the neutron detection efficiency. The same decrease in neutron detection efficiency would result if ^{6}LiF were deposited on Mylar, but to a less degree as a result of the reaction product ranges being significantly longer than those from the $^{10}B(n,\alpha)^{7}Li$ reaction [6,8].

Reported in the present work is the thermal neutron response pulse-height spectra of three suspended natural B foils compared with MCNP6 simulated results. Further, the theoretical intrinsic thermal neutron detection efficiency of multiple layer ^{10}B foil devices is presented. Lastly, the calculated efficiency of the three natural B foils is presented and discussed. The foils tested and results presented here were obtained with *natural* B foils, whereas obtaining similar enriched ^{10}B foils may prove to be difficult.

2. Theoretical considerations

The theoretical intrinsic thermal–neutron detection efficiency of the ^{10}B foil MWPC was calculated using a method described in greater detail by McGregor et al. [9]. The calculations presented by McGregor et al., multiply the total neutron absorption probability by the reaction product escape probability for a specific B foil thickness. In other words, if five ^{10}B foils, each 5 μm thick, were used in a MWPC, then the total neutron absorption probably would be calculated for 25 μm of ^{10}B neutron absorber, and the reaction product escape probability would be calculated for a 5 μm thick ^{10}B foil. These two probabilities multiplied together will result in the theoretical intrinsic thermal–neutron detection efficiency. The results of the theoretical calculations, shown in Fig. 1, are plotted as a function of the ^{10}B thickness for multiple ^{10}B foil layers. Further, from Fig. 1, the theoretical intrinsic thermal–neutron detection efficiency is maximized at a specific B thickness for a specific number of foil layers. A five layer device has maximized detection efficiency at 2.7 μm, while a 20 layer detector would require 1.8 μm thick ^{10}B foils to maximize the efficiency.

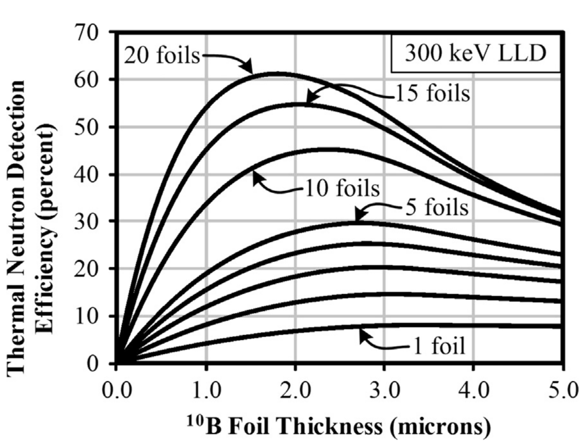

Fig. 1. The theoretical intrinsic thermal neutron detection efficiency of multiple layers of boron foil as a function of foil thickness.

Requiring reaction products to deposit at least 300 keV of energy in the gas region, the effective ranges of the alpha particle and Li ion reaction products in ^{10}B foil are 2.65 μm and 0.81 μm, respectively, for the 94% branch, and 3.52 μm and 1.05 μm, respectively, for the 6% branch [10]. The ideal thickness of the B foils maximizing the neutron detector efficiency in Fig. 1 is less than the *total* summed range of the reaction products in ^{10}B, 4.97 μm ($R_{\alpha}=3.28$ μm, $R_{^{7}Li}=1.69$ μm) and 5.96 μm ($R_{\alpha}=4.06$ μm, $R_{^{7}Li}=1.90$ μm) for the 94% and 6% branches, respectively [10].[1] Consequently, reaction products are able to escape *both* sides of the B foil simultaneously and be measured in the gas volume concurrently.

Theoretical neutron response pulse-height spectra were calculated using MCNP6. For the simulations, a uniformly distributed 1.0 cm diameter collimated thermal neutron beam was centered on a 5 cm × 5 cm ^{10}B foil sheet. A P-10 proportional gas (90% Ar, 10% CH_4) region, $5\times5\times5$ cm^3, was added to each side of the ^{10}B foil. The neutron beam was centered on the B foil, which allowed the entire energy of the alpha particle to be absorbed in the gas region without escaping the boundary of the simulation. For example, the highest energy alpha particle is also the longest range reaction product and travels 1.07 cm in P-10 gas. The closest this reaction product comes to the boundary edge of the simulation is 0.93 cm. Thus, none of the reaction products were able to escape the boundary of the system and all energy deposited in the P-10 gas was recorded. Pulse-height spectra were generated in the simulation by tallying the energy deposited by the reaction products in the P-10 gas. A direct comparison can be made between the experimental suspended B foil pulse-height spectra and the simulated spectra because the neutron beam dimensions and neutron energy were chosen to resemble the diffracted thermal neutron beam at the Kansas State University (KSU) TRIGA Mark II nuclear reactor.

The simulated pulse-height spectra for ^{10}B foils 0.01, 0.5, 1.5, 2.5, and 3.3 μm thick are shown in Fig. 2. The 3.3 μm thickness was simulated because it is the ideal thickness for a single layer of ^{10}B foil that maximizes the intrinsic thermal neutron detection efficiency, approximately 8%, higher than that of a coated device. Similarly, 15 layers of 2.0 μm thick ^{10}B foils would have an intrinsic thermal neutron detection efficiency of 54.8%, and five layers of 2.5 μm thick ^{10}B foils would have an efficiency of 29.5%. An additional 0.01 μm thick ^{10}B foil is presented in the simulated results in Fig. 2. The 0.01 μm thick ^{10}B foil is a benchmark to show the simulation functioned properly. A ^{10}B foil this thin allows both reaction products to escape the foil simultaneously with minimal reaction product self-absorption, thus, two peaks appear in the pulse-height spectrum at approximately the summed characteristic energy of the alpha particle and Li ion from the two neutron absorption branches, 2.31 MeV and 2.79 MeV. Further, the ratio of the two peak heights is also 47:3 (94:6), which is equal to the branching ratios.

Other notable pulse-height spectral features include a valley between the lower channel numbers, where electronic noise typically appears, and the main feature of the pulse-height spectrum. The depth and width of the valley decreases as the ^{10}B foil thickness increases, which is a result of more reaction product self-absorption occurring in the B foil before the reaction products enter the gas region. The valley that occurs between the main peaks of the spectrum and the lower energy channels where electronic noise would reside is a desirable feature because it will assist with achieving acceptable gamma-ray rejection ratios (GRRs) without sacrificing a significant percentage of neutron events. Ideally a lower level discriminator (LLD) or energy threshold would

[1] The summed total ranges do not include a minimum amount of energy deposited in the gas volume.

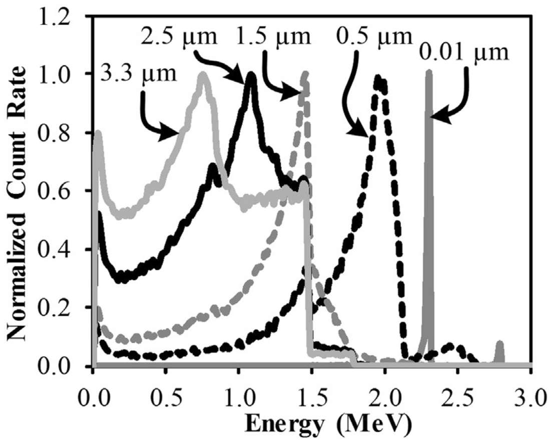

Fig. 2. The theoretical thermal neutron response pulse-height spectra of 0.01, 0.5, 1.5, 2.5, and 3.3 μm thick ^{10}B foils obtained using MCNP6.

be set at the minimum of the valley to eliminate essentially all electronic noise and gamma ray induced events.

Simulated pulse-height spectra shown in Fig. 2 at ^{10}B foil thicknesses of 1.5, 2.5, and 3.3 μm all contain a sudden drop in count rate at 1.47 MeV, which is the energy of the alpha particle reaction product in 94% of the neutron absorptions. The main feature in the 1.5 μm thick ^{10}B foil pulse-height spectrum appears to be centered at approximately 1.47 MeV. As the B foils become thicker, the location of the main spectral feature decreases in energy, which is a result of an increase in reaction product energy self-absorption occurring in the B foil before entering the gas region.

3. Experimental procedure

Three B foils, approximately 1.0 cm in diameter, were obtained from The Lebow Company and a photograph of a single B foil is shown in Fig. 3. Foil thicknesses were reported to be 1.0 μm, but there was uncertainty about the B foil thickness due to the uncharacterized evaporation method used to produce this material. The B foil has a metal support ring, also shown in Fig. 3, which was used to attach the B foils to Al plates using Cu tape. Before attaching the B foil, a hole slightly bigger than the diameter of the B foil was drilled through the Al plate to allow reaction products to escape both sides of the B foil. The foils attached to the Al plates were positioned vertically into a test chamber and spaced 4.5 cm apart, as shown in Fig. 4. The test chamber was $15 \times 15 \times 50$ cm^3 and capable of containing 10 layers of absorber sheets, however only the front four compartments were utilized in the B foil testing. This B foil spacing allowed for all of the reaction product energy to be deposited in the gas region before colliding with an adjacent grounded Al plate or cathode wall. A single 25 μm thick gold coated tungsten anode wire was positioned horizontally in the test chamber and centered directly over the middle of the B foil.

The test chamber was allowed to purge for 20 min with P-10 gas. During the purge time, the device was positioned in a 1.0 cm diameter collimated diffracted thermal neutron beam port at the KSU TRIGA Mark II nuclear reactor. An operating voltage bias of 500 V was used and a 10 min pulse-height spectrum was collected with the reactor power at 500 kW. Next, a Cd plate was positioned between the neutron beam and the detector to block essentially all neutrons from entering the device, and another 10 min pulse-height spectrum was collected. The results of the experiment are presented in the following section and compared to simulated results.

Fig. 3. An elemental B foil obtained from The Lebow Company, approximately 1.0 cm in diameter. (1 square=0.25″ × 0.25″).

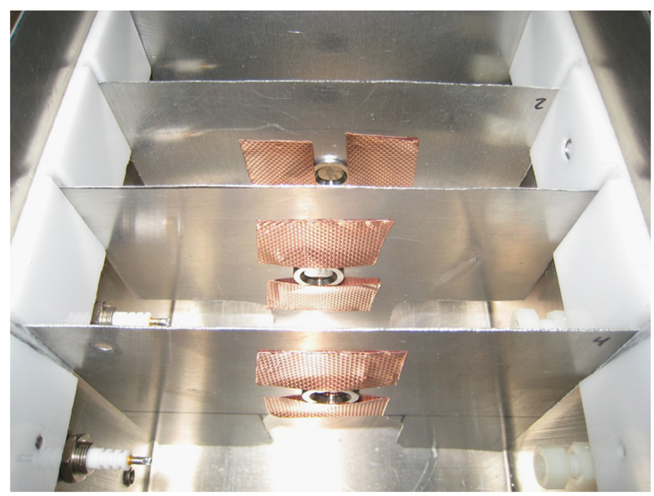

Fig. 4. The three boron foils mounted to the Al plates and positioned vertically in the Al test chamber.

4. Experimental results

The experimentally obtained neutron response pulse-height spectrum is shown in Fig. 5 where two peaks are obvious at channels 210 and 275. There is an additional small shoulder visible in the spectrum near channel 125. Likewise, Fig. 6 illustrates the comparison of the experimental results to simulated pulse-height spectra at ^{10}B foil thicknesses of 1.8 and 2.0 μm. The simulation allows for the spectra to be energy calibrated. Further, the intrinsic thermal neutron detection efficiency was measured to be $3.2 \pm 0.2\%$ for the three natural B foil neutron detector using the method of McGregor and Shultis [11].

5. Discussion

The B foils were requested to be 1.0 μm thick, but the uncertainty of foil thickness required confirmation of B foil thickness.

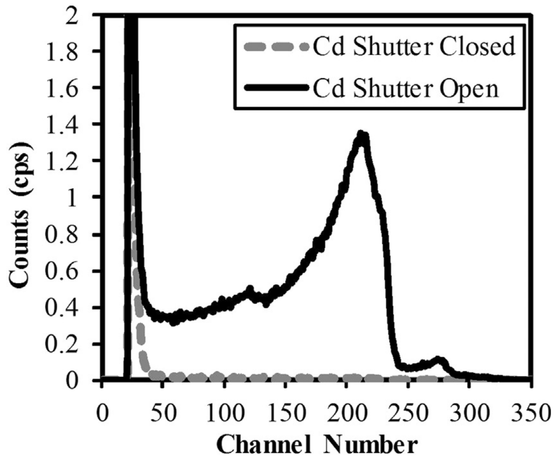

Fig. 5. The thermal neutron response pulse-height spectrum of the three B foils (black) and the collected response when a Cd Sheet was positioned between the neutron beam and detector (grey).

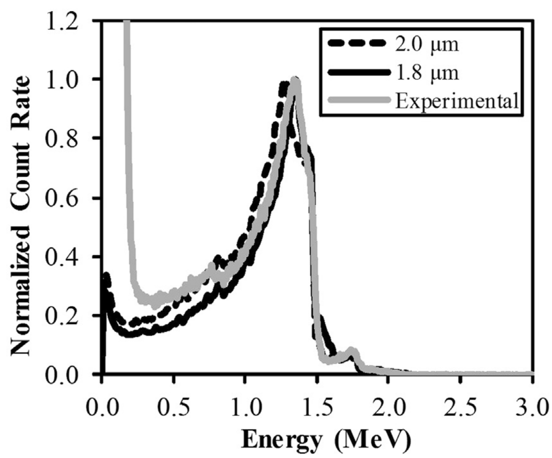

Fig. 6. The thermal neutron response pulse-height spectrum of the three B foils compared to simulated results for B foil thicknesses of 1.8 and 2.0 μm.

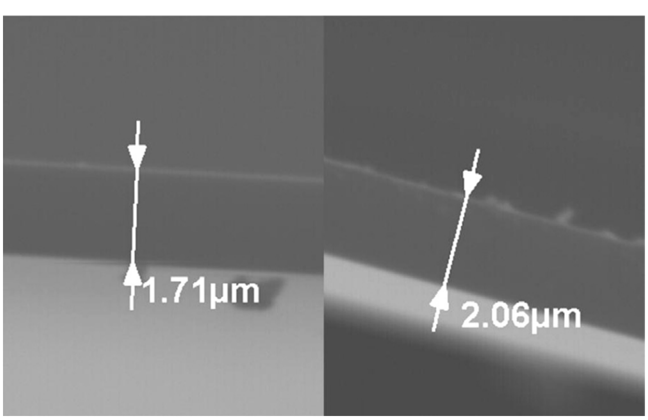

Fig. 7. SEM images of the central portions of the B foils, which show the B foil thickness ranged between approximately 1.7 and 2.0 μm.

One of the B foils was placed in a scanning electron microscope (SEM) to measure the thickness. A majority of the B foil thickness ranged between 1.7 and 2.0 μm, as shown in Fig. 7, but foil thickness increased to as high as 3.76 μm near the foil edges, as shown in Fig. 8. Recall that the MCNP6 simulations were completed for foil thicknesses of 1.8 and 2.0 μm, which plotted together with the experimental pulse-height spectrum, shown in Fig. 6, demonstrate that the simulations match well with experimental data. Further, the smaller peak in the experimental data occurring near 1.75 MeV matches well to the 2.0 μm thick simulated pulse-height spectrum, while the larger peak near 1.33 MeV matches better to the 1.8 μm thick simulated pulse-height spectrum. Both simulated pulse-height spectra contain a shoulder at approximately 0.82 MeV, but the experimental pulse-height spectrum has the same shoulder at a slightly lower energy. This difference in location of the shoulder is most likely a result of the non-uniform electric field in the detectors, because no electric field or charge collection properties were included in the MCNP6 simulations. However, this shoulder is most likely a result of the 840 keV ^{7}Li ion emitted from the ^{10}B(n,α)^{7}Li reaction. The slightly lower energy of the shoulder location (approximately 820 keV from the simulation) is a result of reaction product self-absorption of the ^{7}Li ion occurring in the B foil before the reaction product entered the proportional gas region.

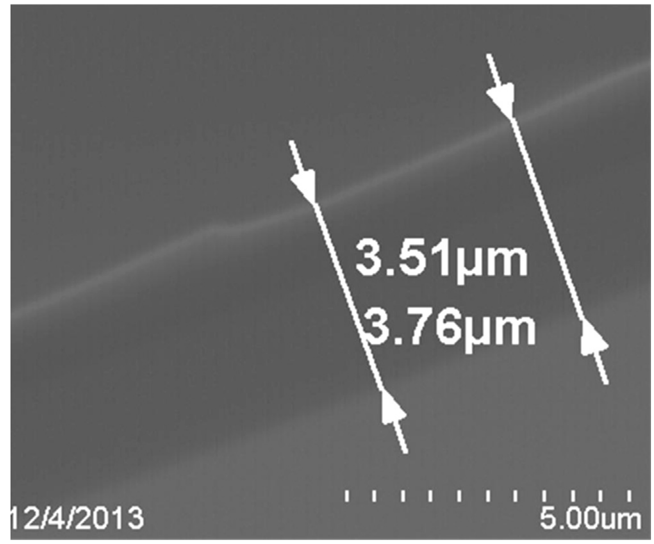

Fig. 8. SEM image of the B foil thickness profile near the edge of the foil close to the support ring, which shows the total B foil thickness was as high as 3.76 μm.

The theoretical intrinsic thermal neutron detection efficiency for three natural B foils, each 1.7 μm thick, is 3.5%, which is greater than the measured efficiency of 3.2%. The difference in experimental efficiency compared to theoretical predictions is most likely a result of either the measurement method or non-uniformity of the B foil thickness. The flux of the diffracted thermal neutron beam port has been measured and calibrated at 10 kW of reactor power, and the flux incident on the three B foils was predicted to be linear in relation for 500 kW of power. This predicted flux value was used to calculate the detection efficiency, although there may be some inaccuracies in predicting a flux 50 times greater than measured.

Although the theoretical intrinsic thermal neutron detection efficiency shows that high efficiency devices can be fabricated using multiple ^{10}B foil layers, there are some hurdles to overcome to accomplish assembling a practical neutron detector. The diameter of the B foils are restricted to 1.0 cm in diameter, and compiling several boron foils together to create a large-area neutron detector covering 1000 cm^{2} is presently unfeasible. Further, through correspondence with The Lebow Company it was recommended to 'hold one's breathe when handling the B foils to prevent breaking the foil when exhaling'. Thus, the detector's ruggedness would most likely not meet standards for backpack or handheld neutron monitoring systems. Further, ^{10}B foils are not readily available due to the increased cost and additional, more difficult, material preparation process for creating the foils. Lastly, based on intrinsic thermal neutron detection efficiency alone, the suspended ^{6}Li foils are presently a better alternative than ^{10}B foils, which have already been demonstrated as neutron detectors [3–7].

6. Conclusions

Here is shown the potential for suspended ^{10}B foil MWPCs to replace ^{3}He neutron detectors. The results of natural B foils have been compared to theoretical calculations, allowing for predicted performance with the use of enriched ^{10}B foils. Based on size, cost, fragility, and neutron detection efficiency, ^{6}Li foil based detectors would be a more practical alternative.

Acknowledgements

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