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Abstract

Intrinsic efficiencies of the multilayer boron detectors have been examined both theoretically and experimentally. It is shown that due to the charge loss in the boron layers, the practical efficiencies of most multi-layer $^{10}$B detectors are limited up to about 42%, much less than 77% of the 2 bar 2" diameter $^3$He detectors. It is suggested that the same charge loss mechanism will prevent essentially all substrate-based boron detectors from ever reaching the efficiencies of high-pressure $^3$He tubes, independent of the substrate geometry and material composition (including silicon). Meanwhile, the experimental data indicate that the multi-layer approach can increase the efficiencies up to the theoretical limit. Good n/γ discrimination has also achieved using the ionization chamber technique.
The shortage of helium-3 \(^{3}\text{He}\) has been recognized world-wide. Boron-10 \(^{10}\text{B}\) has been identified as one of the best replacements because of its close proximity to \(^{3}\text{He}\) in terms of the neutron-capture cross sections. However, BF\(_3\), which is also in the gaseous state at room temperature like \(^{3}\text{He}\), is ruled out as an alternative for neutron detection because of its toxicity. Elemental boron and its other compounds, such as boron carbide, have been studied by many groups. We examine, both theoretically and experimentally, the efficiencies of multi-layer boron thin films for neutron detection. A practical intrinsic efficiency limit of 42\% has been found for multi-layer \(^{10}\text{B}\) detectors due to the charged particle loss in the boron layer, much less than 76\% of the 2 bar 2" diam. \(^{3}\text{He}\) detectors. The same charge loss mechanism will prevent essentially all substrate-based boron detectors from ever reaching the efficiencies of high-pressure \(^{3}\text{He}\) tubes, independent of the substrate geometry and material composition (including silicon). Multi-layer approach can increase the detector efficiencies up to the theoretical limit, with good \(n/\gamma\) discrimination. Below, we first present the analytic results of intrinsic efficiency calculations. Then we show the experimental data of multi-layer boron detectors using an ionization chamber for charge collection.

The film thickness \((T)\) should be comparable to the ranges \((R_0)\) of the charged products, an \(\alpha\) and a \(^{7}\text{Li}\), from the neutron capture \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\) reaction. The \(\alpha\) particle ranges in boron are 3.6 and 4.4 micron at 1.47 (94\%) and 1.78 (6\%) MeV respectively, and 1.9 and 2.2 microns for the 0.84 (94\%) and 1.02 (6\%) MeV \(^{7}\text{Li}\). The percentages are the production probabilities. A 100 keV may be used as the lower energy threshold for ion detection, which is still sufficiently high compared with \(\gamma\)-induced electrons in an ionization chamber.

When neutrons and the film are at the opposite sides of the substrate, it is called transmission mode. Two scenarios are possible: A.) \(T \geq R_0\), and B.) \(T < R_0\). When neutrons and the film are at the same sides of the substrate, it is called back-scattering mode. The back-scattering modes also has C.) \(T \geq R_0\), and D.) \(T \leq R_0\). The efficiency calculations are straight-forward. As an example, in the scenario A, when the film thickness is greater than the charged particle range, the efficiency \((\varepsilon_A)\) is given by

\[
\varepsilon_A = \frac{1}{2} \frac{e^{-n_B \sigma_a T}}{n_B \sigma_a R_0} \left( e^{n_B \sigma_a R_0} - n_B \sigma_a R_0 - 1 \right).
\]

One may introduce an 'absorption number' (particle range normalized to the neutron absorption mean free path)

\[
\xi = n_B \sigma_a R_0.
\]
For thermal neutrons, \( \sigma_a = 3840 \) barn. For pure elemental \(^{10}\text{B} \), \( n_B = 1.28 \times 10^{23} \) cm\(^{-3} \), therefore \( \xi = 4.94 \times 10^{-2} R_0 \) (\( \mu \) m), which is a small number for micron-thick films. Using the small \( \xi \) approximation, one finds out that,

\[
\mathcal{E}_A, \mathcal{E}_B, \mathcal{E}_C, \mathcal{E}_D \leq \frac{\xi}{4} - O(\xi^2),
\]

The largest efficiencies all corresponds to when \( T = R_0 \). The slight difference is \( O(\xi^2) = \xi^2/6 \) for \( \mathcal{E}_A \) and \( \mathcal{E}_B \) and \( O(\xi^2) = \xi^2/12 \) for \( \mathcal{E}_C \) and \( \mathcal{E}_D \). Since \( R_0 \) is different for different charge species, the optimal thickness can only be found numerically using more general expressions like Eq. (1). It is found that \( T_0 = 2.98 \) \( \mu \)m for a single \(^{10}\text{B} \) layer with a total efficiency of \( \mathcal{E}_{\text{sum}} = 5.71\% \), Fig. 1. Next we consider the efficiencies of multi-layer thin films. It can be shown that for detectors with \( 2 \times N_0 \) layers, with \( N_0 \) pairs of transmission and backscattering layers, the efficiencies for different \( N_0 \) are related to each other by a sum of a geometrical sequence of order \( N_0 \). The total efficiencies of the multi-layer boron detectors as a function of number of optimized layer thickness is plotted in Fig. 2, the ultimate efficiency is determined by when \( N_0 \to \infty \). For \(^{10}\text{B} \), \( \mathcal{E}_{\infty}^{\text{sum}} = 41.7\% \). For natural boron, \( \mathcal{E}_{\infty}^{\text{sum}} = 39\% \). In comparison, at 1 atm. \(^3\text{He} \) pressure (S.T.P.) and 5 cm diameter, the efficiency is 51.6%. At 2 atm. and the same diameter, the efficiency is 76.6%. It should be pointed out that in principle, efficiencies greater than \(~ 42\% \) are achievable by using ultra thin films, with film...
FIG. 2: Total efficiencies of multilayer boron neutron detectors as a function of the number of layers. Each layer is assumed to be at the optimal efficiency. A saturation at 41.7% for $^{10}$B is the result of charge loss in the boron layer and the substrate.

thickness much less than the charged particle range. However, the number of layers needed would be impractically large.

We have coated 1/32"-thick aluminum plates with boron-10 powder and used the plates in a planar ionization chamber configuration, which has been described previously. [1] One difference is that there is no $^3$He in the gas mixture. For multiple layers, we sandwiched a high-voltage (HV) wire array in-between two boron-coated plates. Up to four layers have been examined so far, with a boron-to-HV plate separation of about 3.3 mm. Uniformity of the spacing ($\sim 10\%$ error or less) is critical for a uniform response among different coated layers. Typical pulse height spectra for a four-layer configuration are shown for $^{10}$B and natural, in comparison with a single layer in Fig. 3. The results indicate good $n/\gamma$ discrimination, as expected of an ionization chamber.

Finally, we compare the measured intrinsic efficiencies as a function of the layer numbers with the theory, Fig. 4. The efficiencies are normalized to the largest efficiencies by detectors using natural boron. The large variations for several measurements with the same number of layers are from different coating techniques, which indicate that the substrate coverage and coating uniformity can affect the efficiencies strongly. We also found that multi-layer configuration can increase the detector efficiencies up to the theoretical limit, as expected.
FIG. 3: Pulse height spectra (PHS) of two four-layer detectors, one is for $^{10}$B, the other for natural boron. The insert is the PHS of a single-layer natural boron spectrum, where the characteristic energies of the charged particles are more distinct. All spectra show good n/$\gamma$ discrimination for an energy cut at 100 keV.

FIG. 4: Measured efficiencies compared with theory (dashed lines). The efficiencies increase with the number of layers. The efficiencies are also sensitive to coating methods, which implies the sensitivity to coverage/uniformity of the coating.