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Improving spatial resolution in neutron detectors with submicrometric B_4C layers

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Due to their physical properties, neutrons are an excellent probe for the investigation of matter in different scientific fields, such as physics, chemistry and biology as well as for specific medical and industrial applications. Neutron detection is usually achieved via nuclear capture reactions, where the neutron is absorbed by the nucleus of an atom, which decays into two heavy charged particles. These reactions only occur with significant cross-section for a few isotopes and the ones of practical interest for detection applications are, by decreasing cross-section, ^{3}He, ^{10}B and ^{6}Li. Until recent years, proportional counters filled with ^{3}He gas were considered the golden standard for neutron detection. However, when a severe shortage of this gas was acknowledged, prices skyrocketed and heavy acquisition restrictions were implemented, which urged to pursue alternative technologies. Consequently, over the last decade, a lot of effort and investment was put into the development of ^{3}He-free neutron detectors for a wide range of applications. Gaseous detectors equipped with boron layers, deposited on the inner walls of the detector or on substrates that are then inserted into it emerged as the most obvious alternative. Due to momentum and energy conservation, the reaction products of the ^{10}B neutron capture are emitted along the same, in opposite directions. Consequently, in conventional boron coated detectors, for each neutron capture, only one of the reaction products can travel towards the gas to generate a signal in the detector, while the other is absorbed by the boron layer or the substrate. Furthermore, depending on the depth of the nuclear capture, the range of the α particles in typical gases used in gaseous detectors at atmospheric pressure can extend up to about 10 mm, which intrinsically limits their spatial resolution. In this work, we propose an alternative approach that aims at simultaneously detecting both secondary products of neutron capture reactions which can be achieved if thin enough converter and substrate layers are deployed. Monte Carlo simulations were developed to validate the detection concept and to optimize its geometry by computing the detection efficiency as a function of substrate and converter thicknesses. A 0.9 µm Mylar foil was stretched over an aluminium frame obtaining a smooth 100×100 mm^2 effective surface, suitable for boron carbide (B_4C) deposition. Considering this substrate, simulation results indicate that a 1.5% detection efficiency for thermal neutrons can be reached with a total 1 µm thick B_4C (99% enriched) layer, equally distributed over both sides of the substrate surface. Although this value is inferior to that of conventional boron-based detectors employing a thick conversion layer (~4.5%), it offers the advantage of allowing a more precise estimation of the interaction site for each detected neutron, which leads to an improvement of spatial resolution.

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1. Limitations of thick boron converters

When a neutron is captured by a ^{10}B nucleus, a fission reaction occurs that results in the emission of an α particle and a ^{7}Li nucleus, in opposite directions. If one of these secondary charged particles escapes the conversion material to reach the surrounding gas, a trail of electron-ion pairs is created along the track of the particle, which can extend up to about 10 mm for gases at atmospheric pressure [1]. Figure 1 shows GEANT4 simulation results of the range distribution of the boron neutron conversion products originated in a 3 µm thick ^{10}B-enriched B_4C layer as they enter $Ar:CO_2$ (90%:10%), a gas mixture commonly used in boron-coated gaseous detectors, at atmospheric pressure.

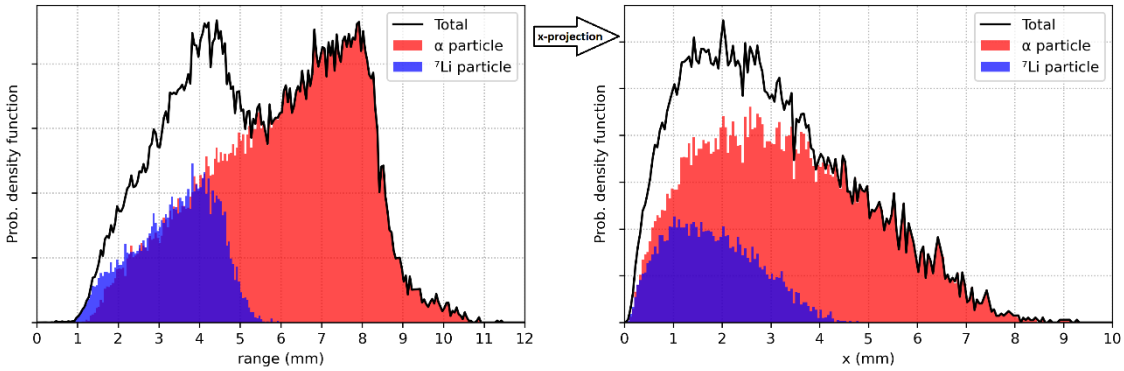

Figure 1: Distribution of ^{7}Li and α particle ranges emerging from a 3 µm ^{10}B-enriched B_4C layer into $Ar:CO_2$ at atmospheric pressure, with incident thermal neutrons from the gas side. An energy cut of 100 keV was applied, which results in a near absence of counts for ranges under 1 mm.

Although the range of the secondary particles from the neutron capture is only of a few microns in solids, conventional gaseous neutron detectors based on solid boron employ layers with a combined thickness of converter and substrate with, at least, hundreds of microns. Therefore, the determination of the neutron interaction site for each neutron detection takes into account only one of the fission fragments, which is isotropically emitted and, depending on the fraction of energy retained when reaching the gas, can generate a long track of electron-ion pairs along a random direction. The precise location of the neutron capture site is therefore impossible to determine from a single neutron capture, since the primary ionizations track will extend over a few millimetres, which in turn results in a readout charge collection across several millimetres as well. This limits the spatial resolution of position sensitive neutron detectors (PSND), being in some cases the greatest limiting factor of position resolution [2].

2. Coincident detection of neutrons with submicrometric boron layers

A novel strategy to improve the spatial resolution of PSND is proposed: using a thin detection layer composed by a submicrometric layer of a B_4C deposited on an equally thin substrate, in such way that both secondary particles from the neutron capture reaction can escape it to ionize opposite sides of the surrounding gas. Two independent multiwire proportional counters (MWPCs), detectors A and B, collect the charge generated by each particle, and by crossing the time coincident information of each readout a more complete profile of the neutron capture reaction is obtained, which allows to pinpoint the neutron interaction site even for a single

neutron capture. Attending to its operation principle, it is designated as the "coincidence detector", and its working principle is depicted in figure 2.

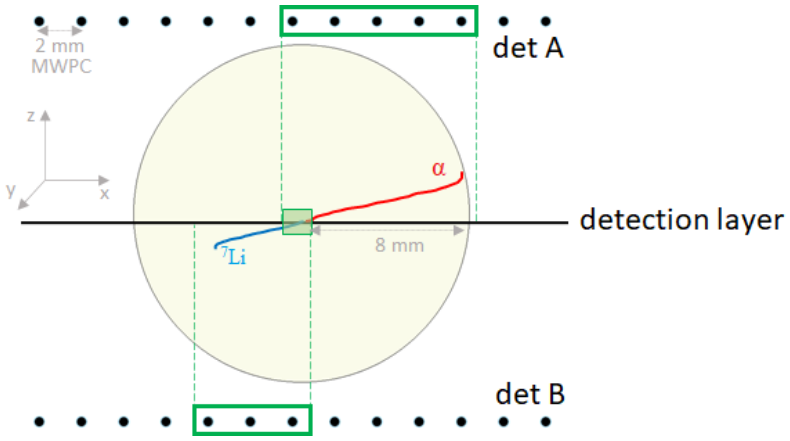

Figure 2: Operation principle of the coincidence detector. The 8 mm circumference identifies the maximum range of the neutron capture reaction products, detectors A and B are two independent MWPCs, and the wires triggered in this particular neutron detection are highlighted by the green rectangles.

An adequate material to use as substrate is Mylar, which has good mechanical properties to handle the stress from the boron coating process and is available in submicrometric thicknesses. A 0.9 µm Mylar foil was stretched and attached to an aluminium frame, producing a smooth surface with 100×100 mm^2 effective area.

3. Monte Carlo Simulation Results

Monte Carlo simulations with GEANT4 were developed to investigate optimal detection layer thickness by irradiating different geometry possibilities with a thermal neutron beam perpendicular to the detection layer, incident from the side of detector A. The materials considered were 99% enriched $^{10}B_4C$, as reported achievable in literature [3], surrounded by Ar:CO_2 (90%:10%), a commonly used gas in boron-coated gaseous detectors, at atmospheric pressure. A 0.9 µm Mylar layer was used as substrate, which despite being indispensable to support the B_4C, does not contribute to the conversion of neutrons, but rather only to the absorption of the reaction secondary products, and therefore should ideally be as thin as practically feasible. Two coating geometries were considered: depositing the full thickness of the neutron converter material on one side of the substrate, or equally dividing it by the opposite sides of the substrate, resulting in a symmetric detection layer. The results, depicted in figure 3, show that for both cases a total coating of 1 µm maximizes the detection efficiency of the coincidence detector. Although this value is inferior to that of conventional boron-based detectors employing a thick conversion layer (equivalent to the efficiency saturation limit of detector A, at ~4.5%), it offers the advantage of allowing a more precise estimation of the interaction site for each detected neutron, which leads to an improvement of spatial resolution. The coincidence detector only accounts for neutron captures that simultaneously deposit energy on both gas regions (above a 100 keV energy threshold). Therefore, the efficiency of the coincidence detector is naturally not equivalent to the sum of the efficiencies of detector A and B, because for some neutron captures only one of the secondary particles reaches the gas, which results in a contribution to the detection efficiency of only one of the detectors (A or B), without contributing to the coincidence detector efficiency.

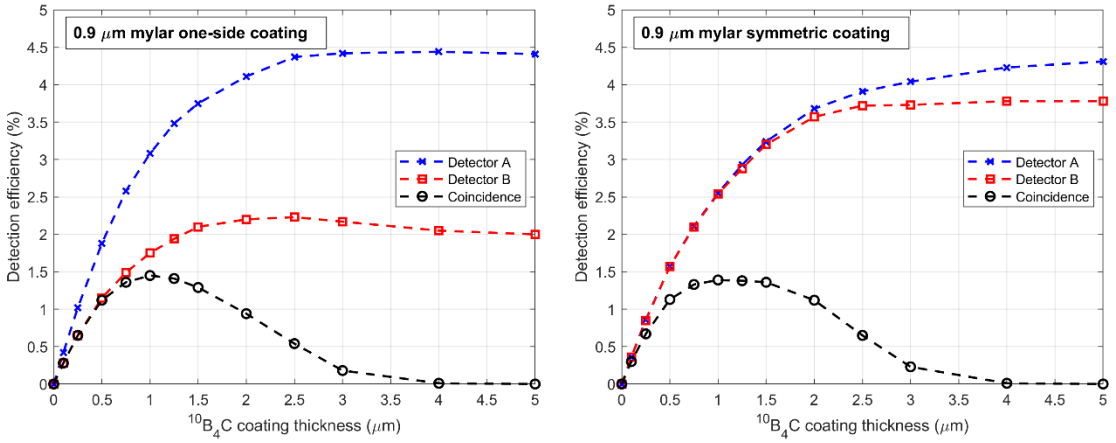

Figure 3: Detection efficiency as a function of the total $^{10}B_4C$ thickness deposited on a 0.9 µm Mylar substrate for one-side coating (left) and symmetric coating (right).

Dividing the total B_4C coating thickness across both surfaces of the substrate, rather than depositing all of it on one-side only, is technically less challenging and offers additional advantages, such as allowing for an even energy distribution across both MWPCs, which makes the coincidence detector essentially symmetric. Also, the symmetric deposition has a broader efficiency peak around 1 µm, which compensates uniformity fluctuations that are inherent to coating techniques.

4. Conclusions

A novel thermal neutron detection concept was presented, relying on the time coincident detection of both secondary particles of a neutron capture reaction to pinpoint the neutron interaction site and thus improving spatial resolution. The detector design in terms of substrate and neutron converter thicknesses was optimized based on GEANT4 simulations. The optimal coating thickness to maximize the detection efficiency of coincident events was determined to be 1 µm for an enriched boron carbide coating, with a value of ~1.5%. Furthermore, dividing this total thickness by both surfaces of the substrate rather than depositing the full thickness on one side only is considered advantageous. The enriched B_4C deposition process by magnetic sputtering on the Mylar substrates is being perfected, and the experimental validation of this technique by neutron irradiation will soon be carried.

References

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