Contribution ID: **436** Type: **Poster**

Improving spatial resolution in neutron detectors with submicrometric B4C layers: Monte Carlo simulation results

Tuesday 7 September 2021 11:07 (1 minute)

The physical properties of neutrons make them 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. Along with neutron imaging, a variety of techniques use neutron irradiation on a sample to characterize it, such as neutron diffraction, reflectometry, spectroscopy, and small angle scattering. All these have a common need: the detection of neutrons that are transmitted or scattered by the sample. Because neutrons are electrically neutral, their detection is usually achieved via nuclear capture reactions, in which the neutron is absorbed by the nucleus of an atom, which becomes unstable and decays into two highly ionizing charged particles. These reactions only occur with significant cross-section for a few isotopes and the ones with practical interest for detection applications are, by decreasing cross-section, 3He, 10B and 6Li. Until recent years, proportional counters filled with 3He gas were considered the golden standard for neutron detection, due to their high efficiency, good gamma-ray discrimination, and non-toxicity. However, when a severe shortage of this gas was acknowledged, prices skyrocketed and heavy acquisition restrictions were implemented, which urged for the pursue of alternative technologies. One additional motivation was given by the fact that 3He detectors were already at the limit of their performance capabilities, namely regarding counting rate and position resolution, which fell short of the requirements of instruments in new neutron facilities such as the European Spallation Source (ESS), that will provide a neutron beam up to one hundred times brighter than currently available in any other existing facility.

Consequently, over the last decade, a great deal of effort and investment was put into the development of 3He-free neutron detectors, and for a wide range of applications, gaseous detectors that rely on the 10B nuclear capture reaction are the most promising. Because elemental boron is a solid at STP conditions, these detectors employ a thin coating of boron or other boron-containing material, such as boron carbide (B4C), surrounded by a proportional gas for charge amplification. These materials are not self-supporting, hence are generally deposited directly on the inner walls of the detector or in aluminium substrates that are then inserted into it.

Due to momentum and energy conservation, the reaction products of the 10B neutron capture (an alpha particle and a 7Li nucleus) are emitted in the same line of action, 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 in which the nuclear capture occurs and the consequent energy lost to collisions inside the boron layer, the range of the 7Li and alpha particles in conventional proportional gases at atmospheric pressure can extend from virtually zero to about 10 millimetres. This intrinsically limits the spatial resolution of such detectors, which generally calculate the centre of gravity from many neutron detections to estimate with greater precision the neutron capture site. While this position uncertainty can be reduced by increasing gas pressure, which results in shorter particle travel ranges, this poses a mechanical challenge that requires the use of thicker entrance windows, which in term increases the probability of neutrons being scattered or absorbed before reaching the sensitive region of the detector.

Although the range of the 7Li and 4He fission fragments from the neutron capture reaction in solids is only of a few microns, current conventional gaseous neutron detectors based on 10B adopt detection layers with a combined thickness of converter and substrate with, at least hundreds of microns, most frequently extending to many millimetres. 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. By using independent readout systems to detect each particle that emerges on opposite sides of the conversion layer, and crossing the information from these two signals, it is possible to reconstruct the neutron interaction site with greater precision than using the centre of gravity approach of conventional detectors, while also requiring less statistic.

Monte Carlo simulations with GEANT4 were developed to compare the position reconstruction uncertainty of a state-of-the-art boron detector with the novel coincidence detector. An incident point thermal neutron beam at a fixed position was considered, and the estimation of the neutron interaction site for each detected neutron was achieved by weighting the energy deposited along the trajectory of each particle in the x-projection of the track. For the same neutron exposure, the simulation results show an improvement of intrinsic spatial resolution (FWHM) by a factor of approximately 8.

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Session Classification: Poster Session I

Track Classification: Development of accelerators and detectors