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Spatial resolution and efficiency of microchannel plate detectors with neutron converter films

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ABSTRACT

An investigation into the potential neutron detection efficiency gains that could be made to microchannel plates (MCPs) has been conducted by a GEANT4 simulation. Thin-film neutron converters are coupled to the upstream-side of the MCP. MCPs with and without pre-existing neutron sensitivity were examined. A study into potential film materials favors a Gd_2O_3 converter film utilized in thin-film and pillar geometries for straight-channel MCPs. The objective was to increase thermal neutron detection efficiency without sacrificing the spatial resolution of the system by studying (1) the balance between capture efficiency and charged particle product production and range to optimize detection efficiency, and (2) the extent of radial straggling that the reaction products undergo as they are transmitted through the neutron converter and MCP, which affects spatial resolution. Our investigation reveals that an increase in efficiency of 9.9% can be achieved for an MCP without preexisting neutron sensitivity using a film geometry neutron converter of 4-μm thickness. An increase in efficiency of 4.3% can be achieved for a neutron-sensitive MCP using a pillar-type converter of 4-μm thickness. Degradation of spatial resolution is not significant for either film or pillar geometries with thicknesses in the range 0.5–10 μm.

1. Introduction

1.1. The use of MCPs for neutron detection

MCPs are routinely used in neutron detection for imaging applications. Neutron beams used for imaging typically consist of thermal or cold neutrons that are well-collimated. MCPs that are sensitive to neutrons may be used directly in conjunction with an image readout (phosphors, pixel array, etc.). MCPs that are not sensitive to neutrons may indirectly detect neutrons if a scintillating converter screen is used in conjunction with a photocathode mounted onto the front end of the MCP [1–3]. MCPs have the advantage of high spatial and temporal resolution and relatively high efficiency [4,5].

1.2. Neutron-sensitive MCP operation and materials

Neutron detection has generally relied on the use of ^{3}He as the primary detection medium for cold and thermal neutrons and serves as a benchmark for the efficacy of other neutron detection architectures. Due to the decreasing supply of ^{3}He, detector designs have been proposed with the intention of phasing-out reliance on ^{3}He [6]. To increase the neutron capture efficiency, neutron-sensitive materials containing large thermal neutron capture cross-section isotopes are incorporated into MCP glass [7–10]. Typical neutron capture nuclides used are given in Fig. 1. Charged reaction products locally deposit their energy while they travel through the MCP wall and interact with channel walls, causing the release of electrons that produces a cascade of secondary electrons within the channel, as shown schematically in Fig. 2. Due to the finite range of the reaction products, the MCP channel diameter and pitch need to be optimized depending on channel shape, the loading of neutron-sensitive material into the MCP glass, and the nuclide selected for loading. The resolution of this MCP type depends on the number of channels the reaction products are able to traverse while losing energy due to travel through the MCP walls. The efficiency is dependent on the chosen nuclide and number density of neutron-sensitive material loaded into the MCP glass, wall thickness, channel shape, and total thickness of the MCP. The MCP resolution and efficiency can also be manipulated through stacking of individual MCPs, which degrades resolution, but increases efficiency [11–13].

1.3. Objectives of study

The objective is to investigate the potential to increase thermal neutron detection efficiency of MCPs with and without preexisting

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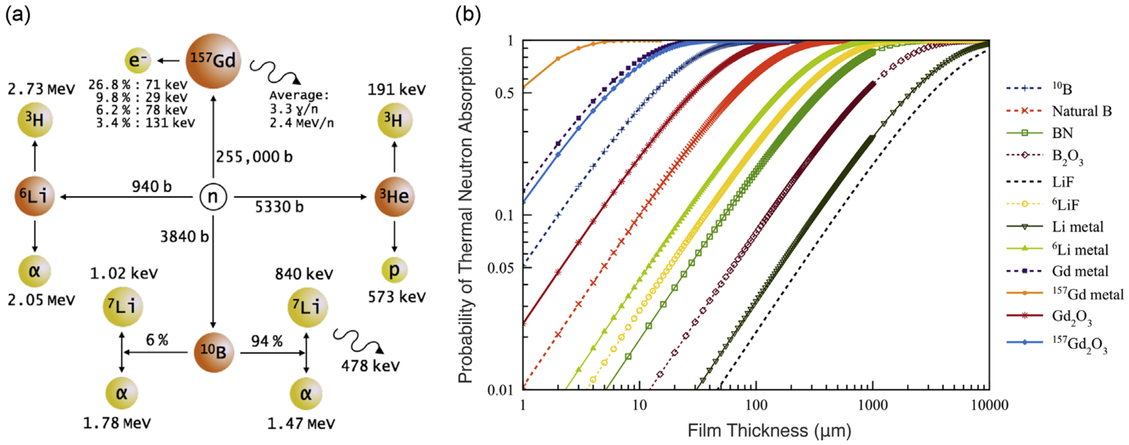

Fig. 1. (a) Nuclides typically used in thermal neutron detection have large thermal neutron capture cross-sections [14]. The charged particle reaction products have short ranges in solid matter and thus deposit their energy locally. While ^{3}He is provided as a reference point, it is not used in neutron-sensitive MCPs. (b) There are a variety of material compositions which incorporate neutron-sensitive elements and isotopes. A number of these materials are utilized in neutron detection schemes outside of MCP applications [15–18]. The probability of thermal neutron absorption, which leads to emission of energetic charged particle products, is dependent on the number density of specific neutron-sensitive nuclides within the material. The selection of a material to be utilized in a converter must balance the neutron absorption probability and reaction product properties with practicalities of material production.

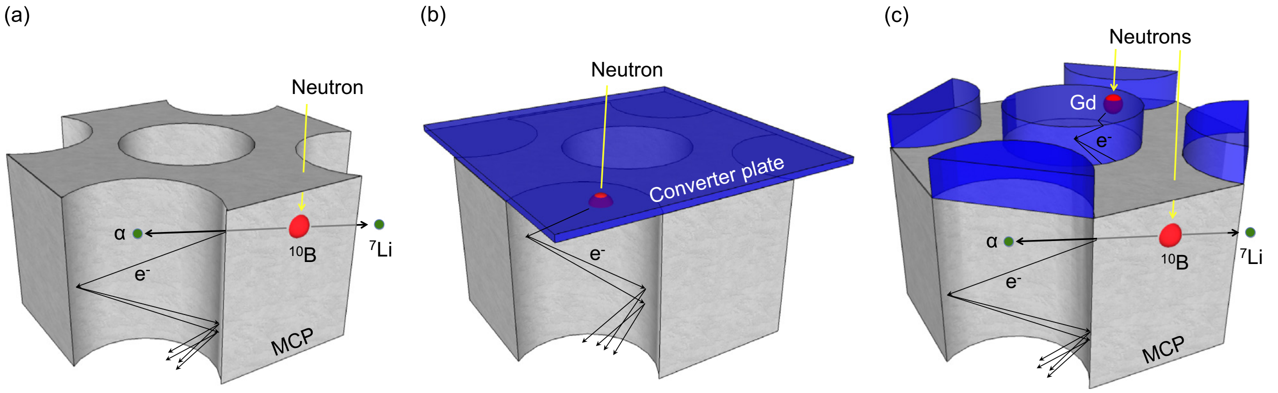

Fig. 2. (a) A neutron-sensitive MCP contains a nuclide/element with high neutron cross-section (typically ^{10}B, ^{6}Li, or Gd), which produces charged particles upon neutron absorption [11,19]. (b) A plate design is based on a thin film neutron-sensitive converter positioned directly onto the top of an MCP. The MCP may or may not be neutron-sensitive. (c) In a pillar-type design, columns of neutron-sensitive material are implemented directly above each channel; this design is intended only for neutron-sensitive MCPs.

neutron sensitivity using a neutron converter film. Two neutron converter geometries are studied, a plate and a pillar-type design, as in Fig. 2(b) and (c), respectively. The study is aided by simulations using GEANT4, which examines radiation transport through plate and pillar-type converters of various thicknesses coupled to a sample MCP. In addition to detection efficiency, degradation of spatial resolution due to the addition of the converter is also examined. This work extends investigation previously undertaken by Fraser et al. [19].

2. Description of simulation, materials, geometry, and physics

2.1. Simulation

The simulation is conducted using GEANT4.10 and involves the converter film coupled to a sample of the MCP geometry. The sample size was selected considering the constraints placed on the efficiency and resolution, as discussed in Section 3.1. The simulation geometry is shown in Fig. 3. Simulated neutron beam properties are selected to resemble those typically used in neutron imaging; thus thermal neutrons (E=0.025 eV) in a well-collimated beam directed

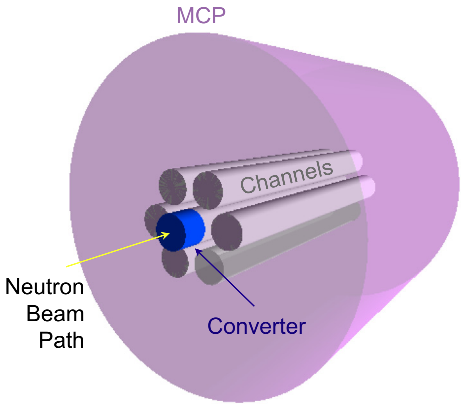

Fig. 3. MCP channels (white) are shown as straight cylinders within the surrounding MCP glass (pink). A thin layer of the neutron-sensitive converter plate (blue) intercepts the incoming neutrons. The converter geometry may be adjusted to study plates or pillar-type designs. In this figure, a pillar-type design is shown. We investigate thermal (E=0.025 eV) neutron irradiation within a pencil-beam (yellow arrow) directed onto the center of the converter, where the central channel exits. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)