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Monte Carlo simulation of a very high resolution thermal neutron detector composed of glass scintillator microfibers

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HIGHLIGHTS

- We proposed a thermal neutron detector with a spatial resolution around micron.
- A very high light-output glass scintillator was tested experimentally.
- A Geant4 work space was built which includes all the detecting physical processes.
- An algorithm to reconstruct the neutron absorption position was developed.
- The factors those may influence the spatial resolution of the detector were studied.

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ABSTRACT

In order to develop a high spatial resolution (micron level) thermal neutron detector, a detector assembly composed of cerium doped lithium glass microfibers, each with a diameter of 1 μm, is proposed, where the neutron absorption location is reconstructed from the observed charged particle products that result from neutron absorption. To suppress the cross talk of the scintillation light, each scintillating fiber is surrounded by air-filled glass capillaries with the same diameter as the fiber. This pattern is repeated to form a bulk microfiber detector. On one end, the surface of the detector is painted with a thin optical reflector to increase the light collection efficiency at the other end. Then the scintillation light emitted by any neutron interaction is transmitted to one end, magnified, and recorded by an intensified CCD camera. A simulation based on the Geant4 toolkit was developed to model this detector. All the relevant physics processes including neutron interaction, scintillation, and optical boundary behaviors are simulated. This simulation was first validated through measurements of neutron response from lithium glass cylinders. With good expected light collection, an algorithm based upon the features inherent to alpha and triton particle tracks is proposed to reconstruct the neutron reaction position in the glass fiber array. Given a 1 μm fiber diameter and 0.1 mm detector thickness, the neutron spatial resolution is expected to reach $\sigma \sim 1$ μm with a Gaussian fit in each lateral dimension. The detection efficiency was estimated to be 3.7% for a glass fiber assembly with thickness of 0.1 mm. When the detector thickness increases from 0.1 mm to 1 mm, the position resolution is not expected to vary much, while the detection efficiency is expected to increase by about a factor of ten.

1. Introduction

Advanced neutron sources and supporting advancements in neutron instrumentation have enabled new research in advanced material characterization, energy engineering, and biological science (Anderson et al., 2009). At the same time, the spatial resolution of currently existing neutron detectors limits the execution of even higher-impact research (Williams et al., 2012; Jung et al., 2012; Nanda et al., 2012). In this work, an assembly composed of cerium doped lithium glass microfibers, each with a diameter of 1 μm, is proposed as a solution to this problem. The fiber pitch is small enough to allow one to reconstruct the neutron absorption location from the resulting charged particle products, thereby overcoming the fundamental position limitation due to finite charged particle range and the variance associated with center-of-gravity-based reconstruction. To suppress the cross talk of the scintillation light generated in any Li glass fiber, it is surrounded by air-filled glass capillaries, each having the same

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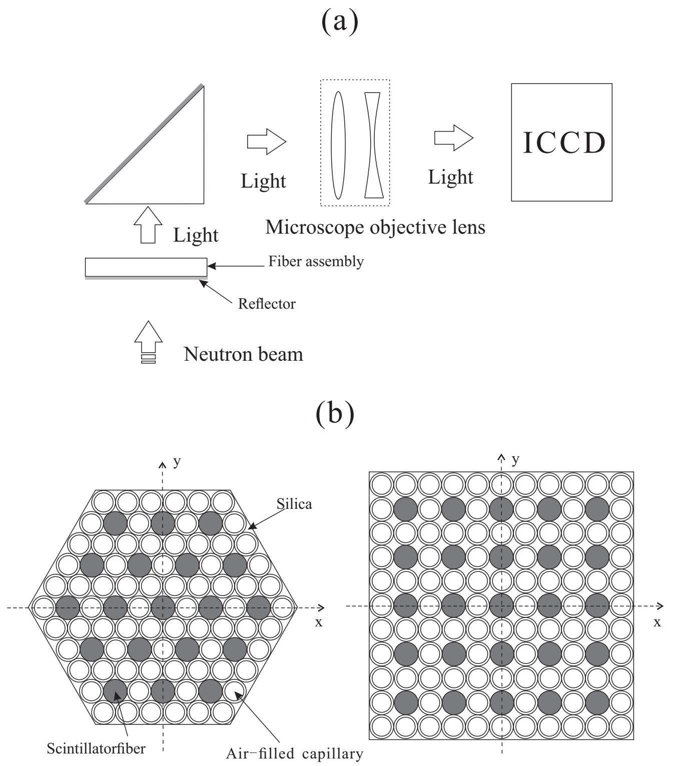

Fig. 1. (a) The schematic layout (not to scale) of the neutron detector system. See text for detail. (b) Both hexagonal and square microfiber assemblies are viewed in neutron beam direction.

diameter as the fiber. This pattern is repeated to form a bulk microfiber detector (see Fig. 1). On one end, the surface of the detector is painted with a thin optical reflector to increase the light collection efficiency at the other end. Thus, the scintillation light emitted by any neutron interaction is transmitted to one end, bent by 90° by an optical mirror mounted at 45° with respect to the neutron beam path, magnified by a microscope objective lens, and recorded by an intensified CCD (ICCD) camera. In this work, a Monte Carlo code based on Geant4 (version 10.0) (Amako et al., 2006) models the complete physics in the fiber assembly when a thermal neutron is incident: neutron interaction, scintillation, and optical boundary behaviors are included and treated meticulously. The optical system performance is also taken into account, although in order to show what may be possible with excellent light collection, potential sources of light loss in between the scintillator and ICCD are not modeled in detail in this work. Such detailed light loss modeling will accompany future work detailing experimental results. In this paper, we also present the results of neutron experimental measurements with a GS20 glass cylinder and a lithium glass from http://www.nucsafe.com/, which validate our Monte Carlo simulation results.

2. Modeling of the microfiber scintillator assembly

In this report, neutron interactions with the scintillator were handled by the data-driven high precision neutron nuclear reaction model provided by Geant4; electromagnetic processes, such as ionization, bremsstrahlung, Coulomb scattering, were dealt with the PENELOPE (https://twiki.cern.ch/twiki/bin/view/Geant4/) code. Scintillation and optical photon processes were also considered by invoking the models in Geant4. The simulation data are output into the ROOT data analysis framework, which is adapted for use with Geant4 to hold data in event-based data structures. Considering in particular the optical photon portion of the simulation, there is a large magnitude of tracks to be processed. In order to avoid the need to allocate and free memory frequently, a pre-allocating memory technique supplied by ROOT was used.

2.1. Detector modeling

Microfiber assemblies are fabricated by a partner at the Optoelectronics Research Center at the University of Southhampton. A monolithic lithium glass rod is first drawn into rods, then the rods are packed together with air-filled capillaries and drawn, and the draw process iterated until the desired microfiber dimensions are achieved. Two possible assembly configurations are given in Fig. 1, where air capillaries are used to optically isolate neighboring glass scintillator fibers. One is a hexagonal pattern and the other is a square pattern (shown in Fig. 1(b)). The air-filled capillary has the same dimensions as the scintillator fiber, and the wall thickness is around 5% of its diameter. The space between the scintillating and capillary microfiber is filled with silica glass during the fiber drawing process. By convention, the incident beam direction is selected as the *z*-axis in the Geant4 simulation. The simulated detector is placed with its axial center aligned with the *z*-axis, and the origin coincidences with its front surface. To save computer memory, a detector assembly of limited extent was modeled, which is large enough in extent to ensure that the charged particles produced by neutron interactions within the certain scintillator fiber (the central one) do not escape. For a parallel neutron beam bombarding on the central fiber, an appropriate number of scintillator fibers in diameter direction n_{fx} that are packed together with air capillaries in the simulation to satisfy this requirement is 150.

In this simulation, the optical system is simplified into a single photon collecting surface which is placed immediately next to the exit surface of the fiber assembly so that all exiting light is collected. Thus, the simulated light collected in this work represents a best case scenario.

The cerium (Ce^{3+}) doped lithium glass scintillator supplied by Nucsafe has similar composition and optical properties as the commercial products GS20. Therefore, the properties of the scintillator fibers are set according to GS20, as specified in Table 1 (Tyrrell, 2005; http://www.detector.saint-gobain.com; Rhodes, 2006). To make the simulation more conservative the light yield is set as GS20's (6000 photon/neutron listed in the table), although Nucsafe glass is brighter according to our experimental test, which will be described in Section 4. In the lithium glass a neutron is captured by the reaction:

$$^{6}\mathrm{Li} + ^{1}\mathrm{n} \rightarrow ^{4}\mathrm{He} + ^{3}\mathrm{He} + 4.78\ \mathrm{MeV}. \qquad (1)$$

The scintillation light is created by the energy deposition of the

Table 1
The properties of lithium glass scintillator GS20.

Composition by weight (Tyrrell, 2005)	SiO_2	56%
	MgO	4%
	Al_2O_3	18%
	Ce_2O_3	3%
	Li_2O	18%
	^{6}Li concentration	95%
Decay time (ns) (http://www.detector.saint-gobain.com)	Fast component	18
	Slow component	57
Density (g/cm^3) (Tyrrell, 2005)		2.5
Light output relative to anthracene (Tyrrell, 2005)		20%
Photon yield per thermal neutron (Rhodes, 2006)		6000
Alpha/beta ratio (http://www.detector.saint-gobain.com)		0.23
Refractive index (Tyrrell, 2005)		1.55