

Development of a directional scintillating fiber detector for 14 MeV neutrons

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Abstract

We have developed a directional detector for 14 MeV neutrons. The detector consists of an 8×8 array of plastic scintillating fibers coupled to a multi-anode photomultiplier tube. Protons in the fibers are scattered by incident neutrons and are detected as they pass through multiple fibers. The direction of the flux of incident neutrons is determined using the energy and direction of the recoil proton. The advantages of the detector are its small size and ability to detect fast neutrons. We used GEANT4 to simulate the detector performance, and report the results of experimental studies with neutrons from a 14 MeV pulsed D-T neutron generator.

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1. Introduction

1.1. The need for a new detector

We aimed to develop a compact fast neutron detector with good angular resolution for neutrons with a fixed energy. After careful review of existing neutron detector design, a scintillating fiber approach was selected. This paper describes the design and performance of this neutron detector.

1.2. Directional neutron detectors

Various neutron detectors have been developed since the discovery of the neutron by Chadwick [1]. Most of these detectors have focused on counting neutrons, measuring neutron energy, or both simultaneously. Several directional neutron detectors have been developed, but they are bulky, require a moderator, or have poor directionality for fast neutrons [2–3].

Prior scintillating fiber directional neutron detectors have used a parallel array of fibers encased in an absorber [4–5]. The absorber stops recoil protons after they escape a fiber. The fiber size is selected to be less than the range of the most energetic protons in the fiber—the protons that recoil at a small angle away from the incident neutron angle. The recoil proton energy spectrum from neutrons incident along the length of the fiber differs from that of neutrons incident perpendicular to the fibers.

Another prototype detector called SONTRAC [6] is being developed to image 20–250 MeV solar neutrons. It uses plastic fibers and reconstructs the proton path in 3D. SONTRAC is an imaging spectrometer; it uses neutron double scatters to measure incident neutron energy and direction.

We developed a directional neutron detector using an array of scintillating plastic fibers in air. Neutrons interact in scintillator by scattering elastically off hydrogen or carbon. When neutrons scatter off hydrogen the recoil proton slows down in the plastic and the energy lost is converted to scintillation light. In our detector, the neutron direction is reconstructed by measuring both the direction and energy of a proton in a single neutron scatter.

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2. Reconstructing direction from a proton track

2.1. Collision basics

When a neutron scatters elastically off a proton in a scintillating fiber, the scattered proton energy, E_p , is related to the incident neutron energy, E_n , by

$$E_p = E_n \cos^2 \theta.$$

θ is the angle of the scattered proton. Therefore,

$$\theta = \pm \cos^{-1} \left(\sqrt{\frac{E_p}{E_n}} \right). \quad (1)$$

Furthermore, the differential scattering cross-section is approximately constant for all angles.

Two possible angles arise from the square root implying that there are two angles reconstructed for each scattering event. When a large number of scattering events are analyzed, however, only one peak will appear as the other angle is uncorrelated.

Fig. 1 shows a neutron–proton scatter of interest in the fiber detector. An incident neutron collides with a proton in a fiber. The scattered proton traverses the fiber, which scintillates as the proton loses energy. If the proton passes into another fiber a track is observed. We choose a reference axis along a row of fibers. The incident neutron angle, β , is reconstructed by adding the measured proton angle away from the reference axis, ϕ , to the derived proton scattering angle, θ :

$$\beta = \phi + \theta.$$

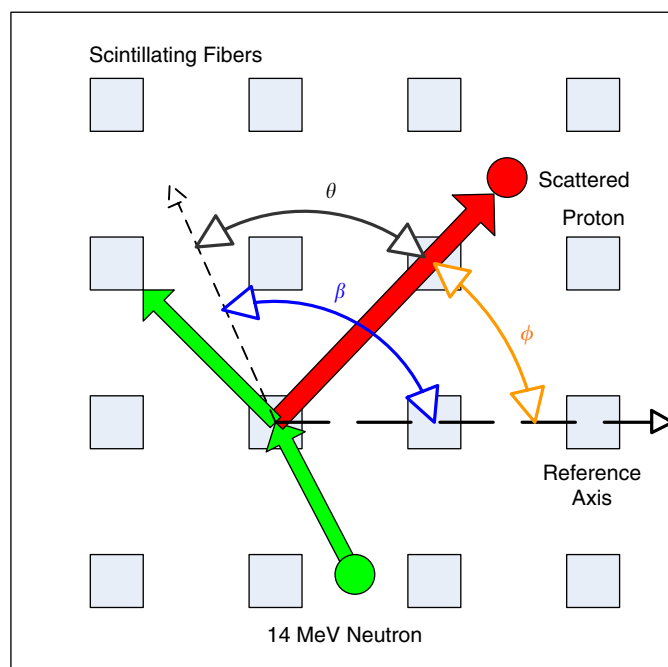


Fig. 1. Illustrative proton scatter in a fiber.

Using Eq. (1), this becomes

$$\beta = \phi \pm \cos^{-1} \left(\sqrt{\frac{E_p}{E_n}} \right). \quad (2)$$

When the incident neutron energy is known (14 MeV for a D-T generator), the neutron angle may be reconstructed by measuring the recoil proton energy, E_p and the angle of the proton track ϕ .

2.2. Issues in reconstructing the neutron direction

Ambiguities in the reconstructed neutron direction arise because the start or end points of the proton tracks cannot be differentiated. Uncertainty in the proton track orientation introduces a 180° ambiguity in the reconstructed neutron direction. In principle, the difference in the stopping power (Bragg peak) for a proton could be used to distinguish the beginning of the track from the end, but, as the stopping and starting points within the fibers are unknown, the Bragg peak cannot be accurately identified. As a result this detector is useful only if the detector can be positioned to localize the source to within 180° .

Our detector uses a two-dimensional design which limits performance. A 2D readout means that the 3D track of the scattered proton will be projected onto a 2D plane. If the incident direction of the neutron flux makes a small angle with the surface of the detecting plane, i.e. is nearly orthogonal to the plastic fibers, a histogram of the reconstructed neutron angles for a large number of scatters will still have a peak at the expected neutron angle. The peak broadens and becomes less pronounced as the incident neutron direction becomes parallel to the fibers. When the incident neutron direction is parallel to the fibers, directionality is lost. The broadness of the peak can, in theory, be used to determine the angle between the incident neutron direction and the length of the fibers, but was not pursued in this study.

3. Detector design

3.1. Description of the detector hardware

The detector consists of 64 Bicron BCF-12 fibers with dimensions $0.5 \times 0.5 \times 100$ mm. The square Bicron fibers are composed of a polystyrene core with an acrylic cladding. The cladding thickness is about 4% of the core size. The fibers are held in place by several plastic spacers. Both ends of the fiber are polished. Each fiber is coupled at one end to an anode of a Hamamatsu H7546B multi-anode photomultiplier tube (PMT) with optical grease. The other end of the fiber is not optically coupled. The fibers are housed in a light-tight cylindrical aluminum casing. Cross-talk between different fibers was reduced by applying a few microns thick extra-mural absorber coating (black paint) to the fibers. Additionally, a thin black Mylar sheath

protected the fibers from possible reflections from the outer aluminum shell.

The neutron detector was calibrated using 14 MeV neutrons incident parallel to the fiber axis and selecting events with a single fiber hit. This cut selected a large number of high energy, small angle scatter events. The upper range of the energy distribution in these events corresponded closely to 14 MeV because that is the maximum proton recoil energy.

3.2. The data acquisition system

Fig. 2 shows the data acquisition flow chart. The 64 outputs from the PMT are read out in the following manner. Each channel is fed into a CAEN N568B spectroscopy amplifier. The fast output of each amplifier is connected to a CAEN V812 constant fraction discriminator (CFD). The shaped output of the amplifier is fed to CAEN V785 analog-to-digital converters (ADCs). The CFDs trigger when a fiber channel exceeds a threshold (50 mV). When ≥ 2 CFDs trigger simultaneously (40 ns overlap) the ADCs are gated. The data acquisition computer reads data from the ADCs at the end of data conversion.

A hardware veto is used to reject events closely correlated in time with a proton scatter. The ADCs acquisition gate is set to 700 ns. If any subsequent fiber is hit during the ADC gate, the event is vetoed.

4. Monte Carlo simulations

Monte Carlo simulations were performed using GEANT4 to study the detector. Using GEANT4 we discovered that protons lose approximately 0.15 MeV in the $\sim 20 \mu\text{m}$ thick acrylic fiber cladding as they passed through it. Proton tracks with many fibers hit have a small initial energy loss in most of the fibers they traverse with a

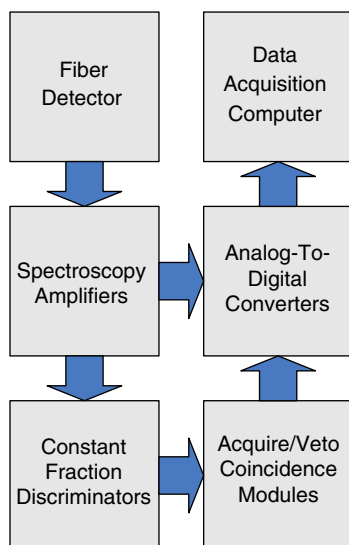


Fig. 2. Data acquisition flow chart.

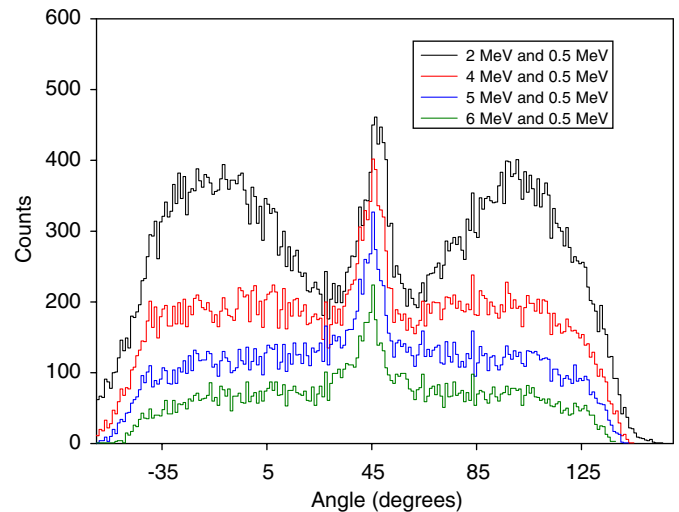


Fig. 3. Histogram of reconstructed neutron angles with various energy cuts from a GEANT4 simulation. The neutrons were incident at 45° . We selected events with two fibers hit with ≥ 5 and ≥ 0.5 MeV in any two fibers for the best peak to shoulder response.

large loss (Bragg peak) in the last fiber. This results in more undetected energy for long tracks as compared to short proton tracks. Also, proton tracks with less total energy will have higher percentage of undetected energy. We used the simulations to study the effect of undetected energy loss in the cladding. Fig. 3 is a histogram of the reconstructed neutron angles generated using GEANT4 with various energy cuts applied. Neutrons were incident to the fibers at 45° . A sharp peak is clearly observed at 45° above a background. The peak to shoulder was found to be best for an energy cut of ≥ 5 and ≥ 0.5 MeV in any two fibers.

Another concern is with recoil protons that partially escape from the fibers. GEANT4 simulations show that this occurs in only 12% of 2-hit events. This may account for some peak broadening.

5. Experimental results

Neutrons were generated with a VNIIA ING07 pulsed 14 MeV D-T generator. The generator was set to a 100 Hz pulse frequency, $100 \mu\text{s}$ pulse width and a total neutron flux of 8.2×10^6 neutrons/s. The detector was placed about 75 cm from the generator to provide approximately unidirectional neutrons at the detector.

The neutron detector was mounted on a rotating stage. Rotating the detector about the center of the 8×8 fiber array simulated moving the source. The incident neutron angle was set to 0° , 15° , 23° , and 45° . Incident angles are measured relative to a reference axis along a row of fibers in the detector. We selected events with two fibers hit with > 5 MeV deposited in one fiber (and > 0.5 MeV in the second). The angle φ was measured from the proton track. The proton energy, E_p , was reconstructed from energy deposited in the fibers. Finally, the neutron angle, β was reconstructed using Eq. (2). Fig. 4 shows the data at each neutron angle. Each histogram shows two peaks because of

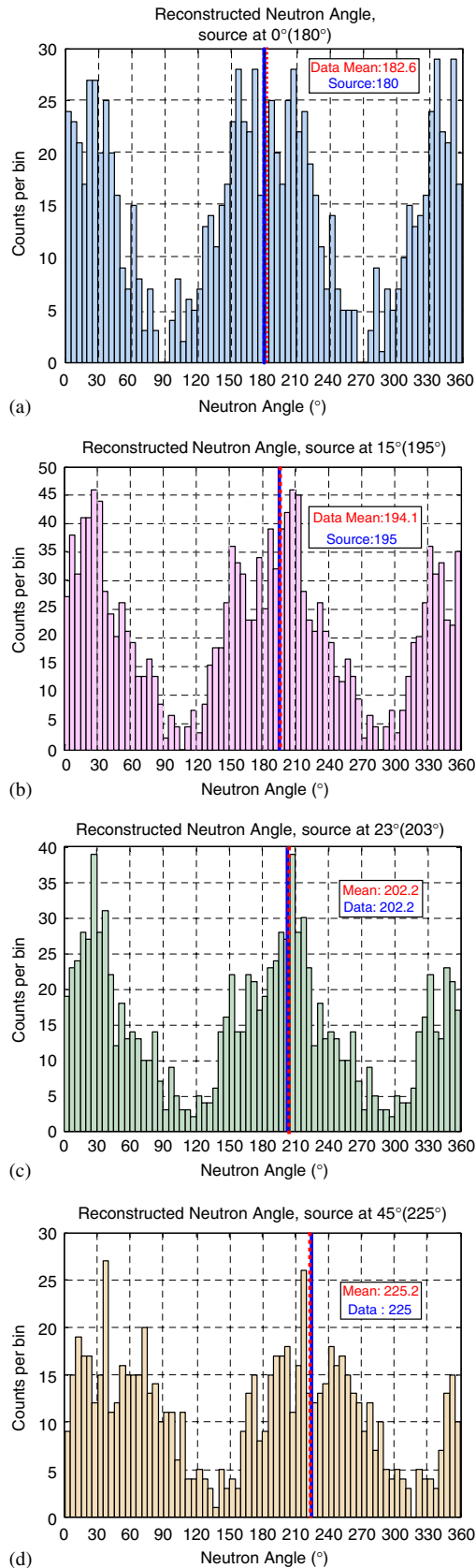


Fig. 4. Histogram of the reconstructed neutron angles. Neutrons are incident at: (a) 0°, (b) 15°, (c) 23°, and (d) 45°.

the 180° ambiguity in the proton travel direction. Approximately, a thousand events were recorded for each angle. The means of the peaks correspond to the incident neutron angle to within a few degrees.

The observed peaks were broader than the peaks in the GEANT4 simulation. This may be due to lower statistics in the data (~ 500 events in the peak region) than in the Monte Carlo (~ 4000 events in the peak region). Another source of peak broadening could be neutrons scattered from the walls of the experimental hall. Scattered neutrons coincident with real events could combine to produce errors in the proton energy E_p or the proton track. Both errors could lead to peak broadening. However, this has not been included in the simulations.

6. Conclusions

We have demonstrated that a scintillating fiber tracking neutron detector can determine the direction of an incident neutron flux using the energy and direction of recoil protons in single neutron scatter events. A shift in the direction of the 14 MeV neutron source could be detected to better than 10° with this detector.

Acknowledgments

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