# Energy and angular distribution of recoil proton of fast neutron in scintillation fiber: a simulation study

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**Abstract** Due to their low cost, big reaction cross-section with neutrons, flexibility, and convenience for long distance data transfer, plastic scintillation fibers (PSF) have been increasingly used as detectors or sensors for high-energy neutron radiography. In this paper, Geant4 Monte Carlo simulation tool was used to obtain some characteristics of energy and angular distributions of recoil protons in plastic scintillation fibers irradiated by fast neutrons. The plastic fiber with BCF-20 as the core and an acrylic outer cladding was used in the simulation. The results show that there is a big range of energy and angular distribution of recoil protons in energies varying inversely with the recoil angle.

**Key words** Angular distribution, Energy distribution, Fast neutron, Scintillation fiber

## 1 Introduction

Fast neutron radiography is a useful imaging technique to inspect thicker objects composed especially of hydrogen-rich materials, where it is difficult to acquire high-quality images with thermal neutron and X-ray radiography[1,2]. At present, few neutron imaging detectors provide high quantum efficiency for fast neutrons. Most existing detectors were developed for neutron radiography applications with collimated beams of thermal neutrons[3]. Available neutron imaging systems[4] include scintillator + CCD-camera, imaging plates, amorphous silicon flat panel, and CMOS pixel detector. The scintillator + CCD-camera has been the most popular detector for fast neutron radiography[5-7]. However, an interesting development in fast neutron detection is scintillating fibers[8-11], which are advantageous in their high fast neutron capture efficiency, good position resolution, low-cost, and the possibility of making large-area detectors.

In this work, Monte-Carlo simulations were performed for a better understanding on neutron-capturing behavior of the scintillating fibers, and energy and angular distributions of recoil protons by the fast neutrons.

## 2 Simulation methods

The simulation was carried out using Geant4[12,13], a toolkit package developed at CERN for simulating performance of detectors in nuclear and high energy physics. The toolkit can be used to trace the particle trajectories and their interactions with atoms of the materials, with results consistent with those from other codes[14-17].

The main data driven models in Geant4 deal with isotope production induced by neutrons and protons, and depict transport of neutrons at low energies (up to 20 MeV). On the analogy of other hadronic processes in Geant4, the interactions of neutrons in the energy range are considered as radiative capture, elastic scattering, fission and inelastic scattering as separate models[18]. The models comply with the interface for use with the Geant4 hadronic processes which enables their transparent use within the Geant4 toolkit together

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with all other Geant4 compliant hadronic shower models. All cross-section data are taken from the ENDF/B-VI[19] evaluated data library. A low energy limit for particle interaction is defined as the minimal energy within the validity range of the model[12].

The simulation was done with plastic scintillation fibers, BCF-20[20]. The core of BCF-20 fiber is made of polystyrene doped with 1% PBD (butyl-phenyl-byphenylyloxadiazole). The cladding layer of BCF-20 fiber is polymethylmethacrylate (PMMA) in thickness of about 3% of the core diameter.

The angular calculation mode in Geant4 simulation is given in Fig. 1. The incident neutron is at ($X_0$, $Y_0$, $Z_0$). A recoil proton is tracked until producing energy deposition, and the ($X_1$, $Y_1$, $Z_1$) is taken to decide the interaction direction. Then $\theta$ is calculated using certain methods.

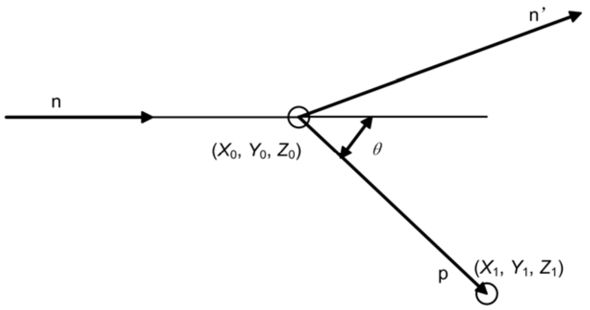


**Fig.1** Angular calculation mode in Geant4 simulation.

## 3 Results

### 3.1 Angular distribution of recoil protons

First, we consider the characteristics of angular distribution of recoil proton in plastic scintillation fibers irradiated by fast neutrons. At $\theta$=90°, the range of a recoil proton is bigger than the fiber radius. The recoil proton cannot deposit all of its energy in the fiber, i.e. an energy leakage. Fig.2 shows the simulation result. When $\theta$>90°, the angle between the recoil proton and incident neutron is an acute angle. As can be seen, the forward and backward distributions are not symmetrical. This is consistent with Refs.[21,22]. On the other hand, 2 MeV neutrons can produce more protons than higher energy neutrons. This should be caused by the bigger cross-section of PSF for low energy neutrons. The consistent distribution shapes for different incident energies make the following simulations convenient.

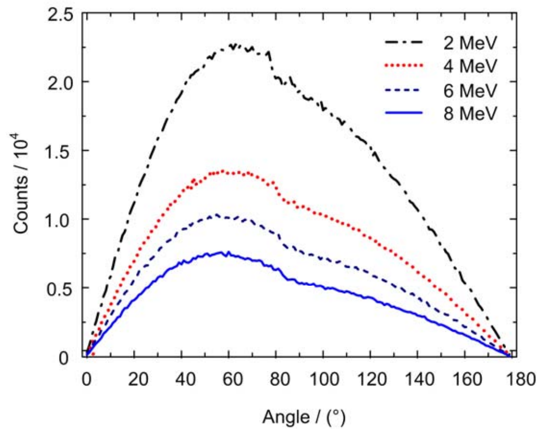


**Fig.2** Angular distribution of recoil proton by incident neutrons of different energies.

### 3.2 Energy distribution of recoil protons

The fiber radius should be decided by the energy distribution of recoil protons (Fig.3). As a common knowledge, there should be a maximum value of recoil proton energy, which is consistent with the incident neutron energy. The incident neutrons will transfer all of their energies to recoil proton as elastic effects happen.Fig.3 illustrates this effect and shows the possibility of proton with different energy.

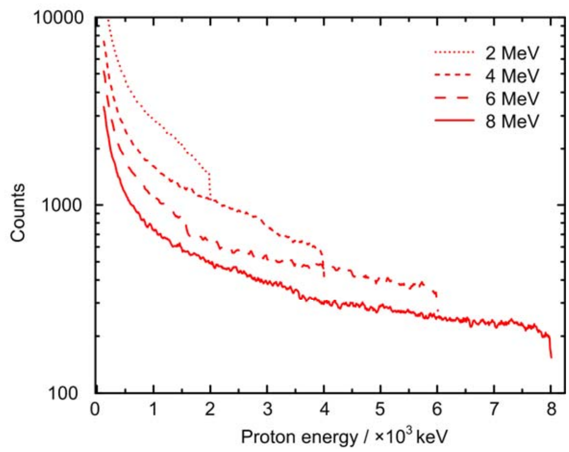


**Fig.3** Energy distribution of recoil proton by incident neutrons with different energies.

### 3.3 Proton range in PSF

As is well known, the main advantage of the use of protons relies on the energy distribution curve obtained when the particles traverse, which can be seen from Fig.4. Charged particles like protons have little scattering when penetrating the matter and give the highest energy near the end of their range just before coming to rest. This is known as Bragg peak.

These characteristics permit one to control very precisely the shape of the distribution of energy deposition inside the fiber. Ranges of 2, 4 and 6 MeV protons in PSF are shown in Fig.4. A 2 MeV proton travels 0.075 mm in PSF, and a 6 MeV proton goes 0.48 mm in PSF. That is, the position of the "Bragg Peak" is changed with the incident energy, which allows us to control the deposition of radiation energy with modulated beam. All these characteristics are accordant with Ref. [23].

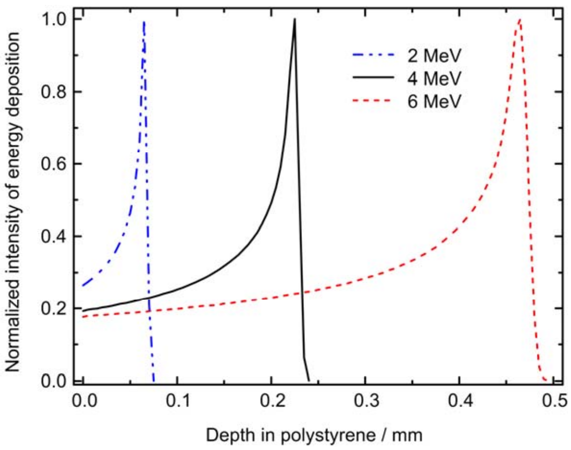


**Fig.4** Ranges for protons with different energies in PSF.

### 3.4 Energy distribution of recoil proton for certain angular ranges

The results show a big range of energy and angular distribution of the recoil protons. It is possible that the high energy protons go along the fiber radius, and this causes severe energy-leak or cross-talk in neutron detection. In this case, we simulated energy distributions of recoil protons in angular ranges of 50°–65°, 0°–40° and 0°–20°(Fig.5). Except for a few background (about 100 protons), the protons have different energies at different angles, varying inversely with the angles. Protons along the neutron incidence have big energies, while protons along the fiber radius have smaller energies. Under 4 MeV neutrons, at about 60°, the recoil protons have about 1.5 MeV, which can be deposited completely in PSF with radius smaller than 0.1 mm, as indicated in Fig.4 and Ref.[23]. Of course, protons produced near the fiber clad will cause reasonable energy-leak or cross-talk. However, the probability should be relatively low.

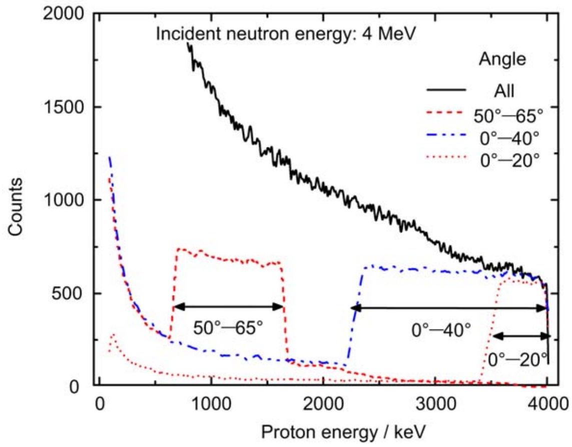


**Fig.5** Energy distribution of recoil proton at different directions.

## 4 Conclusion

As an excellent non-destructive evaluation method, fast neutron radiography attracts increased interests in many countries. Due to their low cost, flexibility, and convenience for long distance data transfer, especially big reaction cross-section with neutrons, PSF have been wildly used for detecting the neutrons. Energy and angular distributions of recoil protons in PSF under fast neutron irradiation are simulated with Geant4. The results show that there is a big range of energy and angular distribution of recoil protons, and the proton energy varies inversely with the recoil angle. The present results can provide some theoretic guidance for future experiments.

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