Radiation Measurements 73 (2015) 46–50

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Simulation study of a "fission electron-collection" neutron detector

Dong Wang [a,*], Chuanfei Zhang [b], Jianhua Zhang [a]

[a] Institute of Nuclear Physics and Chemistry, Mianyang 621900, China
[b] China Academy of Engineering Physics, Mianyang 621900, China

HIGHLIGHTS

- We present a full simulation of physical processes of detection for a FECND.
- Giving the general properties of escaping electrons.
- Confirming the impact of escaping fragments.
- Giving a design to decrease the impact of incoming gamma flux.

ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form
4 January 2015
Accepted 12 January 2015
Available online 13 January 2015

Keywords:
Neutron detector
Fission
Electron collection
Geant4

ABSTRACT

This work studied a "fission electron-collection" neutron detector via the Monte Carlo method. The detector consists of two metal electrodes, labeled the coated and collection electrodes, mounted in a vacuum. The first electrode is coated with triuranium octoxide. The detector uses the "fission electron-collection" technique, which does not require an intermediate material and directly collects electrons from the coating. This detector can achieve rapid, flat-energy responses, which are important for measuring pulsed neutron sources. This paper presents the physical detection processes and Monte Carlo simulation studies using the Geant4 toolkit. The results indicate that the detector sensitivity is approximately 1.5×10^{-21} [C/(n/cm^2)] and the FWHM of response function is 2.5 ns. Additionally, the escaping electrons are characterized, and the detector sensitivity is determined for various coating thicknesses.

1. Introduction

Neutron detectors are important for studies on high-flux neutron sources, such as Z-pinches (Ruggles et al., 2004) and nuclear reactors (Randolph and Sessions, 1989; Filliatre et al., 2010). The efficiency of a neutron detector generally depends on the incident neutron energy. Measuring the absolute neutron fluence for an unknown spectrum requires a detector with a flat-energy response. There are two common options for such measurements: a low-energy neutron detector may be used after moderating the neutrons (Hanson and McKibben, 1947), or the flat characteristic of some cross-section may be utilized in a neutron detector.

Because of the favorable effects of energetic fission fragments (FFs) resulting from fission reactions, many neutron fluence detectors, such as the fission chamber (FC) (Rossi and Staub, 1949), fission track detector (Hashemi-Nezhad et al., 2006), and fission diamond detector (Pietropaolo et al., 2011), are based on FF detection. Fission is particularly useful because of its relatively flat cross-section over several energy regions (e.g., the cross-section for ^{235}U only varies 17% from 1 MeV to 6 MeV). These detectors detect FFs that escape from the fissile material surface. However, numerous secondary electrons are induced by FF interactions with the fissile material because of the former's high kinetic energy. After experiencing a sufficient impulse, these electrons can travel a short distance from their initial position and even escape from the surface if they possess sufficient energy. Effectively collecting the escaping electrons can provide signals to a detector.

The schematic for a "fission electron-collection" neutron detector (FECND) is shown in Fig. 1. The detector, also known as a vacuum FC (Chuklyaev and Pepelyshev, 2003), was named based on its working principle. In a FECND, the shell provides a vacuum for the electrodes. The coated electrode is plated with a fissile material on the side facing the collection electrode, and the collection

* Corresponding author.
E-mail address: carpenter_pw@sina.com (D. Wang).

http://dx.doi.org/10.1016/j.radmeas.2015.01.008
1350-4487/

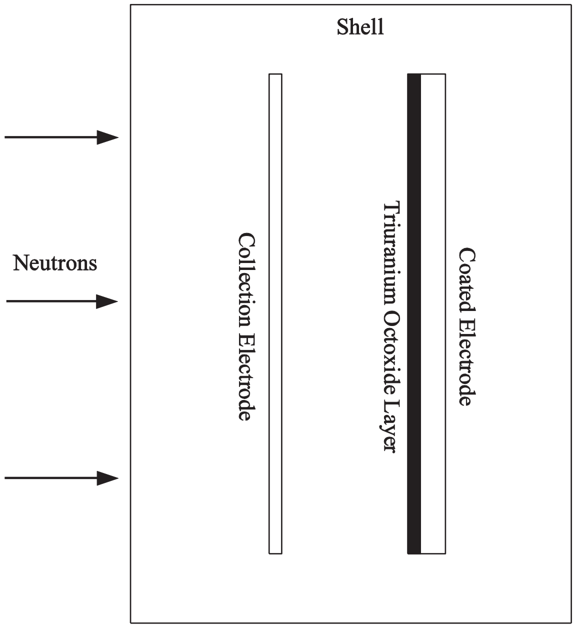

Fig. 1. Schematic for a "fission electron-collection" neutron detector. The detector consists of a coated and collection electrode. A triuranium octoxide layer is coated on the side of the coated electrode facing the collection electrode. The detector shell maintains a vacuum.

electrode is used to collect escaped electrons. Electrical signals are generated when charged particles move between the two electrodes, and the detector operates in the current mode.

This detector does not require working gases and a DC voltage, which avoids adverse effects such as ion pair recombination and electric field distortions (Poujade and Lebrun, 1999). The detector achieves a flat-energy response because the signal intensity is proportional to the fission rate, which is proportional to the fission cross section in turn. Furthermore, the small distance between the electrodes (several millimeters) and vacuum environment for electron movement give the detector a good response time, which is defined as the drift time for an electron in the gap between the electrodes (Calviani et al., 2008). The fluence evolution must be determined as a function of time for pulsed neutron sources, such as the China Fast Burst Reactor II, which requires a rapid-response detector operating in the current mode, and FECND satisfies this requirement. This paper simulates a FECND using the Geant4 toolkit.

2. Physical detection processes

When the FECND is irradiated with neutrons, the coating material generates several fission products, including FFs, neutrons, and gamma rays; here, the FFs carry most of the fission energy (more than 85%). During a fission reaction, two FFs are generated and move in opposite directions. The FFs pass through the fissile material with a straight trajectory because of their large mass relative to extra-nuclear electrons. One FF may move towards the coated substrate and be deposited in it or the fissile material. Another FF may move towards the collection electrode and either escape the fissile material or be deposited in it. This effect is known as self-absorption and is considered negligible in FCs (Jammes et al., 2012).

According to Bohr theory (Bohr, 1913), ions are slowed by two electric fields when passing through matter. These fields are generated by the atomic electrons and nuclei. The energy loss rate, $S(E) = -dE/dx$, defines the stopping power and has two components, namely, the electronic and nuclear stopping powers. Electronic stopping may generate numerous ionized electrons. As a heavy ion, an FF has a high initial kinetic energy. Electronic stopping is the primary factor and bases on the effective charge of the FF (Ziegler et al., 1985), which is a function of the relative velocity between the FF and electrons. FFs are generated with high charge states, and their electronic stopping power decreases as they lose kinetic energy while slowing, because their effective charge decreases with the velocity. This phenomenon differs from that observed for lighter particles such as α-particles or protons. When the kinetic energy of an FF decreases below several tens of kiloelectron-volts, nuclear stopping becomes dominant. Compared to the primary energy for the FF, which is often tens of megaelectron-volts, nuclear stopping only slightly influences the FECND detection process and can be neglected.

The detection efficiency for a FECND depends on the number of electrons collected by the collection electrode. This number is determined by two factors, namely, the number of electrons generated by the FFs and the probability they escape. The first factor depends on the fission reaction probability and FF energy losses, which both relate to the fissile layer thickness. The second factor also relates to the fissile layer thickness. Therefore, the FECND efficiency can be adjusted by modifying the fissile layer thickness.

FFs may also escape and reduce the detector output because of their positive charge. This effect is proportional to the product of the number and average effective charge for these fragments.

3. Simulation description

Simulations were performed using the Geant4 code (Version 4.9.6 p02), which has been successfully used to simulate FC behavior (Kögler et al., 2013). Geant4 is an object-oriented toolkit for radiation detector simulations that can be used to provide detailed information on the process for particles passing through matter. The information provided by the toolkit includes the detector geometry, materials involved, incident particle generation, particles tracking through the matter, the physical processes controlling particle interactions, and event and track storage.

The geometric structure used for this simulation is shown in Fig. 1. A cylindrical aluminum shell with a diameter of 106.2 mm composed the FECND. This shell ensured the electrodes remain in a vacuum. The electrodes were two coaxial circular plates 100 mm in diameter and were located in the center of the shell. The shell, coated electrode, and collection electrode were 0.1 mm, 5 μm, and 5 μm thick, respectively. The gap between the shell and electrode was 2 mm. The coated and collection electrodes were made of aluminum. The coating material was triuranium octoxide containing enriched uranium (90% ^{235}U and 10% ^{238}U). The coating thickness was a few mg/cm^2.

The most important part of the simulation was selecting the Physics List, which contains the interactions available to the simulation. Geant4 provides several predefined Physics Lists (known as the Reference Physics Lists) that were constructed from experience and validated via past applications and experiments. Our simulation used the QGSP_BERT_HP Reference Physics List. Except for the FF generation, this Physics List considers all of the physical processes involved in this study. The G4ParaFissionModel class was introduced to simulate the FF generation.

The EM Physics in the QGSP_BERT_HP Reference Physics Lists was replaced with G4EmStandardPhysics_option4 to ensure a high accuracy level (Geant4 Collaboration, 2012). To simulate low-energy electron generation, the lower limit for the default energy range was set to 250 eV, which is the lower limit for low-energy