



Construction of a Prototype Silver Self-powered Neutron Detector and Simulation of a Developed SPND using MCNP4C Code

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Abstract

Self-powered neutron detectors (SPNDs) are used widely in flux mapping, control, and protection of nuclear reactors. Compared with other neutron detector, SPND has the advantages of small size, low cost, and relatively simple electronics. In this work, a prototype SPND for flux measuring neutron generators has been designed and tested. Using the Monte Carlo simulation code, the output current of the detector was calculated and compared with the experimental results. The agreement between the results suggests that this detector is capable of flux monitoring of the neutron generator. Then, a developed SPND has been introduced with the provision of producing higher output current.

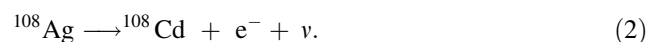
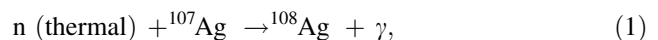
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1 Introduction

The self-powered detectors are based on using a material with relatively large cross section for neutron capture leading to a beta-active radioisotope. An SPND operates by directly measuring the beta decay current. The current is proportional to the rate at which neutrons are captured in the detector. The name self-powered detector derives from the fact that the beta decay current is measured directly and no external voltage is needed. Figure 1 shows schematical

geometry of this kind of detector. An SPND consists of an emitter material and a collector material separated by an insulator. The most common geometry is cylindrical with relatively small diameter so that it can be placed in the core of a reactor. The heart of an SPND is its emitter. In selecting a proper emitter, one should consider its neutron capture cross section, the energy, and the half-life of the resulting beta activity. Low capture cross section leads to low sensitivity of detector, whereas too high cross section leads to rapid burn up of the emitter material in high neutron flux. High-energy beta ray decreases the absorption of electrons in the emitter or insulator. Shorter half-life of the induced beta activity results in decrease in response time of detector to the rapid changes in the neutron flux.

The operation of an SPND is simple. The incident neutrons activated the emitter material through the capture reactions. For silver emitter, we have:



The same happens to ${}^{109}\text{Ag}$ leading to ${}^{110}\text{Cd}$.

The produced current is measured between the emitter and the outer shell, the collector, with a current meter. The current signal is a function of neutron absorption rate in the emitter and, therefore, is a measure of the neutron flux. The gap between the emitter and the collector is filled with an insulator to electrically isolate the emitter from the collector.

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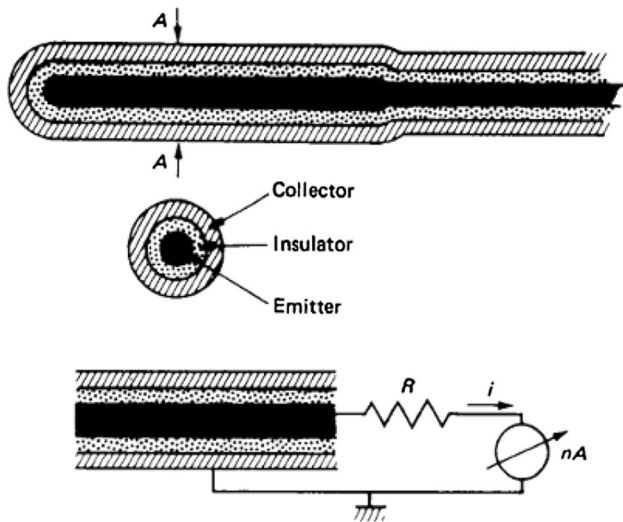


Fig. 1 Cross-sectional view of a typical SPND. The central conductor is called the emitter and is the material responsible for the generation of the signal. The outer conductor, called the collector, is separated from the emitter by an insulator (Tsoulfanidis 1995)

A thin insulator with low atomic number does not attenuate the electrons. The current can be measured using a picoammeter between the collector and the emitter. Except the emitter, the other parts of detector should have relatively low neutron cross sections (Tsoulfanidis 1995; Knoll 1999).

2 Detector Sensitivity

The sensitivity is defined as the ratio of the detector current to the incident neutron flux. The important factor which influences the sensitivity of an SPND is the space charge effect. The low-energy electrons ejected from the emitter lose energy

and stopped inside the insulator. These electrons accumulate space charge and built a static electric field. This field expels the electrons either forward into the collector or backward into the emitter. With the assumption of uniform spatial distribution of the space charge, the electric field is found by solving the Poisson's equation. The boundary condition is that the emitter and the collector sheath are at the same potential.

2.1 Planner Geometry

The Poisson's equation in planner geometry is

$$\frac{d^2V}{dz^2} = -\frac{\rho}{\epsilon} \tag{3}$$

Then, the electric field is found to be

$$V = -\frac{\rho}{2\epsilon}z^2 + \frac{\rho}{2\epsilon}(d_e + d_i)z - \frac{\rho}{4\epsilon}d_e(d_e + d_i), \tag{4}$$

where d_e and d_i are the emitter and the insulator thickness, respectively. The boundary condition $V(\frac{d_e}{2}) = V(\frac{d_e}{2} + d_i) = 0$ has been applied. Note that the center of the emitter has been selected as the origin of coordinates. The electric field will be

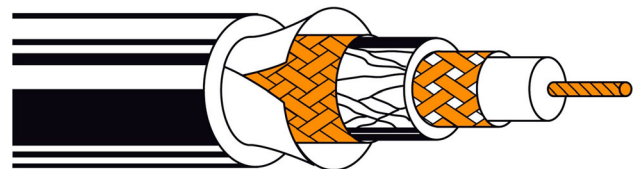


Fig. 3 Schematic diagram of a triaxial cable. A triaxial cable is a special form of the coaxial cable that consists of three concentric conductors. These are separated by a dielectric, as well as a shielding

Fig. 2 Design and dimensions of the prototype SPND. This detector consists of a 10 cm-diameter × 0.5 mm-thickness silver disk, 0.75 mm-thickness powder of aluminum oxide and 0.7 mm-thickness stainless steel sheath

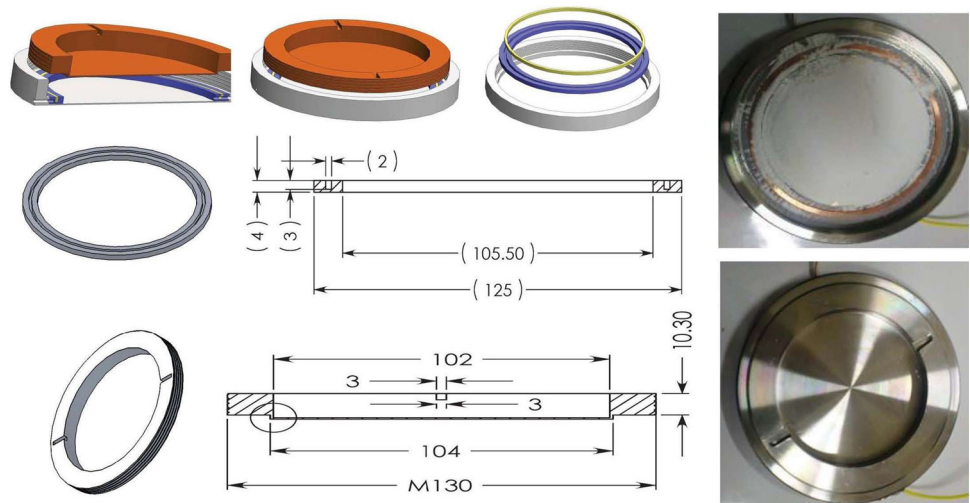


Table 1 Calculated and measured sensitivities of the prototype SPND

	Average measured sensitivity (A/nv)	Calculated sensitivity (A/nv)	% Difference
First mode	17.67×10^{-20}	70.87×10^{-20} (0.0006)	+ 301.1
Second mode	17.67×10^{-20}	18.40×10^{-20} (0.0009)	+ 4.1

$$E = -\frac{dV}{dz} = \frac{\rho}{\epsilon}z - \frac{\rho}{2\epsilon}(d_e + d_i). \tag{5}$$

The voltage is found to reach its maximum value at $z_0 = \frac{d_e+d_i}{2}$. It is called the critical thickness, where the electric field has zero value and changes its direction.

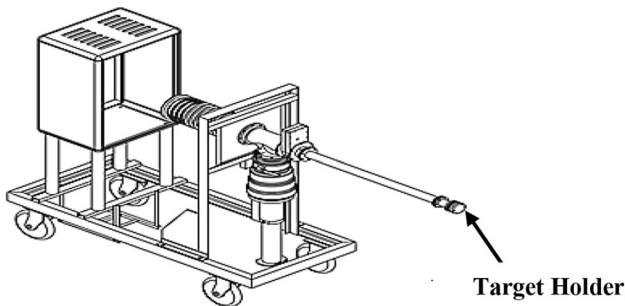


Fig. 4 Schematic of the 150 keV electrostatic accelerator. The generated neutrons in this accelerator from the D–D reaction have energies about 2.5 MeV and the intensity of them is in the range of 10^7 – 10^9 n/s

Electrons from the emitter that loses all kinetic energy before crossing the potential peak are repelled to the emitter. Only electrons have enough to overcome the electric field can generate signals. In this work, $d_e = 0.5$ mm, $d_i = 0.75$ mm, and $z_0 = 0.625$ mm.

2.2 Cylindrical Geometry

The electric field obeys the Poisson’s equation:

$$\frac{dE}{dr} + \frac{E}{r} = \frac{\rho}{\epsilon}. \tag{6}$$

Since the meter used to measure the detector current has negligible internal resistance, the emitter and the collector sheath are at the same potential, the electric field thus found to be

$$E(r) = \frac{2A}{r_i} \left\{ \frac{r}{r_i} - \left[\frac{1 - k^2}{2 \ln(1/k)} \right] \frac{r_i}{r} \right\}, \tag{7}$$

where r is the radial distance is from the emitter’s center to a point in the insulator, r_i is the external radius of the insulator, A is a constant, related to radiation intensity and insulator materials and k is equal to $\frac{r_e}{r_i}$, and r_e is the radius of emitter. The electric potential is given by

$$V(r) = A \left[-\left(\frac{r}{r_i}\right)^2 + \frac{\ln(r/r_e) + k^2 \ln(r_i/r)}{\ln(1/k)} \right]. \tag{8}$$

The potential reach its maximum value at r_0

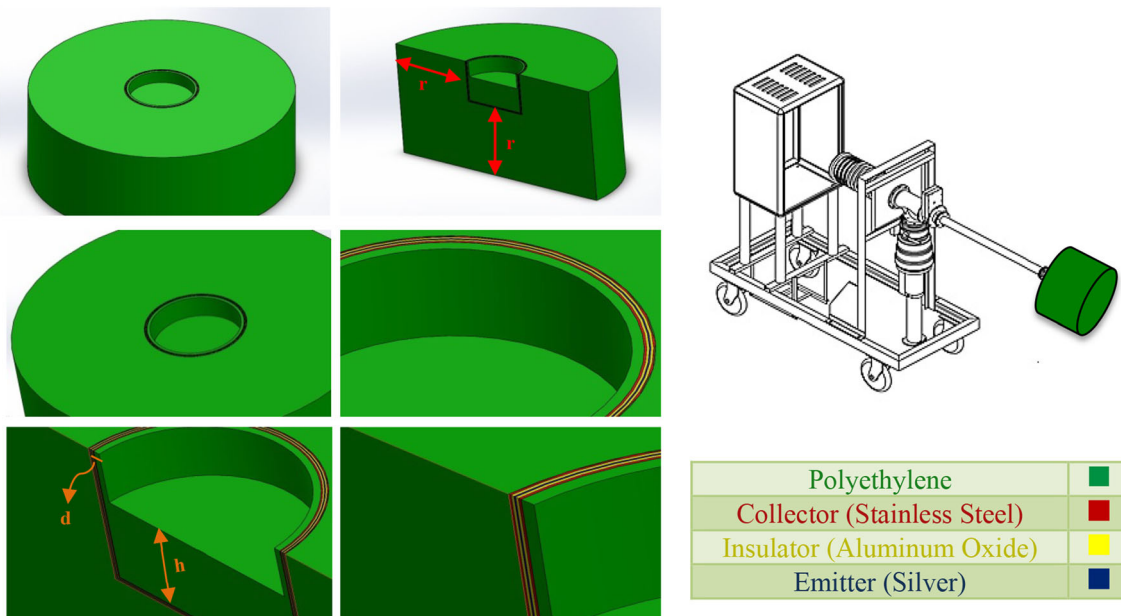


Fig. 5 Design of the developed SPND; h is the inner height of the polyethylene, d is the inner thickness and r is the outer thickness of the polyethylene

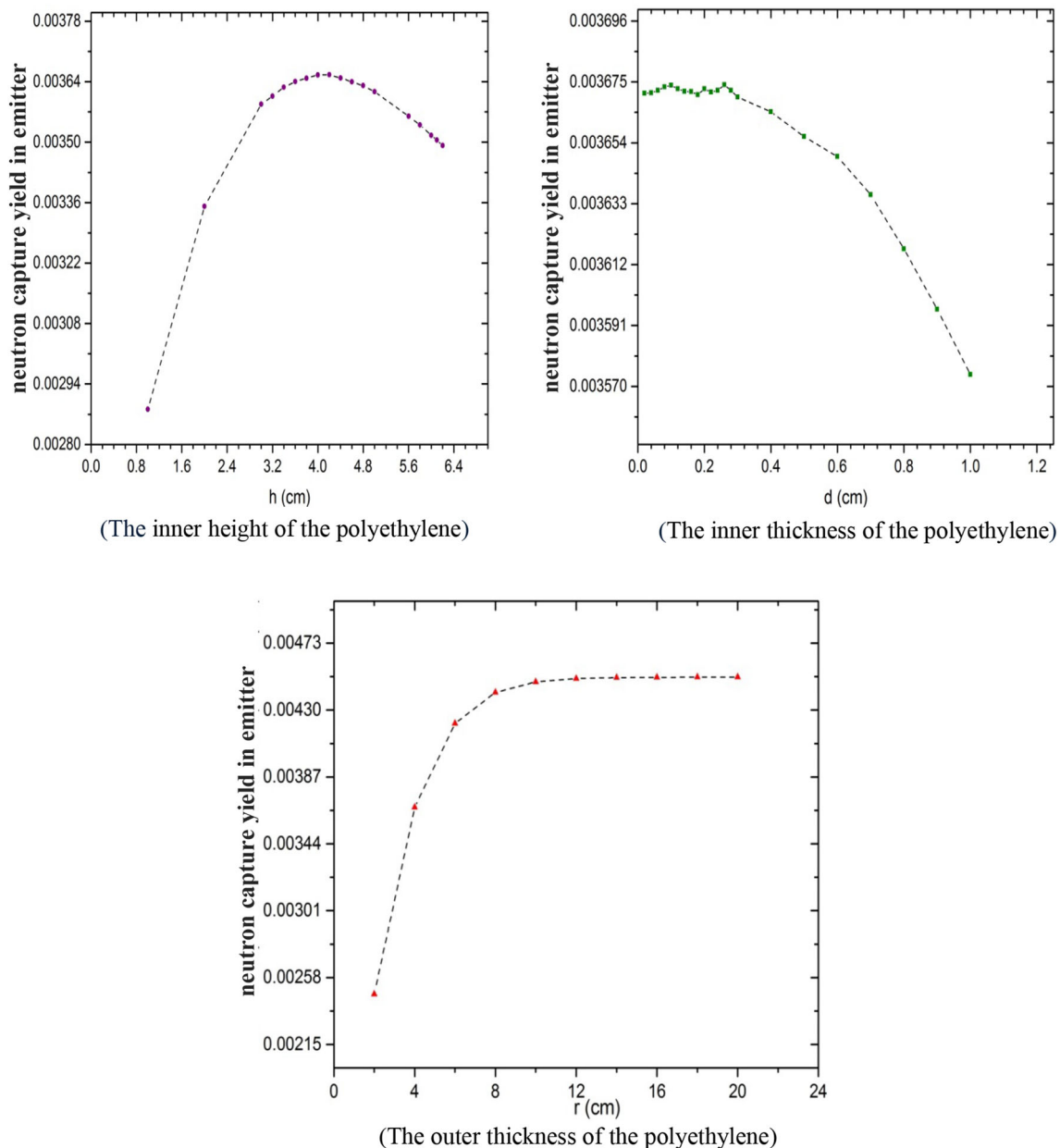


Fig. 6 Neutron capture yield per unit volume in the emitter as a function of the polyethylene thickness. The X-axis shows the thickness of the polyethylene dimensions (cm); and the Y-axis shows

the neutron capture yield per unit volume in the emitter (n/cm^3). The neutron capture yield is maximum with, $h = 4.2$ cm, $d = 0.26$ cm and $r = 12$ cm

$$r_0 = r_i \left[\frac{1 - k^2}{2 \ln(1/k)} \right]^{1/2} \quad (9)$$

This is the critical radius corresponds to z_0 in planar geometry (Warren 1972).

3 A Prototype Construction

3.1 Emitter and Insulator Materials

From different emitter materials such as Vanadium-51, Rhodium-103, Cobalt-59, and Silver used in SPNDs, silver is chosen in this work. Silver has relatively high thermal neutron capture cross section, 46.8 barns. It can be easily manufactured to any desired shapes. An SPND with a silver emitter has an average sensitivity and average burn-up rate, 0.16% per month in a thermal flux of 10^{13} n/s cm^2 ,

which is associated with radioactive decay of the excited nucleus following neutron capture, see Eqs. 1 and 2. An SPND with silver emitter has 66% of the initial signal with half-life of 24.4 s, 25% with half-life of 2.42 min and 9% with prompt signal (Agu and Petitcolas 1991). In this work, the insulator was made of Al_2O_3 . This material has low neutron sensitivity, so electrons are scarcely emitted. In addition, Al_2O_3 resistance does not change with exposure to radiation (Bozarth and Warren 1976), while, for example, that of MgO changes.

3.2 Prototype Geometry

A prototype SPND for continuous measuring the neutron flux of electrostatic accelerator available in AEOI was designed and constructed, see Fig. 2. This detector consists of a 10 cm-diameter \times 0.5 mm-thickness silver disk with powder of aluminum oxide at the top and bottom of the disk. All sensing elements are housed within a type 304 stainless steel sheath which acts as the collector.

When the current is very low (in range of nA, pA, or fA), leakage current in cable is important. Leakage current is the current that flows through the protective ground conductor to ground. In the absence of a grounding connection, it is the current that could flow from any conductive part or the surface of non-conductive parts to ground if a conductive path was available. To prevent this leakage current, *Triaxial Cable* is used. Triaxial cable, Fig. 3, consists of three separate conducting elements, usually arranged in alternating concentric rings of conductor and shielded insulation. The shielding and insulation prevent the individual signals from the conductors from interfering with each other. Connectors for these cables are so designed that it is not possible to connect them with other type of connectors. In addition, a copper ring has been embedded in detector and is connected to inner shield of triaxial cable to prevent measuring the leakage current.

4 Experimental Results

The 150 keV electrostatic accelerator available in AEOI is used as the neutron generator. The intensity of the 2.5 MeV neutrons generated in the D–D reaction is in the range of 10^7 – 10^9 n/s. Since the SPND responds to thermal neutrons, the neutrons should be thermalized before streaming to the detector. Therefore, the detector was placed in a polyethylene shielding. To determine the proper thickness of polyethylene, Monte Carlo simulation code (MCNP4C) was used. The proper thickness of polyethylene is estimated 45.5 mm for intensity of 10^6 n/s. For this amount of flux, 10^2 n/s cm^2 reaches the silver foil. The output current was also estimated by MCNP4C code for two modes. In the

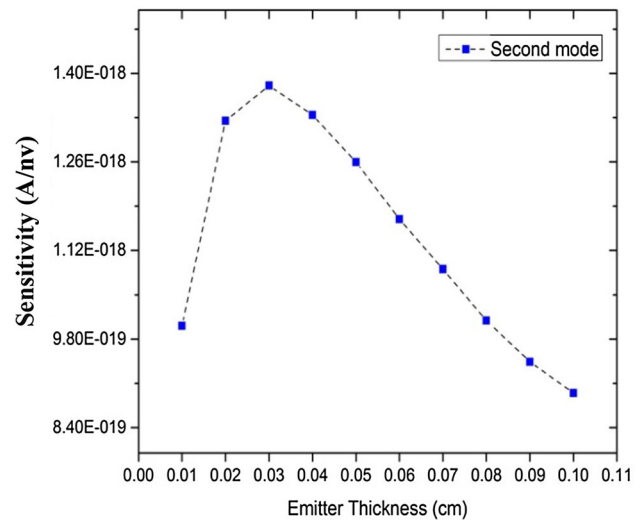


Fig. 7 Sensitivity of the developed SPND as a function of the emitter thickness. The X-axis shows the thickness of the emitter (cm); and the Y-axis shows the sensitivity of the detector (A/nv). As it is seen, the sensitivity is maximum when the thickness is 0.03 cm

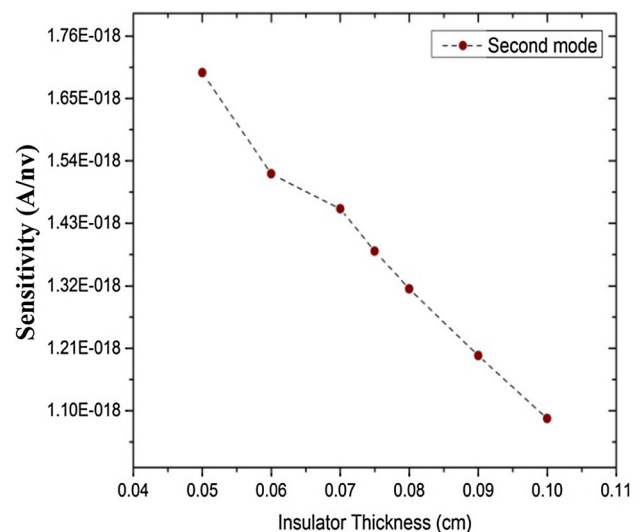


Fig. 8 Sensitivity of the developed SPND as a function of the insulator thickness. The X-axis shows the thickness of the insulator (cm); and the Y-axis shows the sensitivity of the detector (A/nv). The sensitivity reduces by increasing the insulator thickness

first mode, we assumed that the insulator is not saturated, so all electrons appeared at the emitter's surface contributed to the output current and so in the sensitivity of the SPND. In the *second mode*, only the electrons passed the critical thickness at z_0 contributed to the SPND current. Table 1 shows the calculated and the measured sensitivity for the prototype SPND.

The comparison between the measured sensitivity and the calculated one shows that the constructed SPND is useful in estimation of the flux of the neutron generator. To

increase the sensitivity a developed SPND is suggested as it is described in the next section.

5 Simulation of a Developed SPND

Regarding the geometry of the source, Fig. 4, the recommend geometry shown in Fig. 5 is proposed for the developed SPND. The dimensions of the developed SPND were determined using MCNP4C code, Fig. 5, h is the inner height of the polyethylene, d is the inner thickness, and r is the outer thickness of the polyethylene. This geometry enclosed fully the source (4π), so the output current would be higher.

Figure 6 shows the neutron capture yield per unit volume in the emitter as a function of polyethylene dimensions. As it is seen, the neutron capture yield is maximum for $h = 4.2$ cm, $d = 0.26$ cm, and $r = 12$ cm.

The thickness of the emitter and the insulator can also affect the detector sensitivity. As it is shown in Fig. 7, the 0.03 cm thickness is suitable for the emitter, where the sensitivity is maximum.

Figure 8 shows that the sensitivity of the developed SPND increases by reducing the insulator thickness. Nevertheless, the thickness of the insulator is usually selected according to the limitations in the manufacturing process.

6 Conclusion

The designed SPND in this work can be used to measure neutron flux of generators. Thus, the result of testing the prototype SPND shows that this detector is useful in

estimation of the flux of the neutron generators. Then, to increase the sensitivity, the developed SPND, which can enclose the source fully (4π), was simulated and designed. Comparing the calculated sensitivity of the prototype SPND, see Table 1, and that of the developed SPND which is 145.53×10^{-20} A/nv (0.0031), shows that the accuracy in measuring the neutron flux of the developed SPND is much more than that of the prototype detector. Therefore, if limitations in technology are eliminated, sensitivity can be increased several times by manufacturing the developed SPND.

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