A mathematical method to calculate efficiency of BF_3 detectors

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Abstract In order to calculate absolute efficiency of the BF_3 detector, MCNP/4C code is applied to calculate relative efficiency of the BF_3 detector first, and then absolute efficiency is figured out through mathematical techniques. Finally an energy response curve of the BF_3 detector for 1~20 MeV neutrons is derived. It turns out that efficiency of BF_3 detector are relatively uniform for 2~16 MeV neutrons.

Key words BF_3 detector, Absolute efficiency, Relative efficiency, Energy response curve

1 Introduction

BF_3, a convenient and reliable neutron detector, is widely used in scientific research and radioprotection[1-7]. It is advantageous in terms of high efficiency, long flat level ground, high resolution and free-sensitive to γ-rays. High efficiency is of great importance. However, many works focused just on relative efficiency of a BF_3 detector[8], rather than its absolute efficiency, which gives directly its capability and threshold.

The method established by Kushneriuk[1] to calculate absolute efficiency of BF_3 detectors can be applied to a cylinder detector under, neutron incidence in parallel to the cylinder axis, with only two depths of the BF3 chambers. In this paper, numerical simulation of absolute efficiency of a BF_3 detector is simulated with MCNP/4C, a general N-particle transport code developed at Los Alamos National Laboratory[9], and has been widely used in detecting neutron yield and flux, characterizing experimental detectors, modeling neutron scattering and absorption[10-13].

The detector consists of nine BF_3 cylindrical chambers placed separately in a polyethylene block of 32 cm × 32 cm×43 cm. Each BF_3 chamber is Φ 2.7 cm × 34 cm enveloped with 1 mm iron. Pressure of the BF_3 gas (60% ^{10}B) is 93 kPa at 2.5×10^{-3} g/cm^3 density at room temperature. The detector is wrapped with 2 mm iron. The detector's *X*-*Z* plane is shown schematically in Fig. 1.

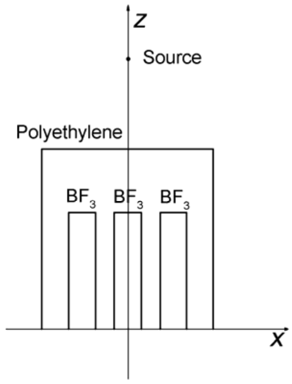

Fig. 1 Two-dimensional sketch map of the BF_3 detector.

First, numerical calculation of relative efficiency of the BF_3 detector was performed with MCNP/4C. The 2.45 MeV D-D neutrons from the D(d, n)^{3}He reaction are essentially isotropic[14]. A comparison with experimental results on an electrostatic accelerator showed that the MCNP/4C simulation is reliable and suitable for this application. Then, a mathematical method to calculate absolute efficiency of BF_3 detectors was developed. An energy response curve of the BF_3 detector for 1~20 MeV neutrons was derived.

2 Relative efficiency of the BF_3 detector

Relative efficiency, ε_r, and absolute efficiency, ε, are defined by

$$\varepsilon_r = N_p/N_0 \quad (1)$$

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$$\varepsilon = N_p / N_1 \qquad (2)$$

where N_p is neutrons detected by the detector, N_0 is the total neutrons emitted from the source in 4π geometry, and N_1 is neutrons incident upon the detector from the source.

From the equations, absolute efficiency can be calculated with relative efficiency by

$$\varepsilon = 4\pi\varepsilon_r / \Omega \qquad (3)$$

where Ω is the solid angular of the detector to the source.

Relative efficiency of the BF_3 detector to D-D neutrons was simulated with MCNP/4C by placing the BF_3 detector at l=50 cm from the source. It simulated the following processes: the incident neutrons were moderated by polyethylene to thermal neutrons, which reacted with ^{10}B of the BF_3 to produce α and ^7Li, of which the ranges in BF_3 are short enough for their detection.

We used the F1: N card and the C1: N card of MCNP/4C to calculate neutrons detected by the BF_3 detector. The results were $N_p = 1.0\times10^8$ and $\varepsilon_r = 3.86 \times 10^{-4}$, normalized as unit starting particle of the MCNP/4C simulation. The simulated relative efficiency agreed within 6.76% with the measured ε_r of 4.14×10^{-4}. The discrepancy may be attributed to 1) the calculated model is an approximately ideal detector, without taking other instruments in the experimental house into account, 2) the electronics system has a threshold for neutron counts, and 3) the fluence and energy of D-D neutrons have slight angle distributions, but in the simulation isotropic and mono-energetic neutrons were assumed. However, the discrepancy is acceptable.

3 Absolute efficiency of the BF_3 detector

For calculating absolute efficiency of the BF_3 detector with Eq.(3), the key is to figure out the Ω in determining the relative efficiency. To accurately estimate the solid angle of the BF_3 detector in a cuboid block, the BF_3 detector was approximated to a surface detector, which has an equivalent-area circle of r=18.05 cm, the equivalent length of L from source to the surface detector, and spherical radius of R (Fig.2). From the figure, one has $L = l_1 + 0.5\,z$, where l_1=50 cm is the distance from neutron source to the BF_3 detector, z =43cm is length of the BF_3 detector along Z-axis, and thus L=71.5 cm and $R= r^2 + L^2$ = 73.74 cm.

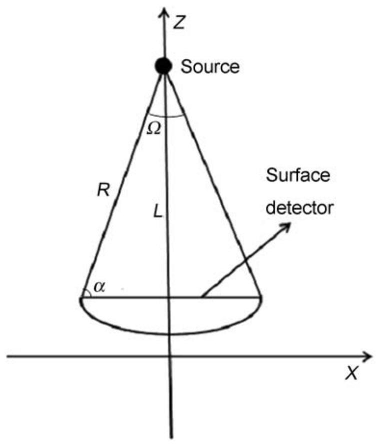

Fig. 2 Sketch map of the approximate BF_3 detector (surface detector).

Ω can be obtained by Eq.(4).

$$\Omega = \frac{\int_{\alpha}^{\pi/2} 2\pi R\cos\theta \cdot R\mathrm{d}\theta}{R^2} \qquad (4)$$

where, $\alpha = \sin^{-1}(L/R)$. Integrating Eq.(4) and substituting Ω to Eq.(3), absolute efficiency of the BF_3 detector can be calculated by,

$$\varepsilon = \frac{2\varepsilon_R}{1 - L/R}, \qquad (5)$$

From Eq.(5), absolute efficiency of the BF_3 detector in this work for D-D neutrons is 2.76%.

Using the Kushneriuk formula, absolute efficiency of the BF_3 detector is 2.83%. The deviation of the two results is just 2.5%.

4 Energy response curve of the BF_3 detector

Relative efficiencies of the BF_3 detector for 1~20 MeV neutrons are given in Fig.3. The energy response is uniform in 2~16 MeV region, with deviations of no more than 8%.

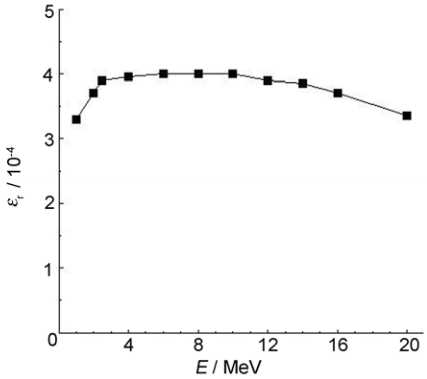

Fig. 3 Energy response curve of the BF_3 detector.

5 Conclusion

This paper mainly focuses on delivering a method to calculate absolute efficiency of BF_3 detectors. Relative efficiency of the BF_3 detector has been calculated by MCNP/4C first. There is an explicit relationship between absolute efficiency and relative efficiency, shown in Eq.(3). Thus the key to figure out absolute efficiency is to work out the solid angular of the detector to the source (Ω). An approximation of the BF_3 detector has been made and Ω is figured out by integrating. As a result absolute efficiency is achieved. Finally energy response curve of the BF_3 detector has been calculated by simulating its relative efficiency for 1~20 MeV neutrons, which has a relatively uniform flat level. It indicates that the BF_3 detector can be used to detect mixed field of neutrons. This reinforces applications of the BF_3 detector.

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