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ScienceDirect
Journal of Taibah University for Science 10 (2016) 182–186
Journal of Taibah University for Science
www.elsevier.com/locate/jtusci

Direct mathematical method for calculating the photofraction and intrinsic efficiency of 4πNaI(Tl) borehole cylindrical detectors

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Available online 6 April 2015

Abstract

A direct mathematical method for calculating the photofraction and intrinsic efficiency of a borehole cylindrical detector is derived using a direct mathematical method. This method depends on the photon path length inside the detector active volume and the geometrical solid angle Ω subtended by the source to the detector. The comparisons with the experimental and Monte Carlo method data reported in the literature indicated that the present method is useful in the efficiency calibration of the borehole detector.

Keywords: Borehole scintillator detector; Geometrical efficiency; Photofraction; Direct mathematical method

1. Introduction

Many important and useful applications exploiting borehole NaI(Tl) cylindrical detectors exist due to the relative simplicity, high mass number and low cost of crystal preparation. NaI(Tl) scintillators are widely used in different detecting systems (well type, parallelepiped, cylindrical, etc.) in environmental radioactivity, low level radioactive waste, prompt gamma-ray neutron activation analysis, some nuclear physics experiments, geology, etc. As a result, achieving a high efficiency in the gamma-ray detection is an important and crucial issue for the low-level gamma activity measurements. To meet this efficiency requirement, a 4πNaI(Tl) borehole cylindrical detector (30.4 cm × 30.4 cm) was developed with a central circular hole of radius 1.75 cm at Dynamitron Tandem Laboratory (DTL) at the Ruhr-Universitat Bochum (Fig. 1). The detector walls around this borehole are made of aluminium with a thickness of only 5×10^{-2} cm to reduce γ-ray absorption [1].

The present work is mainly concerned with introducing a straight-forward theoretical approach to calibrate the upgraded 4πNaI(Tl) gamma-ray detector for isotropic radiating gamma-ray (point, plane and volumetric) sources. This approach is based on the direct mathematical method reported by Selim and Abbas [2–10] and has been used successfully to calibrate point, plane and volumetric sources with cylindrical, well-type and parallelepiped detectors. The fact that the efficiency can be precisely determined by calculation makes the method absolute (or direct). The work described below involves implementing straightforward formulae for the computation of the photofraction and the intrinsic

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Peer review under responsibility of Taibah University

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jtusci.2015.03.001

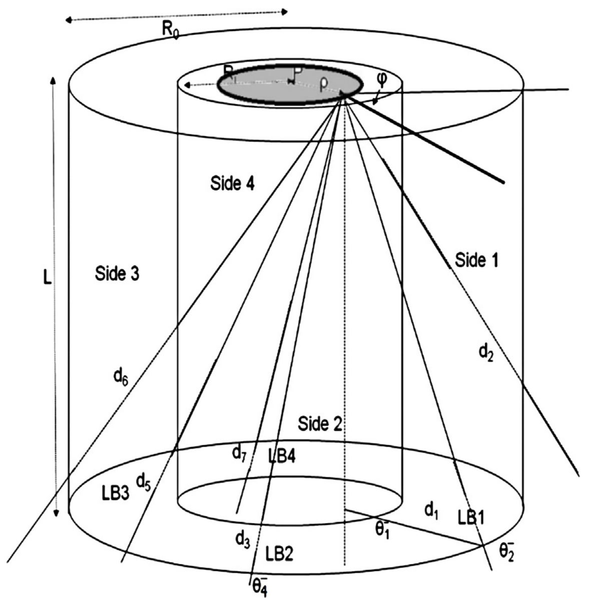

Fig. 1. A schematic drawing of a Borehole cylindrical detector with a coaxial radioactive disc source.

efficiency of a disc source, which is extended to a cylindrical source of radius 1.5 cm and height 3 cm. In this study, we introduce a new method for the determination of the path length $d(\theta,\varphi)$ covered by a photon inside the detector active volume and the geometrical solid angle Ω (the angle subtended by the detector at the source point). The path length $d(\theta,\varphi)$ is derived not only as a function in the polar angle θ but also as a function in the azimuthal angle φ. This approach will reduce the mathematical formulae to an easy and compact shape. The validity of the present work is presented by comparing our results with the published experimental and Monte Carlo simulations ones.

2. Mathematical view point

In the following section, direct analytical expression for the photofraction and intrinsic efficiency of a cylindrical borehole detector is derived using a disc and cylindrical radiating sources. The location of the isotropic disc source is defined by the quantities (ρ,h) and the direction of the photon incidence by the polar (θ) and the azimuthal φ angle [12]. There are eight cases to be considered to find the photon path length d through the cylindrical detector medium, as shown in Fig. 1. The incident photon may enter from the inner side of the cylindrical detector and emerge from:

(a) Lower base one (LB1) and Lower base three (LB3)

$$d_1^{\mp} = \left| \frac{L}{\cos(\theta)} - \frac{R_i \mp 2\rho\cos(\phi)}{2\sin(\theta)\cos(\phi)} \right| \tag{1}$$

(b) Side one and side three

$$d_2 = \left| \frac{(R_0 - R_i)}{2\sin(\theta)\cos(\phi)} \right| \tag{2}$$

(c) Lower base two (LB2) and lower base four (LB4)

$$d_3 = \left| \frac{L}{\cos(\theta)} - \frac{R_i}{2\sin(\theta)\sin(\phi)} + \frac{\rho}{\sin(\theta)} \right| \tag{3}$$

(d) Side two and side four

$$d_4 = \left| \frac{(R_0 - R_i)}{2\sin(\theta)\sin(\phi)} \right| \tag{4}$$

The geometrical notations L, R_0, R_i and ρ are shown in Fig. 1. The photofraction is the ratio between the number of photons that are recorded under a certain peak and the number of photons that are recorded in the spectrum at the same energy. The photofraction is given by

$$P = \frac{\varepsilon_P}{\varepsilon_T} \tag{5}$$

where ε_p is the full energy peak efficiency, and ε_T is the total efficiency [10].

$$\begin{aligned}\varepsilon_T = \frac{2}{S^2}\cdot\frac{1}{4\pi}\Bigg[& \int_0^S\int_0^{\pi/2}\int_{\theta_1^-}^{\theta_2^-} f_1^- \rho d\theta d\phi d\rho \\ & + \int_0^S\int_0^{\pi/2}\int_{\theta_2^-}^{\pi/2} f_2 \rho d\theta d\phi d\rho + \int_0^S\int_{\pi/2}^{\pi}\int_{\theta_1^-}^{\theta_2^-} f_2 \rho d\theta d\phi d\rho \\ & + \int_0^S\int_{\pi/2}^{\pi}\int_{\theta_4^-}^{\pi/2} f_4 \rho d\theta d\phi d\rho + \int_0^S\int_{\pi}^{3\pi/2}\int_{\theta_1^+}^{\theta_2^+} f_1^+ \rho d\theta d\phi d\rho \\ & + \int_0^S\int_{\pi}^{3\pi/2}\int_{\theta_2^+}^{\pi/2} f_2 \rho d\theta d\phi d\rho + \int_0^S\int_{3\pi/2}^{2\pi}\int_{\theta_3^+}^{\theta_4^+} f_4 \rho d\theta d\phi d\rho \\ & + \int_0^S\int_{3\pi/2}^{2\pi}\int_{\theta_4^+}^{\pi/2} f_4 \rho d\theta d\phi d\rho \Bigg]\end{aligned} \tag{6}$$