International Journal of Pure and Applied Physics
ISSN 0973-1776 Vol.1, No.2 (2005), pp. 129-136

http://www.ripublication.com

Calculation of Intrinsic Efficiency of NaI(Tl) Detector Using MCNP Code

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Abstract

In this work the variation of the intrinsic efficiency of the NaI(Tl) detector against the source-detector distance has been calculated for different gamma ray energy by using MCNP code. The intrinsic efficiency depends not only on energy of photons but also on the geometry configuration of source and detector. The intrinsic efficiency variation can be analysis by the mean chord path length of the photons in the detector and the mean interaction length of the photons.

Keywords: Gamma ray detection; NaI(Tl) detector; Intrinsic efficiency; Mean chord path length; Mean interaction length

Introduction

Gamma detection techniques are widely used in gamma ray spectroscopy for nuclear physics, medical radiography [1, 2], neutron activation analyses [4, 5], well going [3], and study of cosmic rays [6]. Between all of detectors used in the spectroscopy of photons, such as NaI(Tl), HPGe, Ge(Li), Si(Li), etc; the inorganic scintillator NaI(Tl) is very suitable and effective for gamma ray detection because of cheapness, applicable in medium temperature, and high density. In the present work, we calculate the intrinsic efficiency of NaI(Tl) detector using MCNP code [7]. The intrinsic efficiency depends not only on energy of photons but also on the geometry configuration of source and detector.

Intrinsic Efficiency of Detection

The efficiency usually defined in two types, total and intrinsic efficiency [8-11], as follows:

$$\text{Total efficiency} = \frac{\text{Number of counted photons}}{\text{Number of photons emitted by the source}}$$

$$\text{Intrinsic efficiency} = \frac{\text{Number of counted photons}}{\text{Number of photons entered to detector}}$$

The following analytical expression is given to determine intrinsic efficiency of an isotropic point source and cylindrical NaI(Tl) detector with length L and radius R, as shown in Fig. 1.

$$\varepsilon_{\text{int}\,rinsic} = \frac{\int_0^{\theta_1} \left(1 - e^{-\mu(E)\left(\frac{L}{\cos\theta}\right)}\right) \sin\theta \; d\theta}{[\,1 - \cos\theta_0\,]} + \frac{\int_{\theta_1}^{\theta_0} \left(1 - e^{-\mu(E)\left(\frac{L}{\sin\theta} - \frac{d}{\cos\theta}\right)}\right) \sin\theta \; d\theta}{[\,1 - \cos\theta_0\,]}$$

Where

$$\tan\theta_0 = \frac{R}{d} \quad , \quad \tan\theta_1 = \frac{R}{d+L}$$

$\mu(E)$= linear attenuation coefficient in NaI(Tl) for photon with energy E.

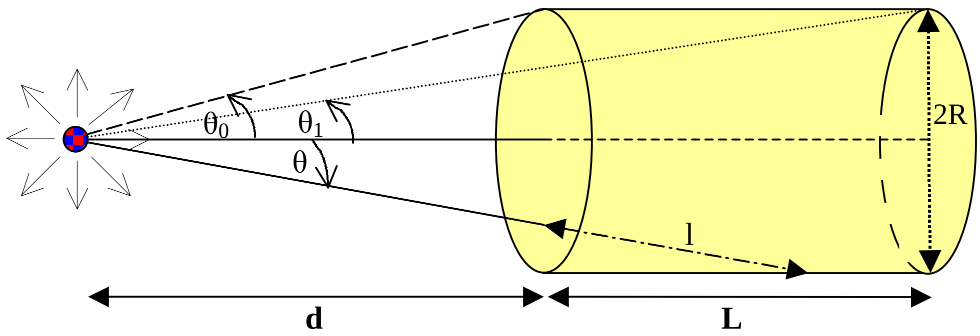

Figure 1: Geometry of source and NaI(Tl) detector.

Calculation of Efficiency

MCNP is a general-purpose Mote Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. The code has an extensive collection of cross section data and is able to simulate the transportation of these particles with energy from 1 keV to 100 MeV in materials as well.

Considering the geometry shown in Fig. 1 with a monoenergitic isotropic point source, we have calculated total and intrinsic efficiency for a 3in×3in NaI(Tl) crystal by F8 tally. Fig. 2 shows the calculated intrinsic efficiency of this detector for 0.2, 1, and 5 MeV photons as a function of d/R ratio (ratio of the detector-source distance to the radius of the detector), and Fig. 3 shows the calculated intrinsic efficiency for 5, 10, and 50 MeV photons as a function of d/R ratio. Note that, in all these figures, the intrinsic efficiency has a minimum around $d/R \approx 0.7$. Calculated total efficiency of

3in×3in NaI(Tl) detector is given in Fig. 4 for 0.2, 1, and 10MeV photons. The relative Monte Carlo error is less than %1 in the all calculations.

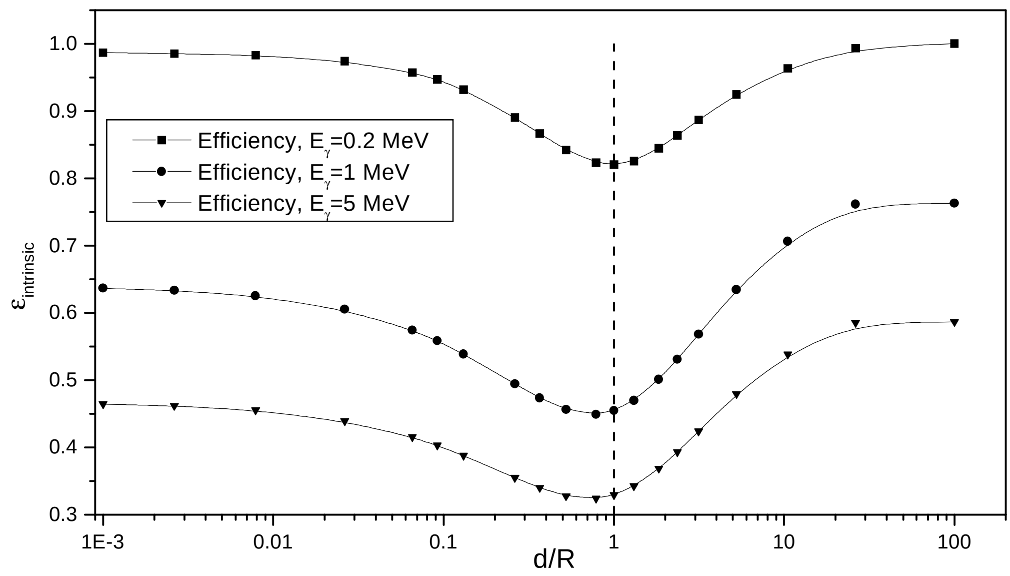

Figure 2: Intrinsic efficiency 3in×3in NaI(Tl) detector as a function of d/R for 0.2, 5, and 10MeV gamma rays.

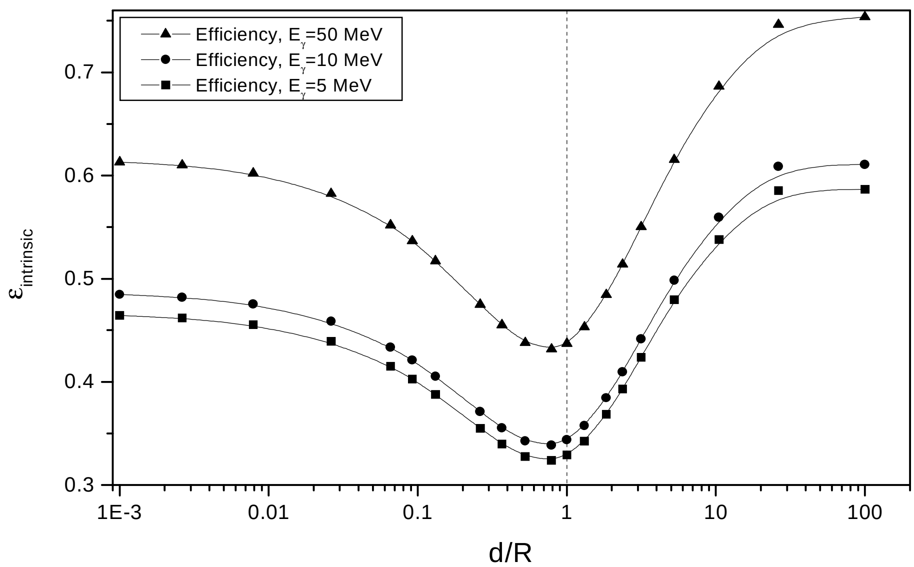

Figure 3: Intrinsic efficiency 3in×3in NaI(Tl) detector as a function of d/R for 5, 10, and 50MeV gamma rays.

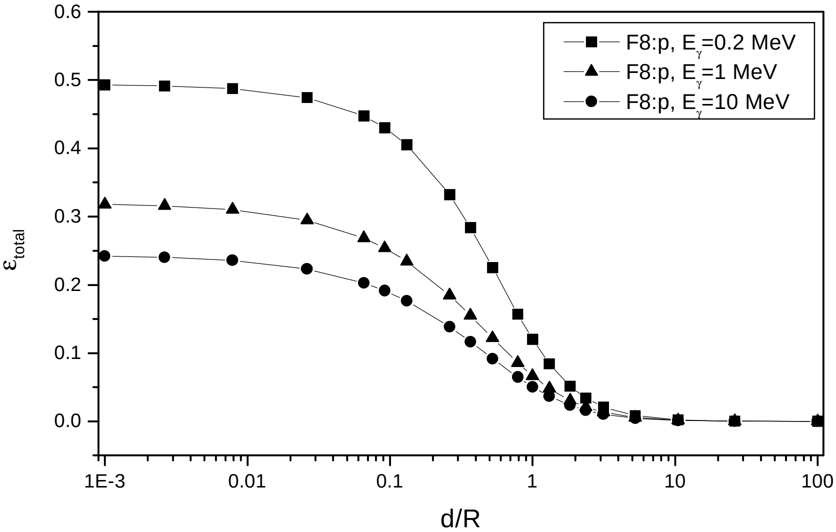

Figure 4: Total efficiency 3in×3in NaI(Tl) detector as a function of d/R, for 0.2, 1, and 10MeV gamma rays.

Analyses of Results

In order to justify the dependent intrinsic efficiency versus d/R, we use *mean chord length* of photons in the detector and *mean interaction length* at any energy.

Mean Chord Length: Analytical expression for measuring photon mean chord length of an isotropic point source in a detector (Fig. 1) is obtained from calculating the average of chord over the source-detector solid angle, as explained below:

$$l = \begin{cases} \dfrac{L}{\cos\theta} & \theta \le \theta_1 \\ \dfrac{R - d\tan\theta}{\sin\theta} & \theta \rangle \theta_1 \end{cases}$$

$$l_m = \frac{\int_0^{2\pi}\int_0^{\theta_0} l\, d\Omega}{\int_0^{2\pi}\int_0^{\theta_0} d\Omega} = \frac{\int_0^{2\pi}\int_0^{\theta_1} \frac{L}{\cos\theta}\sin\theta\, d\theta\, d\varphi + \int_0^{2\pi}\int_{\theta_1}^{\theta_0} \frac{R - d\tan\theta}{\sin\theta}\sin\theta\, d\theta\, d\varphi}{\int_0^{2\pi}\int_0^{\theta_0}\sin\theta\, d\theta\, d\varphi} \Rightarrow$$

$$l_m(R,L,d) = \frac{1}{1-\cos\theta_0}\left[L\,\ln\left(\frac{1}{\cos\theta_1}\right) + R(\theta_0 - \theta_1) - d\,\ln\left(\frac{\cos\theta_1}{\cos\theta_0}\right)\right]$$

Figure 5 shows the photon mean chord length as a function of d/R for the NaI(Tl) detector for different sizes. The mean chord length near to and far from the detector asymptotic goes to limit value as following.

$$\lim_{d\to 0} l_m(R,L,d) = \frac{L}{2}\ln[1+\frac{R^2}{L^2}] + R[\frac{\pi}{2} - \tan^{-1}(\frac{R}{L})]$$

$$\lim_{d\to\infty} l_m(R,L,d) = L$$

As a remarkable point it can be seen that the minimum of intrinsic efficiency and the minimum of mean chord length, are identical.

Mean Interaction Length: Mean interaction length for a photon is defined as the average of distances traveled in medium before an interaction take place. Fig. 6 shows the photon mass attenuation coefficient for NaI(Tl) as a function of energy.
Mean interaction length is the inverse of the total linear attenuation coefficient which is shown in Fig. 7. This curve indicates a maximum in 5MeV. Therefore it is expected that the less the ratio of the mean interaction length to the mean chord is the more the probability of interaction in unit length is and thus the more the intrinsic efficiency is. In Fig. 2, from low values of energy up to 5 MeV, the intrinsic efficiency decreases with the increase of mean chord length but in the values more than 5MeV, as shown in Fig. 3, it starts to increase because of the pair production phenomenon. In table 1 the mass attenuation coefficient and total linear attenuation coefficient of NaI(Tl) are given for several energy.

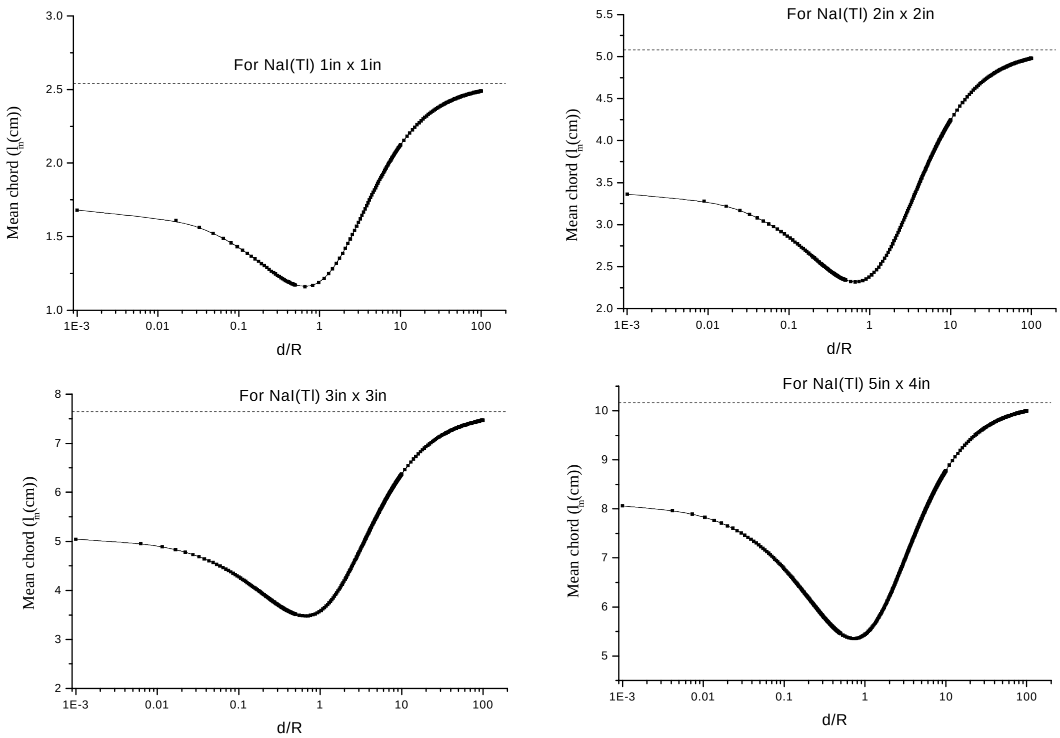

Figure 5: Mean chord of gamma rays in NaI(Tl) detector with different sizes

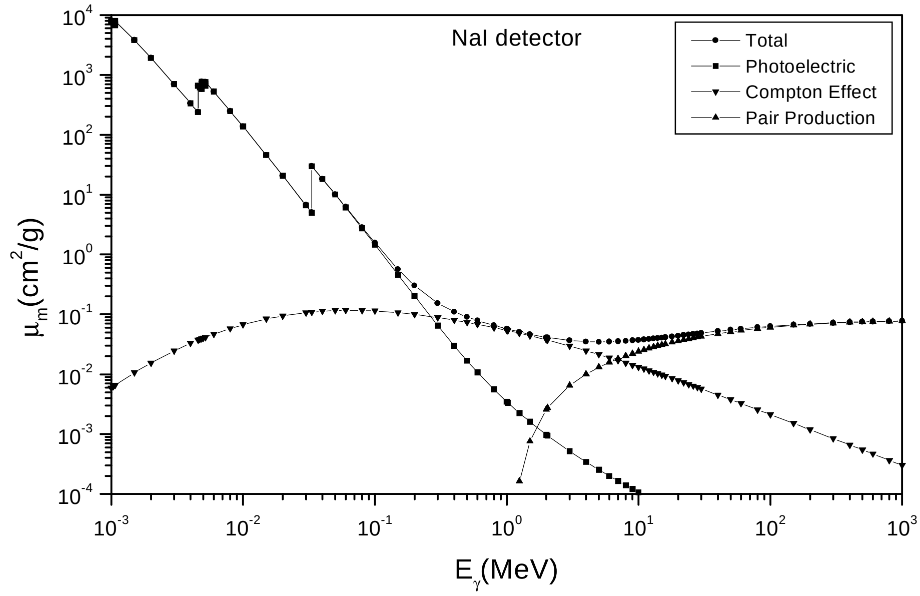

Figure 6: Photon mass attenuation coefficient for NaI(Tl) as a function of energy.

In energies lower than 0.2MeV, where the mean interaction length in comparison with the size of the detector (3in×3in) and the mean chord length is small, the intrinsic efficiency is symmetric around the minimum point. But beyond that point, the mean interaction length is comparable with the detector size and the curve is not symmetric around the minimum point (Figures 3, 4).

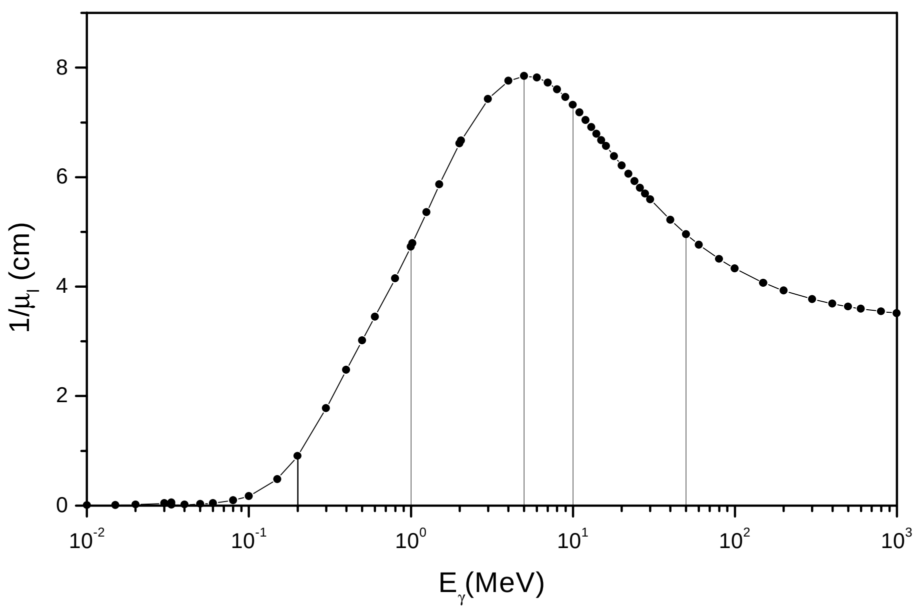

Figure 7: Inverse of photon linear attenuation coefficient for NaI(Tl) as a function of energy.

Table 1: Mass and total linear attenuation coefficient of photon in NaI, for several energy.

$E_\gamma (MeV)$	μ_m (g/cm^2)	μ_l (cm^{-1})	$\frac{1}{\mu_l}$
0.2	0.302	1.10834	0.90225
1	0.05764	0.21154	4.72727
5	0.03472	0.12742	7.84791
10	0.03722	0.1366	7.32078
50	0.05498	0.20178	4.95598

Conclusion

In this paper the change in the intrinsic efficiency of the NaI(Tl) detector with the source-detector distance is simulated and calculated for different gamma rays by using MCNP code. This method can also be generalized for different geometries, sizes of the detector, and the source. Variation of intrinsic efficiency versus d/R can be explained by useing of mean chord path length of the photons in the detector and the mean interaction length of the photons. The results can be used in gamma spectroscopy and determining the activity of sources.

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