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The Effect of Detector Dimensions on the NaI (Tl) Detector Response Function

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Abstract: The well-known MCNP code was used to simulate the NaI(Tl) Detector Response Function (DRF) with 2"×2", 3"×3" and 5"×5" crystal dimensions for gamma rays from ^{241}Am, ^{137}Cs and ^{60}Co sources. Then a code named RNAIGA has been slightly written by us which fitted the Gaussian spectra on the generated Pulse-height spectrums by MCNP code (Monte Carlo N-Particle Transport Code System). The generated spectra by the Monte Carlo were compared with the experimental spectra. In general the agreement between the simulation and the experimental response function was good and at the end the effect of Detector Dimensions (DD) on the NaI(Tl) DRF, the Gaussian Standard Deviation (GSD) and the Energy Resolution (ER) were studied for the full energy peak. It was recognized that with increasing the dimensions of the NaI(Tl) detector crystal, (I.) not only the Compton continuum decreased but also GSD for the full energy peak increased and ER decreased, (II) not only at low energies the variation of the response function of the NaI(Tl) detector was very small but also At high energies variation of response function of the NaI(Tl) detector was very large.

Key words: Pulse-height spectrum, dimensions of NaI(Tl) detector, Gaussian standard deviation, energy resolution, Compton continuum, Monte Carlo simulation

INTRODUCTION

NaI(Tl) detectors are widely used and their response to gamma ray is important especially for the inverse elemental analysis of prompt gamma ray neutron activation (PGNA) analysis (Shyu *et al*., 1993), energy dispersive X-ray fluorescence (EDXRF) analyzers (He *et al*., 1990) and nuclear medicine.

During recent years a large amount of experimental and calculational work have focused on this subject. In the 1970s Berger and Seltzer (1972) used Monte Carlo (MC) simulations to develop sets of data and formulate to calculate the response function of NaI(Tl) detectors. In recent years powerful and convenient MC programs have become more popular. The response function can be obtained by simulating the deposited energy in the detector. In order to EGS4 (Nelson *et al*., 1985), MCNP (Briesmeister, 1997) and special MC programs, can be using. There are some factors which affect the detector response functions such as: detector dimensions, detector-source-distance and detector-collimator. In previous work, the effects of detector-collimator on gamma-ray response function were illustrated and in this work the effects of detector dimensions on the NaI(Tl) DRF will be illustrated. Although, detectors with various dimension are almost used in experimental works, they are not clearly described by Shi *et al*. (2002), Sood and Gardner (2004), Gardner and Sood (2004) and Vitorelli *et al*. (2005), they described the response function of NaI(Tl) detector versus energy, but in this work the effects of detector dimensions on gamma-ray response function, FWHM and energy resolution in the full energy peak for NaI(Tl) detectors with using the MCNP code (Briesmeister, 1997) for 2"×2", 3"×3" and 5"×5" crystal dimensions were studied, then same study was done experimentally and the results due to MC were compared with the measured data. The energy of the sources ranged from 0.026 to 1.5 MeV. Also the time of counts and detector-source-distance were constant.

MONTE CARLO SIMULATION

The MCNP code was applied to perform the calculations in this work. MCNP is a general purpose, three dimensional general geometry, time dependent, Monte Carlo N particle code that is used to calculate coupled neutron-photon-electron transport. For photon, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric

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absorption, absorption in pair production with local emission of annihilation radiation and bremsstrahlung. Figure 1 shows inner structure of a 3″×3″ NaI(Tl) detector which has been produced by the Canberra company. The MC method used to predict incident photon spectra are applied in conjunction with DRF to translate photon spectra incident on the detector to a pulse height spectra. The DRF is defined as the pulse height distribution for an incident monoenergetic γ or χ-ray usually denoted R(E',E) where E' is the pulse-height energy and E is the incident γ- or χ-ray energy. The DRF is Probability Distribution Function (PDF) which has the properties which is always larger than or equal to zero over its entire range and integrates over all E' to unity. To order in, F8 tally was

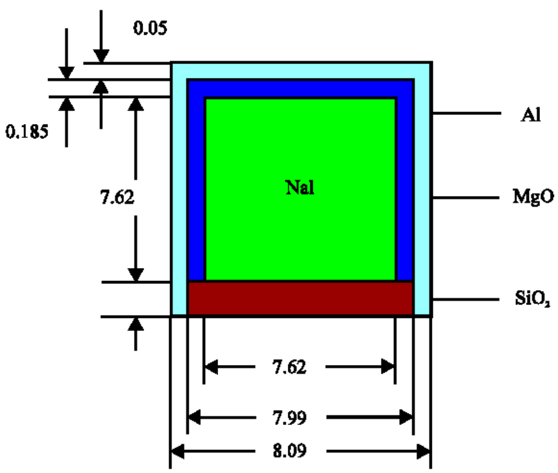

Fig. 1: Plot of inner structure of a 3″×3″ NaI(Tl) detector

sed for 2″×2″, 3″×3″ and 5″×5″ NaI (Tl) detectors for gamma rays emitted by ^{241}Am, ^{137}Cs and ^{60}Co sources. Then a code named RNAIGA has been slightly written by us which fitted the Gaussian spectra on the generated Pulse-height spectrums by MCNP code. This code utilizes a semi-empirical relationship between GSD for the full energy peak and the incident gamma-ray energy which produces that peak (Gardner and Sood, 2004) the form used is:

$$\sigma(E) = a\,E^{b} \qquad (1)$$

where, σ(E) is total GSD which required to the Gaussian spectra of the NaI(Tl) DRF that it consists contribution from both the spread due to NaI non-linearity and the usual spread due to that from the Poisson distribution of electrons arriving at the first dynode of the PMT, E is the incident gamma ray energy, a and b are constants for a given detector that were determined by the least square fit from the experimental data. They are listed in Table 1. The spread spectrums were normalized in this case to the experimental data by the counting number in the mean channel of the full energy peak. Figure 2 shows the MCNP code output and the RNAIGA code output for the 5″×5″ NaI(Tl) detector.

Table 1: The amount of fitting constants

Dimensions of NaI detectors	a	b	c	d
2″×2″	0.0293	0.7628	0.0688	-0.2387
3″×3″	0.0435	0.9028	0.1064	-0.0826
5″×5″	0.0297	0.7208	0.0747	-0.2541

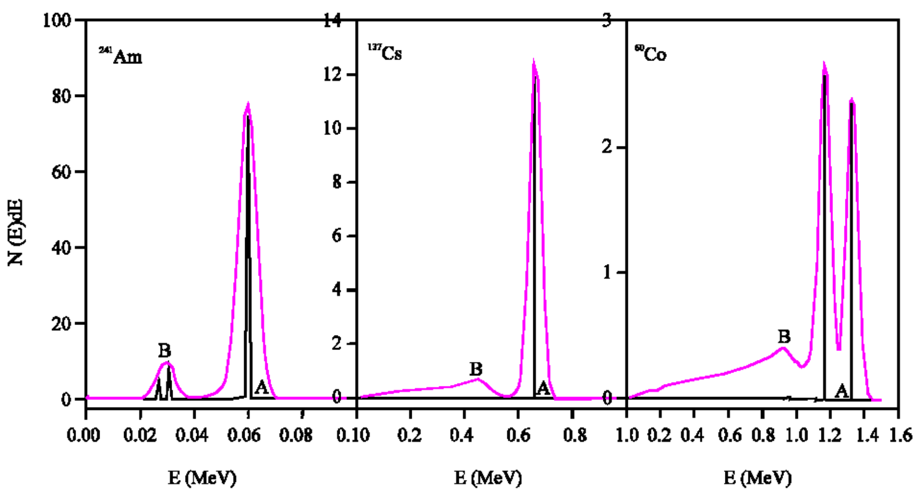

Fig. 2: Plot of DRF versus the incident photon energy for the 5″×5″ NaI (Tl) detector with the three sources. A: Unspread spectrum that it has been produced by the MCNP code and B: spread spectrum that it has been produced by RNAIGA code

MATERIALS AND METHODS

By experimental study, two aims were obtained.

- Determination of FWHM (full width at half maximum) and pulse height vs. energy scale function
- Verification of the calculated results

In presence study, were used from 2"×2", 3"×3" and 5"×5" NaI(Tl) detectors for point isotropic gamma rays from ^{241}Am, ^{137}Cs and ^{60}Co sources located 5 cm along the detector axis from the face of the detector. Then the experimental DRF for each of the three sources and three detectors were measured then they were normalized to unit because of comparing the effect of detector dimensions on DRF. For each case the amount of FWHM, GSD and ER were measured. At the end, experimental data were fitted on Eq. 1 to obtain FWHM, GSD and ER curves versus the incident photon energy.

COMPARISON OF EXPERIMENTAL AND CALCULATED SPECTRA

Comparison at low energies: Figure 3 shows the experimental spectra for the three sources with the corresponding generated spectra by the MCNP code in three NaI(Tl) detectors. In comparison with the experimental data, a small discrepancy can be seen at the Compton edge in the spectra of the MCNP code. For the Compton continuum below the Compton edge energy, all the calculated results are a little lower than the experimental data due to the photon scattered by shielded and the detector support and the uncertainty of the MC simulation of low energy electrons.

Comparison at high energies: Figure 3 shows MCNP code accurately produced the results at high energies. This result can be expected because the effect of the scintillation efficiency fades in the high-energy region where the scintillation efficiency is almost linear.

THE EFFECTS OF DETECTOR DIMENSION ON DETECTOR RESPONSE FUNCTION

Figure 4-6 show the experimental DRF spectra for ^{241}Am, ^{137}Cs and ^{60}Co sources with the corresponding generated spectra by the MCNP code for the three NaI(Tl) detectors, respectively. Figure 7 and 8 show FWHM and ER in the full energy peak with their fitted curves where to obtain ER curves the experimental data were fitted on the equation below (Berger and Seltzer, 1972):

$$R(E) = c \times E^{d} \tag{2}$$

where, E is the incident gamma ray energy, c and d are constants for a given detector that were determined by the least square fit from experimental data. They are listed in Table 1.

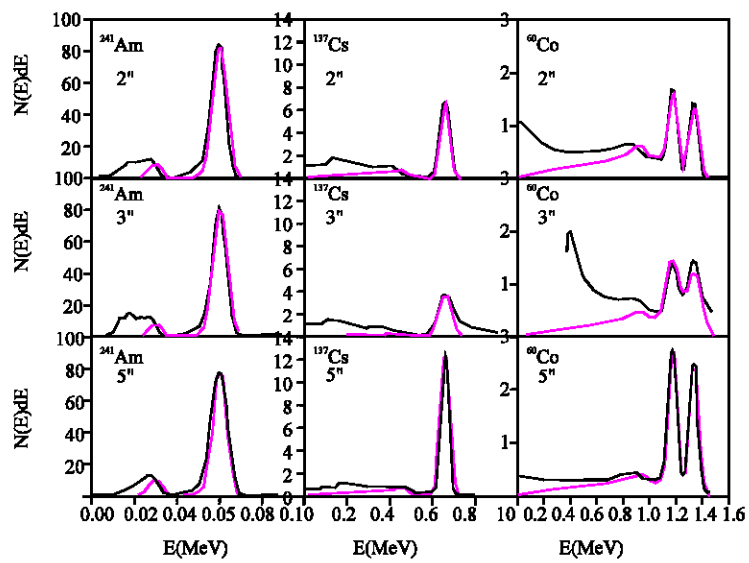

Fig. 3: Plot of DRF versus the incident photon energy that they have been produced by the MCNP code (magenta solid lines) for three detectors (2"×2", 3"×3" and 5"×5") and three sources (^{241}Am, ^{137}Cs and ^{60}Co). There are also comparison between them and the experimental DRF (black solid lines) for each case

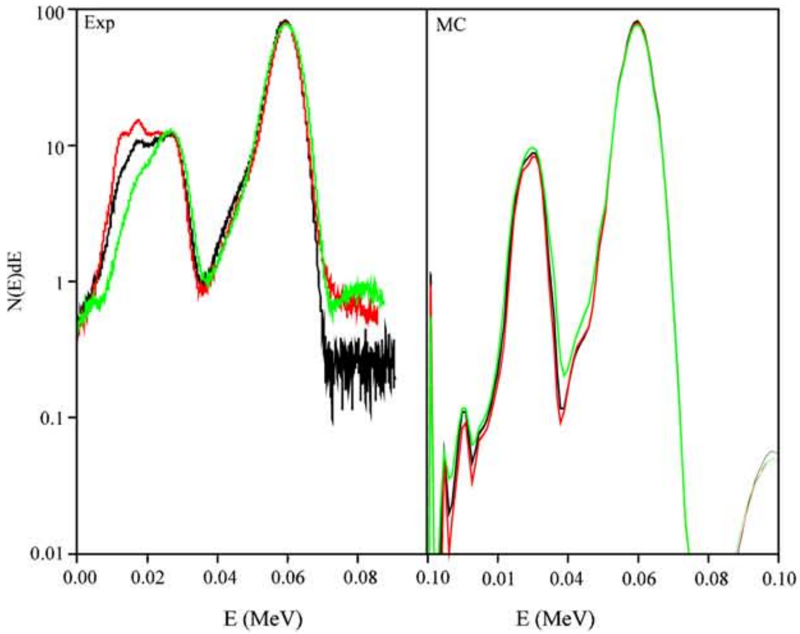

Fig. 4: Plot of DRF versus the incident photon energy for ^{241}Am source and their comparison among 2"×2" (black solid line), 3"×3" (red solid line) and 5"×5" (green solid line) NaI(Tl) detectors for both cases experimental and Monte Carlo

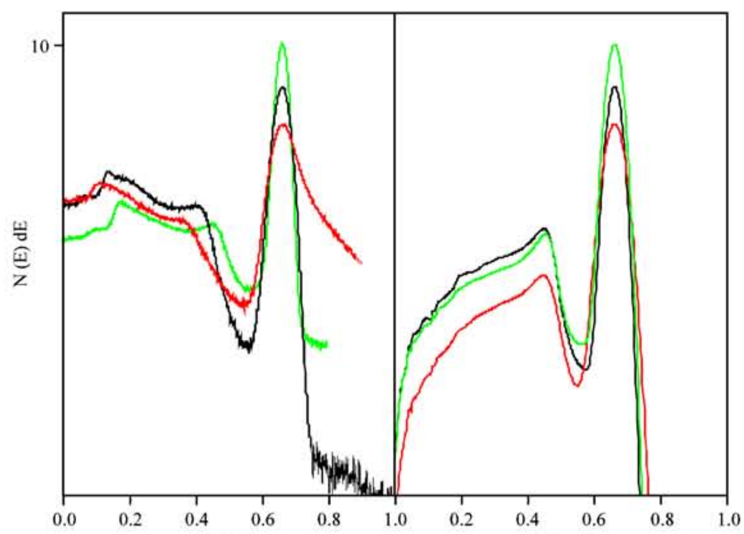

Fig. 5: Plot of DRF versus the incident photon energy for ^{137}Cs source and their comparison among 2"×2" (black solid line), 3"×3" (red solid line) and 5"×5" (green solid line) NaI(Tl) detectors for both cases experimental and Monte Carlo

They show four important aims:

- With increasing the dimensions of the NaI(Tl) detector crystal, the Compton continuum decrease, because of increasing the probability of the Compton scattering gamma photons capture
- At low energies the variation of the response function of the NaI(Tl) detector with increasing the dimensions of the NaI(Tl) detector crystal is very small (Fig. 4), because the mean free pass for low energy photons in the NaI (Tl)

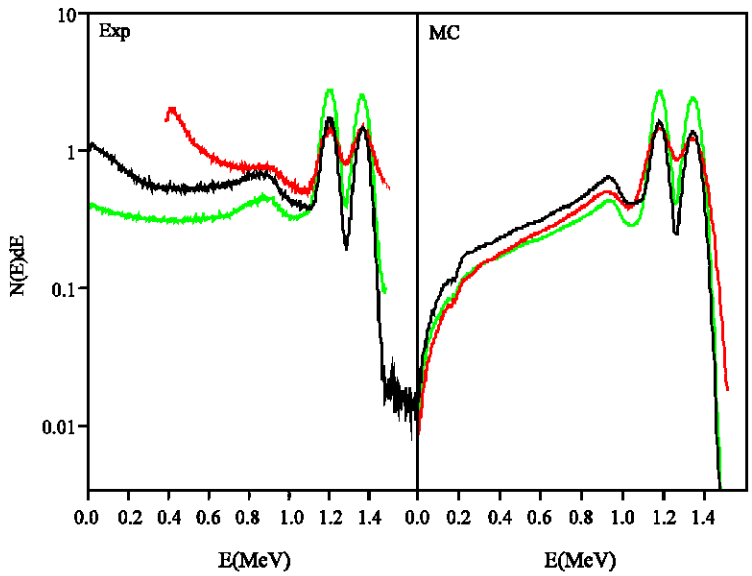

Fig. 6: Plot of DRF versus the incident photon energy for ^{60}Co source and their comparison among 2"×2" (black solid line), 3"×3" (red solid line) and 5"×5" (green solid line) NaI(Tl) detectors for both cases experimental and Monte Carlo

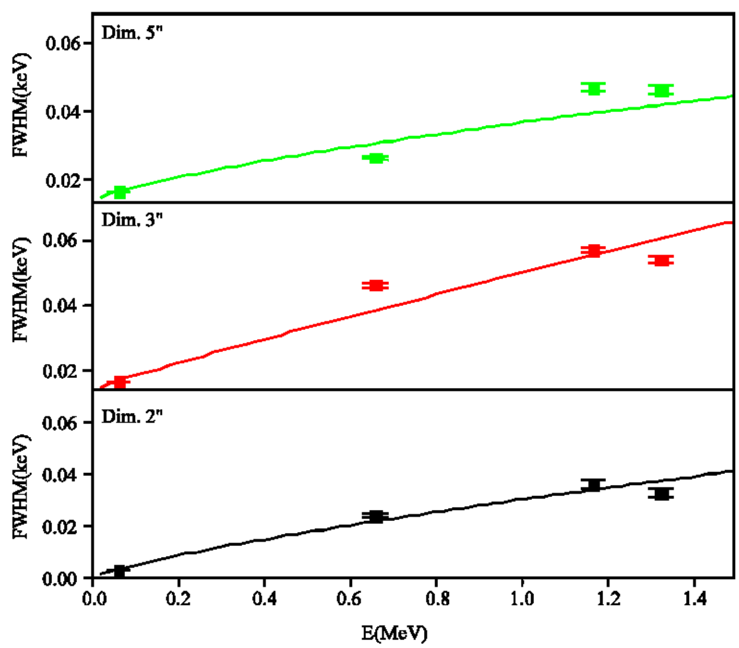

Fig. 7: Plot of the Gaussian standard deviation in the full energy peak versus the incident photon energy for each of the three detectors

crystal is about 0.017" (Fig. 9) therefore it is very least of 2"×2"

- At high energies variation of response function of the NaI(Tl) detector with increasing the dimensions of the NaI(Tl) crystal is very large (Fig. 5, 6), because the mean free pass for high energy photons in the NaI(Tl) crystal is about 2" (Fig. 9) therefore it is large in compare with 2"×2", 3"×3" or 5"×5" dimensions
- With increasing the dimensions of the NaI(Tl) crystal, GSD for the full energy peak increases, but ER decreases (Fig. 7, 8)

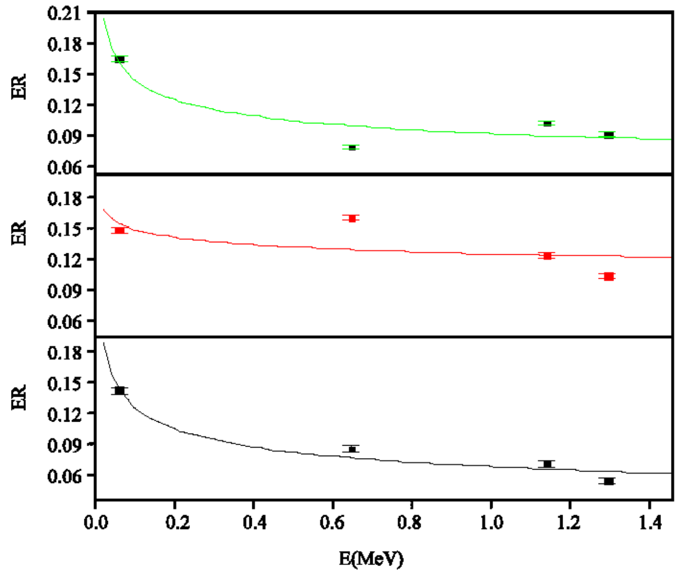

Fig. 8: Plot of the energy resolution versus the incident photon energy for each of the three detectors

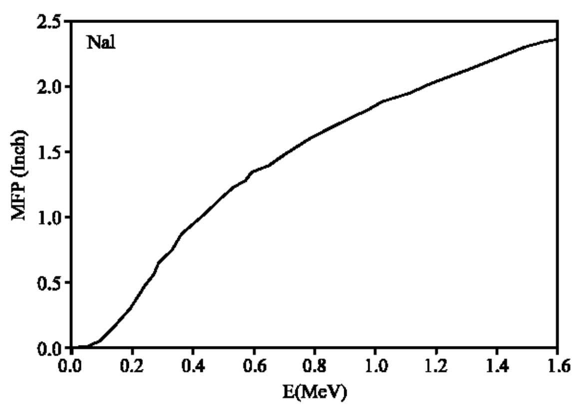

Fig. 9: Plot of mean free pass of gamma rays versus incident photon energy in NaI(Tl) crystal

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