Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 9 (8): 1550-1555, 2009
ISSN 1812-5654

Effects of the Detector-Collimator on the Gamma-Ray Response Function for a NaI(Tl) Detector in a Constant Time of Counts

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Abstract: This study describes the effects of the detector-collimator on the gamma-ray response function for NaI(Tl) detectors with 2"×2", 3"×3" and 5"×5" dimensions. In present study we have used five different detector-collimators and three gamma ray sources (^{241}Am, ^{137}Cs and ^{60}Co). In all states, the time of counts and detector-source-distance were constant. We measured the gamma-ray response function, Full Width at Half Maximum (FWHM) and energy resolution in the full energy peak with and without detector-collimators. Then we perceived that the detector-collimator was very important in gamma ray spectrometry because, in the best state, FWHM and energy resolution decrease about 55%. In the end we obtained the best detector-collimator for each of the three NaI(Tl) detectors.

Key words: NaI(Tl) detector, detector-collimator, gamma-ray response function, NaI(Tl) dimension

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 analysis (Shyu *et al*., 1993), energy dispersive X-ray fluorescence analyzers (He *et al*., 1990) and nuclear medicine.

During recent years a large number of experimental and calculational works have focused on this subject. In the 1970s, Berger and Seltzer (1972) used Monte Carlo simulations to develop sets of data, then they formulated them to calculate the gamma-ray response function for NaI(Tl) detectors. There are some codes like: EGS4 (Nelson *et al*., 1984), MCNP (Briesmeister, 1997) and special Monte Carlo programs can be used to simulate the detector response function for NaI(Tl) detectors.

There are some factors which affect the detector response functions such as: detector dimensions, detector-source-distance and detector-collimator. Although, detector-collimators are almost used in experimental works, they are not clearly described in all of the researchers' works (Shi *et al*., 2002; Sood and Gardner, 2004; Gardner and Sood, 2004; Vitorelli *et al*., 2005), they described the response function of NaI(Tl) detector versus energy. This study presents the effect of detector-collimator on gamma-ray response function, FWHM and energy resolution in the full energy peak for NaI(Tl) detectors with 2"×2", 3"×3" and 5"×5" dimensions were investigated to obtain the best detector-collimator. The energy of the sources ranged from 0.026 to 1.5 MeV. Also the time of counts and detector-source-distance were constant.

MATERIALS AND METHODS

In this study, the 2"×2", 3"×3" and 5"×5" NaI(Tl) detectors were used for different point gamma ray sources: ^{241}Am, ^{137}Cs and ^{60}Co which is located 50 mm along the detector axis from the face of the detector and five different detector-collimators (C_1, C_2, C_3, C_4 and C_5) with a constant length (L = 50 mm) and varied diameters (D = 60, 15, 10, 6 and 3 mm). Figure 1 shows the diagram of the detector without and with detector-collimator. It also shows the cone half-angle (θ) of detector-collimator. The different sizes are listed in Table 1. The length of collimator is 50 mm because the Half-Value-Layer (HVL) of lead at E_γ = 1.33 MeV (maximum incident photon energy) equals to 10.6 mm, therefore the collimator with 50 mm in length has the thickness of lead is about 5 HVL's. For each detector and each source, detector response function, FWHM and energy resolution were calculated without and with detector-collimator but in all cases, the time of count and detector-source-distance were constant. The experimental response function for each NaI(Tl) was normalized to unit in order to compare the effect of

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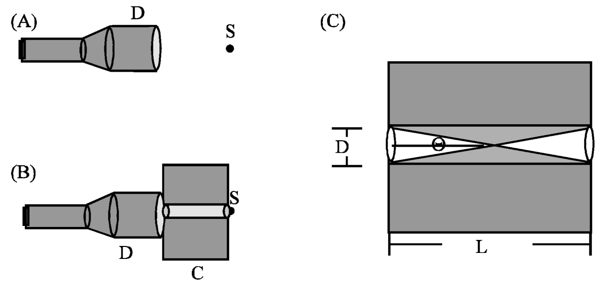

Fig. 1: (A) Schematic diagram of detector without detector-collimator. (B) Schematic diagram of detector with detector-collimator and (C) Plot of single detector-collimator

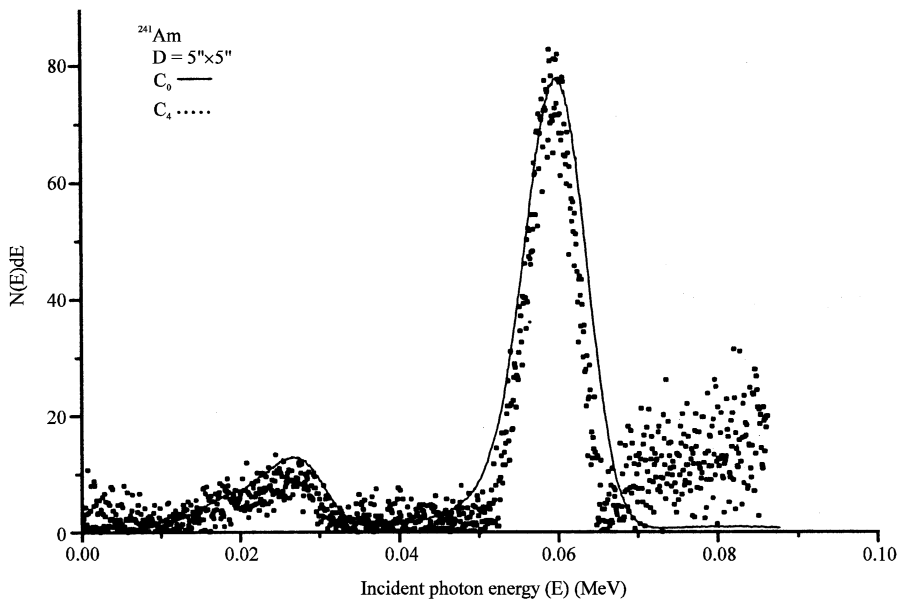

Fig. 2: Plot of detector response function versus incident photon energy and a comparison of the measured detector response function without collimator with C_4 collimator for ^{241}Am source. Detector size is 5"×5"

Table 1: The cone half-angle of the detector-collimator for three detectors

	Angle (θ°)		
Detector-collimator	2"×2" detector	3"×3" detector	5"×5" detector
C_0	45.45	56.73	68.51
C_1	50.19	50.19	50.19
C_2	16.70	16.70	16.17
C_3	11.31	11.31	11.31
C_4	6.84	6.84	6.84
C_5	3.34	3.34	3.34

the detector-collimator on gamma ray response function. Figure 2-4 show the gamma-ray response functions with the most decrease in width for the three sources. The amount of FWHM and energy resolution was obtained for other sources and other collimator.

Because of the constant time of the counts and using different collimators, the uncertainty of FWHM for each of the experiments is not the same. Therefore Eq. 1 was used to calculate the uncertainty of FWHM in percent.

$$\frac{\sigma_{FWHM}}{FWHM} = \frac{204}{\sqrt{N_{Max}}} \tag{1}$$

where, σ_{FWHM} is the uncertainty of FWHM and N_{Max} is the count in the full energy peak. In all experiments, the count in the full energy peak was larger than 1000 therefore, the uncertainty in FWHM was lower than 6.45%; while Eq. 2 is used to calculate energy resolution:

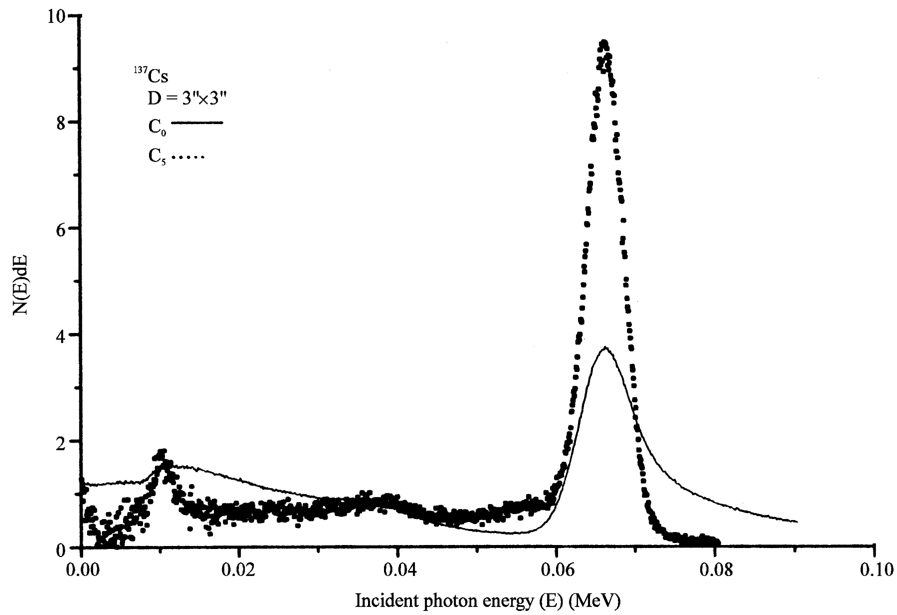

Fig. 3: Plot of detector response function versus incident photon energy and a comparison of the measured detector response function without collimator with C_4 collimator for ^{137}Cs source. Detector size is 3"×3"

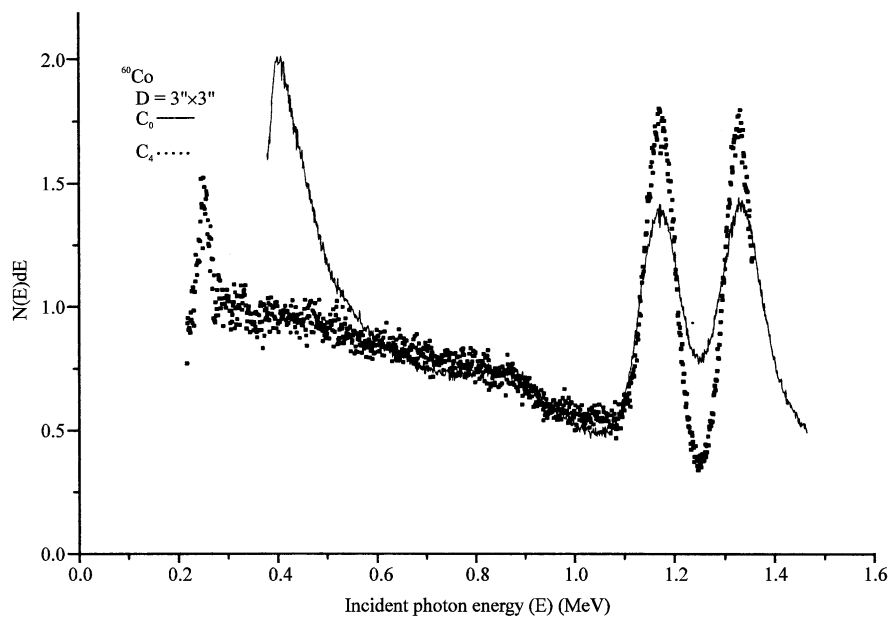

Fig. 4: Plot of detector response function versus incident photon energy and a comparison of the measured detector response function without collimator with C_4 collimator for ^{60}Co source. Detector size is 5"×5"

$$ER(E) = \frac{FWHM}{E} \quad (2)$$

where, ER is energy resolution and E is the incident gamma ray energy. Then the Table 2 presented the quantity P in percent is defined as the difference between the FWHM which was obtained in the presence and absence of the detector-collimator, normalized to that of the absence of the detector-collimator multiply by 100. For all collimators the amount of P was calculated then the best detector-collimator was obtained for each detector and each source using the amount of P.

Table 2: The best collimator for each NaI(Tl) detector and the amount of P

Source	Dimensions of detector	The best collimator	P (%)	±ΔP
^{241}Am	2"×2"	C_4	10.65	9.74
^{241}Am	3"×3"	C_4	17.69	9.26
^{241}Am	5"×5"	C_4	20.21	9.60
^{137}Cs	2"×2"	C_5	8.81	12.16
^{137}Cs	3"×3"	C_5	42.23	16.00
^{137}Cs	5"×5"	C_5	7.89	7.14
^{60}Co (E_1)	2"×2"	C_3	0.00	5.18
^{60}Co (E_1)	3"×3"	C_4	43.32	11.51
^{60}Co (E_1)	5"×5"	C_0	0.00	4.53
^{60}Co (E_2)	2"×2"	C_5	9.16	10.53
^{60}Co (E_2)	3"×3"	C_5	55.69	18.83
^{60}Co (E_2)	5"×5"	C_0	0.00	3.98

E_1 = 1.17 (MeV) and E_2 = 1.33 (MeV) are the incident photons energy of ^{60}Co source

RESULTS

Figure 5A-C shows FWHM versus type of collimator for the four different incident photon energies for each detector to observe the effect of the incident photon energy on FWHM. We observed that for all detectors and collimators, FWHM increases with the increase in photon energy, up to E_γ = 1.17 MeV, then FWHM decreases for the photon energy E_γ = 1.33 MeV. In Fig. 6A-C, respectively, mass attenuation coefficient, mean free path of gamma rays and the probability of each of the photoelectric, the incoherent scattering and the pair production phenomena versus incident photon energy is shown for NaI crystal. It was observed that from 0.25 to 6.77 MeV in incident photon energy the incoherent scattering has the most probability and in Eγ = 1.25 MeV the amount of it is maximum. Therefore, FWHM for a NaI detector increases until Eγ = 1.25 MeV then it decreases after Eγ = 1.25 MeV shown in (Fig. 5A-C).

Figure 7 shows the FWHM versus the type of collimator for the three detectors to observe the effect of detector dimensions on FWHM. In Fig. 7A-D it is observed that FWHM depends not only on collimator diameter but also the detector dimension. It was perceived in E_γ = 0.06 MeV the best detector is 3"×3" detector and the best collimator is C_5, in E_γ = 0.662 MeV the best detector is 5"×5" detector and the best collimator is C_5, in E_γ = 1.17 MeV the best detector is 3"×3" detector and the best collimator is C_4, in E_γ = 1.33 MeV the best detector is 3"×3" detector and the best collimator is C_5. In all plots of Fig. 6 we also observe that this limited range of energy range, E<0.256 MeV and E>1.25 MeV, the amount of FWHM is approximately the same as for each of the three detectors and in the energy range 0.256 MeV<E<1.25 MeV, the amount of FWHM is not the same as 5"×5" detector with 3"×3" and 2"×2" detectors since in energy Eγ = 0.662 MeV not only the incoherent scattering phenomena has the most probability among the other

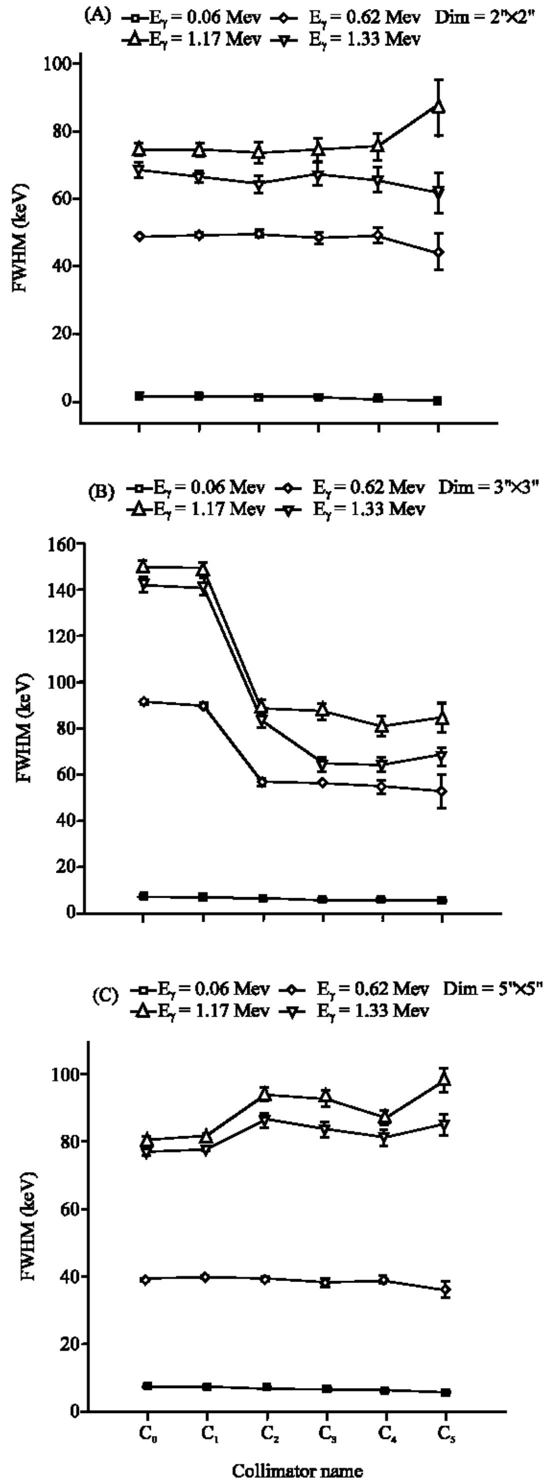

Fig. 5: (A), (B) and (C) Plots of FWHM versus type of collimator (C_0, C_1, C_2, C_3, C_4 and C_5) for the three detectors 2"×2", 3"×3" and 5"×5" with the four incident photon energy (E_γ = 0.06, 0.662, 1.17 and 1.33MeV)

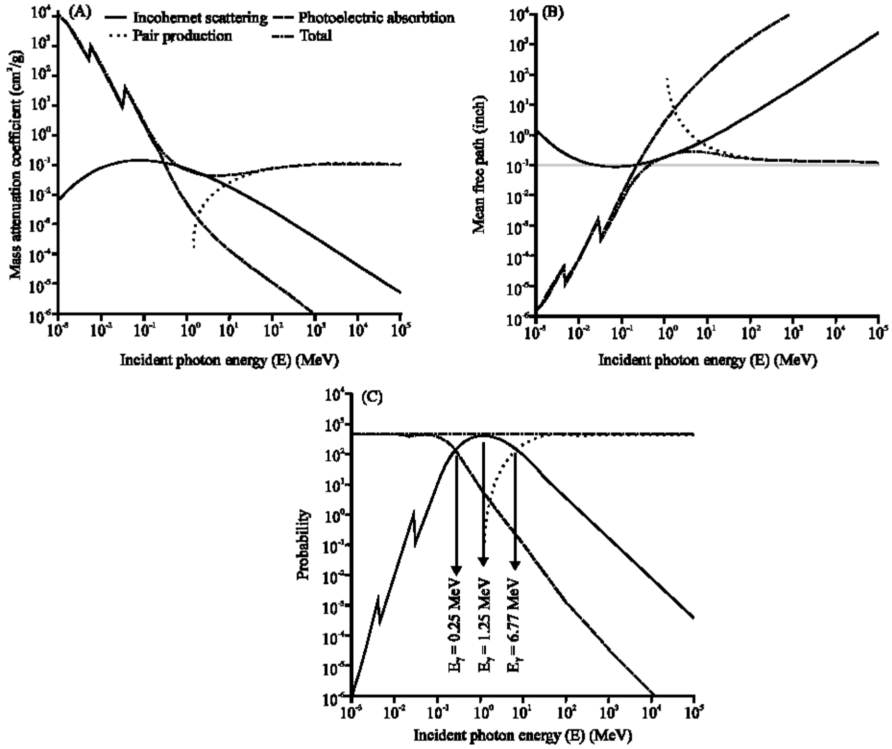

Fig. 6: (A), (B) and (C) Plot of mass attenuation coefficient, mean free path and incoherent scattering, photoelectric and pair production phenomena probability versus incident photon energy in NaI crystal

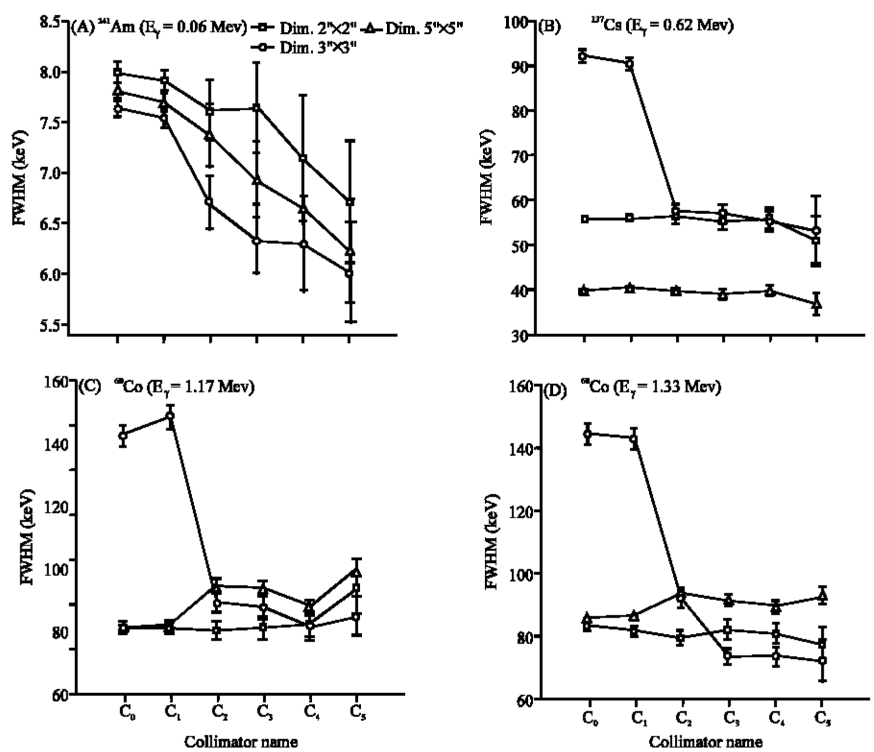

Fig. 7: (A), (B), (C) and (D) Plots of FWHM versus type of collimator (C_0, C_1, C_2, C_3, C_4 and C_5) for four incident photon energy (E_γ = 0.06, 0.662, 1.17 and 1.33MeV) with three detectors (2"×2", 3"×3" and 5"×5")

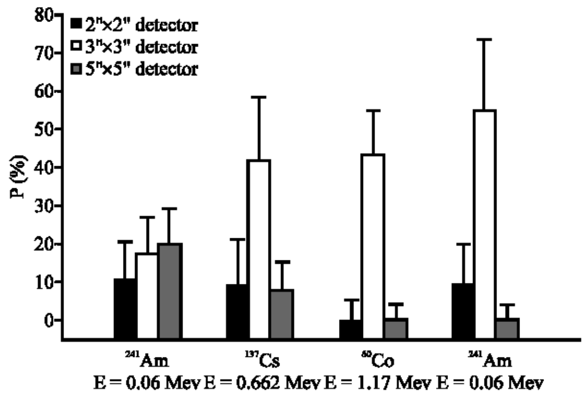

Fig. 8: Plot of P versus E for each of the three detectors with the best detector-collimator

phenomena with mean free path nearly equal to 1" but also both 2"×2" and 3"×3" detectors have more effect on the side surface than 5"×5" detector, therefore in this energy, the FWHM for 5"×5" detector is lower than both 2"×2" and 3"×3" detectors. In all plots of Fig. 7 we also observe that the FWHM without collimator is equal to C_1 collimator, because of large diameter of the C_1 collimator (D = 60 mm). Figure 8 shows the amount of P versus E for each the three detectors with the best detector-collimator. It is observed that the maximum amount of P is 55% which occur for 3"×3" detector in photon energy $E\gamma$ = 1.33 MeV with C_5 collimator (Table 2).

CONCLUSIONS

The effect of the detector-collimator on the gamma ray response function, FWHM and energy resolution in the full energy peak for NaI(Tl) detector with 2"×2", 3"×3" and 5"×5" dimensions for gamma rays emitted by ^{241}Am, ^{137}Cs and ^{60}Co sources were investigated. When the incident photon energy is lower than 0.256 MeV, the amount of FWHM and energy resolution for the three detectors are equal in both state, without and with the collimator because the photoelectric phenomena has the most probability. By increasing the amount of E_γ (0.256 MeV<E_γ<6.772 MeV), the effect of the detector-collimator appears better than the previous state, as we can use each of the three detectors instead of one using a suitable collimator. Also, from E_γ = 0.0 to E_γ = 1.25 MeV, FWHM increases because the photoelectric phenomena probability decreases and the incoherent scattering probability increases and from E_γ>1.25 MeV, FWHM decreases up to a boundary limit, because after this energy not only the incoherent scattering phenomena probability decreases but also the pair production phenomena probability increases. Also by exchanging the type of detector-collimator, the number of peak channels increase and it clearly appears with increasing the incident photon energy so the most increasing peak channel was 111 (0.12 MeV in energy) for ^{60}Co source with 3"×3" NaI(Tl) detector and C_4 collimator. Therefore when detector-collimator or the detector-source-distance is exchanged, the detector must be calibrated again. At the end the best detector-collimators were obtained for each NaI(Tl) detector for each source by considering the amount of P for each of the three detectors and each of the three sources.

ACKNOWLEDGMENT

This research was supported by the research grant No. 50-3358 of Shahrood University of Technology.

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