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Full energy peak efficiency of NaI(Tl) gamma detectors and its analytical and semi-empirical representations

M Sudarshan, J Joseph and R Singh

Department of Physics, North-Eastern Hill University, Laitumkhrah, Shillong 793003, India

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Abstract. The validity of various analytical functions and semi-empirical formulae proposed for representing the full energy peak efficiency (FEPE) curves of Ge(Li) and HPGe detectors has been tested for the FEPE of 7.6 cm × 7.6 cm and 5 cm × 5 cm NaI(Tl) detectors in the gamma energy range from 59.5 to 1408.03 keV. The functions proposed by East, and McNelles and Campbell provide by far the best representations of the present data. The semi-empirical formula of Mowatt describes the present data very well. The present investigation shows that some of the analytical functions and semi-empirical formulae, which represent the FEPE of the Ge(Li) and HPGe detectors very well, can be quite fruitfully used for NaI(Tl) detectors.

1. Introduction

For a precise measurement of gamma ray intensities an accurate determination of the full energy peak efficiency (FEPE) of a gamma detector is required. The former plays an important role in gamma ray spectroscopy. The FEPE values at the required gamma energies can be obtained from a smooth curve drawn through the measured points. Of course, in this process some accuracy has to be sacrificed. A better way of obtaining the FEPE values is to fit the basic data points to some appropriate function or formula and take the required values at appropriate energies from such a fit. For germanium detectors several analytical functions and semi-empirical formulae have been proposed by various authors [1–14]. In fact, very recently we have made a detailed study of the applicability of these functions and formulae to the FEPE of large volume HPGe detectors [15]. However, as far as the NaI(Tl) detectors are concerned, the detection efficiencies have been calculated mostly by using Monte Carlo methods [16–20]. Unlike germanium detectors, neither the analytical functions nor the semi-empirical formulae have been employed for representing the FEPE of NaI(Tl) detectors. For the first time we have attempted to investigate the applicability and usefulness of the analytical functions and semi-empirical formulae, hitherto used only to represent the FEPE of germanium detectors, to describe the FEPE of 7.6 cm × 7.6 cm and 5 cm × 5 cm NaI(Tl) detectors in the 59.5 to 1408.03 keV energy range.

2. Experimental details

The 7.6 cm × 7.6 cm NaI(Tl) detector was procured from Teledyne Isotopes, USA and had a resolution of ~7.5% at 662 keV, and the 5 cm × 5 cm NaI(Tl) detector was procured from Harshaw, USA and had a resolution of ~10%. The FEPEs in both cases were determined in a fixed source–detector geometry by employing a set of calibrated gamma sources consisting of ^{241}Am, ^{60}Co, ^{57}Co, ^{22}Na, ^{54}Mn, ^{137}Cs, ^{133}Ba and ^{152}Eu. This set of gamma sources, procured from IAEA, Vienna, covered an energy range from 59.5 to 1408.03 keV. For the 7.6 cm × 7.6 cm NaI(Tl) detector, the overall errors in the efficiency data varied between ~4.5% and 8.5% whereas in the case of the 5 cm × 5 cm NaI(Tl) detector they ranged between ~4.5% and 7.6%. These errors do not include the contributions from the background subtraction procedure which are estimated to reach up to ~2% at and beyond $E_\gamma = 778.89$ keV.

3. Least squares fits to the analytical functions and semi-empirical formulae

A priori, one can state that the analytical functions and the semi-empirical formulae, which can successfully represent the FEPE data of germanium detectors, should also, in principle, be able to represent the FEPE data of NaI(Tl) detectors as the γ interaction processes in the two media are basically similar. In addition,

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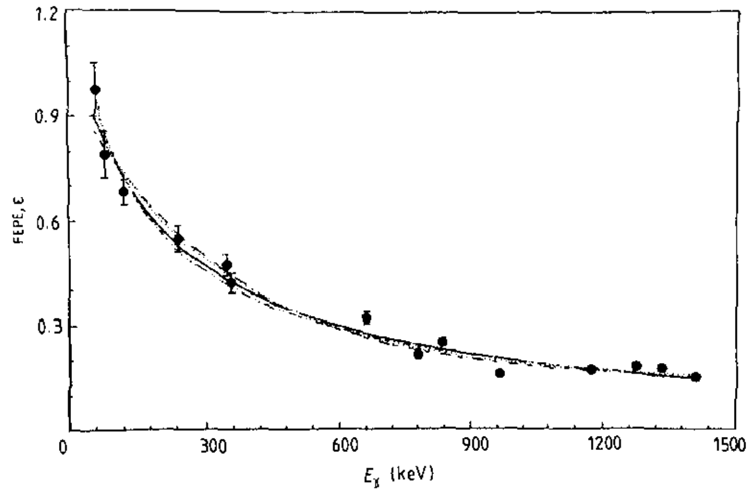

Figure 1. Least squares fits of the FEPE of the 7.6 × 7.6 cm NaI(Tl) detector to equations (1) (full curve), (2) (broken curve), (3) (dotted curve) and (4) (chain curve).

neither the analytical functions nor the semi-empirical formulae involve any details of the mechanism that leads to pulse formation as a result of γ absorption. Of course, as is well known, in the case of the germanium detectors γ absorption finally results in the production of electron–hole pairs whose collection leads to pulse formation whereas in the case of NaI(Tl) detectors it results in the production of light that in turn produces electrons leading to the pulse formation. Further, the atomic numbers and the densities of the two detector materials are certainly very different.

In the following sections we shall examine the validity of these analytical functions and semi-empirical formulae for the FEPE of two (7.6 cm × 7.6 cm and 5 cm × 5 cm) NaI(Tl) detectors.

3.1 Analytical functions

The efficiency ε of a 9 cm^3 coaxial Ge(Li) detector in the energy range from 0.2 to 3.0 MeV was successfully described by Kane and Mariscotti [3] by the following two parameter function

$$\ln \varepsilon = bx + cx^2 \qquad (1)$$

where $x = \ln(1.022/E_\gamma)$. Here E_γ is the gamma energy and b and c are the parameters. By taking $x = \ln(a/E_\gamma)$ and treating a, b and c as parameters we attempted a fit to the FEPE data of the 7.6 cm × 7.6 cm NaI(Tl) detector and obtained a good fit in the energy range from 59.5 to 1408.03 keV (see figure 1). For the 5 cm × 5 cm NaI(Tl) detector the representation was equally good (see figure 2) in the same energy range.

East [4], employed a four parameter function

$$\varepsilon = \alpha_1 \exp(\beta_1 E_\gamma) + \alpha_2 \exp(\beta_2 E_\gamma) \qquad (2)$$

and ended up with a good representation of the efficiency of a 50 cm^3 coaxial Ge(Li) detector in the gamma energy range from 511.0 to 1332.48 keV. Later investigations of this function involving the FEPE of Ge detectors of different sizes [2, 5, 15] gave equally good or even better results. This function described the data of the 7.6 cm × 7.6 cm NaI(Tl) detector very well as can be seen in figure 1. In the case of the 5 cm × 5 cm detector the FEPE representation was good but somehow the quality of fit was not as good, specially at energies below ~300 keV (see figure 2).

In their attempt to represent the efficiency of a 25 cm^3 Ge(Li) coaxial detector McNelles and Campbell [5] arrived at an eight parameter (the as) function

$$\varepsilon = (a_1/E_\gamma)^{a_2} + a_3 \exp(-a_4 E_\gamma) + a_5 \exp(-a_6 E_\gamma) + a_7 \exp(-a_8 E_\gamma) \qquad (3)$$

which best represented their data. Singh [2] showed that the last term in the above function was really unneccessary, and that the six parameter function gave an equally good fit to the efficiency of a 38 cm^3 Ge(Li) detector. This result was further corroborated by us when we used the above function to represent the FEPE data of our large volume HPGe detectors [15]. For the present 7.6 cm × 7.6 cm NaI(Tl) detector as well, equation (3) without the last term gave a very good fit as can be noted from figure 1. The quality of fit was the same for the 5 cm × 5 cm detector data (see figure 2). Indeed the addition of the last term made little change.

Willet [6] proposed the following three parameter function to represent the FEPE of Ge(Li) detectors in an energy range from 392 to 1332.5 keV.

$$\ln \varepsilon = A \ln E_\gamma + B(\ln E_\gamma)^2 - C/(E_\gamma)^3 \qquad (4)$$

with A, B and C as the parameters. This gave a reasonable description of the data for various germanium detectors. A fit of the present 7.6 cm × 7.6 cm NaI(Tl) detector data to this function gave a good representation as shown in figure 1. In the case of the 5 cm × 5 cm detector as well, the fit (not shown here) was reasonably good except for the lower energy region of ~250 keV to ~900 keV. It is not clear why this should be so for the smaller detector.

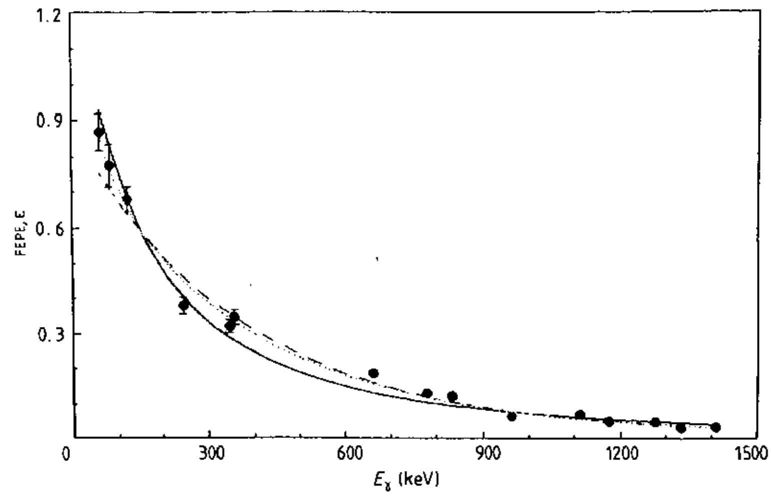

Figure 2. Least squares fits of the FEPE of the 5.0 × 5.0 cm NaI(Tl) detector to equations (1) (full curve), (2) (broken curve) and (3) (dotted curve).

The efficiency data of a number of Ge(Li) detectors were fitted by Gray and Ahmed [7] using a six parameter (the ps) polylog function

$$\varepsilon = [p_1 + p_2(\ln E_\gamma) + p_3(\ln E_\gamma)^2 + p_4(\ln E_\gamma)^3 + p_5(\ln E_\gamma)^5 + p_6(\ln E_\gamma)^7]/E_\gamma. \quad (5)$$

We found that above ~250 keV, the fit to the data of the 157 cm^3 HPGe detector was quite good [15]. A fit of the FEPE data of the 7.6 cm × 7.6 cm NaI(Tl) detector showed that this function does not represent the efficiency well in the energy range from ~150 to ~700 keV (see figure 3). In fact, for the 5 cm × 5 cm detector the fit was not good in the $150 \leqslant E\gamma \leqslant 900$ keV region. Perhaps such an energy dependence (as given by equation (5)) of the FEPE is not appropriate for the NaI(Tl) detectors.

We [15] rewrote the function (initially used by Hubert *et al* [8] for a 174 cm^3 HPGe detector from ≃ 110 keV to 5 MeV)

$$\varepsilon = 10^{-3}\exp[8.544 - 0.8588\,(\ln E_\gamma) + 0.002701\,(\ln E_\gamma)^2] \quad (6)$$

as

$$\varepsilon = a_1 \exp[a_2 - a_3(\ln E_\gamma) + a_4(\ln E_\gamma)^2] \quad (7)$$

with a_1, a_2, a_3 and a_4 as the parameters. This formula represented the data of both the 157 cm^3 and 114 cm^3 HPGe detectors, in the energy range from 244.66 to 1408.03 keV, exceedingly well [15]. For the present detectors, however, the representation was not as good, especially in the region between ~150 and ~700 keV (see figure 3 for the 7.6 cm × 7.6 cm NaI(Tl)

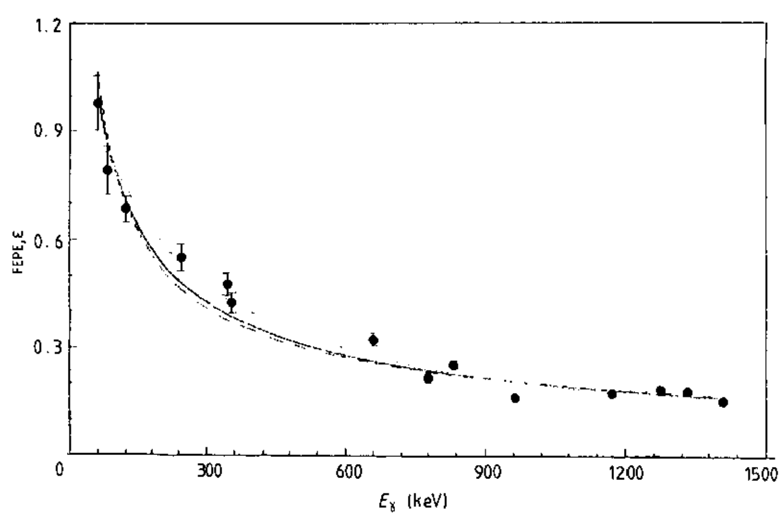

Figure 3. Least squares fits of the FEPE of the 7.6 × 7.6 cm NaI(Tl) detector to equations (5) (full curve), (7) (broken curve) and (8) (chain curve).

detector). This is caused by the inclusion of two data points below ~110 keV in the fits.

A function of the form

$$\varepsilon = [\phi^n/(1+\phi^n)]^{1/n} \qquad (8)$$

was proposed by Mitchell *et al* [9] to calculate the gamma ray response functions for scintillation and semi-conductor detectors. Here $\phi = \exp(\alpha x + \beta x^2)$ and $x = 0.1\ (\ln E_\gamma - \ln E_0)$, where α, β and E_0 are the parameters and $n = 7$ and 4 for HPGe and NaI(Tl) detectors respectively. We performed a least-squares fit of the FEPE data of both the 7.6 cm × 7.6 cm and 5 cm × 5 cm detectors to this function and obtained reasonably good fits in both cases (especially for the 7.6 cm × 7.6 cm detector as shown in figure 3). For both the detectors the values of n ($n = 3.3$ for the 7.6 cm × 7.6 cm detector and $n = 4.1$ for the 5 cm × 5 cm detector) matched well with the values quoted by Mitchell *et al* [9].

All the parameters, for both the detectors, obtained by fitting their FEPE data to the above mentioned analytical functions, are listed in table 1 along with the corresponding χ^2 values and per cent mean deviations.

As in the case of the HPGe detectors, from this investigation, too, it is seen that the analytical functions mentioned above (except for equations (5) and (7)) generally give good representation of the FEPE of both the NaI(Tl) detectors from 59.5 to 1408.03 keV. Thus, although the fits are not as good as for the HPGe detectors [15] (perhaps due to stronger γ absorption in NaI(Tl) because of higher effective Z), on the whole the representation is reasonably satisfactory. Here too,

Table 1. Parameters obtained from the least squares fits of the FEPE data to the analytical functions (designated by appropriate equation numbers, see text).

Equation number	NaI(Tl) detectors	Parameters
(1)	7.6 × 7.6 cm	$a = 0.3093465 \times 10^2$ $b = 0.81742 \times 10^{-1}$ $c = -0.1096602$ $\chi^2 = 1.83 \times 10^{-1}$ % mean deviation = 9.15
	5 × 5 cm	$a = 0.358171 \times 10^2$ $b = 0.2865 \times 10^{-1}$ $c = -0.22898$ $\chi^2 = 5.11 \times 10^{-1}$ % mean deviation = 15.42
(2)	7.6 × 7.6 cm	$\alpha_1 = 8.65502 \times 10^{-1}$ $\beta_1 = -0.28717 \times 10^{-2}$ $\alpha_2 = 1.28545 \times 10^{-1}$ $\beta_2 = 0.80178 \times 10^{-4}$ $\chi^2 = 1.49 \times 10^{-1}$ % mean deviation = 8.74
	5 × 5 cm	$\alpha_1 = 6.7437 \times 10^{-1}$ $\beta_1 = -0.26676 \times 10^{-2}$ $\alpha_2 = 0.10993 \times 10^{-1}$ $\beta_2 = 0.7815 \times 10^{-4}$ $\chi^2 = 2.53 \times 10^{-1}$ % mean deviation = 11.1
(3)	7.6 × 7.6 cm	$a_1 = 1.56813$ $a_2 = 0.39762$ $a_3 = 0.69077$ $a_4 = 0.288 \times 10^{-2}$ $a_5 = 0.075611$ $a_6 = -0.2476 \times 10^{-4}$ $\chi^2 = 1.49 \times 10^{-1}$ % mean deviation = 8.49
	5 × 5 cm	$a_1 = 1.65832 \times 10^1$ $a_2 = 1.36672$ $a_3 = 0.79526$ $a_4 = 0.2668 \times 10^{-2}$ $a_5 = 0.011827$ $a_6 = -0.2234 \times 10^{-4}$ $\chi^2 = 2.22 \times 10^{-1}$ % mean deviation = 9.72
(4)	7.6 × 7.6 cm	$A = 0.314746$ $B = -0.07934$ $C = 0.82709 \times 10^{-2}$ $\chi^2 = 1.89 \times 10^{-1}$ % mean deviation = 9.32
	5 × 5 cm	$A = 0.58815$ $B = -0.14142$ $C = 0.7857 \times 10^{-2}$ $\chi^2 = 7.74 \times 10^{-1}$ % mean deviation = 19.77
(5)	7.6 × 7.6 cm	$p_1 = 0.240404 \times 10^{-5}$ $p_2 = 0.202232 \times 10^{-1}$ $p_3 = 0.298606 \times 10^1$ $p_4 = 0.1417824$ $p_5 = 0.48714 \times 10^{-3}$ $p_6 = 0.51374 \times 10^{-5}$ $\chi^2 = 2.32 \times 10^{-1}$ % mean deviation = 10.74
	5 × 5 cm	$p_1 = 0.508028 \times 10^2$ $p_2 = 0.108219 \times 10^2$ $p_3 = 0.59142 \times 10^{-1}$ $p_4 = 0.1815 \times 10^{-2}$ $p_5 = 0.1901 \times 10^{-2}$ $p_6 = 0.625 \times 10^{-5}$ $\chi^2 = 4.21$ % mean deviation = 42.61
(7)	7.6 × 7.6 cm	$a_1 = 0.23787 \times 10^{-3}$ $a_2 = 0.108219 \times 10^2$ $a_3 = 0.59142$ $a_4 = 0.2834 \times 10^{-4}$ $\chi^2 = 2.78 \times 10^{-1}$ % mean deviation = 11.82
	5 × 5 cm	$a_1 = 0.3395 \times 10^{-3}$ $a_2 = 0.124228 \times 10^2$ $a_3 = 0.104406 \times 10^1$ $a_4 = 0.1342 \times 10^{-5}$ $\chi^2 = 1.48$ % mean deviation = 27.18
(8)	7.6 × 7.6 cm	$\alpha = -0.545241 \times 10^1$ $\beta = -0.553103 \times 10^1$ $E_0 = 0.9237907 \times 10^2$ $n = 0.33 \times 10^1$ $\chi^2 = 1.81 \times 10^{-1}$ % mean deviation = 9.62
	5 × 5 cm	$\alpha = -0.19152 \times 10^1$ $\beta = -2.96345 \times 10^1$ $E_0 = 0.66875 \times 10^2$ $n = 0.4132 \times 10^1$ $\chi^2 = 3.55 \times 10^{-1}$ % mean deviation = 12.83

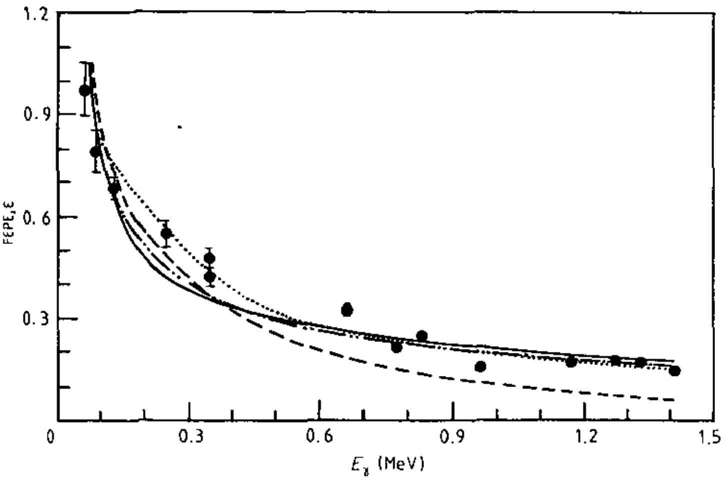

Figure 4. Least squares fits of the FEPE of the 7.6 × 7.6 cm NaI(Tl) detector to equations (10) (full curve), (12) (dashed curve), (13) (dotted curve) and (14) (chain curve).

equations (2) and (3) best fit the data. It might be remarked that it is really not surprising that some of the analytical functions, originally developed for representing the FEPE of the germanium detectors work so well for the NaI(Tl) detectors. After all the energy dependence of the FEPE of both types of detectors is very similar. Therefore, with the appropriate adjustment of parameters in the process of least squares fitting it is found that these functions represent the data well in both cases.

3.2 Semi-empirical formulae

Most of the semi-empirical formulae were initially intended for planar configurations of small volume germanium detectors. Very recently [15] it was shown that most of these formulae hold good even for large volume coaxial germanium detectors. According to Freeman and Jenkin [10] the relative efficiency ε could be related to the gamma energy E_γ and detector thickness x as follows

$$\varepsilon \propto 1 - \exp(-\tau x) + A\sigma \exp(-BE_\gamma) \quad (9)$$

where A and B are the parameters, and τ and σ are the photoelectric and Compton absorption coefficients at energy E_γ respectively. The above equation was written as

$$\varepsilon = K[1 - \exp(-\tau x) + A\sigma \exp(-BE_\gamma)] \quad (10)$$

and used to fit the FEPE data of the present two detectors, treating x, A, B and K as parameters. The values of τ and σ for NaI were taken from Kai Seigbahn [21]. It was observed that the qualities of fits obtained were not good (for example equation (10) underestimated the data up to ~25% from ~122 to ~700 keV for the 7.6 cm × 7.6 cm NaI(Tl) detector (see figure 4)). It is possible that this formula does not have so good an application to detectors having such large thicknesses.

Paradellis and Hontzeas [11] rewrote equation (9) in a much more generalized form as

$$\varepsilon = K[1 - \exp(-0.044\tau V^{1/3}) + 0.0012V\sigma \exp(-0.8E_\gamma)]. \quad (11)$$

The corresponding formula for the NaI(Tl) detectors becomes

$$\varepsilon = K[1 - \exp(-0.0147\tau V^{1/3}) + 0.00032V\sigma \exp(-0.8E_\gamma)] \quad (12)$$

where K is the proportionality constant and V the volume of the detector in cm^3. Though Paradellis and Hontzeas [11] claimed that equation (11) could represent the FEPE of Ge(Li) detectors of all shapes and sizes quite well, some other authors had obtained results contrary to this [1, 2, 15, 22]. In fact, for the present 7.6 cm × 7.6 cm NaI(Tl) detector the FEPE representation was also not at all encouraging over the entire energy range (see figure 4). But interestingly enough, the fit was much better, although still not satisfactory, in the case of the 5 cm × 5 cm NaI(Tl) detector. Since equation (11) does not really describe the FEPE data of even the germanium detectors well [1, 2, 15, 22] it is not expected to do justice to the data of the NaI(Tl) detectors.

Mowatt [12] introduced a factor T in equation (9) to account for the absorption of gamma rays in the materials present between the source and the intrinsic region of the detector, and modified the same as

$$\varepsilon = KT\{[\tau + \sigma Q \exp(-RE_\gamma)]/(\tau + \sigma)\} \times \{1 - \exp[-P(\tau + \sigma)]\} \quad (13)$$

where K is the proportionality constant and Q, R and P are the parameters. We omitted the factor T as we had already made the necessary corresponding corrections in our determination of the FEPE, and carried out a fit of the data of the NaI(Tl) detectors using equation (13). For both cases (7.6 cm × 7.6 cm and 5 cm × 5 cm NaI(Tl) detectors) it was observed that the FEPE representations were quite good at energies above ~122 keV (see figure 4 for the 7.6 cm × 7.6 cm detector). It may be mentioned that the same formula gave quite good fits of the data for the Ge(Li) and HPGe detectors [15, 23].

A three parameter formula, which related the volume of the detector to the efficiency, was suggested and used successfully to describe the efficiency of a Ge(Li) detector by Vano *et al* [13]. The formula was written as

$$\log\varepsilon = A_3 + (A_1 \log V + A_2)\log E_\gamma \qquad (14)$$

where V is the active volume of the detector, and As are the parameters. It was successfully employed by Zhong [24] to describe the FEPE data of seven large volume coaxial detectors with volumes ranging from 67.5 to 172 cm^3 and in the energy range from 242 to 3550 keV. Later investigations [1, 15] led to the same conclusion. We treated V (in fact $\log V$) as an additional parameter (A_4), and obtained quite reasonable fits below ~150 keV and above ~700 keV (see figure 4 for the 7.6 cm × 7.6 cm NaI(Tl) detector). Between 244.69 and 661.64 keV equation (14) underestimated the FEPE values up to ~25% or so. The quality of fit was even poorer for the 5 cm × 5 cm detector. Nevertheless the value of V turned out to be 362.13 cm^3 compared to its actual value of about 347.50 cm^3 (i.e. within ~4% of the actual value). The value of V for the 5 cm × 5 cm detector was found to be 102.88 cm^3 which matched remarkably well with the actual physical estimate of 102.96 cm^3. On the whole it seems that the volume and energy dependence of the FEPE given by equation (14) is not so well applicable to NaI(Tl) detectors. All the parameters and the χ^2 values along with the per cent mean deviations obtained from the fits to the semi-empirical formulae are given in table 2.

Again it might be pointed out that apart from the γ absorption coefficients (τ and σ occur in equations (10), (12) and (13)) the semi-empirical formulae also do not involve any details of the mechanism that leads to pulse formation which finally has the FEPE information and, therefore, it is not surprising that Mowatt's formula (equation (13)) works so well for the NaI(Tl) detectors.

Table 2. Parameters obtained from the least squares fits of the FEPE data to the semi-empirical formulae (designated by appropriate equation numbers, see text).

Equation number	NaI(Tl) detectors	Parameters
(10)	7.6 × 7.6 cm	$x = 0.53913 \times 10^{-4}$ $A = 0.19928 \times 10^{2}$ $B = 0.51 \times 10^{-4}$ $K = 0.7795 \times 10^{-3}$ $\chi^2 = 4.77 \times 10^{-1}$ % mean deviation = 15.68
	5 × 5 cm	$x = 0.9127 \times 10^{-3}$ $A = 0.1151185 \times 10^{4}$ $B = 0.115128 \times 10^{1}$ $K = 0.139 \times 10^{-4}$ $\chi^2 = 6.72 \times 10^{-1}$ % mean deviation = 18.71
(12)	7.6 × 7.6 cm	$K = 0.140815$ $\chi^2 = 2.16$ % mean deviation = 35.50
	5 × 5 cm	$K = 0.1366926$ $\chi^2 = 7.39 \times 10^{-1}$ % mean deviation = 19.44
(13)	7.6 × 7.6 cm	$Q = 0.33008$ $R = 0.25448$ $P = 0.98302 \times 10^{-1}$ $K = 0.85628$ $\chi^2 = 1.93 \times 10^{-1}$ % mean deviation = 9.61
	5 × 5 cm	$Q = 0.54877$ $R = 0.232471 \times 10^{1}$ $P = 0.137036$ $K = 0.718537$ $\chi^2 = 3.51 \times 10^{-1}$ % mean deviation = 13.23
(14)	7.6 × 7.6 cm	$A_1 = 0.80625$ $A_2 = -0.265549 \times 10^{1}$ $A_3 = 0.107303 \times 10^{1}$ $A_4 = 0.2558861 \times 10^{1}$ $\chi^2 = 2.79 \times 10^{-1}$ % mean deviation = 11.72
	5 × 5 cm	$A_1 = 0.756275$ $A_2 = -0.256249 \times 10^{1}$ $A_3 = 0.191276 \times 10^{1}$ $A_4 = 0.2012319 \times 10^{1}$ $\chi^2 = 1.48$ % mean deviation = 27.01

4. Conclusions

According to the present investigation the four and six parameter analytical functions (equation (2), and equation (3) without the last term) gave the best representation of the FEPE data of both the detectors. The trend of the results was more or less the same for the large volume HPGe detectors [15]. The efficiency curves of the present detectors were well represented by equation (8), treating n as a parameter also.

Like the germanium detectors [15, 23], for the present (NaI(Tl)) detectors, the semi-empirical formula proposed by Mowatt [12] gave the best representation of the FEPE data, particularly above ~120 keV. The other semi-empirical formulae, however, did not work well for the present detectors, particularly when viewed in the light of their performance for the FEPE of the germanium detectors.

In general it can be stated that the analytical functions, equations (1), (2), (3) and (8), give a better representation of the FEPE data of the present detectors than the semi-empirical formulae. Incidentally this was also true in the case of the large volume HPGe detectors [15]. Thus the present investigation shows that some of the analytical functions (equations (1), (2), (3) and (8)) and the semi-empirical formula of Mowatt [12] can be quite fruitfully used for the NaI(Tl) detectors.

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