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Contribution of pair production process in full-energy peak efficiency calculation of semiconductor detectors for axial point sources with high-energy γ-rays

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Abstract

Study has been made of the contribution of the pair production process in calculation of detector efficiency. Particular attention has been paid to positron annihilation in flight and subsequent scattering of the annihilation quanta in the detector material. A mathematical formula has been derived to directly calculate the liner attenuation coefficient of the full-energy peak (μ_p) for a Ge (Li) detector using an axial point source. The calculated values of the photopeak efficiency are found to be in a good agreement with published experimental data.

Keywords: High-energy γ-rays; Photopeak efficiency; Semiconductor detectors; Pair production; Positron annihilation

1. Introduction

When investigating γ-rays emitted by radioactive isotopes or dose produced in nuclear particle reactions, it is mostly necessary to know the efficiency of the detector. The mathematical derivation of the efficiency has been given in some previous works (see for instance, Selim et al., 1998; Selim and Abbas, 2000) using an arbitrarily positioned radiating point source are derived in polar coordinates as

$$\varepsilon = \frac{1}{4\pi}\int_{\theta}\int_{\phi} f_{\mathrm{att}}(1 - \mathrm{e}^{-\mu \mathrm{d}_i})\sin\theta \,\mathrm{d}\,\phi\,\mathrm{d}\theta, \tag{1}$$

where θ and Φ are the polar and azimuthal angles, respectively, define by the direction of incident of a γ-ray photon, d_i is the photon path length through the detector active volume and the factor f_{att}, determines the photon attenuation by the source container and the detector end cap material is expressed as

$$f_{\mathrm{att}} = \mathrm{e}^{-\sum_j \mu_j \delta_j}, \tag{2}$$

where μ_j is the linear attenuation coefficient of the jth absorber for a γ-ray photon with energy E_γ (Hubbell and Seltzer, 1995) and δ_j is the path length of the γ-photon through the jth absorber. The calculation of total efficiency is obtained by replacing μ with the total attenuation coefficient μ_{t} (of the detector material for γ-ray energy E_γ excluding the coherent scattering part). For different incident energy γ-rays, measurements are

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confined to the maximum peak. Thus, we have to consider the so called photopeak efficiency (full-energy peak efficiency (FEPE)). Instead of considering the total attenuation coefficient of the detector material, we consider the peak attenuation coefficient which contributes to the photopeak only (μ_p). Considering the partial coefficients, and remembering that the photoelectric part always leads to electrons of maximum energy, we must have:

$$\mu_p = \tau + f_m\sigma + g\kappa_n, \tag{3}$$

where, f_m and g are average fractions of Compton scattering and pair production respectively, which are primarily dependent on the detector dimensions, types (in particular, elemental make up), and incident photon energy.

For an incident photon with energy less than 2 MeV, where the influence of pair production is typically neglected, only photoelectric effect and Compton scattering are significant. Therefore, the photopeak attenuation coefficient is given by

$$\mu_p = \tau + f_m\sigma \tag{4}$$

and has been studied by Selim et al. (2001). The present work is concerned with high energy γ-rays. To take into account the contribution of pair production, review will first be made of the basic facts of the interaction.

2. Mathematical viewpoint

If the energy of the incident photon ($h\nu_o$) exceeds ($2m_oc^2$), then pair production process becomes increasingly important, the creation of an electron–positron pair becomes possible at 1.022 MeV. The photon is completely absorbed and in its place appears an electron–positron pair whose total energy is just equal to ($h\nu_o$), where

$$h\nu_o = E_- + E_+ = (T_- + m_o\mathrm{c}^2) + (T_+ + m_oc^2), \tag{5}$$

where T_- and T_+ are the kinetic energies of the electron and positron, respectively, and $m_oc^2 = 0.511$ MeV is the electron rest energy.

The annihilation of positrons may occur either (i) when the positron is in flight, or (ii) when it has already been stopped. Until now in efficiency calculations it has been assumed that positron annihilation takes place if the positron comes to rest in the detector material only. Two quanta of energy 0.511 MeV are emitted in this case, whose directions are assumed to be isotropically angularly distributed and opposite to one another (Grosswendt and Waibel, 1975).

Bethe and Wills (1935) found that, in the case of higher positron energies, positron annihilation in flight should be taken into account in efficiency calculations. The total probability that a positron of initial energy (ε_0) in flight is annihilated before being completely stopped can be calculated as follows. The probability that the positron is annihilated in the time during which it has total energy between ε and $\varepsilon + \mathrm{d}\varepsilon$, is given by

$$\mathrm{d}P/\mathrm{d}\varepsilon = f(\varepsilon)/\left\{4\ln\left[m_oc^2/(IZ)\right]\right\}, \tag{6}$$

where I is the ionization potential of hydrogen, Z is the atomic number of the stopping material and $f(\varepsilon)$ is the differential annihilation probability, given by Bethe and Waibel (1975)

$$f(\varepsilon) = \frac{1}{\varepsilon^2(\varepsilon+1)}\Big[\left(\varepsilon^2 + 4\varepsilon + 1\right)\ln\left(\varepsilon + \sqrt{\varepsilon^2 - 1}\right) - (\varepsilon + 3)\sqrt{\varepsilon^2 - 1}\Big]. \tag{7}$$

For historical reasons, in this part of work, ε (includes the rest energy) is not to confused with the efficiency symbol in Eq. (1). The total probability $P(\varepsilon_o)$ of annihilation in flight for a positron with a total initial energy (ε_o) is given by

$$P(\varepsilon_0) = F(\varepsilon_0)/4\ln\left\lfloor m_oc^2/IZ\right\rfloor \tag{8}$$

with

$$F(\varepsilon_o) = \int_o^{\varepsilon_o} f(\varepsilon)\mathrm{d}\varepsilon \tag{9}$$

2.1. Average positron energy at which annihilation takes place ($\bar{\varepsilon}$)

A positron, which after creation has an energy (ε_o), will be annihilated at an average value of energy $\bar{\varepsilon}$ before coming to rest. the latter being given by

$$\bar{\varepsilon} = \int_1^{\varepsilon_o} \varepsilon * f(\varepsilon)\mathrm{d}\varepsilon \Big/ \int_1^{\varepsilon_o} f(\varepsilon)\mathrm{d}\varepsilon, \tag{10}$$

where f (ε) is the positron differential annihilation probability given by Eq. (7).

2.2. Energy and angular distribution of the positron annihilation radiation

The annihilation of a positron with the resulting emission of two quanta is one of the fundamental processes of quantum electrodynamics. Very few direct quantitative measurements of the rate or cross section for this process have been reported in the literature (Kendall and Deutsch, 1956). The differential electron cross section for the annihilation of a positron is given in Heitler (1954), in the center-of-mass coordinate system.

A Lorentz transformation yields the differential cross section per unit solid angle $\mathrm{d}\sigma/\mathrm{d}\Omega$ for annihilation of a positron of total energy (ε) and momentum (P) with an electron at rest in the laboratory coordinate system, with emission of two γ-ray quanta of energy K_1 and K_2.

The differential cross section is given by

$$\frac{d\sigma}{d\Omega} = -\frac{e^4(\varepsilon+m_o)}{P}\left[\frac{1}{(\varepsilon+m_o-P\cos\theta_1)^2} - \frac{3m_o+\varepsilon}{2m_o(\varepsilon+m_o)(\varepsilon-P\cos\theta_1)} + \frac{(\varepsilon+m_o-P\cos\theta_1)^2}{2(\varepsilon+m_o)^2(\varepsilon-P\cos\theta_1)^2}\right], \quad (11)$$

where θ_1 is the angle of the γ-ray emission K_1 with respect to the incident positron direction, and m_o is the electron rest mass.

The energy of the first γ-ray photon K_1 is given by

$$K_1 = m_o\left[1-\frac{\varepsilon-m_o}{\varepsilon+m_o}\cos\theta_1\right]^{-1}. \quad (12)$$

The second photon emitted in the positron annihilation process has an energy given by

$$K_2 = \varepsilon + m_o - K_1. \quad (13)$$

From Bethe and Wills (1935), the relation between the two photons emitted are given by

$$\frac{1}{K_1}+\frac{1}{K_2} = \frac{1}{m_o}(1-\cos\theta_1), \quad (14)$$

where θ is the angle between the directions of propagation of the two emitted photons. From the previously mentioned discussion of annihilation process, it can be concluded that if a positron in flight has an initial energy (ε_o) it will be annihilated at certain value of energy between ε and ε−dε, resulting in two photons with energies K_1 and K_2 as shown in Fig. 1. For every positron annihilation the expectation values of the average energies of the resulting photons will be as follows.

The average value of photon energy (K_1) can be calculated as a result of varying (θ_1).

$$\overline{K}_1 = \frac{\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} K_1(d\sigma/d\Omega)d\Omega}{\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi}(d\sigma/d\Omega)d\Omega}, \quad (15)$$

where, $\frac{d\sigma}{d\Omega}$ is the differential cross section per unit solid angle for the annihilation process and θ and ϕ are polar and azimuthal angles. The direct result of the integration is

$$\overline{K}_1 = I_1/I_2, \quad (16)$$

where

$$I_1 = \frac{-m_o(\bar\varepsilon-m_o)}{(\bar\varepsilon+m_o)(\bar\varepsilon-m_o-P)^2}\left[\ln\frac{(1-\alpha)(\bar\varepsilon+m_o+P)}{(1+\alpha)(\bar\varepsilon+m_o-P)}\right] - \frac{P}{(\bar\varepsilon+m_o)(\bar\varepsilon-m_o-P)} + \ln\frac{(1-\alpha)(\bar\varepsilon+P)}{(1+\alpha)(\bar\varepsilon-P)}$$

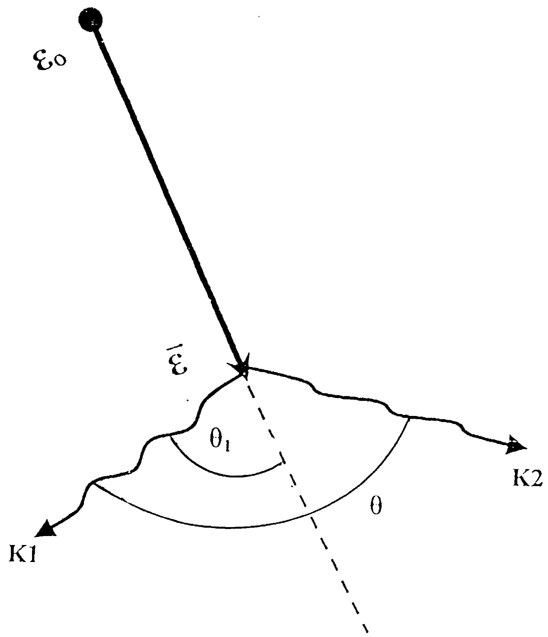


Fig. 1. Positron Annihilation Process. $\varepsilon_o \rightarrow$ Initial total energy. $\varepsilon_o \rightarrow$ Most probable energy of annihilation. K_1 and $K_2 \rightarrow$ Emitted annihilation γ-rays.

$$\times\left[\frac{3m_o+\bar\varepsilon}{2(\bar\varepsilon+m_o)(\alpha\bar\varepsilon-P)} + \frac{m_o^2}{(P-\alpha\bar\varepsilon)(\varepsilon+m_o)^2} - \frac{\alpha m_o^3}{2(\bar\varepsilon+m_o)^2(P-\alpha\bar\varepsilon)^2}\right] + \frac{m_oP}{(P-\alpha\bar\varepsilon)(\bar\varepsilon+m_o)^2} + \frac{m_o}{2P^2}\left[\ln\frac{1+\alpha}{1-\alpha}\right],$$

$$I_2 = \frac{3m_o+\bar\varepsilon}{m_o(\bar\varepsilon+m_o)^2} - \ln\left(\frac{\bar\varepsilon+P}{\bar\varepsilon-P}\right)\frac{(\varepsilon+m_o)^2+2m_o\bar\varepsilon}{2Pm_o(\varepsilon+m_o)^2},$$

where

$$\alpha = \frac{\bar\varepsilon-m_o}{\bar\varepsilon+m_o}, \quad P=\sqrt{\varepsilon^2}-m_o^2.$$

K_2 is obtained by using a form of equation similar to Eq. (15). The angular distribution after annihilation for the two photons (see Fig. 1) θ_1 (the angle of the γ-ray emission K_1 with respect to the incident positron direction) and θ (the angle between the directions of propagation of the two emitted photons), are thus deduced from the following equations:

$$\theta_1 = \cos^{-1} - \left(\frac{1-\overline{K}_1}{\alpha\overline{K}_1}\right), \quad (17)$$

$$\theta = \cos^{-1} - \left[\frac{m_o(\bar\varepsilon+m_o)}{K_1K_2} - 1\right]. \quad (18)$$

The calculated results are given in Table 1.

Table 1
Averaged values of annihilation of positron

ε_o	$\bar{\varepsilon}$	$\overline{K}_1$	0^o_1	$\overline{K}_2$	θ^o
5	2.89	1.4348	51.4	2.4551	95.98
10	4.67	1.9304	41.87	3.7395	77.6
15	6.41	2.4202	36.5	4.9897	67.26
20	8.09	2.8932	32.96	6.1967	60.46
25	9.72	3.3412	30.39	7.3687	55.53
30	11.31	3.7969	28.41	8.5130	51.74
35	12.86	4.2305	26.82	9.6294	48.71
40	14.67	4.7357	25.27	10.9342	45.78
45	16.17	5.1536	24.18	12.0168	43.71
50	17.66	5.568	23.23	13.091	41.92
60	20.79	6.4367	21.56	15.3532	38.78
70	23.57	7.206	20.35	17.3632	36.52
80	26.38	7.9826	19.32	19.3973	34.59
90	29.10	8.7329	18.46	21.367	32.99

All unit of energy in m_oc^2 (μ)

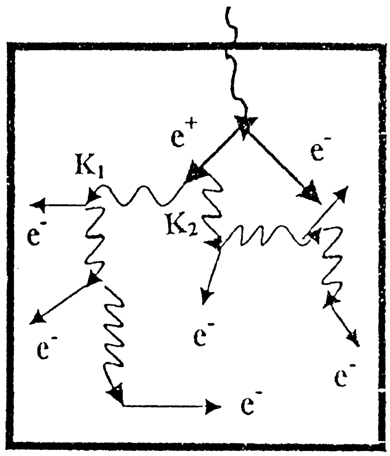


Fig. 2. Schematic behavior of annihilation photons in the detector.

Table 2
Photopeak attenuation coefficient for different sizes of Ge detector

Photon energy (MeV)	Photopeak attenuation coefficient (μ_p) cm^{-1}		
	Detector size, [dia* height (in)]		
	(3″*1″)	(3″*3″)	(5″*4″)
0.3	2.378E-01	2.378E-01	3.684E-01
0.4	1.983E-01	1.983E-01	1.983E-01
0.5	1.589E-01	1.589E-01	1.594E-01
0.6	1.123E-01	1.141E-01	1.171E-01
0.8	6.510E-02	7.381E-02	7.480E-02
1	5.350E-02	5.350E-02	5.490E-02
1.25	3.700E-02	3.760E-02	3.780E-02
1.5	2.970E-02	2.990E-02	3.450E-02
2	1.930E-02	1.990E-02	2.470E-02
3	1.160E-02	1.600E-02	1.620E-02
4	8.200E-03	1.170E-02	1.190E-02
5	6.700E-03	9.200E-03	9.300E-03
6	6.000E-03	7.200E-03	7.800E-03
8	3.900E-03	5.600E-03	6.900E-03
10	3.200E-03	3.800E-03	5.300E-03
15	2.200E-03	2.800E-03	3.300E-03
20	1.766E-03	2.510E-03	2.630E-03
30	1.150E-03	1.700E-03	1.850E-03
40	8.410E-04	1.300E-03	1.360E-03
50	6.100E-04	1.210E-03	1.290E-03
60	4.830E-04	1.110E-03	1.220E-03
80	3.210E-04	6.100E-04	8.870E-04
100	2.270E-04	3.600E-04	7.000E-04

2.3. Contribution of pair production in calculation of photopeak attenuation coefficient (μ_p)

As mentioned before, if the incident photon energy is sufficiently large (several MeV), pair production becomes evident in the electron energy spectrum. Fig. 2 illustrates the behavior of the two annihilation photons inside the detector. The detector dimension are assumed to be sufficiently large so that all secondary radiations, including Compton scattered photon annihilation photons, are interacting within the detector active volume (through Compton scattering or photoelectric absorption) and none escapes from the detector surface.

In order to obtain the peak attenuation coefficient (μ_p), we have to calculate the average fraction of the pair production component (g). After a positron annihilation takes place, the two resulting photons have averaged values ($\overline{K}_1, \overline{K}_2$). These two photons undergo further interaction through Compton scattering and end in photoelectric absorption, all within the detector, with registration probability (f_{m_1}) and (f_{m_2}), respectively.

From the above, the overall probability (g) given by

$$g = [f_m(K_1) \times f_m(K_2)]. \tag{19}$$

Therefore, the fraction g is defined as the most probable fraction of pair production, leading to the full-energy peak after successive scatterings of the annihilation photons. Thus, the photopeak attenuation coefficient becomes

$$\mu_p = \tau_o + f_m\sigma_o + [f_m(K_1) \times f_m(K_2)] \times \kappa_n. \tag{20}$$

In accordance with Eq. (20), Table 2 reproduces the full energy peak attenuations coefficients for photon energy up to 100 MeV, for different sizes of a Ge (Li) semiconductor detector. For others sizes of detectors interpolation can be used.

3. Validation of the present calculations

The following comparison has been made with results from previously published experimental work for different sizes of germanium Ge (Li) detector, and for axial point sources with photon energies from a few keV to several MeV placed at different source to detector distance heights. Figs. 3–8 illustrate the comparisons between the results of the FEPR (ε_p) calculated using the present mathematical expression for the full-energy peak attenuation coefficient (μ_P), and values previously determined.

Fig. 3 presents a comparison of present work with the absolute FEPE measured experimentally by Cecil et al. (1985) for a 65 cm^3 Ge (Li) detector. The measurements were made primarily at photon energies of 2.61, 4.44, 11.67 and 16.11 MeV emitted from a point source placed along the detector axis with a source-to-detector distance of 3 cm. The error in the measured efficiency values was about 10%, due to uncertainties in the photo absorption and pair production absorption coefficients and, 2% due to counting statistics. Fig. 4 shows a comparison of calculated absolute peak efficiencies with experimental values measured by Young et al. (1971) using a 50 cm^3 coaxial Ge (Li) detector, for an axial point source placed at distance of 10 cm from the detector, photon energies extending from 122 keV to 9.17 MeV were investigated. The uncertainties in these experimental measurements were 10%. Fig. 5 represents results for absolute efficiency of the photopeak for photon energies up to 3 MeV, measured experimentally for a true coaxial Ge (Li) detector of 44 cm^3 active volume, by Schotzig et al. (1973). Use was made of a point source at 16 cm from the detector surface. As seen from Fig. 5, there is a good agreement between the calculated and the experimental results within the limits of 10% measurement error. Figs. 6A–C represent a comparison of the absolute FEPE determined experimentally by Seyfarth et al. (1972) using two true coaxial

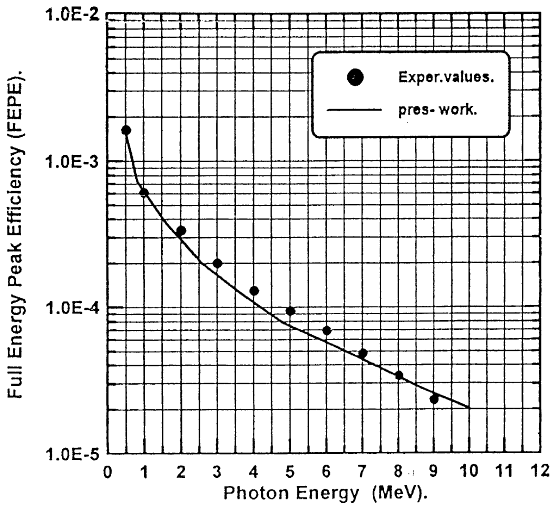


Fig. 4. Comparison of present calculations for full-energy peak efficiency with experimental values measured by Young et al. (1971) for a 50 cm^3 coaxial Ge (Li) detector and an axial point source at a height of 10 cm above the front surface of the detector.

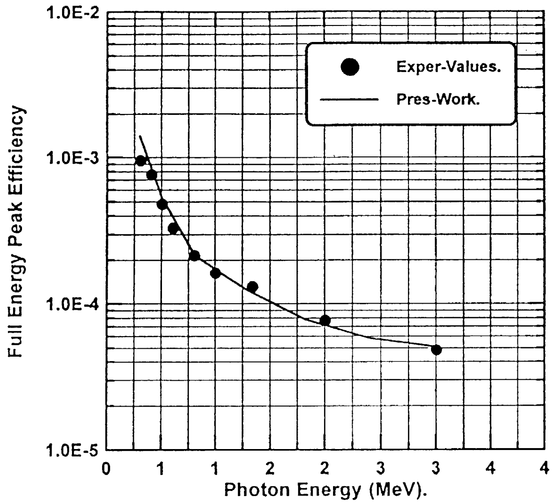


Fig. 5. Comparison of present calculations of full-energy peak efficiency with experimental values measured by Schotzig et al. (1973) for a 44 cm^3 Ge (Li) detector and an axial point source at a height of 16 cm above the front surface of the detector.

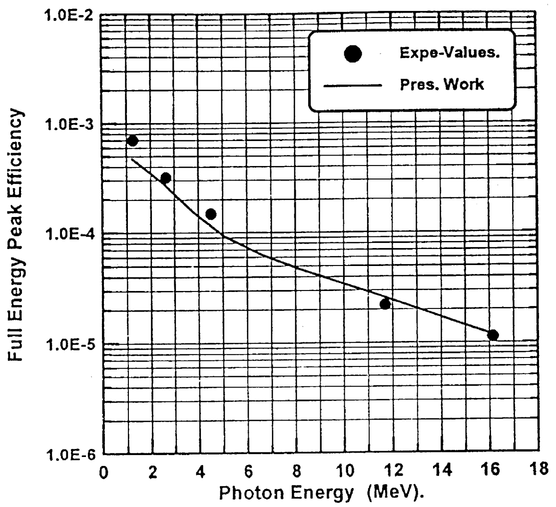
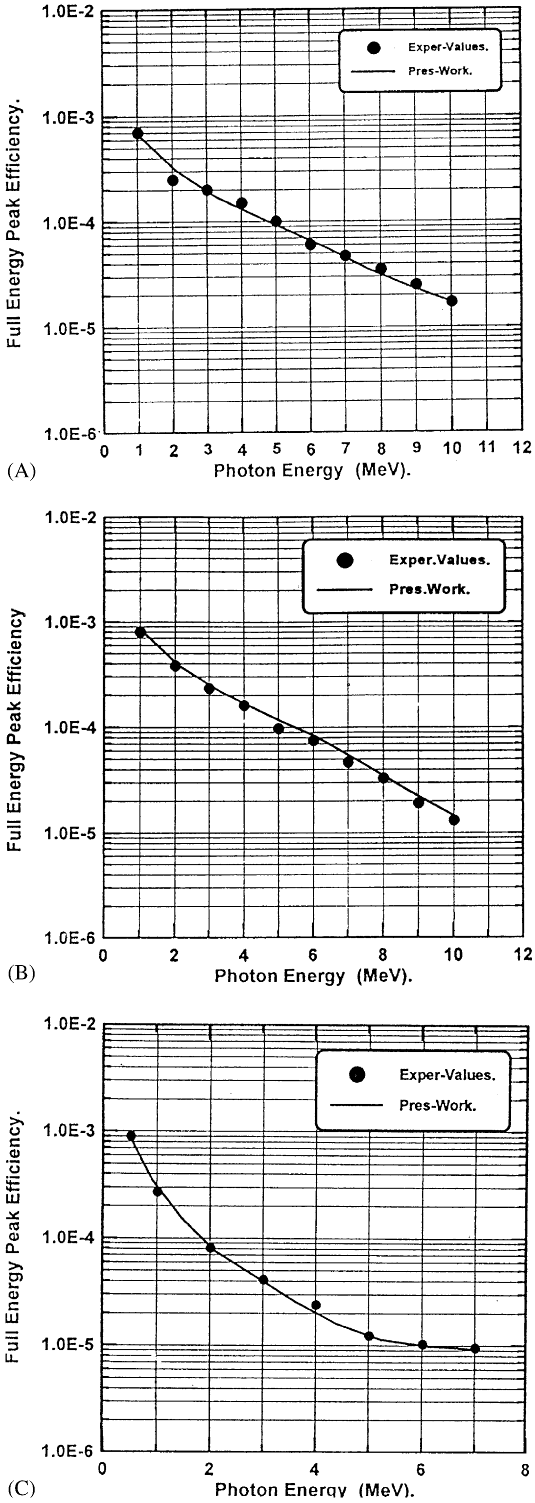


Fig. 3. Comparison of present calculations for full-energy peak efficiency with experimental values measured by Cecil et al. (1985) for a 65 cm^3 Ge (Li) detector and an axial point source at a height of 13 cm above the front surface of the detector.

Ge (Li) detectors with sensitive volumes of 38 and 31 cm^3 and one planar Ge (Li) detector with sensitive volume of 5.8 cm^3, with source-to-detector distance 8.3, 6.2 and 5.4 cm, respectively, for incident photon energies ranging from 0.5 to 11 MeV. The relative error in this experimental measurement is estimated to be within 5% over the whole range of the curves. Fig. 6C depicts the absolute FEPE curve for the planar detector; this curve shows the same trend as results for the true coaxial detector shown in Figs. 6A and B, but with a steeper decrease due to the smaller sensitive volume. Fig. 7 shows a comparison of present results with absolute photopeak efficiency in the energy range 0.66–12 MeV for a true coaxial Ge (Li) detector of volume 26 cm^3 with a source-to-detector distance of 4.83 cm (Waibel and Grosswendt, 1975). The experimental errors were about 5%. It clear that the experimental and calculated values are again in very close agreement taking into account the experimental errors. Finally, Fig. 8 shows a comparison between calculated values for peak efficiency and measurements using a 2 cm^3 right circular cylindrical Ge (Li) detector (Cline, 1968). The photon source was placed axially at a distance of 5 cm from the detector face. These results are also compared with the theoretical results of Lal and Iyengar (1970), Wainio and Knoll (1966) and De Castro Faria and Levesque (1966, 1967), where each of these used the Monte Carlo method. It is evident that our calculations compare favorably with the experimental results of Cline (1968) and the theoretical results of Faria and Levesque (1967), but do not agree with those Lal and Iyengar (1970) and Wainio and Knoll (1966). The discrepancies arise from consideration of the pair production term ($g\kappa_n$) in present calculations.

From the above comparisons it is evident that there is a good agreement between the present calculations and published experimental results.



Figs. 6. A–C: Comparison of present calculations for full-energy peak efficiency with experimental values measured by Seyfarth et al. (1972) for different volumes of Ge (Li) detector and an axial point source at different heights. (A) detector volume of 38 cm^3 and source at height of 8.3 cm from front face of detector. (B) detector volume of 31 cm^3 and source at height of 6.2 cm from front face of detector and (C) detector volume of 5.8 cm^3 and source at height of 5.4 cm from front face of detector.

4. Conclusion

In this paper, a direct mathematical expression has been derived to calculate the photopeak attenuation coefficient (μ_P), taking into account contributions from the pair production process, in particular positron annihilation in flight and subsequent scattering of the annihilation qunta in the detector material of the Ge (Li) semiconductor detector. Investigation concerned an

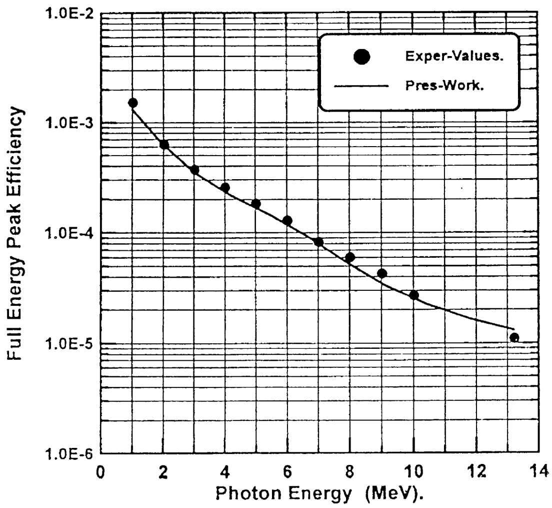


Fig. 7. Comparison of present calculations for full-energy peak efficiency with experimental values measured by Waibel and Grosswendt (1976) for a 26 cm^3 true coaxial Ge (Li) detector, with an axial point source at a height of 4.83 cm above front face of detector.

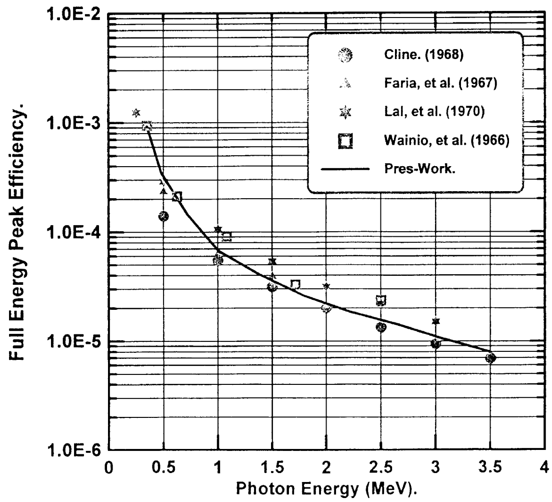


Fig. 8. Comparison of present calculations for full-energy peak efficiency with experimental values measured by Cline (1968) and theoretical results of Lal and Iyengar (1970), Wainio and Knoll (1966) and Faria and Levesque (1967) using the Monte Carlo method. The experiment and simulations concerned a 2 cm^3 Ge (Li) detector with axial point source at a height of 5 cm above the front face of the detector.

axial isotropically radiating point source, with photon energies up to several MeV . The FEPE has been calculated and compared with the results of earlier workers. The results of the photopeak efficiency are in excellent agreement with the published experimental data. These calculations could be extended to any type and size of scintillator or semiconductor detector.

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