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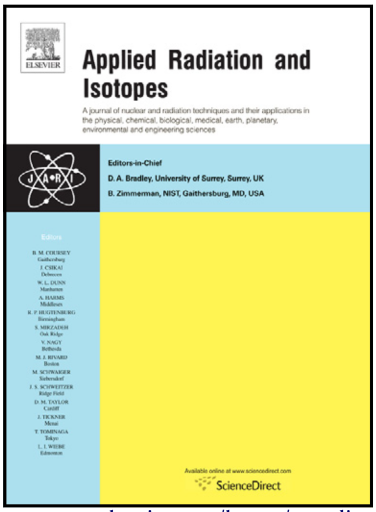

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Mohsen B. Challan

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Gamma-ray efficiency of a HPGe detector as a function of energy and geometry

Mohsen B. Challan

Nuclear Physics Department, Nuclear Research Center, AEA, Cairo 13759, Egypt

Physics Department, College of Education in Zulfi, Majmaah University, Riyadh 11932, Saudi Arabia

Abstract

The concept of double points detector model approach (DPDM) is developed as a procedure to find the full energy peak efficiency of the coaxial 120 cm^3 closed hyperpure germanium (HPGe) detectors. Usually in the experimental nuclear physics work, which involves using HPGe detector for gamma-ray spectrometry, the full energy peak efficiency function must represent adequately the HPGe detector response. In the current work the gamma-ray energy in the range from 60 to 1332 keV and gamma-ray intensity changes by changing source to detector distance from 10 to 800 mm. The detector was characterized using a number of point–like standard sources. The calculated efficiencies obtained by (DPDM) are in good agreement with experimental data.

Key Words: HPGe Detector, Efficiency, Gamma-ray Sources, and Spectrometry

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Corresponding Author: *Dr. Mohsen Challan*

E-mail: ChallanMB@hotmail.com

Present Address: Physics Department, Faculty of Education in Zulfi, Majmaah University, P. O. Box. 552, Al-Zulfi 11932, Kingdom of Saudi Arabia.

Phone numbers: +966543680294

1. 1. Introduction

The quantitative γ-ray spectrometry at different geometries is a commonly encountered problem. Accurate relative intensity calibration of photon emitted is usually performed by counting a sample and standard sources in the same geometry. It is therefore important to have available method to correct measurement taken with HPGe detectors from the effects of geometry change, hearing in mind that HPGe detector efficiency curves are most often and conveniently determined using point-like standards. In general, one or two efficiency curves are obtained at different distances. This is usually done in order to minimize the detector's use time and to maximize the area under full energy peak, a higher surge in the photo-peak area is found due to the changing in counting geometry. Hence, changing counting geometry is a mandatory for comparison between measurements, introduces a need for solid angle geometry corrections as well as for coincidence summing if applicable. Many authors commented of the importance of measurement geometries (Grant, 1975; Maia et al., 1997).

2. Experimental Procedure

2.1. Experimental set up

The detector used in these measurements was ORTEC hyperpure germanium detector. The germanium crystal was nominally 55 mm in diameter and 60 mm long. It was mounted inside a protective aluminum end, with its axis vertical, on a liquid nitrogen Dewar, with an energy resolution of 2.0 keV for a γ-ray energy of 1332 keV. The source holder was made of cylindrical hard paper with seven slots to accommodate the point sources which are at the center of a polyethylene dish. The detector active volume was estimated to be (120 ± 6) cm^3. The detector was biased to + 4500V using an ORTEC-459 power supply. Pulses from the detector were amplified and shaped by Canberra-2021 spectroscopy amplifier before being transmitted to multi-channel analyzer (MCA) of type, Trumf-8192 and the data were buffered from the analog-to-digital converter and were saved to computer memory.

2.2. The γ-ray sources

For the point-like sources we used γ-ray reference standard sources from the Oak-Ridge, The Tennessee, U.S.A. These take the form of ion-exchange beads 2 mm in diameter held in clear plastics cases fitted with polyethylene windows 0.5 mm thick. The radionuclides used were ^{241}Am, ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{65}Zn, ^{109}Cd and ^{60}Co these span the energy range from 60-1332 keV. All point sources are located at a distance range from 100 to 400 mm in front of the detector cap. The uncertainties of the activities of these sources were all 2% and the uncertainties of their corresponding peak areas did not significantly exceed 1 %. The resulting FEPE curve is shown in Fig. 1. The error bars are mostly hidden by the size of the point-symbol used.

2.3. Efficiency calculation

Once the full energy peak area is obtained, the intrinsic efficiency can be calculated by the following equation:

$$\epsilon_i\left(E_\gamma\right)=\frac{N_C\left(E_\gamma\right)}{A_o\cdot f_t\left(E_\gamma,t\right)} \qquad (1)$$

Where:

$\epsilon_i\left(E_\gamma\right)$ is the intrinsic peak efficiency, is defined as the probability that a photo striking the detector will produce a pulse residing in the full energy peak of the spectrum.

$N_C\left(E_\gamma\right)$ is the corrected net peak area in counts/s

A_o is the activity of the source at the time of standardization in (Bq),

$f_t=I_\gamma\cdot\lambda^{-1}\cdot\exp\left(-\lambda t_D\right)\cdot\left(1-\exp\left(-\lambda t_C\right)\right)$

I_γ is the absolute γ-ray emission probability

λ is the decay constant. ($\tau=1/\lambda$)

t_D t is the elapsed time since standardization

t_C is the duration of the count (sec).

The experimental uncertainties dependence on time (t) and distance (d) were negligible thus the standard deviation on ε, σ_E was determined by the uncertainties on N_C, I_γ, A_o, and λ and was calculated by the propagation of error equation according to (Bevington and Robinson, 2010):

$$\left(\sigma_E\right)^2=\left[\left(\frac{\partial\epsilon}{\partial N_C}\right)^2\cdot\left(\sigma_{N_C}\right)^2+\left(\frac{\partial\epsilon}{\partial A_o}\right)^2\cdot\left(\sigma_{A_o}\right)^2+\left(\frac{\partial\epsilon}{\partial I_\gamma}\right)^2\cdot\left(\sigma_{P_\gamma}\right)^2+\left(\frac{\partial\epsilon}{\partial\lambda}\right)^2\cdot\left(\sigma_\lambda\right)^2\right] \qquad (2)$$

The fractional uncertainty in the number of counts was always arranged to be < 0.5% and so the absolute uncertainty measurements were dominated by the uncertainty in the initial activity (~1%). Uncertainties in the relative efficiency measurements with a given source as a function of distance were generally determined by a combination of counting statistics and positioning uncertainties (< 0.3 mm).

3. Efficiency measurements

The samples were positioned on axis above the detector by placing them on light weight cord a top light weight cord cylinders (Challan, 2007). Distances were measured from the center of the source to the external front face of the detector end cap. In the case of short half-life, it will be necessary to apply correction factors for the radioactivity decay before and during the measurements period. Following small corrections for dead time losses (5% in the most severe case) and room background, the number of counts, C, in the full energy peak (FEP) was obtained by fitting a Gaussian profile superimposed on a linear background to the spectrum. This was related to the absolute (FEP) efficiency, $\epsilon_a\left(E_\gamma\right)$, in counts per γ –emitted according to full energy peak efficiency as a function of energy. This function has the great advantage over the other considered functions.

$$\epsilon_i\left(E_\gamma\right) = \left(p_1 + p_2\cdot\left(\ln E_\gamma\right)^1 + p_3\cdot\left(\ln E_\gamma\right)^2 + p_4\cdot\left(\ln E_\gamma\right)^3 + p_5\cdot\left(\ln E_\gamma\right)^4 + p_6\cdot\left(\ln E_\gamma\right)^5\right)\Big/E_\gamma \quad (3)$$

Where ε represents the full energy peak efficiency,

E is the γ -ray energy in MeV,

$p_1 \rightarrow p_6$ are the function fitting parameters.

A number of analytical functions describing the dependence of the full energy peak efficiency as a function the energy have been proposed by several authors (Debertin and Helmer, 2001; Sanchezreyes et al., 1987). The efficiency function used in this work has the form logarithmic positive power transferred series; it has been proposed by Hammed (Hammed et al., 1993). Fig.(1) shows the efficiency function as a function of energy was fitted to the experimental points.

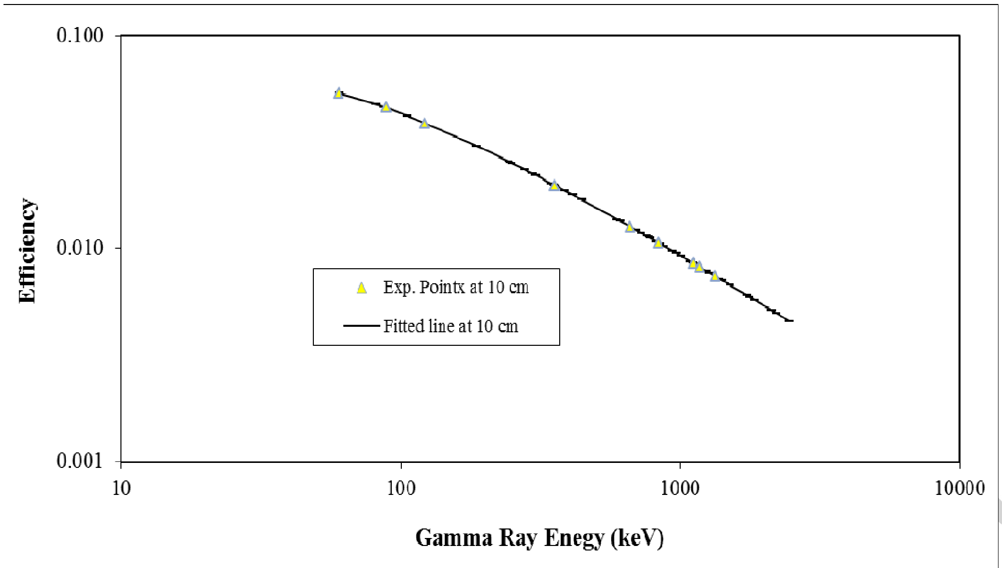

Fig. 1. Full Energy Peak Efficiency of the HPGe Detector vs Energy

The uncertainty in the calculated efficiency is given by (Bevington and Robinson, 2010) :

$$\sigma_{\epsilon}^{2} = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial \epsilon_{(E,p)}}{\partial p_i} \times \frac{\partial \epsilon_{(E,p)}}{\partial p_j} \times \rho_{i\,j} \times \sigma_i \;\; \sigma_j \qquad (4)$$

Where σ is error in the parameter

$\rho_{i\,j}$ is correlation coefficient related to σ_i and σ_j

$\mathrm{n} = 6$ is the number of parameters

4. Double Points Detector Model Approach

In the present work, a procedure is suggested to solve the above-mentioned difficulties. In (Notea, 1971) a point-detector approximation was first proposed, in this point-detector approximation, the detector is considered to act as a point located along the detector axis at an effective distance r_o behind the external window several authors latter (Alfassi et al., 2007; Çelik, 2012; Hoover, 2007; Mahling et al., 2006; Marzocchi et al., 2010; Mohammadi et al., 2011; Rizzo and Tomarchio, 2010; Xiong et al., 2011) used techniques to calculate efficiencies at different distances. In the double points detector model approach, the detector is considered to act as a point of a definite active volume, the standard source also act as a point of infinitesimal size as well, both are located along the mutual axis at an effective distance $(r_o + r)$ separate them, where in this case $r = 0$. Then, the solid angle of source subtended by detector will equal to unit Steradian (Sr), if the distance between them increases than r_o, i.e. $r \succ 0$ the solid angle of one point represents the source subtended by at the other point represents the detector will be less than unity, if the distance decreased than r_o the solid angle will be more than unity. We then multiply the intrinsic detector efficiency by a factor to complete the whole solid angle surrounding the point source.

We could write down the absolute efficiency as:

$$\epsilon_a\left(E_\gamma, r\right) = \epsilon_i\left(E_\gamma\right) \cdot \epsilon_\Omega\left(r\right) \cdot \epsilon_{CS}\left(I_\gamma, r\right) \qquad (5)$$

Substituting from eq. (1)

$$\epsilon_a\left(E_\gamma, r\right) = \frac{N_C\left(E_\gamma\right) \cdot \epsilon_\Omega\left(r\right) \cdot \epsilon_{CS}\left(I_\gamma, r\right)}{A_o \cdot f_t} \qquad (6)$$

Where

$\epsilon_a\left(E_\gamma, r\right)$ is the absolute full energy peak efficiency,

$\epsilon_\Omega\left(r\right)$ is geometrical efficiency due to solid angle subtended by detector

$\epsilon_{CS}\left(I_\gamma, r\right)$ is a correction for coincidence summing due to radionuclides having decays in cascades

5. Full energy peak efficiency as a function of distance

There are several authors dealt with analytical formulae considering for examples the detector active volume and the geometrical solid angle due to bulk samples to obtain a simple formula for the efficiency. In addition, the self-attenuation coefficient of the source matrix, the attenuation factors of the source container and the detector housing materials are also treated by calculating the average path length within these materials (Agarwal et al., 2011; Badawi et al., 2012) concentrated mostly on the extended sources that imply efficiency transfer (Bell et al., 2012; Liye et al., 2006; Vargas et al., 2003). In this work, the full energy peak efficiency as a function of distance could be represented as follow:

$$\epsilon_a\left(E_\gamma, r\right) = \frac{N\left(E_\gamma\right) \cdot \epsilon_{CS}}{A_o \cdot f_t} \cdot 4\pi \cdot \frac{\left[r + r_o\right]^2}{\left[r_o\right]^2}$$

Where

$$\epsilon_\Omega = 4\pi \cdot \frac{\left[r + r_o\right]^2}{\left[r_o\right]^2}$$

r_o can be determined by plotting the efficiency formula, representing the counting rate N in a certain photo-peak, E_γ varies with the source-detector distance according with Notea (Notea, 1971) and Grant (Grant, 1975).

$$\frac{1}{\sqrt{N\left(E_\gamma\right)}}=\left(\frac{r}{r_o}+1\right)\cdot\left[\frac{4\pi}{A_o\cdot f_t\cdot\varepsilon\left(E_\gamma\right)}\right]^{1/2}\Rightarrow\sqrt{\epsilon\left(E_\gamma\right)}=\left[\frac{4\pi\cdot N\left(E_\gamma\right)}{A_o\cdot f_t}\right]^{1/2}\cdot\left(\frac{r}{r_o}+1\right)$$

(5)

The determination of r_o can be done by plotting $N^{-1/2}$ against r, and extrapolating the straight line obtained to the zero value of $N^{-1/2}$. Typical plots of this type using a coaxial close-ended HPGe detector as shown in Fig. (2).

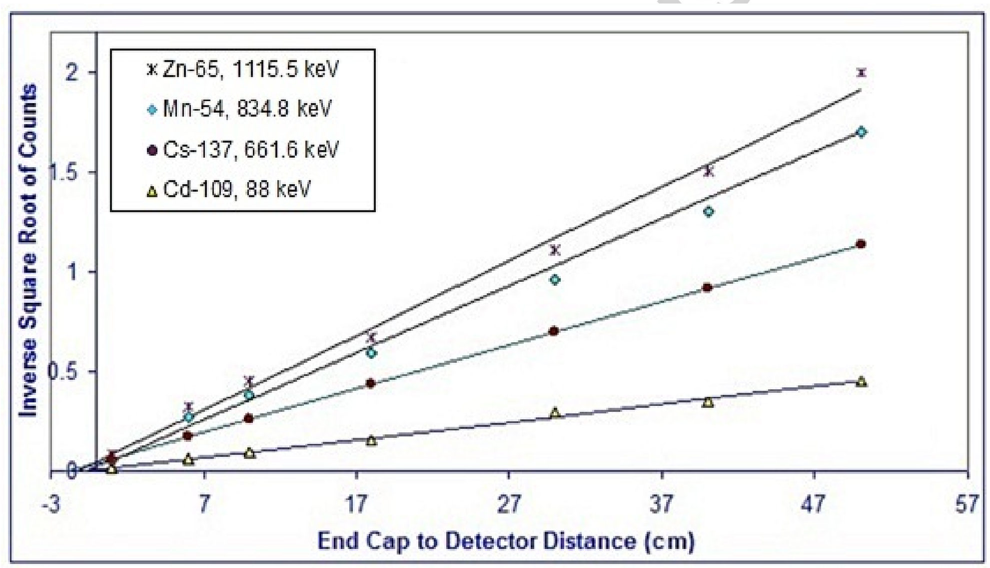

Fig. 2. Typical plots for determining r_o using a coaxial close-ended HPGe detector.

The lines obtained for sources with different photon energies and intensities, differ in r_o and slopes, herein (Grant, 1975)declared that, the slope of the linear portion of a Ge(Li) log(efficiency) vs log(energy) plot varies with the source-to-detector distance and crystal geometry, (Hnatowicz, 1977) as a function of detector volume and/or shape.

$$Slope\ (S)=\left[4\pi/A\cdot f_t\cdot r_o^2\cdot\epsilon_i\left(E_\gamma\right)\right]^{1/2} \qquad (7)$$

The function which fits best the experimental values is [cf. 5]:

$$r_o = p_7 \cdot \left[1 - \exp\left(- p_8\left(E_\gamma + p_9\right)\right)\right] \qquad (8)$$

E_γ in MeV , $\boldsymbol{r_o}$ in mm

From eq. (5):

$$\sqrt{\epsilon\left(E_\gamma, r\right)} = \frac{\sqrt{N_C\left(E_\gamma\right)}}{K} \cdot \left(\frac{r}{r_o\left(E_\gamma\right)} + 1\right) \qquad (9),$$

where $K^2 = \dfrac{A_o \cdot f_t}{4\pi}$ (10)

$$\epsilon_a\left(E_\gamma, r\right) = \frac{N_C\left(E_\gamma\right)}{K^2} \cdot \left(\frac{r}{p_7 \cdot \left[1 - \exp\left(-p_8\left(E_\gamma + p_9\right)\right)\right]} + 1\right)^2 \qquad (11)$$

For a given γ-ray energy, The FEP efficiency for a point source on axis at a distance r from the external face of the end-cap can, according to this scheme be written as Eq.(11) where, p_7, p_8, p_9 are fitting parameters. From Eq. (12) which follow that a plot of the FEP efficiency root against separation should be the straight line described by

$$\sqrt{\epsilon_a\left(E_\gamma, r\right)} = \left(\frac{\sqrt{N_C\left(E_\gamma\right)}}{K}\right) \cdot \left(\frac{r}{p_7 \cdot \left[1 - \exp\left(-p_8\left(E_\gamma + p_9\right)\right)\right]} + 1\right) \qquad (12)$$

This is the case as shown from fig (3) which shows such a plot together with the best fit line to the data. From the ratio of the intercept to the slope we could deduce a value for r_o the intercept located at -2.69 mm behind the aluminum end cap, intersect a part from y-axis equivalent to 1.55 mm. The superposition occurs for the three gamma lines of 88, 661.6, and 1115.5 keV for ^{109}Cd, ^{137}Cs, and ^{54}Mn, respectively.

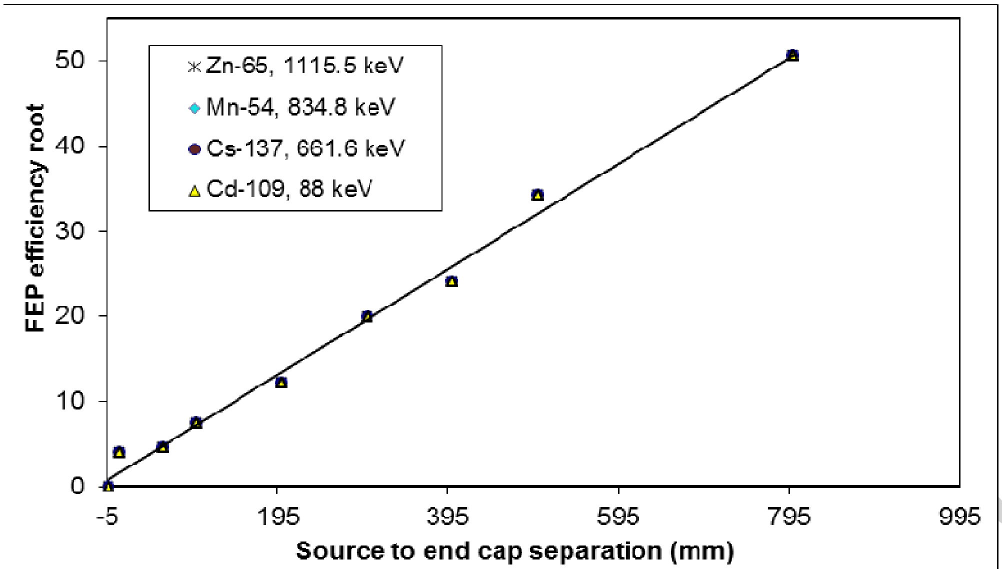

Fig. 3. Typical Plots of the FEP efficiency root for point sources of against source to end cap separation of a Coaxial Close-Ended HPGe detector, showing the linearity predicted by the point detector approximation.

The full energy peak formula as a function of both energy and distance can also be obtained by fitting an empirical function to the data points. The method is essentially the same as in the case of fitting the correlations that exist due to the counting of the same source at different distances have to be taken into consideration, fitting techniques are reviewed in literature as (Longoria and Benitez, 1996; Longoria et al., 1990).

The function which adequately represents the efficiencies between 60-1332 keV and distances between 10-800 mm has the form:

$$\epsilon_a(E_\gamma, r) = \epsilon_{pt}(E_\gamma) \cdot \left[\left(1 + \frac{r}{p_7[1-\exp\left(-p_8\left(E_\gamma + p_9\right)\right)]}\right)\right]^2 \quad (13)$$

Where,

$\epsilon_{pt}(E_\gamma) = 1/E_\gamma\left[p_1 + p_1 \cdot \ln E_\gamma + ... + p_6 \cdot \ln E_\gamma^5\right]$, represents the fitting of the full energy peak efficiency for point like at a fixed distance, including correction for coincidence if exist.

E_γ the gamma energy in MeV

r the distance from the source to detector window in mm

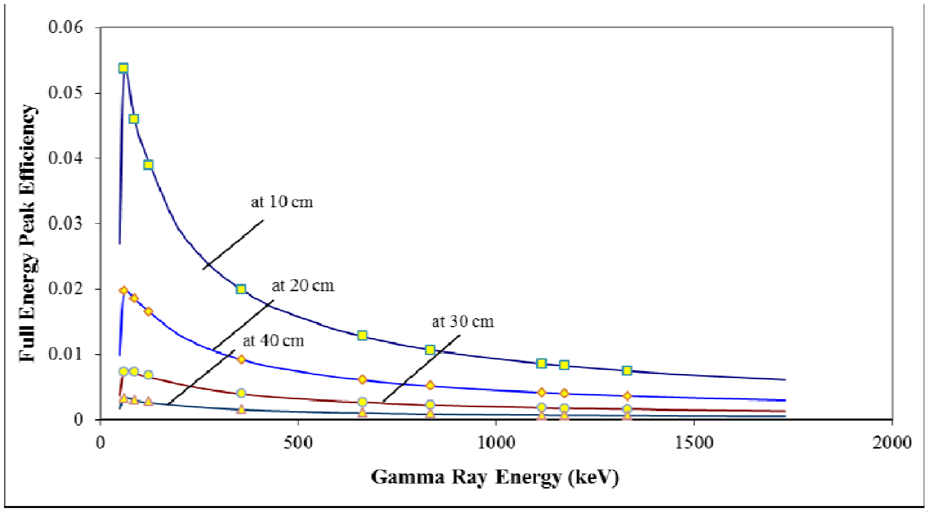

Fig. 4. Shows the absolute full energy peak detection efficiency of the HPGe detector for point sources on axis as a function of γ–ray energy and separation, these functions fitted to the experimental points.

6. Conclusions

The full energy peak efficiencies were calculated in the energy range from 60 to 1332 keV and in distance between 10 and 800 mm. A new theoretical function has been proposed which adequately represents the experimental points. The advantage of using a function of this type is that it is possible to determine the efficiency at point where experimental measurements do not exist. It is worthwhile mentioning that the coincidence summing effects must be taken into account while carrying out measurements at short distances from detector window, using radioisotopes emitting gamma-rays in cascades.

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Highlights:-

- We introduced the concept of a double point detector model approach (DPDM).
- Examining the detector efficiency depended on source detector separation.
- Gamma-ray energies covered in this work span from 59 to 1408 keV.
- Gamma-ray counting dependence on source to detector distance from 10 to 800 mm.
- The efficiencies obtained by (DPDM) are in good agreement with experimental data