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STUDY ON THE EFFECT OF THE SELF-ATTENUATION COEFFICIENT ON γ-RAY DETECTOR EFFICIENCY CALCULATED AT LOW AND HIGH ENERGY REGIONS

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The present work used the efficiency transfer method used to calculate the full energy peak efficiency (FEPE) curves of the (2"*2" & 3"*3") NaI (Tl) detectors based on the effective solid angle subtended between the source and the detector. The study covered the effect of the self attenuation coefficient of the source matrix (with a radius greater than the detector's radius) on the detector efficiency. ^{152} An Eu aqueous radioactive source covering the energy range from 121.78 keV up to 1408.01 keV was used. In this study an empirical formula was deduced to calculate the difference between the measured and the calculated efficiencies [without self attenuation] at low and high energy regions. A proper balance between the measured and calculated efficiencies [with self attenuation] was achieved with discrepancies less than 3%, while reaching 39% for calculating values [without self attenuation] due to working with large sources, or for low photon energies.

KEYWORDS : Self Attenuation Coefficient, NaI (Tl) Detectors, Full Energy Peak Efficiency (FEPE), New Empirical Formula and Efficiency Transfer Method

1. INTRODUCTION

Determination of detector efficiency is very important for a wide range of activation analysis applications where the self attenuation coefficient of the sample must be considered. The calculation of full-energy peak efficiency (FEPE) and the self attenuation of source material using experimental, semi-empirical and Monte Carlo approaches has been discussed by several authors [1-4] and recently as [5-12].

Radioactive substances are deposited on a backing material in thin deposits, but no matter how thin, the deposit has a finite thickness and may cause absorption of some photons emitted by the source. [13] Carrier solution in liquid sources must absorb some photons according to the source dimension. Consider the source-detector configuration as shown in Fig. 1. Particle 1 traverses through the source material and enters the detector. Particle 2 is absorbed inside the source and will not be counted. Therefore, the source self-absorption will produce a decrease in the counting rate (efficiency) and strongly affect the efficiency of the detector.

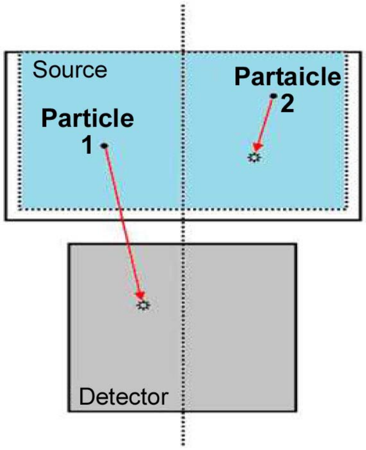

Fig. 1. Source Self-absorption
(Photons May be Absorbed in the Source Matrix).

2. THEORETICAL BASIS

Consider the spherical coordinate system, where the direct analytical elliptic integrals were derived to calculate the detector efficiencies (total and full-energy peak) for any source-detector configuration, [14].

The effective solid angle, Ω_{eff}, subtended by the detector and the point source is defined as [15]:

$$\Omega_{eff} = \int_{\theta}\int_{\varphi} f_{att}.\sin\theta d\varphi d\theta \tag{1}$$

Where, f_{att}, factor determines the photon attenuation by all absorbers between source and detector, and is expressed as:

$$f_{att} = e^{-\sum_i \mu_i \delta_i} \tag{2}$$

Where, μ_i, is the attenuation coefficient of the, i^{th}, absorber of a gamma-ray photon with energy, E_γ, and, δ_i, is the average photon path length through the, i^{th}, absorber.

The effective solid angle of a cylindrical detector of radius, R, using a cylindrical radioactive source of radius, S, and height, H, where (S≥R) [14] can be expressed by:

$$\Omega_{eff(Cyl)} = \frac{\int_{h_o}^{H+h_o}\int_0^{2\pi}\int_0^{S} f_{att}.\, S_f .\Omega_{eff(Point)}.\rho d\rho d\alpha dh}{\pi S^2 H} \tag{3}$$

As previously described, part of the emitted photons from the source will be absorbed only in the source itself or attenuated, and the factor concerning this effect is called the self-attenuation factor, S_f, which is given by:

$$S_f = e^{-\mu_s . d_s} \tag{4}$$

Where, μ_s, is the source self attenuation coefficient and, d_s, is the distance traveled by the emitted photon inside the source, (as seen in Fig. 2).

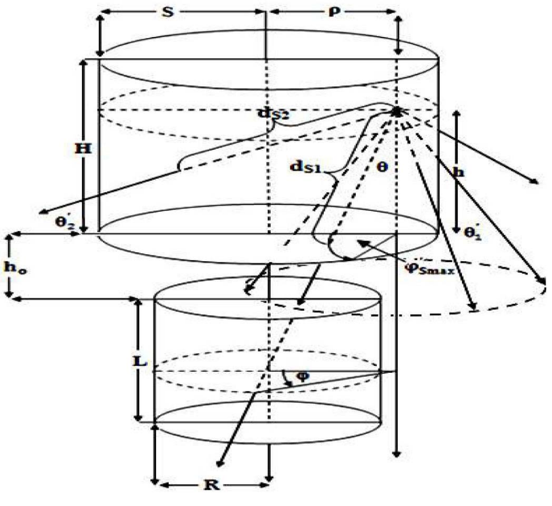

Fig. 2. A Schematic Diagram of the Source-detector Configurations.

The distance is found to be related to the polar and azimuthal angles (θ,φ) inside the source itself according to the following equations [16]:

$$d_s = \frac{h - h_o}{\cos\theta} \quad \text{for } \theta \le \theta_2^{'} \text{ and } \quad \varphi \le \varphi_{Smax}^{'} \tag{5}$$

and the source polar angles can be given as:

$$\theta_1^{'} = \tan^{-1}\left(\frac{S-\rho}{h-h_o}\right) \;\&\; \theta_2^{'} = \tan^{-1}\left(\frac{S+\rho}{h-h_o}\right) \tag{6}$$

Where, θ'_1 and θ'_2 are the extreme polar angles of the source.

The maximum source azimuthal angle will be:

$$\varphi_{Smax}^{'} = \cos^{-1}\left(\frac{\rho^2 - S^2 + (h-h_o)^2\tan^2\theta}{2\rho(h-h_o)\tan\theta}\right) \tag{7}$$

Where, φ'_{Smax}, is the maximum azimuthal angle for the photon to exit from the source and, h_o, is the source-detector separation.

For cylindrical radioactive sources, the detector efficiency ε(E,Cyl) can be calculated by the efficiency transfer principle as follows:

$$\varepsilon(E,Cyl) = \varepsilon(E,P_o)\frac{\Omega_{eff}(Cyl)}{\Omega_{eff}(P_o)} \tag{8}$$

Where ε(E,P_o) is a reference efficiency of a point source of energy, E, measured at distance P_o. While, Ω_{eff}(Cyl), and, Ω_{eff}(P_o), are the effective solid angle subtended by the detector-to-cylindrical radioactive source and the reference geometry respectively.

The efficiency transfer method is particularly useful due to its insensitivity to the inaccuracy of the input data, e.g. to the uncertainty of the detector characterization [17-18].

The full energy peak efficiency is calculated by the use of equations (1, 3 and 8), where all the integrals encountered are elliptic integrals and does not have a closed form solution, so a numerical solution is obtained using the trapezoidal rule. Although the accuracy of the integration increases by increasing the number of intervals n, the integration converges fully at n = 20. A computer program (using the Microsoft Basic Program) has been written to calculate the effective solid angles for arbitrarily located a point as well as volumetric sources based on the derived equations.

3. EXPERIMENTAL SETUP

The experimental study was conducted in the radiation physics laboratory in Alexandria University, Egypt, where NaI scintillation detectors Canberra Model 802 (2”*2” and 3”*3” crystal sizes) are available. The NaI detectors were calibrated by measuring low activity points and cylindrical sources. Full Energy Peak Efficiency value of these detectors was determined by considering the source self attenuation effect and without the source self attenuation effect. The PTB point source used in the calibration procedure was ^{152}Eu measured at 20 cm axial distance from the detector surface using a homemade Plexiglas holder. The holder was placed directly on the detector entrance window as an absorber to avoid the effect of β- and x-rays and to protect the detector heads, so there no correction was made for x-gamma coincidences, since in most cases the accompanying x-rays were soft enough to be highly absorbed before entering the detector, and also the angular correlation effects can be negligible for the low source-to-detector distance [19]. In general, gamma-gamma coincidence events are assumed to be negligible at a far distance of 20 cm counting geometry due to small solid angles. The details of this point source are listed in table (1). The experimental (FEPE) value obtained from this point source is used as a reference efficiency curve to calculate the (FEPE) values in the case of using a cylindrical radioactive volumetric source according to equation (8).

To study the source of the self-attenuation coefficient, 500 ml Polypropylene volumetric vials were made by Nalgene Lab ware, catalog number (NG-2118), size code (16) filled with 200 ml, 300 ml and 400 ml ^{152} of Eu radioactive solution of known activity. The specific activity principle was used [20] to prepare these homemade sources; the prepared source's properties are tabulated in table (2).

The volumetric sources were measured on a 0.1 cm thick Plexiglas cover, which was placed directly on the detector end-cap. The radioactivity measurements were done by using the two cylindrical scintillation detectors denoted D1 (2”*2” NaI) and D2 (3”*3” NaI), respectively. The cylindrical source and cylindrical detector were placed at the same axis during the measurements. The spectra was acquired by the detector-source geometry (D2-V1) and (D1-V2) etc, where, V1 and V2 are the volume sources and D1 and D2 are the detectors, respectively The spectrum was acquired by winTMCA32 software made by ICx Technologies, and analyzed by the Genie 2000 data acquisition and analysis software (Canberra, Inc).

4. RESULTS AND DISCUSSION

The measured efficiency values as a function of the photon energy, $\varepsilon_{meas}(E)$, for both NaI Scintillation detectors were calculated by:

$$\varepsilon_{meas}\left(E\right)=\frac{N(E)}{T\cdot A_S\cdot P(E)}\prod C_i \qquad (9)$$

Where, N(E), is the number of counts in the full-energy peak which can be obtained by using Genie 2000 software, T, is the measuring time (in second), P(E), is the photon emission probability at energy, E, A_S, is the radionuclide activity and, C_i, are the correction factors due to dead time, radionuclide decay.

The dead time was always less than 3% and the coincidence summing effects were negligible. The acquisition time was high enough to get at least the number of counts 20,000, so the statistical uncertainties of the net peak areas were smaller than 0.5%. The background subtraction was done and the decay correction, C_d, for the calibration sources from the reference time to the run time was calculated as:

$$C_d = e^{\lambda\cdot\Delta T} \qquad (10)$$

Where, λ, is the decay constant and, ΔT, is the time interval over which the source decays corresponding to the run time.

Table 1. An ^{152}Eu Point Source used in the Measurements

Nuclide	Activity (kBq)	Reference Date	Energy (keV)	Emission Probability %	Half Life (Days)
^{152}Eu	290.0±4.0	1.June, 2009	**121.78**	28.4	4943.29
			244.69	7.49	
			344.28	26.6	
			778.93	12.96	
			964.13	14.0	
			1408.01	20.87	

Table 2. Properties of the Volumetric Radioactive Sources used in the Measurements

Source code	Nuclide	Source Volume (ml)	Activity (kBq)	Reference Date	Note
V1	**^{152}Eu**	200	5±1.98%	1.Jan, 2010	Homemade prepared
V2		300			
V3		400			

The uncertainty in the measured full-energy peak efficiency, σ_ε, was given by:

$$\sigma_\varepsilon=\varepsilon\cdot\sqrt{\left(\frac{\partial\varepsilon}{\partial A}\right)^2\cdot\sigma_A^{\,2}+\left(\frac{\partial\varepsilon}{\partial P}\right)^2\cdot\sigma_P^{\,2}+\left(\frac{\partial\varepsilon}{\partial N}\right)^2\cdot\sigma_N^{\,2}} \qquad (11)$$

Where, σ_A, σ_P, and, σ_N, are the uncertainties of A_S, P(E), and, N(E), respectively.

Figs. 3, 4 and 5 show the full-energy peak efficiencies of scintillation γ-detector which includes the measured, (EFFEXP), the calculated with self attenuation, (EFFW), and those calculated without self attenuation, (EFFWO), for using volume radioactive sources [200, 300 and 400 mL] denoted by (V1, V2 and V3) as functions of the photon energy.

Obviously, the absence of the self attenuation coefficient corrections in the calculations caused an increase in the full energy peak efficiency values, for this reason and to get correct results; the self attenuation coefficient of the source matrix must be considered. The percentage of deviations, Δ%, between the calculated energy peak efficiency values (with and without self attenuation) full- were calculated by:

$$\Delta\%=\frac{\text{EFFWO - EFFW}}{\text{EFFW}}\times 100 \qquad (12)$$

The percentage of deviations, Δ%, were calculated for each source with the detectors (D1 and D2) and tabulated in table (3). In addition, the data of , Δ%, versus the photon energy were plotted as shown in Fig. 6 and 7 for both detectors D1 and D2 using different source volumes versus the photon energy. The curves revealed that; the source self-attenuation is more effective in the low energy regions and the deviation percentage values are exponentially decreased until reaching a fixed value at extremely high energies.

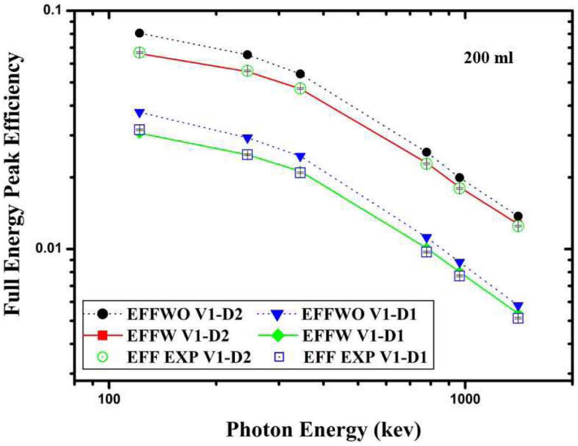

Fig. 3. Comparison between Calculated (FEPE) (with and without Self Attenuation) and the Measured Efficiency of V1-D1, and V1-D2.

The fitting equation of each curve is obtained from the Origin 8 program (www.originlab.com) and found to be as tabulated in table (4). These equations were used to

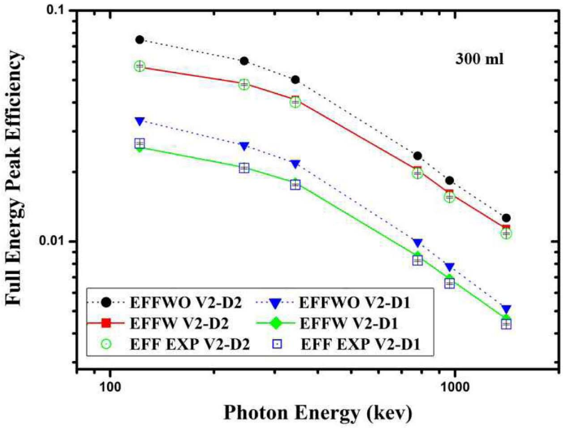

Fig. 4. Comparison between Calculated (FEPE) (with and without Self Attenuation) and the Measured Efficiency of V2-D1, and V2-D2.

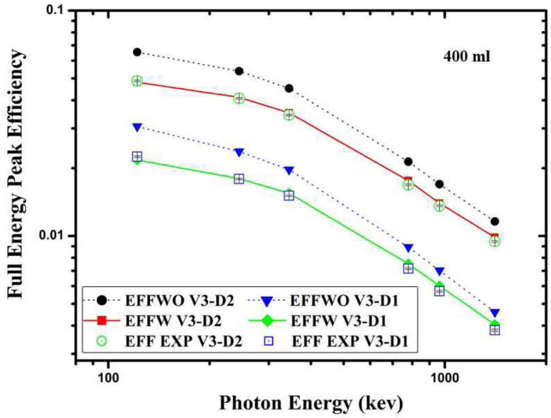

Fig. 5. Comparison between Calculated (FEPE) (with and without Self Attenuation) and the Measured Efficiency of V3-D1, and V3-D2.

Table 3. The deviation Percentage, Δ%, between Calculated (FEPE) with and without Source Self- attenuation.

Energy (keV)	Deviation Percentage Δ%					
	Source-detector geometry					
	V1-D1	V2-D1	V3-D1	V1-D2	V2-D2	V3-D2
121.78	22.48	30.96	38.61	21.92	31.44	38.48
244.69	17.99	24.67	30.66	17.58	25.07	30.57
344.28	15.78	21.59	26.79	15.43	21.95	26.72
778.9	11.07	15.06	18.63	10.85	15.33	18.59
964.13	9.98	13.57	16.76	09.79	13.81	16.73
1408.01	8.21	11.13	13.74	08.05	11.34	13.71

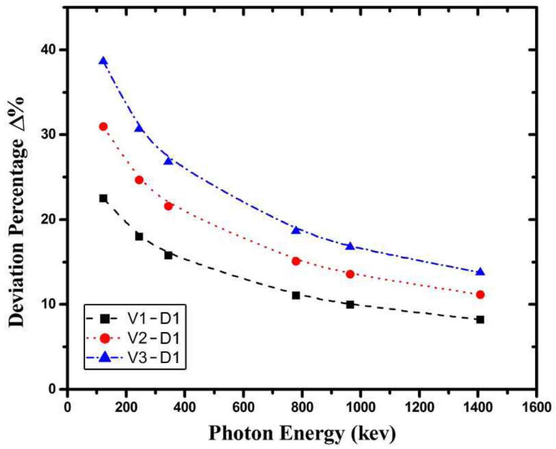

Fig. 6. The Percentage Difference (Δ%) Calculated as a Function of the Photon Energy for Detector, D1, using Volume Sources (V1, V2 and V3).

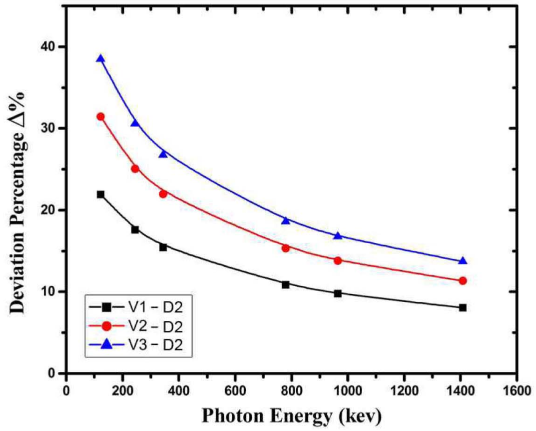

Fig. 7. The Percentage difference (Δ%) Calculated as a Function of the Photon Energy for Detector, D2, using Volume Sources (V1, V2 and V3).

Table 4. The Fitting Parameters and Empirical Formula that Calculated from Deviation Percentage, Δ%, for Both Detectors (D1 and D2) with using the Three Radioactive Volumetric Sources (V1, V2 and V3)

Equation	$\Delta\% = Y_o + A_1 e^{\left(-E/t_1\right)} + A_2 e^{\left(-E/t_2\right)}$			
Detector	**D1(2inchx2inch)**		**D2(3inchx3inch)**	
Source	**V1 (200 ml)**			
Fitting parameters	**Value**	**Standard Error**	**Value**	**Standard Error**
Y_o	5.76	0.18	5.64	0.18
A_1	13.55	0.28	13.20	0.27
t_1	823.06	44.46	829.11	44.23
A_2	11.58	0.28	11.18	0.27
t_2	146.05	7.31	147.03	7.20
Source	**V2 (300 ml)**			
Y_o	7.83	0.26	7.97	0.26
A_1	18.70	0.41	18.99	0.416
t_1	812.05	44.87	814.58	44.63
A_2	16.33	0.39	16.52	0.393
t_2	144.46	7.46	144.92	7.383
Source	**V3 (400 ml)**			
Y_o	9.68	0.32	9.65	0.32
A_1	23.36	0.53	23.27	0.53
t_1	804.63	45.04	806.45	44.83
A_2	20.70	0.49	20.57	0.48
t_2	143.44	7.54	143.78	7.48
E	**Photon Energy**			

Table 5. Calculated Deviation Percentage, Δ%, of (V1, V2 and V3) Sources Over the Energy range from 25 keV to 100 Mev for Both Detectors (D1 and D2)

Photon Energy (keV)	Empirical formula Deviation Percentage Δ%					
	D1			D2		
	V1	V2	V3	V1	V2	V3
25	27.88	40.28	49.49	28.67	39.70	49.71
50	26.02	37.52	46.05	26.74	36.97	46.23
100	23.00	33.04	40.47	23.60	32.54	40.61
121.78	21.92	31.44	38.48	22.48	30.96	38.61
150	20.68	29.62	36.22	21.20	29.16	36.34
200	18.88	26.97	32.93	19.34	26.54	33.03
244.69	17.58	25.08	30.58	18.00	24.67	30.67
250	17.44	24.88	30.33	17.85	24.47	30.42
300	16.28	23.19	28.25	16.66	22.81	28.32
344.28	15.43	21.94	26.71	15.78	21.58	26.78
350	15.33	21.80	26.53	15.67	21.43	26.60
400	14.52	20.63	25.10	14.85	20.29	25.16
450	13.83	19.63	23.87	14.14	19.30	23.93
500	13.23	18.77	22.80	13.52	18.45	22.86
550	12.70	18.00	21.87	12.98	17.70	21.92
600	12.23	17.32	21.03	12.49	17.02	21.07
650	11.80	16.70	20.27	12.05	16.41	20.31
700	11.41	16.14	19.58	11.65	15.86	19.62
750	11.05	15.62	18.95	11.28	15.35	18.99
778.90	10.85	15.34	18.60	11.08	15.07	18.64
800	10.72	15.14	18.36	10.94	14.88	18.40
850	10.41	14.70	17.82	10.62	14.44	17.86
900	10.12	14.29	17.31	10.33	14.04	17.35
950	9.85	13.90	16.85	10.05	13.66	16.88
964.13	9.78	13.80	16.72	9.98	13.56	16.75
1000	9.60	13.54	16.41	9.79	13.31	16.44
1050	9.37	13.21	16.00	9.55	12.98	16.03
1100	9.15	12.89	15.61	9.33	12.67	15.64
1150	8.94	12.60	15.25	9.12	12.38	15.28
1200	8.75	12.32	14.91	8.92	12.10	14.94
1250	8.56	12.06	14.60	8.73	11.85	14.62
1300	8.39	11.82	14.30	8.56	11.61	14.32
1350	8.23	11.59	14.02	8.39	11.38	14.04
1400	8.08	11.37	13.76	8.23	11.17	13.78
1408.01	8.06	11.34	13.71	8.21	11.14	13.74
1450	7.94	11.17	13.51	8.09	10.97	13.53
1500	7.80	10.98	13.28	7.95	10.78	13.30
2000	6.82	9.60	11.60	6.95	9.43	11.62
2500	6.29	8.85	10.70	6.41	8.69	10.72
3000	5.99	8.44	10.22	6.11	8.30	10.24
3500	5.83	8.22	9.96	5.95	8.08	9.98
4000	5.74	8.11	9.82	5.87	7.97	9.84
4500	5.70	8.04	9.74	5.82	7.91	9.77
5000	5.67	8.01	9.70	5.79	7.87	9.73
5500	5.66	7.99	9.68	5.78	7.85	9.70
6000	5.65	7.98	9.67	5.77	7.85	9.69
6500	5.64	7.97	9.66	5.77	7.84	9.69
7000	5.64	7.97	9.66	5.76	7.84	9.68
7500	5.64	7.97	9.66	5.76	7.84	9.68
8000	5.64	7.97	9.66	5.76	7.83	9.68
8500	5.64	7.97	9.65	5.76	7.83	9.68
9000	5.64	7.97	9.65	5.76	7.83	9.68
9500	5.64	7.97	9.65	5.76	7.83	9.68
10000	5.64	7.97	9.65	5.76	7.83	9.68
20000	5.64	7.97	9.65	5.76	7.83	9.68
30000	5.64	7.97	9.65	5.76	7.83	9.68
40000	5.64	7.97	9.65	5.76	7.83	9.68
50000	5.64	7.97	9.65	5.76	7.83	9.68
60000	5.64	7.97	9.65	5.76	7.83	9.68
70000	5.64	7.97	9.65	5.76	7.83	9.68
80000	5.64	7.97	9.65	5.76	7.83	9.68

calculate the deviation percentage due to the source self-attenuation of the three volumetric sources over a wide energy range that starts from the low energy region (25 keV) to the high energy region are presented in table (5) for both detectors. The tabulated values reveal that the deviation between the measured (FEPE) and the calculated without self attenuation increase as the source volume increase for the same source activity till reach for slight difference fixed at high energy. i.e. [This deviation at low energy regions is high and starts to decrease as the energy increases, This due to the photon energy effect when its chance increases to escape from the source, and the source self attenuation effect will be decreased].

4. CONCLUSION

The present work introduces an empirical formula based on the discrepancies of the source self-attenuation behaviour and was used to calculate the difference between the measured and calculated efficiencies [without self attenuation] from low to high γ-ray energies regions. The approach was tested experimentally up to about 2 MeV, the minimum value of the percentage of deviation for the three discussed sources was found empirically to be around 2 MeV, and above this energy value the source self attenuation effect on the detector efficiency is found to be nearly constant. The examination of the present results reveals a large difference between the calculated and measured efficiencies, and reflects the importance of considering the attenuation factors due to a large volumetric source or low photon energies in studying the detector efficiency.

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