

**EFFECT OF PHOTON INTERACTION DEPTH IN THE
DETERMINATION OF ABSOLUTE EFFICIENCY OF HPGe DETECTOR
FOR LIQUID VOLUME SOURCE**

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Abstract

For practical measuring purposes in high pure Ge detectors, some useful semiempirical approaches are often used to calculate the peak efficiency (absolute efficiency) for any source-to-detector distance (d) if the efficiency has been measured at one known distance (d_1). In all approaches considered, normally, one begins an experimental efficiency calibration for single measuring geometry at a distance (d_1), and then derives the efficiency for any other arbitrary distance (d), from the relation

$$\frac{\epsilon(d)}{\epsilon(d_1)} = \frac{\Omega(d)}{\Omega(d_1)}$$

where ϵ denotes the detector efficiency for any gamma ray energy and Ω is solid angle that is subtended by detector to the source position. However, this relation is only valid when the distances used in the relation was corrected for the effective photon interaction depth for any gamma-ray energy (Debertin and Helmer, 1988; Yücel et al.1996) since the efficiency ratio, $\epsilon(d)/\epsilon(d_1)$, is not equal to the inverse ratio, d_1^2/d^2 . In the present work, the photon interaction depths depending upon gamma- ray energies in the range of about 50-2000 keV for point gamma sources (^{241}Am , ^{137}Cs , ^{60}Co , ^{133}Ba and ^{152}Eu) and a liquid volume (cylindrical) source containing ^{57}Co , ^{88}Y , ^{113}Sn , ^{137}Cs , ^{109}Cd , ^{139}Ce and ^{60}Co radionuclides were measured. Then, the calculation of the peak efficiency of a p-type HPGe detector is experimentally tested for both point and the extended (cylindrical) liquid source at various distances from the surface of the end cap of the detector by introduction of the effective photon interaction for any gamma-ray energy.

1. Introduction

In the last forty years γ -ray spectrometer with germanium detector is one of the fundamental instruments in experimental nuclear physics. Experimental work with γ -ray semiconductor detectors requires very often accurate knowledge of the

detector efficiency. Many efforts on the measurement of the efficiency of Ge detectors of various sizes and configurations have been discussed at some conferences (Debertin et al., 1976; Hirshfeld et al., 1976). An excellent review of the attempts at calculating detector efficiencies is given in a recent book by Debertin and Helmer (1988). "Although detector efficiencies must, in the end, be measured, it is useful to consider what information can be obtained from various related calculations." So begins the section on detector efficiency calculations in that book. Nonetheless, there are many obvious incentives for calculating efficiency (or greatly reducing the calibration effort), rather than laboriously measuring it (Gunnik, 1990). For practical measuring purposes, some useful semi empirical approaches are often used to calculate the efficiency for any source-to-detector distance if the efficiency has been measured at one known distance. In all approaches considered, normally, one begins an experimental efficiency calibration for single measuring at a distance d_1 , and derives the efficiency for any other arbitrary distance d , from the relation

$$\frac{\epsilon(d)}{\epsilon(d_1)} = \frac{\Omega(d)}{\Omega(d_1)} \quad (1)$$

Where d and d_1 are distances measured from the surface of the end cap of detector to the radioactive source, $\epsilon(d)$ is the efficiency of the detector at d , $\epsilon(d_1)$ is the efficiency of the detector at d_1 , and Ω is solid angle that is subtended by detector at the source position.

The exact expression for the solid angle for a point source is

$$\Omega(d) = 2\pi \left(1 - \frac{d}{\sqrt{d^2 + R^2}} \right) \quad (2)$$

Where R is the radius of a right circular cylindrical detector and d is distance of point-source positioned on the symmetry axis of a detector. Equation (1) assumes the validity of the concept of geometry independent intrinsic detector efficiency. As long as d and d_1 are large in comparison with the detector radius R , or if $d \approx d_1$, this concept may be acceptable. However, this relation is not acceptable approximation especially for thicker detectors because of the coincidence summing effects that play an important role on the counts in the full-energy peaks at low source-to-detector distances (Debertin and Schötzig, 1979).

For thicker detectors, where photon interactions do not only occur at the surface, but are distributed over the detector volume, the detection efficiency for a point source is proportional to the solid-angle Ω which varies approximately as $1/d^2$. Of course, the detector is never, and the source is seldom, a point. However, the single point-to-point distance implied by Eqn (1) is determined by using semi empirical model that, for calculating purposes, reduces the detector volume to an equivalent point (a point B shown in Fig. 1). It is a point where all γ -ray interactions are

The calculations on effective photon interaction depth is based on an equivalent point-detector concept suggested by Notea (1971). Although the concept of an effective interaction depth for thicker detectors is questionable, it is still an applicable approximation in most practical cases. Therefore, some functions which have a semi empirical character can be useful to determine the effective interaction depth of γ -rays in the Ge detectors.

In the present study, semi-empirical functions which relates the given γ -ray energy and the effective interaction depth in Ge is used to fit the measured interaction depth values for point sources and volume sources. The present concept involves that a given fraction of the total photon interactions for a particular energy of γ -ray distributed over the detector has occurred in a distance within the detector described from the real surface of the detector to any imaginary point. In the study, we have tested the concept of effective interaction depth depending on the gamma-energy for an extended source (a cylindrical ampoule) containing radioactive standards (^{57}Co , ^{88}Y , ^{113}Sn , ^{137}Cs , ^{109}Cd , ^{139}Ce and ^{60}Co) because the real samples to be measured are rarely point sources, but in general, they are the extended sources in practice. The measurements for the determination of photon interaction depths have been carried out in a high purity germanium detector.

2. Experimental

The γ -ray spectrometer consists of one high purity Ge detector with a charge-sensitive preamplifier, a linear amplifier, an analog-to-digital converter (ADC) and a Canberra series 35+ MCA with 4096 channel. The commercially available HpGe detector in this investigation is the closed ended coaxial p-type Ge crystal with active volume of approx. 57 cm^3 . The detector configuration and characteristics as specified by manufacturer are given in Table 1. The γ reference point source set and a calibrated standard solution used are obtained from the Amersham Int. Ltd. and Isotope Products Inc., respectively. The calibrated point sources (^{241}Am , ^{133}Ba , ^{152}Eu , ^{137}Cs , ^{60}Co , ^{22}Na) provide a sufficient number of full energy peaks for this investigation. The standard solution in a 5 ml ampoule contains the radionuclides, ^{57}Co , ^{88}Y , ^{113}Sn , ^{137}Cs , ^{109}Cd , ^{139}Ce and ^{60}Co . The activities of the present calibrated sources are known to be accurate less than 3%. The standard point sources are encased in a thin plastic holder.

The peak count rates were measured at various source-to-detector distances and different photon energies. The distance, d , from the source to the detector endcap was altered from 8 to 21 cm for the different γ -emitters used. Since the activities of the sources used in experiments are not too high, the pile-up losses (random summing) from the full-energy peak counts are negligible. Also, there is no problem from point of view of dead-time correction since MCA works in the live-time mode, the analyzer corrects its dead-time losses. The full-energy peak areas obtained from the ^{133}Ba and ^{152}Eu measurements may some losses because of the coincidence summing effects on the spectra of multi energy γ -ray emitters

(Debertin and Schötzig, 1979). Although the coincidence summing losses may occur in the peak counts obtained from especially ^{133}Ba and ^{152}Eu sources at closer distances. The measurements with ^{133}Ba and ^{152}Eu were also carried out at a distance of 8 cm below the nominal value of 10 cm. The counting time for each measurement predetermined was 30 min but some spectra were collected at different counting times in the range of 10-20 min. The counting time is high enough to ensure good statistical quality of the data. The count rate measurements at each selected distance were repeated five times to improve the statistical precision. Thus the mean values of the measured count rates were used in the calculations. The series 35+ MCA interfaced to a PC for the transfer of γ -ray spectra. The number of counts under each full-energy peak were evaluated by a software, and then divided these counts by the counting time to calculate the count rate. The variation in the full-energy peak areas is estimated to be less than 0.5%.

Table 1. Detector Specifications and performance data

Description	
Detector model	Canberra AL-30-C
Relative Efficiency*	12,4%
Energy Resolution (FWHM)** (keV)	1,96
Peak-to-compton ratio	42,1:1
Detector geometry	Closed-ended-coaxial
Detector material	p-type Ge
Diameter, D (cm)	4,5
Length, H (cm)	3,6
Active area facing window (cm ²)	15,9
Window material and thickness, d _w (mm)	Al, 0,5
Distance from the window, d _c (mm)	5
Crystat and dewar configuration	Vertical Dipstick Canberra Standard 7500

3. Results and discussion

The various plots of $N^{1/2}$ as a function of the distance d_s are obtained for different photon energies by using the mean peak count rates measured independently in detector. The plots of $N^{1/2}$ are shown in Fig.2 for the point sources ^{241}Am , ^{137}Cs , ^{22}Na and ^{60}Co , and the multi energy point sources in Fig.3 for ^{133}Ba , and in Fig. 4 for ^{152}Eu . In addition a plot of $N^{1/2}$ is shown for a liquid volume source containing the radionuclides, ^{57}Co , ^{88}Y , ^{113}Sn , ^{137}Cs , ^{109}Cd , ^{139}Ce and ^{60}Co in Fig. 5. The effective interaction depth d_e is determined by plotting the root of the reciprocal count rates $N^{-1/2}$ against the source-detector endcap distance (d_s) at the particular energy of γ -ray, and extrapolating the line to obtain the zero of $N^{1/2}$. The

experimental points are fitted by linear least squares method. The experimental and the calculated points are in good agreement.

The regression constants obtained are order of 0.999. If the effective interaction radius $r_e(E_\gamma)$ is neglected, the intercept of the line on the d_s axis at $-(d_c + d_w + d_e(E_\gamma))$, the quantity of interest. Since the distance ($d_c + d_w = 5.5$ mm) is known as the detector specification $d_e(E_\gamma)$ in given Table 1 $d_e(E_\gamma)$ is easily calculated from the intercept value of the line for a γ -ray of a particular energy. Thus, the γ -ray energies and respective the interaction depths for the detector used are given in Table 2 for all point sources and in given Table 3 for a volume source, respectively.

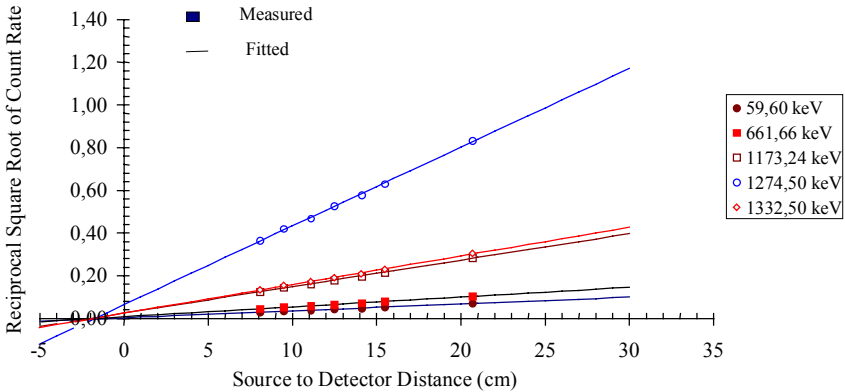


Fig. 2. Plot of Square Root of Reciprocal Count Rates for ^{241}Am , ^{137}Cs , ^{22}Na , ^{60}Co Point Sources

The dependence of $d_e(E_\gamma)$ on the photon energy obtained for the high purity Ge detector is shown in Fig. 6 for the point sources ^{241}Am , ^{137}Cs , ^{22}Na and ^{60}Co and the multi energy point sources in Fig.7 for ^{133}Ba , and ^{152}Eu and is shown in Fig. 8 for a liquid volume source.

The absolute efficiency is calculated by taking the ratio of the measured activity for that particular γ -ray and given geometry to the stated activity of the calibrated source. The absolute efficiencies at 9,5 cm, at 15,4 cm and at 20,7 cm as a function of γ -ray energy for Ge detectors is shown in Fig 9 for point sources and in Fig. 10 for a volume source. The experimental and the calculated values for the absolute efficiencies at these distance are also given in Table 4 for point source geometry and in Table 5 for a cylindric volume source. For the absolute efficiency curve for

a volume source, the acceptable fit is obtained although the fit in the low energy region (50-90 keV) is not done as can be seen in Fig 9 due to the lack of experimental points, especially in the energy range.

The measured and calculated absolute efficiencies give in Table 4 agree within 0.1 to 7% when effective interaction depths were taken into account in Eq. 3 for two different distances of at $d_1=9,5$ cm and $d=15,4$ cm. The validation of Eq. 3 introducing interaction depths for a volume source given in table 5 is obtained by 0,1 to 7,6%, assuming that all photons are emitted from the source at its half height. Besides, the experimental interaction depths for point sources and a volume source can be approximated well using Least Square Methods (LSQ) by the following function;

$$d_e(E_\gamma) = a(1 - e^{b(E_\gamma+c)})$$

Where the coefficients, a,b and c are determined by LSQ method, and E_γ was chosen in MeV and d_e in cm. It is apparent that the curves shown in Figures 6, 7 and 8 exhibit the same behaviour. The curves increase with increasing gamma ray and level out at higher energies of photons.

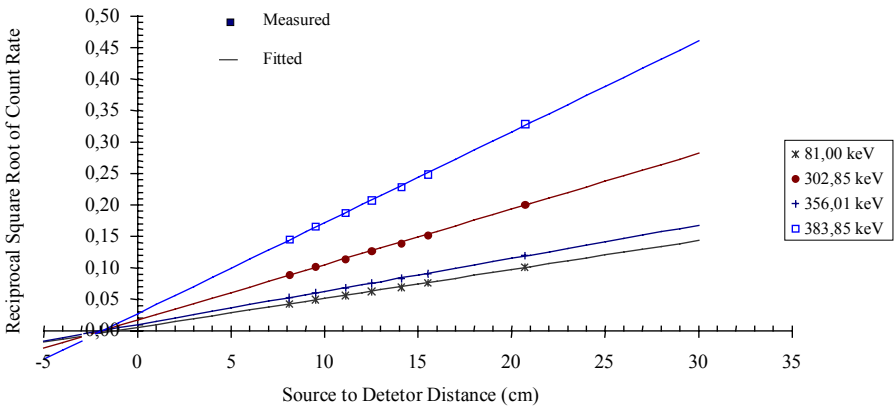


Fig. 3 Plot of Square Root of Reciprocal Count Rates for a ^{133}Ba Point Source

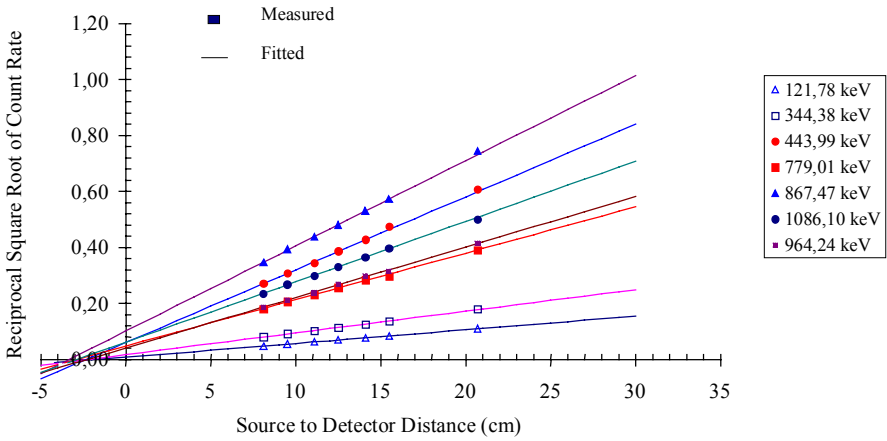


Fig. 4. Plot of Square Root of Reciprocal Count Rates for a ^{152}Eu Point Source

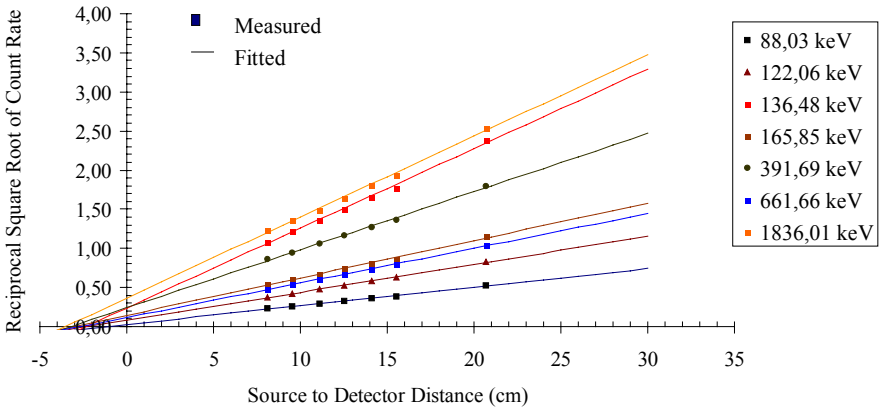


Fig. 5 Plot of Square root of Reciprocal Count Rates for a Volume Source

Conclusion

The well established procedures for the efficiency calibration of Ge-detector spectrometers appeared in the literature, however, an attempt was made to show that a semi empirical function relating the particular energy of γ -ray and effective interaction depth in Ge can facilitate the achievement of absolute efficiency calibration of a coaxial Ge detector without the necessity of much laboriously calibration effort. If an experimentalist determines the absolute efficiency at a distance, e.g at 10 cm by a calibrated source, then these values can be used to determine the efficiencies at any sample to detector distance by using the effective interaction depths.

Table 2. Photon Interaction Depth for all point sources

Nuclide	Photon Energies	Interaction Depth (mm)
Am-241	59,60	9,15
Cs-137	661,66	17,26
Co-60	1.173,24	19,85
Co-60	1.332,50	18,00
Na-22	1.274,50	17,43
Ba-133	81,00	11,43
	302,00	18,80
	356,00	19,12
	384,00	19,02
Eu-152	121,78	16,58
	344,32	21,48
	411,17	22,07
	443,99	23,09
	779,01	28,56
	867,47	33,11
	964,24	22,52
	1.086,10	28,41
	1.112,30	31,37
	1.299,50	36,43
	1.408,30	22,35

Table 3. Photon Interaction depth for volume sources

Nuclide	Photon Energies	Interaction Depth (mm)
¹⁰⁹ Cd	88,03	11,69
⁵⁷ Co	122,06	21,97
⁵⁷ Co	136,48	23,41
¹³⁹ Cd	165,85	30,29
¹¹³ Sn	391,69	32,23
¹³⁷ Cs	661,66	26,13
⁸⁸ Y	898,02	32,56
⁶⁰ Co	1173,24	28,16
⁶⁰ Co	1332,50	29,39
⁸⁸ Y	1836,01	35,14

Table 4. The Measured and Calculated Efficiencies for Point Sources

Energy (keV)	Measured efficiency($\times 10^{-3}$)			Interaction Depth (cm)	(ϵ_1/ϵ_2) (meas.)	(ϵ_1/ϵ_2) (calc.)	%Bias
	ϵ_1 (9,5 cm)	ϵ_2 (15,4 cm)	ϵ_3 (20,7 cm)				
59,60	5,43	2,27	1,23	0,92	2,40	2,37	-1,3
81,00	7,97	3,41	1,91	1,14	2,34	2,33	-0,2
121,78	7,26	3,23	1,83	1,66	2,24	2,26	0,8
302,85	3,34	1,49	0,86	1,88	2,24	2,23	-0,3
344,32	2,82	1,29	0,74	2,15	2,19	2,20	0,6
356,01	2,80	1,25	0,72	1,91	2,24	2,23	-0,5
383,85	2,64	1,18	0,67	1,90	2,25	2,23	-0,7
661,66	1,50	0,66	0,38	1,73	2,28	2,25	-1,1
779,01	1,15	0,56	0,32	2,86	2,07	2,12	2,7
867,47	0,98	0,46	0,36	3,31	2,12	2,08	-2,2
964,24	0,97	0,44	0,25	2,25	2,19	2,19	0,1
1.086,10	0,88	0,44	0,33	2,84	1,98	2,12	6,6
1.112,30	0,84	0,38	0,22	3,14	2,19	2,10	-4,6
1.173,24	0,83	0,37	0,22	1,99	2,24	2,22	-1,0
1.299,50	0,67	0,35	0,19	3,64	1,90	2,05	7,0
1.274,50	0,75	0,33	0,19	1,74	2,25	2,25	0,0
1.332,50	0,73	0,33	0,19	1,80	2,24	2,24	0,3
1.408,30	0,62	0,29	0,16	2,23	2,17	2,19	0,8

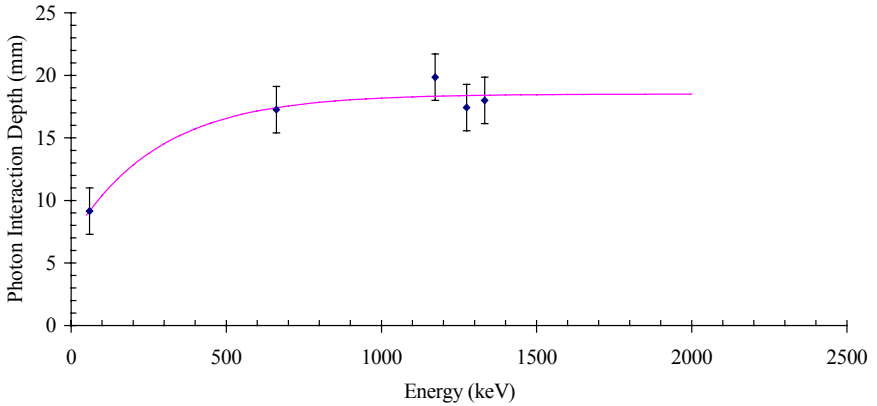


Fig. 6 Effective Photon Interaction Depth for ^{241}Am , ^{137}Cs , ^{22}Na and ^{60}Co Point Sources

Table 5. The Measured and Calculated Efficiencies for Point Sources

Energy (keV)	Measured efficiency($\times 10^{-3}$)			Interaction Depth (cm)	(ϵ_1/ϵ_2) (meas.)	(ϵ_1/ϵ_2) (calc.)	%Bias
	ϵ_1 (9,5 cm)	ϵ_2 (15,4 cm)	ϵ_3 (20,7 cm)				
88,03	5,20	2,20	1,19	1,17	2,36	2,33	-1,5
122,06	5,04	2,23	1,28	2,20	2,25	2,20	-2,6
136,48	4,85	2,23	1,25	2,34	2,18	2,18	0,1
165,85	4,40	2,02	1,17	3,03	2,18	2,11	-3,3
391,69	1,92	0,86	0,51	3,22	2,23	2,09	-6,9
661,66	1,08	0,51	0,29	2,61	2,13	2,15	0,8
898,02	0,78	0,37	0,21	3,26	2,13	2,08	-2,2
1.173,24	0,62	0,29	0,17	2,82	2,13	2,13	0,0
1.332,50	0,53	0,25	0,15	2,94	2,13	2,11	-0,6
1.836,01	0,40	0,18	0,11	3,51	2,22	2,06	-7,6

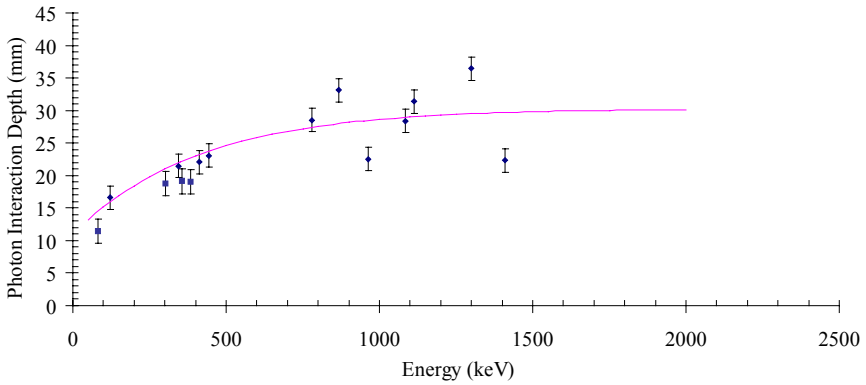


Fig. 7 Effective Photon Interaction Depth for ^{152}Eu and ^{133}Ba Point Sources

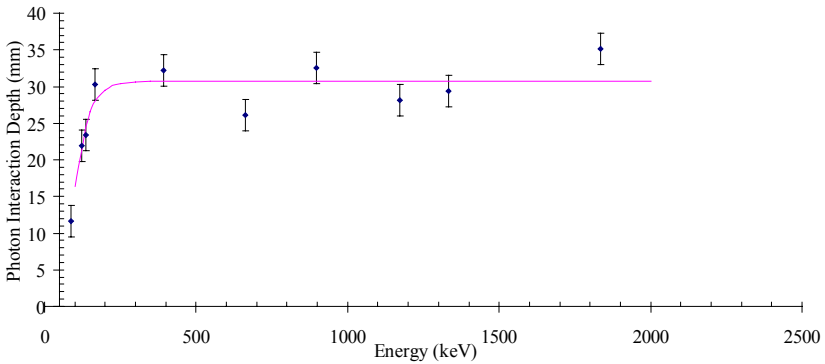


Fig. 8 Effective Photon Interaction Depth For Volume Source

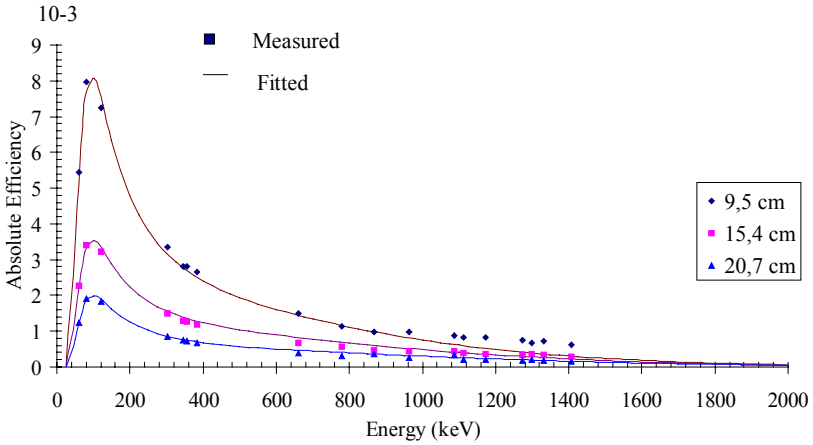


Fig. 9 Absolute Efficiency for point sources

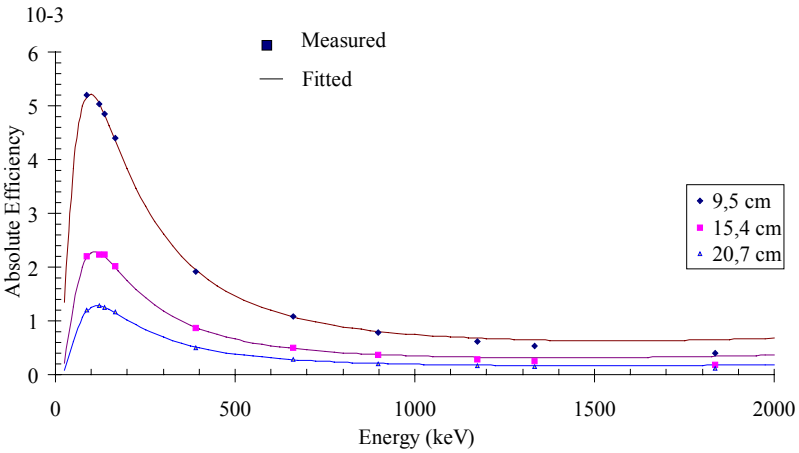


Fig. 10 Absolute Efficiency for a Volume Source

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