RESEARCH ARTICLE

Full-energy peak efficiency and response function of 1 cm³ CdZnTe detectors

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Abstract

The energy dependence of the full-energy peak (FEP) efficiency and response function of 1 cm³ CdZnTe detectors that use gamma rays were investigated in the present study. Specifically, full-energy peaks from 60 keV to 1.3 MeV were evaluated. ^{214}Am, ^{133}Ba, ^{137}Cs, ^{54}Mn, and ^{60}Co radionuclides with good source activities were employed. The results showed that the absolute peak efficiencies decreased at higher energies, and the calculated (EGS5 code) efficiencies were nearly 70% greater than the experimental values when above 100 keV photon. Below 100 keV, disagreement is within 35%. The measured and calculated peak efficiencies peak agreed within 5% in a wide energy range when the "effective" of the crystal area was down to 0.8 x 0.8 cm². Agreement corresponding to response function curve at the region of interest (full-energy peak) and Compton plateau region for ^{137}Cs achieved once considering the 0.8 x 0.8 cm² effective area of the crystal and the source plastic casing. The results of the present study provided important insights on the calibration of the FEP efficiency as a function of the gamma ray energy. The detectors must be individually calibrated to obtain reliable results.

Keywords: CdZnTe, gamma ray, full-energy peak efficiency

INTRODUCTION

Calibration of the full-energy peak (FEP) efficiency and total efficiency is essential to fully understand the ability and performance of the detector. Knowledge of detector efficiency is important when performing quantitative gamma spectrometry. It is commonly measured by using standard gamma sources or Monte Carlo simulations. To decrease the relative uncertainty of an isotropic source (instead of a point source), only the peak efficiency must be determined. According to Knoll [1], the peak efficiency should be evaluated because the number of full events is not sensitive to scattering from surrounding objects or noise, while the total efficiency is strongly dependent on the background. Since the peak efficiency values are the characteristics of the detector, different detectors cannot be accurately compared.

The cadmium zinc telluride (CdZnTe or CZT) is a semiconductor detector material which recently has received much attention because of its good energy resolution and has a high effective atomic number [2] in comparison to plastic scintillator [3]. These properties made it possible to be used as γ-ray detector which has a wide range of device applications including nuclear spectroscopy and understand the photons field [4,5,6]. Figure 1 shows an example of measured pulse height spectra of ^{241}Am sources by the CdZnTe (a) and NaI(Tl) (b) detector. The narrow peak width obtained by the CdZnTe indicates a good energy resolution of the detector.

In previous studies, the problems of inactive layer and incomplete charge collection efficiency had been reported for the CdZnTe detector of 1-cm³ [7,8]. Several scientists had introduced the phenomena such as modelling nonideal charge collection in their simulations [9].

In our work, the absolute peak efficiency and response function of a 1-cm³ CdZnTe (KROMEK Model GR1) detector was studied by comparing experimental and simulated values. Electron Gamma Shower 5 (EGS5) is a Monte Carlo code that simulates the transport of photons, electrons and positron in any element, compound or mixture [10].
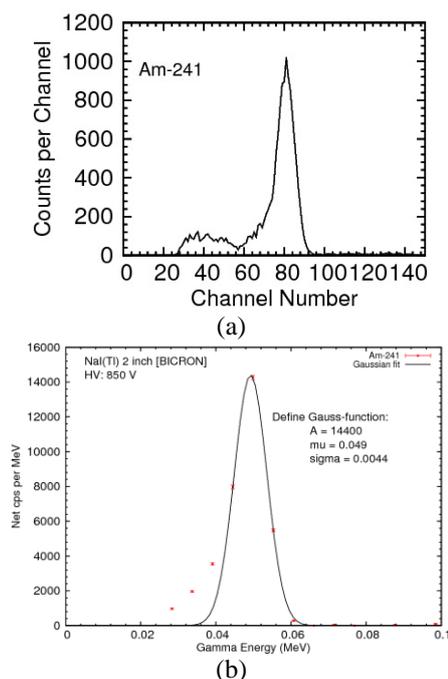
Figure 1. The example measured pulse height spectra of ^{241}Am by using (a) 1-cm³ CdZnTe (KROMEK Model GR1) and (b) from a calibrated 5.08 cm x 5.08 cm NaI(Tl) (Model BICRON).

The used CdZnTe detector in our work has the same problem of producing significantly different values for absolute peak efficiency between the measurements and calculations. The measured peak efficiency (%) was compared to the literature [11] and calculated data in absolute values.

MEASUREMENT – CALCULATION GEOMETRY

The experiment was performed with standard gamma sources at the radiation calibration facility, KEK, Japan. The facility was covered by a wire mesh where about 3 meter above the concrete floor. The pulse height spectra were measured from 60 keV to 1000 keV energy range by a $Cd_{1-x}Zn_xTe$ detector (KROMEK, Model GR1), with the dimension of 1 cm x 1 cm x 1 cm [13]. ^{214}Am, ^{57}Co, ^{137}Cs, ^{54}Mn, and ^{60}Co were employed as standard sources. The check sources (as listed in Table 1) were placed to be aligned to the center of CdZnTe surface as shown in Figure 2. All the sources used were encased in a plastic discs.

A distance of 10 ± 0.15 cm was adequate to avoid significant dead time losses. The lower energy threshold of the CdZnTe was set to 24 keV (lower than default energy=32 keV) without any significant dead time effect observed for measurements. The data acquisition and analysis of the photon spectrum were performed with its software (KSpect) running on a personal computer. The background radiation was taken at the same place as where the measurements were conducted.

Table 1. The list of check sources used for measurements. The sources activity ranging from 120 to 400 kBq.

Source	Energy (MeV)	Branching ratio (%)	Activity (kBq)
^{241}Am	0.06	35.9	405.2
^{57}Co	0.122	85.6	263.2
^{137}Cs	0.662	85.1	348.9
^{54}Mn	0.835	83.5	323.6
^{60}Co	1.173	99.9	122.3
	1.332	100	

Monte Carlo code for electron and photon transport (EGS5 code) was used to calculate the detector pulse height spectra. The photons interaction such as photoelectric absorption, Compton scattering and pair productions were considered. The branching ratio of the gamma sources were sampled as the JRIA data book [12]. The detector material data and its density for the calculations correspond to the manufacturer's data.
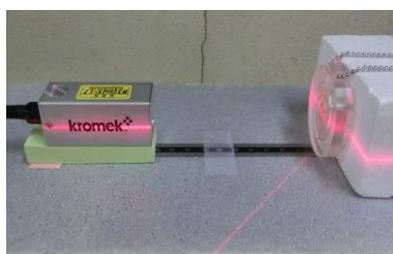
Figure 2. The experimental setup used for measuring the absolute peak efficiency values. The gamma sources were aligned to the center of CdZnTe front surface at a distance of 10 cm. The measured values obtained were compared to the literature and calculated data.

Figure 3 shows the model of CdZnTe detector in EGS5-CGview for particle trajectory [14]. The main parameters of the geometry are:
(a) The active crystal area is 1.0 x 1.0 cm^2,
(b) The active crystal thickness is 1.0 cm,
(c) The outer case is 1.2 mm thick aluminum,
(d) The window is 0.5 mm thick aluminum,
(e) The distance from the window to the surface of the crystal is 5 mm.

The proportion numbers of CdZnTe material components are 0.9, 0.1, and 1 for Cd, Zn, and Te, respectively. Density is set as 5.86 g/cm^3. The source was positioned at a 10 cm distance from the window corresponding to the measurement and literature geometry. The 4π isotropic source photons go toward the CdZnTe and cover only the front face of CZT crystal area as shown in Figure 3.
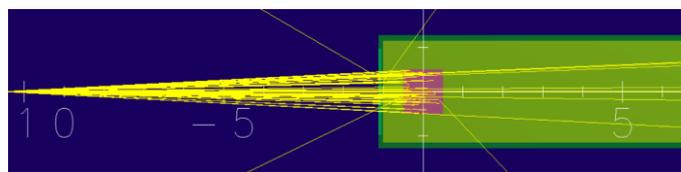
Figure 3. The model of CdZnTe 1 cm^3 crystal (KROMEK, Model GR1) in EGS5-CGview for particle trajectory. The outer case is aluminum of 1.2 mm in thickness. The window is aluminum of 0.5 mm in thickness. The distance from the window to the surface of the crystal is 5 mm. The density is 5.86 g/cm^3. The proportion numbers of CdZnTe material components are 0.9, 0.1, and 1 for Cd, Zn, and Te, respectively.

As we know, the peak efficiency depends on the geometry of the detector and crystal size. To assume the effect of insensitive region, the active crystal area was re-modeled. While remaining the original size of the crystal area (1.0 cm x 1.0 cm), the "effective" area that registered the events was reduced. The outer part of the "effective" area would become the reflector. Thus any reflected photons and electrons from the reflector to the "effective" area will be scored for its energy deposition. The geometries of the remodeled crystal depicted in Figure 4.
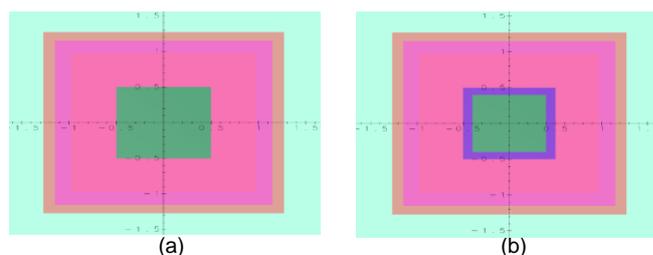
Figure 4. The calculated crystal areas of CZT from the front view. Several areas of the crystals were calculated. Figure (a) is the original area of 1.0 x 1.0 cm^2 and (b) is 0.9 x 0.9 cm^2 area of the region used to score in calculation while remaining its original size as reflector.

As a benchmark of our study, we also performed the same measurement and calculation of the well-known inorganic scintillators of NaI(Tl) detectors (Manufacturer: OKEN standard type 8A8) of 5 cm in diameter and 5 cm in length by coupling to the photomultiplier (Hamamatsu, R375). A diagram of the experimental setup used for the case of NaI(Tl) measurements is shown in Figure 5 where the concrete floor below is at about 70 cm. The gamma sources used are ^{137}Cs and ^{60}Co gamma sources.
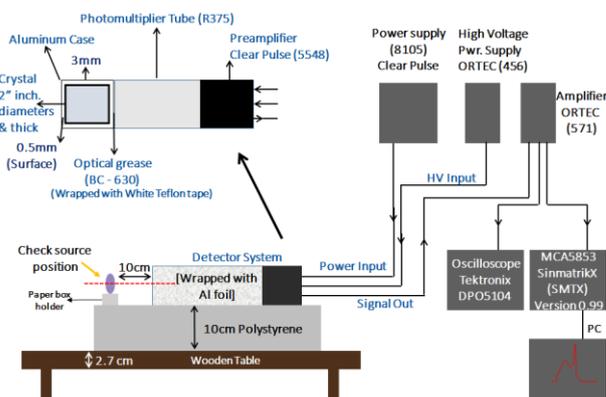
Figure 5. The experimental setup used for measuring the pulse height distribution spectra. The gamma sources were aligned to the front surface at a distance of 10 cm.

The accuracy of the simulation for this detector in a geometry similar to that used for CdZnTe simulations establishes our code predictive capabilities. The cylindrical NaI(Tl) is housed in aluminum case (0.5 mm at the surface and 3 mm surrounds the crystal) with optical window. The crystal density is 3.67 g/cm³. As the same geometry mention earlier, the 4π isotropic source photons emitted and cover only the front face of NaI area as shown in Figure 6 for EGS5 calculation.
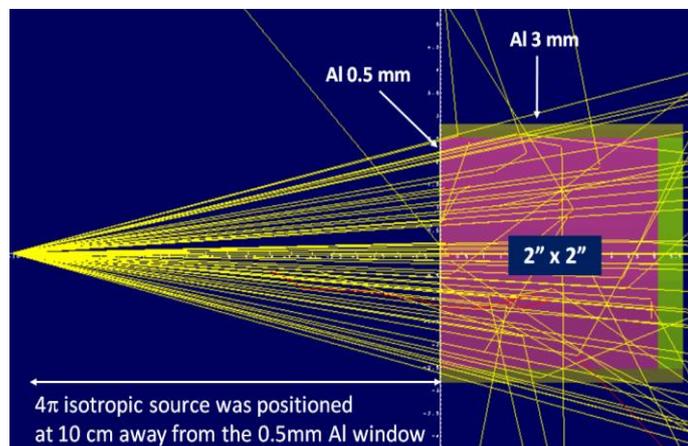
Figure 6. The model of 2 inc x 2 inc.NaI cylindrical crystal (Model: OKEN) in EGS5-CGview for particle trajectory. The outer case is aluminum of 3 mm in thickness. The window is aluminum of 0.5 mm in thickness. The density is 3.67 g/cm³. The proportion numbers of Na and I material components are 1.

COMPARISON OF PEAK EFFICIENCY AND PULSE HEIGHT SPECTRA

For the case of NaI(Tl), the measured and calculated absolute peak efficiency (PE) are in a good agreement within 3.5% as shown in Table 2. The comparison of measured and calculated pulse height spectra is presented in Figure 7 (a) for ^{137}Cs and (b) for ^{60}Co sources. The full energy peak, Compton edge, and Compton area were in agreement where they appeared at the correct value and intensity. It should be noted that the "backscatter peak" of Figure 7 around 200 keV energy region was not reproduced by the simulations. This peak arises from Compton scattering of gamma rays surrounding the detector including concrete floor [3]. We simulated only the detector-source system rather than the whole experimental setup. The resulting agreement between measured and calculated indicated that the EGS5 code can be successfully used to study the phenomena of the detector response functions.

For the case of CdZnTe detector, the absolute values and ratio of the measured and calculated peak efficiency are shown in Figure 8 (a) and (b), respectively. The uncertainty of measured absolute peak efficiencies are within 2.3% while 0.15% for the calculated ones. The literature values of absolute peak efficiencies were also included. The measured and literature data [8] are in well agreement thus justifying of our measurements. The average percentage of disagreement for all gamma sources is about 2.6% as shown in Table 3. However the calculated data of 1.0 cm x 1.0 cm CdZnTe area show a significant disagreement with measured data. Both measured and calculated peak efficiencies decrease as a function of photon energy. Above 100 keV the calculated peak efficiency overestimated the measured within 70%. For example, the measured absolute peak efficiency of [137]Cs (662 keV) is about 71% lower than the calculated value. Below 100 keV the overestimation is within 35%. The calculated value agreed with measured value within 5% in a wide energy range when the "effective" area was down to 0.8 x 0.8 cm².

(a)

(b)
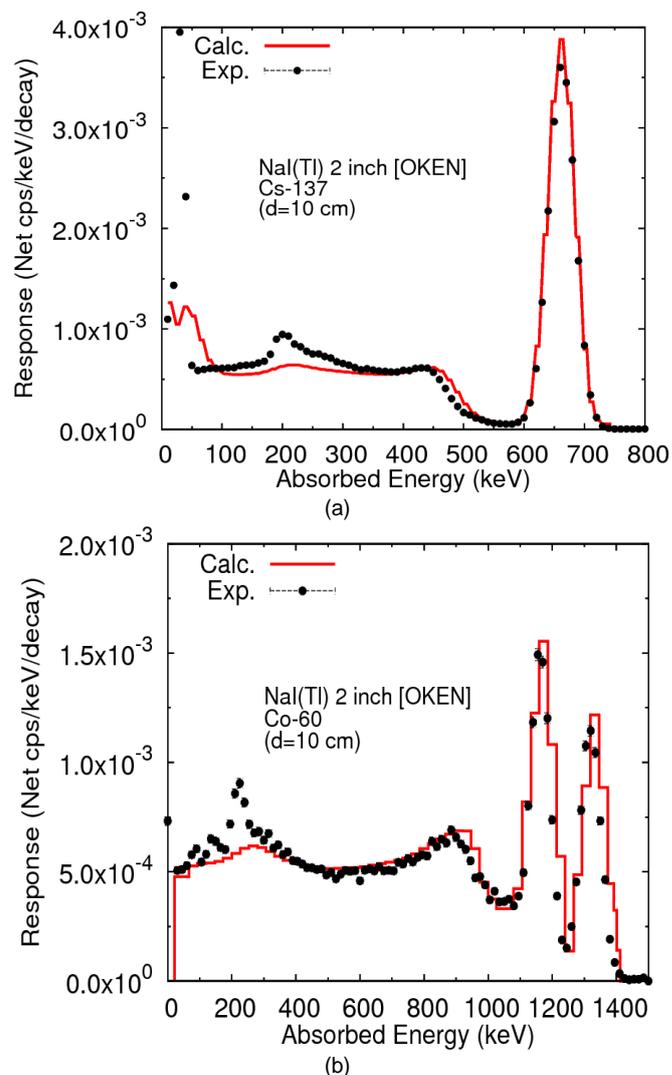
Figure 7. Measured and calculated absorbed energy spectra of [137]Cs (a) and [60]Co (b) source by NaI(Tl) detector. The calculated (solid line) photopeak, Compton edge and Compton plateau of both sources well agreed with the experimental data (black dotted).

Table 2. The comparison of measured and calculated absolute peak efficiency (%) of a 2 inc. x 2 inc. cylindrical NaI (Tl) detector.

Source	keV	Absolute Peak Efficiency (%)		Difference (%)
		Exp.	Calc.	
[137]Cs	662	21.478	22.430	4.43
[60]Co	1173	11.701	12.060	3.07
[60]Co	1333	10.162	10.570	4.02

Table 3. The comparison of measured and literature absolute peak efficiency (%) of a 1 cm³CdZnTe crystal (KROMEK, Model GR1) detector.

Source	keV	Absolute Peak Efficiency (%)		Difference (%)
		Exp.	Literature [8]	
[241]Am	60	69.8	67.4	3.49
[57]Co	122	57.1	55.95	2.05
[133]Ba	356	15.3	15.64	2.08
[137]Cs	662	4.82	495	2.75
[60]Co	1333	1.49	1.46	2.62

(a)

(b)
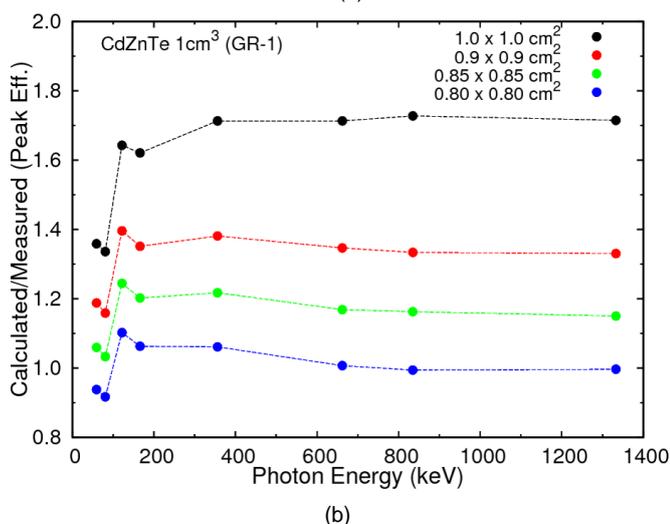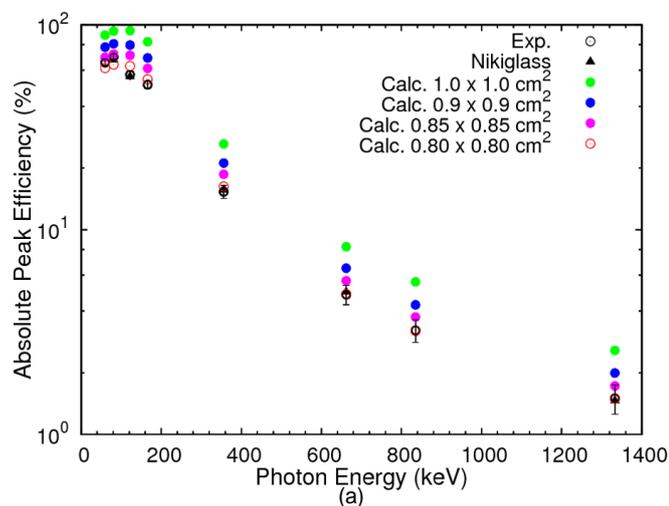
Figure 8. Comparison of measured and calculated absolute peak efficiency. In (a), the measured data (circles) are in agreement with literature (triangles). The calculated values are shown by closed circles for several areas of the CdZnTe. Figure (b) shows the ratio of calculated to measured peak efficiency as the area of CdZnTe was reduced.

The measured photopeak of ^{137}Cs was fitted by Gaussian function to obtain FWHM for smearing of calculated data as in Figure 9. The comparable of measured and calculated pulse height spectra is presented in Figure 10. The black dotted is the experimental data, the red, blue and green lines are calculated spectra for the crystal area of and 0.8 x 0.8 cm^2. The K X-ray peak, Compton edge and photopeak appeared at the correct energies with reasonable agreement of the peak widths. By comparing the red and green lines, a small peak around 200 keV was known due to the backscattered photons from the Al housing that surround the crystal. The scattered photon from the concrete floor may negligible as the measurements were performed at above 3 m distance from the concrete floor. The FEP reproduced by the calculation in close agreement to the measured one for the crystal size of 0.8 x 0.8 cm^2. The agreement in the Compton part was improved once considering the plastic source casing as indicated by the blue line.

The low energy tail of the FEP in the measured spectra indicated an incomplete charge collection efficiency and short carrier mobility-lifetime especially for holes [7]. Bolonikovet al. [8] had demonstrated by the algorithm to identify the effect of incomplete charge collection efficiency which caused by the crystal defects or "bad" regions in CdZnTe detector. Despite unknown reason with problems that have been identified, the good properties of this CdZnTe detector such as its small and compact size, stable and good resolution is very useful such as application in the development of calibration photon field [3,4] and study of transmitted photon energy spectrum for radiation shielding design [15].
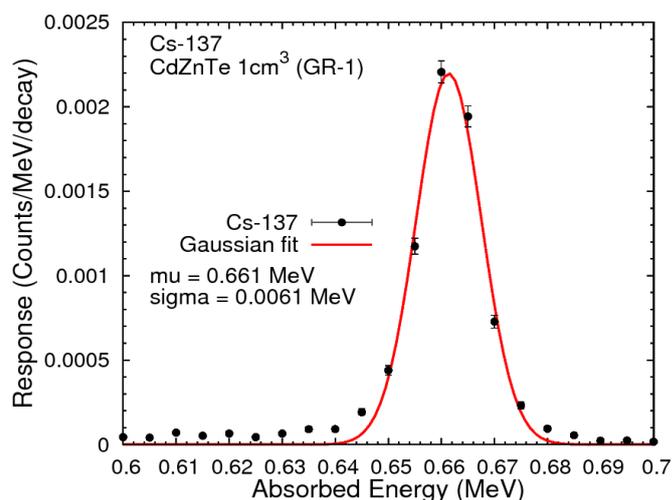
Figure 9. Measured photopeak of ^{137}Cs source (dotted) by CdZnTe was fitted by Gaussian function (R-squared value = 0.9892) to deduce the FWHM=2.16%. The calculated spectra were smeared with the same FWHM.
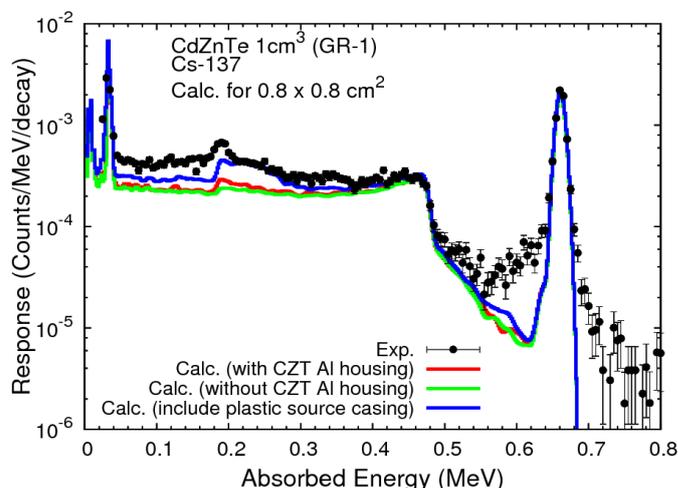
Figure 10. Measured and calculated absorbed energy spectra of ^{137}Cs source by CdZnTe. The calculated photopeak of 662 keV agreed with the experimental data (black dotted) by reducing the "effective" crystal area. By comparing the red and green line, a small peak around 200 keV was known due to the backscattered photons of Al housing.

CONCLUSION

Comparison of pulse height spectra between measurement and calculation is very important in order to understand the phenomena inside detector. Problem of disagreement of absolute peak efficiency (%) CdZnTe as reported was investigated by calculations. The insensitive region of CZT detector was estimated through experiment and calculation. The sensitive area of 0.8 x 0.8 cm^2 (instead of 1.0 x 1.0 cm^2 from the manufacturer data) was found adequate to give reasonable good agreement of the measured and calculated absorbed energy spectra.

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