ORTECⓇ

Overview of Semiconductor Photon Detectors

ORTEC offers a wide range of semiconductor photon detectors and options which, as seen in Figure1, cover energies for X rays in the few hundred eV range up to gamma rays in the 10 MeV and above. These detectors are made of high purity germanium (HPGe both P and N type), and are cryogenically cooled.

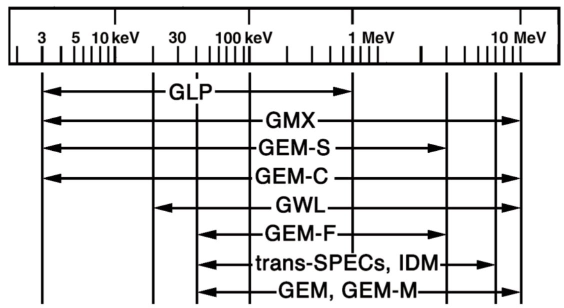

Fig. 1. ORTEC Detectors Cover the Entire Spectrum from 3 keV to >10 MeV.

GEM (P-type) and GAMMA-X (N-type) Coaxial Detectors

GEM and GAMMA-X (GMX) coaxial detectors maybe characterized by the following specifications:

Specifications	Coaxial Detector Type
Relative Efficiency at 1.33 MeV	GEM and GMX
Energy Resolution at: 1.33 MeV 122 keV 14.4 keV 5.9 keV	 GEM, GEM-S, GEM-C and GMX GEM, GEM-S and GEM-C GEM-S and GEM-C GMX
Peak-to-Compton Ratio at 1.33 MeV	GEM, GEM-S, GEM-C and GMX
Peak Shape at 1.33 MeV FW.1M/FWHM FW.02M/FWHM	GEM and GMX
^{109}Cd 22-keV/88-keV Peak Area Ratio	GMX

The PROFILE Series GEM detectors are characterized in terms of crystal dimensions being optimized for applications such as filter paper or Marinelli beaker counting.

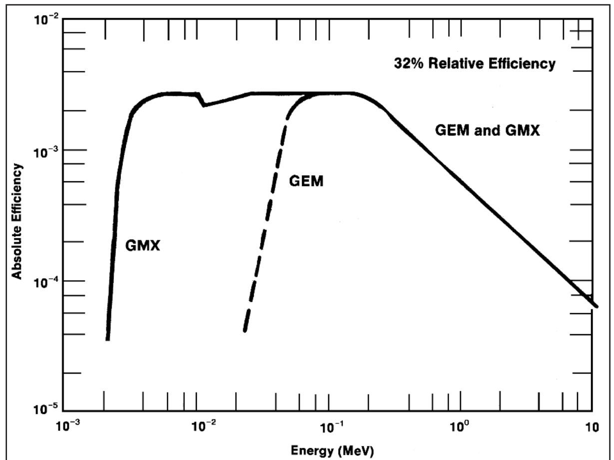

Fig. 2. Absolute Efficiency vs. Energy for 32% GEM and GAMMA-X HPGe Coaxial Detectors.

Efficiency as a Function of Energy

As shown in Fig. 2 (Refs. 1–3), the absolute efficiency of HPGe coaxial detectors varies with energy. The ratio of the number of counts in the full-energy photopeak to the total number of gamma rays emitted from a source is known as the absolute full-energy photopeak efficiency. This includes the effect of the solid angle subtended by the detector, and thus the source-to-detector distance. This absolute detection efficiency is a function of energy. For a gamma-ray or x-ray to be detected, the photon must transfer part or all of its energy by one of three interaction modes: photoelectric effect, Compton scattering, or pair production. For a count to occur within a nuclide's full-energy photopeak, all of the photon's energy must be deposited in the detector's active volume, either as a single photoelectric interaction or as a multiple event. At 1.33 MeV, ~80% of the full-energy counts start with a Compton interaction.

At gamma-ray and x-ray energies up to ~40 keV, the relationship of efficiency to energy is dominated by the attenuation of these photons by materials outside the detector and by any dead layers on the detector periphery. For this reason, the GEM (p-type) and GAMMA-X (n-type) detectors have different responses.

In GAMMA-X detectors, the 0.3-μm boron ion-implanted contact and thin beryllium front window allow photons of energy down to 3 keV to enter the active volume of the detector. Except for the anomaly at the 11-keV germanium absorption edge, virtually all photons up to 200 keV are detected. Above that energy, the efficiency falls off with the total absorption cross section of Ge, which is dominated by the fall-off in the photoelectric cross section (Fig. 3).

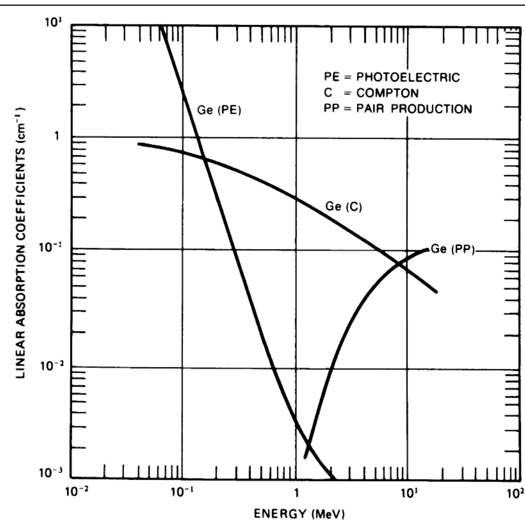

Fig. 3. Linear Absorption Coefficients vs. Gamma-Ray Energy.

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Due to the 700-μm-thick Li-diffused outer contact of the GEM detector, it experiences a fall-off of efficiency below ~100 keV, with almost all photons below 40 keV being absorbed in the outer dead layer. The GEM-S and GEM-C have much thinner front contacts (<15-μm of Ge), and are capable of seeing energies below 10 keV through the front contact. Carbon fiber windows and low-background carbon fiber endcaps are an alternate window material for seeing energies below 10 keV (Fig. 4). At higher energies the relationship between efficiency and energy is dominated by the average path length in the active volume of the detector. The efficiency decreases with increasing energy because the probability that the photon will interact within the detector also decreases with energy. Because it is primarily the detector volume (and somewhat the detector dimensions) that determines this average path length, both GEM and GAMMA-X detectors have the same efficiency at high energies (Refs. 1, 2, and 3).

A useful presentation is in Figure 5 (after Vano*), which demonstrates there is little relationship between the relative efficiency at 1.33 MeV and the relative efficiency at other energies.

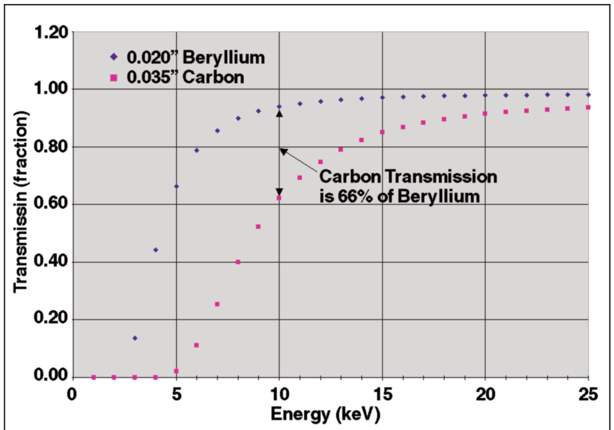

Fig. 4. Transmission through Beryllium and Carbon (0.35").

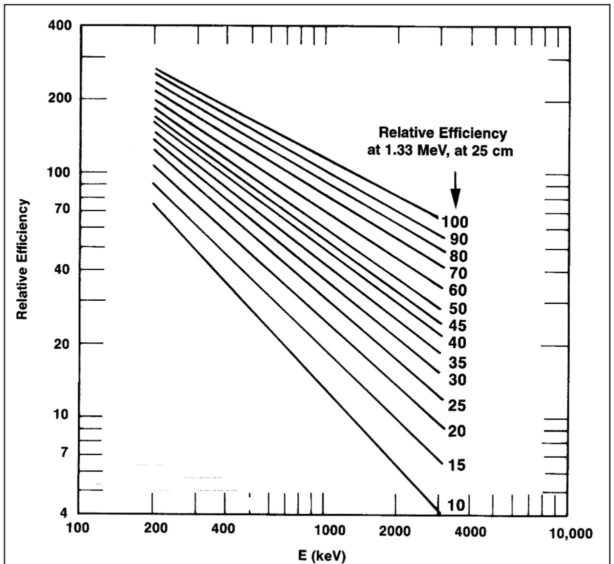

Fig. 5. Relative Efficiency as a Function of Energy for Detectors with Relative Efficiency from 10% to 100% at 1.33 MeV.

Attenuation Effects

An example of attenuation effects in external materials is shown in Table 1, the **percentage of photons transmitted through 1 mm of aluminum**, a material commonly used in detector endcaps. The relationship describing this attenuation is:

$$N = N_0 e^{-\mu x}$$

where N is the number of remaining photons in the beam of original intensity N_0 after traversing distance x, and μ is the absorption coefficient for aluminum.

Another example is the percentage of photons transmitted through 0.7 mm of germanium, which is the typical thickness of the outer contact of a GEM (p-type) detector (Table 2).

A practical example of the effects of detector dead layers on low-energy spectra is shown in Fig. 6.

Relative Efficiency (at 1.33 MeV)

For historical reasons, the relative detection efficiency of coaxial germanium detectors is defined at 1.33 MeV relative to that of a standard 3-in.-diameter, 3-in.-long NaI(Tl) scintillator. The measurement is performed by the method that is described in the IEEE Standard Test Procedures for Germanium Detectors for Ionizing Radiation (ANSI/IEEE 325–1996) and in the equivalent IEC standard. A National Institute of Standards ^{60}Co source with known intensity is positioned 25 cm from the endcap face, and a fixed-time count is taken for the 1.33-MeV peak. The absolute efficiency is the ratio of the number of counts in the photopeak divided by the number of gamma rays emitted from the source during the same period of time. This absolute efficiency is then divided by 1.2 X 10^{-3}, which is the absolute efficiency at 1.33 MeV of a standard 3-in. by 3-in. NaI(Tl) crystal 25 cm from the source. The ratio of these measurements is the basis for the relative efficiency specification of the germanium detector.

Relative efficiency, while giving a general indicator of detector performance, can be highly misleading in regards to specific geometries (e.g., filter paper or Marinelli beakers). For this reason, ORTEC offers the PROFILE Series GEM detectors with warranted crystal dimensions.

Table 1. Percentage of Photons Transmitted, as a Function of Energy, through 1 mm of Aluminum.

Energy (keV)	% Transmitted
3	0
5	0
10	8.5×10^{-2}
20	40
30	74
50	91
80	95
100	96
400	97
1000	98

Table 2. Percentage of Photons Transmitted, as a Function of Energy, through 0.7 mm of Germanium..

Energy (keV)	% Transmitted
20	1.5×10^{-7}
30	.6
40	10
50	29
60	47
80	70
100	81

*Nucl. Instrum. Methods, **23** (1975) 573–4.

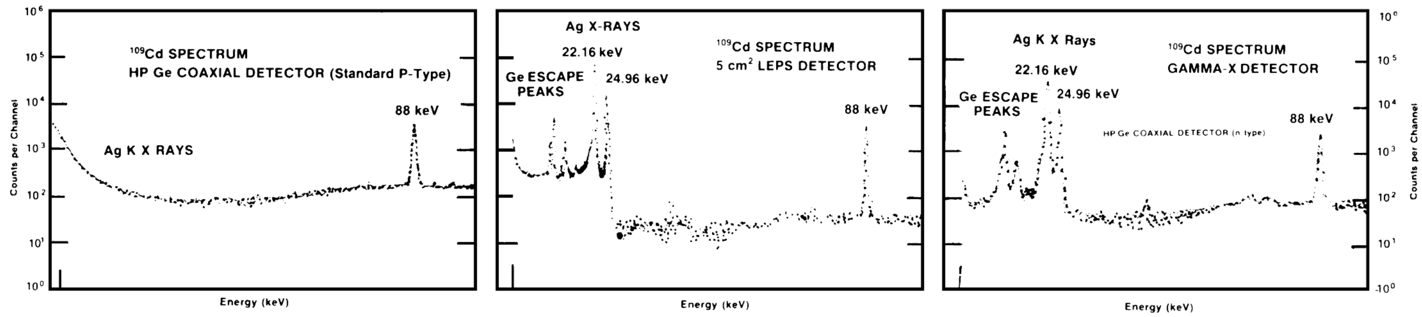

Fig. 6. ^{109}**Cd Spectrum Observed with: (a) a 10% Relative Efficiency GEM Detector; (b) a 5-cm^2 Active Area, 10-mm Active Depth HPGe LEPS Detector; (c) a 10% Relative Efficiency GAMMA-X Detector.**

The Efficiency Advantage

Many ORTEC coaxial germanium detectors have a measured relative efficiency substantially higher than the warranted value.

The PROFILE Advantage

PROFILE Series GEM detectors offer warranted crystal dimensions, greatly increasing detection limit predictability.

Relationship of Relative Efficiency to Active Volume

As the volume of a coaxial detector increases, so does its relative efficiency (measured at 1.33 MeV). However, there is not a simple relationship between volume and relative efficiency. The efficiency increases faster with detector radius than with detector length. An approximate (**not** dimensionally correct) relationship is:

$$\text{Relative Eff (\%)} = \frac{\text{Volume (cc)}}{4.3}$$

Since the density of germanium is 5.33 g/cc, ~23 g of Ge in the finished detector is required for each “percent” of efficiency.

A more recent empirical formula relating volume to efficiency is the following (courtesy of Dr. T.L. Khoo of Argonne National Lab):

$$\text{Relative Eff (\%)} = KD^{\alpha} L^{\beta},$$

where D = active crystal diameter, L = crystal length, K = 2.4321, α = 2.8155, and β = 0.7785. (Diameter and length in decimeters.)

This formula illustrates how detectors of the same % relative efficiency (IEEE 325) can have very different dimensions.

Energy Resolution

The energy resolution is a measure of the detector’s ability to distinguish closely-spaced lines in the spectrum. The method used to measure the energy resolution is also described in ANSI/IEEE 325–1996.

Energy Resolution as a Function of Energy

For the energy range **up to 1.5 MeV**, the following approximate (and **not** dimensionally correct) expression is useful for predicting the resolution of a Ge detector:

$$R = (N^2 + 2E)^{1/2}$$

where R is the energy resolution (FWHM) at the energy of interest, N is the noise line width, and E is the energy of interest, with all quantities expressed in eV (**not** in keV).

For the range from 1.5 MeV to 10 MeV (as shown in Ref. 2), the expected resolution (FWHM) is *approximately* 0.08% to 0.1% of the energy of the line of interest. At the higher energies the measured resolution can be worse than this due to even minor trapping. The actual measured values depend on the quality of the Ge crystal used to manufacture the detector element, the depth of the hole in the center of the crystal, extent of shaping of the crystal’s front “corners,” and other manufacturing details. All Ge detectors are not created equal!

Energy Resolution as a Function of Temperature

Most HPGe detectors begin to show increasing leakage current and electronic noise at temperatures above ~110 K. Due to the different cooling capabilities of various cryostats, HPGe detectors normally operate at temperatures in the range from 85 to 100 K. A stable operating temperature is essential. Because E, the average energy necessary to create an electron hole-pair (see Table 3), varies with temperature at a rate of 2.53×10^{-4} per degree K (Ref. 4), temperature variations during a measurement result in a peak shift that degrades the energy resolution. Temperatures below 40 K may result in deterioration in energy resolution due to trapping effects.

There are several references[5,6] useful for those planning to use germanium detectors at temperatures higher or lower than the customary temperature. Because the FET that is in the first stage of the preamplifier is inside the cryostat and yet must be held at ~115 K, the use of germanium detectors at unusual operating temperatures may result in increased first-stage preamplifier noise.

Table 3. Some Basic Properties of Germanium.*	
Atomic number	32
Density (300 K); $g \cdot cm^{-3}$	5.33
Atoms; cm^{-3}	4.41×10^{22}
Dielectric constant	16
Forbidden energy gap (300 K); eV	0.665
Forbidden energy gap (0 K); eV	0.746
Electron mobility (300 K); $cm^2 \cdot V^{-1} \cdot s^{-1}$	3900
Hole mobility (300 K); $cm^2 \cdot V^{-1} \cdot s^{-1}$	1900
Electron mobility (77 K); $cm^2 \cdot V^{-1} \cdot s^{-1}$	3.6×10^4
Hole mobility (77 K); $cm^2 \cdot V^{-1} \cdot s^{-1}$	4.2×10^4
Carrier saturation velocity; $cm \cdot s^{-1}$ (300 K)	5.9×10^6
Carrier saturation velocity; $cm \cdot s^{-1}$ (77 K)	9.6×10^6
Energy per hole-electron pair (77 K); eV	2.96
*All ORTEC semiconductor radiation detectors are made of germanium.	

Operation in Magnetic Fields

If it is necessary to operate a germanium detector in a high magnetic field (~ several hundred millitesla) there is danger that even with a good vacuum a Penning discharge may cause surface leakage current, which will make the detector inoperable.

ORTEC can, on request, prevent such an occurrence by providing a modified detector mount which includes an insulator between the endcap wall and the detector outer contact sitting at high voltage.

Peak-to-Compton Ratio

The peak-to-Compton ratio, also measured in accordance with ANSI/IEEE 325–1996, is the key indicator of a detector's ability to distinguish low-energy peaks in the presence of high-energy sources. **The peak-to-Compton ratio is one of the most important and yet most often overlooked — sometimes even unspecified — measures of detector performance.** The Compton plateau results from Compton interactions in the detector in which the resulting photon, reduced in energy, escapes from the sensitive volume of the detector. The peak-to-Compton ratio is obtained by dividing the height of the 1.33-MeV peak by the average Compton plateau between 1.040 and 1.096 MeV. Again, the typical measured peak-to-Compton ratio for ORTEC detectors is substantially better than the warranted specifications. For a given value of the relative efficiency, **higher peak-to-Compton values are achieved with better values of energy resolution**. [Note: For two HPGe detector elements **having the same diameter and length**, the product of resolution (at 1.33 MeV) times the peak-to-Compton ratio is a constant; therefore, if one detector has 10% better resolution, it will have a 10% higher peak-to-Compton ratio.]

Peak Shape

In cases where two peaks have nearly identical energies (and the smaller peak is on the low-energy side of the larger peak), near-perfect Gaussian peak shape is essential to quantify the smaller peak's net area. As demands for reduced MDAs become more pervasive, excellent peak shape is increasingly important. Even when the most sophisticated software is employed to deconvolute interferences, the precision of the result and the MDA is limited by the extent of the interference of the peaks with each other.

The ratios FW.1M/FWHM (FW.1M = Full Width at One-Tenth Maximum) and FW.02M/FWHM (FW.02M = Full Width at One-Fiftieth Maximum) are excellent means of describing this shape. The theoretical Gaussian peak has a FW.1M/FWHM ratio of 1.83 and an FW.02M/FWHM ratio of 2.38. *Most ORTEC detectors have peak shapes close to these theoretical numbers.*

22-keV Peak/88-keV Peak Area

This specification quantifies the thinness of the entrance window in GAMMA-X detectors. The natural ratio of gamma rays from the 22-keV and 88-keV lines of a ^{109}Cd source is ~21:1. A GAMMA-X detector typically displays a ratio >20:1. For comparison, the ratio for a GEM (p-type) detector is ~1:100.

Table 4. Typical Timing Results Measured with ORTEC's Coaxial Detectors.													
					Timing Resolution (ns)								
					Mean Energy (keV) Using ^{22}Na				Mean Energy (keV) Using ^{60}Co				
Detector System	Detector Type	Efficiency (%)	Optimum Delay (ns)	Measure	150	250	350	511	511	750	950	1170	1330
1	HPGe-P	11.0	24	FWHM	9.2	6.7	5.8	4.0	3.9	3.0	2.6	2.0	1.7
				FW.1M	–	45.3	22.2	9.9	10.2	8.4	7.5	5.6	5.1
2	HPGe-N	19.8	23	FWHM	12.5	8.6	7.0	4.5	4.9	3.7	3.1	2.2	2.0
				FW.1M	84.0	33.0	18.1	10.2	11.9	8.6	7.7	5.5	4.9
3	HPGe-P	28.0	34	FWHM	11.3	8.8	7.7	5.6	6.2	5.7	4.0	3.6	3.4
				FW.1M	–	55.8	27.1	12.8	13.4	12.3	11.8	9.8	9.0

Timing with HPGe Coaxial Detectors

The timing performance of a coaxial detector defines its ability to distinguish between two events closely spaced in time.

Timing performance depends greatly on proper electronic setup. Table 4 shows some typical timing results measured with ORTEC detectors. The timing performance of a 61% GAMMA-X detector (with a Model 583 Constant-Fraction Discriminator threshold set at 50 keV and the energy range selected with a Model 551 Timing Single-Channel Analyzer) is as follows:

At E > 100 keV	FWHM = 5.5 ns
At E = 1.33 MeV (±50 keV)	FWHM = 3.7 ns
	FW.1M = 8.9 ns

Results obtained with large GAMMA-X detectors are shown in Table 5.

Table 5. Timing Data Obtained on Three High Efficiency GAMMA-X Detectors Included in the EUROGAM Array
(P. Nolan, *et al.*, Internal Daresbury Report – July 1991).

Detector	Efficiency (%)	E (keV)	FWHM (nsec)
A	69.2	50–1332	5.8
		1332	4.3
		779	6.8
		344	9.0
		122	19.0
B	80.2	50–1332	9.2
		1332	6.7
		779	8.7
		344	13.3
		122	18.1
C	70.2	50–1332	7.2
		1332	4.7
		779	6.0
		344	10.6
		122	22.2

GLP HPGe Coaxial Low-Energy Photon Spectrometers

Detectors of choice for high-resolution, low photon energies are GLP Series (Planar) detectors. The following information is provided for these detectors: active diameter, active depth, resolution at 5.9 keV measured with optimal time constants, and energy resolution at 122 keV.

Intrinsic Efficiency

Intrinsic (full-energy) efficiency is the probability that a photon of a given energy ε, impinging on the front of the detector will be completely absorbed by the detector element. Although the intrinsic efficiency is not a standard specification for GLP detectors, it is a parameter of interest from 3 to 100 keV. The curves in Fig. 7 show the intrinsic efficiency values for GLP detectors.

Typically, GLP series detectors are “black” for energies up to 120 keV.

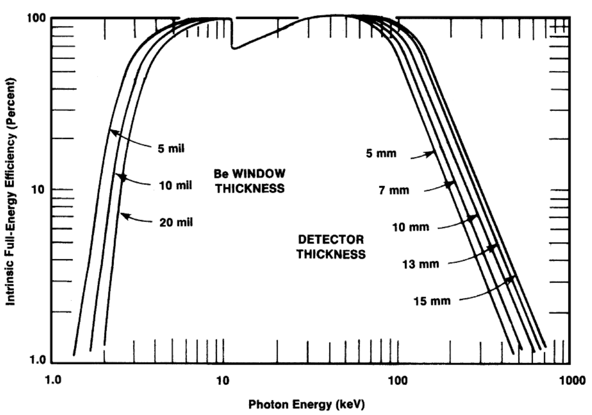

Fig. 7. Intrinsic Full-Energy Efficiency vs. Energy for GLP Detectors as a Function of Be Window Thickness and Detector Thickness.

Overview of Semiconductor Photon Detectors

Timing at Low Energies with Planar Germanium Detectors

For timing measurements at energies below 150 keV planar HPGe (GLP series) detectors are the best choice. Table 6 shows results obtained with GLP detectors of 10 cm^2.

Table 6. Timing at Low Energies with 10 cm^2 Active Area Planar Detectors*.

Source	Energy (keV)	Time Resolution(ns)
^{22}Na	20 ±10	20 ±2
	100 ±10	8.5 ±1
	511 ±5	4.5 ±0.2
^{133}Ba	31 ±3	19 ±2
	81 ±3	Isomer
	85 ±5	11 ±1
	356 ±5	6.0 ±0.5
^{152}Eu	41 ±3	15 ±1
	122 ±5	Isomer
	125 ±5	6.5 ±0.5
	344 ±5	5.0 ±0.2
	779 ±5	3.8 ±0.3

*Data courtesy of Dr. Kim Lister, Argonne National Lab.

Well Detectors (GWL Series)

Well detector design maximizes efficiency for small samples. The Well detector is actually a p-type HPGe coaxial detector mounted with a large central hole facing the front of the endcap.

Historically, Well detectors have been characterized by the following parameters:

- Active volume (cc)
- Diameter (mm) of endcap well
- Depth (mm) of endcap well
- Energy resolution at 1.33 MeV (keV FWHM)
- Energy resolution at 122 keV (keV FWHM)

Efficiency of Well Detectors

Data on efficiency of Well detectors can be found in the literature (Ref. 8). Figure 8 shows a typical efficiency curve for point sources placed at the bottom of the Well.

The ORTEC Well Detector Advantage

The “blind well” approach pioneered by ORTEC puts sensitive germanium immediately under the sample, and thus increases the detector efficiency, particularly for low-energy lines.

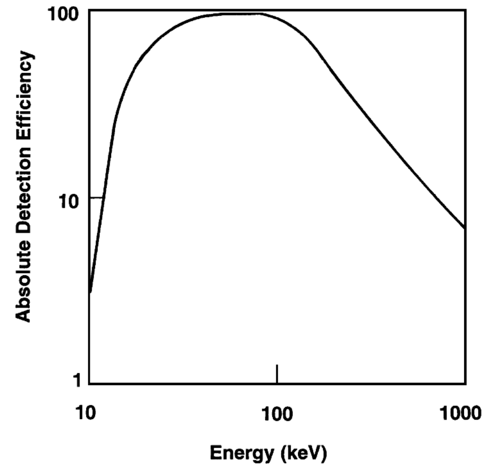

Fig. 8. Absolute Detection Efficiency vs. Photon Energy for a Typical ORTEC Well Detector.

Detector Microphonics

After more than 50 years of germanium detector production the phenomenon of microphonics is still not well understood. A back-of-the-envelope calculation leads to the false conclusion that no germanium detector will ever operate. For example, consider a metal part, such as the cup that holds the detector, which has a small, but non-zero capacitance with respect to the FET gate. Assume that sound waves, such as from a voice, induce a variation of merely 0.5 femtofarads in the value of this capacitance; the result would be a signal equivalent to 10 keV!

Although there is no IEEE standard on the measurement of the extent of microphonics, considerable work has been done in this field:

1) Special design: ORTEC has always been at the forefront in this field, for example production of a rugged detector designed for the U.S. Navy (Ref. 9). ORTEC has also provided arrays of germanium detectors for helicopter aerial surveillance.

2) Proper electronic setup: As the microphonics spectrum is primarily in the few kcps range, a high pass filter (shorter amplifier time constants and baseline restorer “on”) will often improve detector performance.

3) Vibration decoupling: Users typically obtain improvement by using soft foam rubber around and under the detector.

References

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