The Best Gamma-Ray Detector

What is the best detector for gamma-ray spectroscopy? Amptek, Inc. provides signal processing electronics which can be used with a variety of detectors (some available from Amptek, Inc) and so this question is frequently asked. But there is no single answer: the right choice depends on the application. We recently obtained spectra which illustrate some of the trade-offs for gamma-ray spectroscopy. Specifically, we measured spectra using a cryogenic high purity germanium (HPGe) detector, a NaI(Tl) scintillator with photomultiplier tube, and a Peltier cooled CdTe Schottky diode. The detectors vary considerably in energy resolution and in sensitivity[1]. Their properties are shown in Table 1, but briefly:

1. HPGe is known for its high energy resolution. In Figures 1 through 3, the photopeaks are extremely sharp: the resolution is 1.8 keV FWHM (0.3%) at the 662 keV peak of ^{137}Cs. Many distinct emission lines can be seen from the uranium sample. But an HPGe detector is costly, particularly for large volumes, and must be cooled with liquid nitrogen.
2. NaI(Tl) produces much broader peaks (~7% FWHM at 662 keV) but has much higher sensitivity because large volumes are much less expensive. The 7.6 cm dia x 7.6 cm long crystal used here (Amptek's standard Gamma-Rad5) has four times the photopeak count rate of the HPGe used here and it costs about 1/5th as much. A 10x10x40 cm^3 NaI(Tl) has a photopeak count rate ten times higher than the 7.6 cm.
3. CdTe diodes (25 mm^2 x 1 mm thick in the example here) have resolution a bit worse than HPGe, 6 keV (1%) at 662 keV, but the efficiency is much less, particularly above roughly 200 keV. Its advantages are practical: the system is compact (200 cm^3 for the whole spectrometer), it requires no liquid nitrogen, and it tolerates rugged handling and varying temperatures.
4. There are many other options, for example a CZT ($Cd_{1-x}Zn_xTe$) detector using special electrodes to achieve single carrier collection. The planar CdTe is well suited to X-ray detection (with its low noise) while the CZT is better suited to gamma-rays, with a typical volume of 1 cm^3 and a typical resolution of 13 keV (2%) at the 662 keV photopeak. No CZT was available for comparative data.

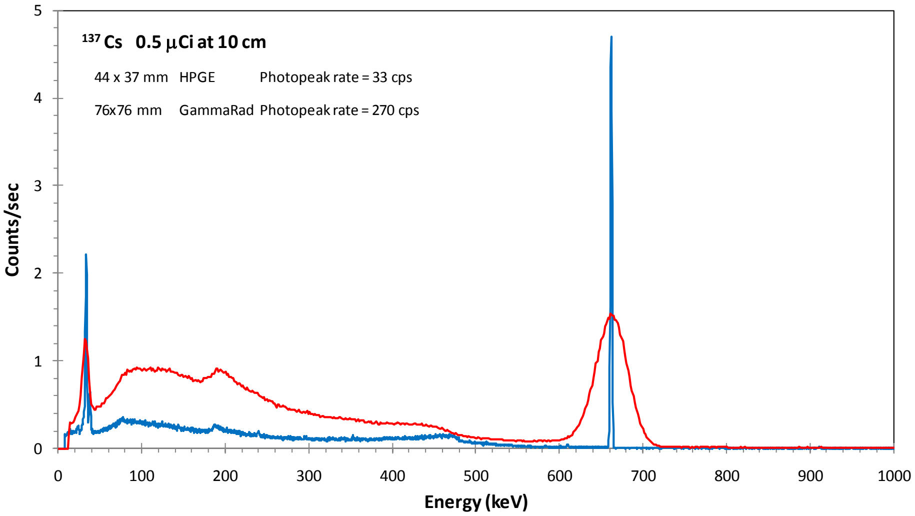

Figure 1. Plot comparing ^{137}Cs spectra measured by a cryogenic HPGe detector and a NaI(Tl) scintillator with PMT at equal distance and equal time.

---

[1] Each detector type mentioned here is available with a wide range of parameters, including size and resolution. The study done here is not exhaustive but illustrates the major trade-offs, using detectors available in our lab. The data shown here illustrate that, in general, HPGe provides very high energy resolution, scintillators have lower resolution at large volume and low costs, while the CdTe and CZT semiconductors offer practical advantages.

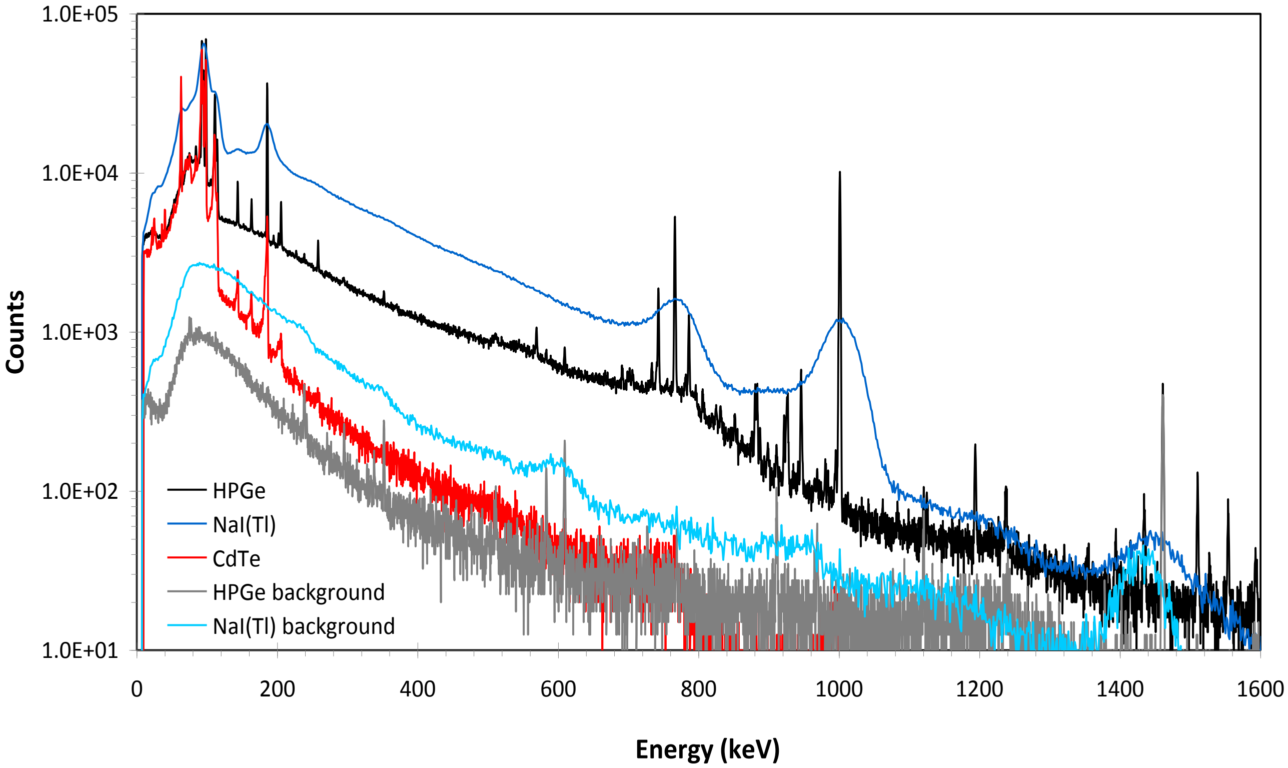

Figure 2. Plot comparing spectrum from 0.5 kg natural UO_3 measured by a cryogenic HPGe detector, a NaI(Tl) scintillator with PMT, and a CdTe diode at equal distance. The HPGe and NaI(Tl) data were taken for equal acquisition time, while the CdTe data were taken for 100 times longer.

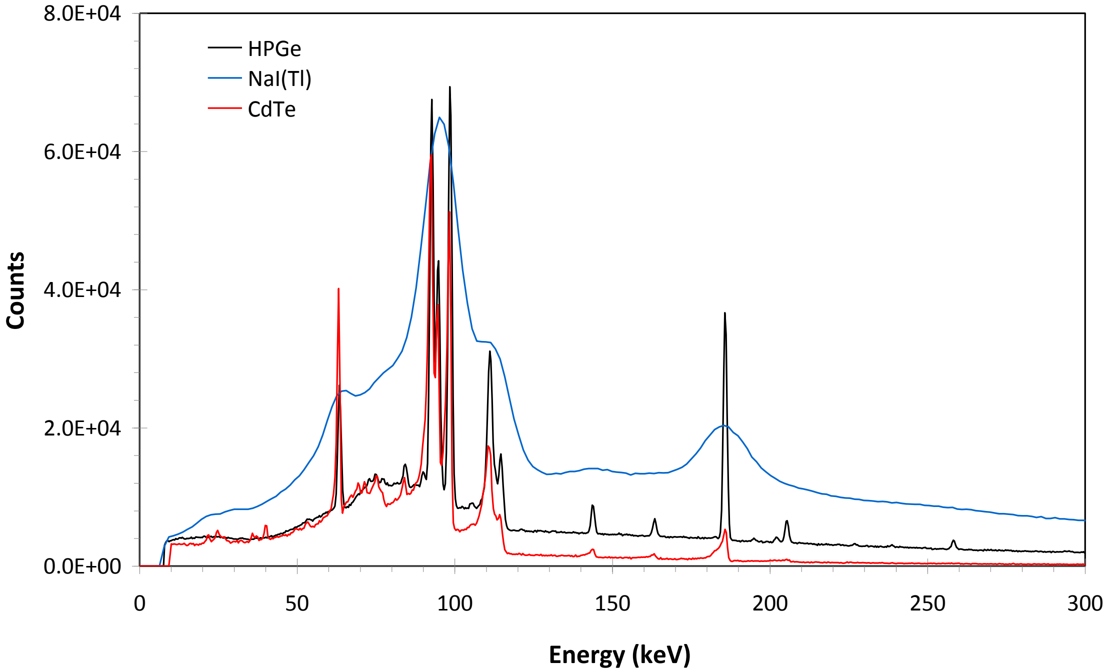

Figure 3. The low energy portion of the spectra shown in Figure 2 on a linear scale.

Minimum Detectable Activity

Which detector is more sensitive? The HPGe give sharp peaks, for a very high signal to background, but the NaI(Tl) has more counts in the photopeak. Which is better, high resolution or more counts? The answer depends on the on the measurement conditions.

There are many definitions of sensitivity. One of practical importance is the "minimum detectable activity", or MDA, the minimum amount of radioactive material which can be reliably detected above background, where "reliably" typically means the 3σ limit. This is discussed in detail by several authors (see list of references). The signal, the net counts *N* in the photopeak, is obtained by subtracting the background counts *B*, and any counts *P* from overlapping photopeaks, from the gross counts *G* in the photopeak:.

$$N = G - (B + P)$$

The MDA is defined to be such that $N_{MDA} > 3\sigma N$. Due to Poisson statistics,

$$\sigma_N^2 = \sigma_G^2 + \sigma_B^2 + \sigma_P^2 = G + B + P = N + 2B + 2P$$

which gives

$$\frac{\sigma_N^2}{N^2} = \frac{N + 2B + 2P}{N^2}$$

The HPGe detector minimizes *B* and *P* while the NaI(Tl) detector maximizes *N*. The NaI(Tl) detector will have a better MDA when there is a strong photopeak, i.e. when *B* and *P* are low even with poor energy resolution. The HPGe detector will have a better MDA when the photopeak signal is obscured by background and/or overlapping photopeaks, i.e. when *B*>>*N* and/or *P*>>*N* for the NaI(Tl).

The spectra shown in Figure 4 and Figure 5 illustrate these conditions. Figure 4 shows spectra which were obtained from a shielded ^{137}Cs source. This was a 100 µCi source, inside its lead container, located 2 m from the detectors. These spectra where acquired for 1800 seconds. The HPGe peak is much sharper, but the NaI(Tl) peak has more counts and the background is small. We obtained a set of quick spectra, 5 seconds each. The ratio N/σ_N was 4.4 for the NaI(Tl) and 2.5 for the HPGe, implying that the NaI(Tl) met the 3σ criterion for detection while the HPGe did not not. With this simple spectrum, with a known photopeak stronger than background, the NaI(Tl) demonstrated a lower MDA.

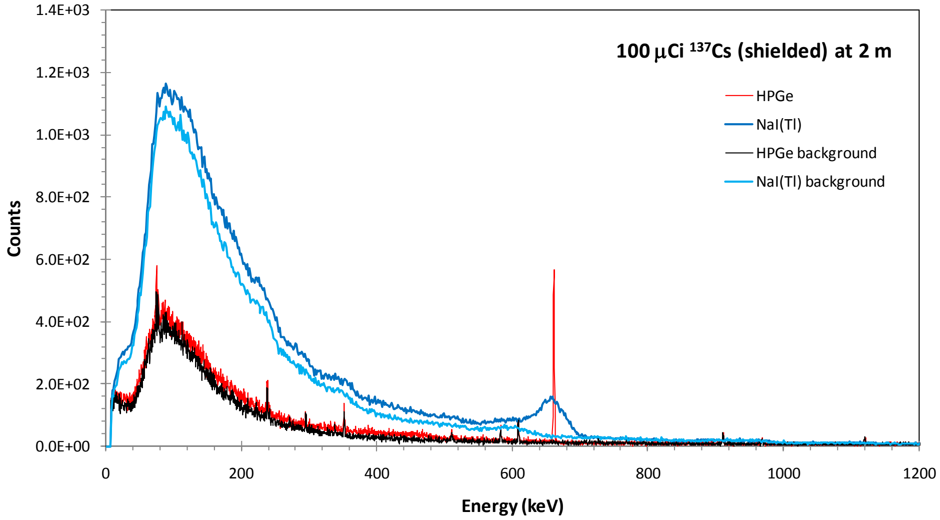

Figure 4. Spectra of a shielded 137Cs source and background.

Figure 5 shows a very different limiting case, where the photopeaks are hidden in background and in overlapping peaks. A lantern mantle containing thorium was placed close to the two detectors, then 0.5 kg of natural (unenriched) UO_3 was placed at a distance of 2 m. The red spectrum from the HPGe shows clearly two uranium peaks, the 185 keV line from ^{235}U and the 1.001 MeV line from ^{238}U. These two peaks are completely lost in the NaI(Tl) spectrum. The HPGe can detect these lines when the NaI(Tl) cannot.

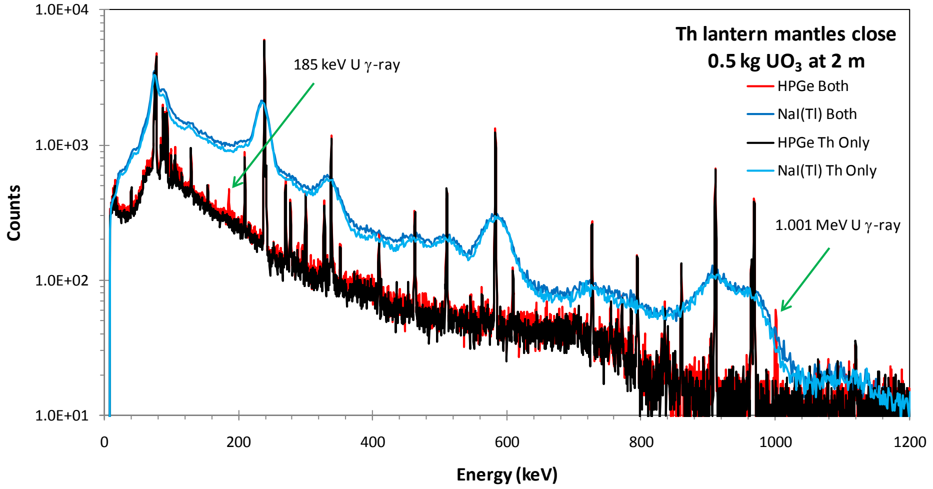

Figure 5. Spectra of a 0.5 kg UO_3 source at a low count rate, in the presence of thorium lantern mantles close to the detectors.

	CdTe Planar diode	CZT Coplanar grid	HPGe Coaxial	NaI(Tl) GammaRad 5	NaI(Tl) Large Vol
Area (cm^2)	0.25	1	15	45	400
Depth (cm)	0.1	1	3.7	7.6	10
Detector Volume (cm^3)	0.025	1	55	340	4,000
Resolution (keV)	6 keV	13 keV	1.8 keV	45 keV	50 keV
Intrinsic Photopeak Efficiency (%)	1	5	7	30	45
System Volume (cm^3)	7 x 10 x 2.5	18 x 6 x 5.5	16 (dia) x 56	10 (dia) x 32	10 x 10 x 62
Cost	$ 7,800			$ 6,900	
Other			Liquid nitrogen		

Table 1. Key properties of the detectors used here, along with two other detectors commonly used in gamma-ray spectroscopy, a coplanar grid CZT detector and a large volume NaI(Tl) scintillator. The data for the CZT was obtained from the manufacturer's web site while the large volume scintillator is from by Amptek, Inc.

Which detector is best?

- If you have a complicated spectrum so need high energy resolution at hundreds of keV, and you can accept a large system requiring liquid nitrogen and hours to cool down, HPGe is best.
- If you have simple spectra with high signal to background ratios and low signal rates, and can accept a relatively large system susceptible to temperature variations and mechanical shock, then NaI(Tl) is best. There is a trade space between size and cost.

- If you need better resolution than NaI(Tl), and sensitivity to a few hundred keV but also need small size and need to avoid cryogenic solutions, then a CZT detector with a single carrier electrode structure is best.
- If you need better resolution at energies below a few hundred keV, need small size, and need to avoid cryogenics, then the Peltier cooled CdTe diode is best.

Suggested Reading

G. Gilmore, J. Hemingway, **Practical gamma-ray spectrometry**, John Wiley & Sons, 1995

G.F. Knoll, **Radiation detection and measurement** (4th ed), John Wiley & Sons, 2010

N. Tsoulfanidis, **Measurement and detection of radiation**, Hemisphere publishing, 1983

"How sensitive is the Gamma-Rad?", at http://www.amptek.com/pdf/angrd001.pdf