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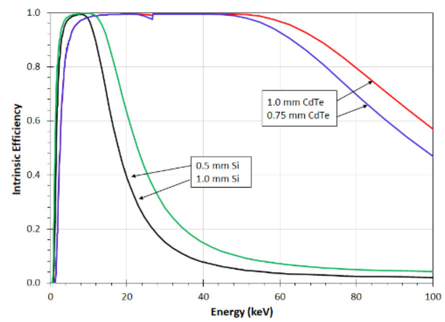
Response of CdTe detectors in X-ray spectroscopy

Amptek is the world's leading supplier of detectors and signal processing electronics for use in X-ray spectroscopy, typically used to measure the characteristic X-rays of elements in applications such as X-ray fluorescence. Silicon based detectors (FASTSDD®, SDD, and SiPIN) are the most widely used because they offer excellent energy resolution and high count rates but they suffer from low intrinsic efficiency above ~15 keV, as shown below. Amptek also offers CdTe detectors; these offer much better efficiency >15 keV (by up to a factor of 100) but their energy resolution and count rate are not as good.



As a rule of thumb, a CdTe detector is better above 20 or 30 keV while a FASTSDD® or SiPIN is better below this. Above 20 keV, the resolution is dominated by Fano broadening and the peaks of adjacent elements are widely spaced, so the FWHM of the CdTe is adequate, and the superior efficiency improves the detection. Below 20 or 30 keV, there are many overlapping peaks and good resolution is more important, so a FASTSDD® or SiPIN is superior.

Amptek has released research papers and application notes which describe the response of CdTe detectors; this application note builds on the prior notes to show typical measured spectra from CdTe and FASTSDD® detectors. We recommend the reader review the other notes before studying this one [1, 2, 3]. These notes and paper shows how the response function of a CdTe detector is different from silicon detectors:

1) The electronic noise (*ENC*) is higher in CdTe, typically 400 eV FWHM instead of <100 eV. Because the resolution is $\Delta E = \sqrt{(ENC^2 + F_{Fano} E)}$, where F_{Fano} is the Fano factor, ΔE is greatly impacted by the noise at low energies but less so at high energies.
2) CdTe detectors exhibit hole tailing, a non-Gaussian photopeak shape with a tail extending to lower energies. The tail arises from X-rays interacting deep in the crystal so is negligible at low energies (where interactions are near the entrance) but important at high energies. It extends down to some minimum energy, typically 95% of the photopeak energy.
3) CdTe exhibits very prominent escape peaks: there are four visible escape peaks for every photopeak, from the Cd K_α, Cd K_β, Te K_α, and Te K_β lines. These are in the 20-30 keV range so can escape from fairly deep in the detector.

These three effects, along with the higher efficiency, will be clearly seen in the spectra that follow. For this note, spectra were measured using (1) a 1 mm x 25 mm^2 CdTe detector (with reset preamp, 800V bias, 240K temperature), (2) a standard 0.5 mm x 25 mm^2 FASTSDD® detector, and (3) a newly released 1 mm x 25 mm^2 FASTSDD® detector. All acquisitions used an Amptek X123 with standard shaping parameters.

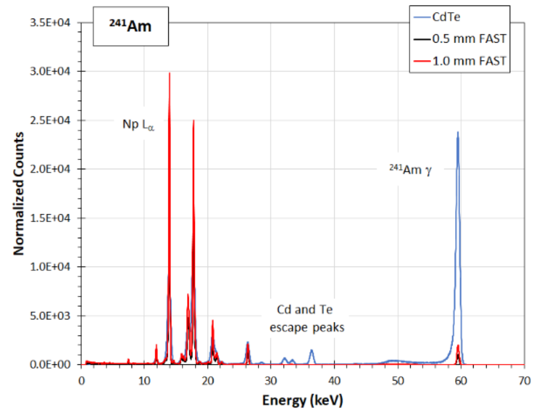
[1] Redus, R.H., J.A. Pantazis, T.J. Pantazis, A.C. Huber, and B.J. Cross, *Characterization of CdTe detectors for quantitative X-ray spectroscopy*, IEEE Transs. Nucl. Sci., Vol 56, No. 4, pp 2524 – 2532, Aug. 2009.

[2] Redus, R.H., Huber, A., Pantazis, T., Pantazis, J. and Cross, B., *Combining CdTe and Si detectors for Energy-Dispersive X-Ray Fluorescence,* X-Ray Spectrom, Vol 41, No 6, pp 393-400, Nov/Dec 2012.

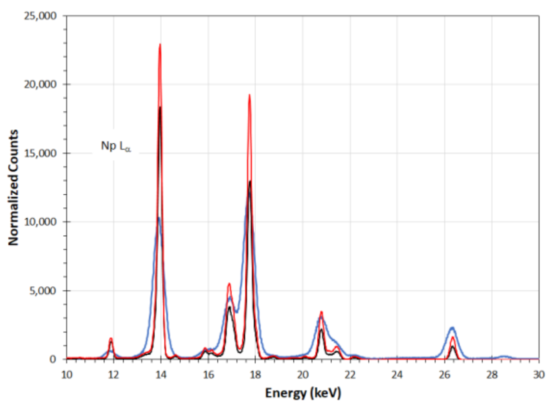
[3] *Understanding charge trapping in Amptek CdTe detectors*, Amptek application note.

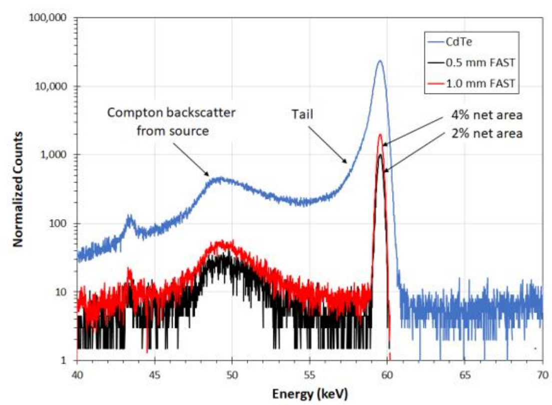
^{241}Am

The plot to the right shows spectra measured from an ^{241}Am source and illustrates the main features of spectra from CdTe versus silicon detectors. The intrinsic efficiency at 60 keV is about 25x (50x) higher than the 1 mm (0.5 mm thick) FASTSDD®. The CdTe detector has much better sensitivity to the γ photopeak; for the same conditions, the statistical precision of its response is a factor of 5 (7) time better. The 59.5 keV peak is visibly asymmetric with a tail on the low energy side; the Cd and Te escape peaks are clearly seen.



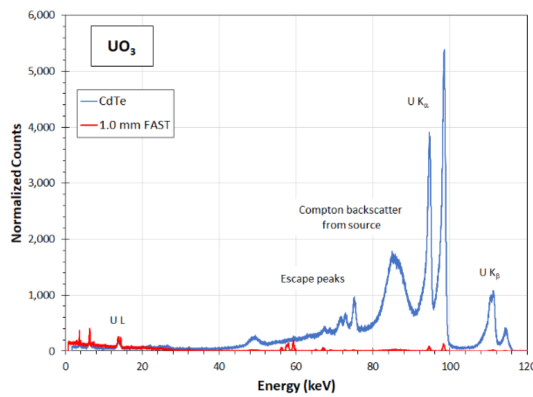
The two plots below zoom in on two energy ranges of interest. In the low energy plot on the left, for the Np L_α line, the net area of the CdTe is the same as that measured with the 1.0 mm thick FASTSDD®; both are essentially 100% efficient. The 0.5 mm thick FASTSDD® clearly has lower efficiency. The two FASTSDDs® have the same resolution; the resolution of the CdTe is clearly not as good. Whether this matters will depend on the application: if one is trying to deconvolve overlapping photopeaks, the better resolution of the FASTSDDs® will help, but if one is measuring counts in well separated peaks, the resolution of the CdTe is quite sufficient. At the 17 keV L_β lines, the two FASTSDDs® exhibit a deeper valley due to the improved FWHM but the CdTe has higher net area due to its higher sensitivity. At the 26.3 keV γ line, the differences in efficiency are very clear: the 1 mm FASTSDD® has 1.5x the net area of the 0.5 mm, and the CdTe has 3x the net are of the 1 mm.



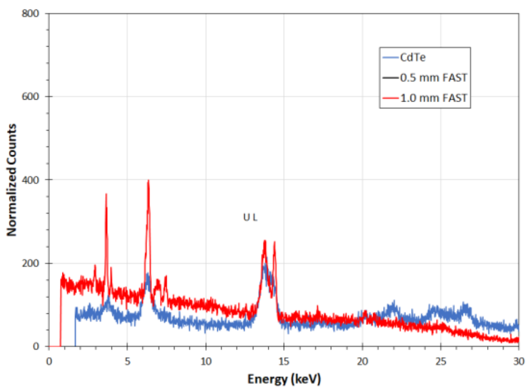


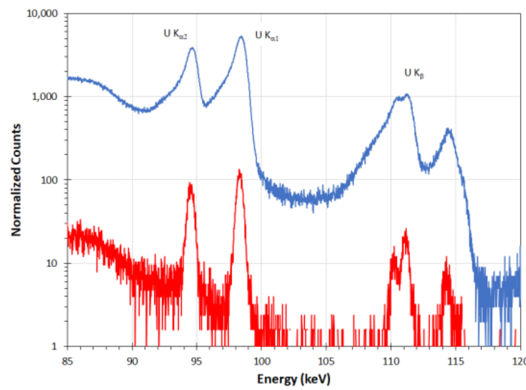
In the high energy plot, at 59.5 keV the CdTe yields a net area that is 50x that of the 0.5 mm FASTSDD® and 25x that of the 1 mm FASTSDD®. This improved efficiency will greatly improve the statistical precision or measurement time of spectroscopy in this energy range. The two FASTSDDs® have a Gaussian response with a resolution of ~400 eV FWHM (dominated by Fano broadening). The CdTe has a resolution of 650 eV FWHM with a non-Gaussian tail. The tail terminates at about 55 keV; the curve below this arises from 59.5 keV photons Compton backscattering out of the source. The backscattered continuum is visible in the FASTSDD® spectra. If one is trying to deconvolve photopeaks in the 50- 55 keV range, then properly modeling the tail is important.

Uranium ore



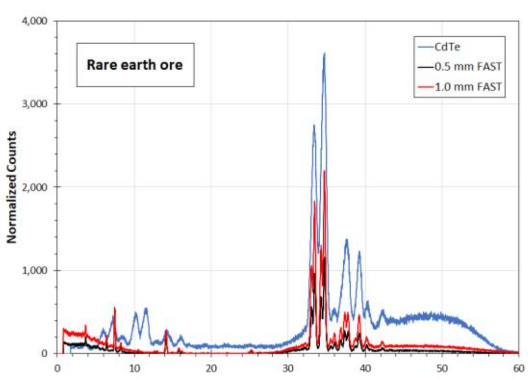
The plot to the right shows spectra measured from natural uranium oxide (yellowcake), excited by a ^{57}Co source. At the K$_\alpha$ lines, around 95 keV, the intrinsic photopeak efficiency of the CdTe detector is almost 100x higher than that of the 1 mm FASTSDD®. To achieve the same statistical precision, under the same conditions, one can measure for 1 minute with CdTe and almost 2 hours with a FASTSDD®. Further, the cross-section for Compton scattering is much higher in the FASTSDD® so the lower energy spectral background is much worse in the FASTSDD®. The plot on the lower right zooms into the K lines, making clear the higher efficiency and the shape of the tails. To measure U with a FASTSDD® or other silicon based detector, the L lines are typically used. The plot on the left below shows the low energy portion of the spectrum (the ore was inside a glass container so the glass attenuated the low energy lines; the U L lines are visible, along with K lines from Fe and Ca). The superior FWHM of the FASTSDD® is clear.

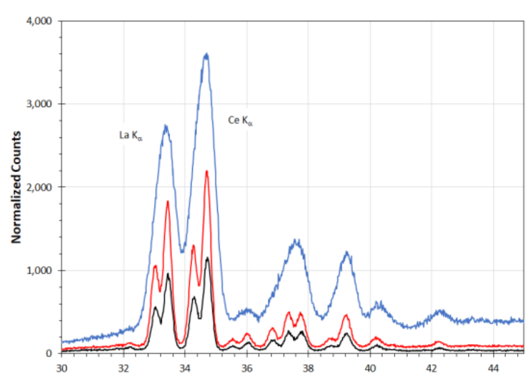




Rare earth ore

The plots below show spectra measured from a rare earth ore, excited by an X-ray tube (70 kV, Au anode). The plot on the right shows the K lines of La and Ce. The energy resolution of the CdTe is worse than that of the FASTSDD® (it cannot resolve the K$_a$ lines of each element) yet it is sufficient to resolve the Ce and La photopeaks. Because of Fano broadening and peak splitting, even the FASTSDD® needs a broad region of interest for these two lines so the resolution of the CdTe is adequate and it has 4 (8) times the sensitivity of the 1 (0.5) mm FASTSDD®.



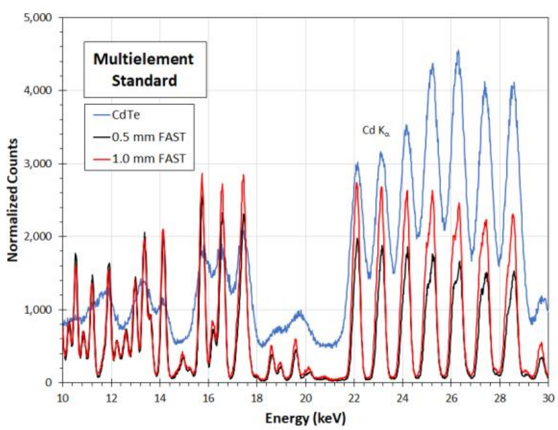


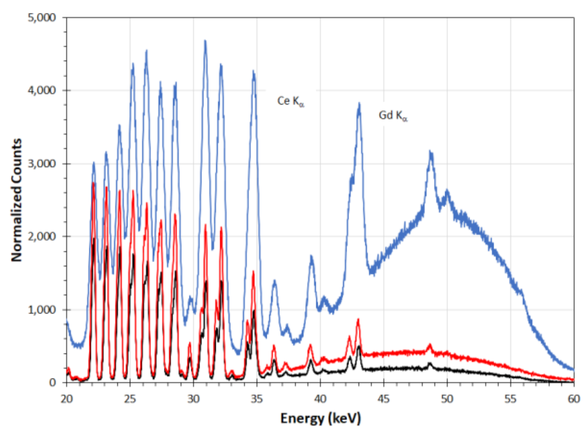
The hole tailing is not important at this energy: the Ce K$_\alpha$ peak is clearly non-Gaussian but is the sum of two Gaussians and this is the main factor forming the asymmetry in the peak. In the low energy portion of the spectrum, shown on the left, the CdTe detector shows peaks at about 10 keV not present in the FASTSDD®; these are the Cd and Te escape peaks. Between the additional escape peaks and the poorer resolution, the advantages of the FASTSDD® below 15 keV are quite clear.

Multielement standard

The plots below show similar results obtained rom a multielement standard, also excited by the Au anode, 70 kV X-ray tube.

- For the rare earth elements, above 30 keV (Ce, La, and Gd) , the CdTe detector has much better intrinsic efficiency and the resolution is adequate to resolve the photopeaks.
- For elements with K lines in the 20 to 30 range (Ag, Cd In, Sn), note that even the FASTSDD® cannot resolve the two K$_\alpha$ lines: the two lines are split by much, so Fano broadening leads to overlap even with a FASTSDD®. The CdTe detector can resolve the K$_\alpha$ lines almost as well and with a much higher intrinsic efficiency.
- For elements with K lines in the 15 to 20 keV range, the photopeaks exhibit far more overlap with the CdTe detector than with the FASTSDD® and the intrinsic efficiency is not significantly better.
- For elements with K lines below 15 keV, the CdTe detector does not resolve the individual lines. This is partly due to all the escape peaks which are formed here from the higher energy lines, along with the superior resolution of the FASTSDD®.





Conclusions

These measured spectra clearly illustrate how the response of the CdTe detector differs from that of silicon based detectors: far higher intrinsic efficiency at high energies but coupled with increased noise, hole tailing, and escape peaks. They show the important of these effects in measured spectra. They also show clearly that the CdTe detector is superior for measuring photopeaks above 20 to 30 keV while the silicon based detectors are superior to measuring photopeaks below this range.