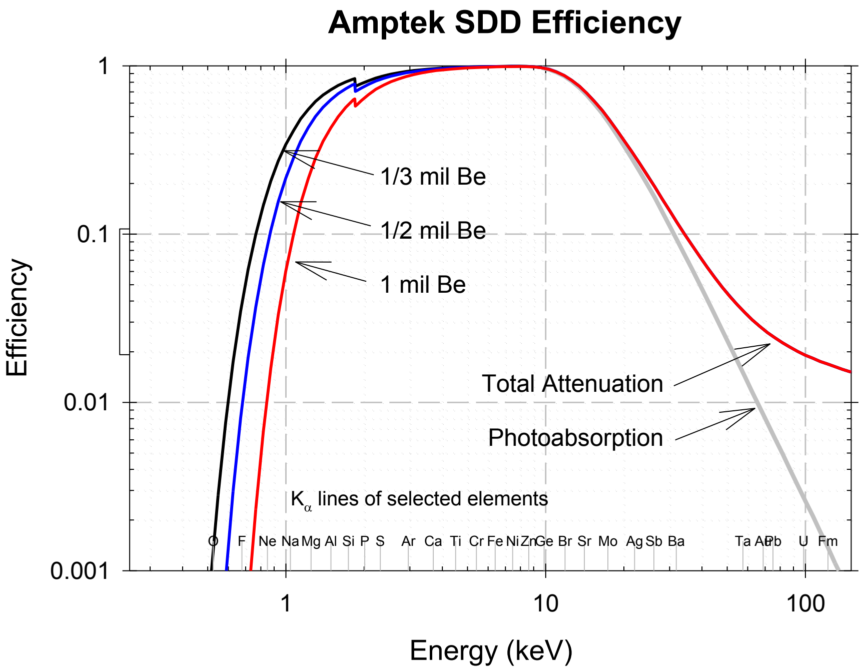
Understanding Detector Efficiency

Amptek publishes tables and charts depicting the efficiency or sensitivity of the detectors to X-rays and γ-rays. Figure 1 shows, at the top, a typical plot of efficiency versus energy. This plot shows the results for a silicon drift diode (SDD), with three different Be window thicknesses. The table on the bottom shows a fragement of ASCII data file for the same configuration.



Amptek Silicon Drift Diode (SDD)
Efficiency versus energy for 3 window thickness
For each configuration, the first column is total attenuation, second is photoabsorption
Data computed using NIST attenutation values (physics.nist.gov) and nominal device spec

For more information, visit www.amptek.com

Window	1/3 mil Be window		1/2 mil Be window		1 mil Be window	
Energy keV	Total Atten	P.E. Atten	Total Atten	P.E. Atten	Total Atten	P.E. Atten
1.07E+00	4.13E-01	4.13E-01	2.84E-01	2.84E-01	1.00E-01	1.00E-01
1.14E+00	4.84E-01	4.84E-01	3.56E-01	3.56E-01	1.52E-01	1.52E-01
1.22E+00	5.52E-01	5.52E-01	4.30E-01	4.30E-01	2.14E-01	2.14E-01
1.30E+00	6.15E-01	6.15E-01	5.01E-01	5.01E-01	2.83E-01	2.83E-01
1.39E+00	6.71E-01	6.71E-01	5.67E-01	5.67E-01	3.56E-01	3.56E-01
1.49E+00	7.21E-01	7.21E-01	6.29E-01	6.29E-01	4.29E-01	4.29E-01
1.59E+00	7.65E-01	7.65E-01	6.84E-01	6.84E-01	5.00E-01	5.00E-01
1.70E+00	8.03E-01	8.03E-01	7.32E-01	7.32E-01	5.67E-01	5.67E-01
1.80E+00	8.30E-01	8.30E-01	7.68E-01	7.68E-01	6.19E-01	6.19E-01
1.82E+00	8.35E-01	8.35E-01	7.75E-01	7.75E-01	6.29E-01	6.29E-01
1.83E+00	8.37E-01	8.37E-01	7.77E-01	7.77E-01	6.32E-01	6.32E-01
1.84E+00	8.39E-01	8.39E-01	7.79E-01	7.79E-01	6.36E-01	6.36E-01
1.85E+00	7.57E-01	7.57E-01	7.04E-01	7.04E-01	5.76E-01	5.76E-01
1.88E+00	7.64E-01	7.64E-01	7.13E-01	7.13E-01	5.88E-01	5.88E-01
1.95E+00	7.84E-01	7.84E-01	7.37E-01	7.37E-01	6.21E-01	6.21E-01
2.08E+00	8.16E-01	8.16E-01	7.76E-01	7.76E-01	6.75E-01	6.75E-01
2.22E+00	8.46E-01	8.46E-01	8.12E-01	8.12E-01	7.25E-01	7.25E-01

Figure 1. Typical efficiency plot (top) and table (bottom).

What do the values shown in the efficiency plots and tables represent?

- The "total interaction probability" represents the fraction of photons, incident on the front window of the detector hybrid, which undergo some interaction in the active volume of the detector.
- The "photoelectric interaction probability" represents the fraction of photons, incident on the front window of the detector hybrid, which undergo a photoelectric interaction in the active volume of the detector.
- The figures and tables show computed values, assuming normal incidence (perpendicular to the detector), using nominal values for the thickness and properties of the various layers, and using published values for the attenuation coefficients in these materials.

Is this all I need to know to calculate the count rate?

The count rate is a product of the source intensity, attenuation in the source and along the path (e.g. in air), the relative geometric factor (solid angle fraction), and the intrinsic efficiency. Amptek's published curves show only the intrinsic efficiency.

$$R_{in} = R_{source} \Omega \varepsilon_{source} \varepsilon_{path} \varepsilon_{\det}$$

Why is the measured count rate different from the calculation?

These numbers permit a first order estimate of the count rates but neglect some very important second order effects and effects outside the detector itself. To find the first order estimate of the count rate in the photopeak, you must

1. Compute the number of photons incident on the active area of the detector. If you have a point source at some distance d, and the active area is A, then the fraction is ($A/4\pi d^2$).
2. Multiply by the photoelectric probablity at the energy of interest. For example, the table above shows that, at 1.95 keV, an SDD with a ½ mil Be window has a photoelectric efficiency of 77.6%.

This is, however, only a first order approximation! There are many important additional factors:

(1) The $1/r^2$ approximation only holds for a point source; in many cases, the source is distributed in area and the solid angle calculation is more complicated.

(2) The photons may be attenuated before they reach the detector, for example in air. At low energy, attenuation in air may be more important than the Be window.

(3) Photons may not all pass through the detector and window at 90°. A range of angles corresponds to a range of path lengths and hence to a range of attenuations.

(4) Photons will scatter from the window, the collimator, shielding around your sample, etc, thus increasing the apparent count rate.

(5) Some of the photons which interact in the detector volume will scatter from the detector or will produce secondary particles which escape the active volume, thus decreasing the photopeak count rate.

(6) In some interactions, the primary photons does not undergo photoabsoprtion. It scatters, but the scattered particle may get absorbed in the active volume, thus increasing the photopeak counts.

(7) There are tolerances in the actual thickness of the materials used in making the detectors and some uncertainty in the attenuation coefficients. These contributions to the error are usually much smaller than t the other terms.

What limits the efficiency at high and low energies?

At high energies, the attenuation length is longer than the detector's active volume, so photons pass through the detector without interacting. To increase efficiency at high energies, one needs either a thicker detector or a material with higher stopping power (CdTe has much higher stopping power than Si).

At low energies, the photons interact in the Be window or in the dead layers or contact material at the front of the detector. To increase efficiency, one needs a thinner window (or no window at all) or thinner dead layers. This application note does not consider air, since it is outside the detector, but attenuation in air can be very important.

Can you explain what physically happens during these "interactions"?

Figure 2 is a conceptual sketch of the Amptek detector hybrid, illustrating the interactions. For the photons incident, there is a layered structure. Layer 1 is the window, layer 2 is a contact and/or dead layer, layer 3 is the active volume, and layer 4 is inactive volume. Other materials are outside the primary path, so are important only for scattering and secondary interactions. For a photon incident on the window of the detector, heading towards the detector's active volume, one of three things can happen:

1. The photon may interact before reaching the detector (blue arrows). It may interact in the Be window, in a contact material, or in a dead layer at the top of the detector. These photons will not be detected. Interactions in these layers are responsible for the loss of efficiency at low energies.
2. The photon may interact in the detector's active volume (red arrow), producing a signal. The X-ray's energy may be completed absorbed, contributing to the photopeak or fuill energy peak. However, in some interactions (pink arrow), the X-ray will scatter from the active volume or a secondary particle will escape the active volume. This leads to events with reduced energy.
3. The photon may pass through the active volume without interacting (green). These photons will not be detected, leading to the loss of efficiency at high energies.

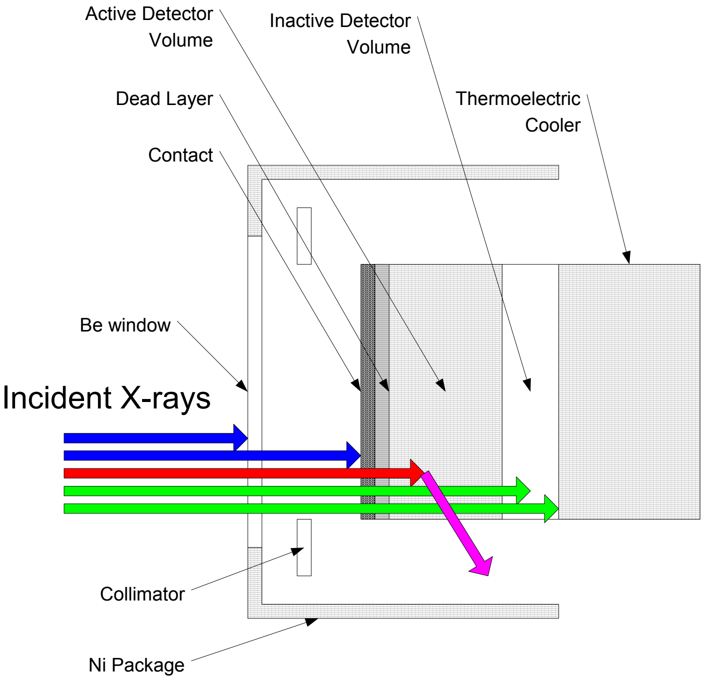


Figure 2. Sketch showing the detector hybrid and the first order model of detector efficiency.

Are these measured or computed values?

These values were computed using the nominal values for the material of the detector itself and the Be window in the hybrid package. They are not measured, although measurements have validated the calculations at a few energies. The coefficients were computed using an online calculator provided by NIST, at http://physics.nist.gov/PhysRefData/FFast/html/form.html.

What is the tolerance on these values/

- This is hard to answer, but generally, errors due to ignoring scattering and angular effects are much larger than errors in the attenuation calculation. At high energies, where the efficiency peaks and above, the computed efficiency is within 2-3%. At low energies, where the efficiency is limited by the windows and contacts, the attenuation numbers are likely to have larger errors, growing as the energy decreases.
- It is best to think of the error in the calculation of the number of photons which are not detected. If the model predicts 95% efficiency, then 5% are not detected. A 10% error in attenuation coefficients or thicknesses will lead to 0.5% error in the number not detected, hence a 0.5% error in efficiency. If the model predicts only 10% efficiency, so 90% are not detected, then a 10% error leads to a 9% error in the number not detected, so 100% uncertainty in efficiency!
- The attenuation coefficients are known to 1% well above the K edges, but are known to only 10% at the lower energies. The thickness of the active volume is known to 1-2%. The thickness of the Be windows, dead layers, and contacts have much larger tolerances.

How are the efficiencies computed?

Each layer has a specific composition, density, and thickness. The NIST calculator provides, at each energy E, the attenuation coefficients μ for each layer, in units of cm^2/g. We use the total attenuation coefficients for the layers in front of the active volume, computing the probability of absorption or scatter. For each layer, λ represents the area density, i.e. the mass density ρ (in g/cm^3) multiplied by the thickness d (in cm). The efficiency is then

$$\varepsilon(E)=\left[e^{-(\mu_1(E)\lambda_1+\mu_2(E)\lambda_2+\ldots)}\right]\left[1-e^{-\mu_{DET}(E)\lambda_{DET}}\right]$$

where the term in the first bracket is probability of transmission through the front layers and the term in the second bracket is the probability of interaction in the detector. One can use either the total or photoelectric probability for this.

What properties do you assume for the layers?

Silicon Detectors

1. Be window: Specified as 1/3 mil, ½ mil, or 1 mil.
2. Dead Layer: Typically 0.15 µm. There is no contact material (implanted junction).
3. Silicon active volume: Depends on the detector.

CdTe Detectors

1. Be window: Specified as 4 mil (100 µm)
2. Contact: Typically 0.2 µm Pt.
3. Dead Layer: Typically 0.15 µm CdTe.
4. Active volume: Depends on the detector.

Note: The density of CdTe is specified by the manufacturer as 5.85 g/cm^3. Other numbers are sometimes found in the literature.

How can I more accurately determine the efficiency or sensitivity?

In many cases, one does not need to know the efficiency of the detector per se. In X-ray fluorescence, the photopeak area is related to the concentration of the corresponding element in the sample. There are many factors which are important. The best approach is to directly measure the photopeak area with a known sample.

If one needs to know the efficiency, separate from other effects, measurement is still the best approach, but must be carried out carefully. If one uses a radioisotope of a known activity, then not only must the activity be known very well, one must include terms for self-absorption, geometric factors, etc. It usually proves extremely difficult to do this measurement with an uncertainty lower than the simple calculation! A better alternative is to use a radioisotope which emits photons at multiple energies, with a known ratio, and then look at the ratio of detected photons, using an energy high enough to neglect self-absorption. To compute the efficiency, the best solution is Monte Carlo simulation software. There are several software packages available.