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Title: Detector Fundamentals for Reachback Analysts

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Detector Fundamentals for Reachback Analysts

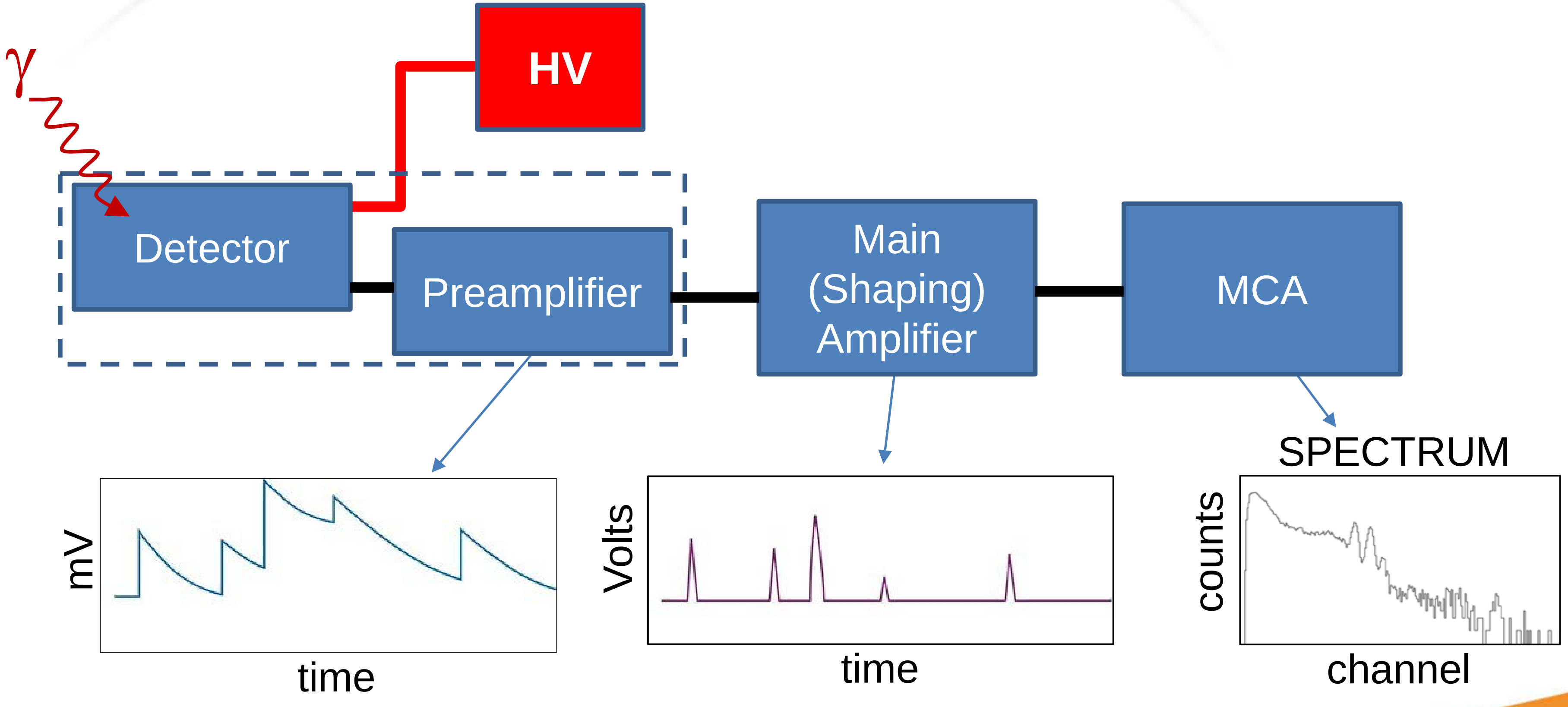
Pete Karpius & Steve Myers

August 2016

Introduction

- This presentation provides an overview of common detector concepts
  - Detector system components
  - Intrinsic and absolute efficiency
  - Resolution and linearity
  - Operational issues and limits

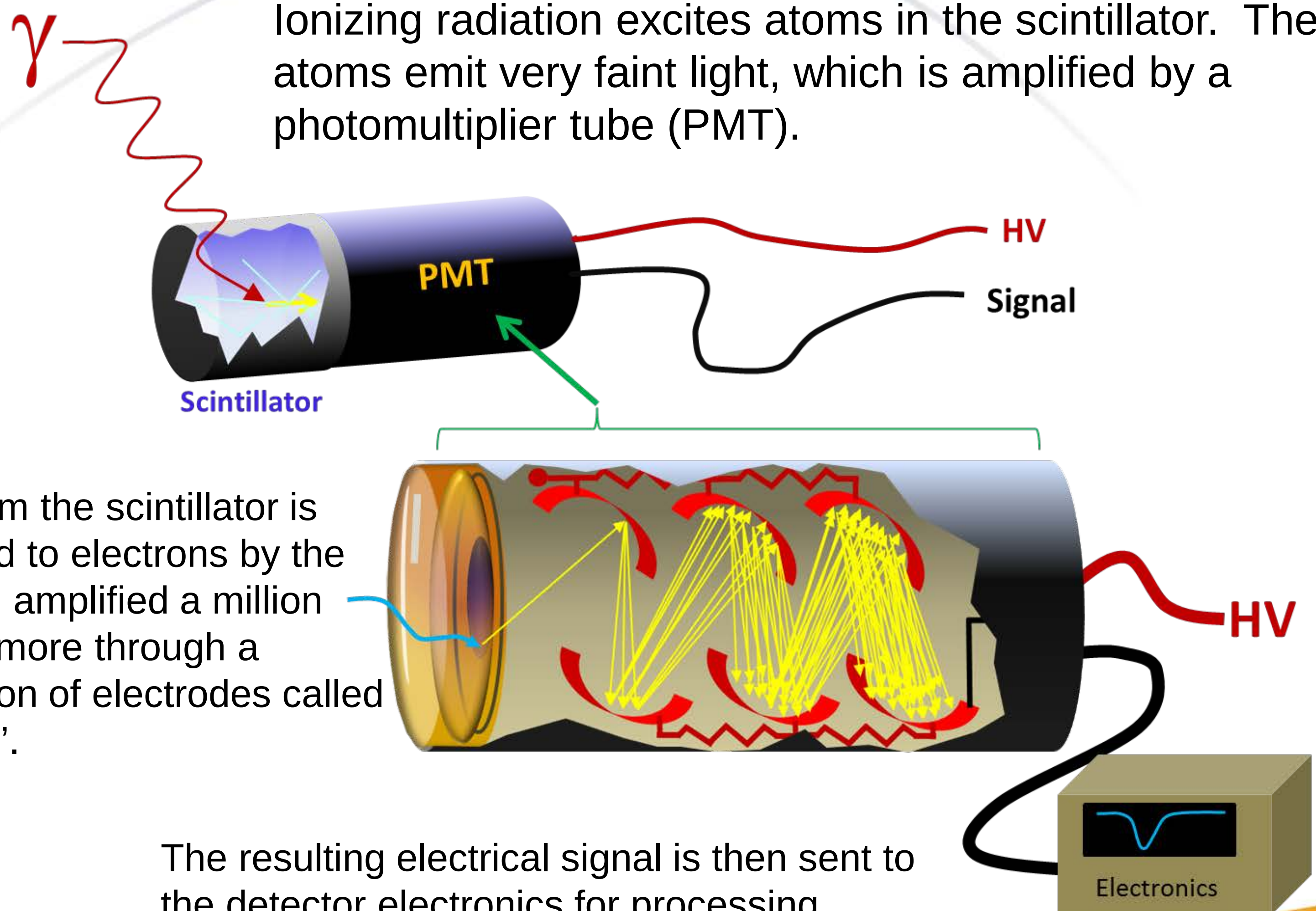
Typical Detector System Layout



Scintillation Detectors

Los Alamos NATIONAL LABORATORY EST. 1943

Ionizing radiation excites atoms in the scintillator. These atoms emit very faint light, which is amplified by a photomultiplier tube (PMT).



Light from the scintillator is converted to electrons by the PMT and amplified a million times or more through a succession of electrodes called ‘dynodes’.

The resulting electrical signal is then sent to the detector electronics for processing.

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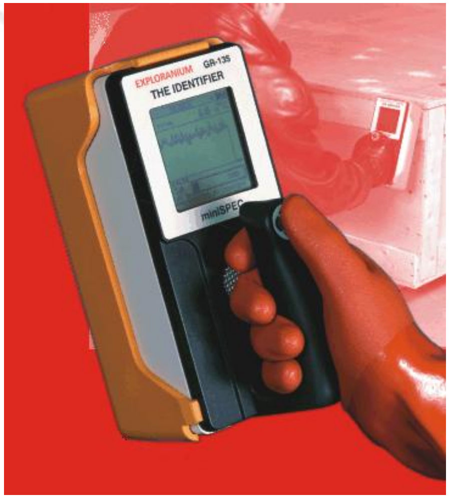
Commercial Scintillation-Based Detectors



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Problems with Scintillators

- Low resolution
  - Few information carriers result in poor statistics
  - Generation of signal is inefficient, typically requiring ~100 eV/carrier
- Temperature sensitivity
  - Gain fluctuations and non-linearities result in difficult energy calibrations

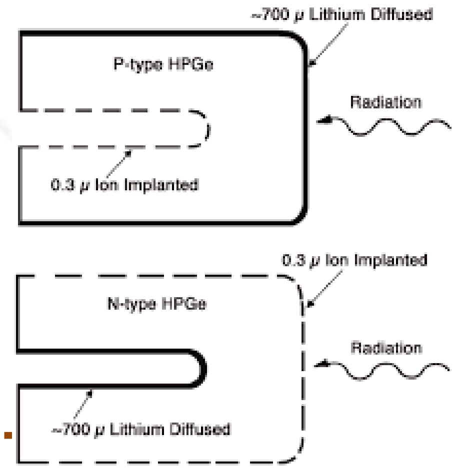
The only way to improve resolution is to get more information carriers per incident gamma ray.

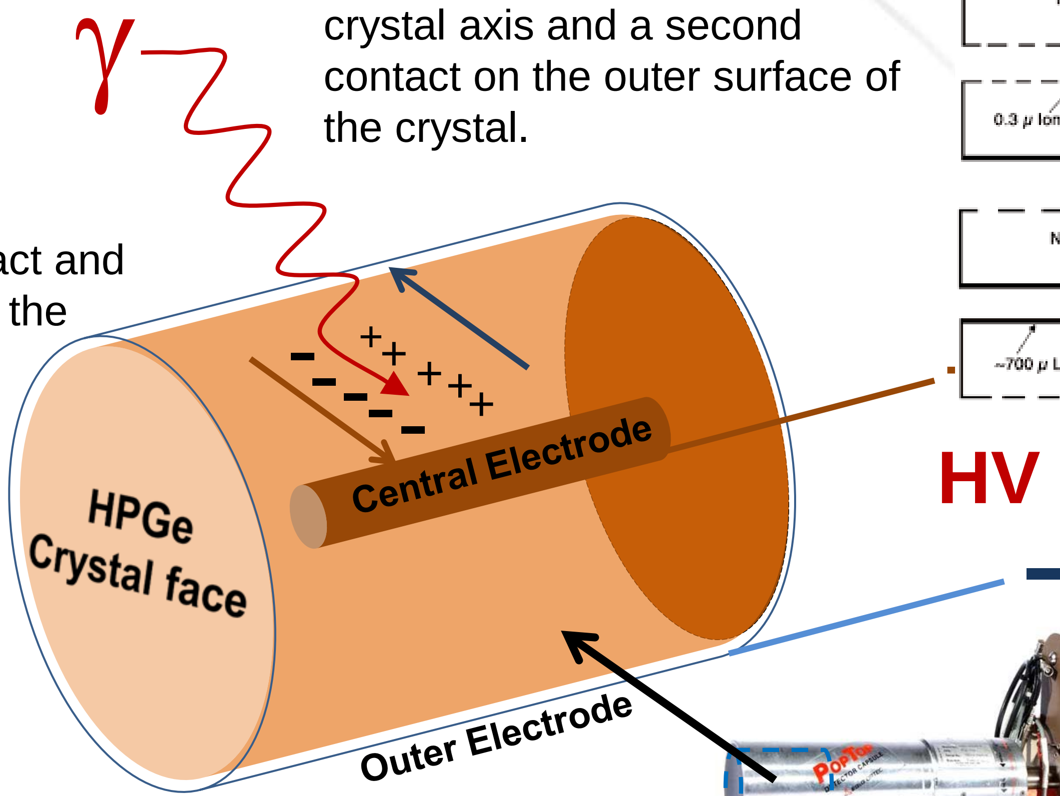
High-Purity Germanium (HPGe)

Gamma rays create "electron – hole" pairs in the detector crystal.

When high-voltage is applied, electrons are collected at one contact and holes are collected at the other contact.

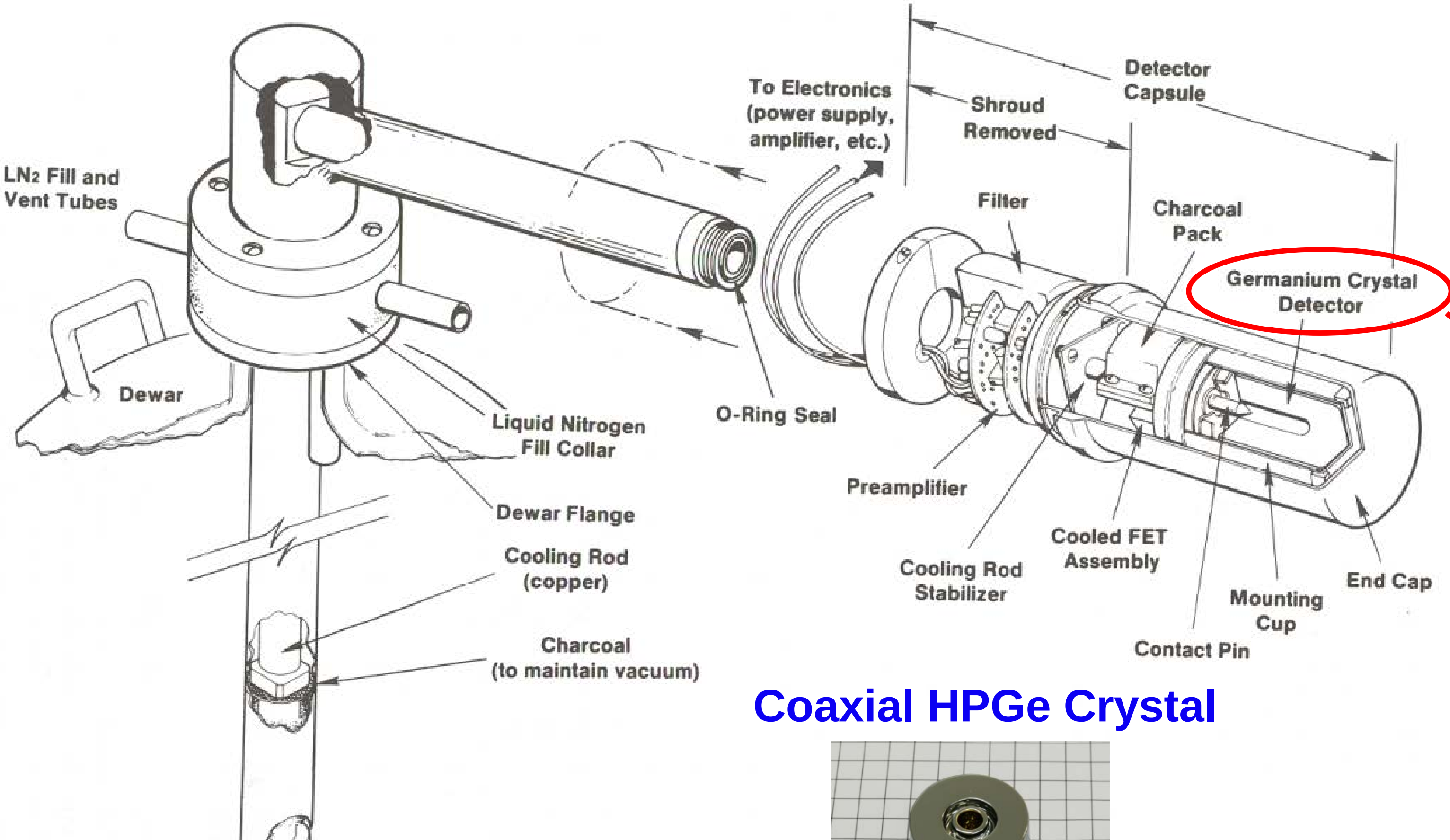
A coaxial HPGe detector has an electrical contact on the crystal axis and a second contact on the outer surface of the crystal.





HPGe detectors must be cooled to ~77 K (-321 F)

LN2-Cooled HPGe Schematic



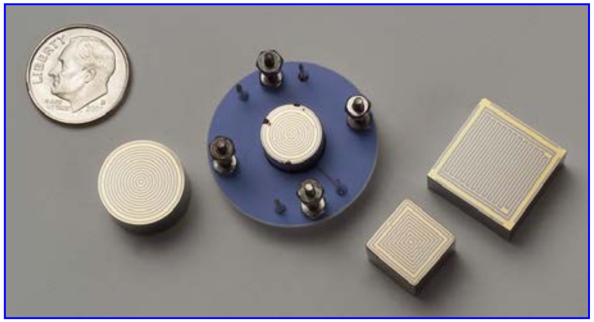
Coaxial HPGe Crystal

High Purity Germanium (HPGe)

- Excellent charge carrier mobilities
  - Results in much improved energy resolution
- Band gap = 0.74 eV
  - Must cool to LN temperatures to avoid thermal excitation of electrons
- Large crystal growth allows good efficiency
  - 140-160% not uncommon (relative to a 3” x 3” NaI)

CdZnTe

- E_g large enough for room-temperature operation
- Typically can attain <3% resolution but with new signal processing now <1%
- Difficult to grow large crystals (~ 6 cm^3 max)
- Poor hole mobility requires very sophisticated electrodes and read out



Commercial Semiconductor-Based Detectors

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Quantifying Source Activity or Mass

$$Activity = \frac{C(E)}{Y(E)} \cdot \frac{1}{\varepsilon_{Abs}(E)}$$

$$Mass = Activity \cdot \frac{T_{1/2}}{ln2} \cdot \frac{A}{6.022E+23}$$

C(E): count rate for a specific gamma-ray peak
Y(E): yield (branching ratio) for that gamma ray
ε_{Abs} (E): absolute detection efficiency at that gamma ray energy
$T_{1/2}$: half life of the nuclide emitting that gamma ray
A: atomic mass of this nuclide

Detection Efficiency

- Absolute efficiency

$$\varepsilon_{Abs} = \frac{\text{number of events recorded}}{\text{number of photons emitted}}$$

- Intrinsic efficiency

$$\varepsilon_{I} = \frac{\text{number of events recorded}}{\text{number of photons incident}}$$

- How are these related?

$$\varepsilon_{Abs} = \varepsilon_{I} \cdot \underbrace{Atten}_{\text{Attenuation Factor}} \cdot \underbrace{\frac{\Omega}{4\pi}}_{\text{Solid-Angle Fraction}}$$

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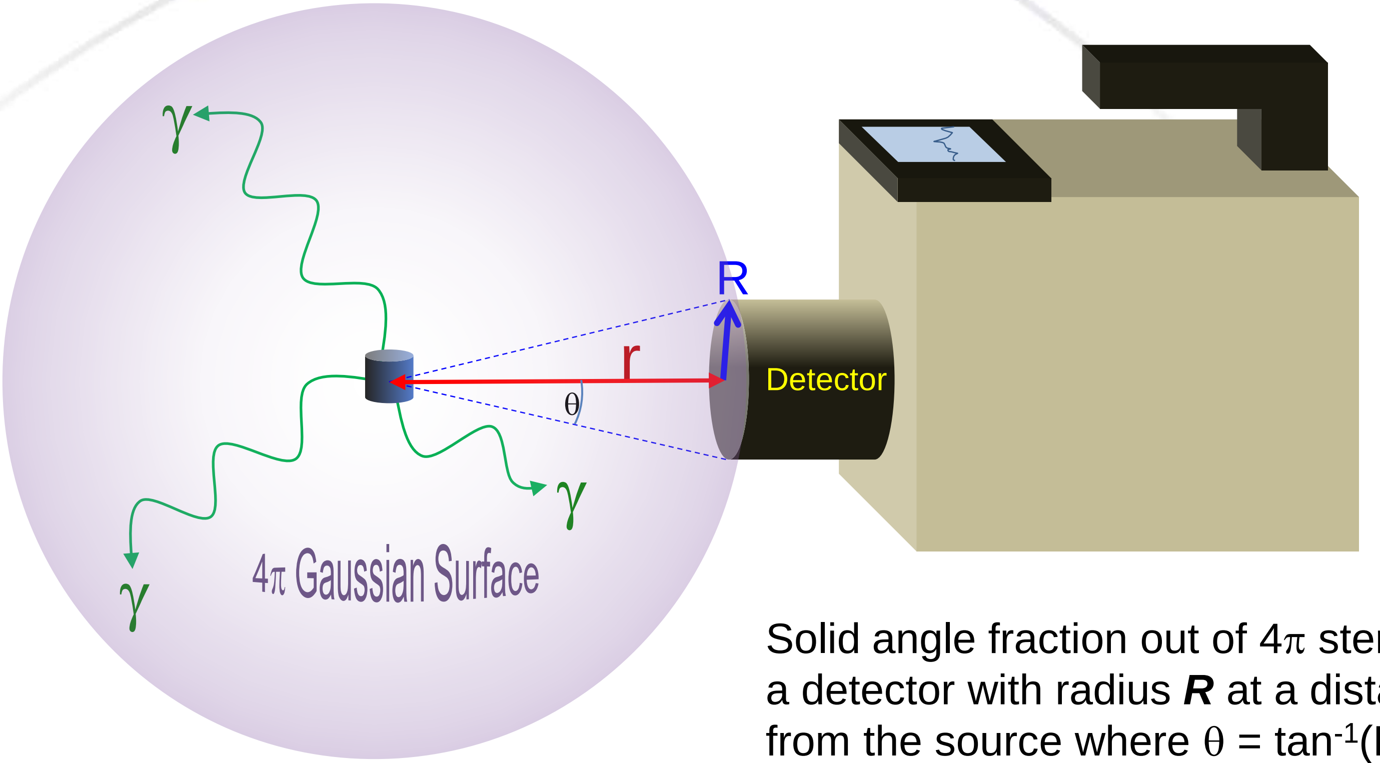
Detector Solid Angle Fraction



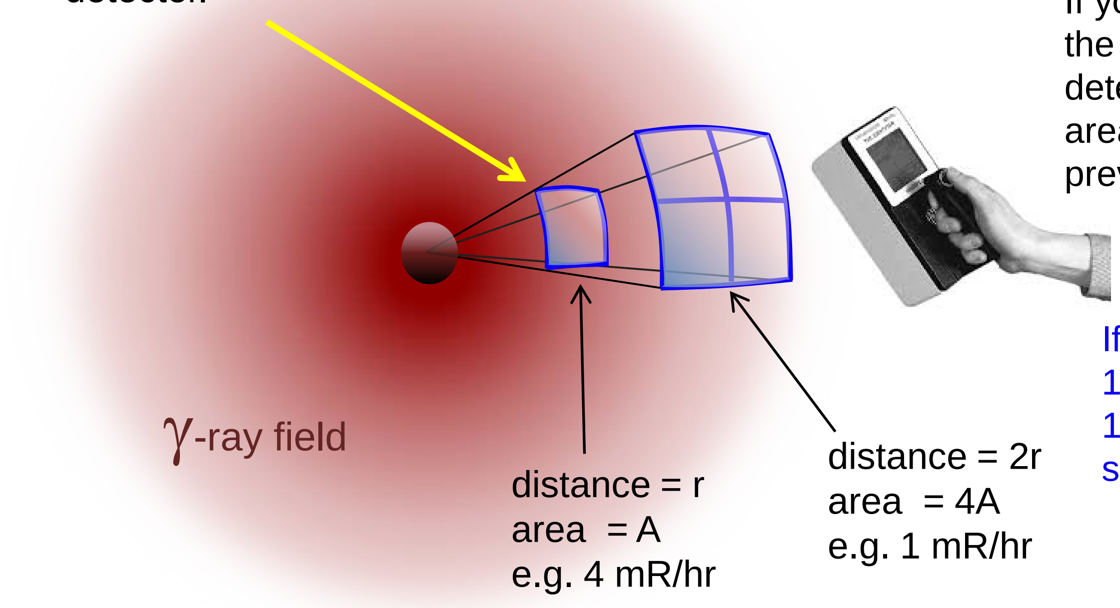
Solid angle fraction out of 4π steradians for a detector with radius ***R*** at a distance ***r*** from the source where $\theta = \tan^{-1}(R/r)$:

$$\frac{\Omega}{4\pi} = \frac{1}{2}\left(1 - \cos\theta\right)$$

The Inverse Square Law ($1/r^2$)

Area of a Sphere = $4\pi r^2$
Solid Angle $\propto 1/r^2$

Let's say 1 square = the area covered by your detector.



If you double the distance between the source and the detector, the detector will only cover 1/4th of the area of the radiation field it did previously.

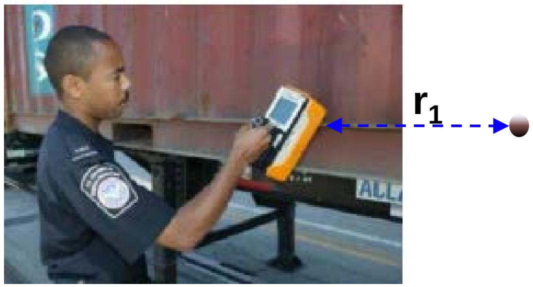
If the detector only covers 1/4th of the area then only 1/4th of the gamma rays will strike it.

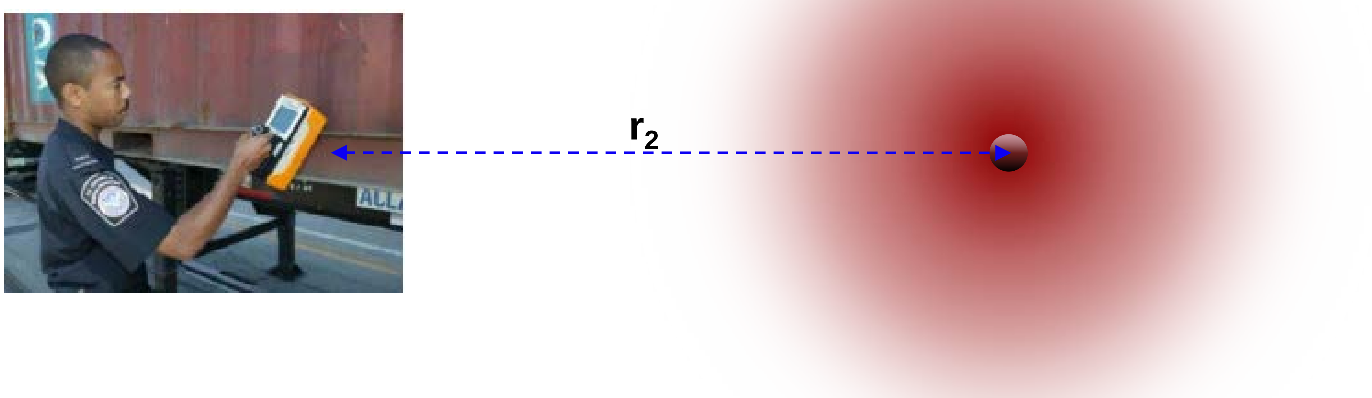
Detection *very strongly* depends on source-to-detector distance!

Why is distance important?

The observed dose rate in these two cases *could* be the same.

We need to know the source-to-detector distance to calculate the activity or mass of the source.



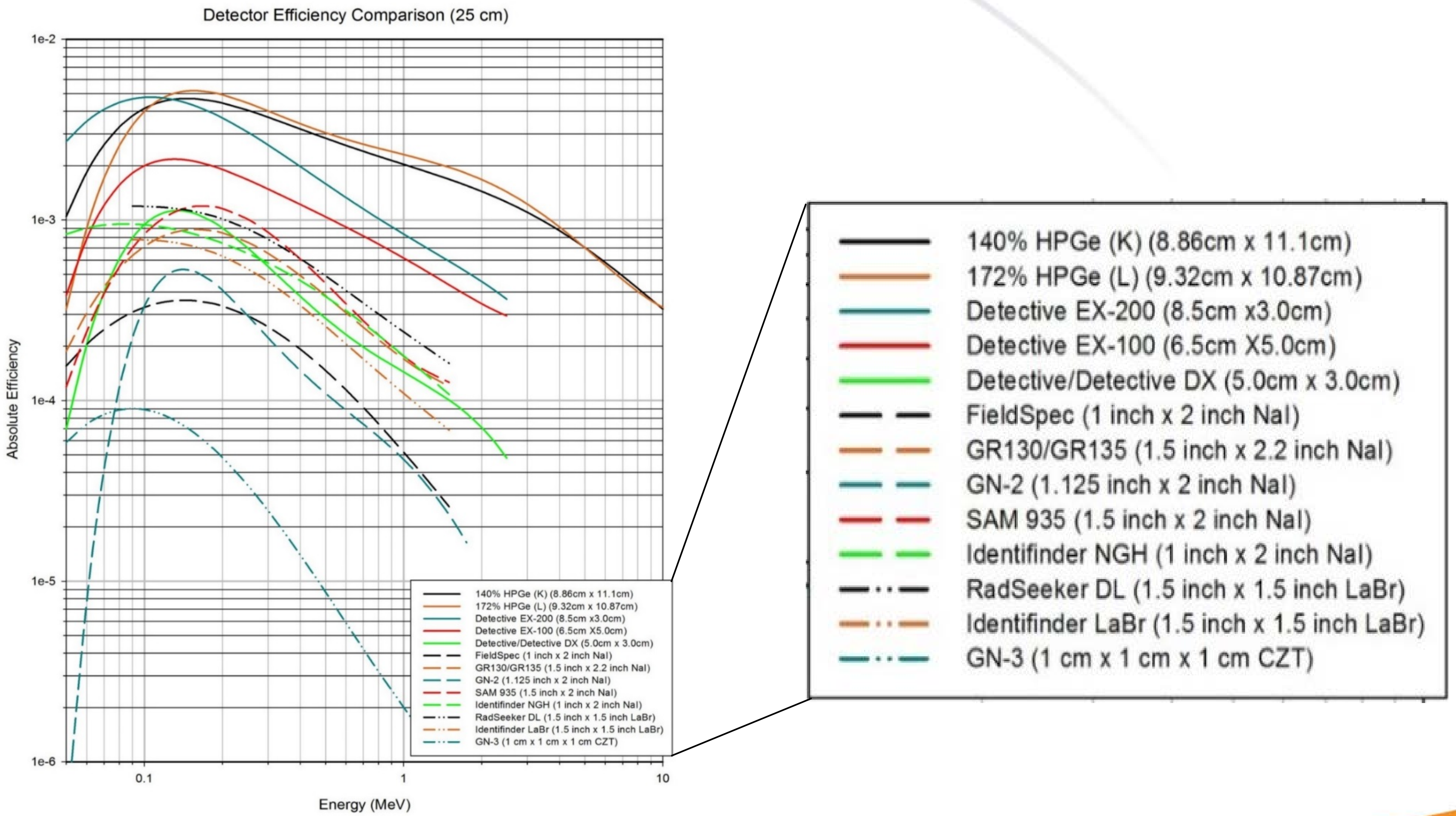


But the farther source is much more intense!

Intrinsic Detector Efficiency

- Generally intrinsic detector efficiency is optimal at some low-intermediate energy (~80-120 keV)
  - Below this energy gammas are more likely to be attenuated before entering the sensitive part of the detector.
  - Above this, gammas are more likely to Compton scatter in the detector and therefore not deposit their full energy.

Example Intrinsic Efficiency Curves



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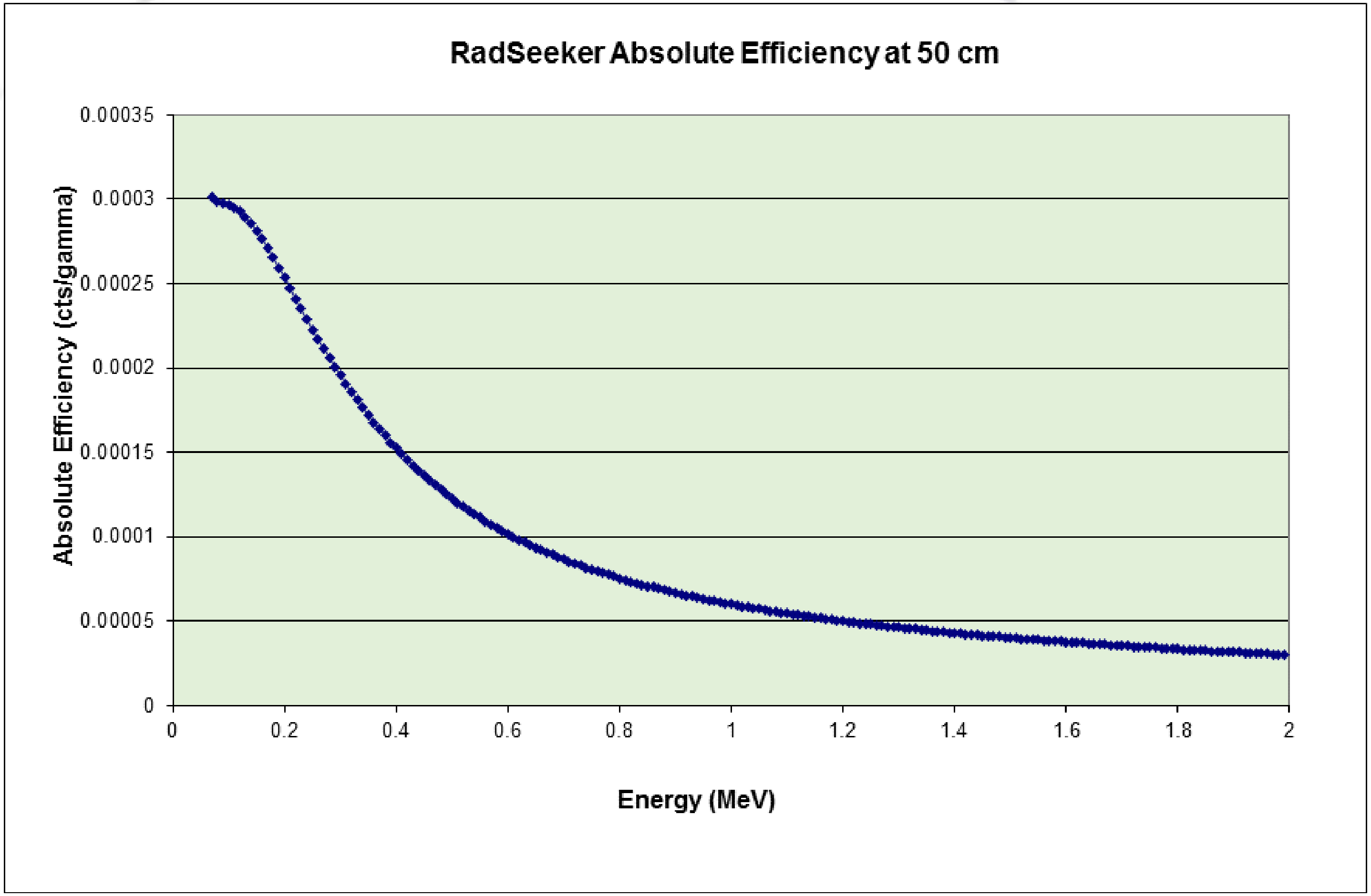
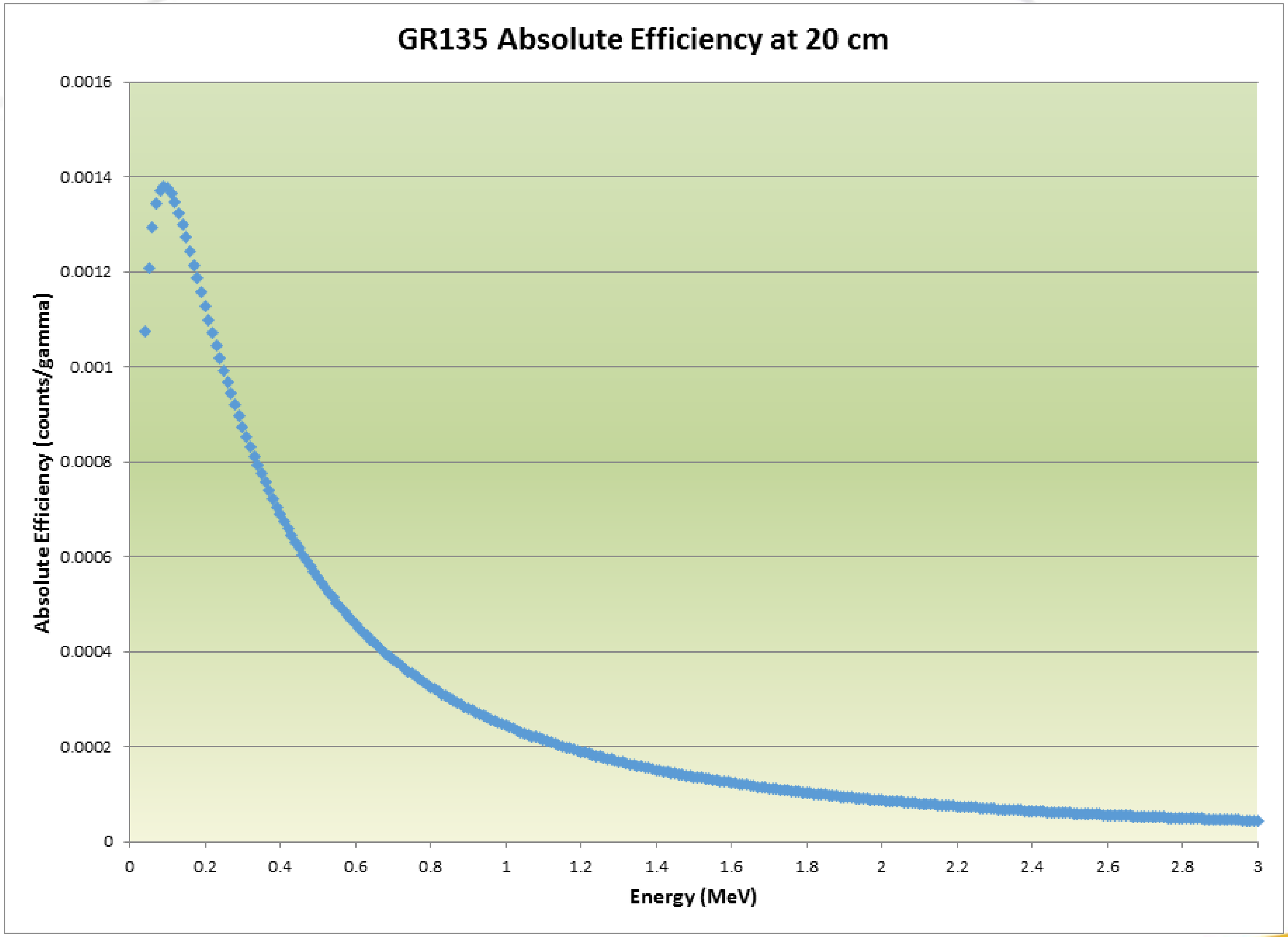
Radseeker Efficiency



GR-135 Efficiency



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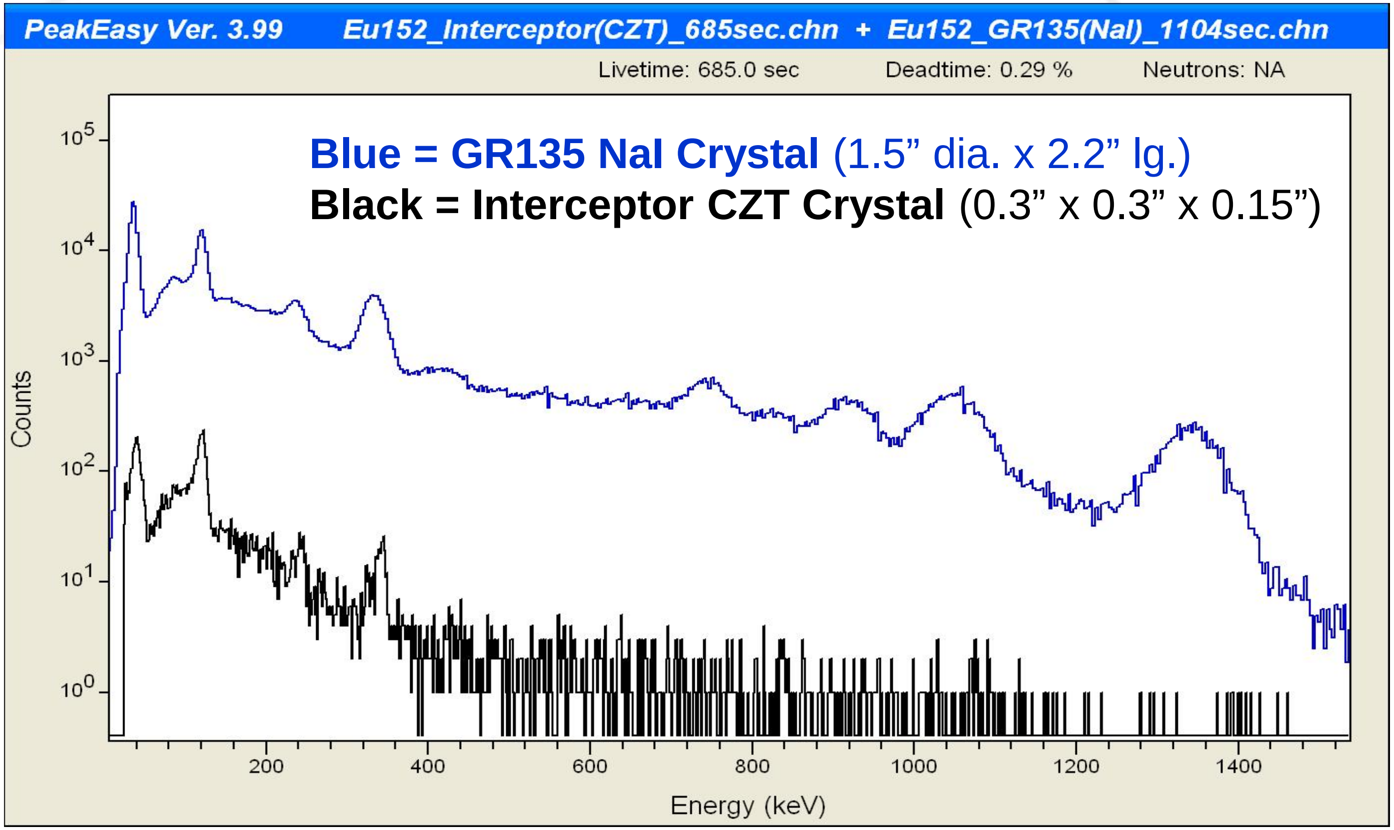
Importance of Intrinsic Efficiency

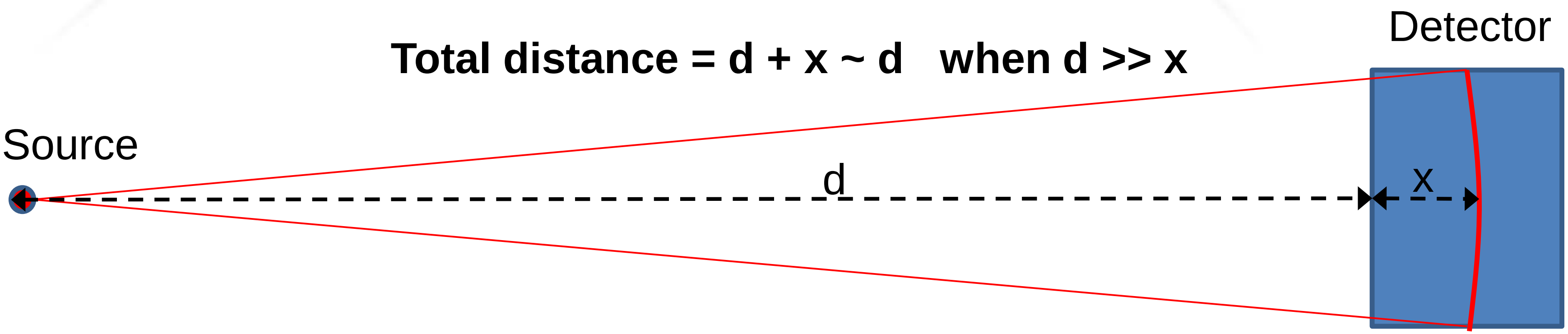


Both measurements of same Eu-152 source at 1 meter

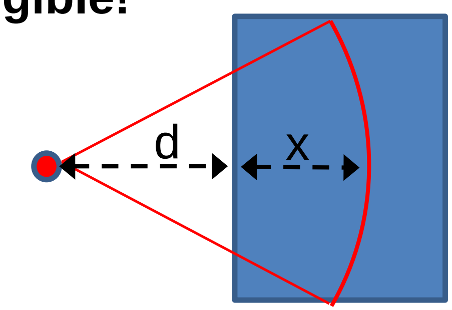
Average Interaction Depth

The average gamma interaction depth, ***x***, in the detector depends on energy.

Total distance = d + x ~ d   when d >> x

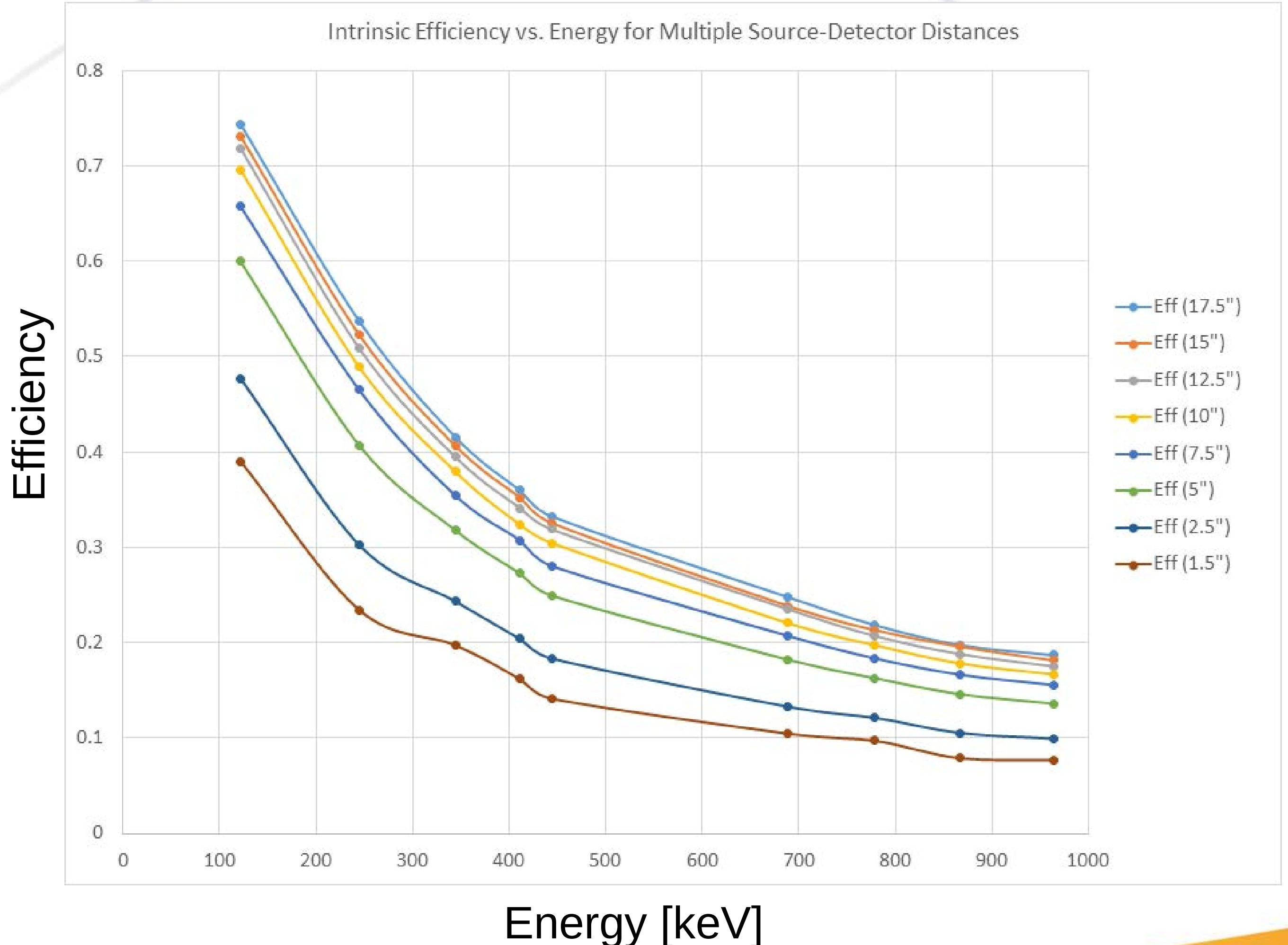


But when d ≅ x, the latter is not negligible!



In this case, the distance that matters with regard to *solid angle* as well as *intrinsic* efficiency is that from the source to the average interaction depth inside the crystal

Intrinsic Efficiency and Distance



Relative Efficiency: Definition #1

- This definition concerns intrinsic detector efficiency coupled with the area of the detector face.
  - This is useful for comparing detectors.
- By convention, this is the **1332-keV** (Co-60) photopeak efficiency of any gamma detector relative to a 3” x 3” NaI at 25 cm

  Usually, HPGe detectors are quoted as having a relative efficiency for comparison (e.g. 32%)

Relative Efficiency: Definition #2

- This definition concerns the efficiency of detecting gamma rays at one energy relative to all other energies in the spectrum.
  - It is critical for quantitative calculations and is defined as:

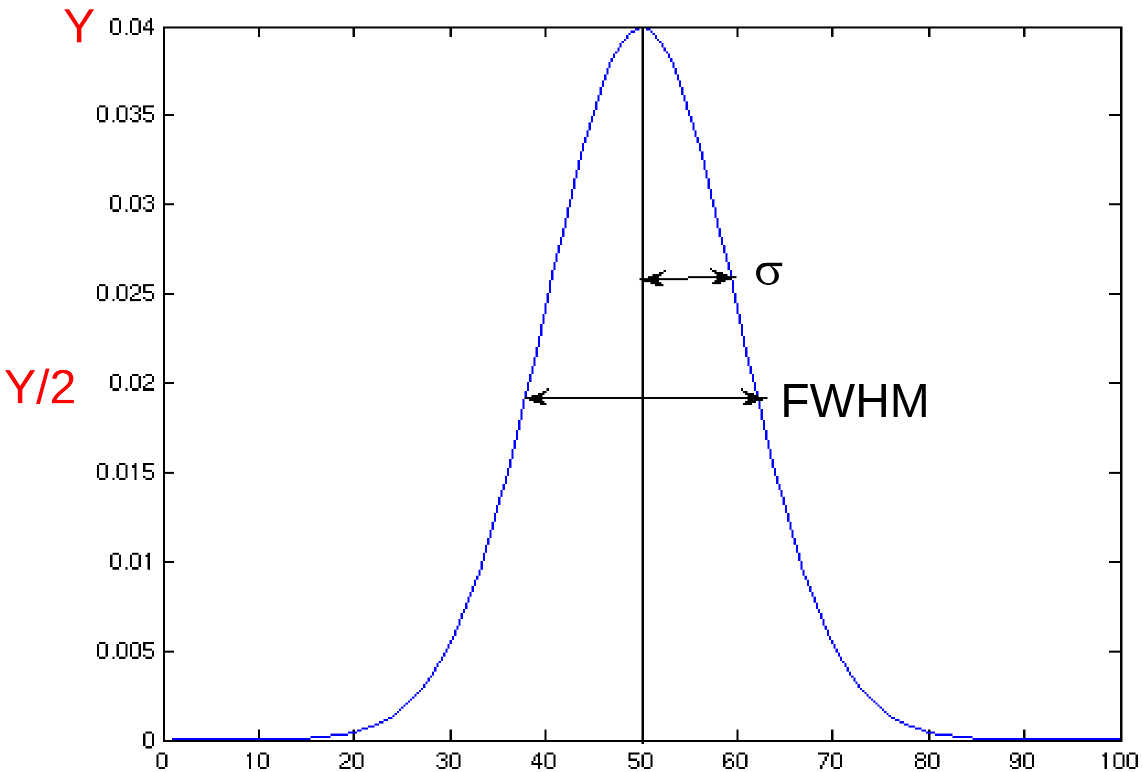
$$\mathrm{RE(E)} \propto \frac{C(E)}{Y(E)}$$

Counts in peak at energy *E*

Photon yield for peak at energy *E*

- It accounts for three things:
  - Intrinsic detector efficiency
  - Attenuation due to shielding
  - Self-attenuation by the source

What is Resolution?



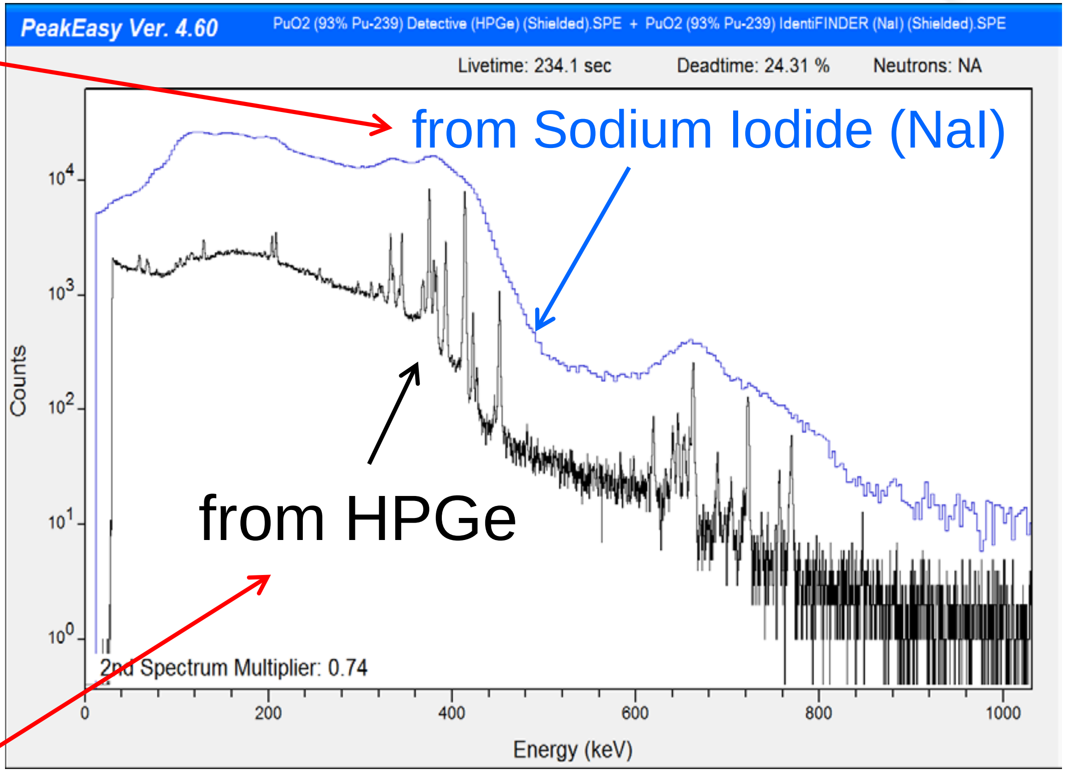
FWHM = Full Width at Half Maximum

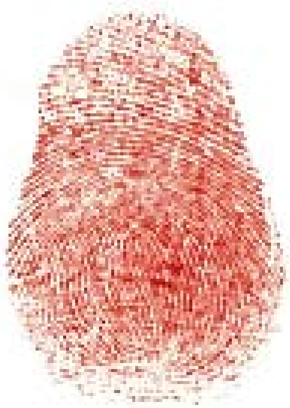
$$Y(H) = Y \exp\left(-\frac{(H - H_0)^2}{2\sigma^2}\right)$$

$$FWHM = 2.35\sigma$$

The Importance of Resolution

Two spectra of the same Pu item





HPGe is more of a burden but it provides data that are far more detailed and useful than low-resolution detectors (NaI, LaBr3)

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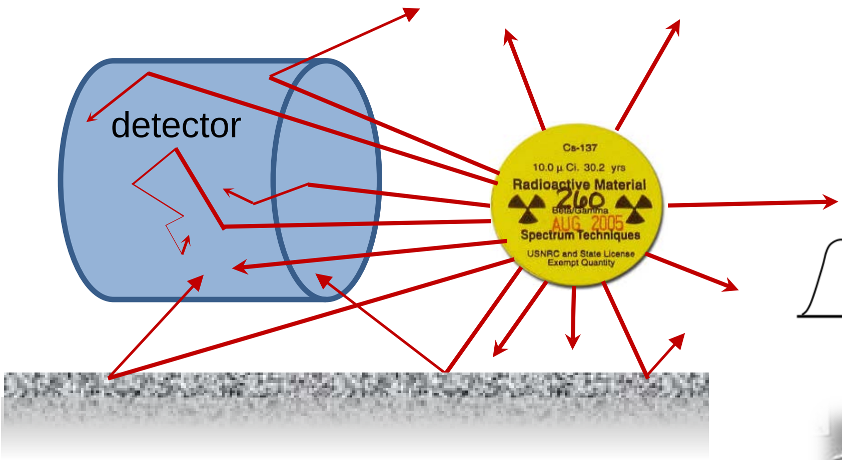
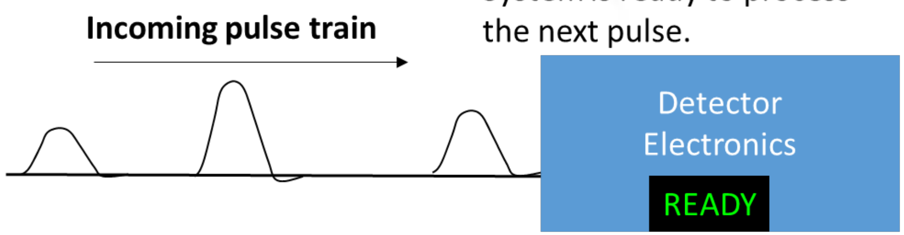
Electronic Dead Time

Function of electronics where they are “dead” for a short time while processing a pulse.

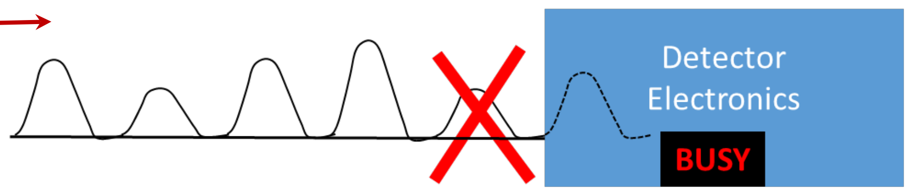
Multiple gammas may hit the detector so <u>close in time</u> that the system can’t process them all.



System is ready to process the next pulse.



The system is busy processing a pulse so the next pulse is lost.



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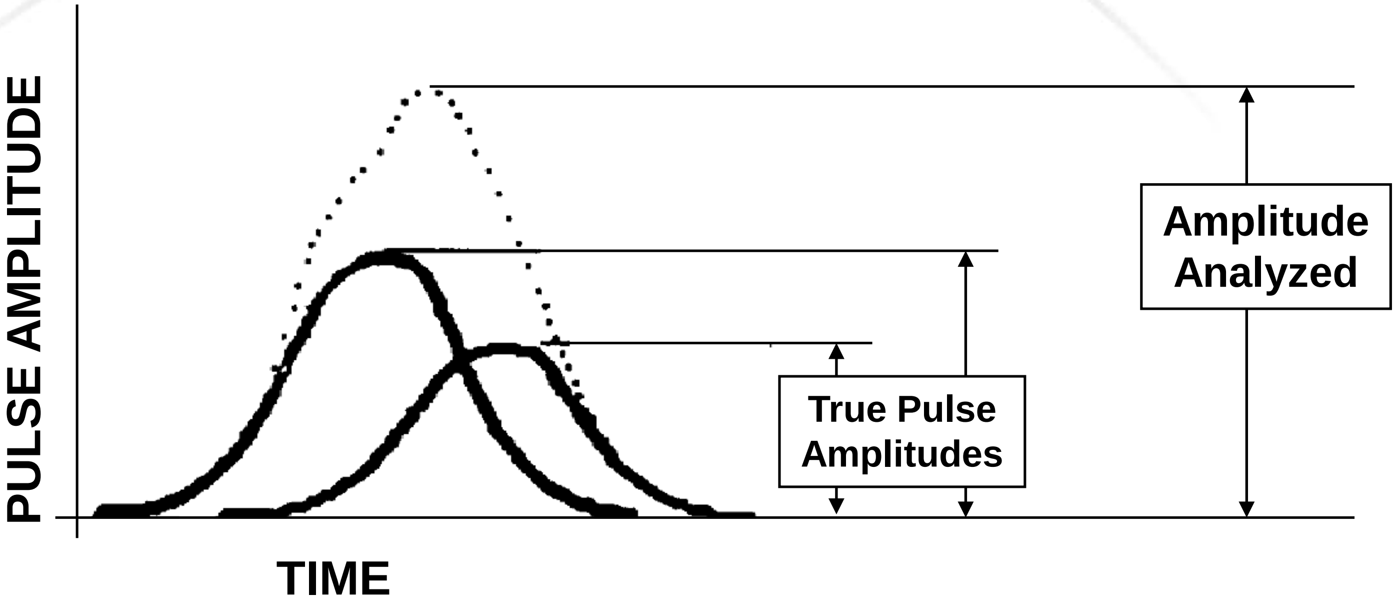
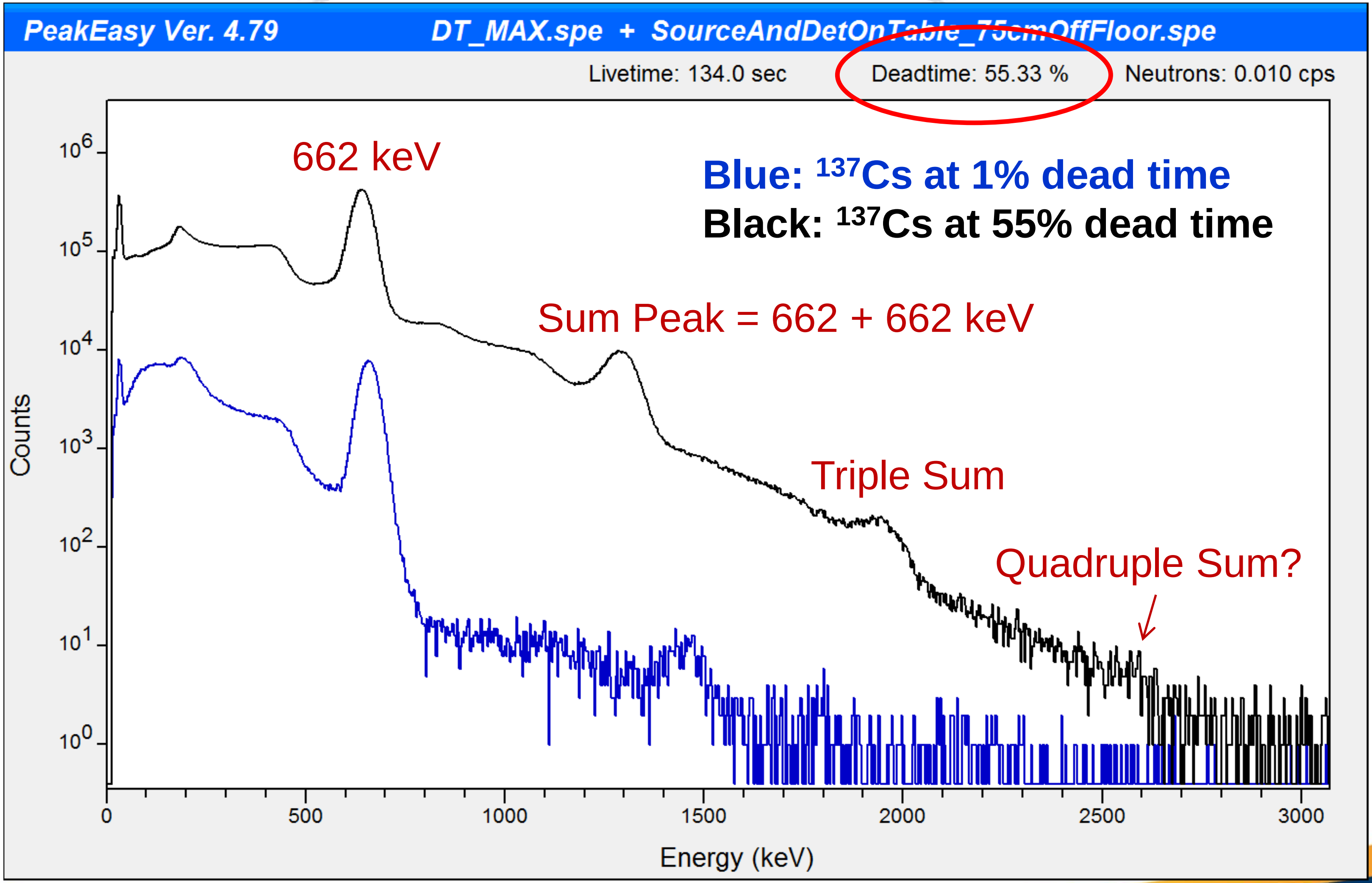
Pulse Pile-up



Two or more γ rays are detected at almost the same time. The result is a combined pulse amplitude that is different from that of either pulse. Information on individual pulses is lost, and data, in the form of sum-peaks, are stored in the spectrum.

Effects of High Count Rate



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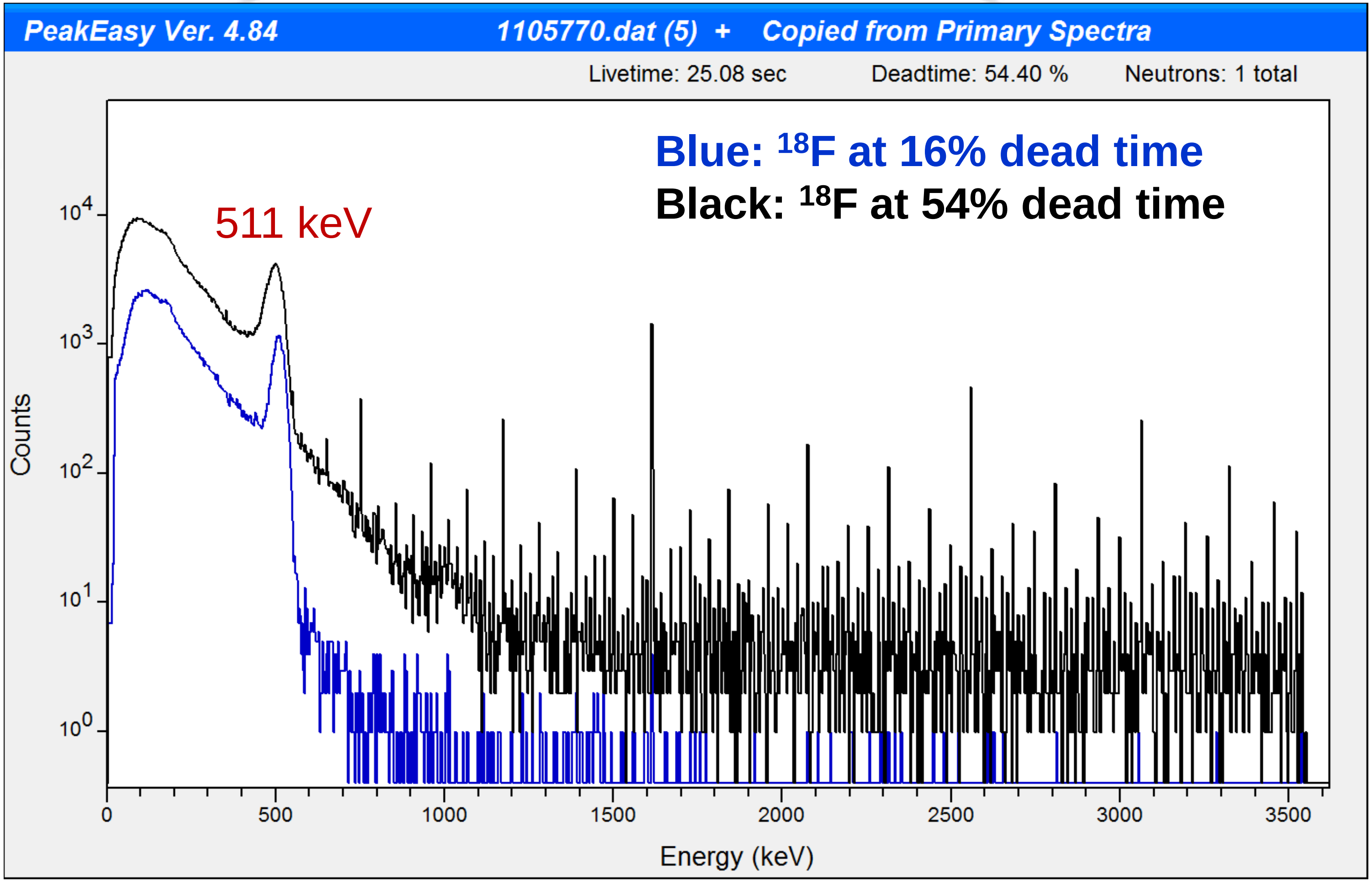
High Dead Time and the GR-135+



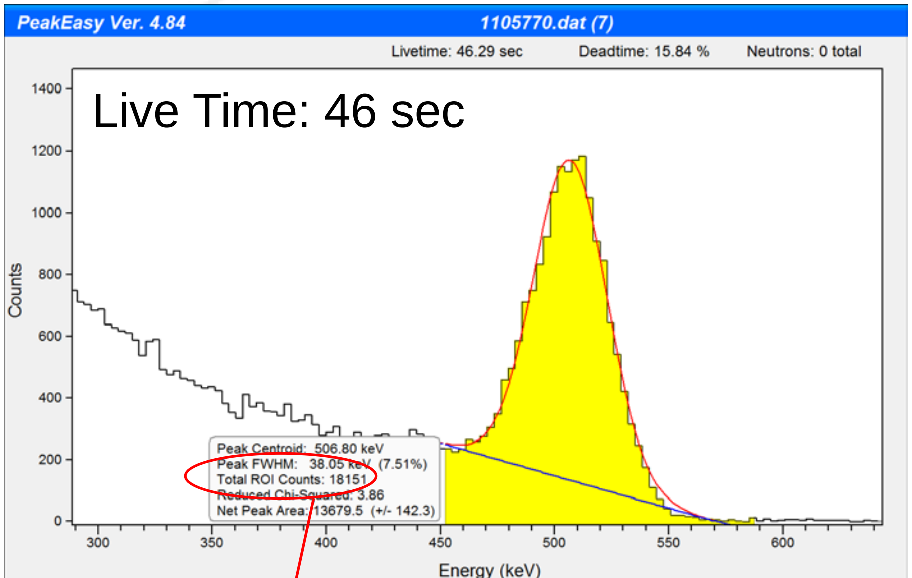
Statistics

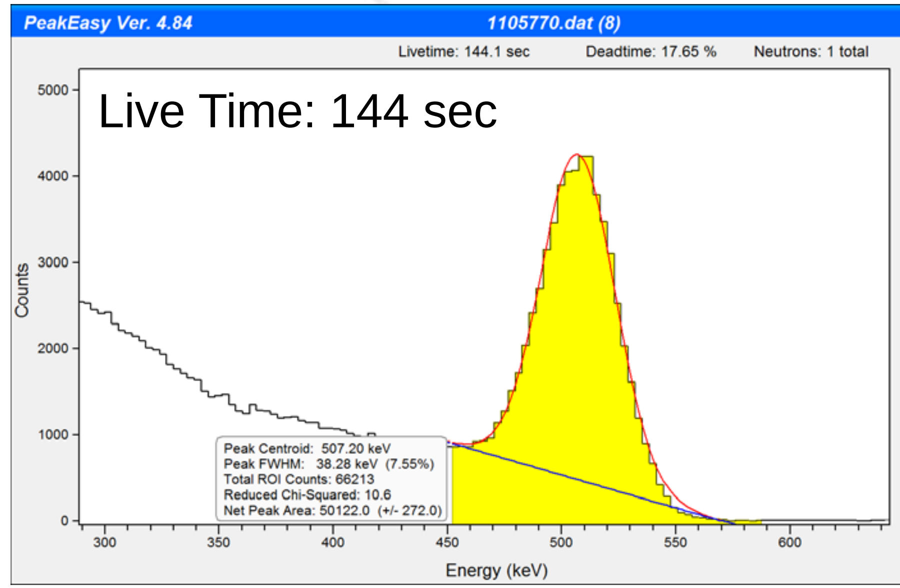
- For a measured number of *gross* counts, **N**, from a random nuclear decay process, the standard deviation is: $\sigma = \sqrt{N}$
- Relative Standard Deviation: $\sigma_R = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$
- What is the % uncertainty (or RSD) if N = 100?
- How many counts do we need to get 1% error?

The terminology 'standard deviation', 'uncertainty', and 'error' are often interchanged.

Uncertainty on Gross Counts

If you count three times as long, your uncertainty drops by a factor of $\sqrt{3}$.





N = 18151

$$\sigma_R = \frac{\sqrt{18151}}{18151} \rightarrow 0.7\%$$

N = 66213

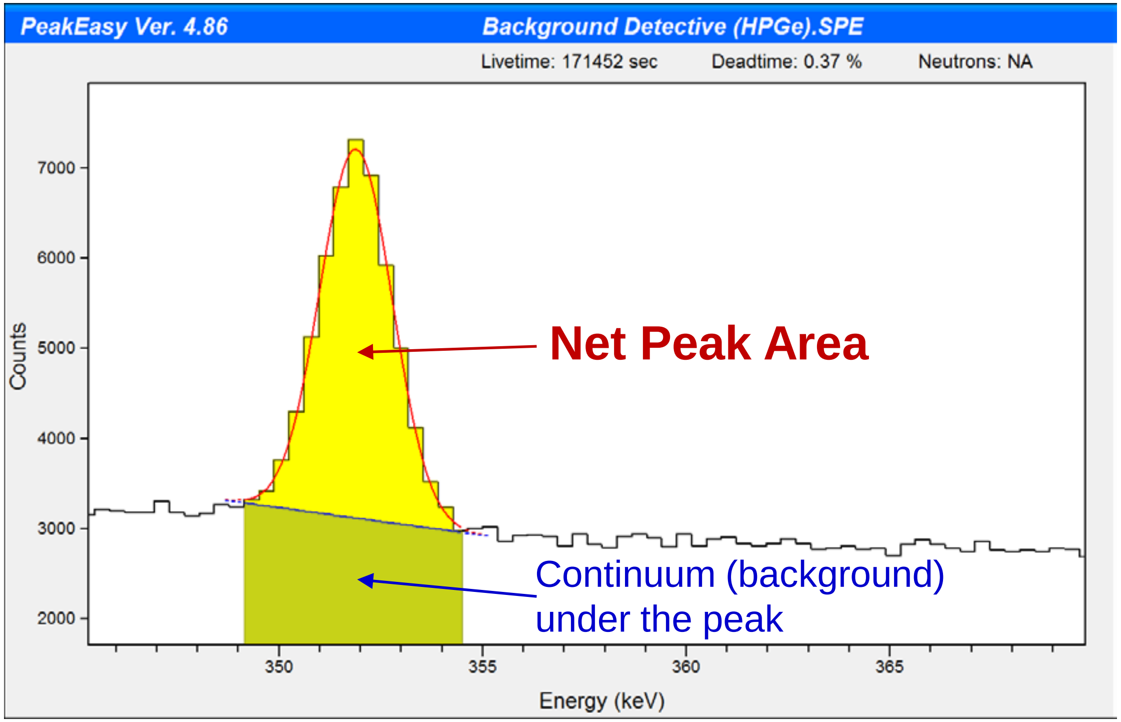
$$\sigma_R = \frac{\sqrt{66213}}{66213} \rightarrow 0.4\%$$

Uncertainty on Net Counts

We are usually interested in the NET peak area.

Net Area = Total Counts - Background

Uncertainty = $\sqrt{Total + Background}$



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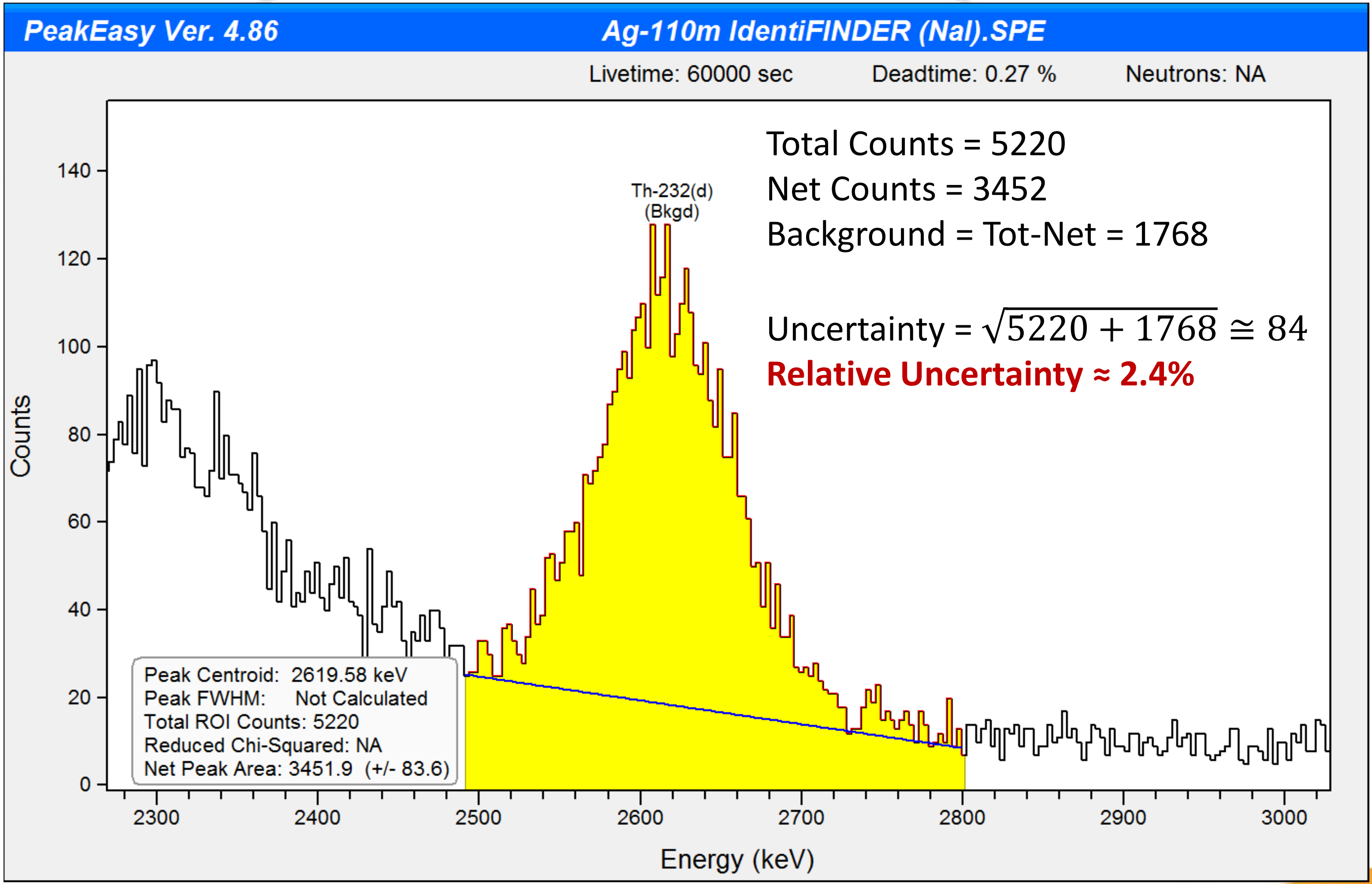
Net Area Uncertainty Example



Total Counts = 5220

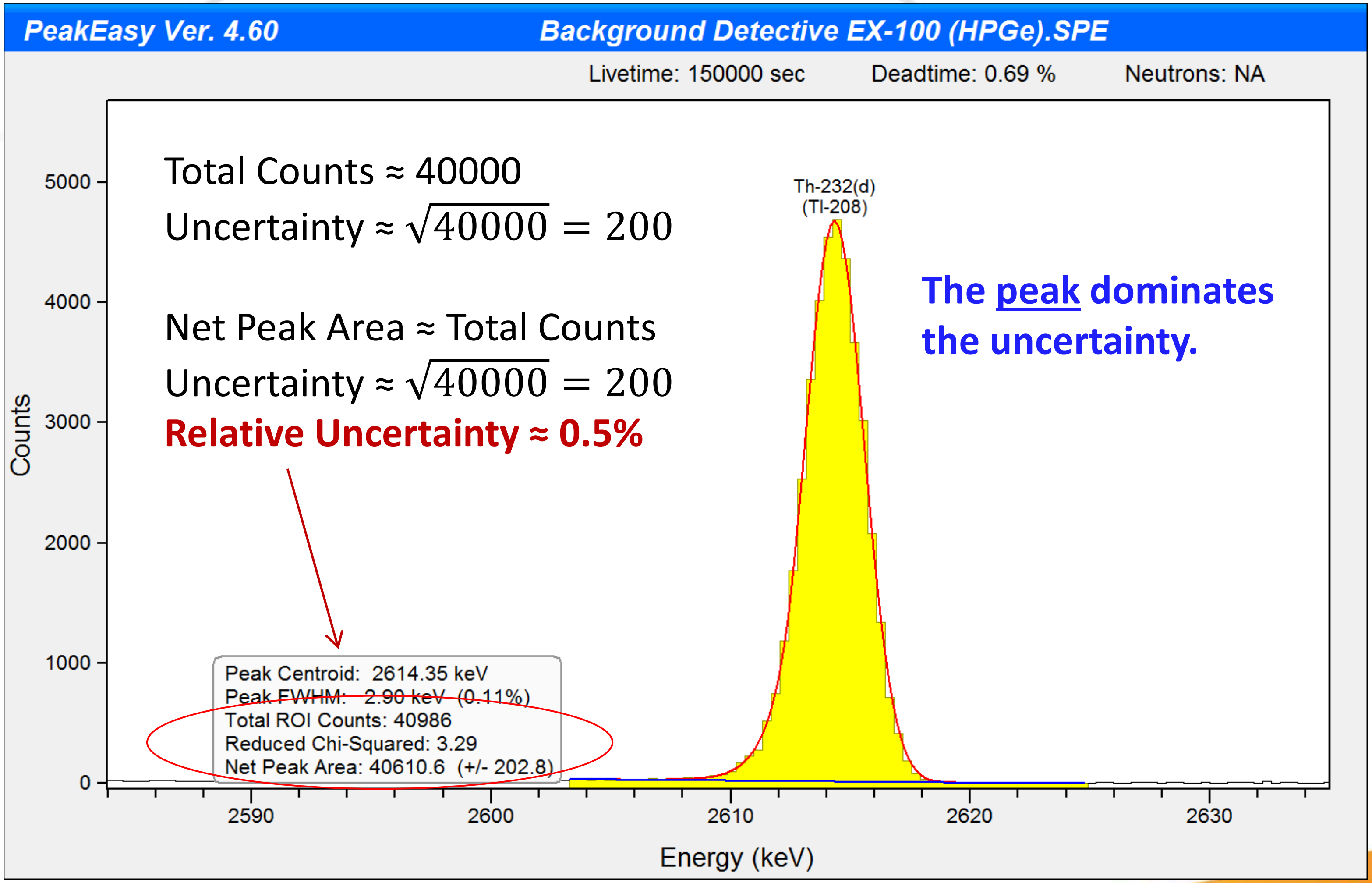
Net Counts = 3452

Background = Tot-Net = 1768

Uncertainty = $\sqrt{5220 + 1768} \cong 84$

Relative Uncertainty ≈ 2.4%

Large Peak on Small Continuum



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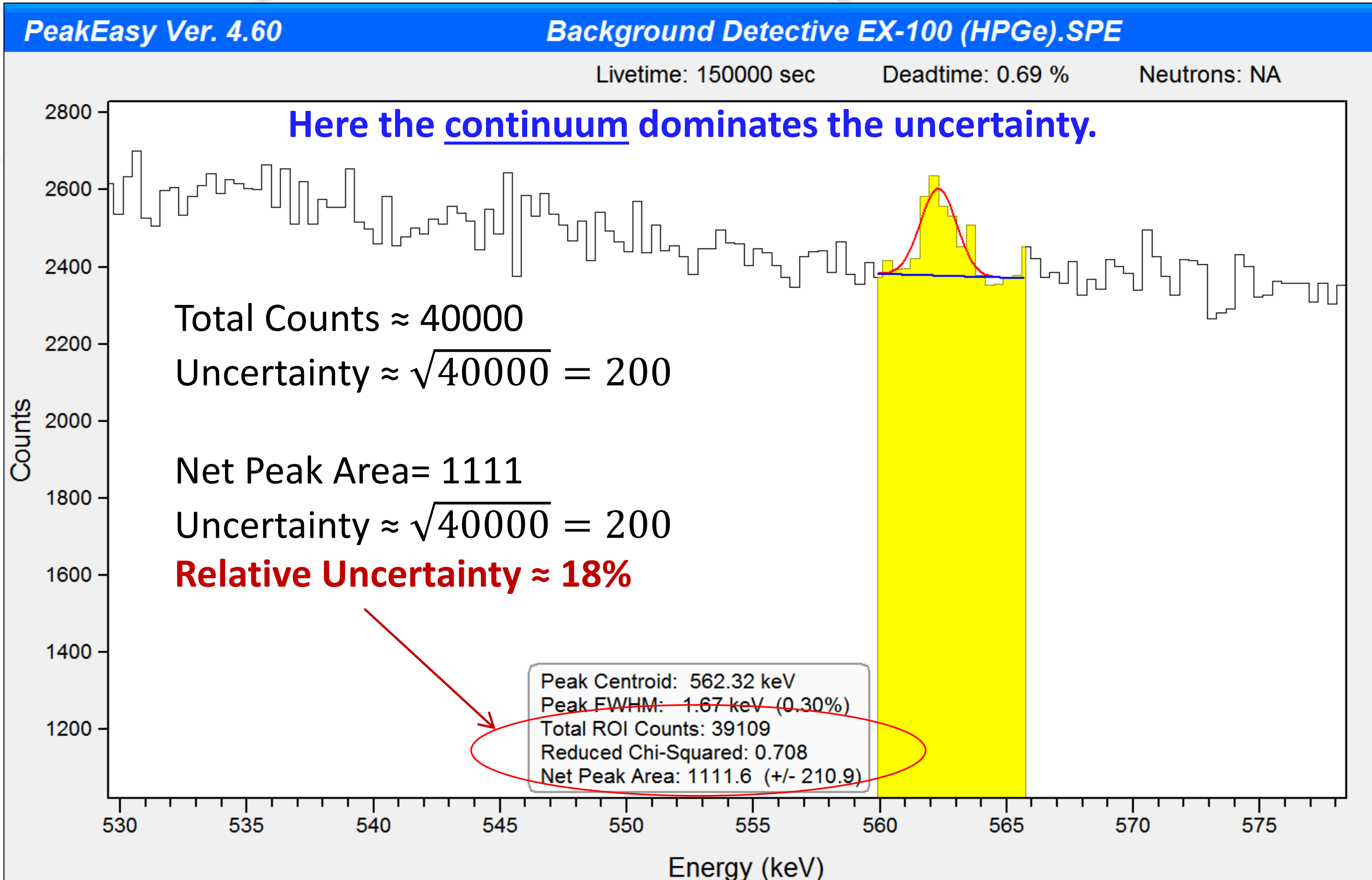
Small Peak on Large Continuum



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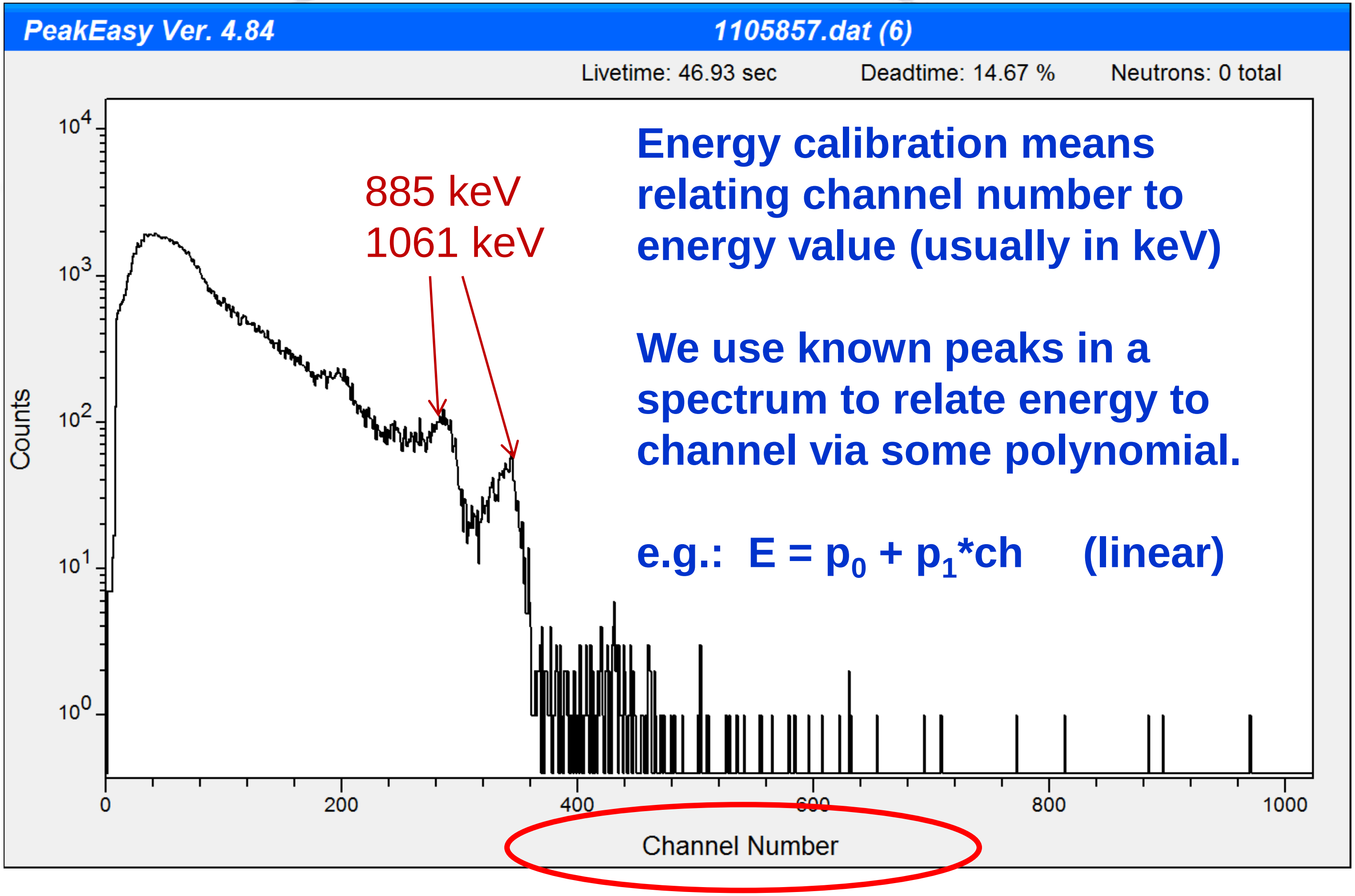
Energy Calibration



Energy calibration means relating channel number to energy value (usually in keV)

We use known peaks in a spectrum to relate energy to channel via some polynomial.

e.g.: $E = p_0 + p_1 * ch$ (linear)

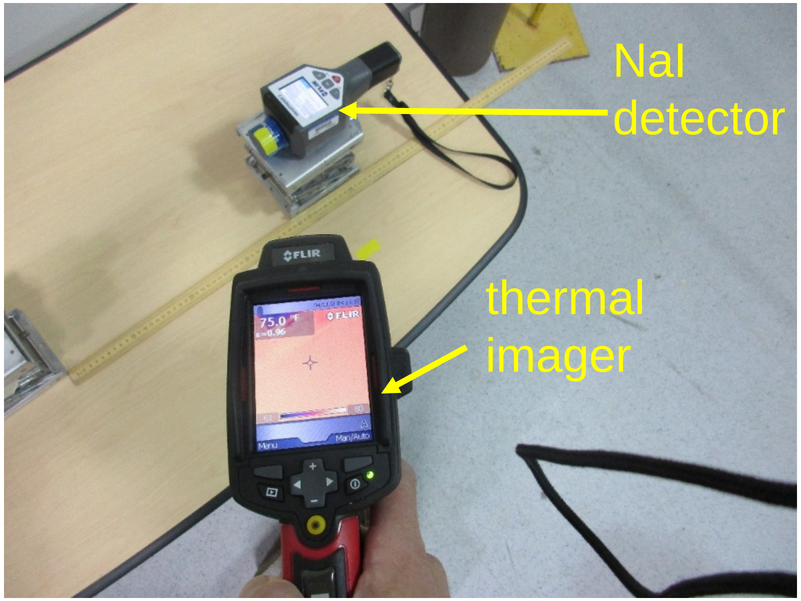
More on Energy Calibration

- Many detectors are at least somewhat nonlinear
  - In most cases, a linear calibration is not sufficient
  - 2nd order polynomial for a good detector, higher order polynomial for a bad detector
- Calibration spectrum must have at least as many peaks as the order of the polynomial being fit
  - This means that, when using the 662-keV peak alone, ^{137}Cs is usually a pretty poor calibration source.

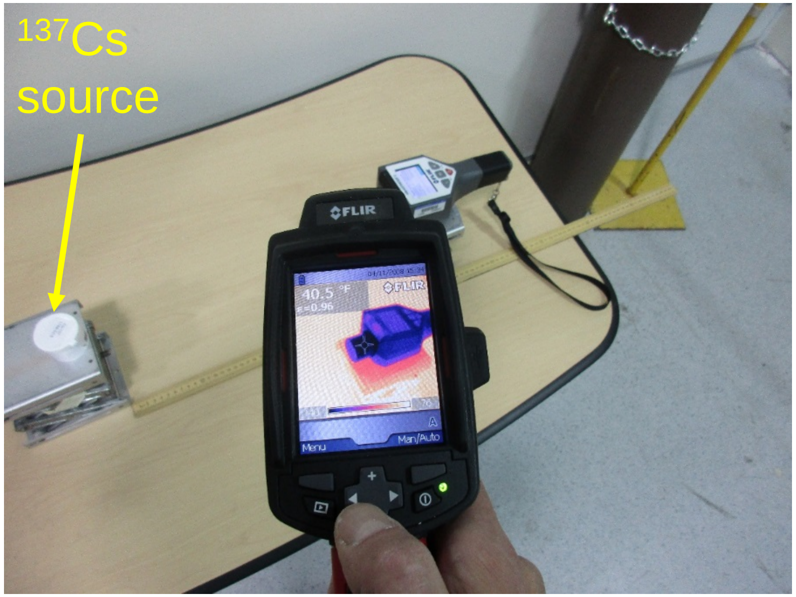
NaI Temperature Dependence

A NaI detector was cooled in a refrigerator until it was 41 F and then data were taken with a ^{137}Cs source as it warmed.

Room temp was approximately 75 F at table top.

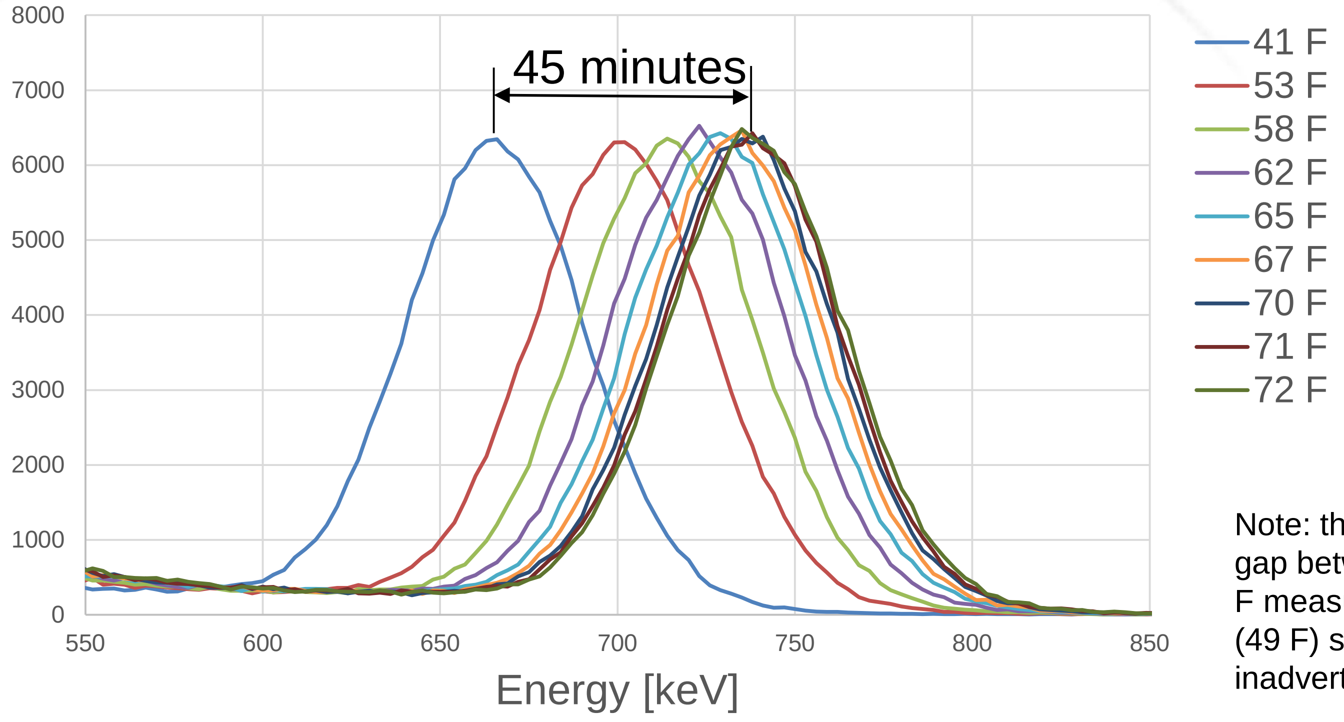


Initial detector temp was ~ 41 F at crystal.



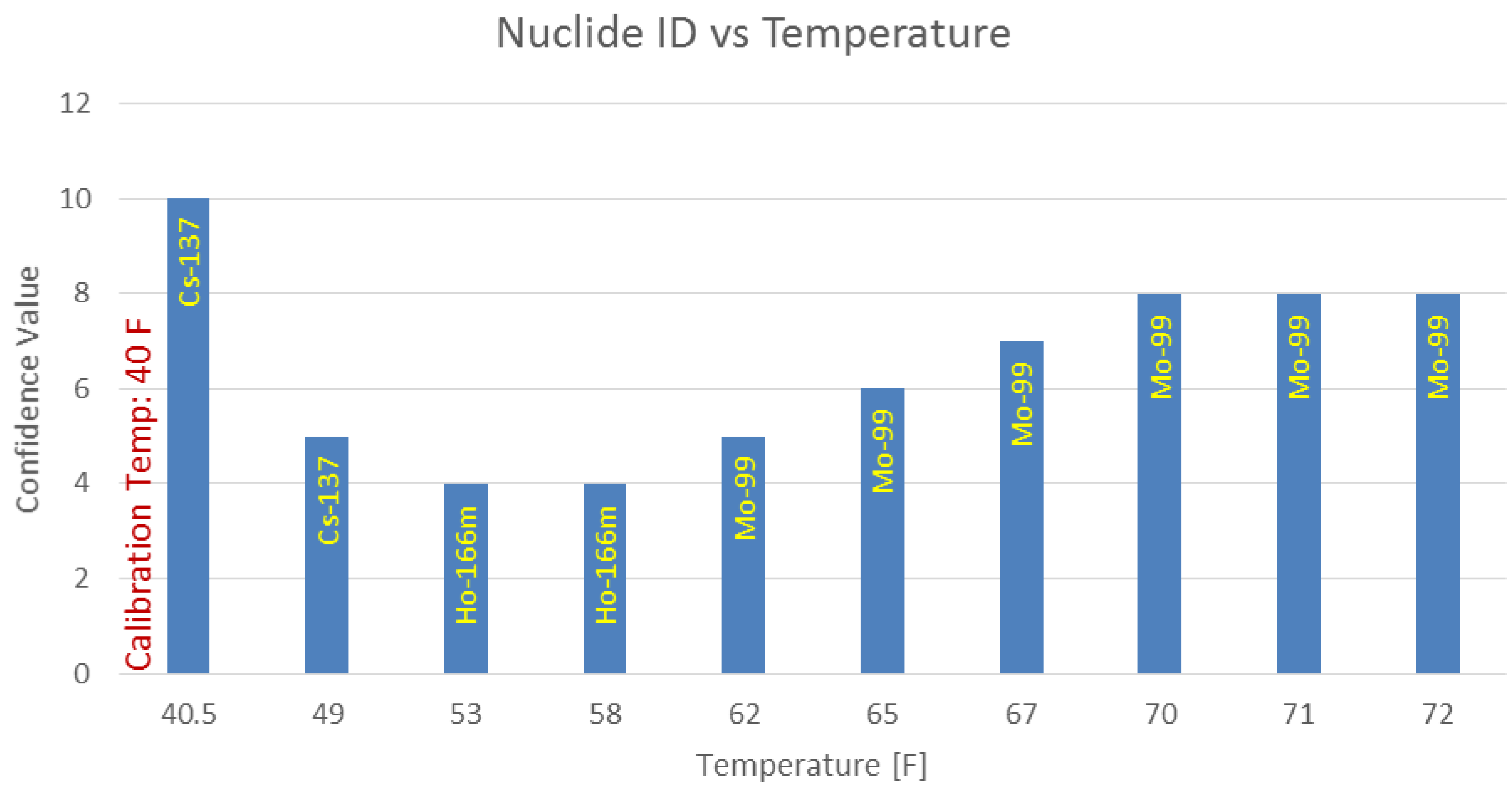
Note: tape was placed on the detector and table top for a controlled emissivity.

^{137}Cs 662-keV Peak versus Temperature

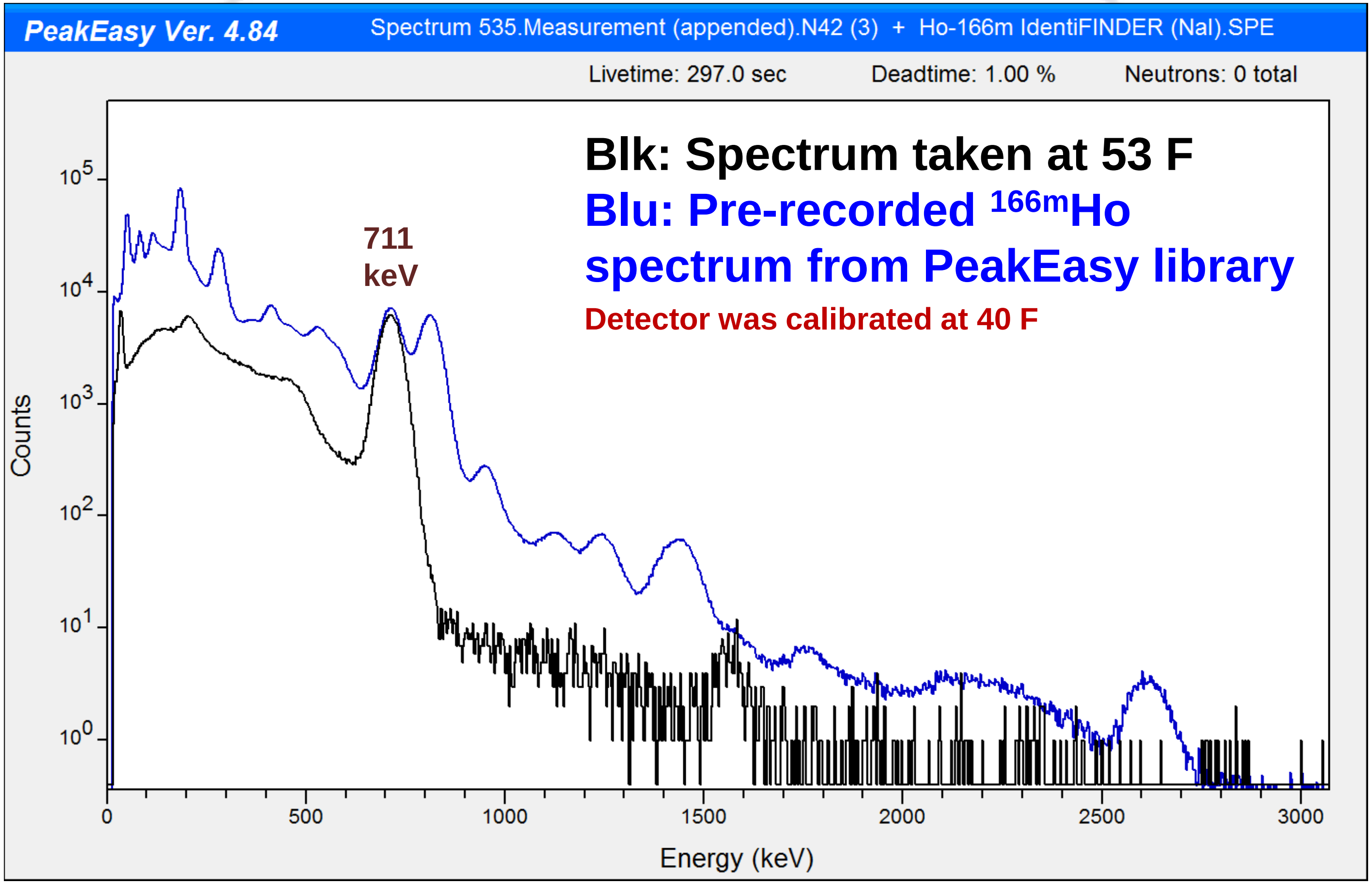


Note: there was a 10-minute gap between the 41 F and 53 F measurements as the 2nd (49 F) spectrum was inadvertently not saved.

Nuclide ID results vs. Temperature



Why ^{166m}Ho for the 53 F spectrum?



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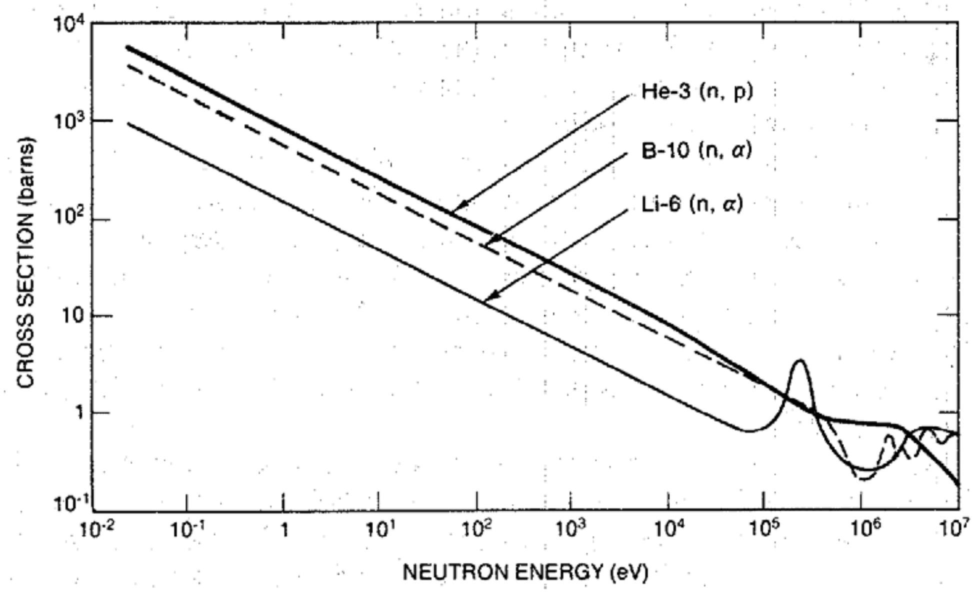
Mechanisms for Neutron Detection

- None are direct since they are neutral particles
  - Must detect charged secondaries or gamma rays
- Two detection modalities
  - Neutron capture reactions release protons, alphas, recoil atoms, gammas, or fission fragments that can subsequently be detected
  - Scatter neutron off light nucleus (H or He) transferring some energy to it, which then ionizes surrounding material

Neutron Cross Section for Common Materials

- Cross section is strongly a function of neutron energy (1/v)
  - Most commercial detectors are moderated
- Many materials have peaks or valleys in cross section superimposed on 1/v relation
  - Example: ^{6}Li



Passive Nondestructive Assay of Nuclear Materials (1991)

Neutron-Sensitive Gas Detectors

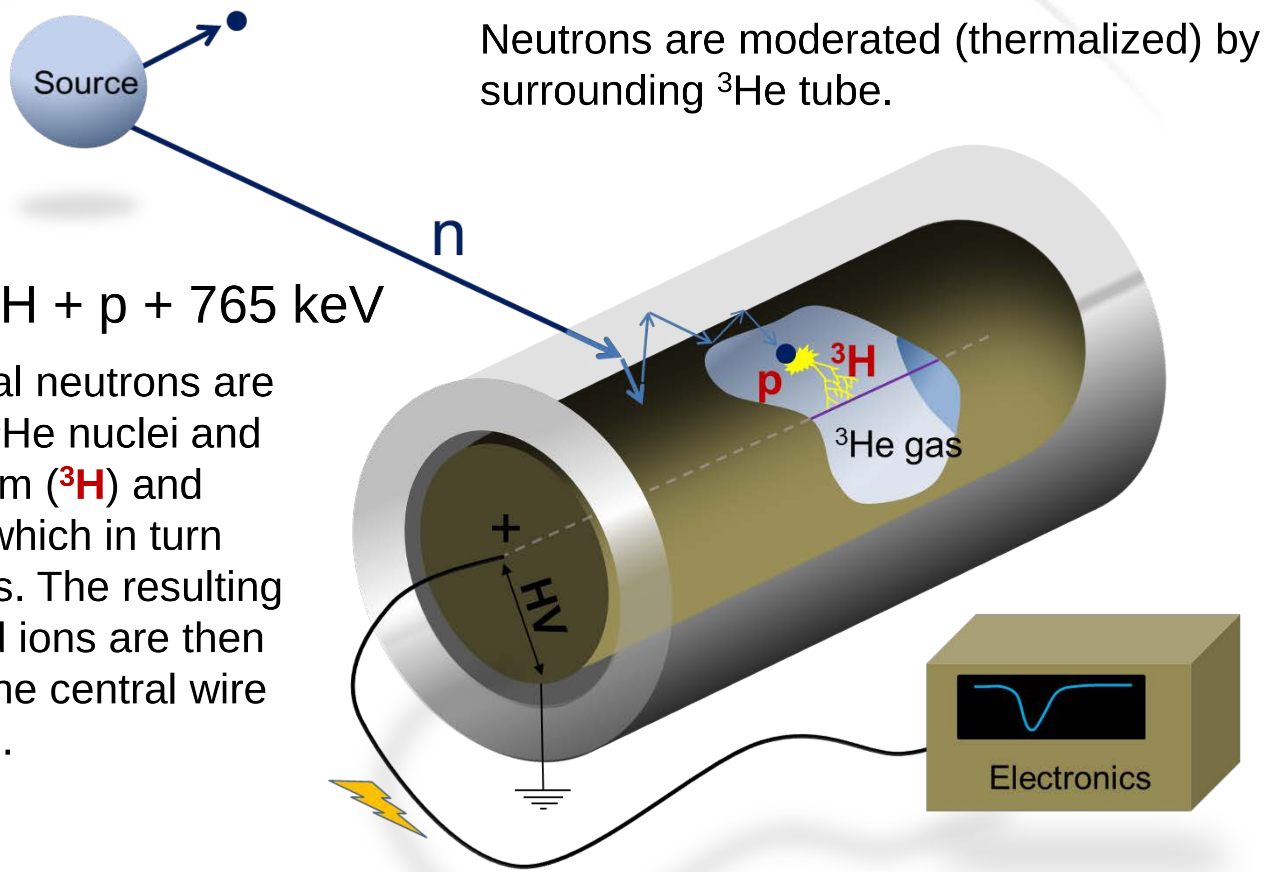
- ^{3}He
  - Typically operated < 10 atm (except RIIDs)
  - ~75% efficient for thermal neutrons
  - Currently, the most common neutron detector in portal monitors
- $^{10}BF_3$
  - Typically operated < 1.5 atm (recombination occurs at high pressures)
  - < 50% efficient to thermal neutrons
- ^{10}B-lined tubes ("Straws")
  - Neutron interaction occurs on walls, resulting in secondary charge within gas (< 10% efficient for thermal neutrons)

^{3}He Neutron Detector

Neutrons are moderated (thermalized) by **polyethylene** surrounding ^{3}He tube.

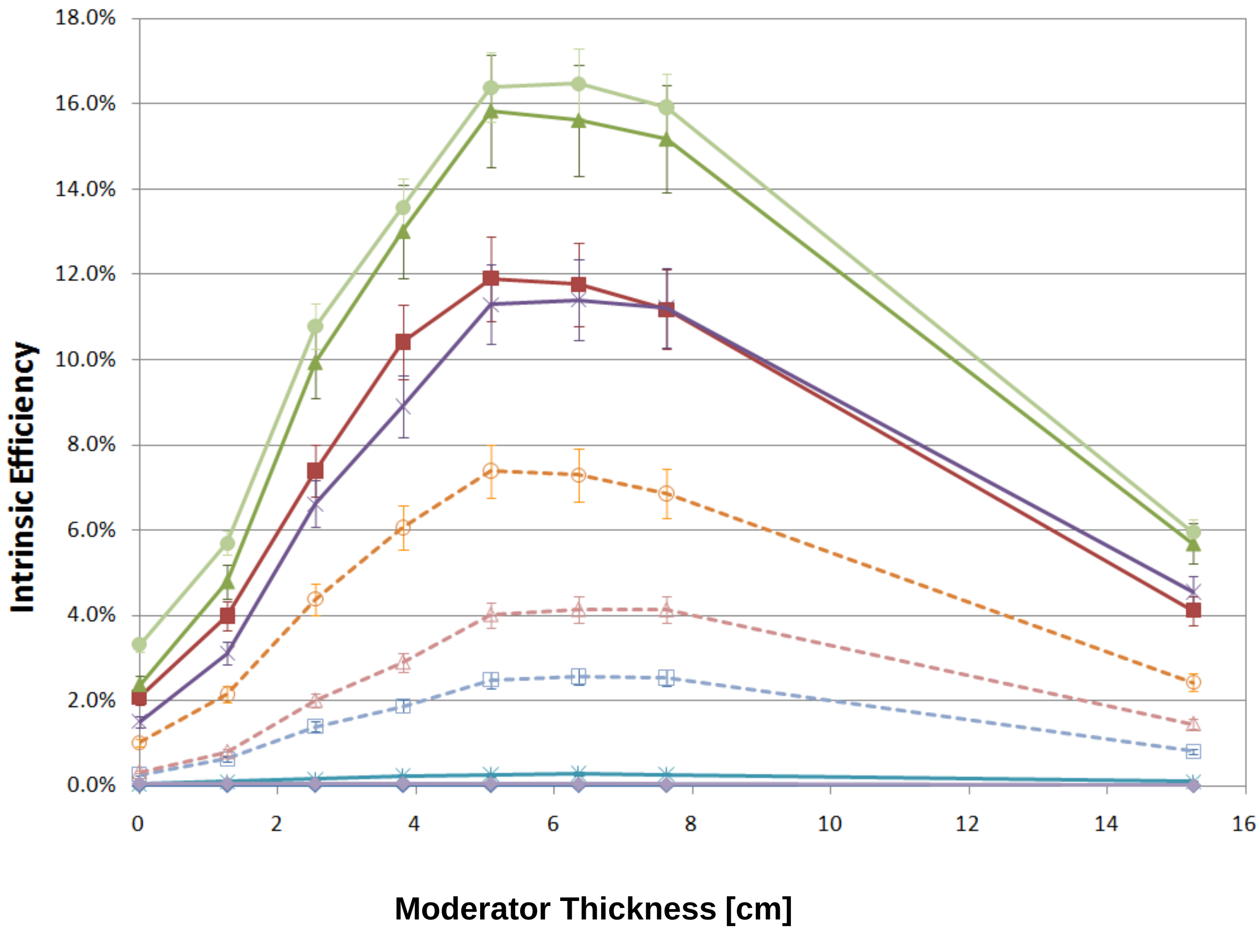
$^3He + n \rightarrow {}^3H + p + 765\ keV$

These thermal neutrons are captured by ^{3}He nuclei and produce tritium (**^{3}H**) and protons (**p**), which in turn ionize the gas. The resulting electrons and ions are then collected at the central wire and tube wall.



The resulting electrical signal is then sent to the detector electronics for processing.

Moderation Effects on Detector Response



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Neutron-Sensitive Scintillators

- Plastic or liquid organics
  - Used more for fast neutron detection
  - Very sensitive to gamma rays
  - Efficiency can be ~ ^{3}He
- ^{6}Li-loaded glass
  - Used in older GR-135s handheld detectors (new model uses He-3 tube)

Next Generation Neutron Detectors

- CLYC (Cs_2LiYCl_6:Ce) gamma-neutron scintillation crystal
- ^{6}LiFZnS(Ag) scintillator screens with wavelength shifting fibers
- High-efficiency ^{10}B-lined proportional tubes ("Straws")
- And a host of others

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Problems with Neutron Detection

- Useful spectroscopy can be difficult since neutrons rarely deposit their full energy in the detector
  - For ^{3}He detectors, neutrons must be thermalized for detection therefore forfeiting all incident energy information.
- RIID detectors will only tell you the neutron count rate
- Can be sensitive to gamma rays as well, so setting a proper threshold is important (pulse shape discrimination might also be necessary)
- Cosmic ray spallation in nearby massive and dense materials will cause false neutron counts (e.g. cargo of car batteries)

Summary

- General knowledge of detector concepts is important for spectroscopists
- Although the general concepts are important to master, there is often a lot of variation from one detector to the next. Sometimes even with identical models from the same company.
- It is very helpful to be familiar with the idiosyncrasies of the most common detectors from which you receive data.