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Title: Radiation Detection Overview for Nuclear Emergency Response

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Radiation Detection Overview for Nuclear Emergency Response

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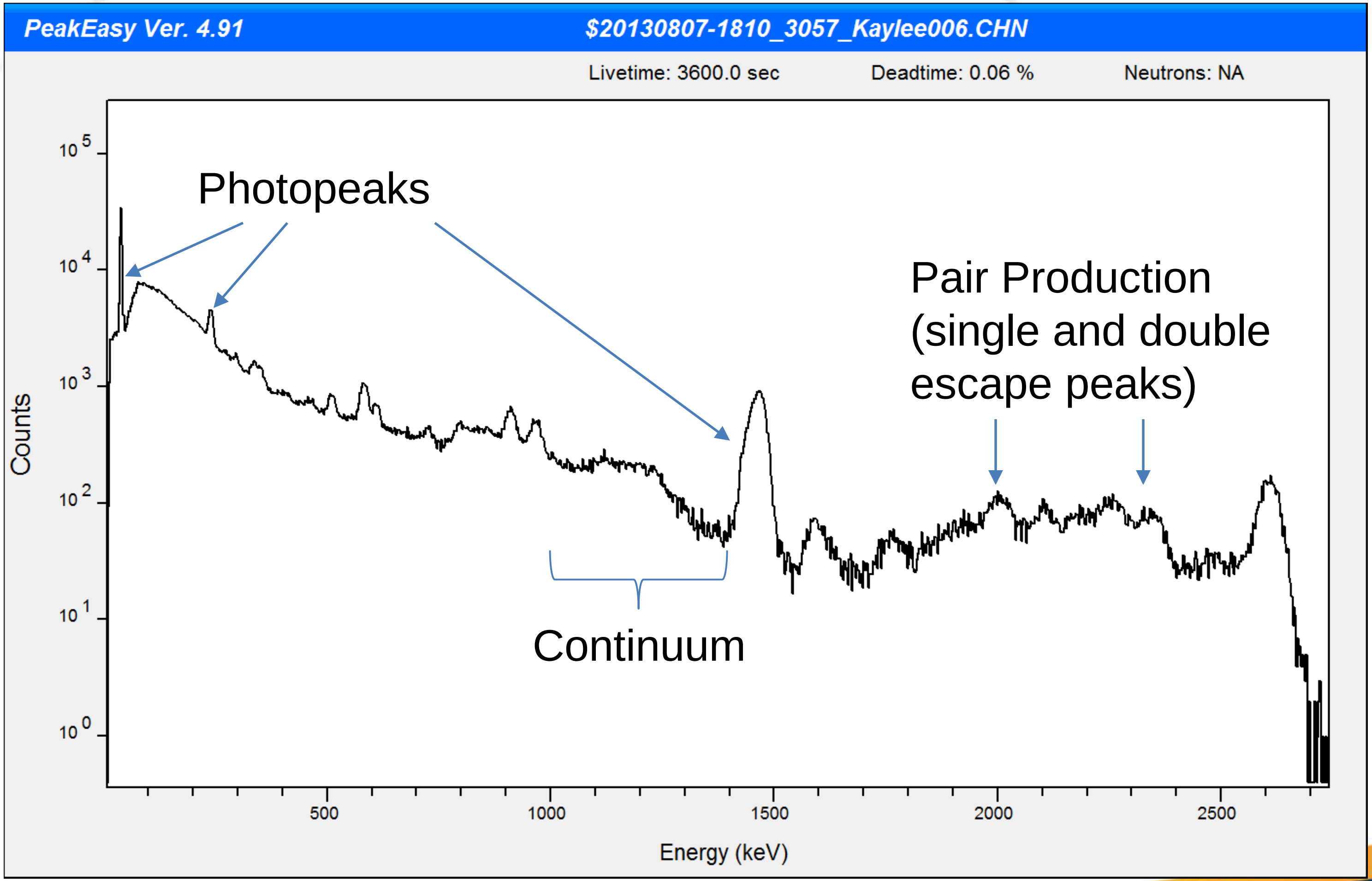
Abstract

- Fundamentals of Gamma and Neutron Detection
- Overview of the DOE Triage and JTOT Programs
- Gamma and Neutron Signatures in Select Measurements
- Detector Demonstration

Basic Gamma Ray Interactions

- Photoelectric effect: all of the energy of the incoming gamma ray is absorbed by the detector – this produces a full energy photopeak in the spectrum
- Compton scattering: only some of the energy of the incoming gamma ray is absorbed while the rest of it scatters out (think “billiard ball” interactions). This interaction adds counts in the spectrum’s continuum
- Pair production: gamma rays above a threshold energy of 1022 keV can be converted to an electron-positron pair (a classic energy to mass conversion)

Elements of Gamma Ray Spectra



Desirable Qualities in Gamma Ray Detectors

- High efficiency
  - Size, stopping power (i.e. density), etc.
- High resolution (if spectroscopic)
  - Improved ability to discriminate between benign and threat sources
- Good Linearity (proportional energy-channel match)
- Good background discrimination
  - High signal-to-noise
- Easy to operate/Few operational constraints
- Cheap

Detection Efficiency

- Absolute efficiency

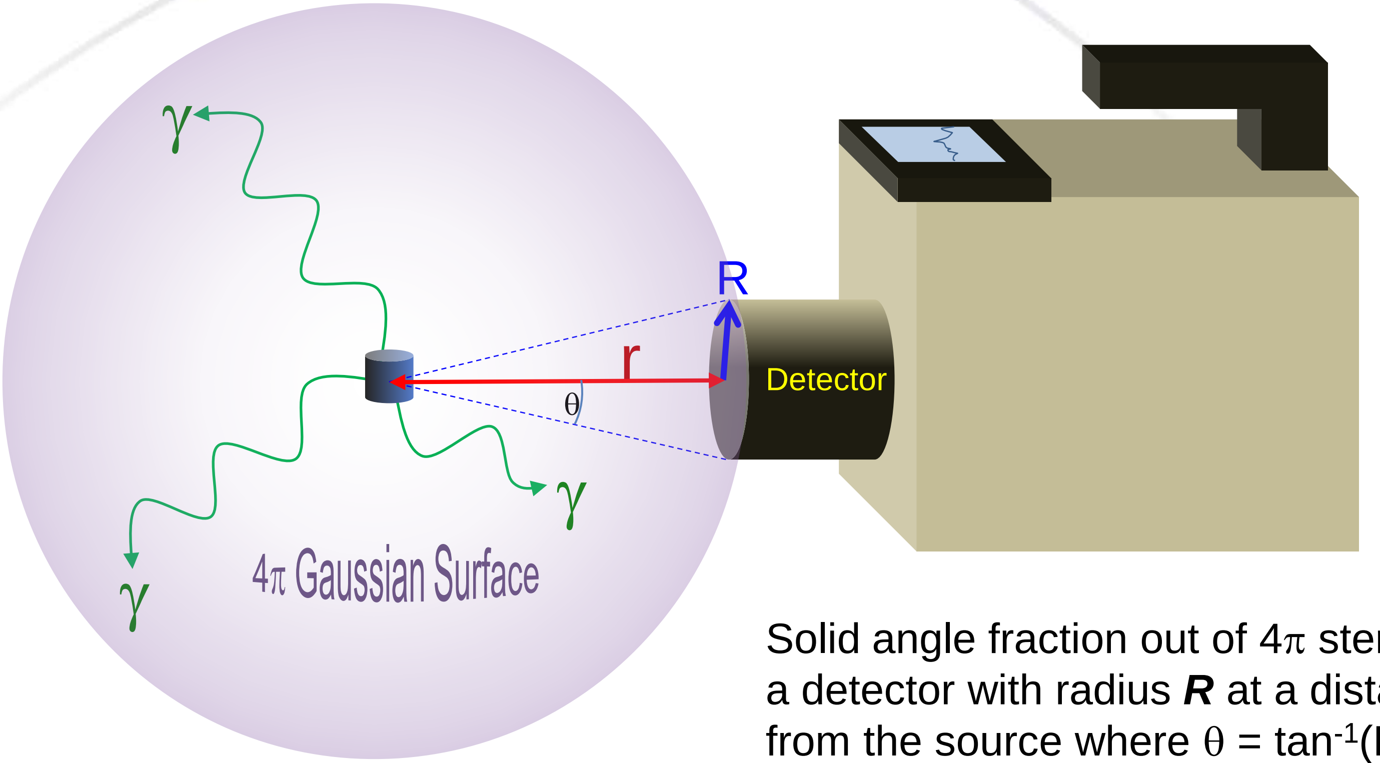
$$\varepsilon_{Abs} = \frac{number\ of\ events\ recorded}{number\ of\ photons\ emitted}$$

- Intrinsic efficiency

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

- Intrinsic efficiency values only consider the gammas that actually enter the detector

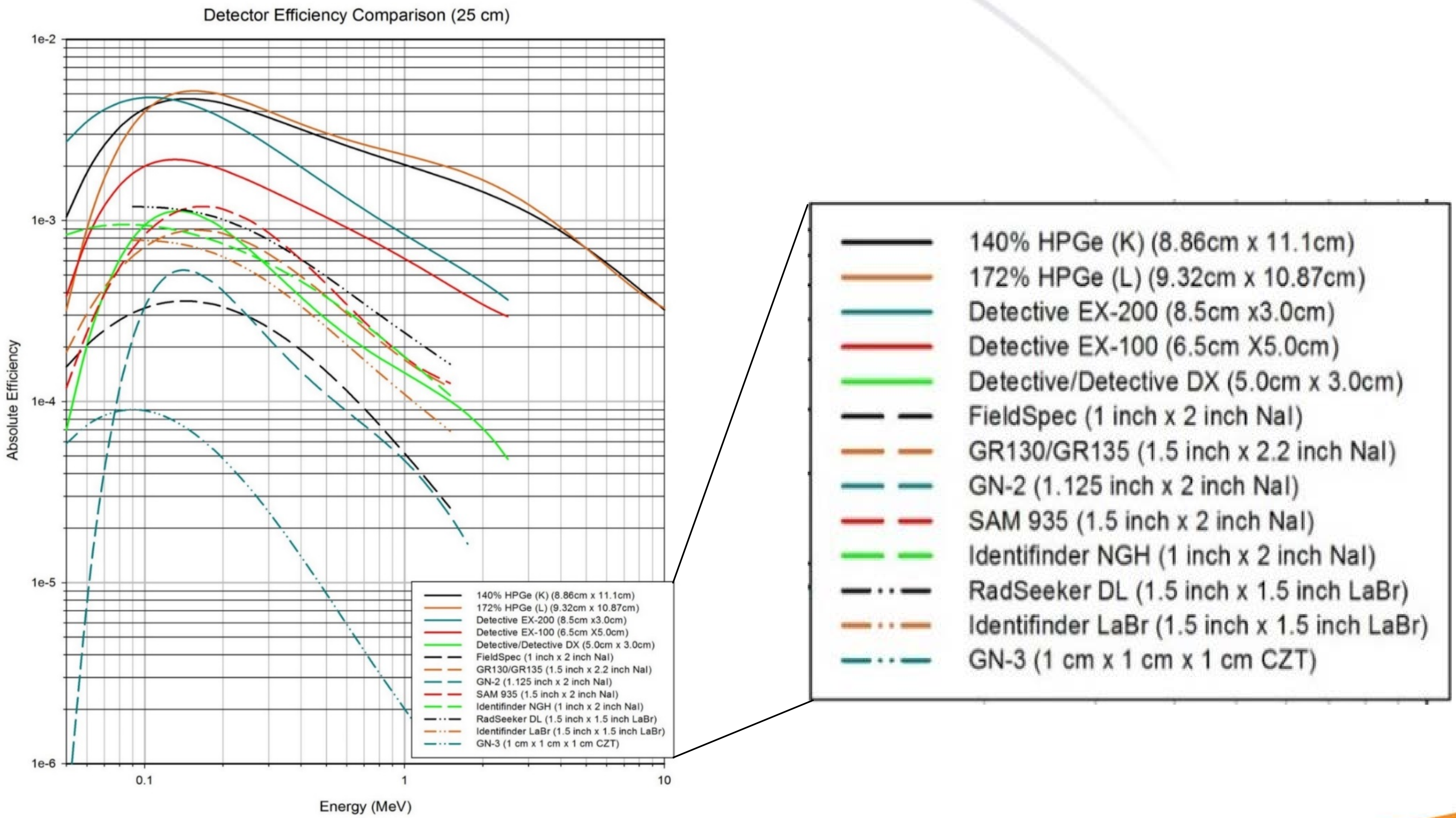
Detector Solid Angle Fraction



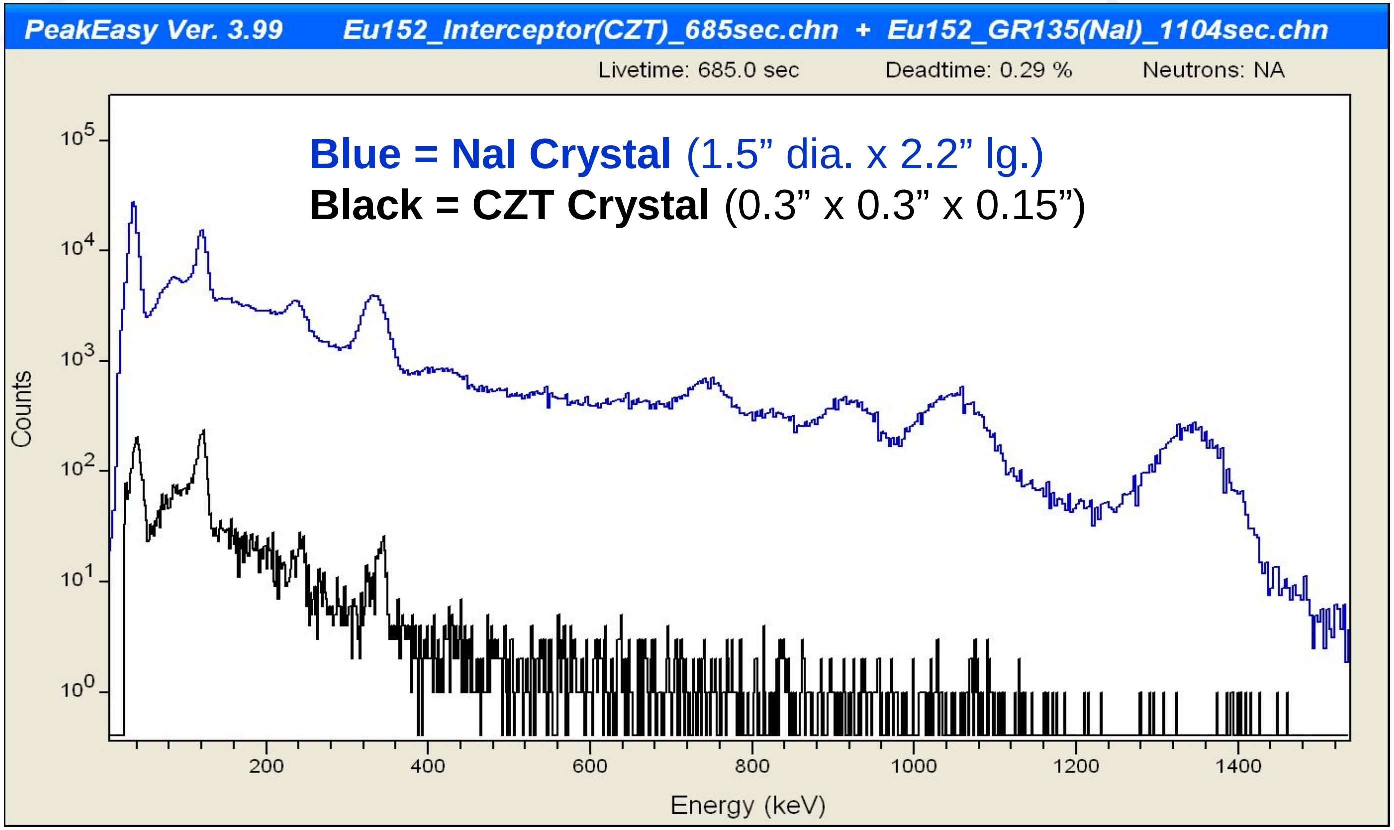
Solid angle fraction out of 4π steradians for a detector with radius ***R*** at a distance ***r*** from the source where $\theta = \tan^{-1}(R/r)$:

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

Example Efficiency Curves

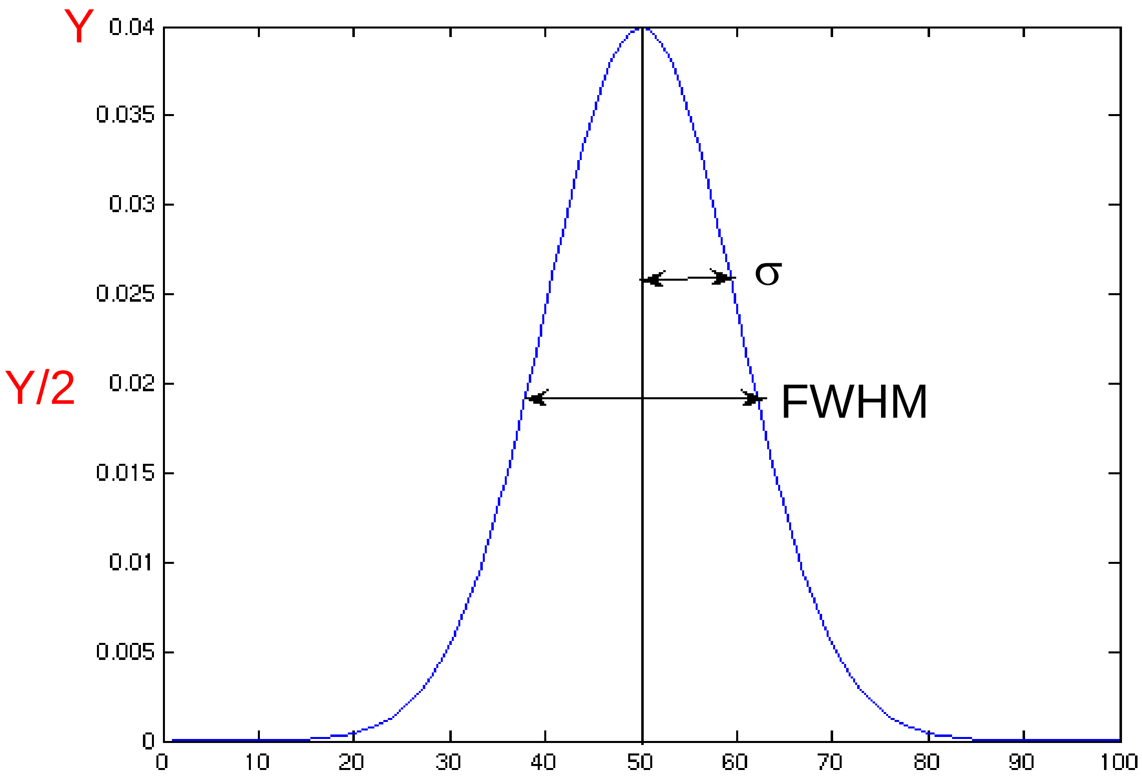


Importance of Efficiency



Both measurements of same Eu-152 source at 1 meter

What is Resolution?



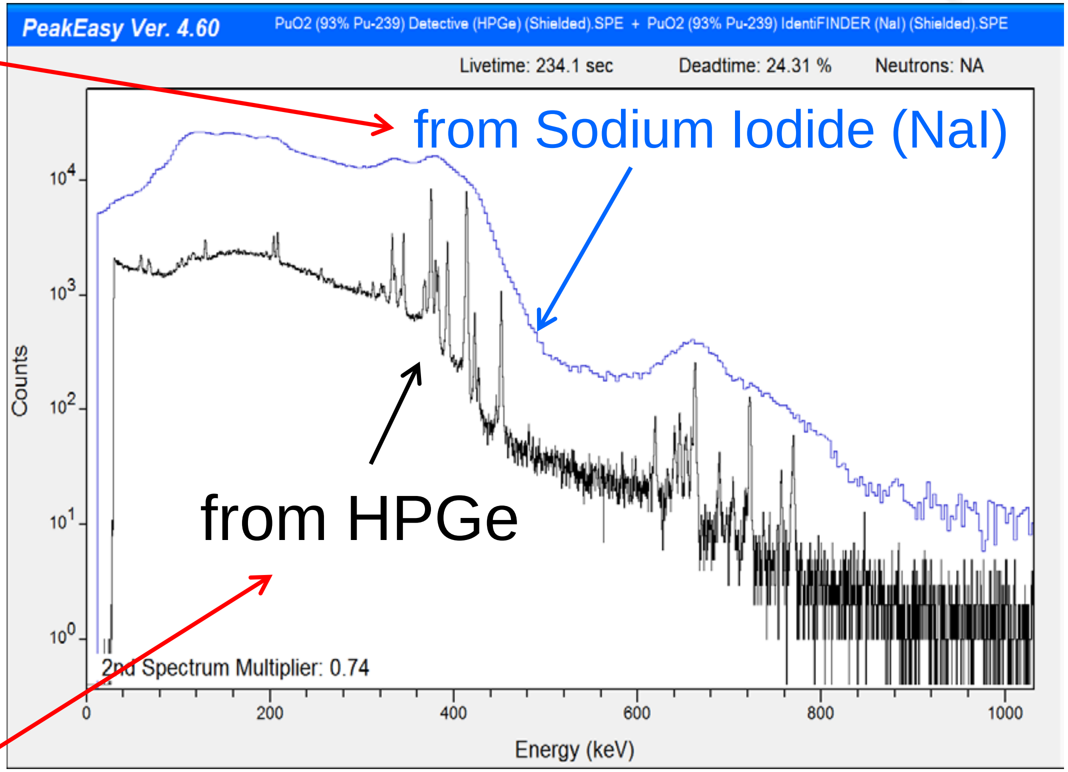
$$Y(H) = Y \exp\left(-\frac{(H - H_0)^2}{2\sigma^2} \right)$$

$$FWHM = 2.35\sigma$$

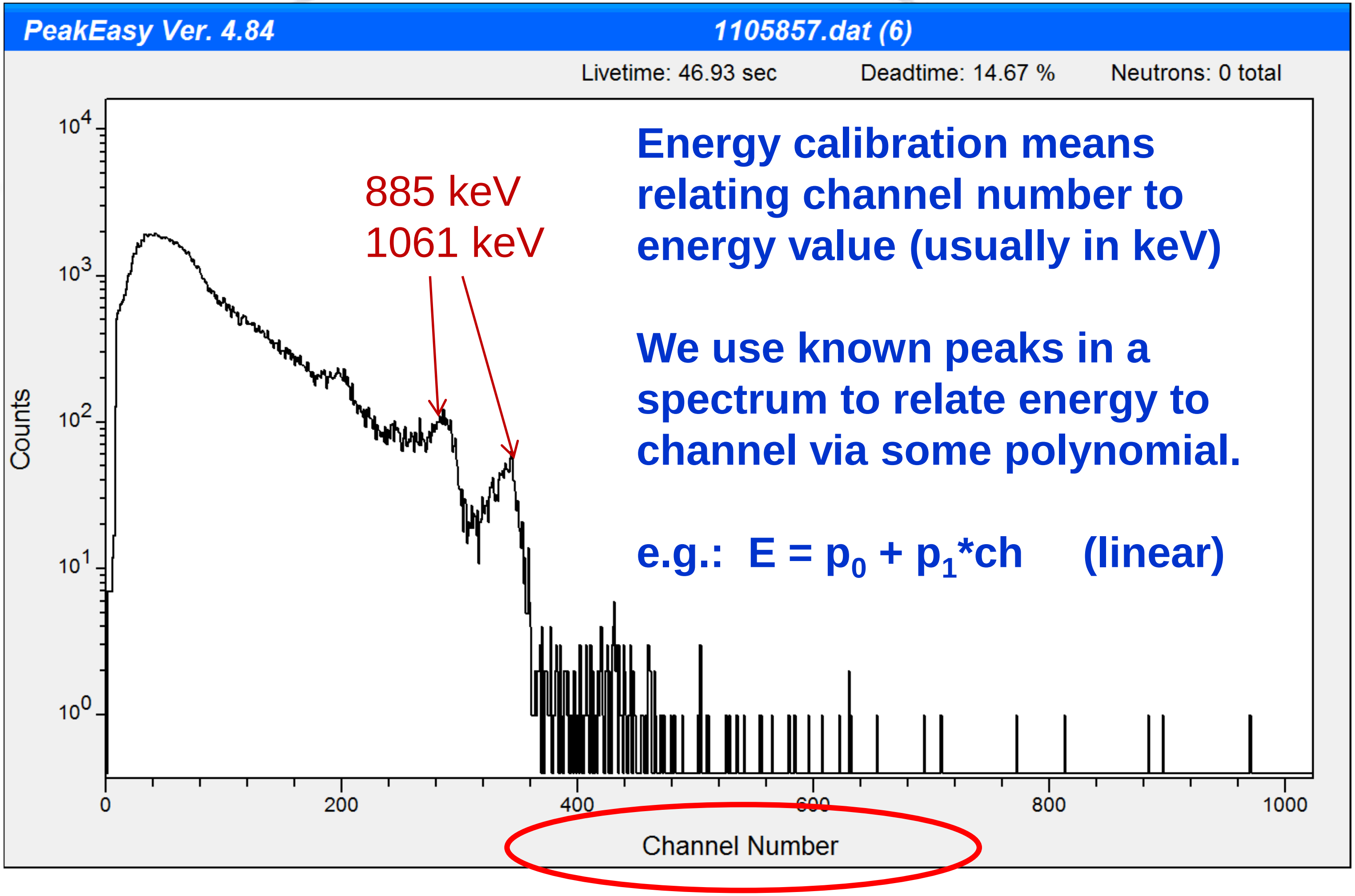
FWHM = Full Width at Half Maximum

The Importance of Resolution

Two spectra of the same Pu item



Linearity and Energy Calibration



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

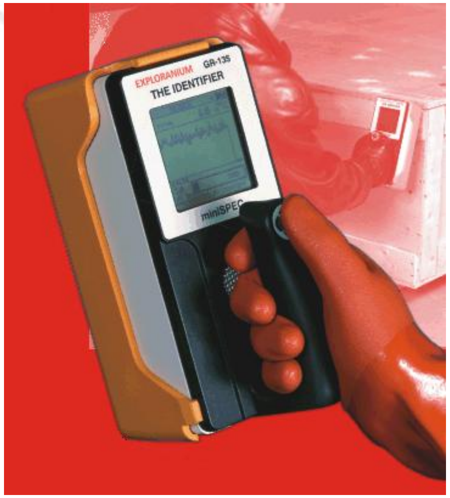
We use known peaks in a spectrum to relate energy to channel via some polynomial.

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

Scintillation Detector Media

- NaI and CsI are the most common and least expensive
- $LaBr_3$ has gained in popularity during the last decade (better resolution than NaI)
- PVT plastic scintillators can be made very large and are commonly used in portal monitors
- Two emerging technologies include –
  - Cs_2LiYCl_6 (CLYC) which also detects neutrons (Li)
  - SrI_2 prototypes have relatively good resolution compared to other scintillators

Commercial Scintillation-Based Detectors



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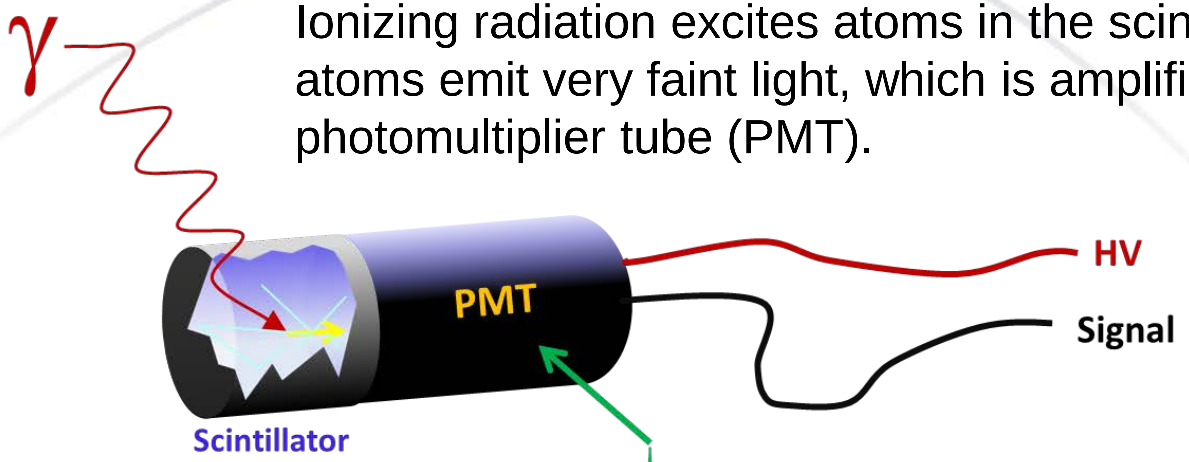
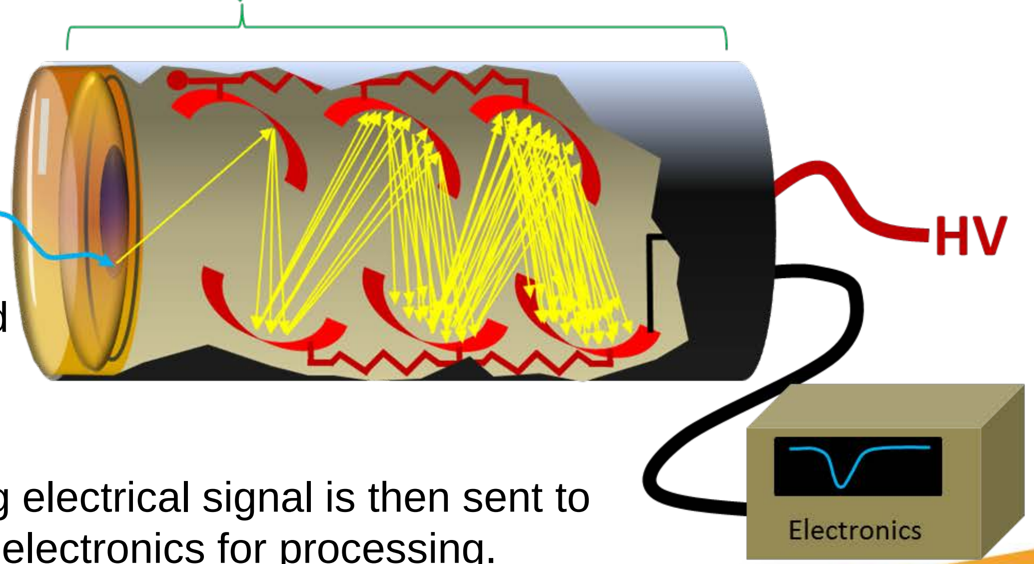
Scintillation Detectors

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

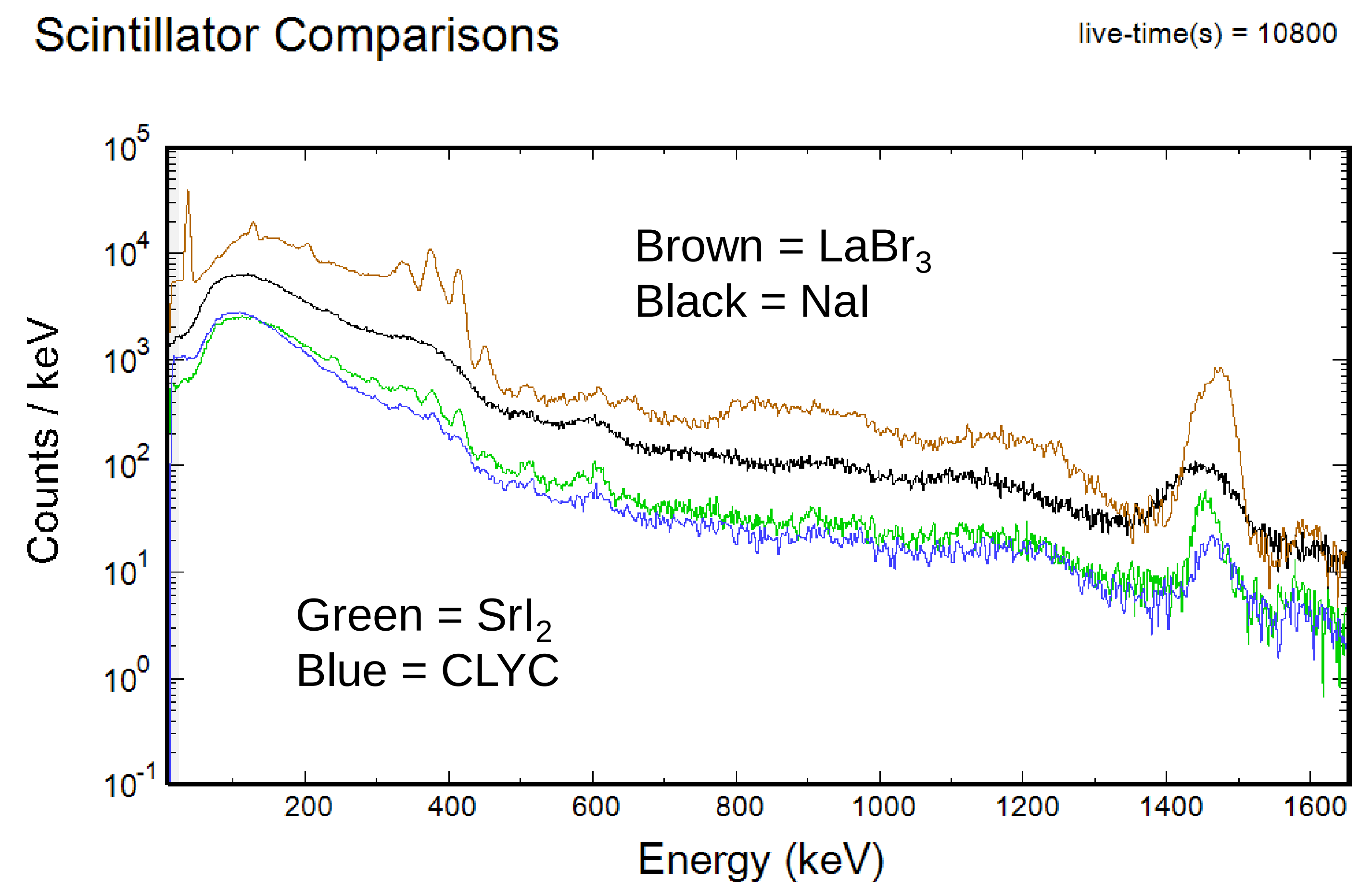


Light from the scintillator is converted to electrons by the PMT and amplified a million times or more through a succession of electrodes called 'dynodes'.



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

Comparisons of Scintillators



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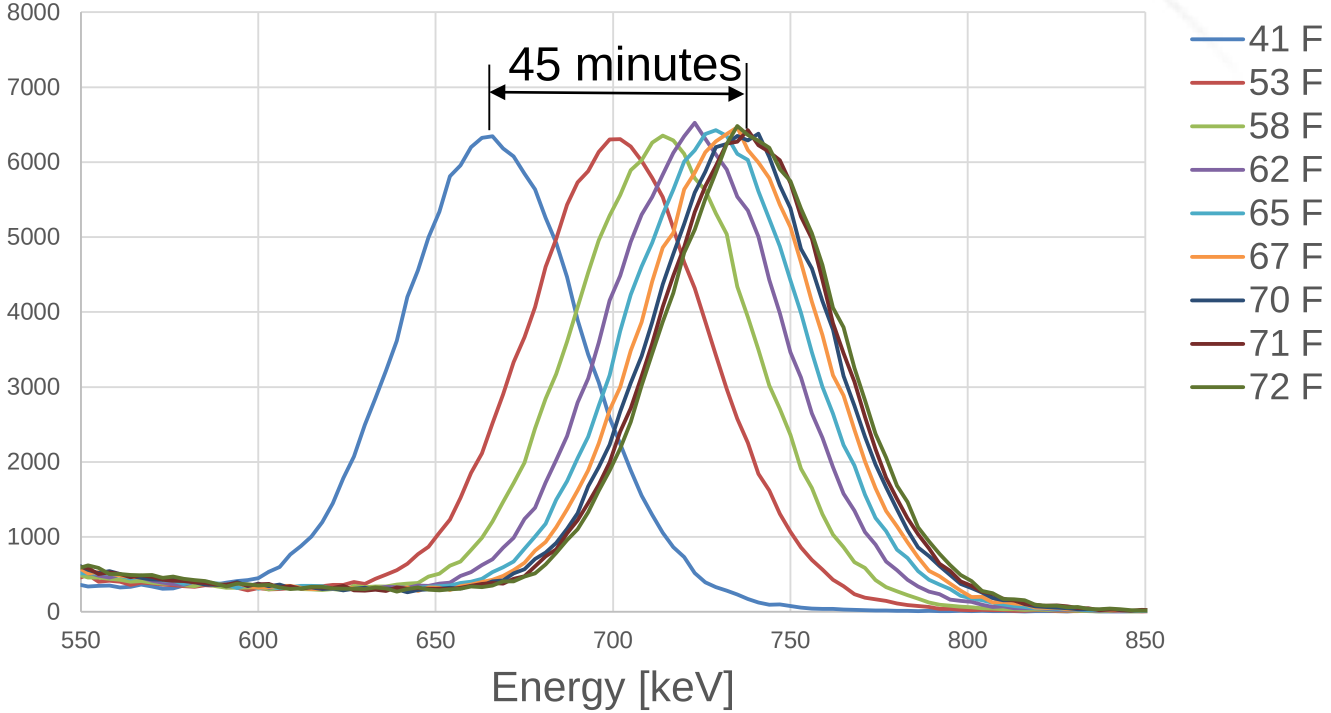
Energy Changes with Temperature



^{137}Cs Photopeak at 662 keV

Scintillation Detector Score Card

- **Efficiency can be extremely high**
- **Low Cost (especially NaI and PVT)**
- Low (poor) resolution
  - Few information carriers (light photons) result in poor statistics
  - NaI resolution equals 7%, $LaBr_3$ resolution equals 3.5%, CLYC resolution equals 4.5%, SrI_2 resolution equals 3%, PVT resolution is generally greater than 25%
- Temperature sensitivity = Gain drift
  - Gain fluctuations and non-linearities result in difficult energy calibrations
  - Both the PMT and crystal have temperature sensitivities

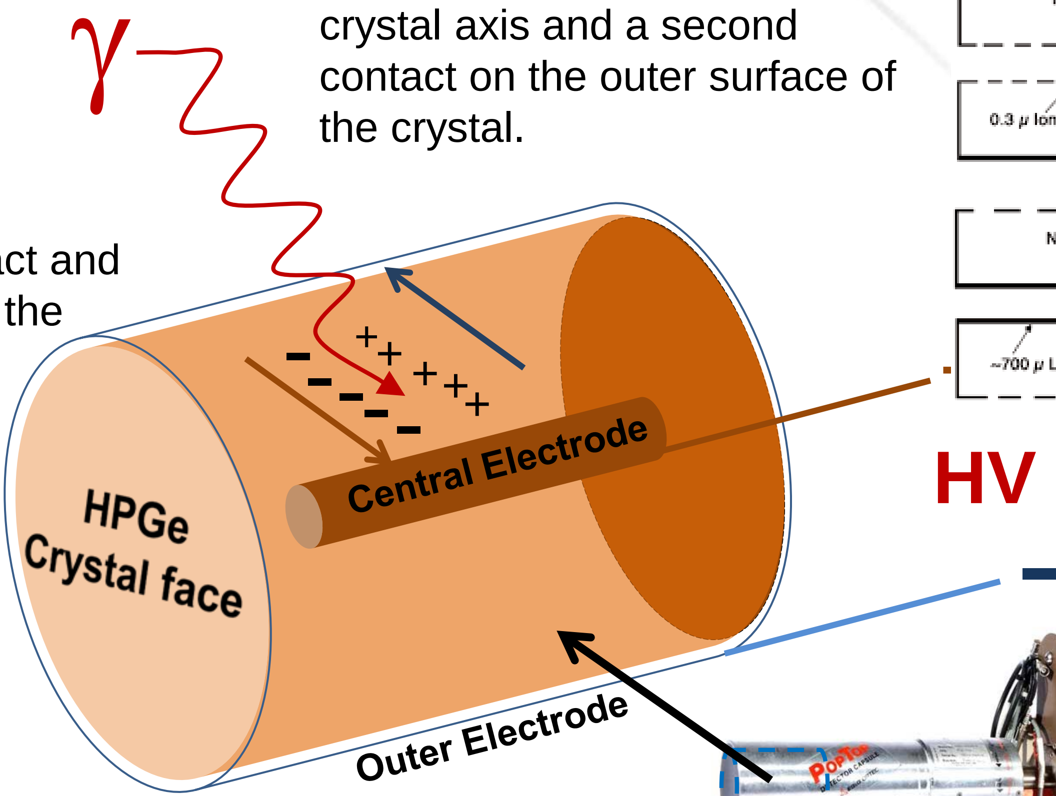
Commercial Semiconductor-Based Detectors

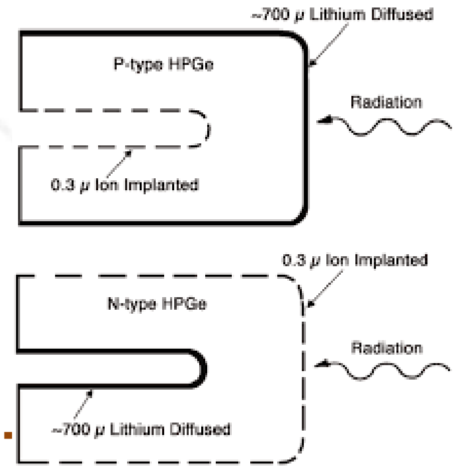
High-Purity Germanium (HPGe)

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)

HPGe Detector Score Card

- Excellent energy resolution (0.2%)
  - Large number of charge carriers created
- Large crystal growth allows good efficiency
  - 140-160% possible (relative to a 3” x 3” NaI)
- Excellent linearity
- Operational issues: must cool to LN_2 temperatures to avoid thermal excitation of electrons (can use mechanical cooling)
- Cost: most expensive of gamma ray detector types

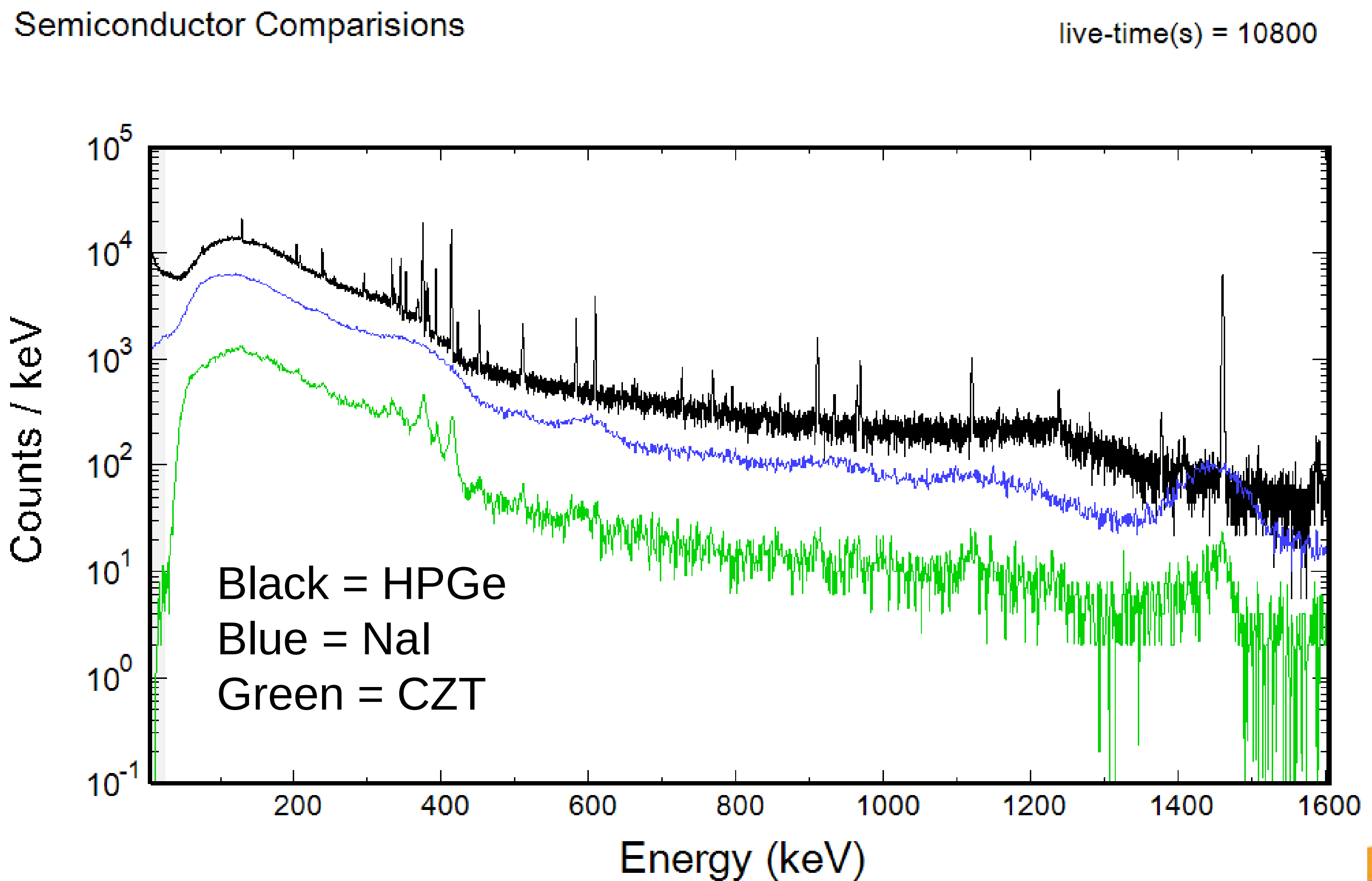
CdZnTe (CZT) Description

- CZT is an alloy of cadmium telluride and zinc telluride
- CZT is a bandgap semiconductor that can be operated at room temperatures
  - Bandgap ranges from 1.4 to 2.2 eV (HPGe is 0.74 eV)
- Coercing the electric signal out of the electron-hole pairs is challenging
  - Use of coplanar grids and pixelating the crystal are common methods

CZT Score Card

- Very good resolution: usually<3%, but with new signal processing now 1% is achievable
- Very good linearity
- Band gap large enough for room-temperature operation
- Reasonable costs (usually)
- Poor efficiency: Difficult to grow large crystals (~ 6 cm^3 max)
- Poor hole mobility requires very sophisticated electrodes and read out

Semiconductor Comparisons



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Gamma Radiation Search and the Inverse Square Law ($1/r^2$)

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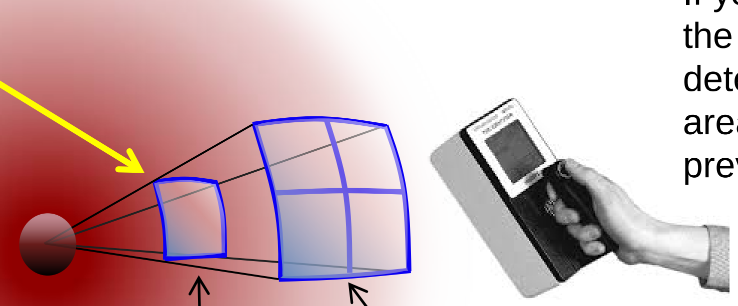
Area of a Sphere = $4\pi r^2$
Solid Angle $\propto 1/r^2$

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.

γ-ray field

distance = r
area = A
e.g. 4 mR/hr

distance = 2r
area = 4A
e.g. 1 mR/hr

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

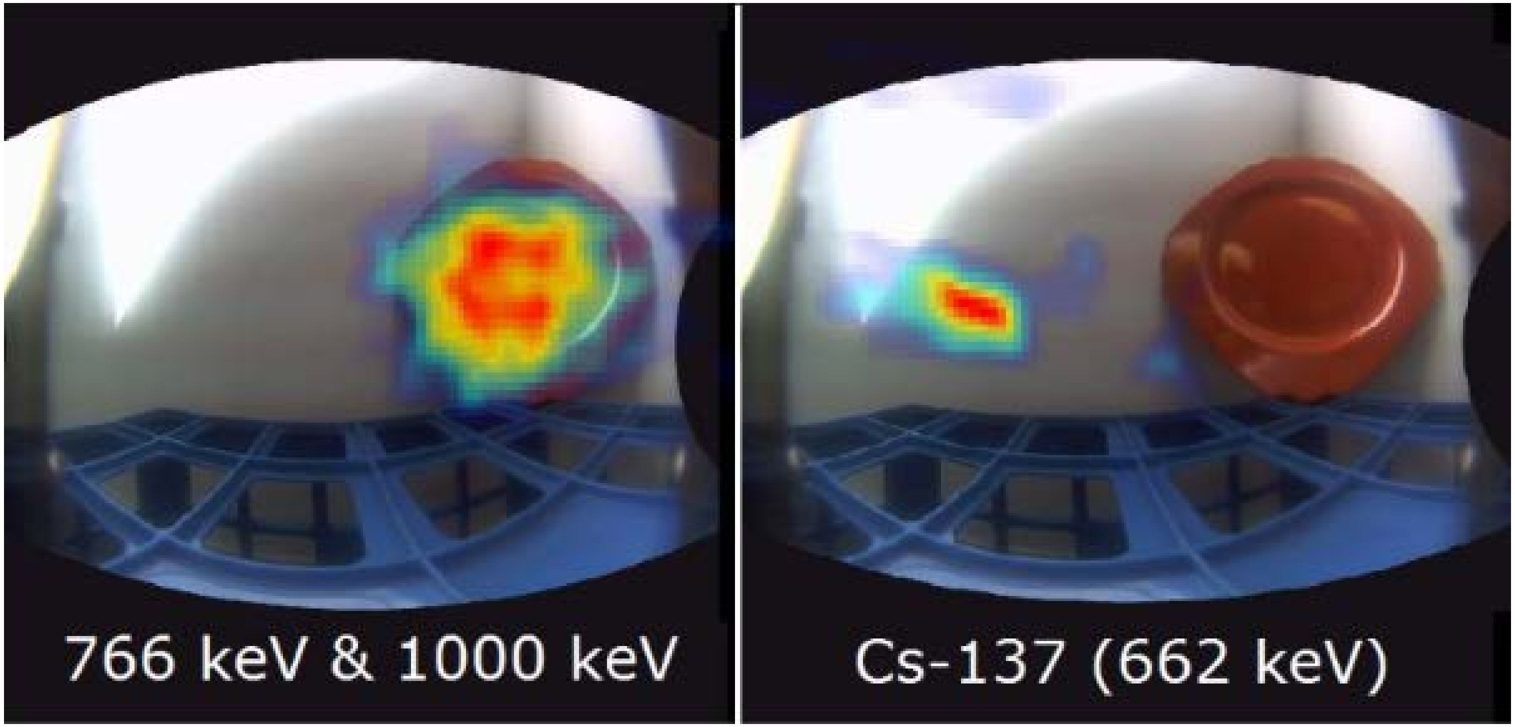
Detection *very strongly* depends on source-to-detector distance!

NNSA National Nuclear Security Administration

Detectors for the Search Mission

- Arrays of large NaI logs (2” x 4” x 16”) are commonly mounted on aircraft and helicopters
- They are similarly used in vehicles which often include large volume neutron detectors
- A number of backpack radiation detectors have been developed (generally speaking, bigger is better)
- Gamma cameras have been developed to localize the signals

CZT Gamma Camera



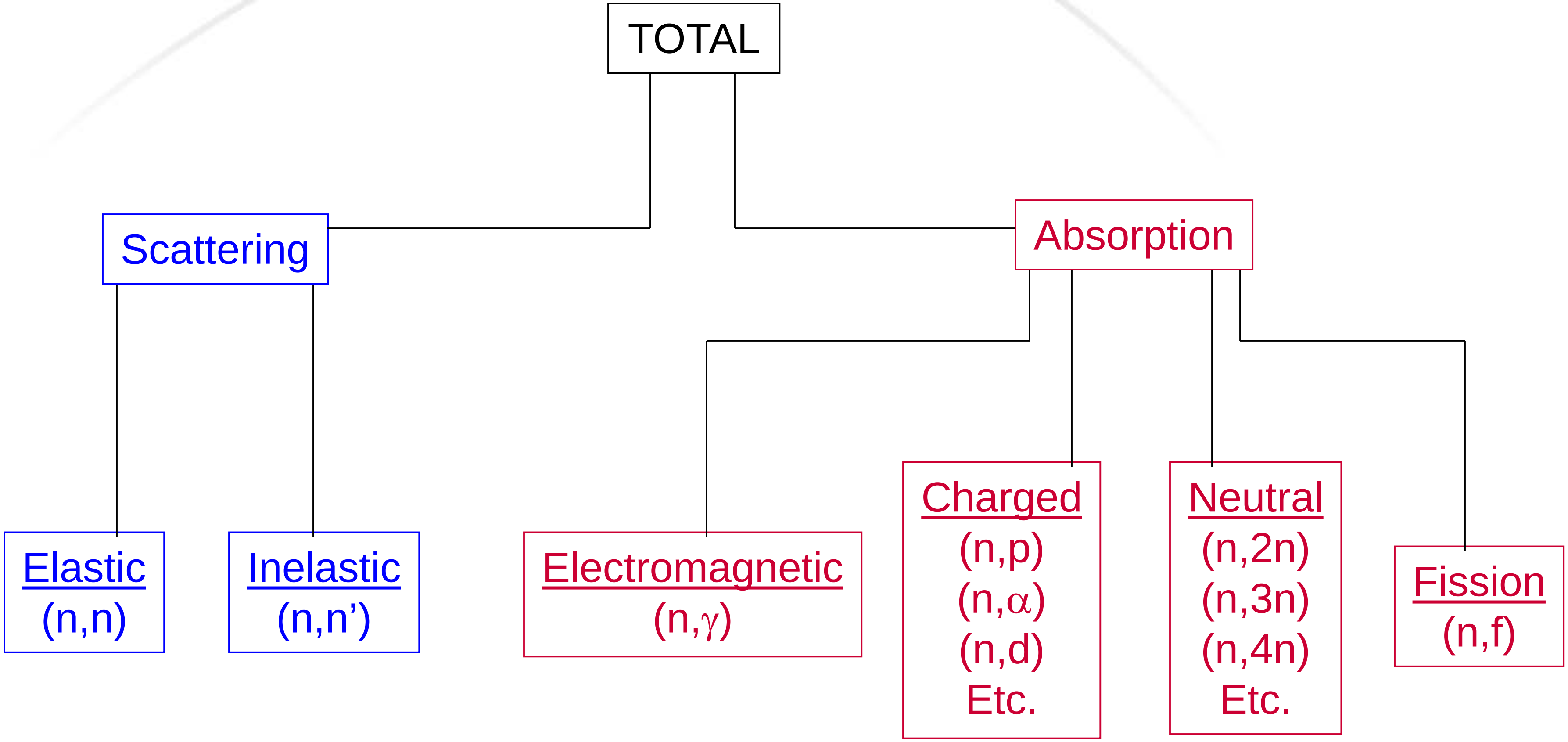
U238 and Cs137 are successfully located and discriminated

Mechanisms for Neutron Detection

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

Again, it is all about converting the neutron energy to charge or light (and then charge) and then collecting that charge, JUST LIKE GAMMA-RAYS!

Neutron Interactions with Matter

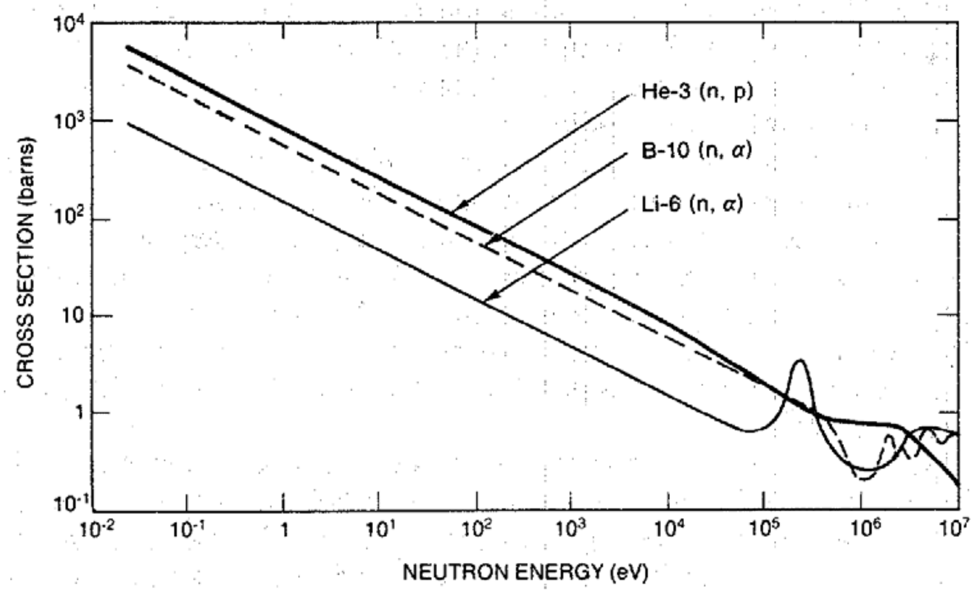


Q-Values for Neutron Interactions

	Q-Value
^{3}He(n,p):	
$^{3}He + ^{1}n \rightarrow ^{3}H + ^{1}p$	0.764 MeV
^{10}B(n,α):	
$^{10}B + ^{1}n \rightarrow ^{7}Li + ^{4}\alpha$	2.792 MeV
$^{10}B + ^{1}n \rightarrow ^{7}Li^{*} + ^{4}\alpha$	2.310 MeV
^{6}Li(n,α):	
$^{6}Li + ^{1}n \rightarrow ^{3}H + ^{4}\alpha$	4.78 MeV

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

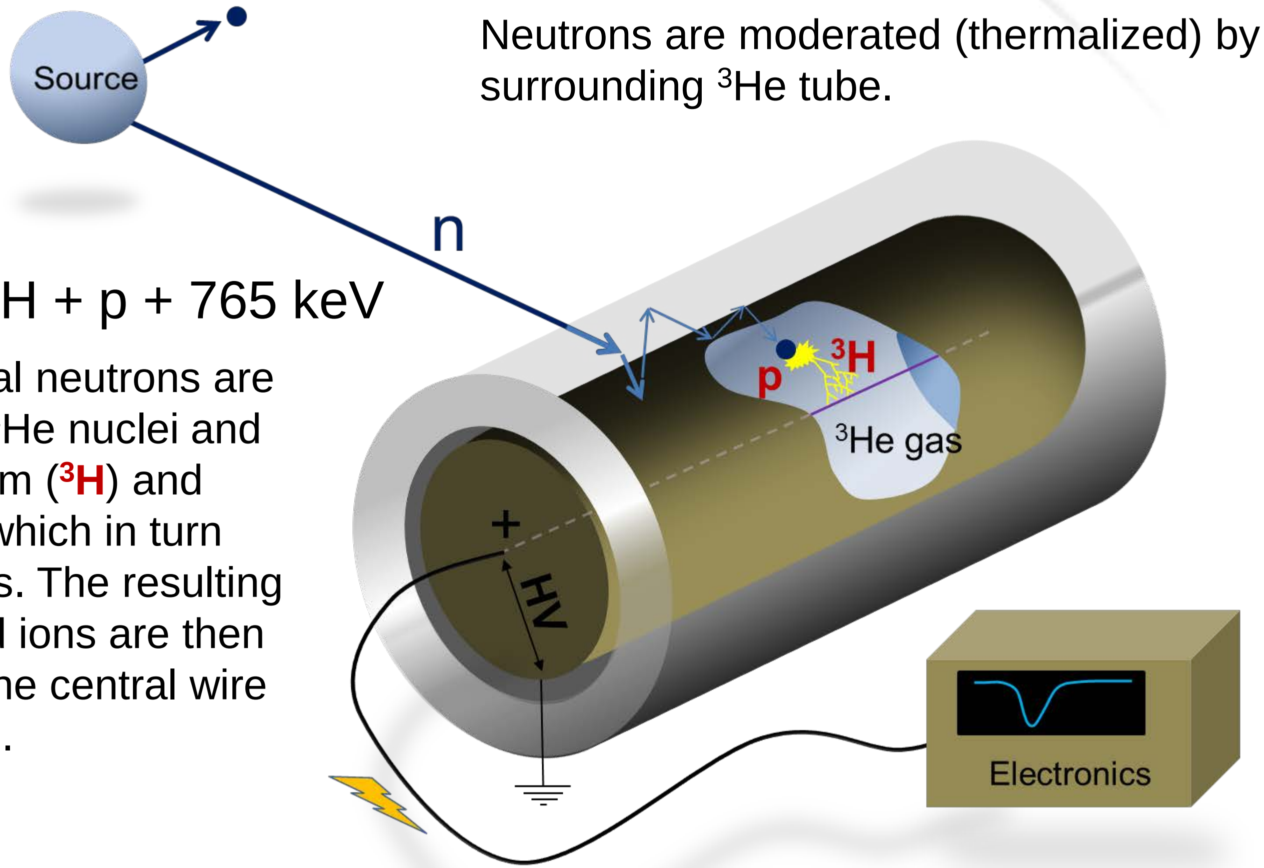
- ^{3}He
  - Typically operated < 10 atm (except RIIDs)
  - ~75% efficient for thermal neutrons
  - Currently, the most common neutron detector in portal monitors
- $^{10}BF_3$
  - Typically operated < 1.5 atm (recombination occurs at high pressures)
  - < 50% efficient to thermal neutrons
- ^{10}B-lined 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.

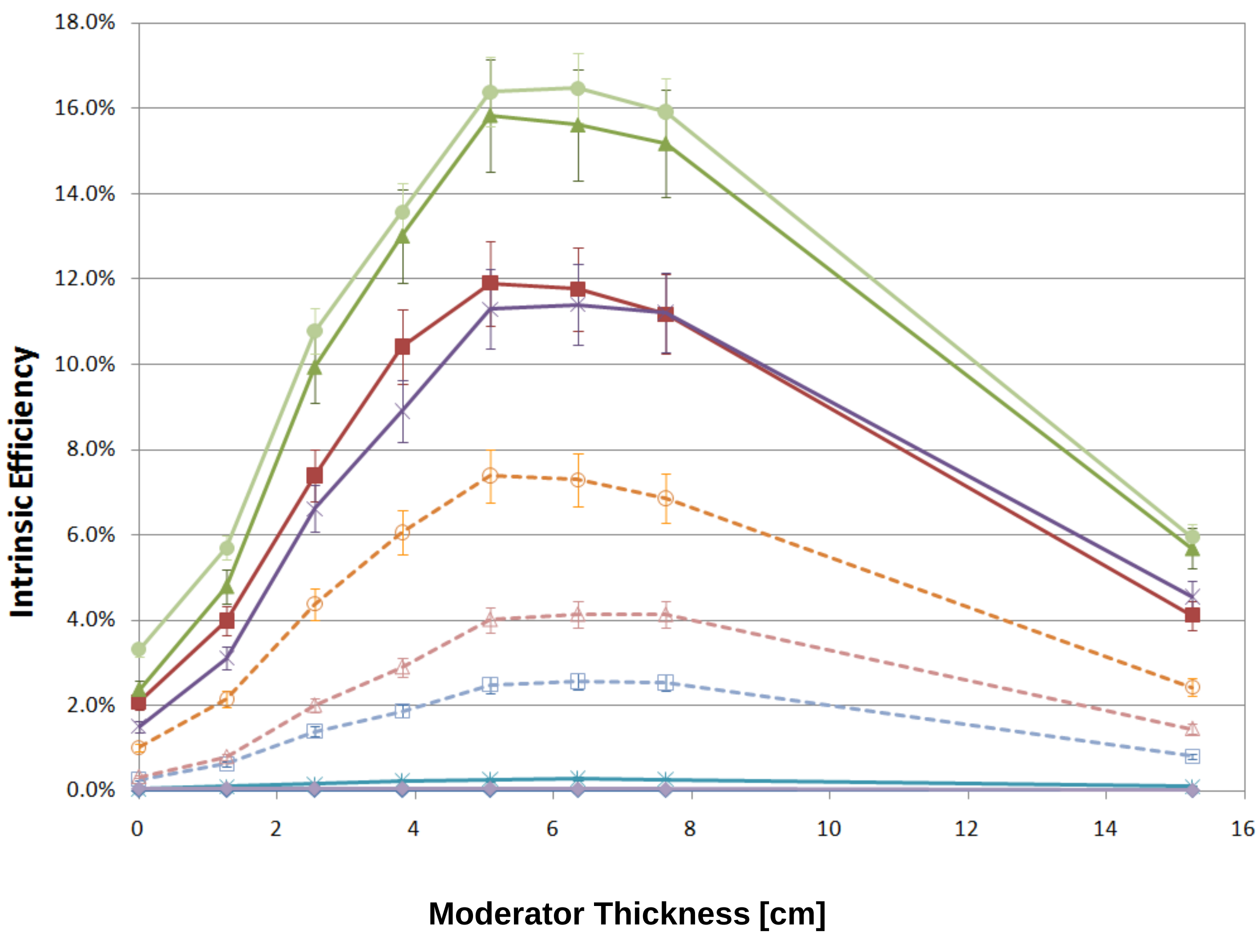
$^{3}He + n \rightarrow {}^{3}H + p + 765\ keV$

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



Several detectors of varying volume and efficiency

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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 some older handheld detectors – relatively inefficient

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”)
- All are being researched due to the ^{3}He shortage (portal monitors have used up most of the stored amounts)

Problems with Neutron Detection

Los Alamos NATIONAL LABORATORY EST. 1943

- Useful spectroscopy can be difficult since neutrons rarely deposit their full energy in the detector
  - For ^{3}He detectors, neutrons must be thermalized for optimal detection therefore forfeiting all incident energy information
- Handheld detectors will only give neutron count rates
- Can be sensitive to gamma rays as well, but only in very strong gamma ray fields
- Cosmic ray spallation in nearby massive and dense materials will cause false neutron counts (e.g. cargo of car batteries)

Neutron Radiation Search

- For gamma rays we saw the signal strength drops off according to the $1/r^2$ rule
- Not so for neutrons!
  - Due to the fact that neutrons undergo many more scatter events before they are fully thermalized they propagate farther than gammas
  - Drop off can vary from $1/r$ to $1/r^{1.6}$
  - Since neutron background rates are far lower than gamma background rates they become much easier to detect – when present

DOE Triage Program

- On-call support (24/7) to frontline officers
  - Specialize in interpretation of spectra from portable radioisotope identifiers (RIIDs), but must be prepared for any radiation detector.
  - Respond within 10 minutes, usually provide results in 30-60 minutes.
  - Accurate identification of real threats, minimize the cost of a false or innocent alarm.
- Team includes two federal officers and three scientists from Livermore, Los Alamos, or Sandia. At least two different laboratories are required for peer review.
- Typically process about 100 real-world events per year, plus about 600 training events.

First Event

- Jan 2002: Toy soldiers smuggled into USA from Mexico were found to contain radioactive black powder.
- Early results suggest highly-enriched uranium.
- Analysis proved the powder was depleted uranium (0.25±0.05%) U-235.

United States Department of Energy “Triage” Program was established.

Hardware Supported

(these and many more)

CLASSI

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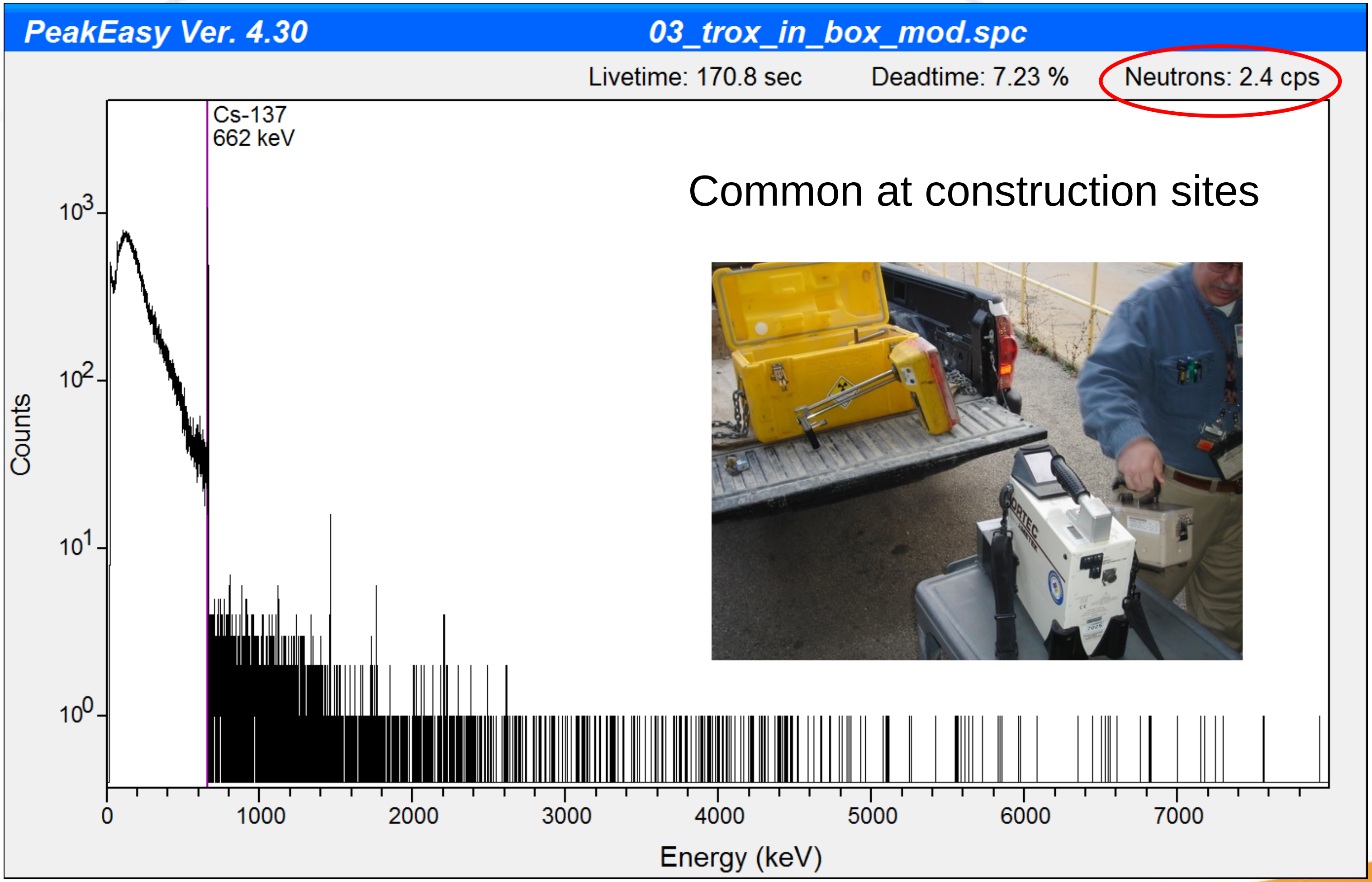
Soil Moisture Density Gauge



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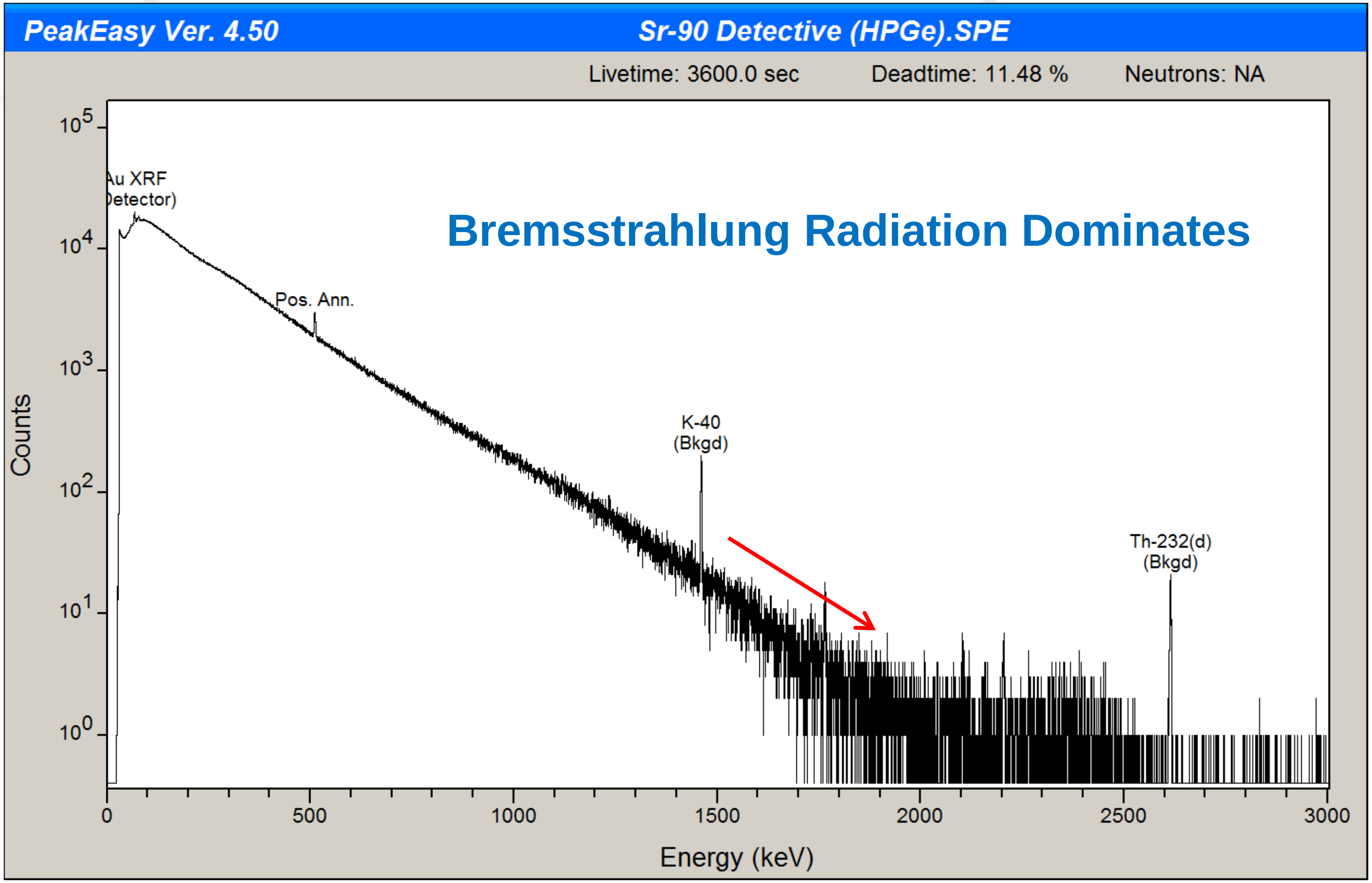
Radioisotopic Thermoelectric Generators (RTG)

Used to produce power in remote locations

Radioisotopic Thermoelectric Generators (RTG)



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Neutron Sources in Scrap Metal

Honduras

Sri Lanka / India

Canada / USA

Mexico

Recovered Sources

Data from Many Places…

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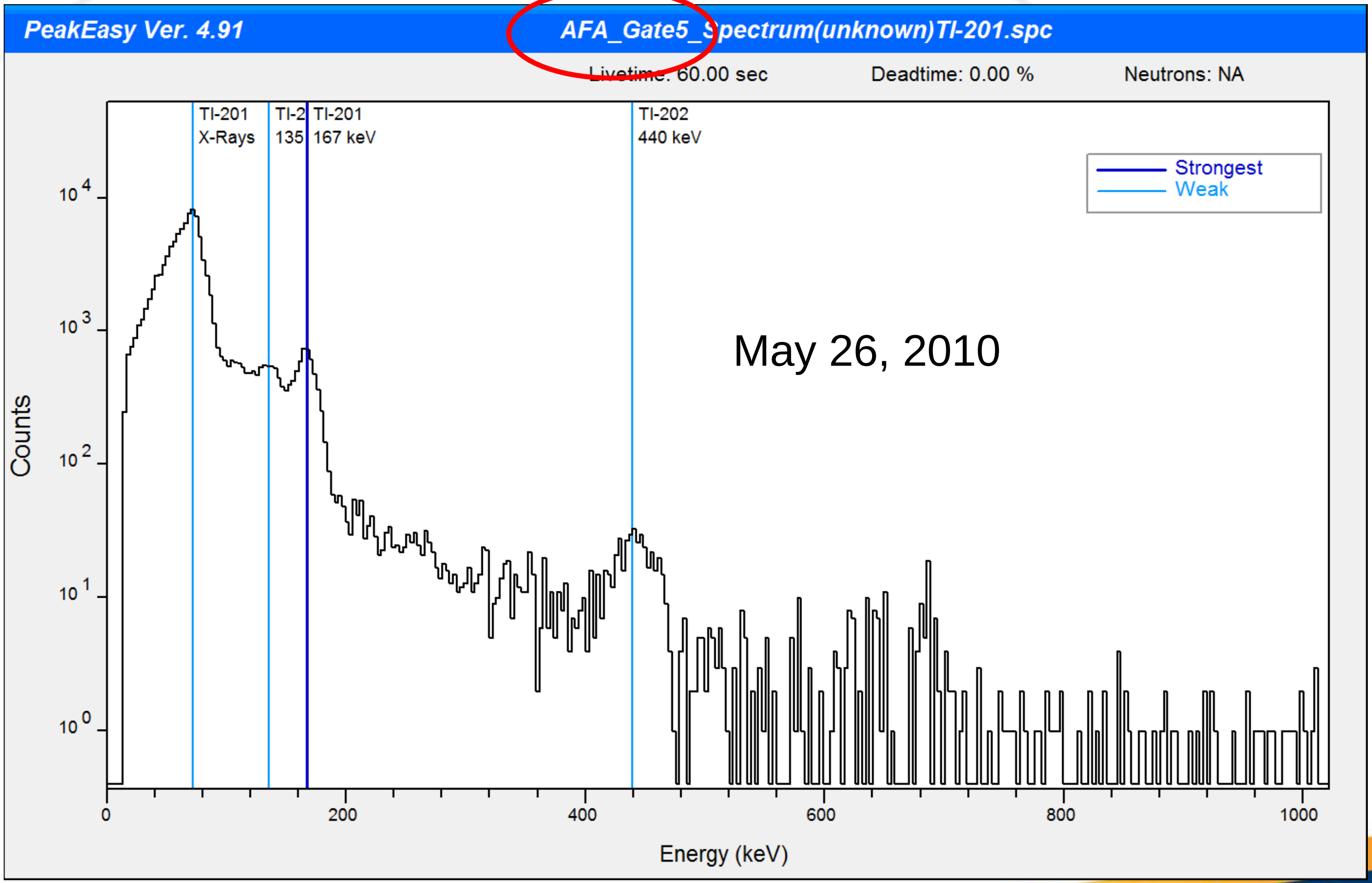

May 26, 2010

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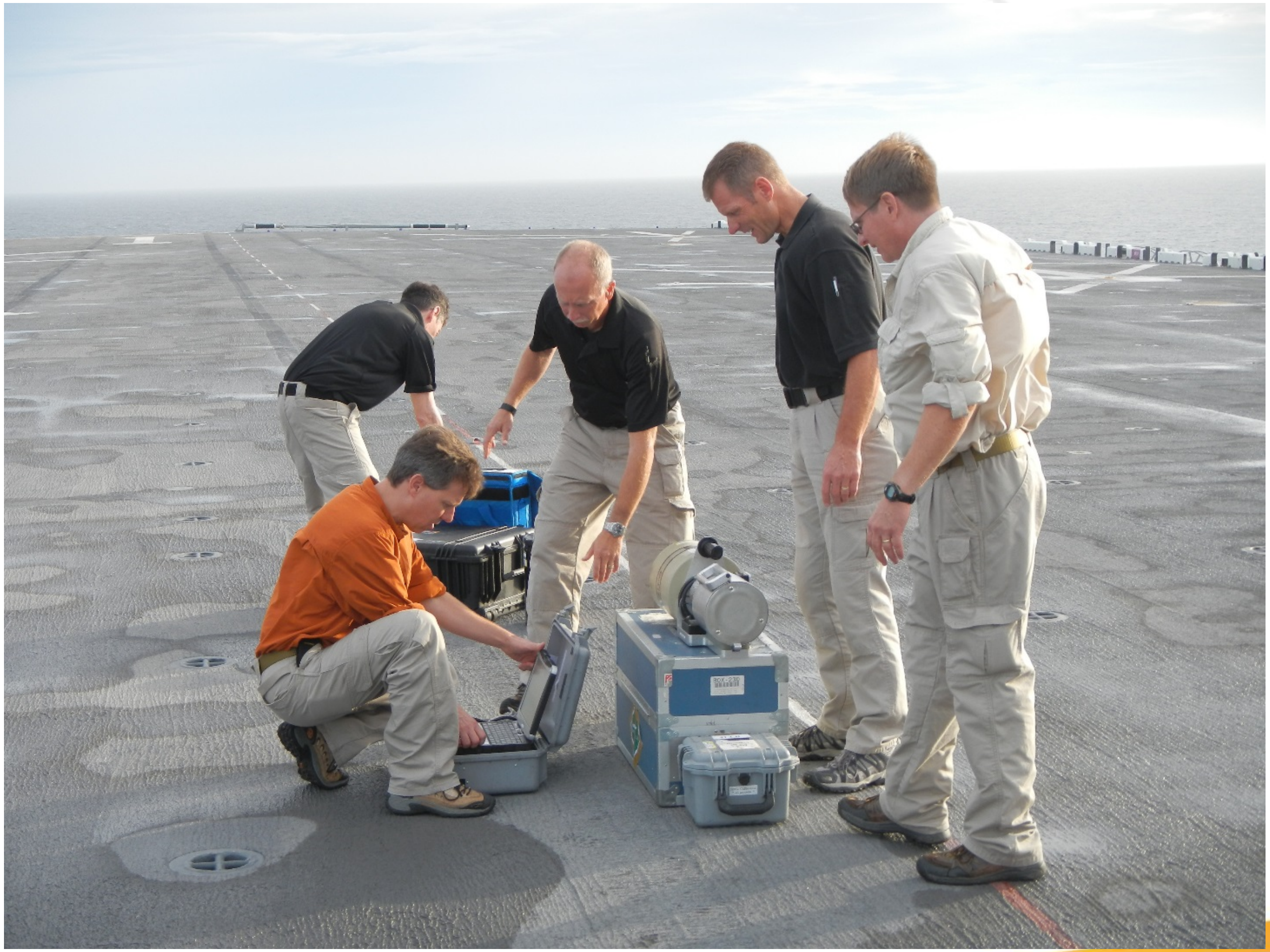
DOE JTOT Overview

- JTOT = Joint Technical Operations Team
- Several Phases of Deployment
- Exercises performed frequently with theme that "you should train the way you expect to play"
- Technical expertise in several skill sets

Team Members at Sea



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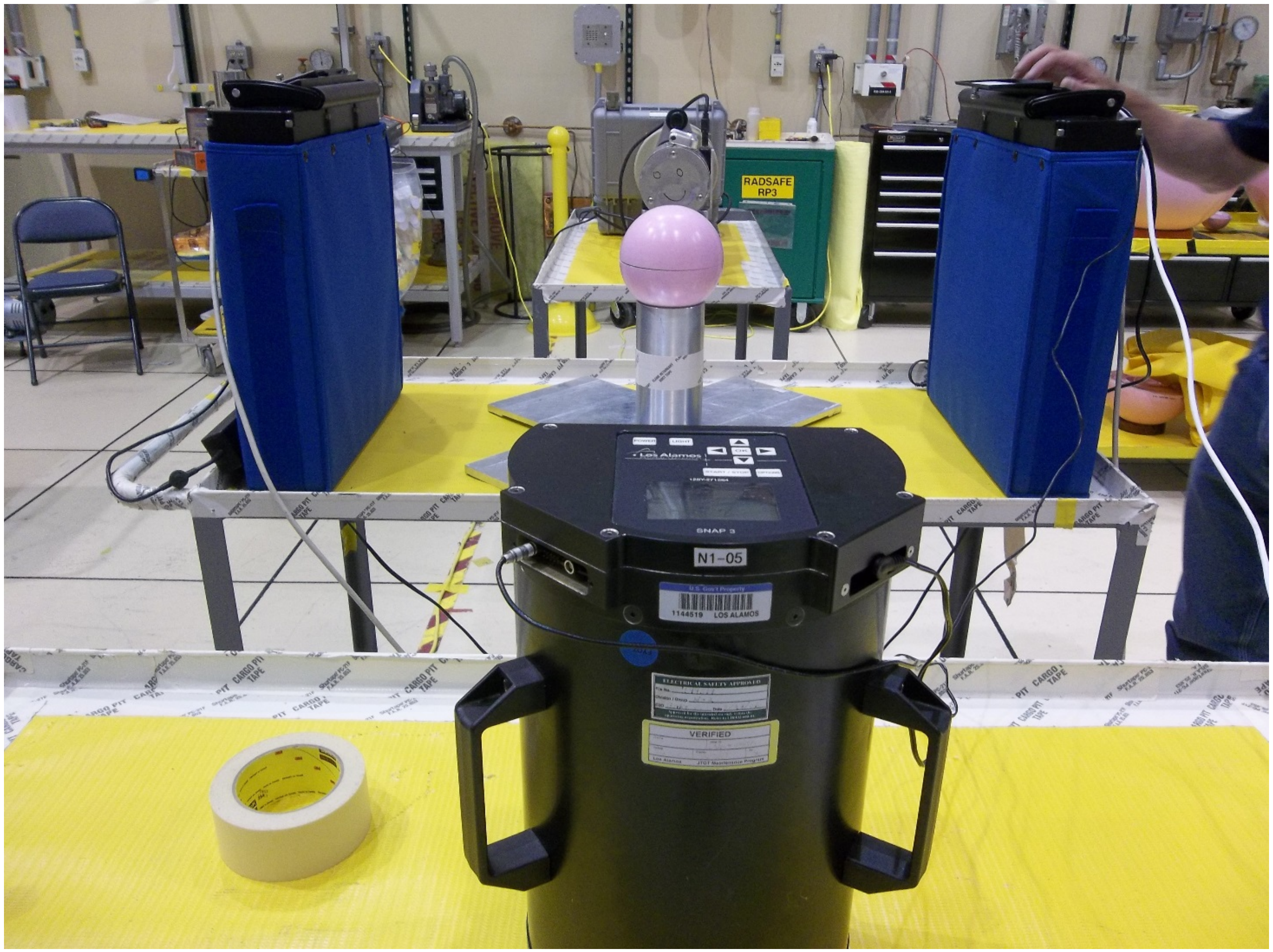
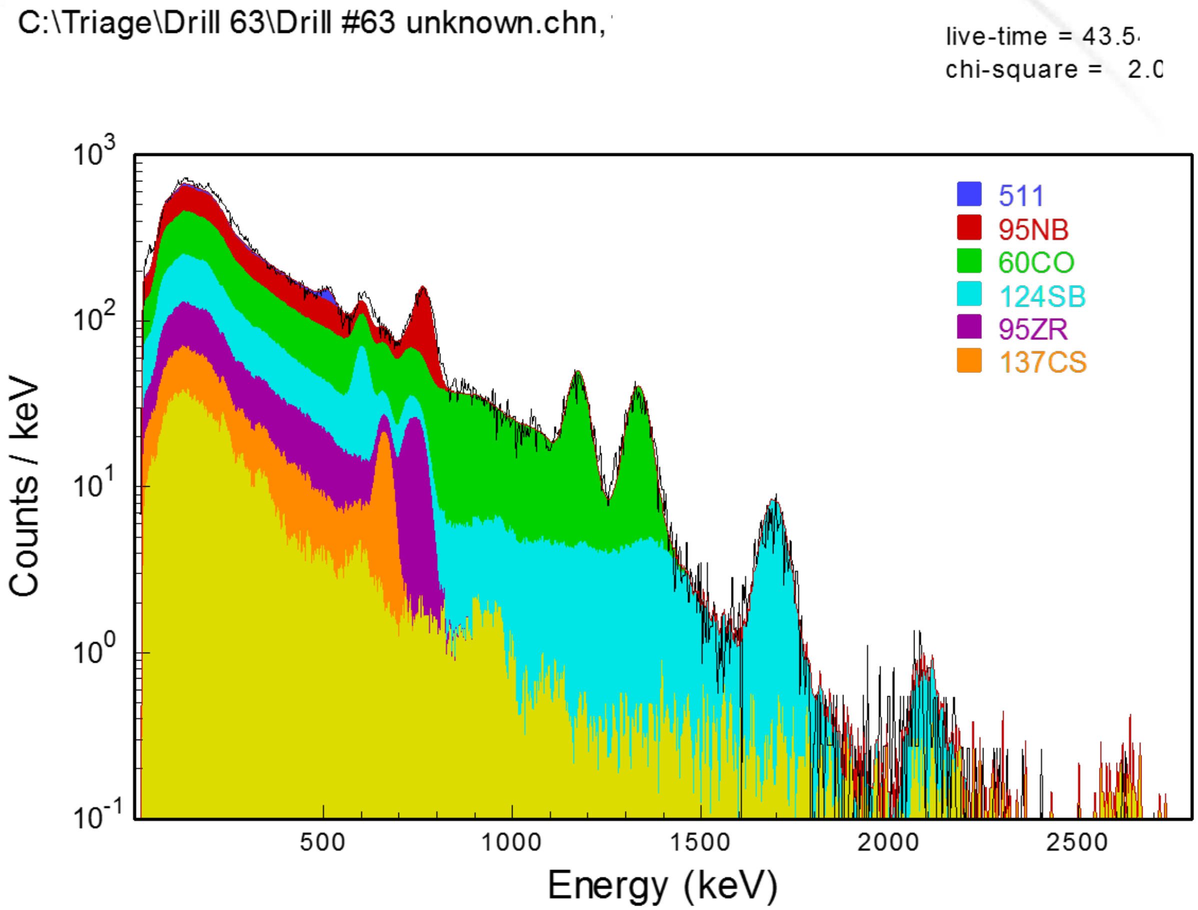
Subset of Diagnostic Equipment



Analysis Tools - Gamma

- LANL PeakEasy – exceptional gamma ray database and spectrum viewing tool
  - Assists with the human interpretation factor
- SNL Gamma Detector Response Analysis Software (GADRAS)
  - Automated nuclide identification tool
  - Exceptional gamma ray spectrum modeling tool
  - Supplements the device modeler's evaluation

Analysis Tools - GADRAS



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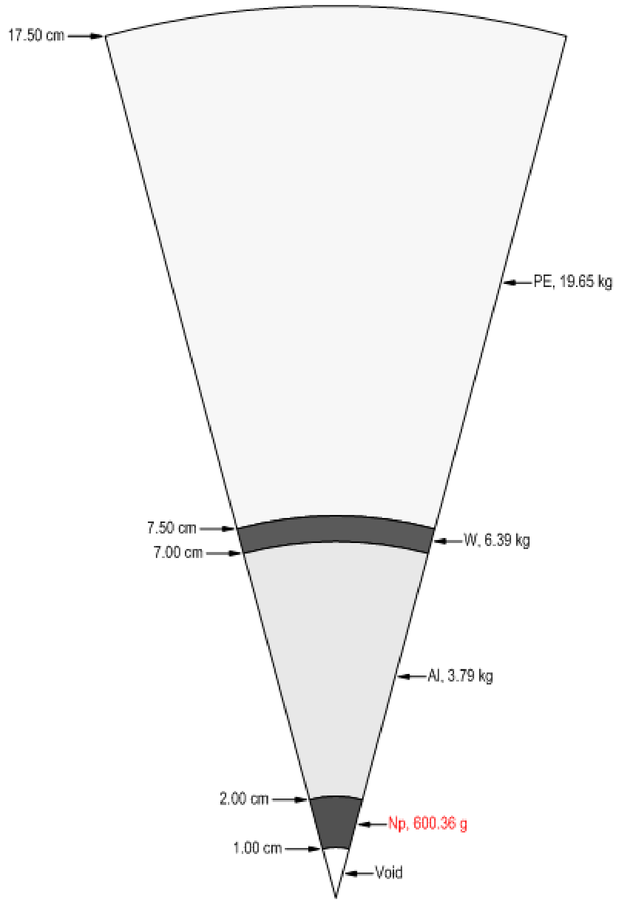
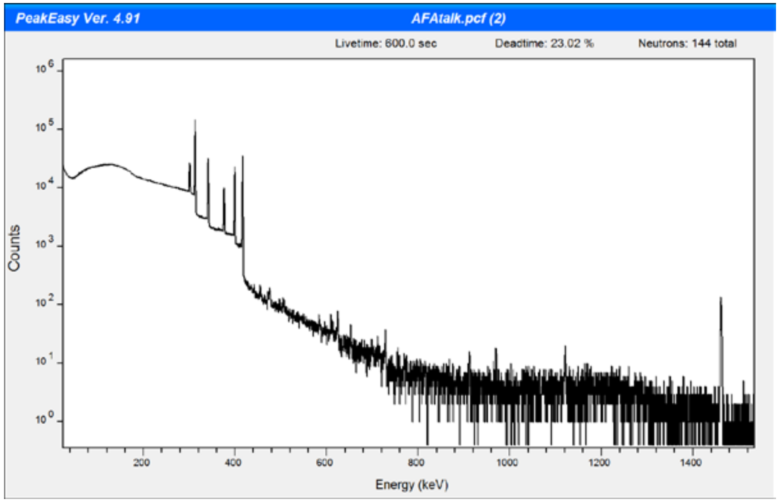
Analysis Tools - GADRAS



1D Modeling capability can predict spectra for possible solutions



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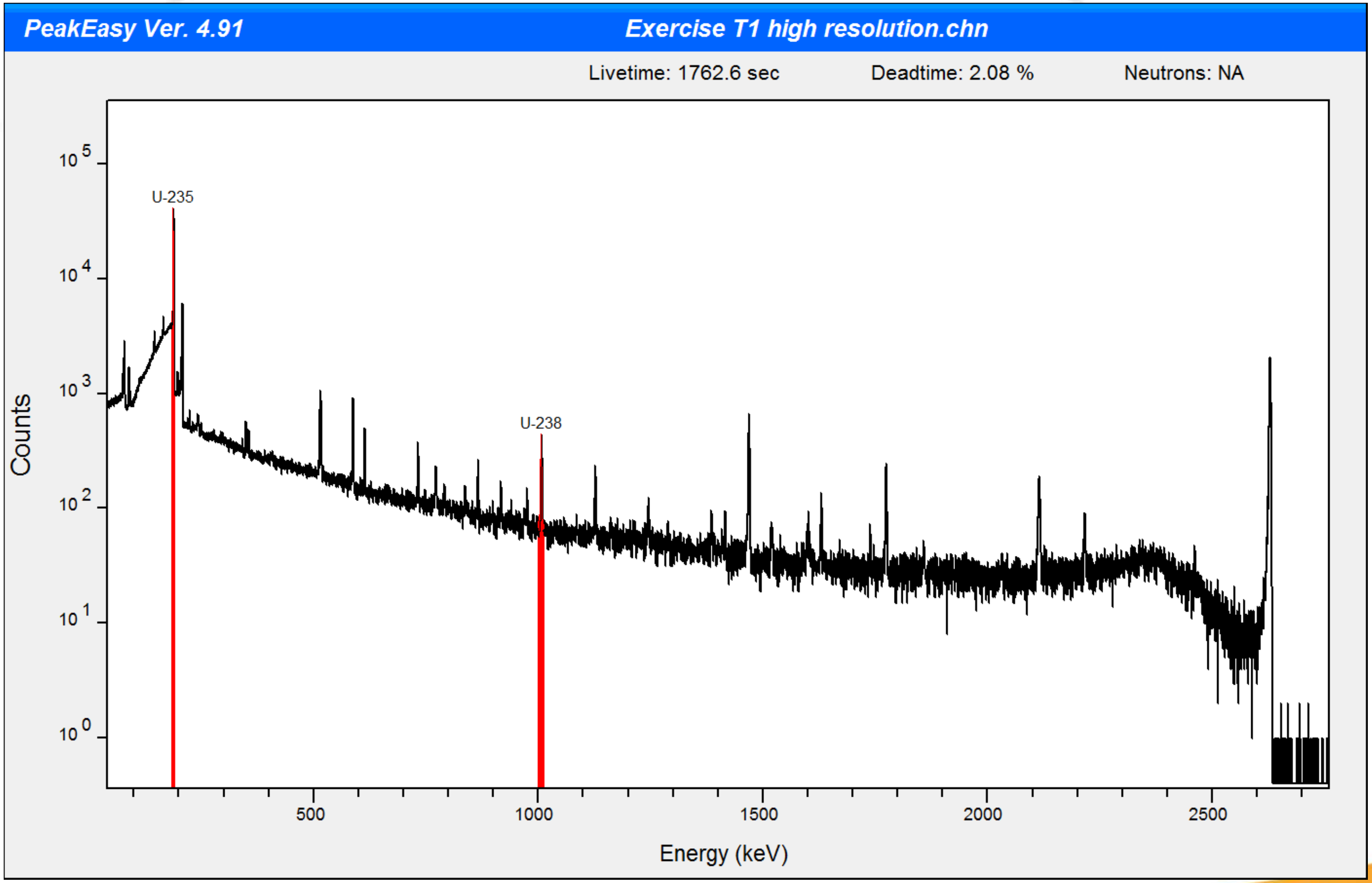
Analysis Tools – Neutron

- LANL initially developed “Neutron Replay” software and is in the process of upgrading that analysis tool to one named “Momentum”
  - Momentum alludes to the fact that mathematical moments are used in the analysis of multiplication
- LLNL developed and uses “BigFit” for neutron multiplication analyses
- Current focus is on tool refinement for both labs

General Signatures of SNM

- HEU: gammas at lower energies
  - 144, 163, 186, and 205 keV
  - Neutrons: approximately 1 n/s/kg for HEU
- Plutonium: Gammas low to medium energy (375 and 414 keV)
  - Neutrons from ^{240}Pu (60,000 n/s/kg for WGPu)
- ^{237}Np: gammas at medium energies (<1 n/s/kg)
- ^{233}U: Weak gammas at medium energies
  - Most intense gammas from ^{232}U (at ppm concentrations)
  - Less than 1 n/s/kg
- ^{238}U: Gammas from 740-1000 keV (13.7 n/s/kg)

Selected Measurements Example 1



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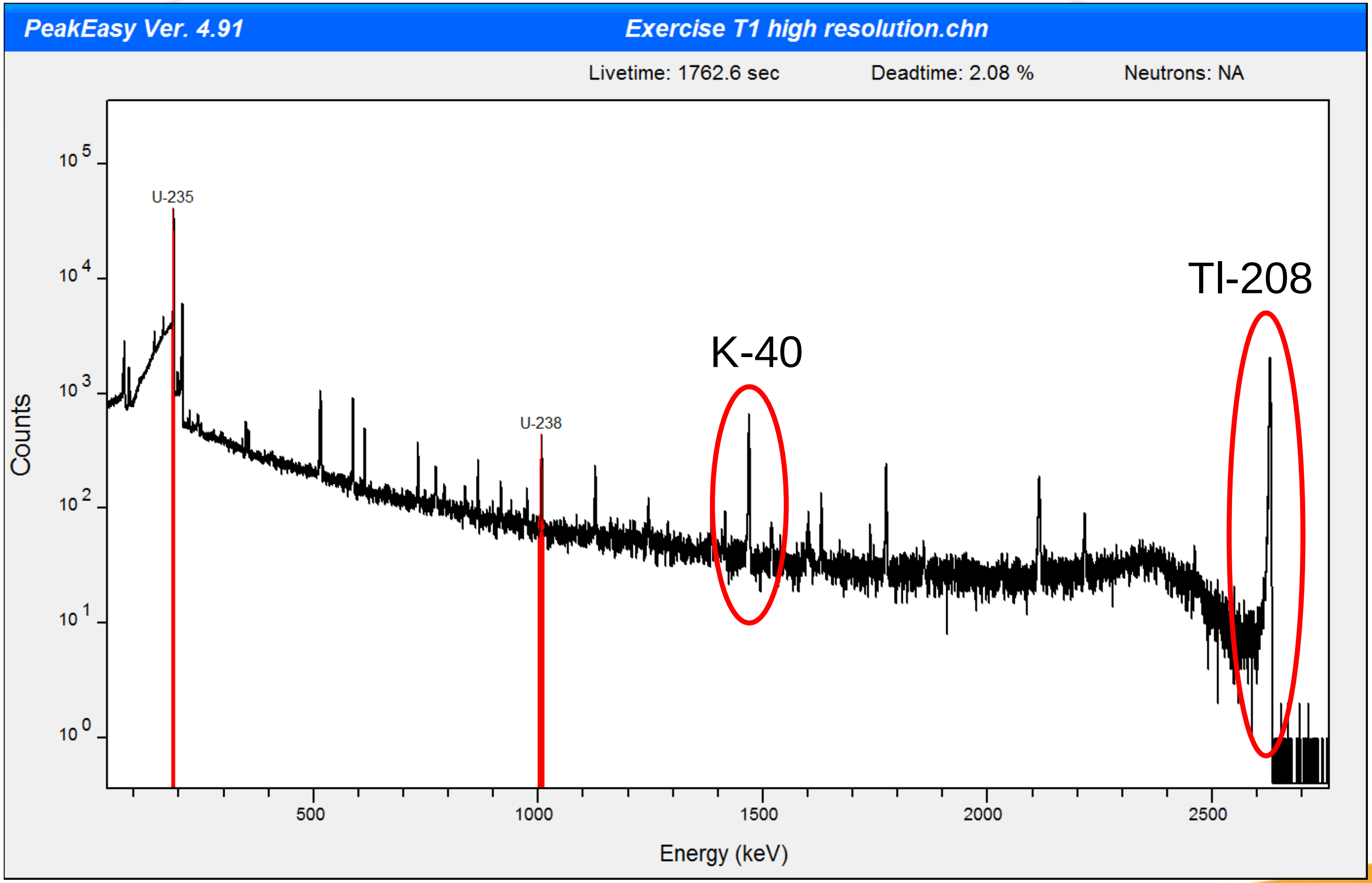
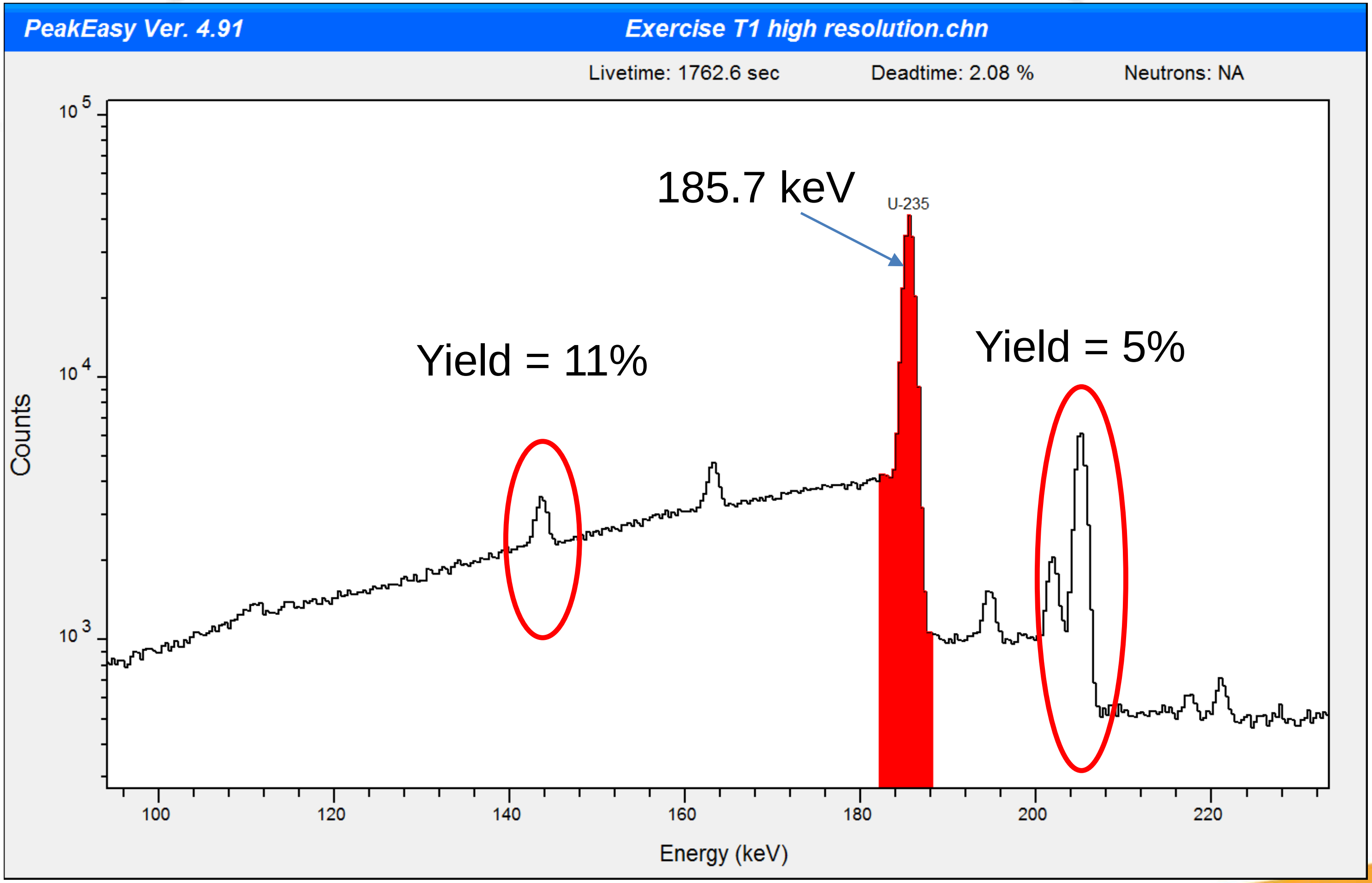
Example 1 continued



Example 1 Shielding Effects



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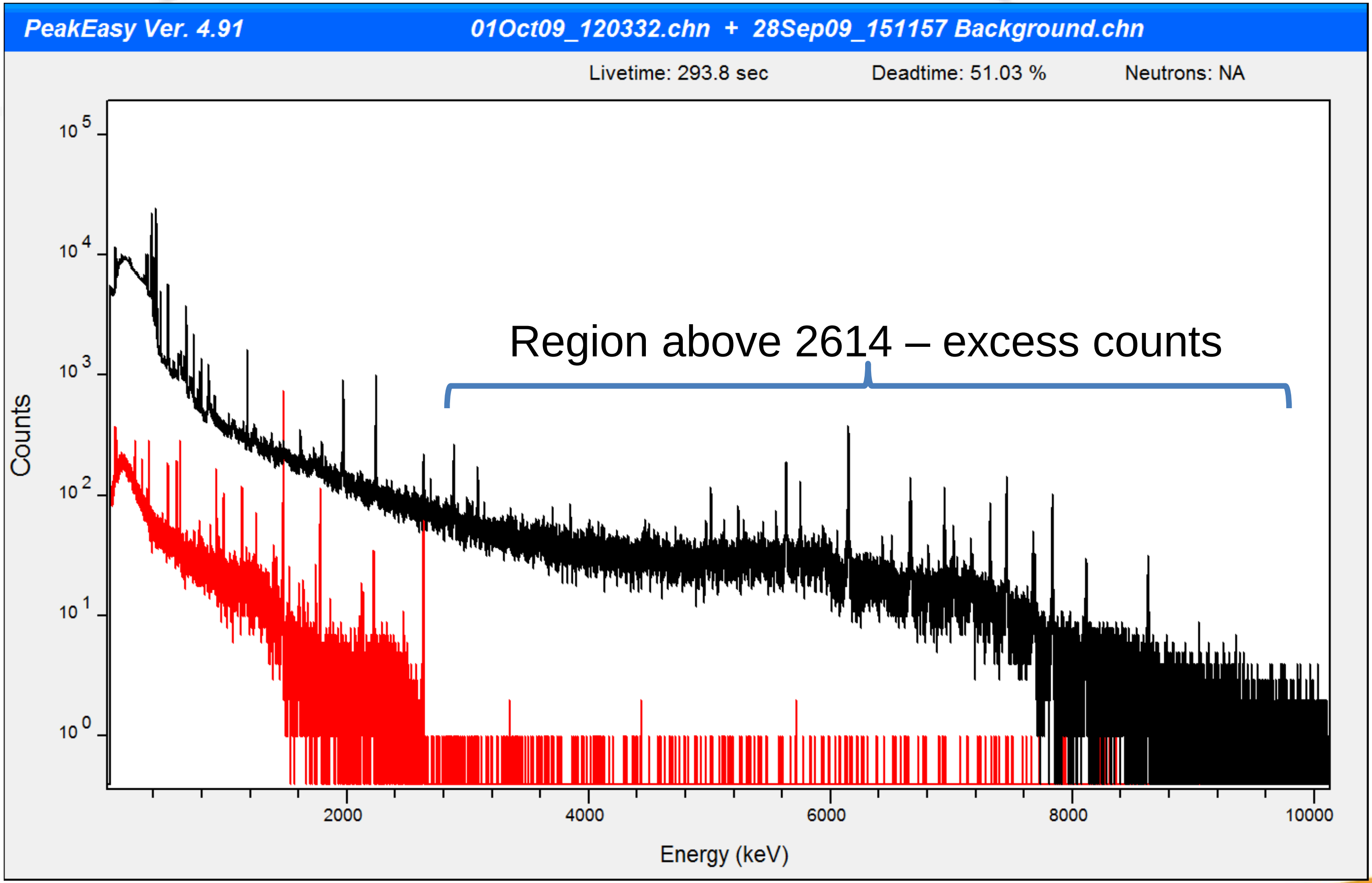
Example 2 - Neutrons in Gamma Ray Spectra



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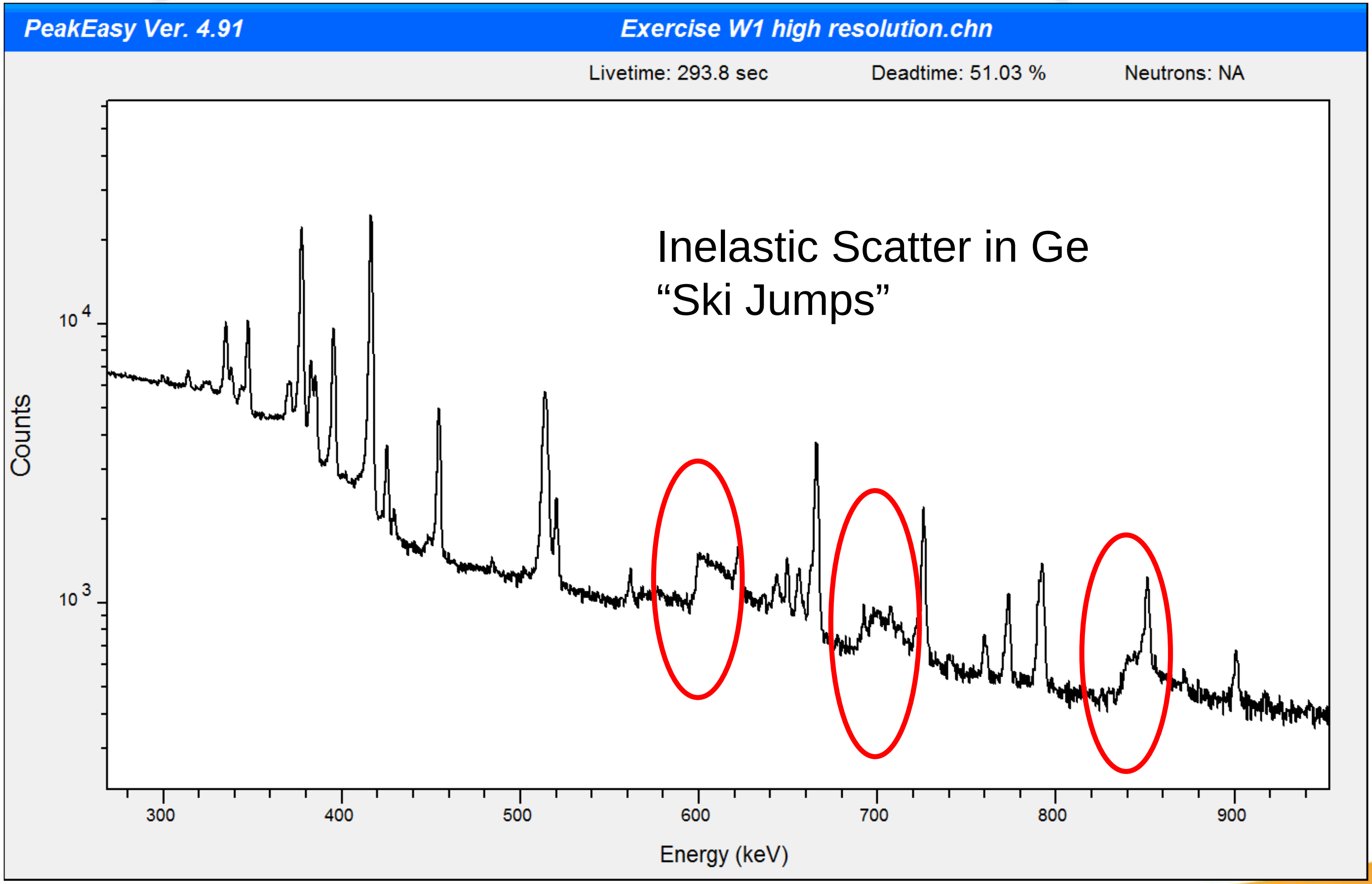
Evidence of Neutrons II



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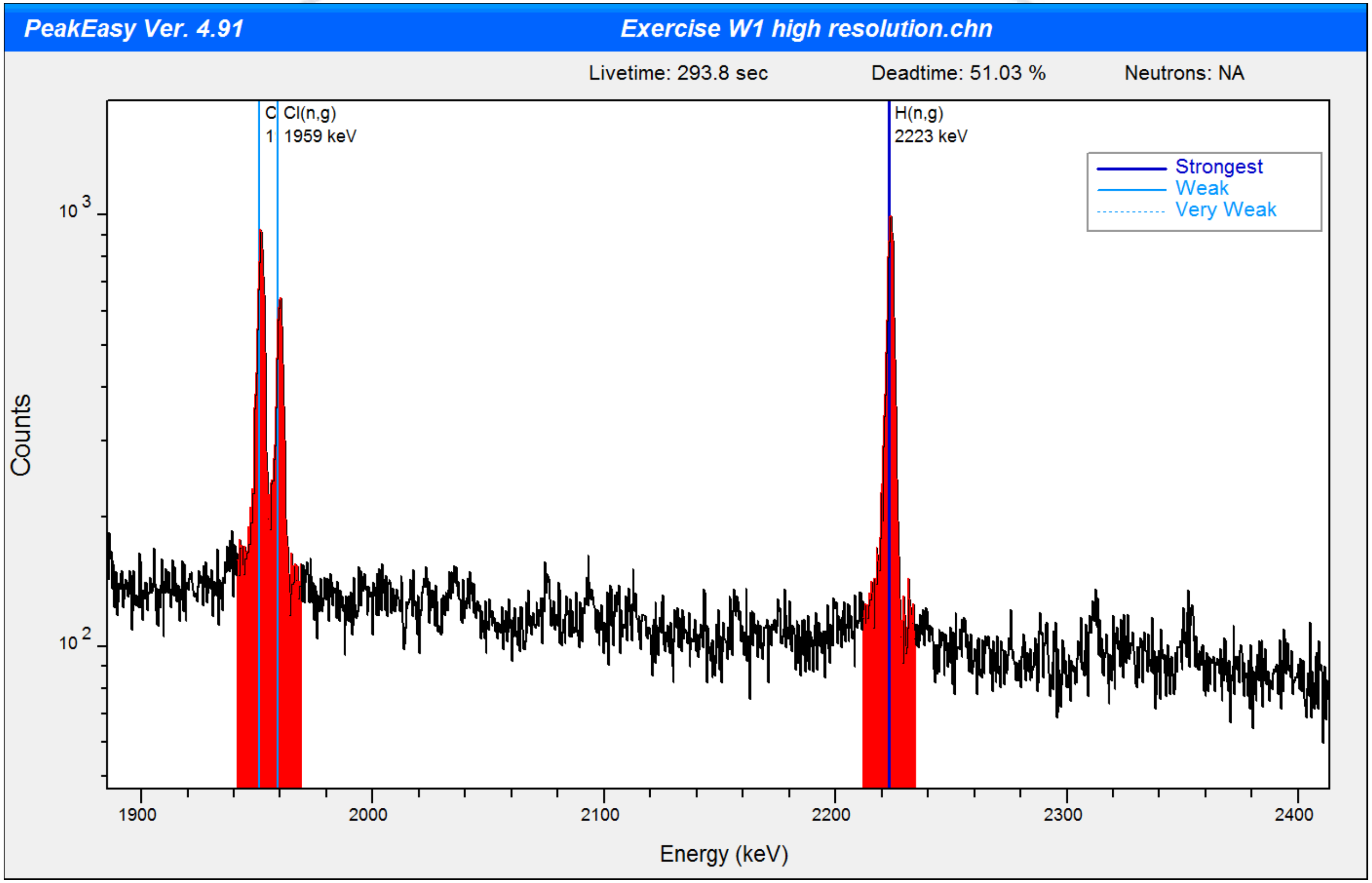
Neutron Capture



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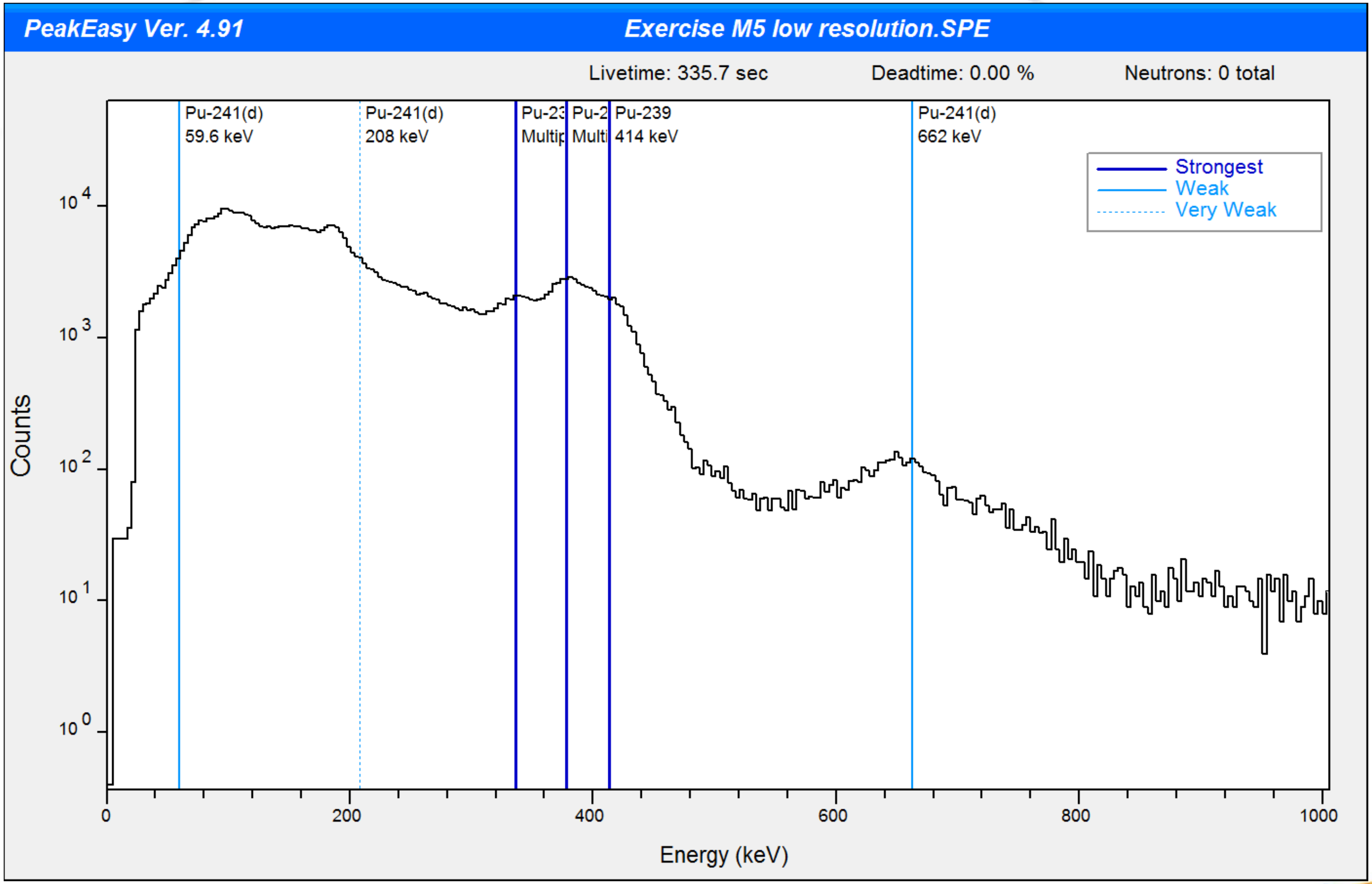
Example 3



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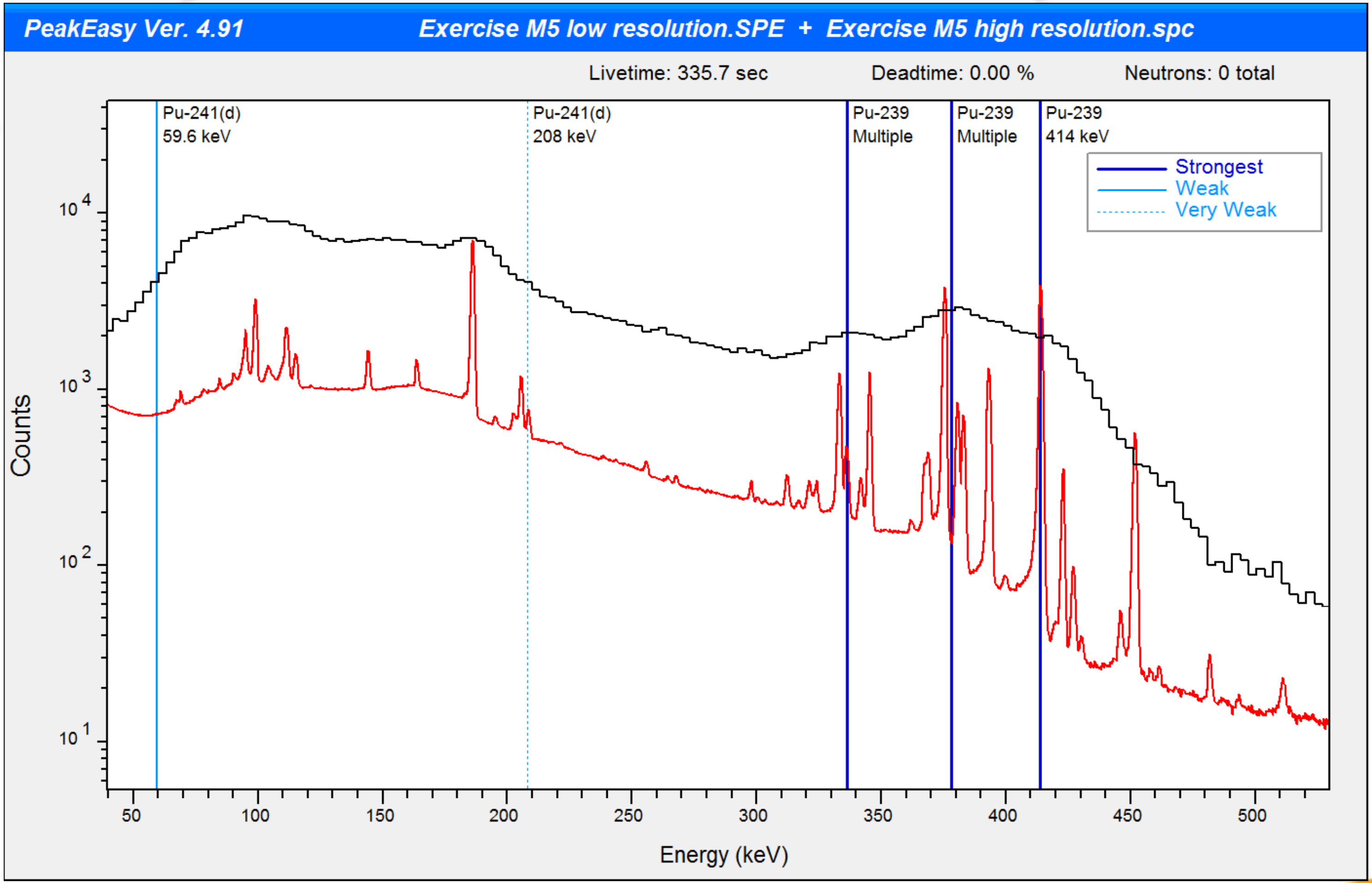
Example 3 Continued



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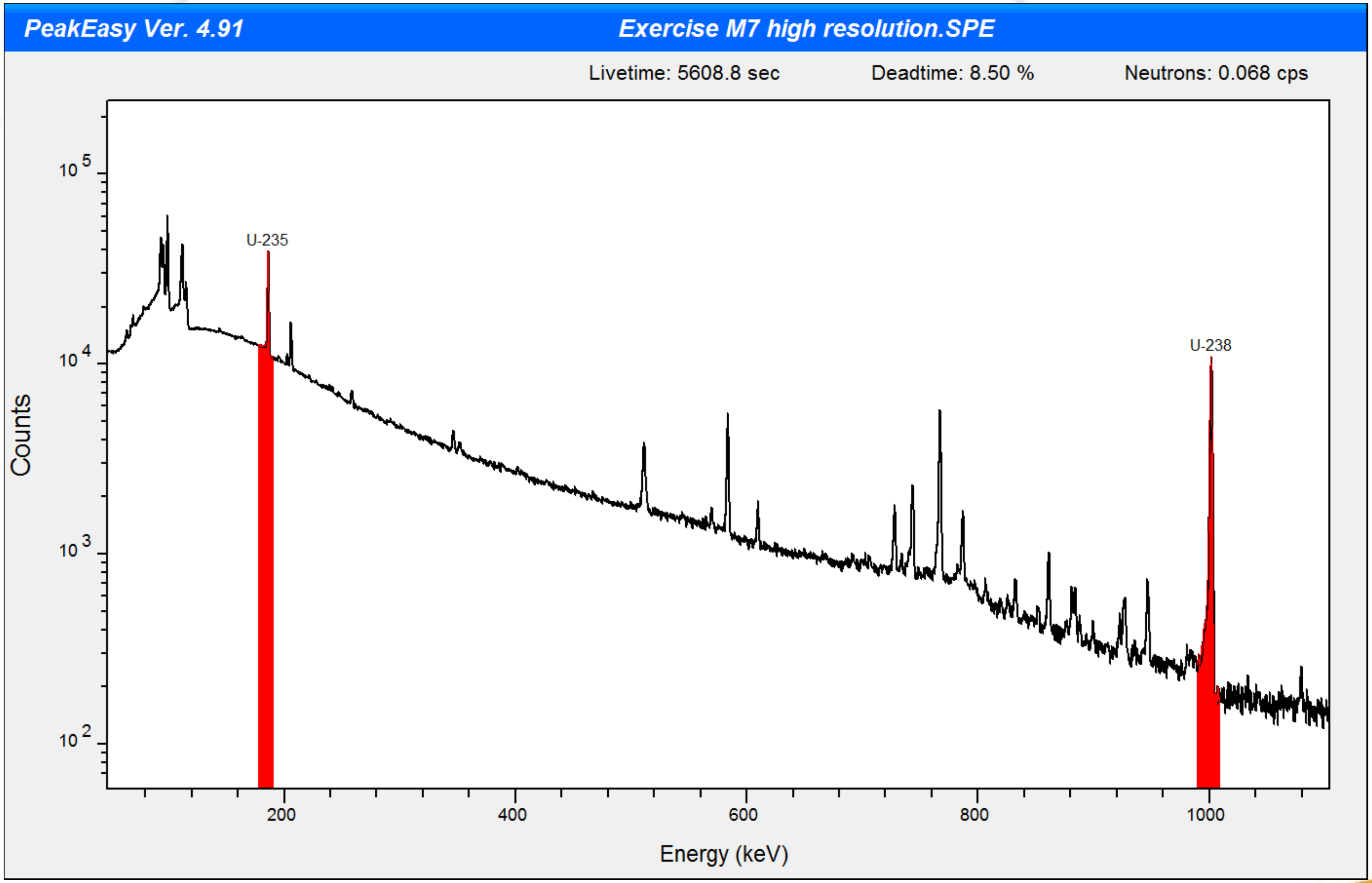
Example 4 – Natural Uranium?



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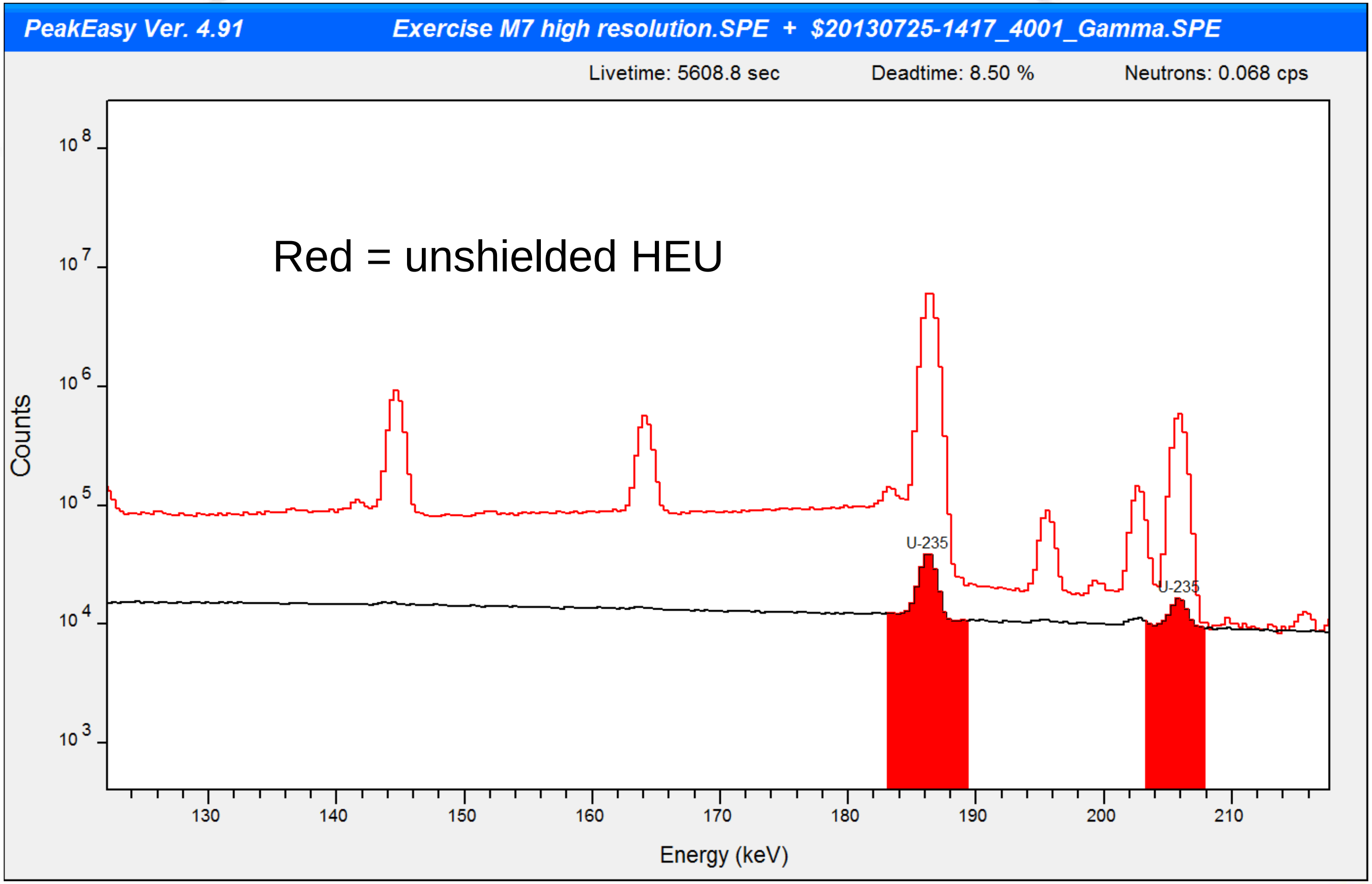
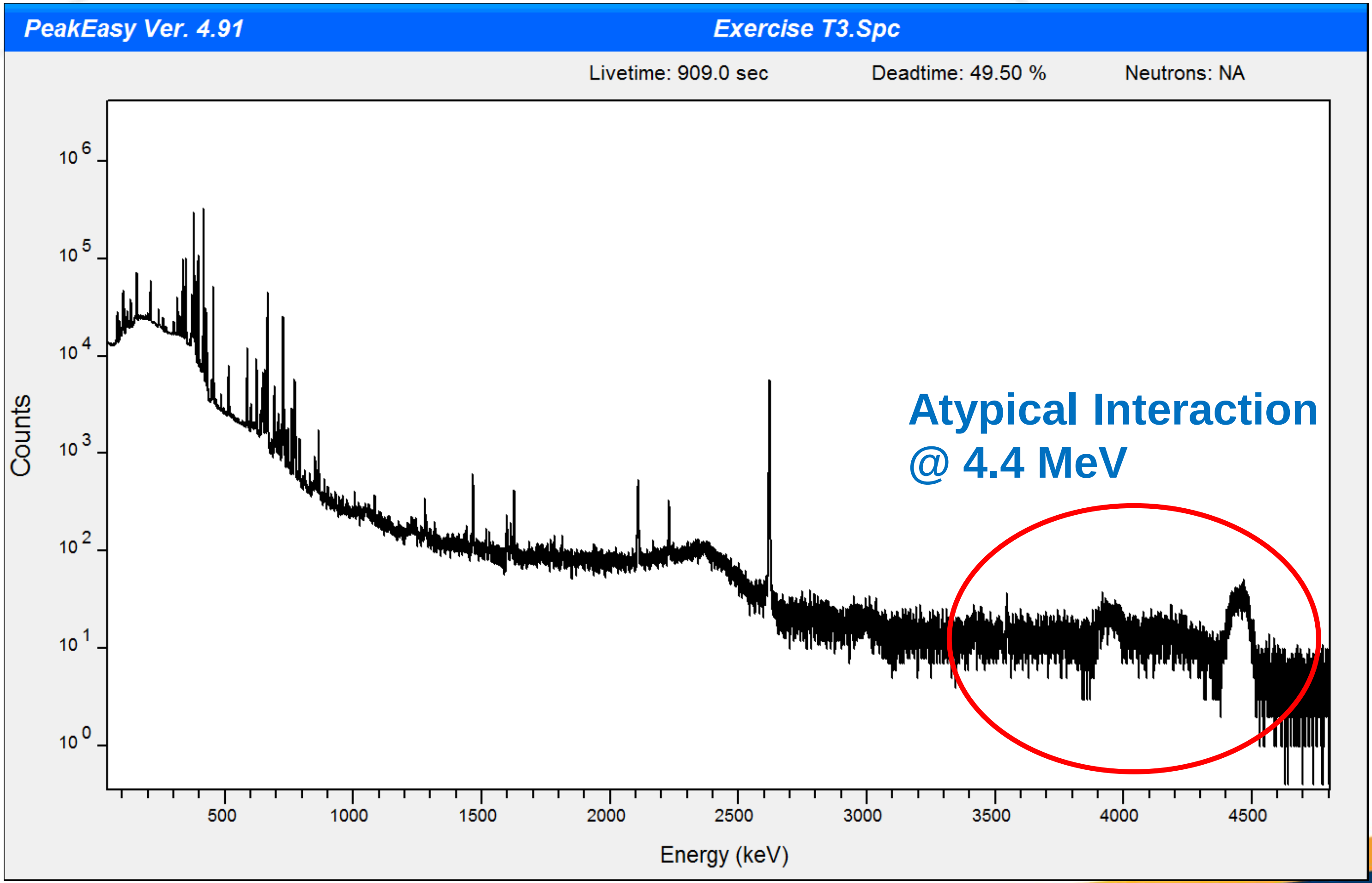
Example 4 Zoom



Example 5



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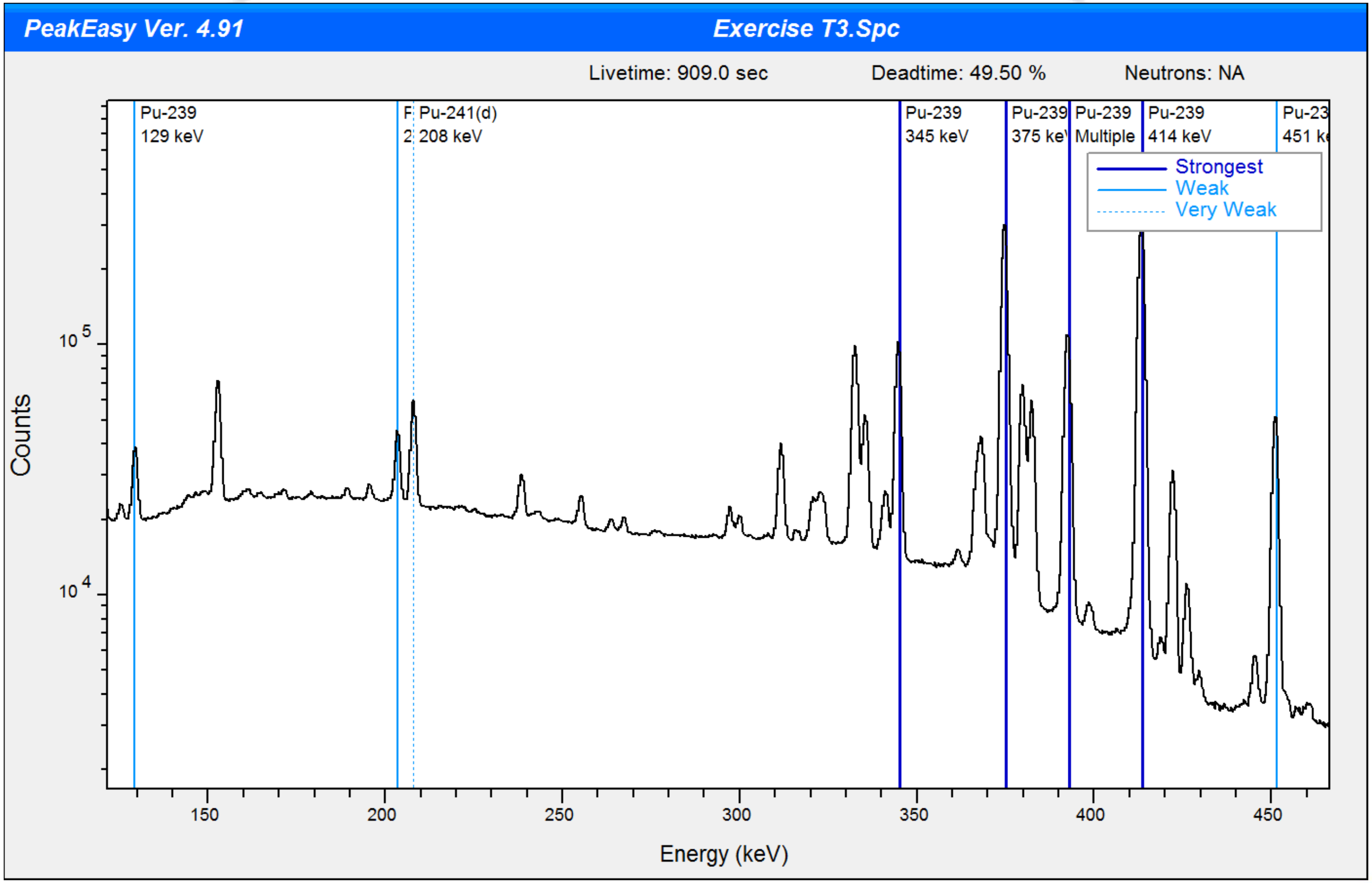
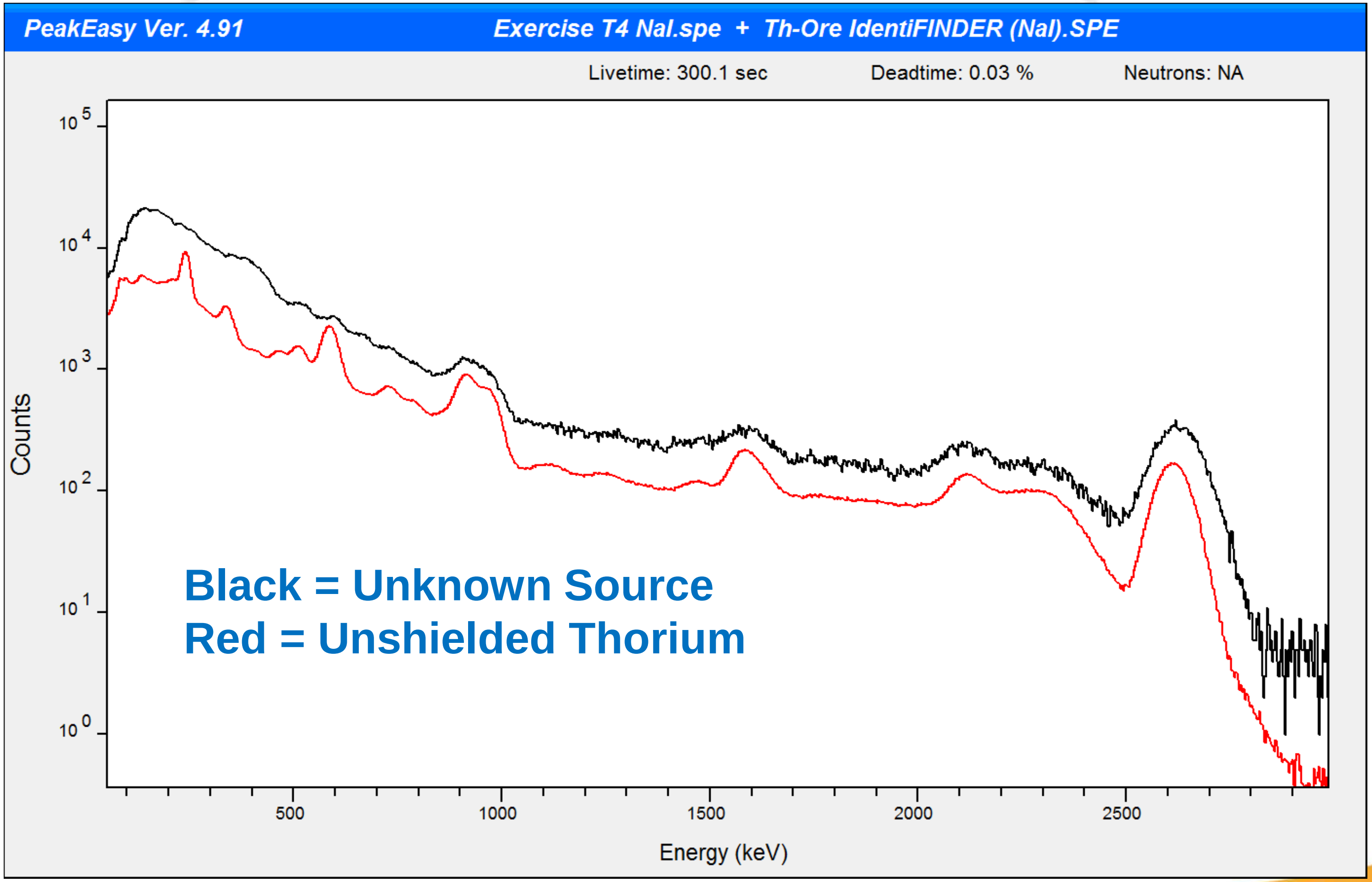
Example 5 Seen at Low Energy



Example 6



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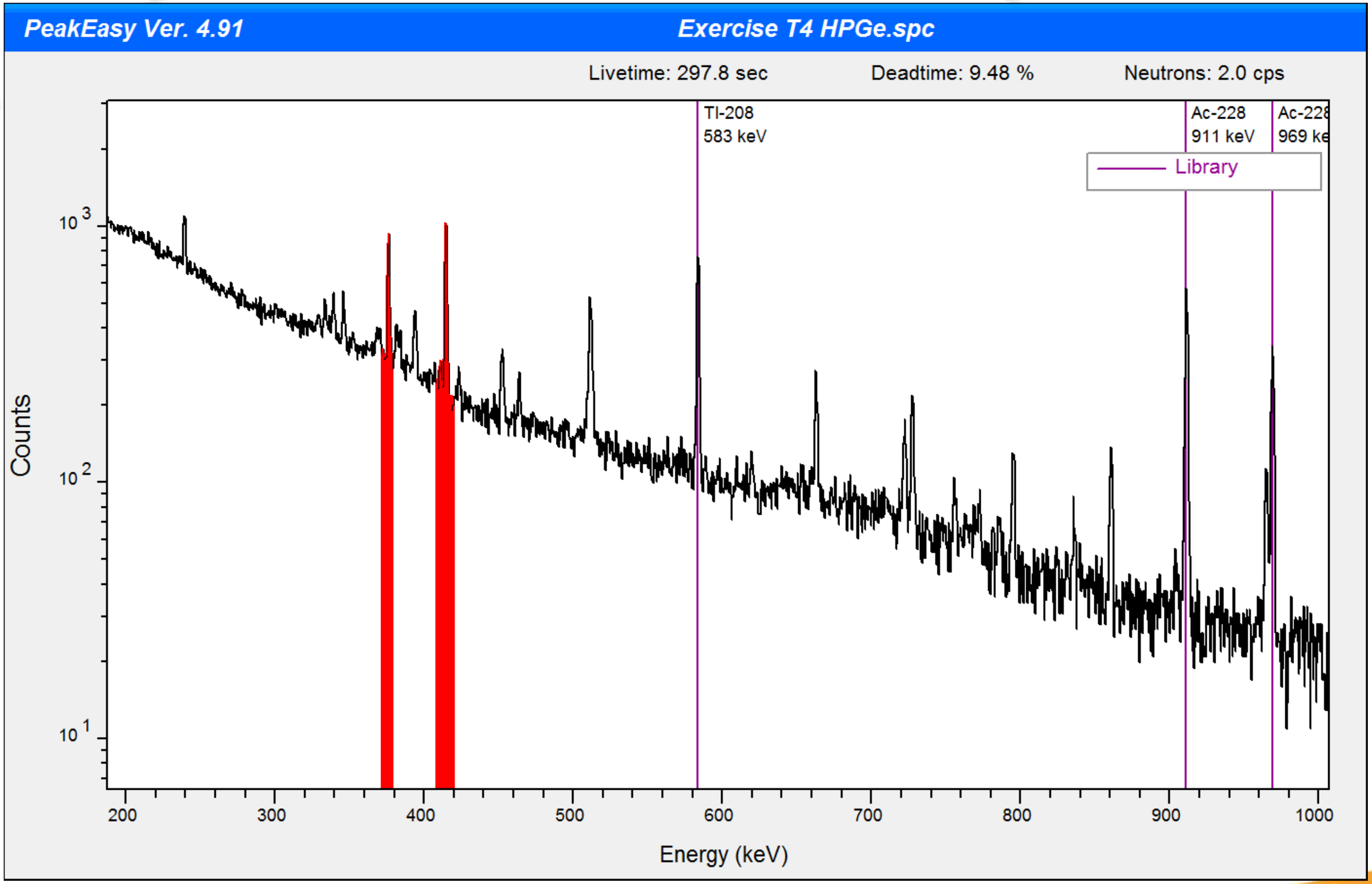
Example 6 in HPGe



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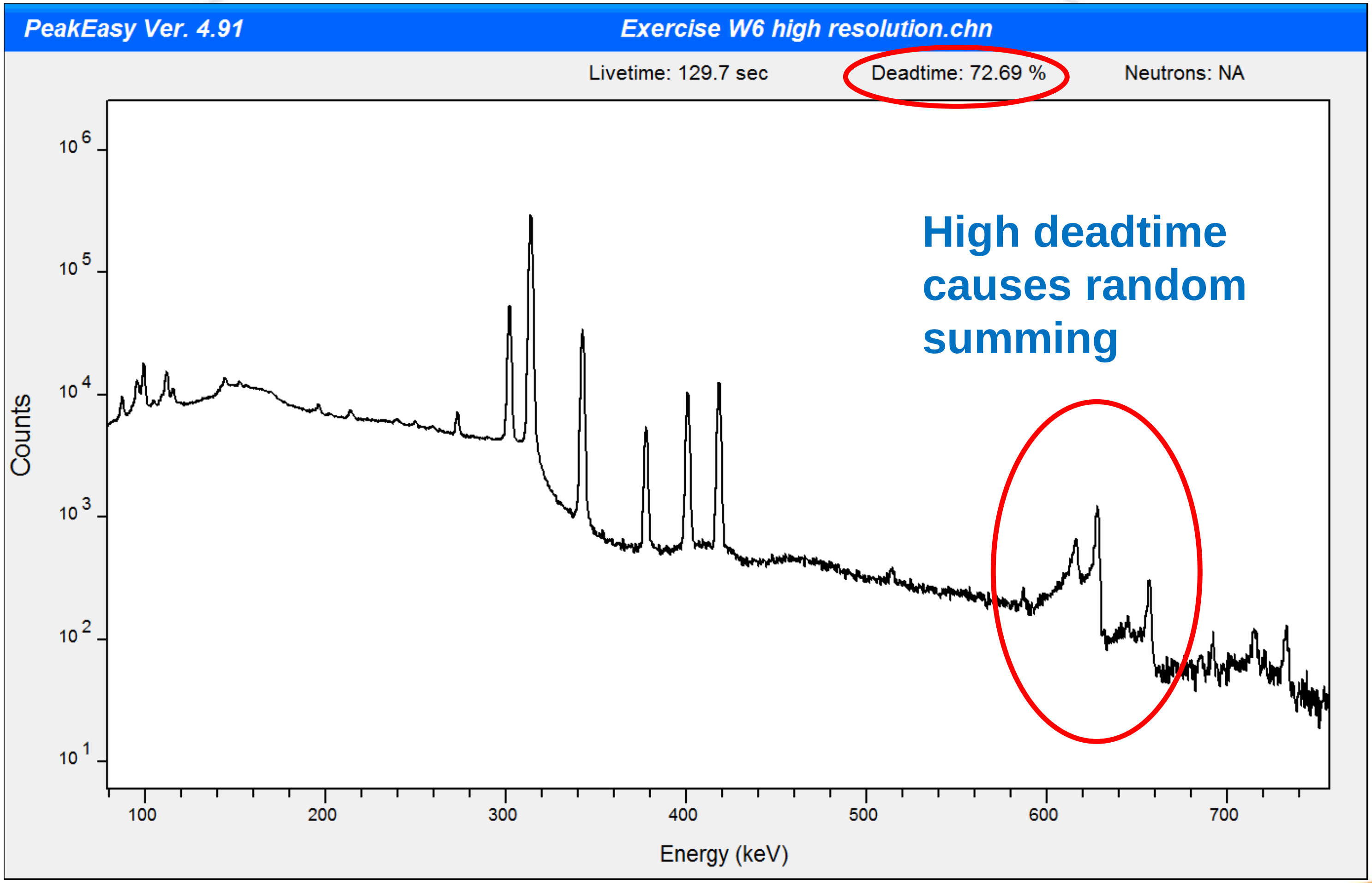
Example 7



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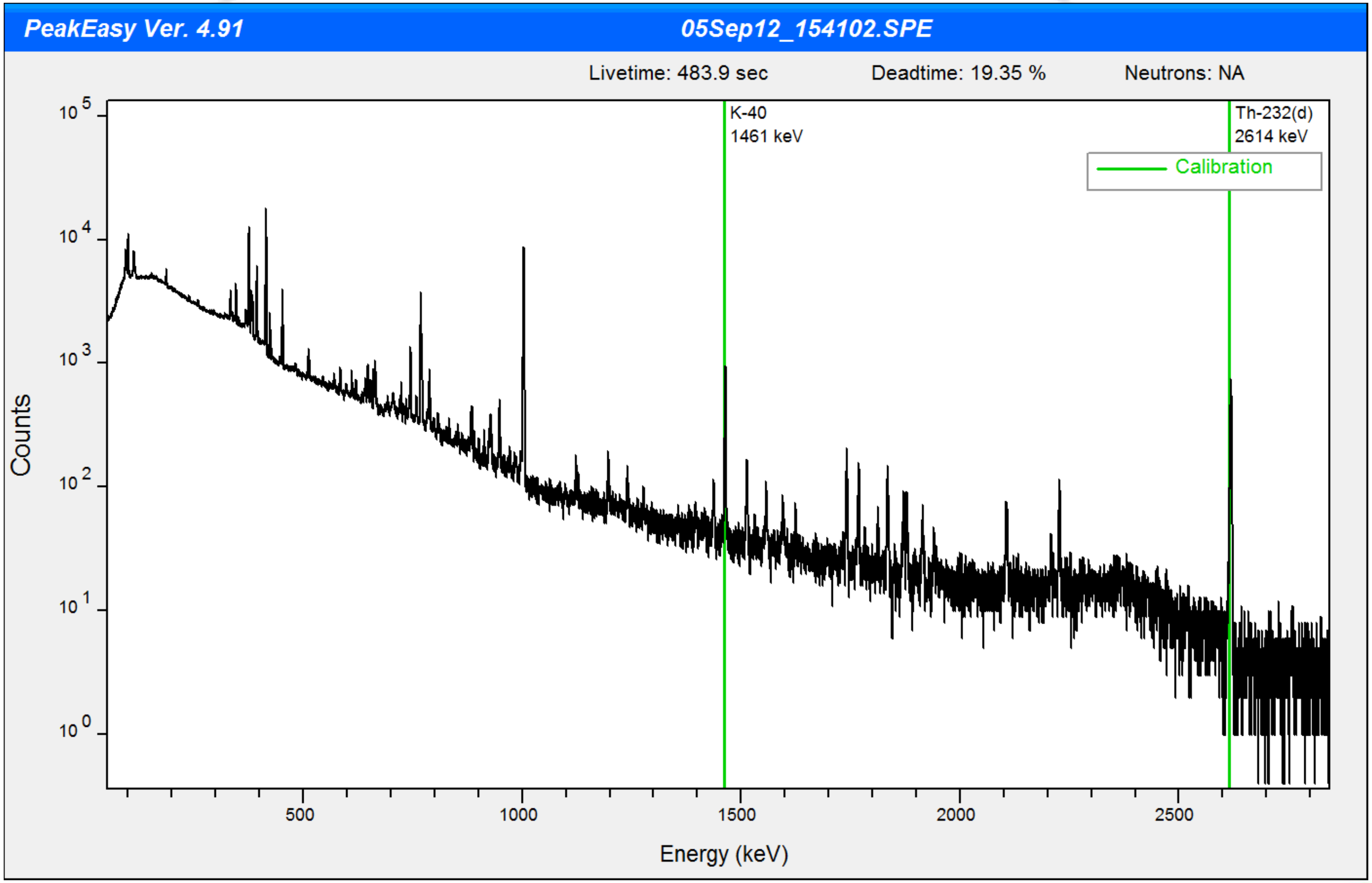
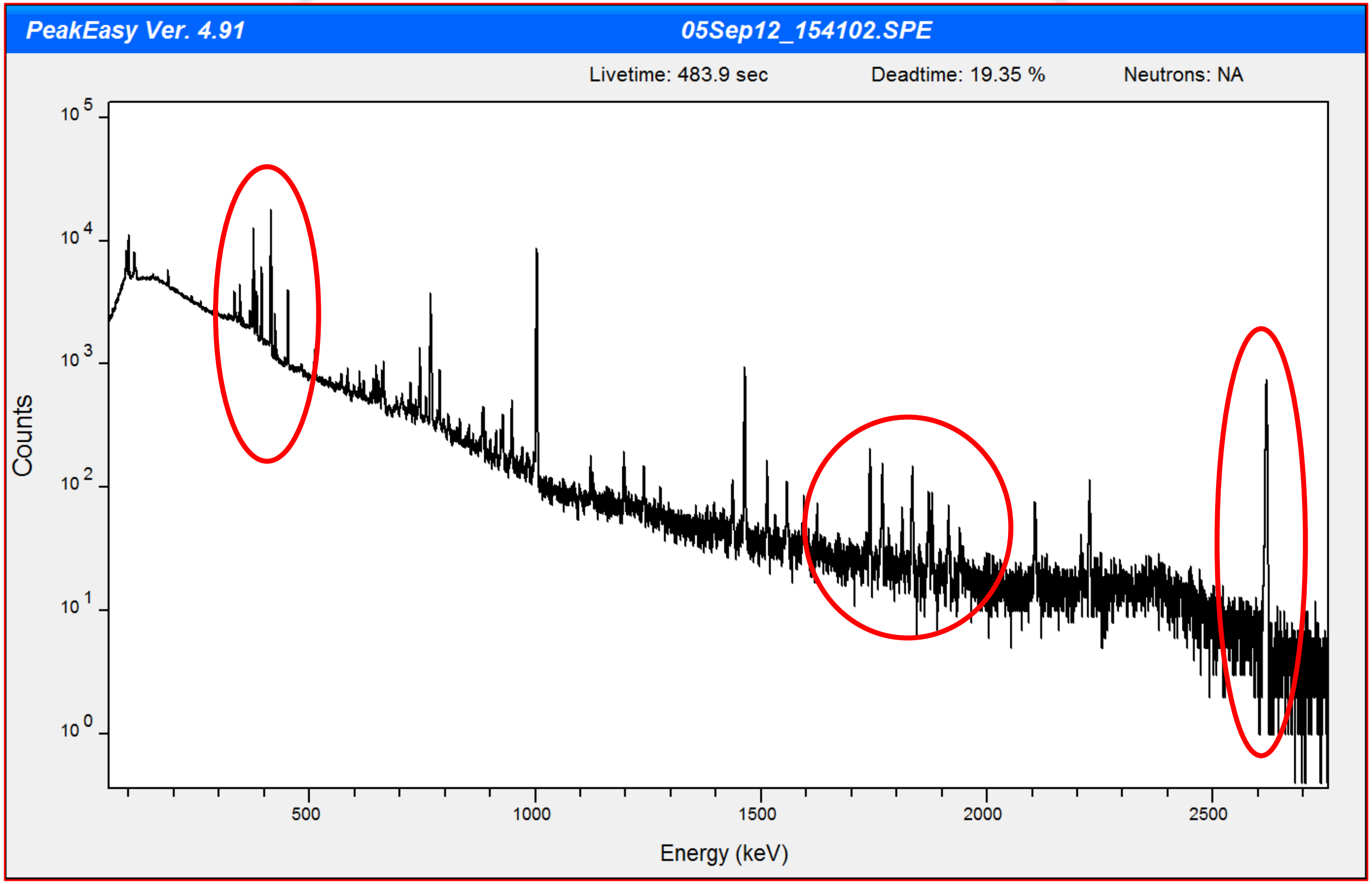
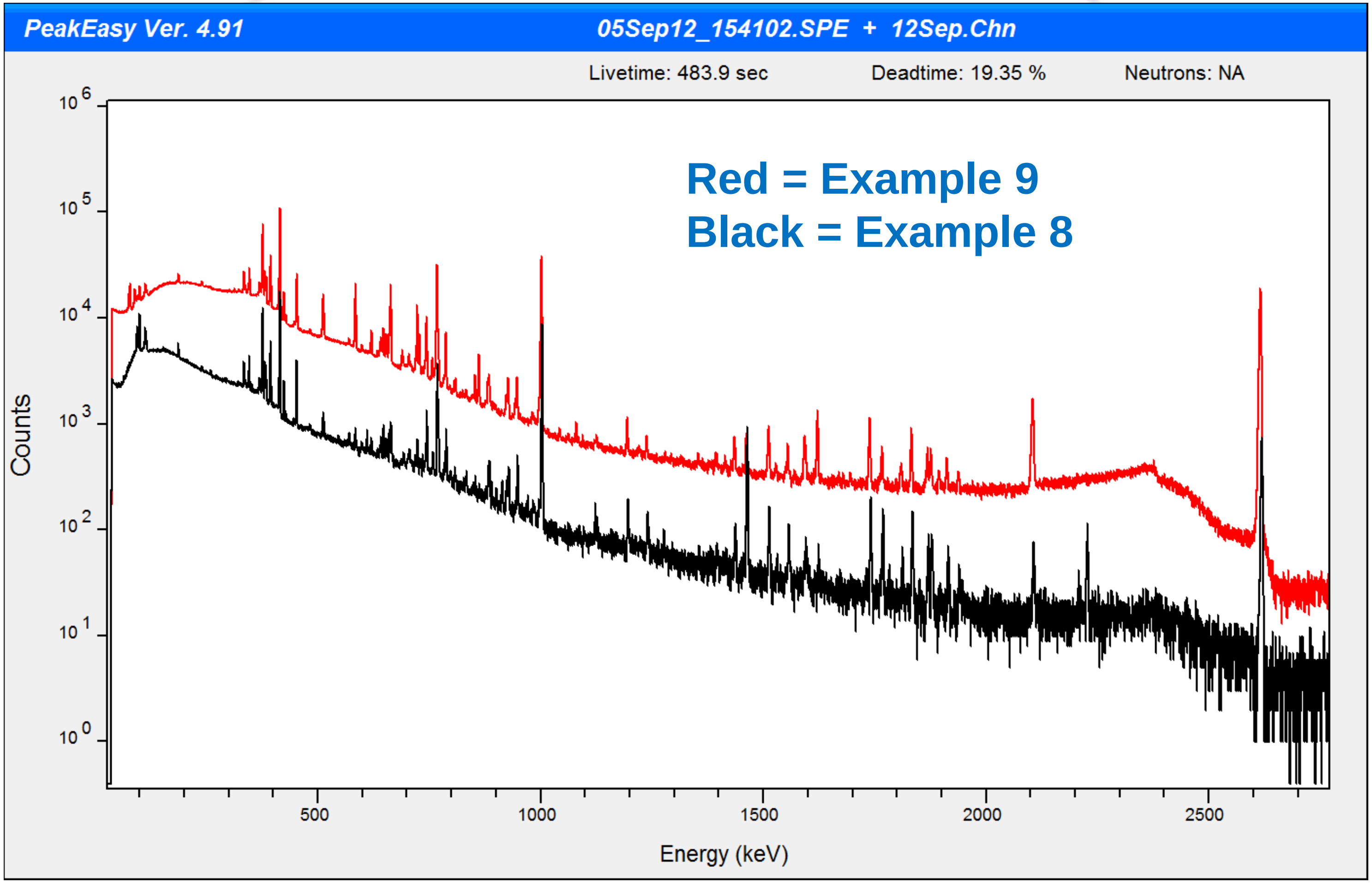
Example 8


PeakEasy Ver. 4.91
05Sep12_154102.SPE
Livetime: 483.9 sec
Deadtime: 19.35 %
Neutrons: NA
K-40
1461 keV
Th-232(d)
2614 keV
Calibration
Counts
Energy (keV)
10^5
10^4
10^3
10^2
10^1
10^0
500
1000
1500
2000
2500

Example 8 Continued



Example 9



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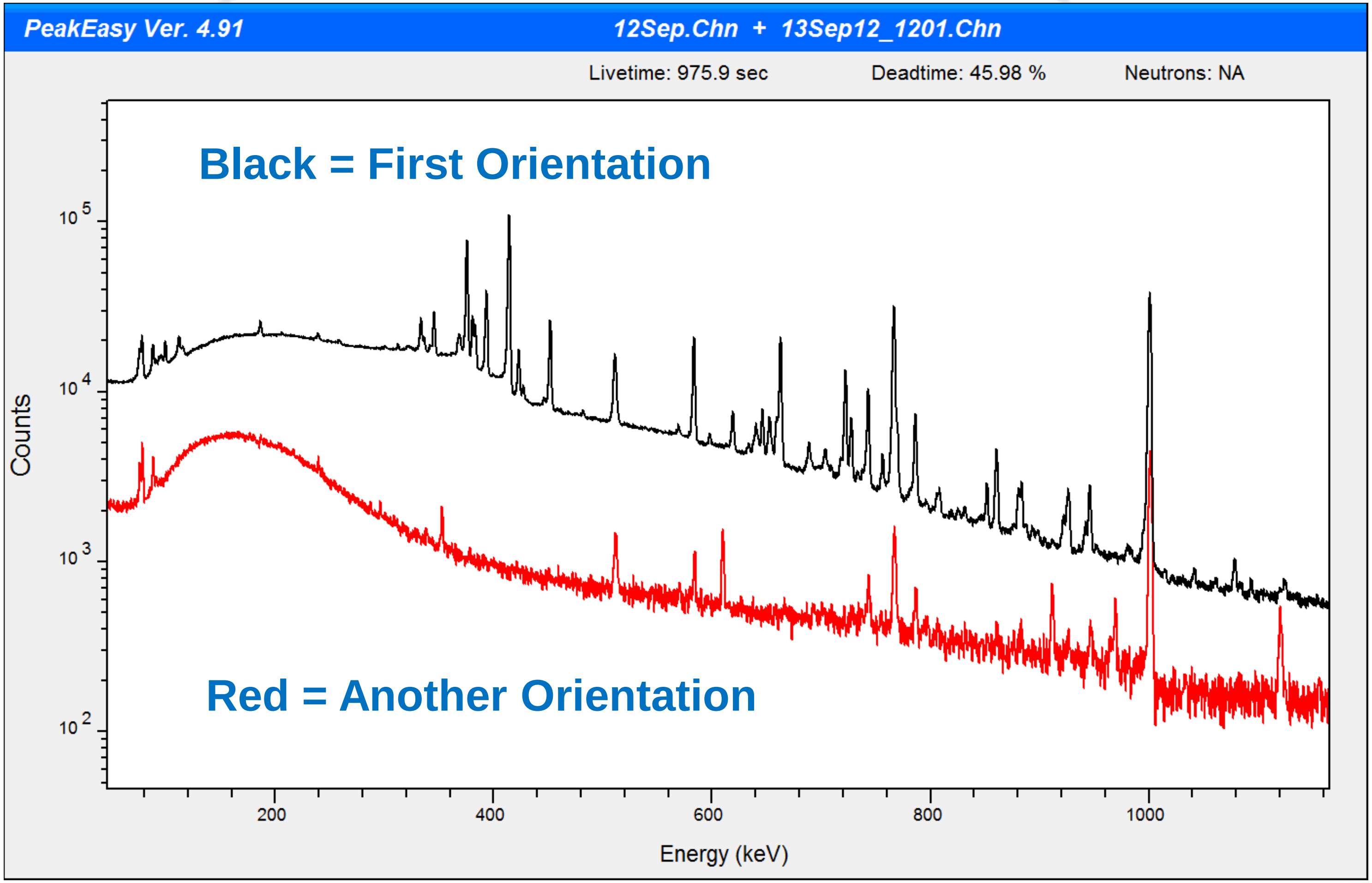
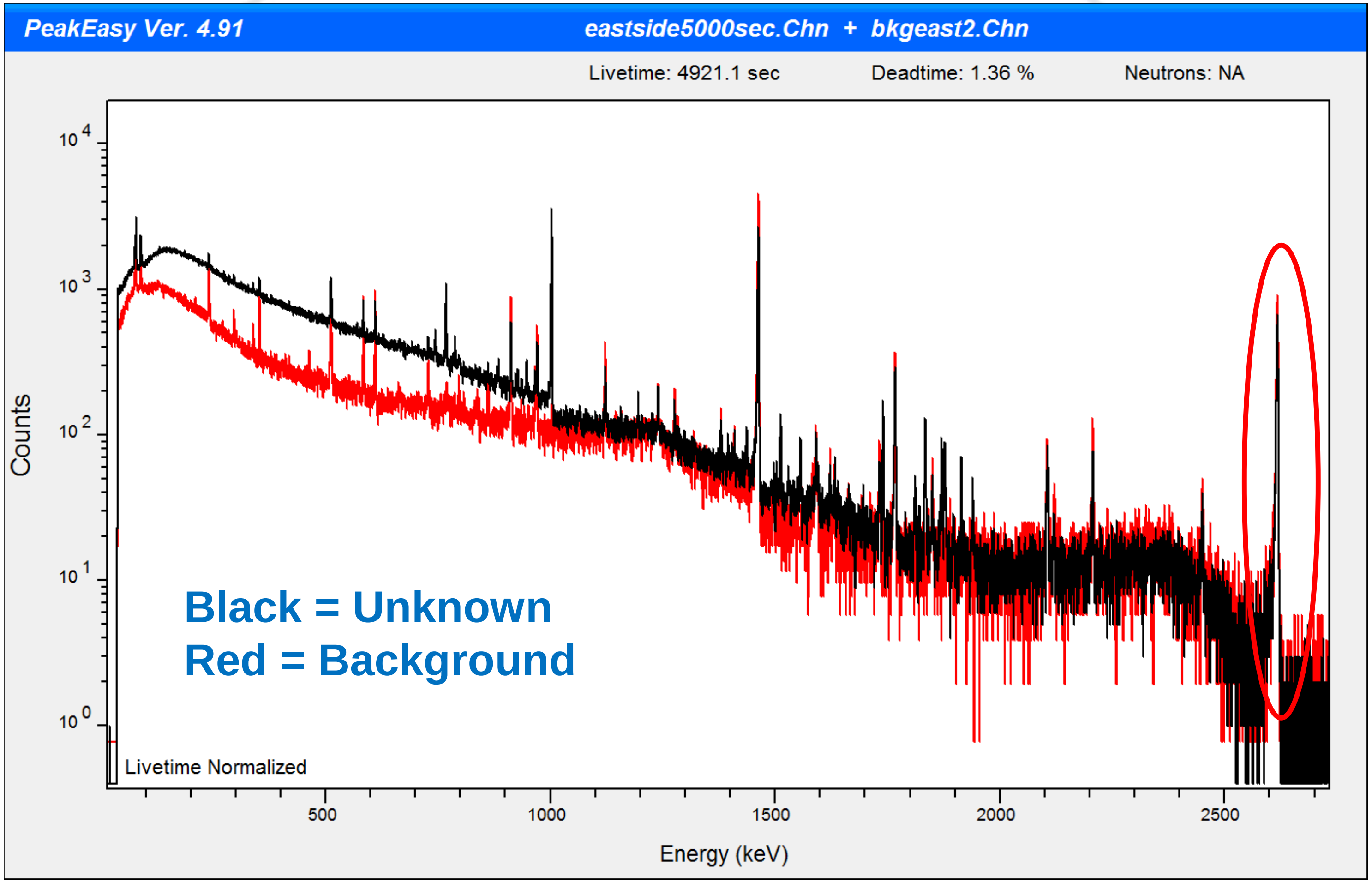
Example 9 Continued



Example 10



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