Lawrence Livermore National Laboratory

New and Novel Nondestructive Neutron and Gamma-Ray Technologies Applied to Safeguards

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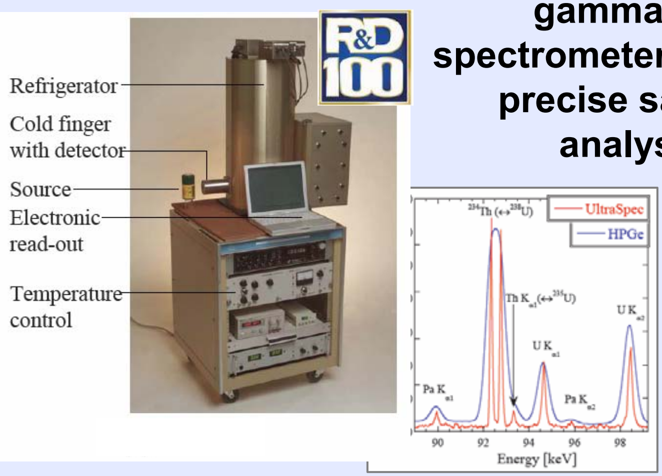
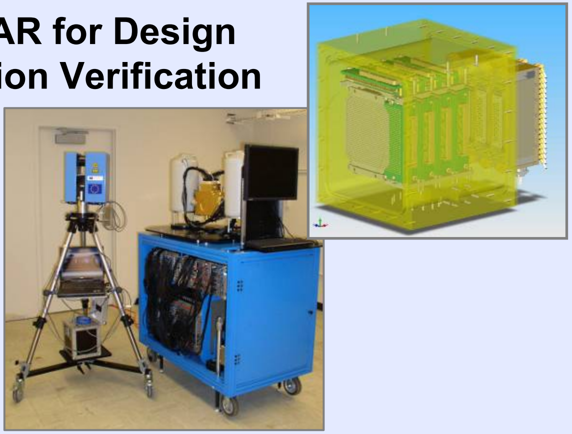
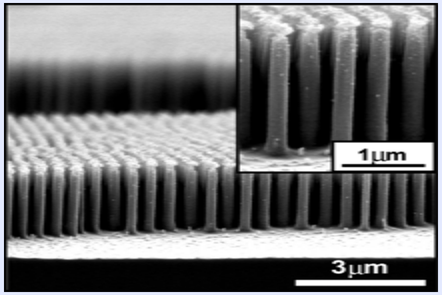
Novel Science and Technology Solutions for Safeguards

Superconducting gamma-ray spectrometer for ultra-precise sample analysis

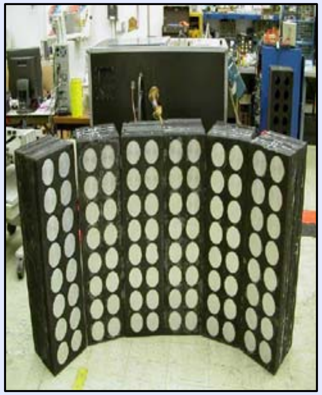


Compact Compton imager combined with 3D LIDAR for Design Information Verification





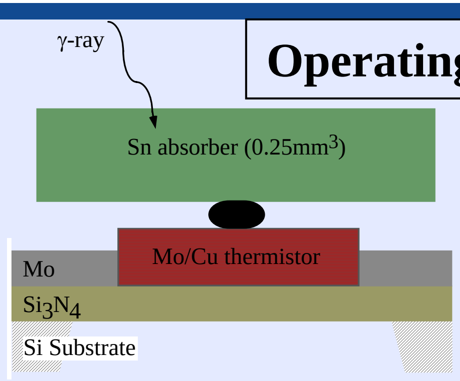
Next generation high efficiency neutron detectors based on pillar technology



New Correlated Fast Neutron Counting technique using Liquid Scintillator Multiplicity counter and nanosecond timing

Superconducting γ-Ray Spectrometer (Ultra-Spec)

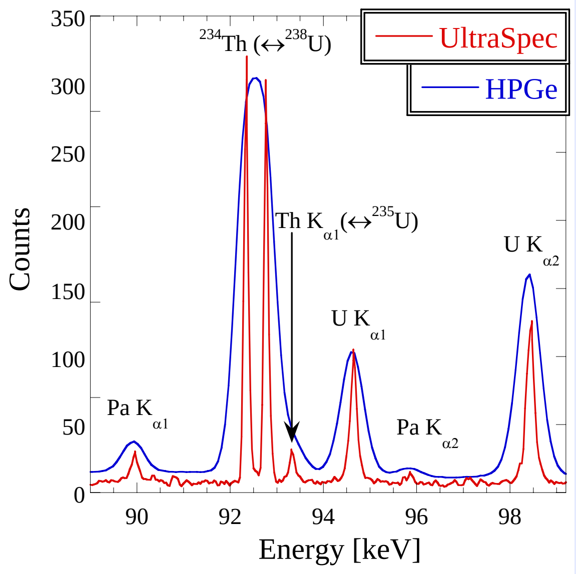
Operating Principle



Gamma-ray absorption increases absorber temperature, which is measured with a superconducting thermometer

Energy resolution $\Delta E_{FWHM} = 2.355\sqrt{k_B T^2 C}$

Results

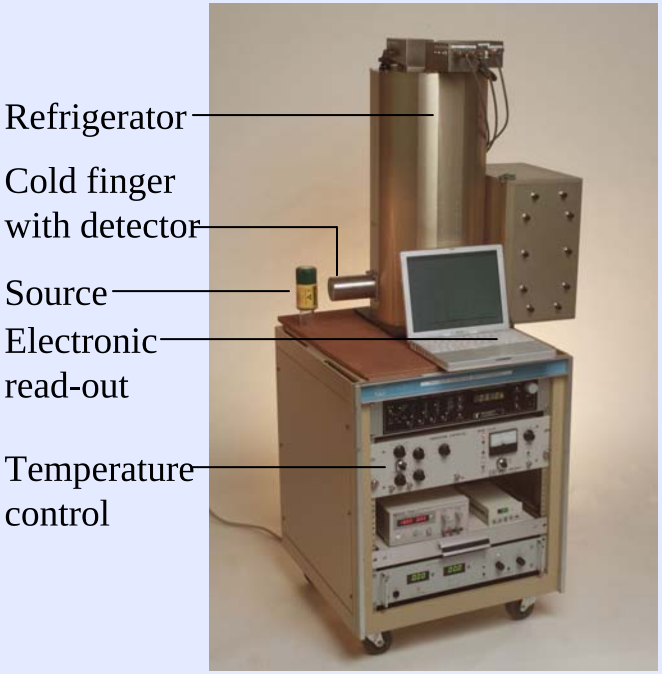


Low-temperature operation enables ultra-high energy resolution, <80 eV FWHM.

R&D 100

2006

Spectrometer



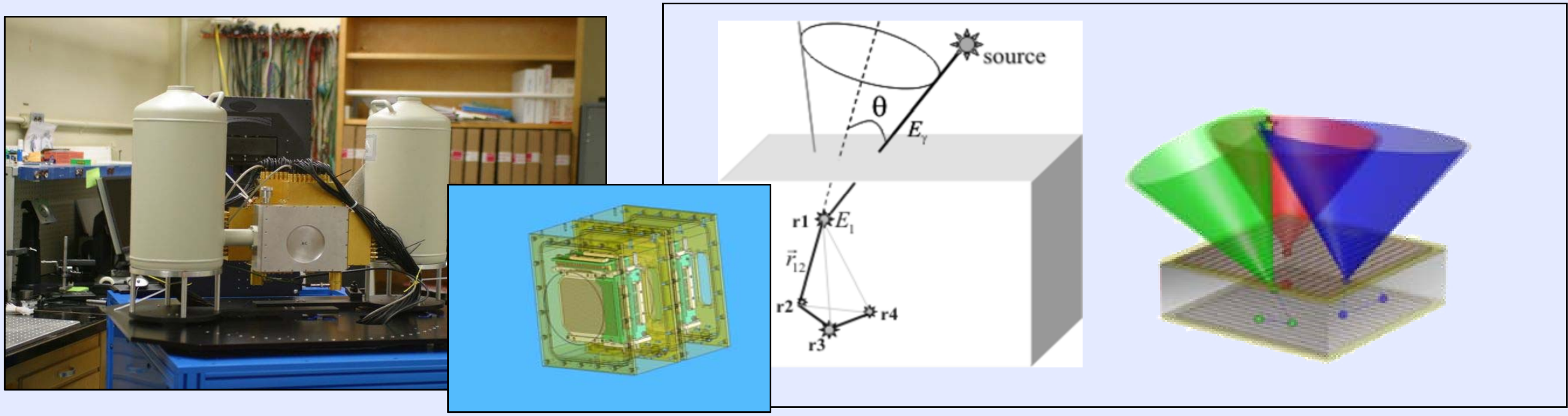
Applications

Ultra-high energy resolution greatly increases precision of isotope ratio measurements in cases where HPGe detectors are affected by line-overlap.

e.g. MGA for Pu at 100keV, MGA-U for U at 92keV

We are developing a compact Compton imager

- The Compton camera determines the direction of the gamma ray by tracking its interactions inside a multilayered detector system.
- Compton imaging provides 180 deg field of view, 2 deg angular resolution (3 cm at 1 m), 2 keV energy resolution, and can image the 186 keV ^{235}U line and the 375 and 414 keV ^{239}Pu lines.
- It takes 5 min to image 1 g ^{239}Pu in a 6 cm pixel, 2 m away

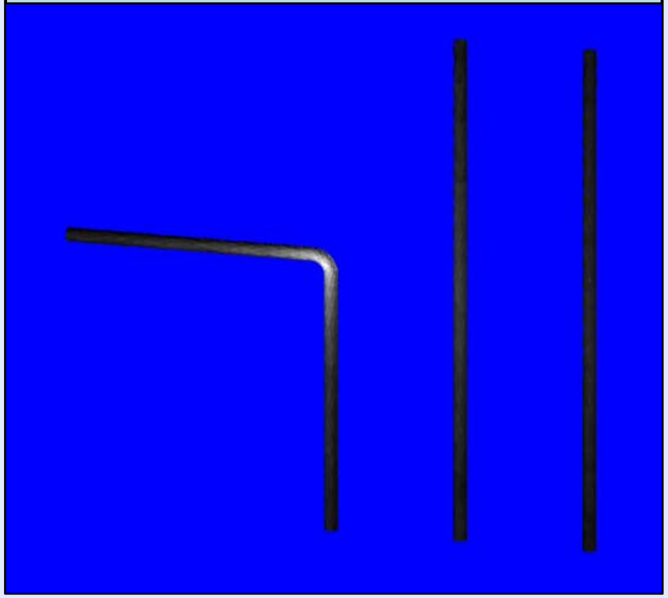


We have built and tested the first Compton camera to take advantage of the new semiconductor strip detector technology that enables high-spatial-resolution, collimatorless imaging.

Verification of material hold-up and diversion in enrichment plants by combining 3D laser ranging with Compton camera gamma-ray imaging

Lidar scans will provide the map of objects in the environment. The Compton camera measures the gamma-ray image.

Monte Carlo simulation of the gamma-ray intensity image of Pu-239 hold-up in a pipe elbow.

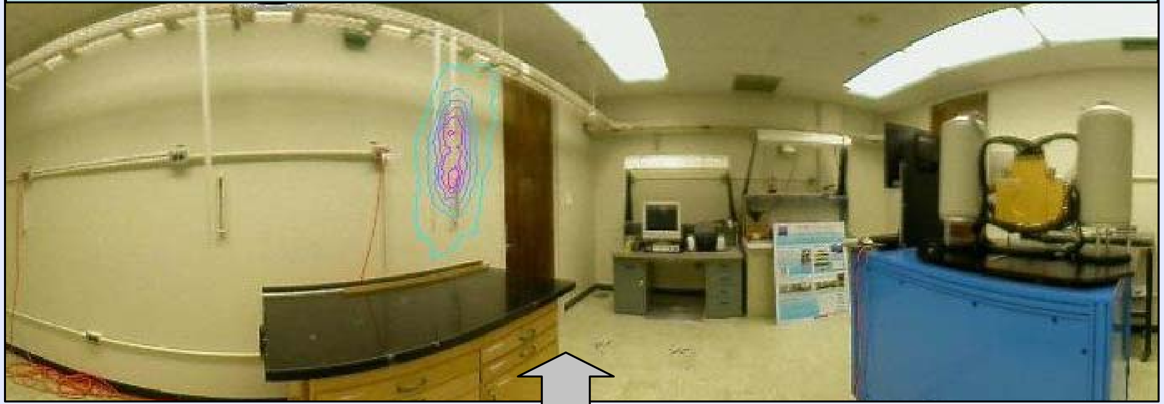


Combining wide field-of-view gamma-ray imagers with 3D range maps obtained with a Design Information Verification (DIV) lidar scanner improves the fidelity of the gamma-ray image and adds a capability to directly measure isotope hold-up information compared to using laser ranging alone.

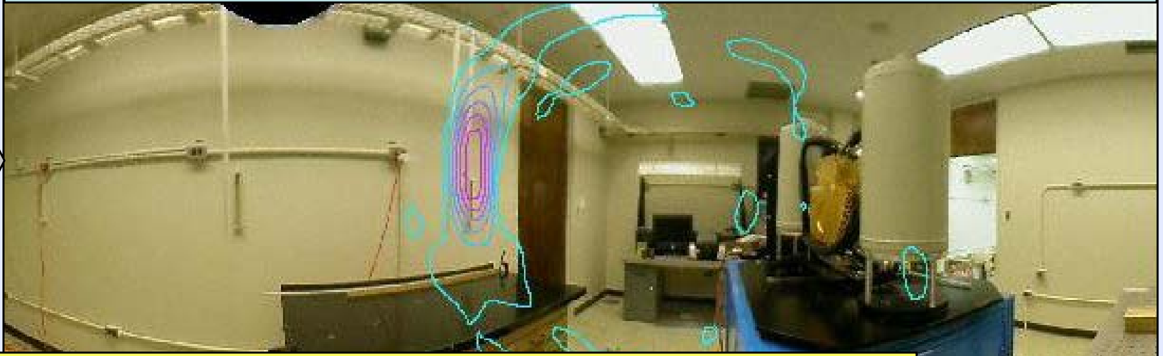
Measurements demonstrate gamma-ray imaging of materials in pipes

Reconstructed gamma-ray image measurements of a Eu-152 344 keV gamma-ray line source (analog for the Pu-241 414 keV line) hidden in a pipe are shown as contour plots on top of visual panoramic images of the Lab.

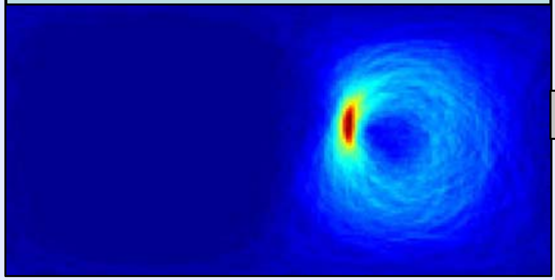
Expectation-Maximization Maximum Likelihood (EM-ML) Algorithm



Filtered Back-projections using Spherical Harmonics

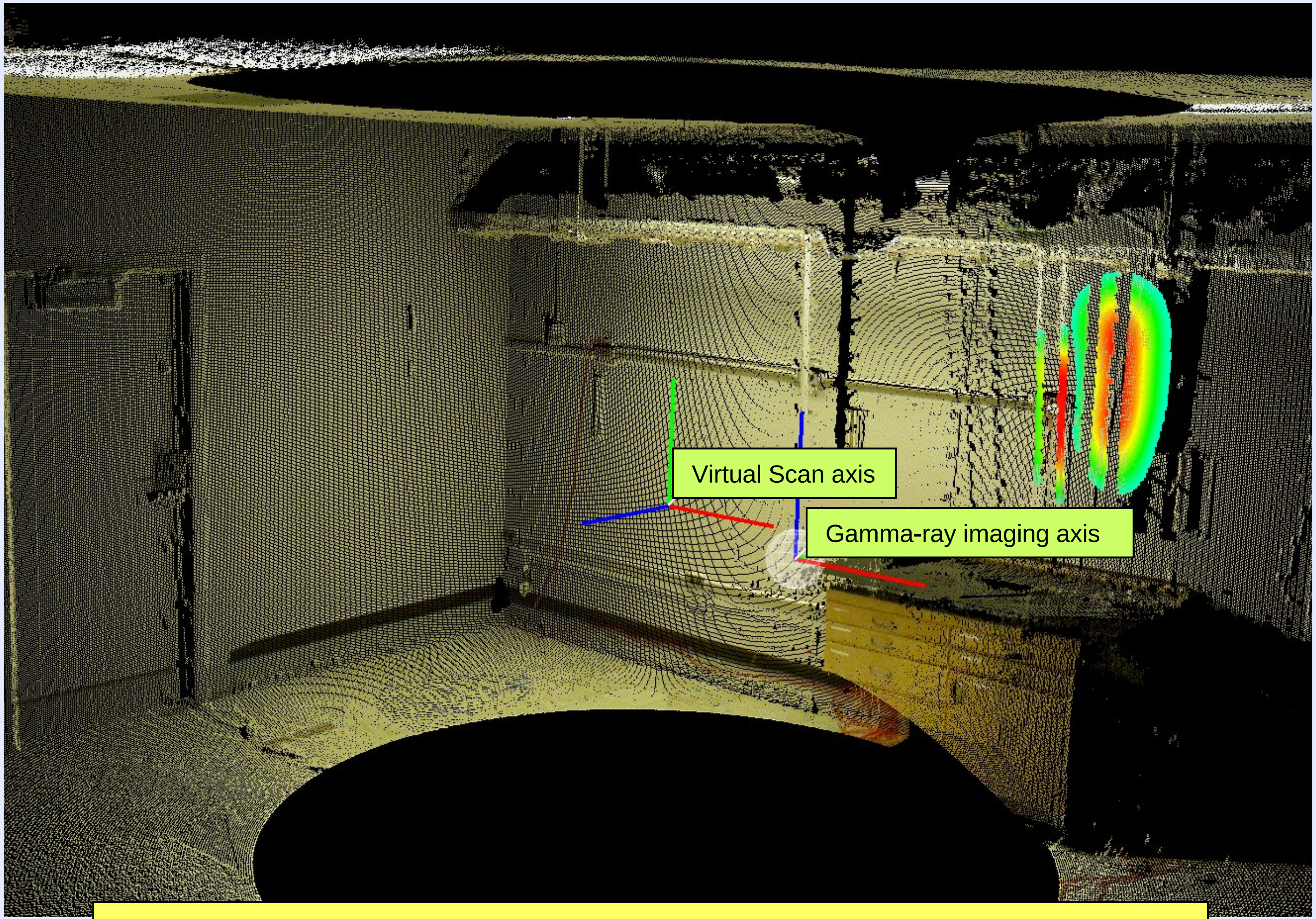


Raw Compton image



Compton imaging will help inspectors verify plant designs, design changes, diversion of SNM, movement of SNM, hold-up and material accumulation.

Mapping of gamma-ray images onto 3D range maps – side view



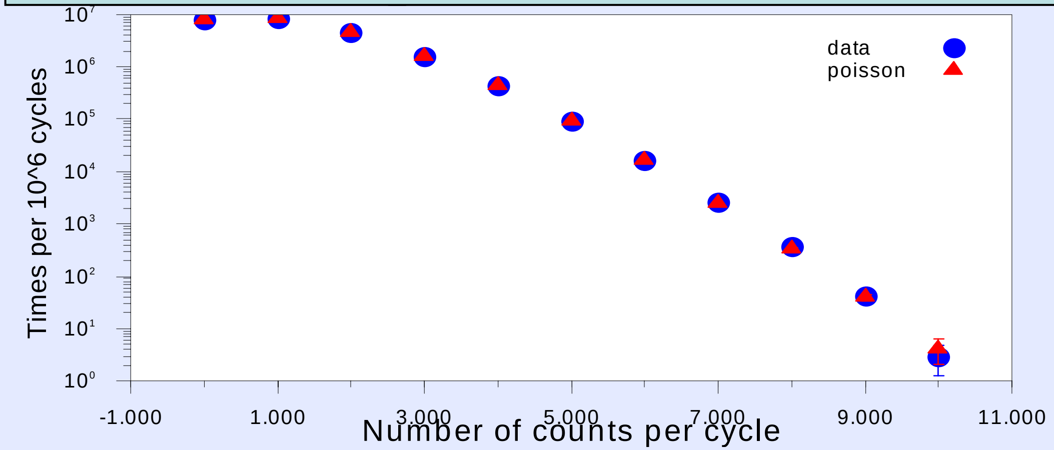
A gamma-ray image is back-projected onto the range map – snapshot of the 3D model (side view)

New method: Correlated Fast Neutron Counting

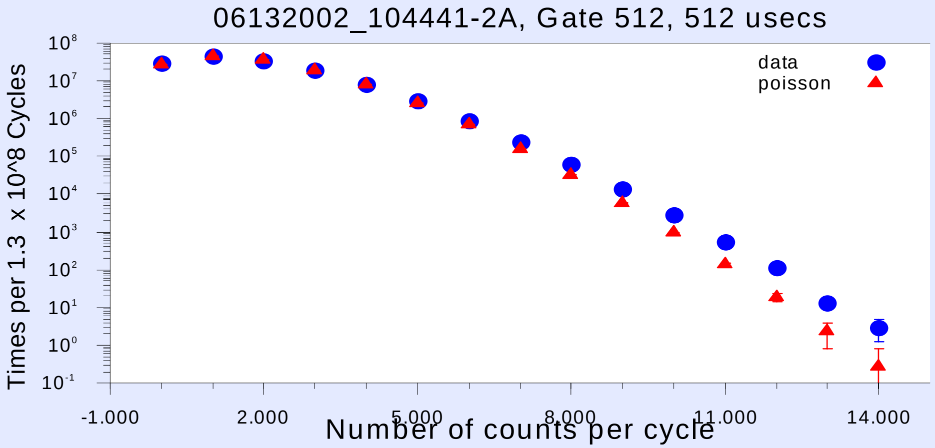
- Fast neutron counting enables isolation of individual fission events
- This will enhance the capability to statistically determine the fission isotopes in a mixed TRU stream
  - Cm versus Pu
- With 60 keV active interrogation, we can preferentially fission ^{239}Pu (and ^{235}U) over ^{242}Cm
  - ^{239}Pu and ^{240}Pu dominate in concentration and fission cross section

Measured Count Distributions

Correlated Fission Source has wider distribution than predicted from Poisson (Random) with the same count rate



Random Source (AmBe) 2.1K cts/sec



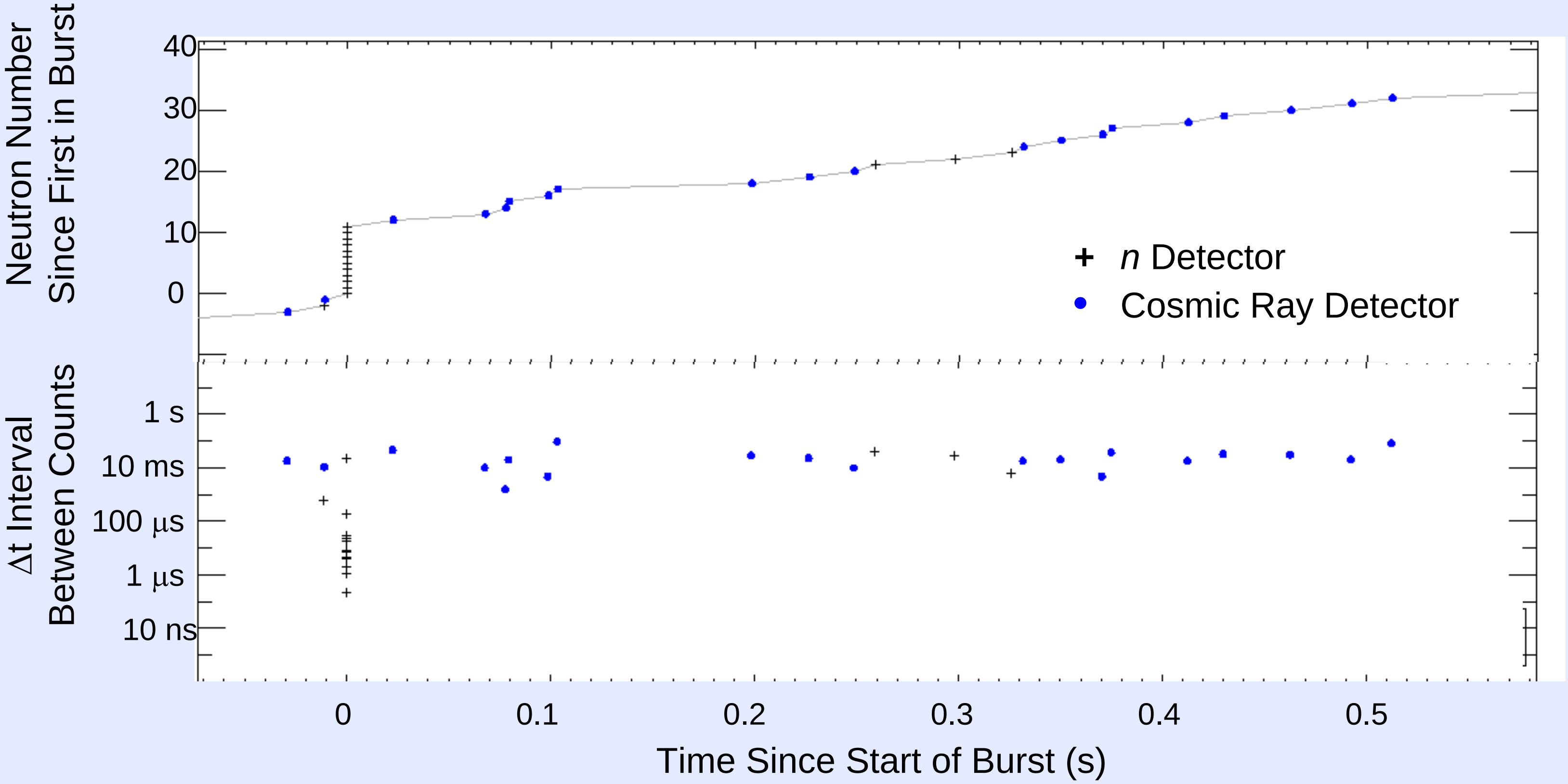
Fission Source

S.F., M=1, eff ~ 3%

^{252}**Cf** 3.1K cts/sec

Individual Fission Chain Detection

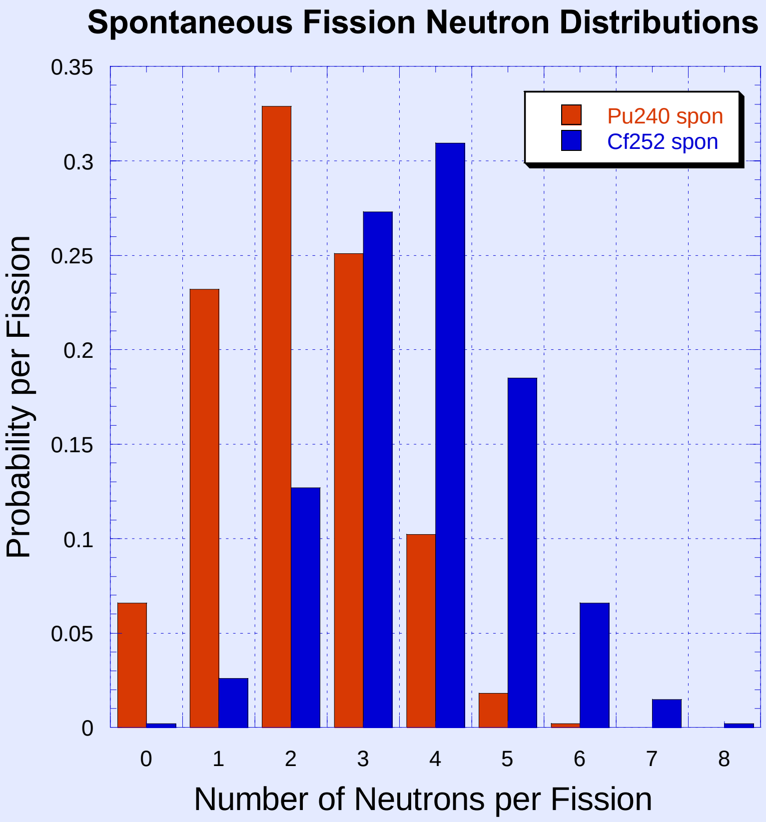
- **Measured data from 22 kg bare HEU shell**

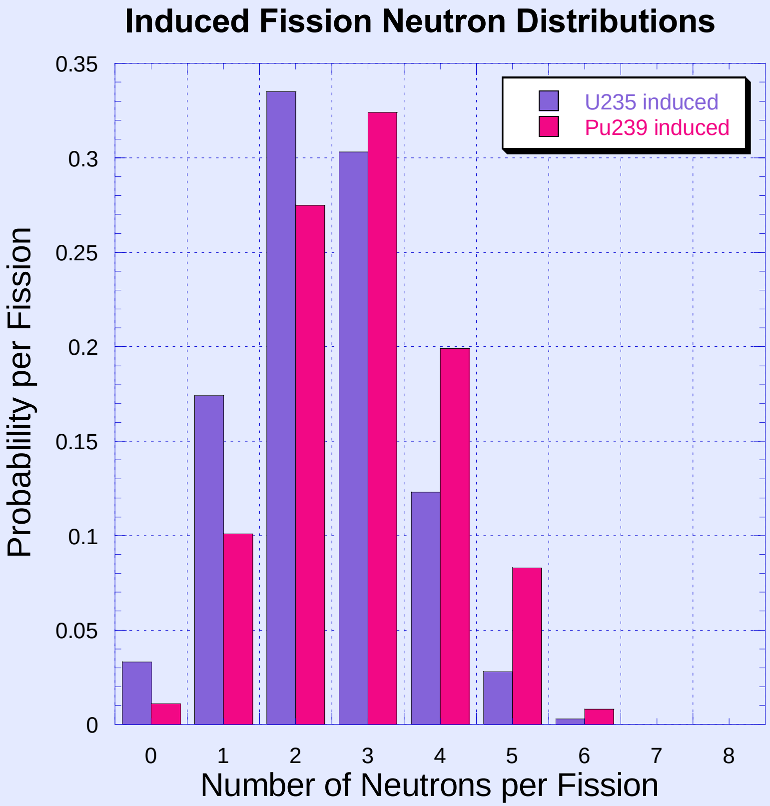


Fission chain burst is easily distinguished from cosmic ray background

Fission Neutron Distributions

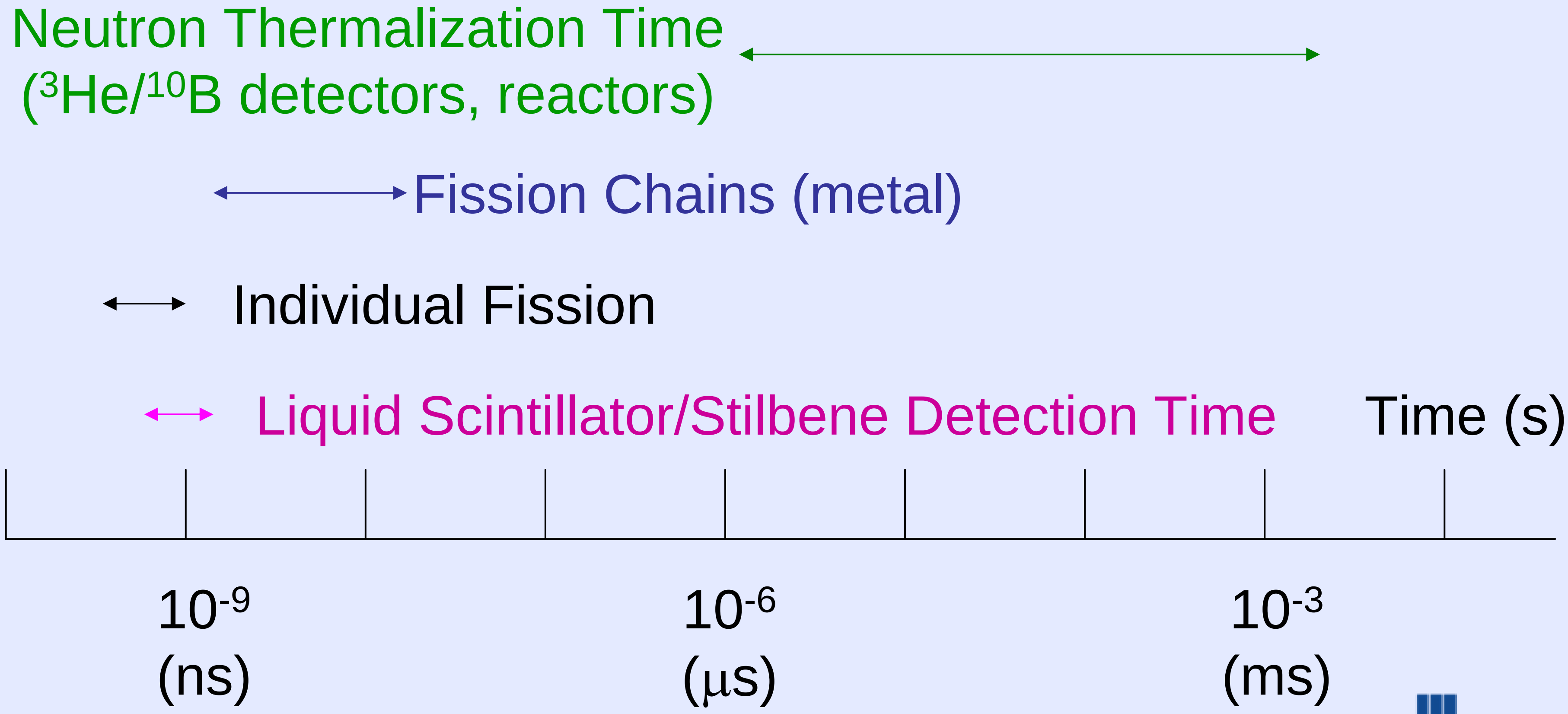
- SNM fissions with an expectation of 2-4 neutrons
- Finite probability of more (especially with multiplication)





Time Scales: What does timing buy?

Liquid Scintillator is fast (nanoseconds) can detect *individual fissions* even in high count rate environments



Neutron Thermalization Time
($^{3}He/^{10}B$ detectors, reactors)

Fission Chains (metal)

Individual Fission

Liquid Scintillator/Stilbene Detection Time

Time (s)

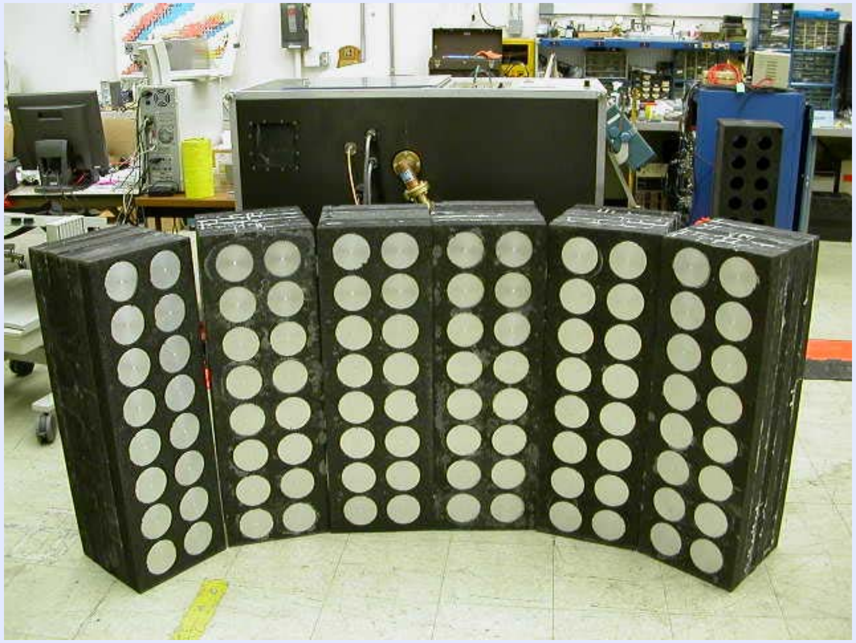
10^{-9} (ns)

10^{-6} (μs)

10^{-3} (ms)

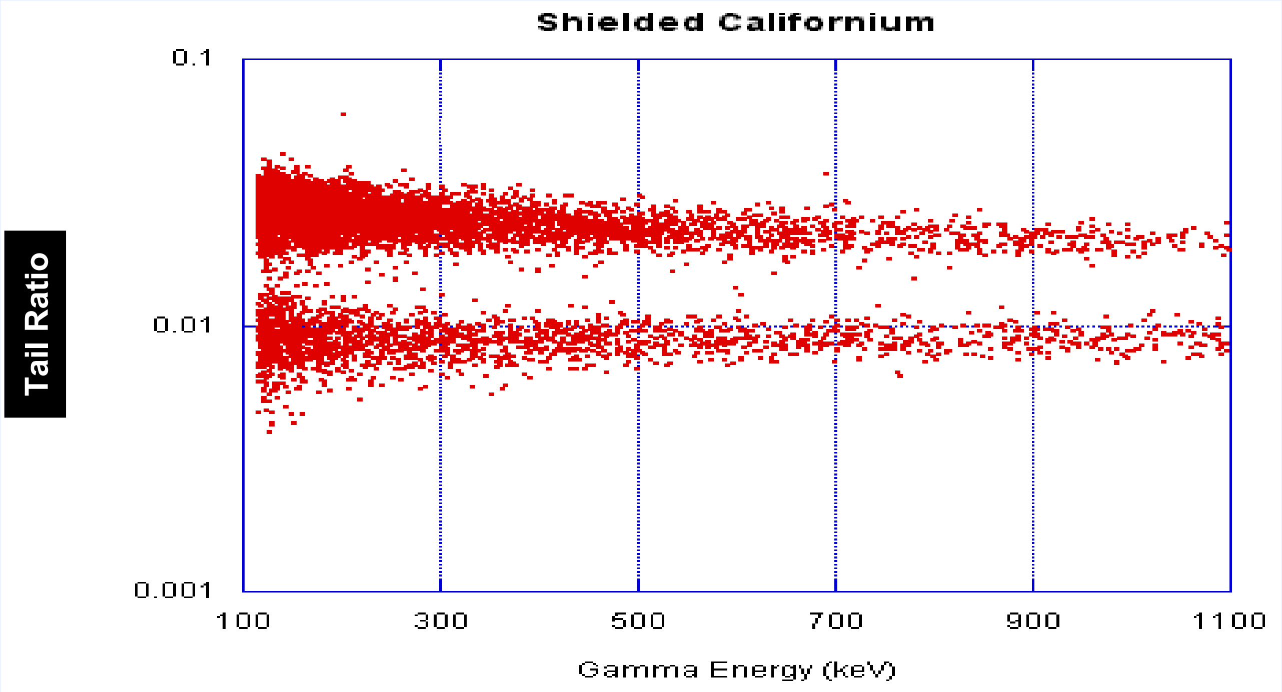
High source count rate requires new technologies

- **With our new Liquid Scintillator array and nanosecond timing data acquisition**



We have demonstrated isolation of fission chains in Pu

Discrimination of neutrons and gamma-rays with liquid scintillator

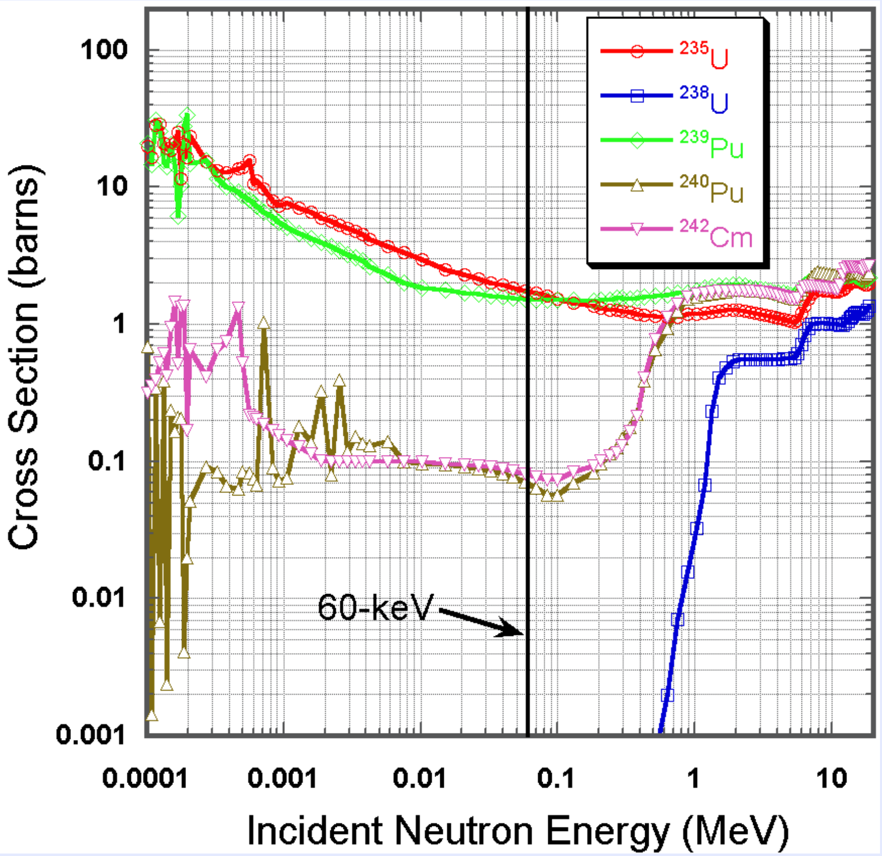


2” lead between ^{252}Cf and stillbene detector

10^5 discrimination of neutrons and gamma-rays above 500 keV neutron energy

Active interrogation

- Use low-energy neutrons to induce fission in ^{235}U and ^{239}Pu
- Detect fission neutrons
  - Liquid Scintillator detectors
  - Pulse-shape discrimination
  - High-energy neutrons
  - Low background



Proof-of-Concept

System

Diagram

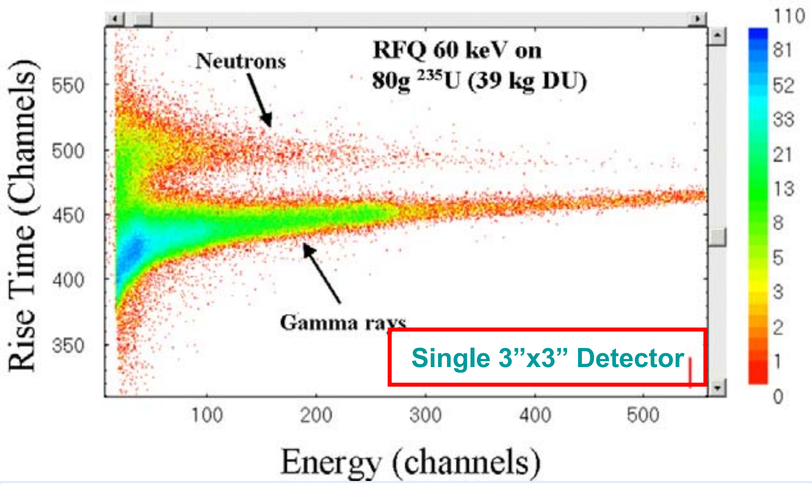
60 keV neutrons preferentially fission ^{235}U and ^{239}Pu over ^{242}Cm

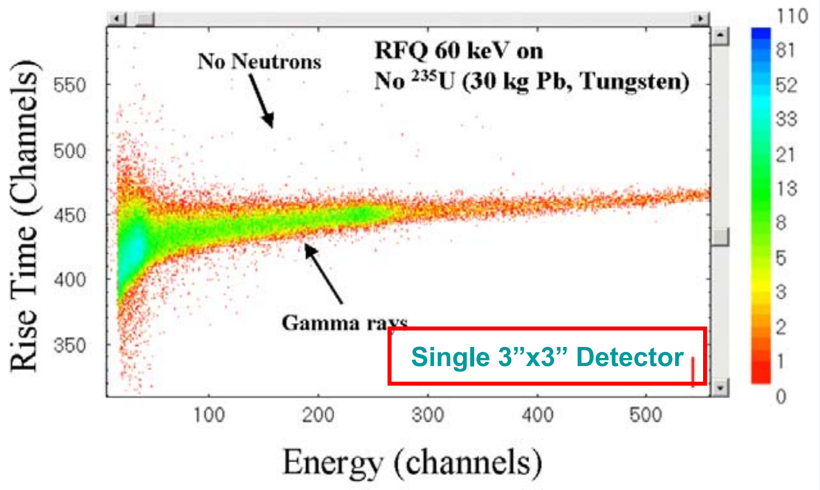
The fission cross section for ^{238}U is even smaller

60-keV neutron interrogation

- Induce fission in Pu
  - Detect high-energy fission neutrons with Liquid Scintillator Detectors
  - Pulse-shape discrimination separates fission neutrons and gamma rays
    - Energy Threshold detectors
    - Neutron beam energy well below detector energy threshold

60-keV neutrons from proton beam RFQ: ^{7}Li(p,n)





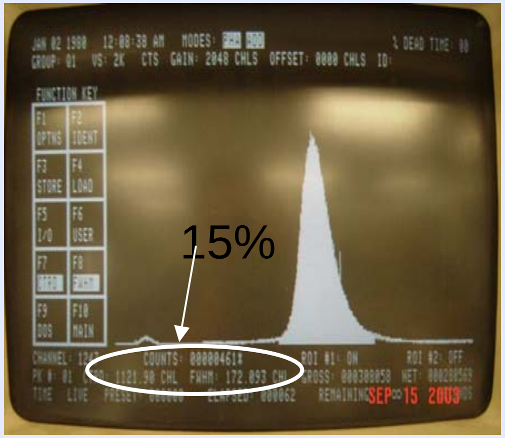
Low-energy neutron interrogation provides a rapid signature for the presence of ^{235}U

Low Energy Neutron Interrogation with fast scintillator detection

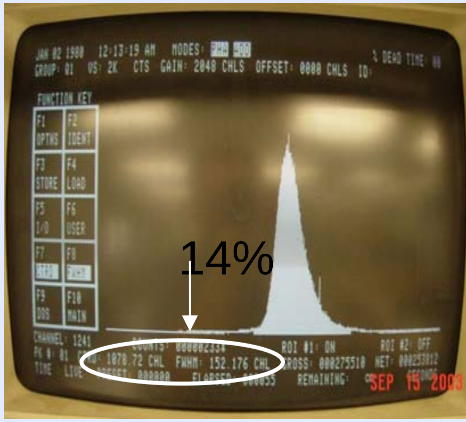
- Only SNM Pu, ^{235}U readily fission from low energy neutrons
- Measuring with fast scintillator preserves neutron energy
- Detector can be made invisible to interrogation Beam
- Changes in Fast Neutron Signature can help distinguish Neutron Source (e.g. Cm from Pu, HEU from LEU or DU)
- Fast Neutron Detection allows Pulsed Interrogation with Portable D-D or D-T generators.

Solid-state neutron detectors

- LiF, ^{10}B solid state neutron detection
- Ubiquitous neutron detection
- Low power consumption
- Insensitive to gammas
- Preamplification for each detector, signals can be transmitted via wire or wireless
- Preamplifier performs as well as commercial unit



LLNL preamp

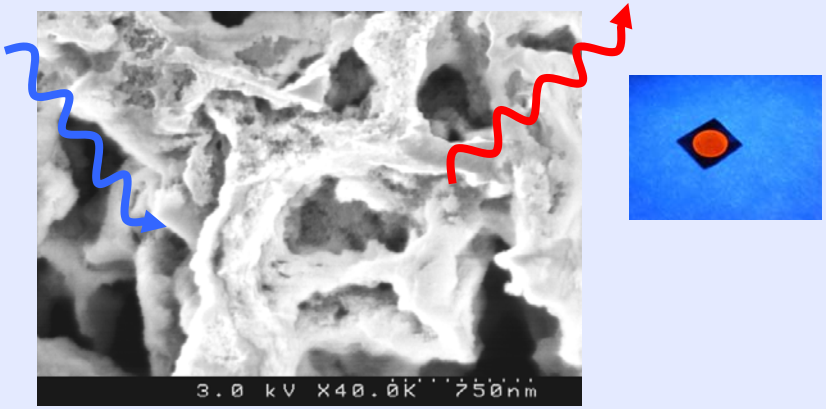


Commercial preamp

Nanotechnology can lead to dramatic improvements in radiation detection

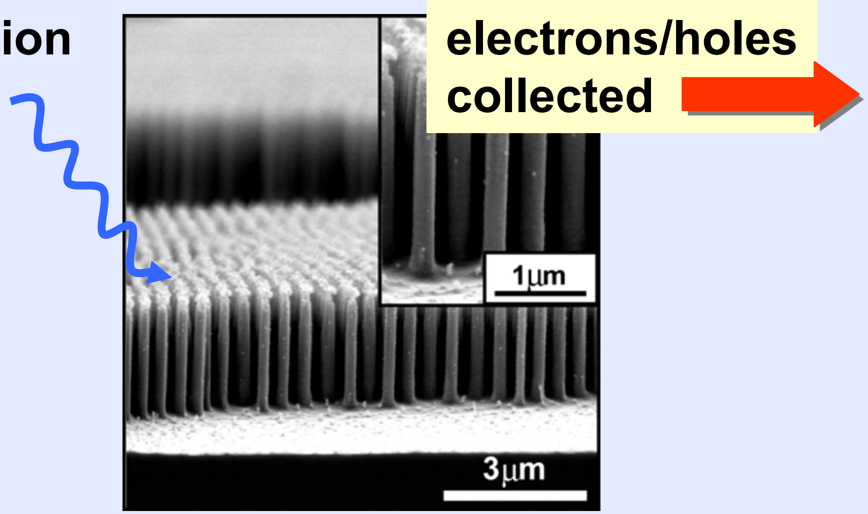
For gamma-ray detection

- 3D matrix of semiconductor nano-crystals
  - Tuning the size of the nano-crystals will allow optimal scintillator-photodetector match.



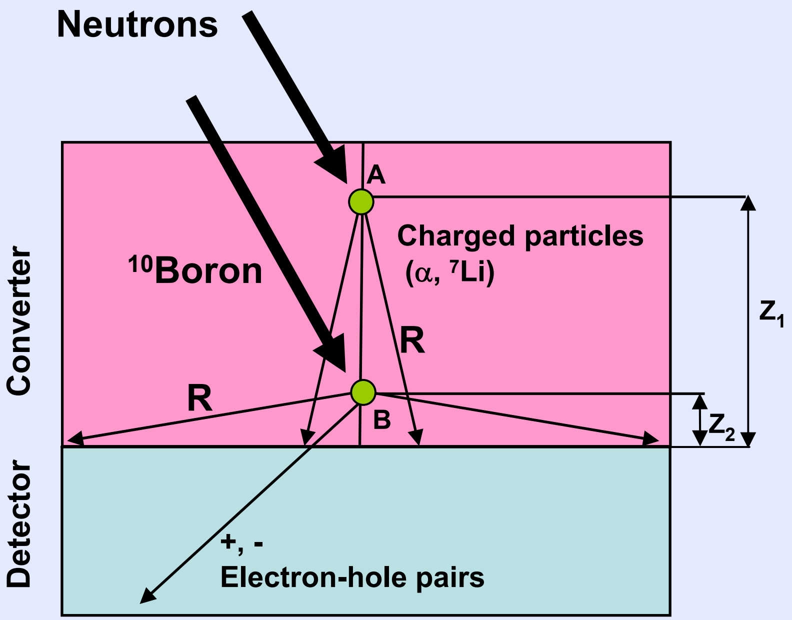
For neutron detection

- 3D semiconductor pillars surrounded by a boron-10 matrix
  - Tuning the size of the pillars will lead to improved efficiency.

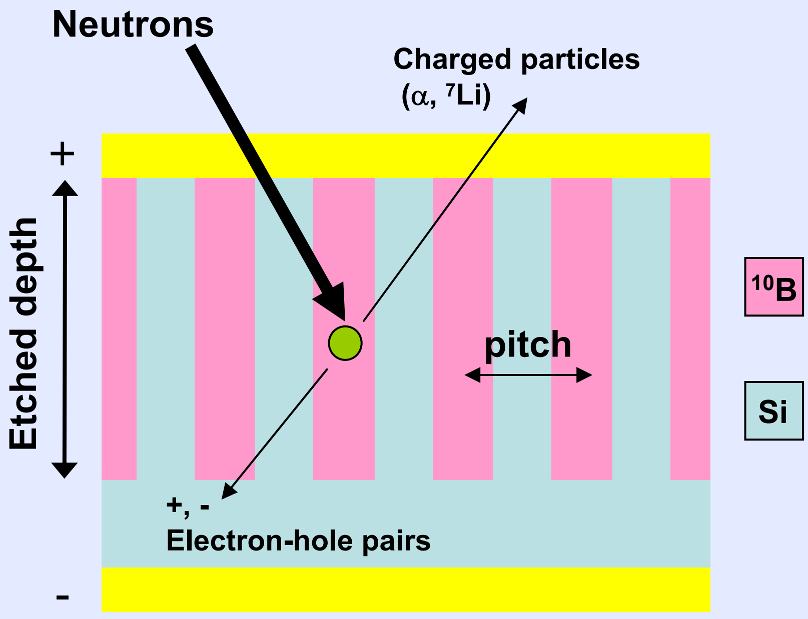


The ability to control semiconductor dimensions at the nano/micro-scale can potentially lead to the next generation radiation detectors.

Pillar device for high efficiency neutron detection



Planar 2D Design



LLNL Pillar 3D Design

- ❖ ^{10}B efficiently produces α particles

94 %	**$^{10}B+n \rightarrow\ ^7Li(0.84MeV) + \alpha(1.47MeV)$ ($Q=2.31MeV$, $\sigma=3571b$)**
6%	**$^{10}B+n \rightarrow\ ^7Li(1.01MeV) + \alpha(1.78MeV)$ ($Q=2.79MeV$, $\sigma=269b$)**

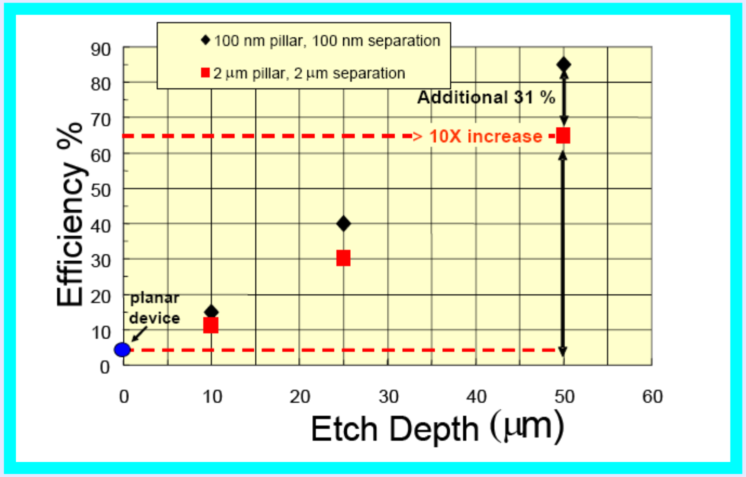
But….

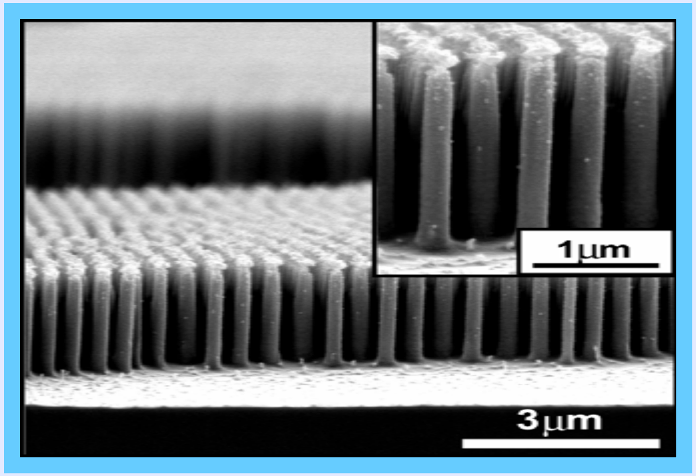
- ❖ Most α particles do not reach the detector!
- ❖ Limited efficiency: 2-5%/cm^2 (@ thermal)

- ❖ Simulations indicate this 3-D structure will increase efficiency towards 85+% / cm^2 !
- ❖ Device geometry:
  - ➢ etch depth → capture neutron flux
  - ➢ pitch → alpha particle range

Next generation high efficiency detectors based on pillar technology

- Neutron detection efficiency can be as high as 50%
- Can be filled with ^{10}B, LiF or threshold fission materials





Applications for solid-state neutron detectors

- “Smart tags” for tracking material flow
- Monitor centrifuge hall
- Storage area, transport through pipes, etc.
- Ubiquitous detection

Next steps: Need to do simulations and measurements to demonstrate this capability for specific Safeguards regimes