Nuclear Security in the 21st Century

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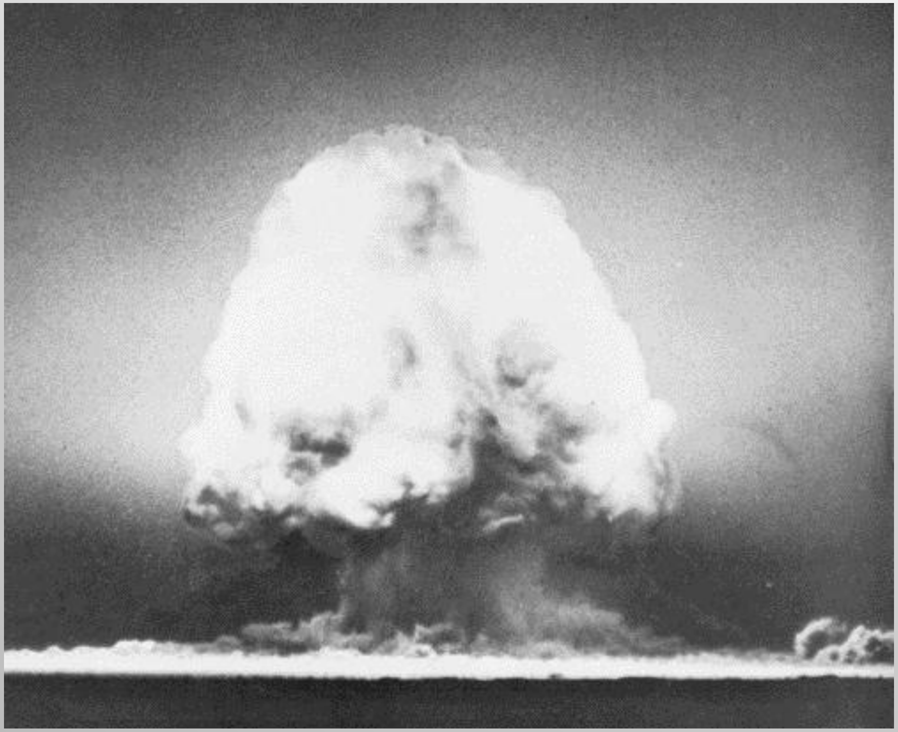
Defining National Security Images

- 20th Century



- 21st Century

- Goal : to prevent a superposition of these images
- 9/11 attacks demonstrated desire and delivery

Fog of (cold) war begins to lift ...


COMMENTARY

A World Free of Nuclear Weapons

By GEORGE P. SHULTZ, WILLIAM J. PERRY, HENRY A. KISSINGER and SAM NUNN

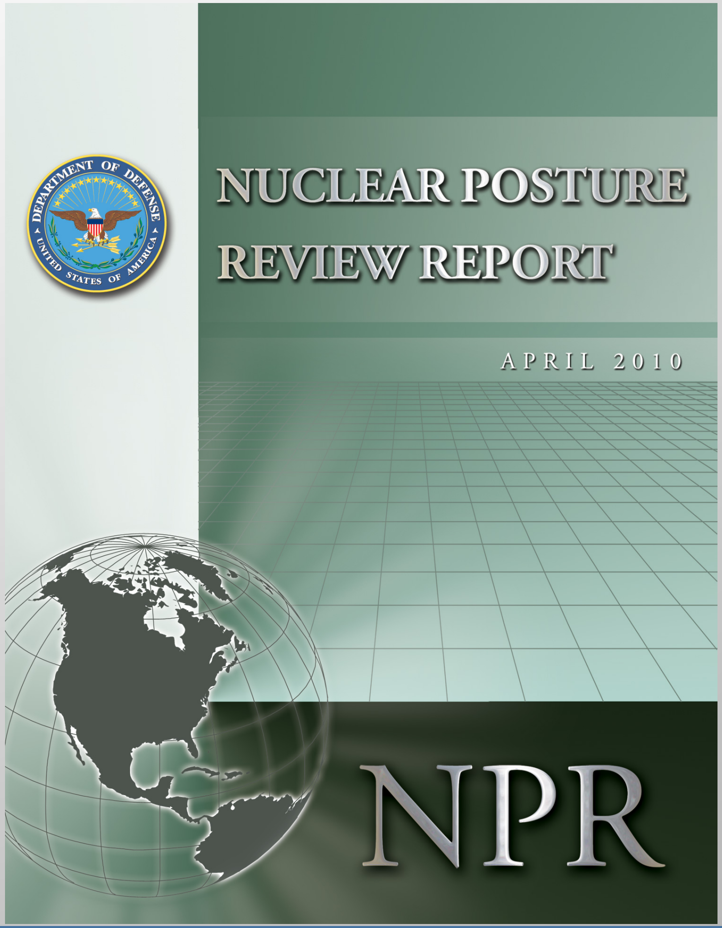
Updated Jan. 4, 2007 12:01 a.m. ET

Nuclear weapons today present tremendous dangers, but also an historic opportunity. U.S. leadership will be required to take the world to the next stage -- to a solid consensus for reversing reliance on nuclear weapons globally as a vital contribution to preventing their proliferation into potentially dangerous hands, and ultimately ending them as a threat to the world.

Nuclear weapons were essential to maintaining international security during the Cold War because they were a means of deterrence. The end of the Cold War made the doctrine of mutual Soviet-American deterrence obsolete. Deterrence continues to be a relevant consideration for many states with regard to threats from other states. But reliance on nuclear weapons for this purpose is becoming increasingly hazardous and decreasingly effective.

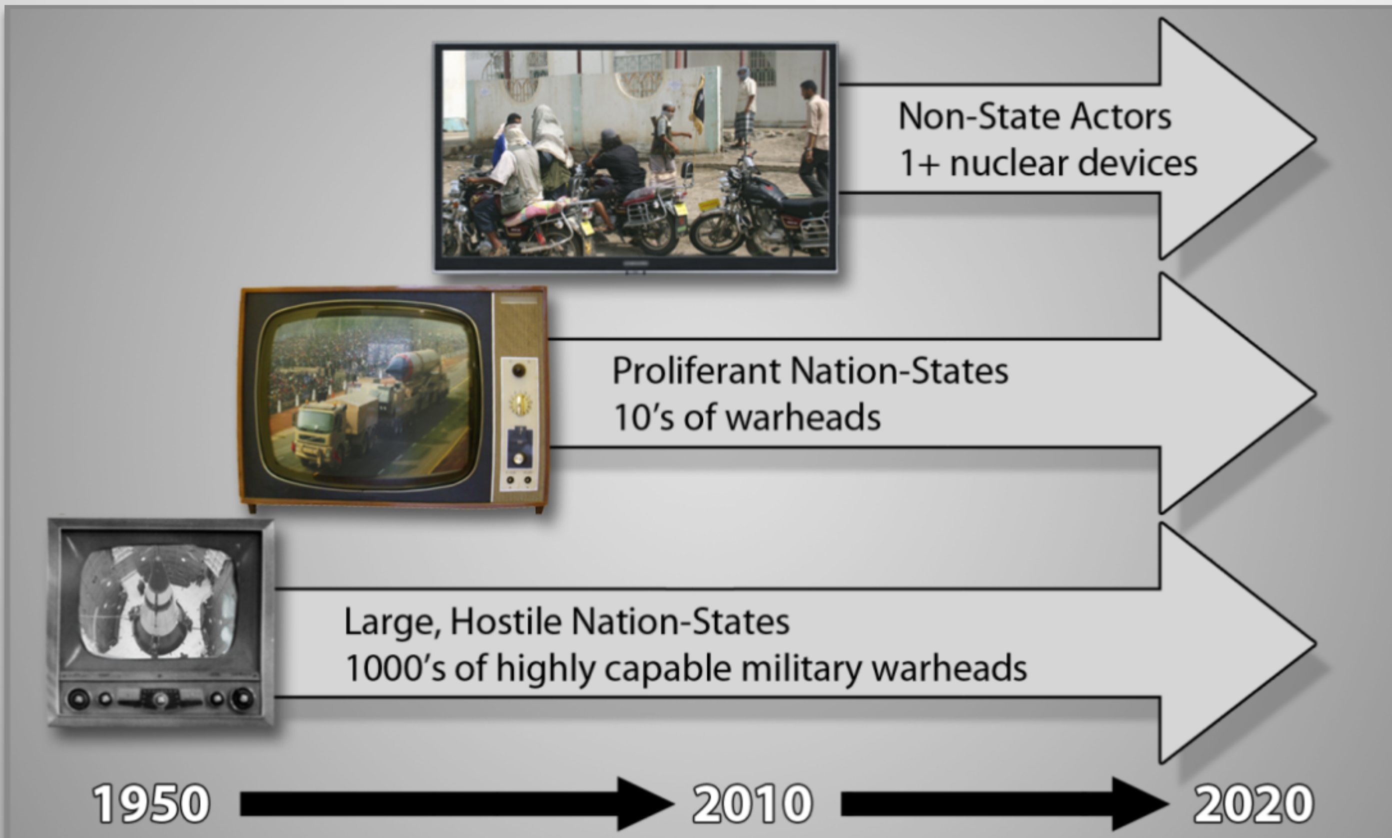
The 2010 Nuclear Posture Review (NPR) identified five key objectives

1. Prevent nuclear proliferation and nuclear terrorism
2. Reduce the role of nuclear weapons
3. Maintain strategic deterrence and stability at reduced nuclear force levels
4. Strengthen regional deterrence and reassurance of US allies and partners
5. Sustain a safe, secure, and effective nuclear arsenal



For the first time, the NPR places preventing nuclear proliferation and nuclear terrorism atop the U.S. nuclear agenda.

The nuclear threat environment today is challenging…



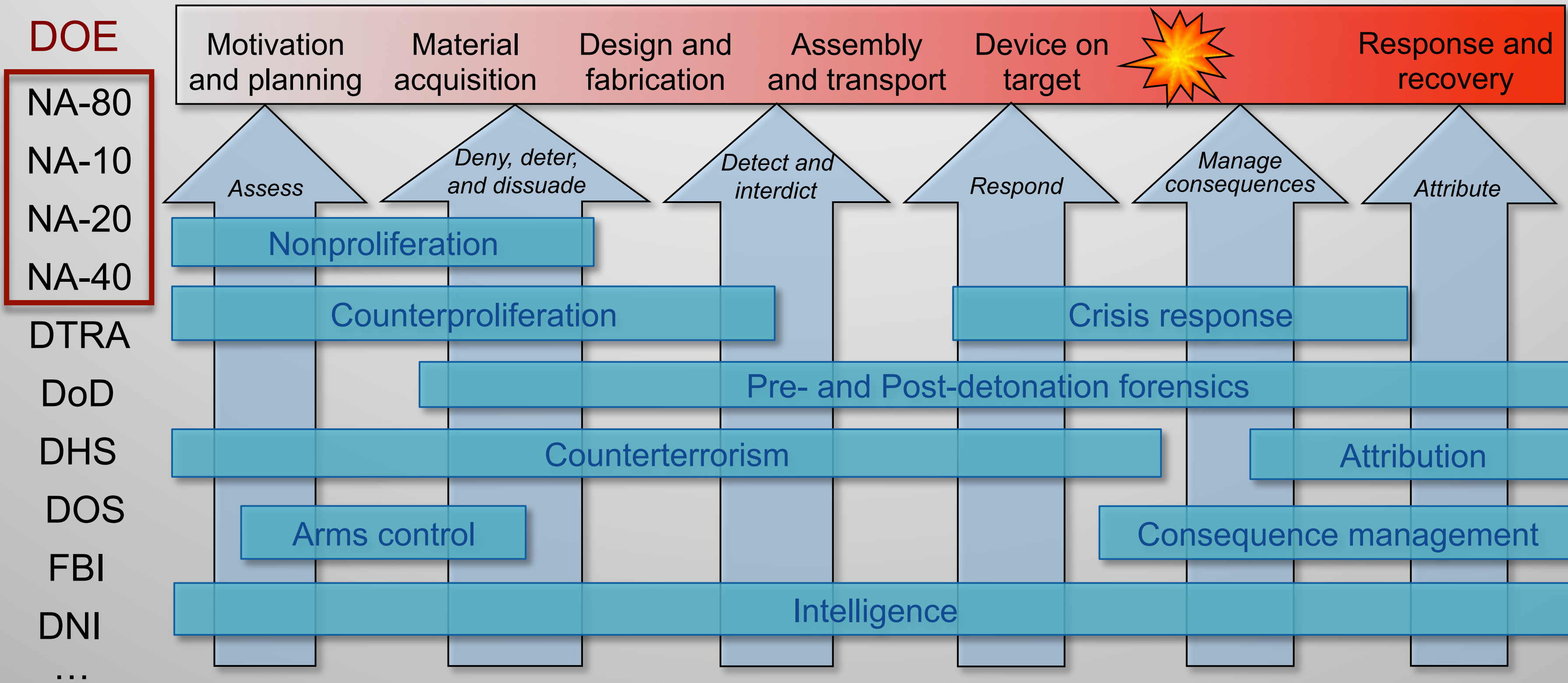
DOE/NNSA Capabilities

- Intelligence
- Nonproliferation
- Counterterrorism
- Counterproliferation
- Forensics and Attribution
- Emergency Response
- Consequence Management
- Stockpile Stewardship
- Arms Control
- Treaty Verification

Our National Security programs evolved out of the capabilities and expertise developed to support the core nuclear weapons program

Approach to reduce/counter nuclear threats

Threat: Foreign, proliferant, stolen, or improvised nuclear devices



IAEA also a major player in the area of Non/Counter-Proliferation

The national labs play a key role as integrators across this mission space

US R&D Efforts Cast Wide Net

- National Labs
  - LANL, LLNL, SNL, ORNL, PNNL, IDNL, LBNL, BNL, ...
- Universities
  - Nuclear Physics/Chemistry/Engineering, Material Science, Computer Science, ...
- Private Sector
  - From large defense contractors to small start-ups

This Talk (1)

- Complete review of nuclear security R&D beyond scope of any talk
- Focus on Special Nuclear Materials (SNM)
  - Convention explosive w/ radioactive debris (dirty bomb) terrorist threat, but not WMD
  - U-235 (separated from U-238)
    - Natural abundance of 0.7%, less = Depleted Uranium (DU)
    - Low Enriched Uranium (LEU) < 20%, reactor grade = 3-5%
    - Highly Enriched Uranium (HEU) > 90%
  - Pu-239
    - made in reactors, U-239 with 2-beta decays

This Talk (2)

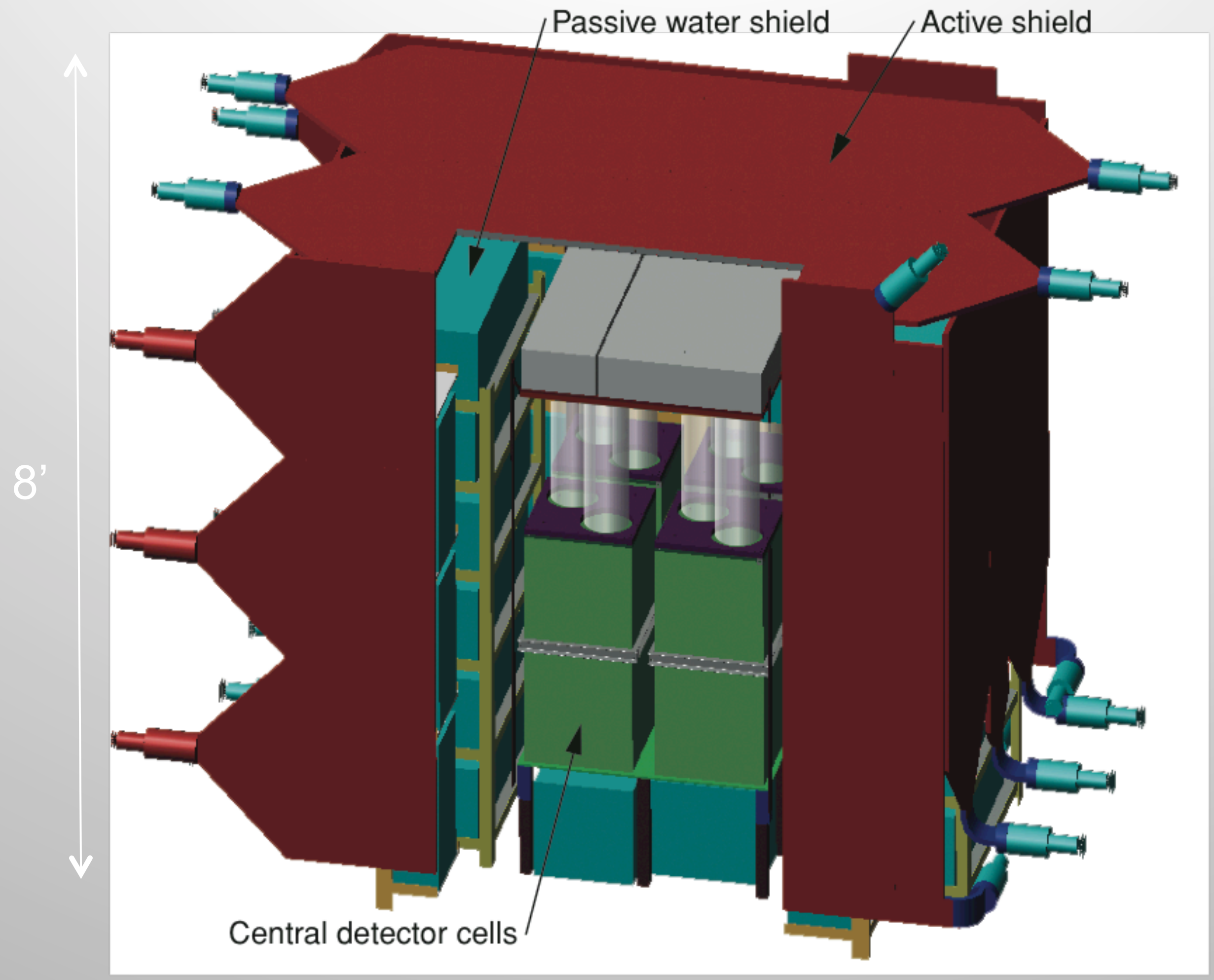
- Reactor Monitoring = likely starting point
  - neutrino detection (Bernstien, LLNL)
  - high-res germanium (Burke, LLNL)
- Transit Detection
  - Roadside Tracker (Ziock, ORNL)
  - Muon Tomography (Morris, LANL)
- Points of Entry
  - NRF (Bertozzi, Passport Systems)
  - Neutron Time-Correlations
- Novel Detectors
  - organic scintillators (Zeitseva, LLNL)
  - nano-thermite materials (Univ. Mich.)

Reactor Monitoring with anti-neutrinos

- U-235 and Pu-239 fission products β-decay at different rates
- ν-rate sensitive to Pu-239 content
- Gd-doped water-Cerenkov detection
  - $\nu + p \rightarrow e^+ + n \rightarrow Gd(n,\gamma)$
- Bowden, *et al,* Nucl. Instr. Methods A572, 985 (2007)

Parameter	Precision	Dwell times
Operational Status (on/off)	99.99%	hours
Power level	3% accuracy	days
Fissile Pu/U content	<10 kg Pu, core-wide, 1 sigma accuracy	3 months

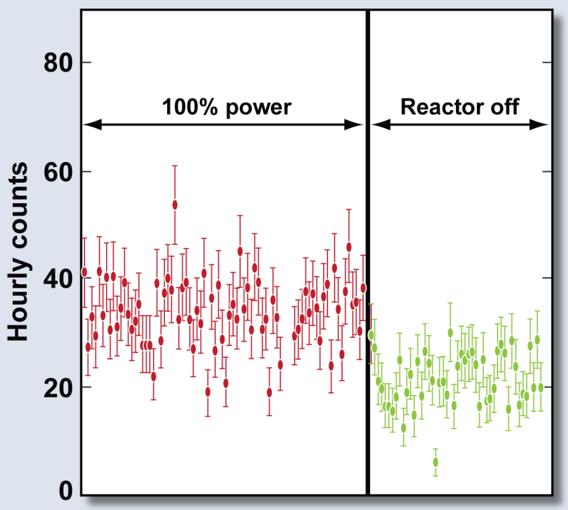
Songs Detector



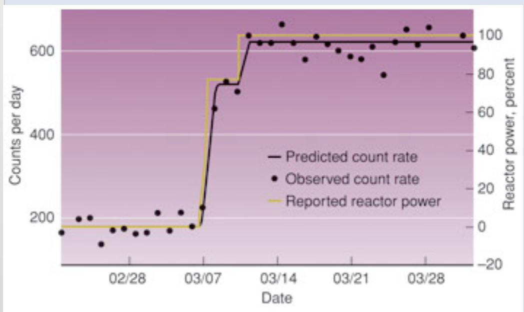
The prototype antineutrino detector consists of three subsystems: a central detector and two shields. Photomultiplier tubes above the central detector cells detect the antineutrino's signature.

SONGS: small, deployable near field antineutrino detector

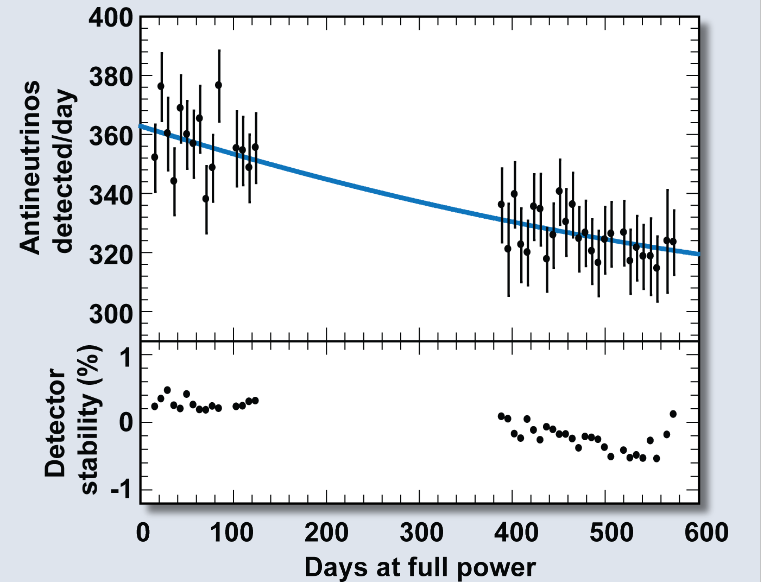
Determine reactor on/off status within 5 hours with 99.9% C.L.



Measure thermal power to 3% in one week



Detect switch of 70 kg Pu-U with known power and initial fuel content



Rate-based measurements (count rate only)

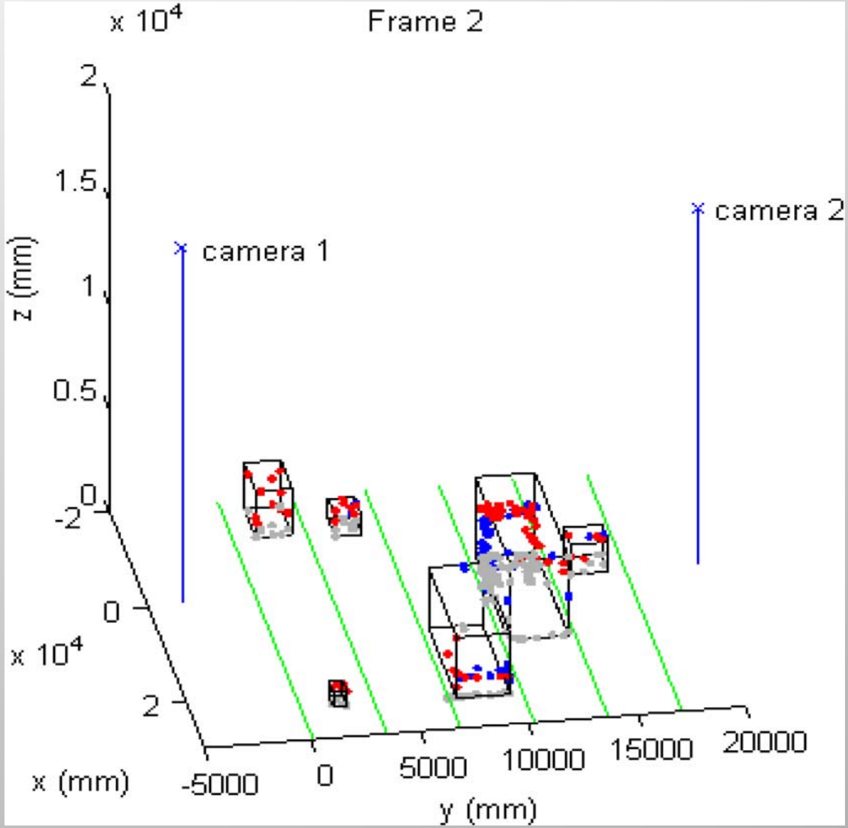
- **Simple detector design**
- **Stable operations**
- **25 m from core, outside containment**

The Roadside Tracker

- Combine visible (camera) and gamma (CsI) detection to track radiation in highway transit
- Image reconstruction to track vehicle motion
- Coded aperture to track gamma-ray source
- Detects 37 MBq-class at 113 km/hr over 5-lanes

Roadside Tracker picture/schematic

Ziock, *et al.*, IEEE Trans. Nucl. Sci., 60,, 2237 (2013)

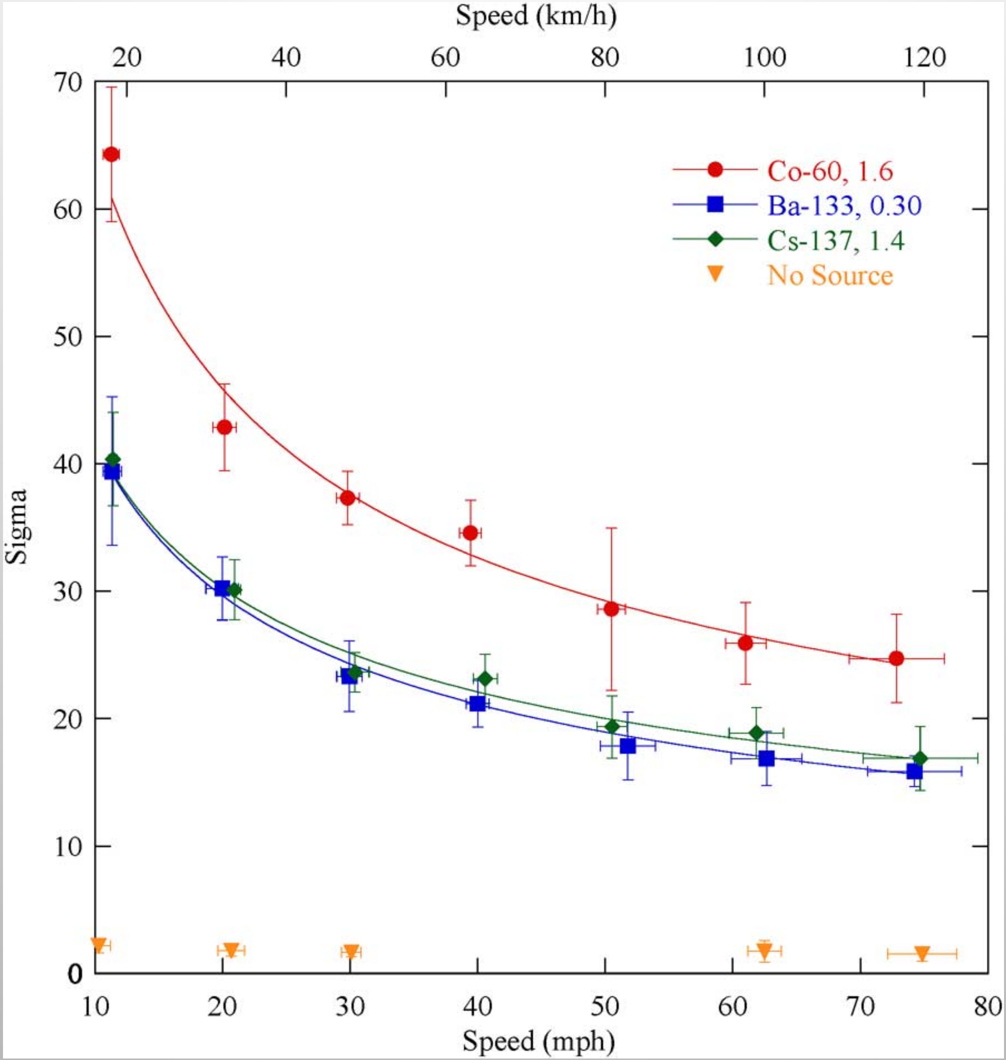


Roadside Tracker signals

Fig. 9. Results for a vehicle with (left) and without (right) a source. In this case the source was 1.1 MBq of ^{137}Cs in a vehicle traveling at 19.2 km/h.

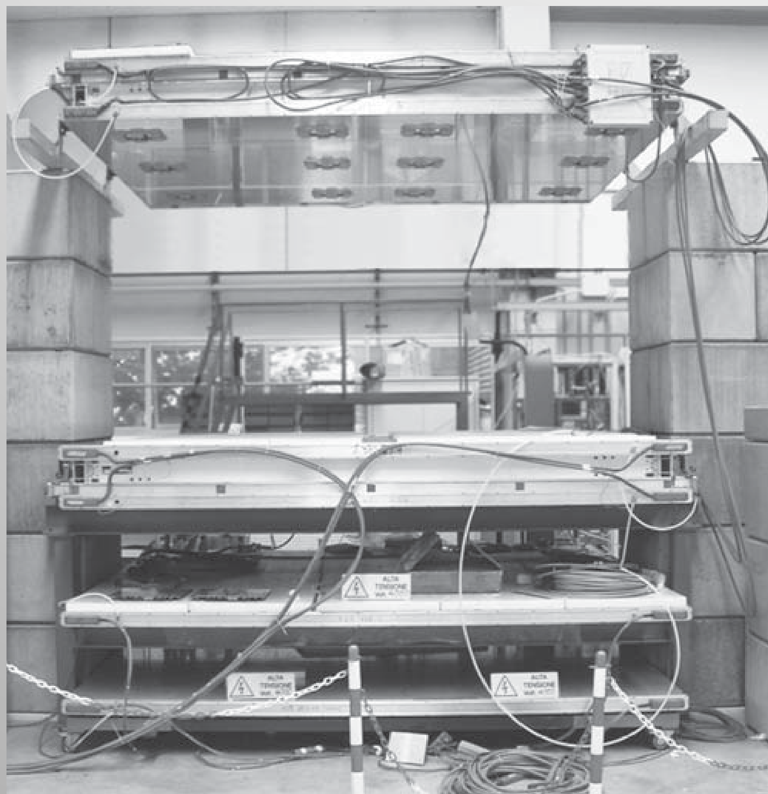
Fig. 10. System results obtained with vehicles crossing in the field of view. No cross-talk is observed between the source and no-source vehicles.

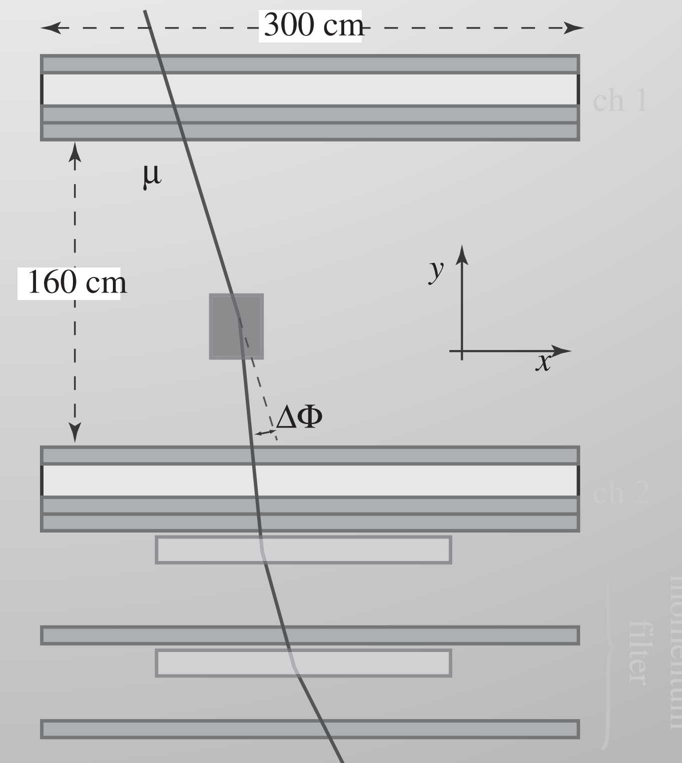
Roadside Tracker detection



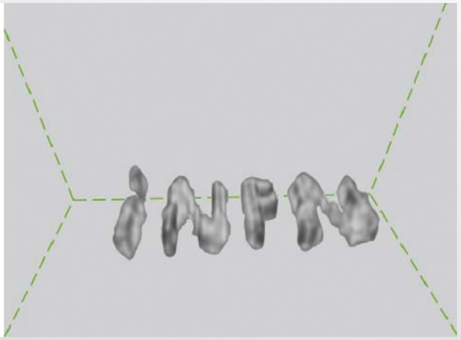
Muon Tomography

- Passive scanning with cosmic-ray muons
- Drift chamber detection of multiple scattering





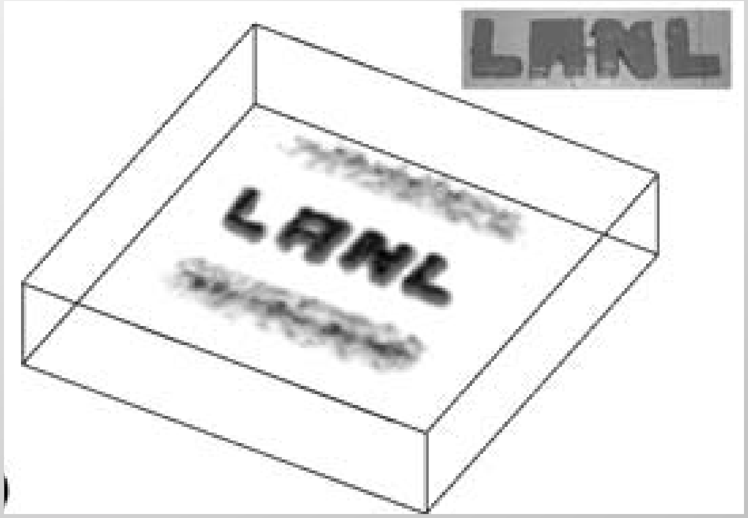
Self-identifying efforts



Nucl. Instr. Nucl. Instr. Meth. A 604, 738 (2009)A

$$\sigma = \frac{13.6\,\mathrm{MeV}}{\beta p c}\sqrt{\frac{x}{X_0}}[1 + 0.038\ \log(x/X_0)] \approx \frac{13.6\,\mathrm{MeV}/c}{p}\sqrt{\frac{x}{X_0}}$$

$$X_0 = \frac{716.4\,(\mathrm{g/cm^2})}{\rho}\frac{A}{Z(Z+1)\ \log(287/\sqrt{Z})}$$



IEEE Trans. on Image Proc. 16, 1985 (2007)

- Some material ID is possible

Muon Tomography example

- Sensitive to shielding
- Combine with other techniques

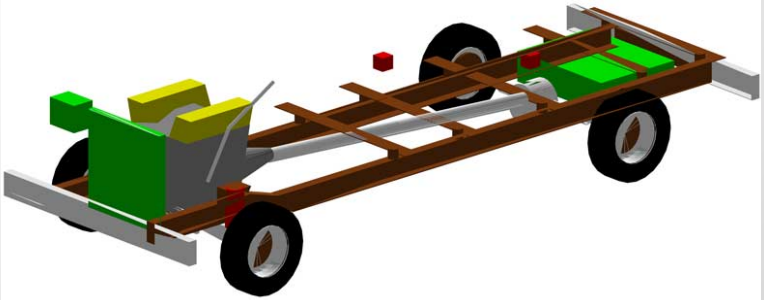


Fig. 13. Illustration of major objects in a simulated passenger van.

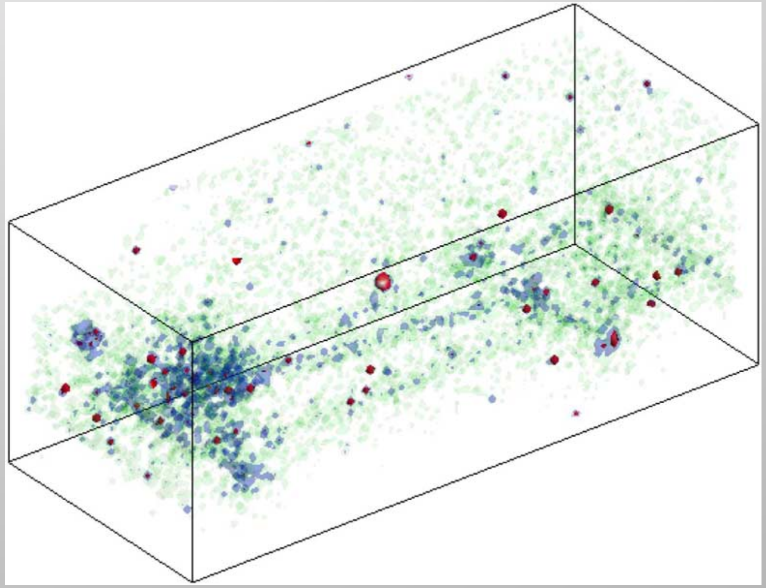
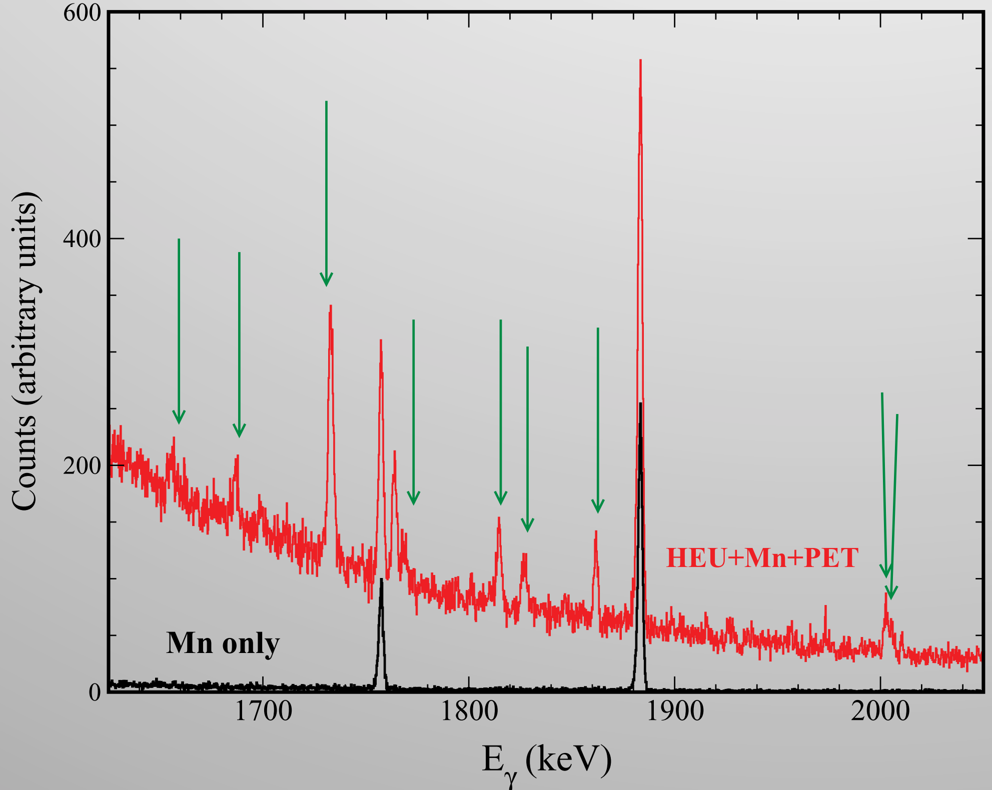


Fig. 14. Reconstruction of 1 min of simulated muon exposure of the passenger van via the *mean* method.

Nuclear Resonance Fluorescence

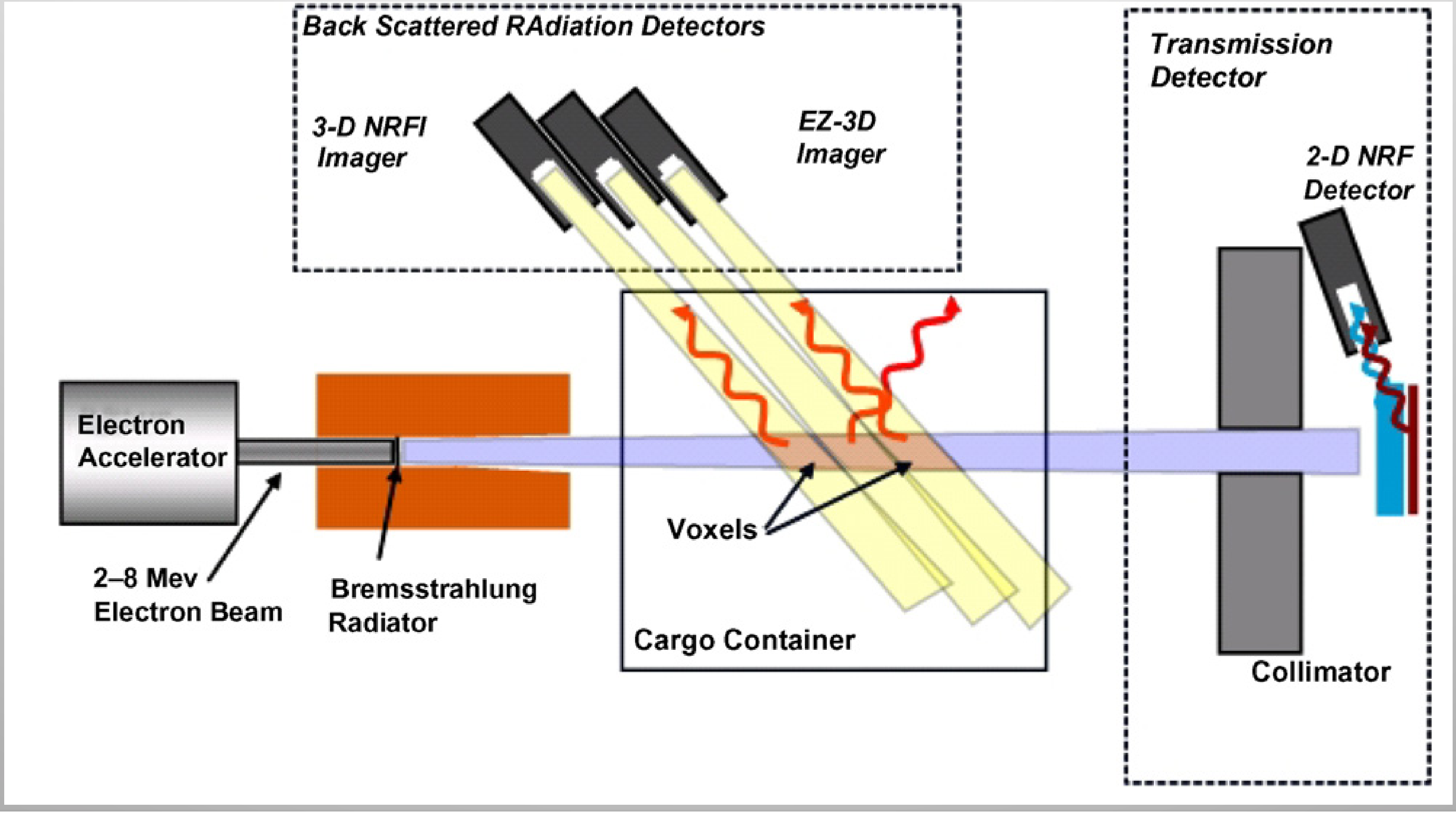
- Collective nuclear oscillations (i.e. GDR) provide unique & narrow excitations at penetrating (MeV) gamma energies



Bertozzi, *et al.*,
Phys. Rev. C 78, 041601 (2008)

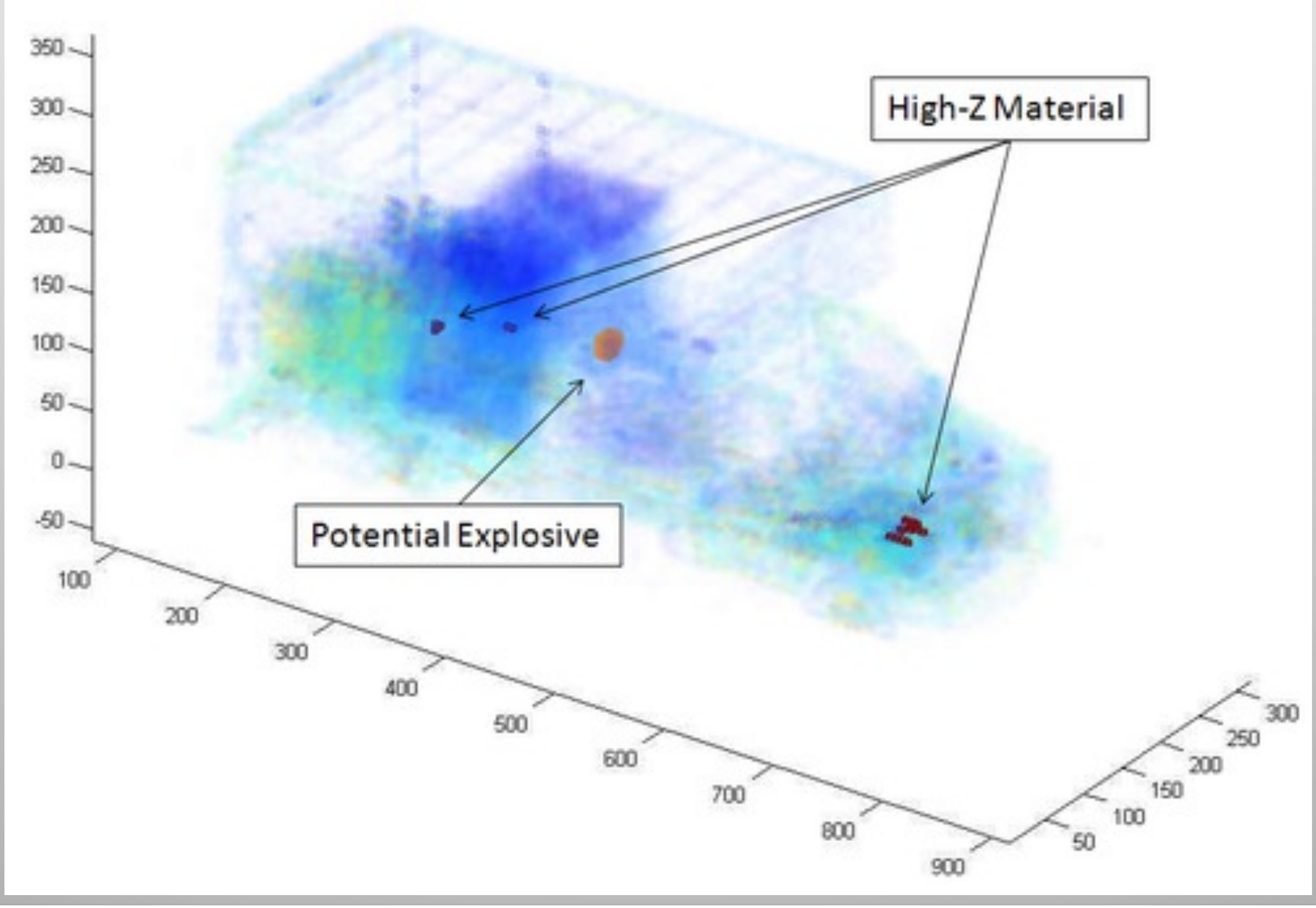
Passport Systems NRF + EZ-3D™

- Bremsstrahlung Cargo Scanner



3D Image Reconstruction

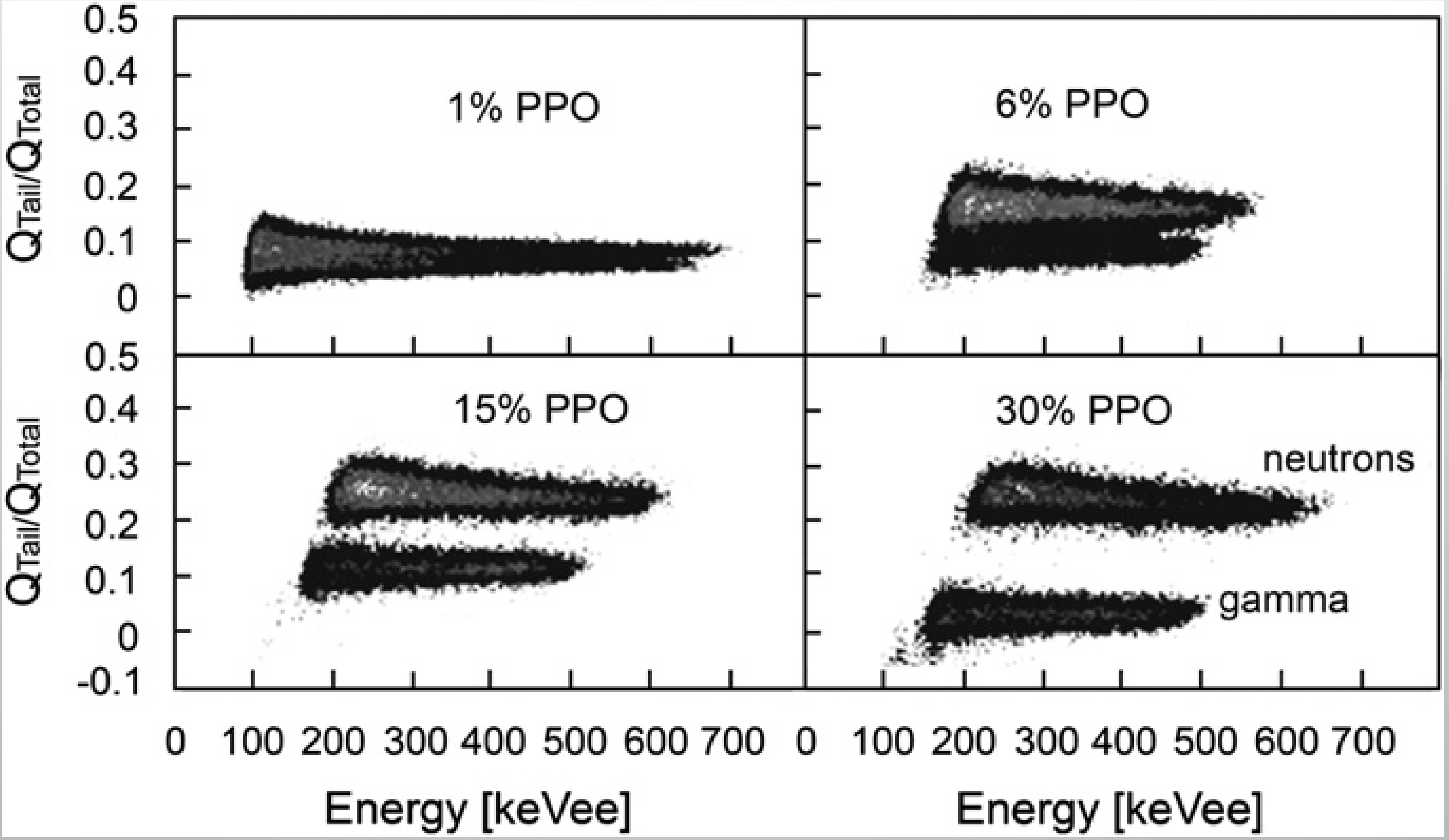
Bertozzi *et al.*, Nucl. Instr. Meth. B 261, 331 (2007



Plastics with improved PSD

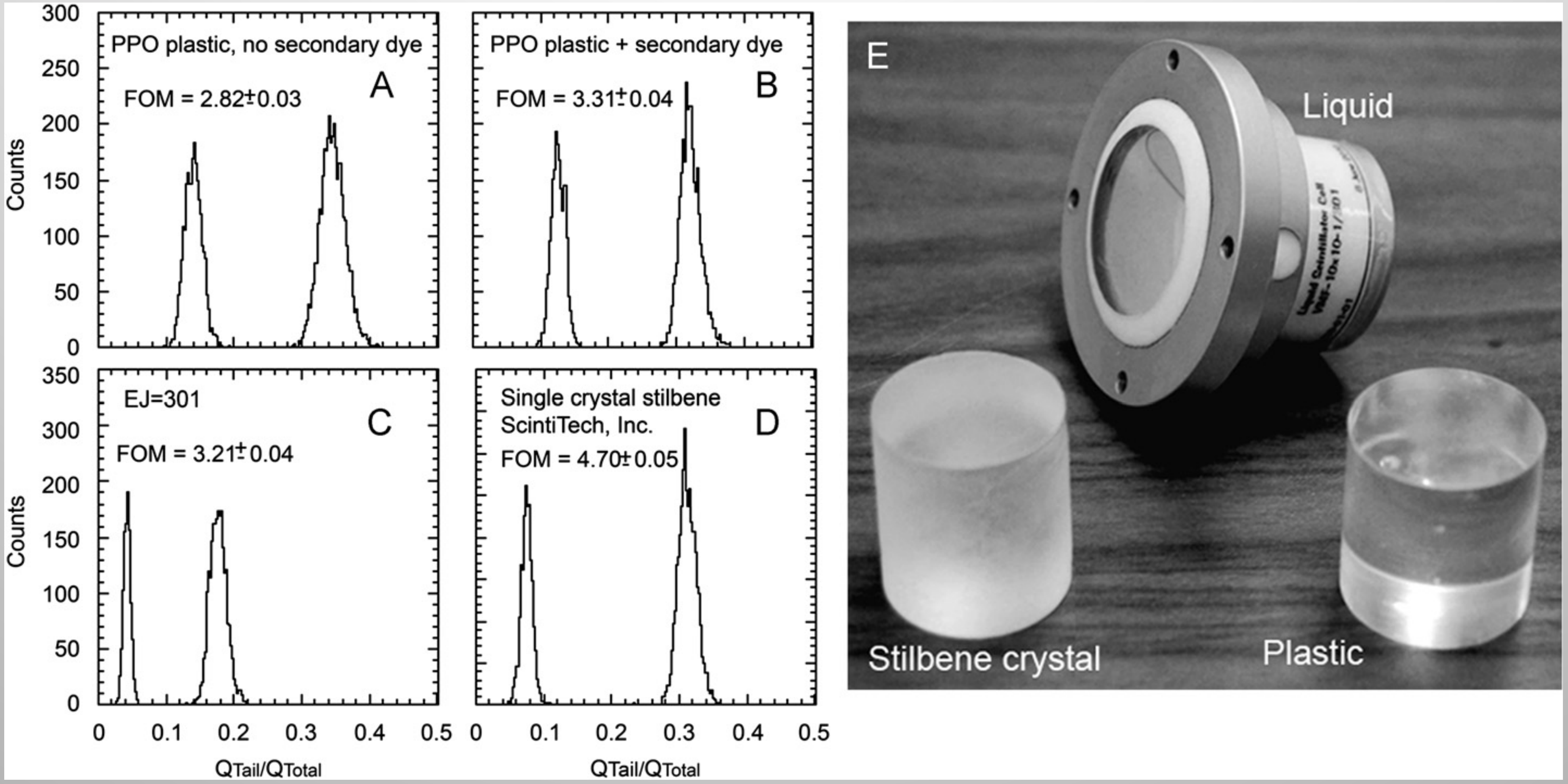
- Standard Pulse Shape Discrimination
  - gamma (e- recoils) → S_1 excitation → photon
  - neutron (p+ recoilds) → T_1 excitation
    - $T_1 + T_1 \rightarrow S_0 + S_1 \rightarrow$ photon
    - photon delay depends on T_1 mobility
- Work with PVT (polyvinyltoluene)
  - add PPO (2,5 diphenyloxazole)
  - able to tune PSD separation via triplet de-excitation
    - Zaitseva *et al.*, Nucl. Instr. Meth. A 668, 88 (2012)

Results of PPO Doping



- Q_{Tail} = charge in delayed component

Scintillator Comparison

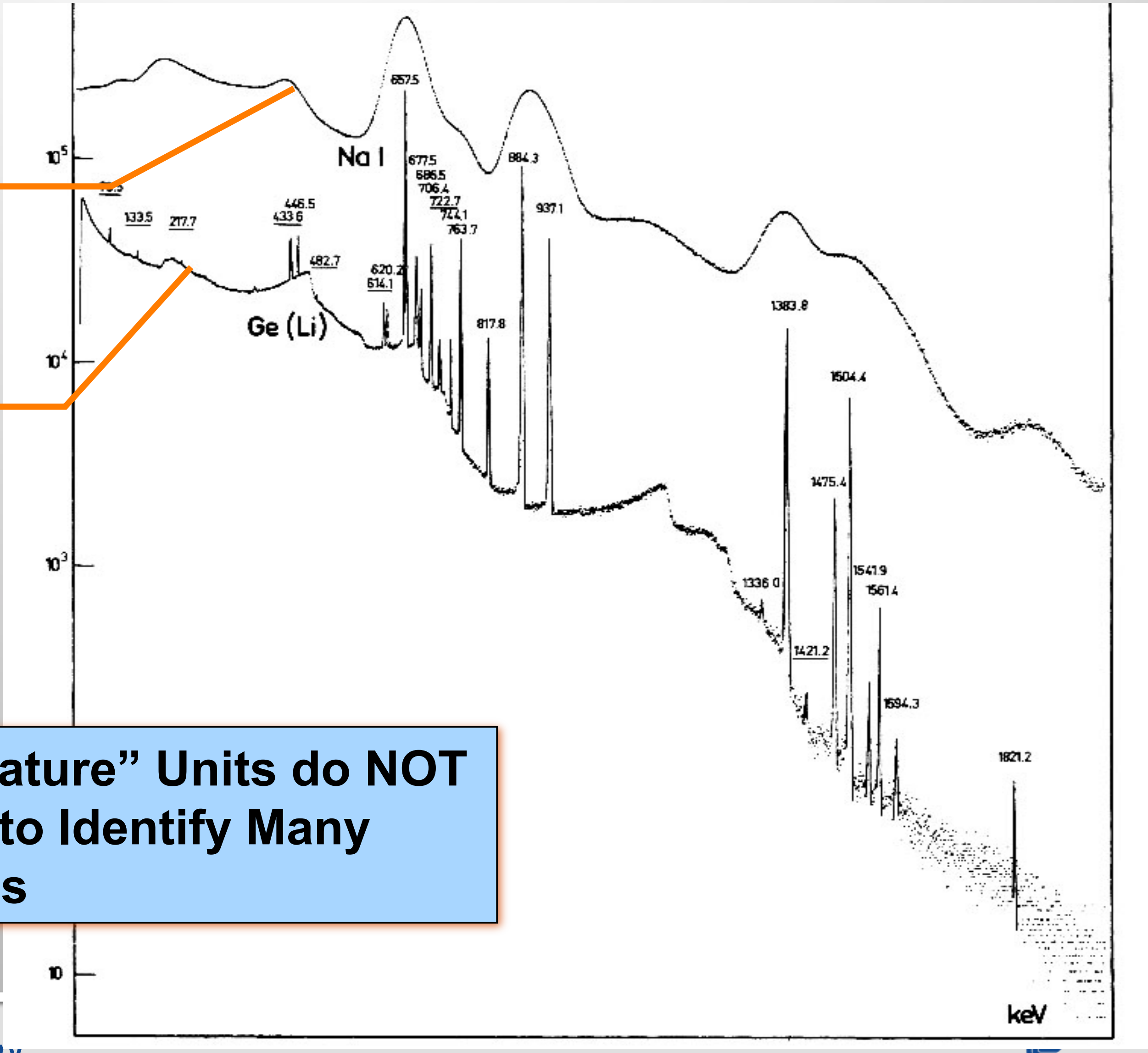


Addition of 0.2% DPA (9,10 diphenylanthracene) further improves PSD

Good spectral resolution is important

Room temperature (NaI) Spectrum

Liquid Nitrogen Cooled (HPGe) Spectrum



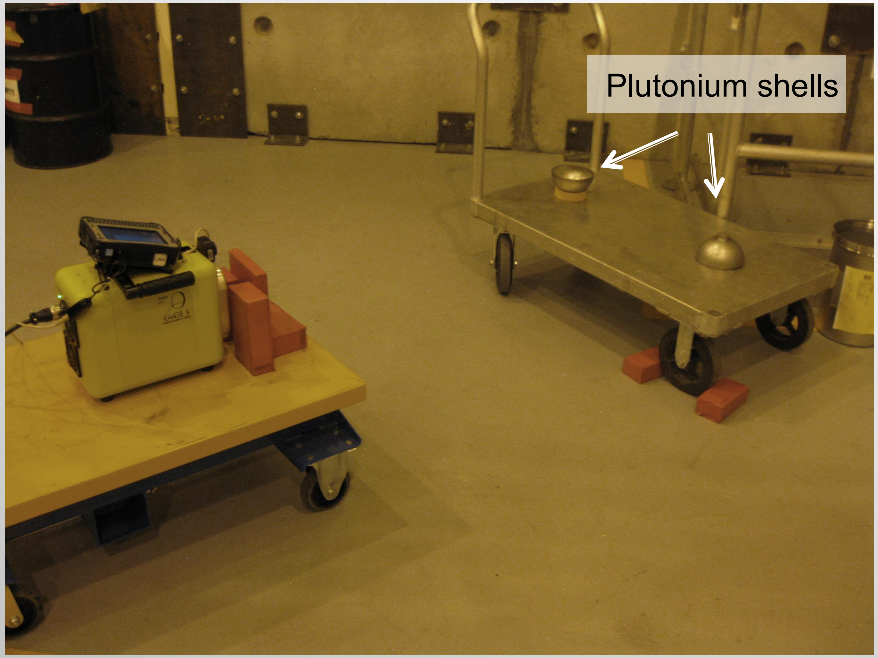
Most “Room Temperature” Units do NOT have the Resolution to Identify Many Complicated Isotopes

GeGI (**Ge**rmanium **G**amma-ray **I**mager)

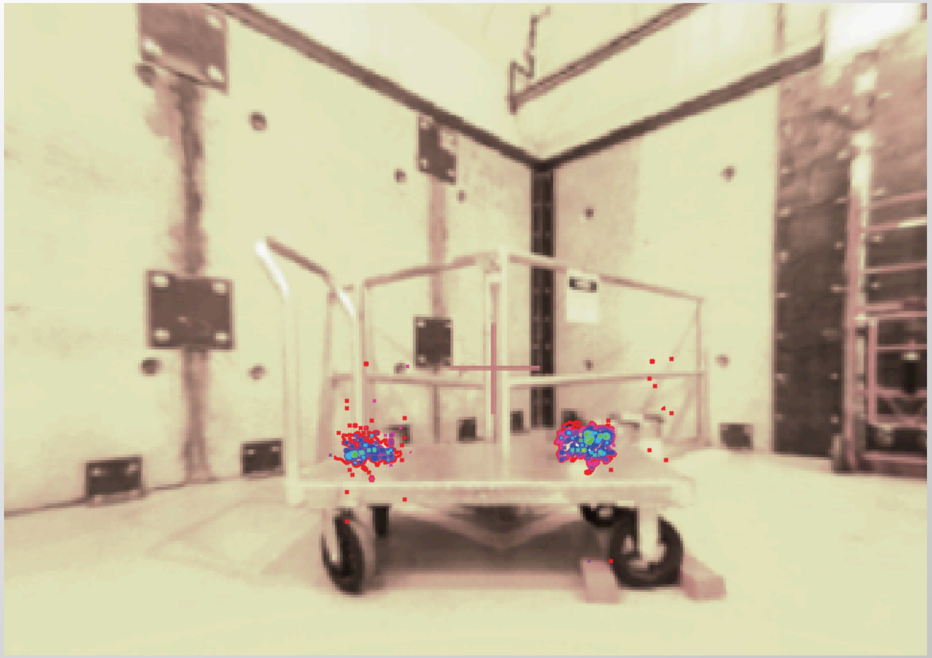
Specifications

- **Germanium crystal**: 9cm diam x 1 cm thick planar
- **Spectral resolution**: 2 keV at 1332 keV
- **Imaging accuracy:** ~3^{o}
- **Imaging resolution**: ~6^{o}
- **Cool-down time**: 5 hours
- **User interface**: notebook PC w/ Windows XP
- **Optical**: 180^{o} panoramic camera
- **Power**: AC power; internal battery (1 hour); external battery (3 hours per)
- **Weight**: 37 lbs

Pinhole Image of two Pu shells



Measurement setup: GeGI and two Pu shells at 1.5 meters



Pinhole overlay: photo taken with GeGI's onboard panoramic camera, overlaid with Pinhole image

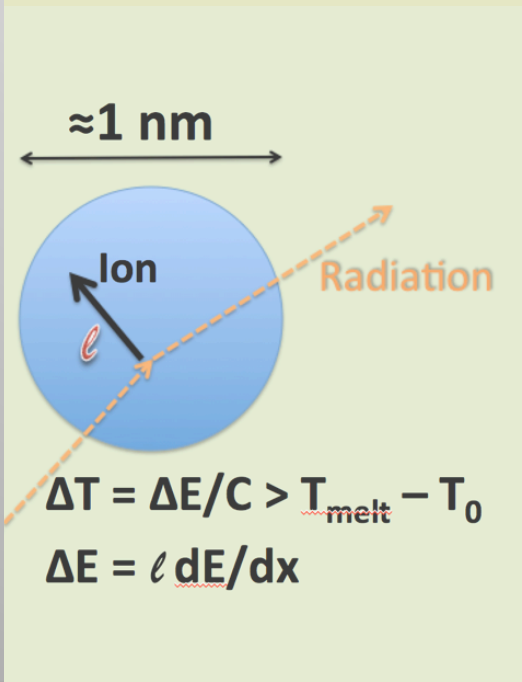
- Plutonium shells each contained ~200 grams of Pu
- Isotopic composition: 94% Pu-239 and 6% Pu-240
- Pinhole imaging was able to individually image multiple sources.

Nano-Thermite Detectors

- The new bubble-chamber detectors
- Thermites ignite above T~1000^{o}K
- Tune grain size to match ΔE deposit
- One grain explosion will induce others
- Under investigation for WIMP detection
- Lopez-Suarez, Univ. Mich. http://arxiv.org/abs/1403.8115

Nano-thermite example

- $Al_2 + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$ + 851.5 kJ/mole
- $\Delta T = \Delta E/c_n$, c_n = 1.5e-5 keV/K/nm^3
- for 1nm sphere, 1keV deposited $\rightarrow$ ΔT =1.6e4 ^oK



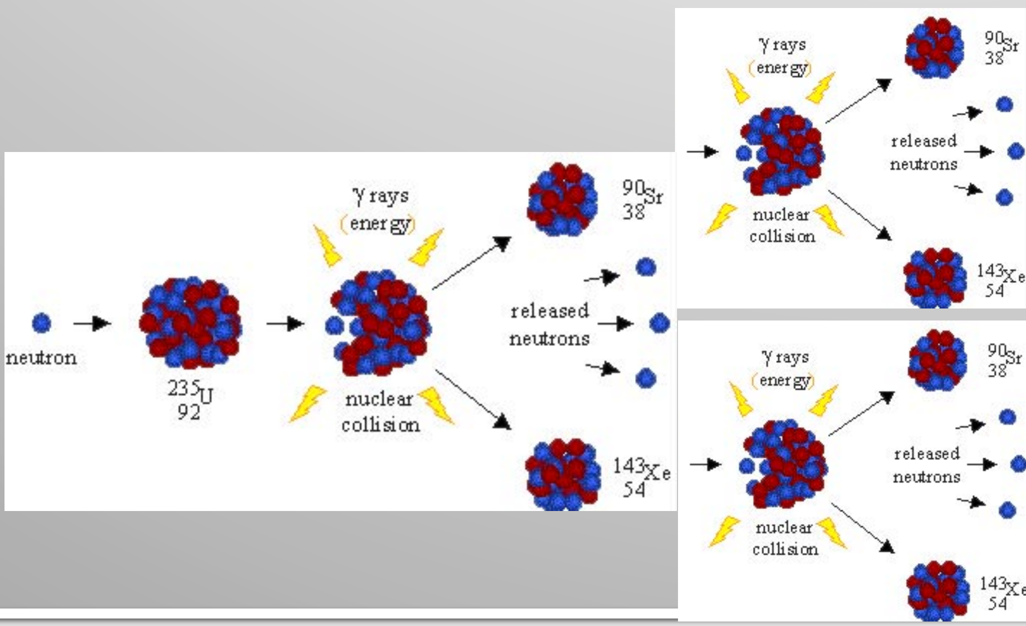
Also exploring possible applications for radiation detection

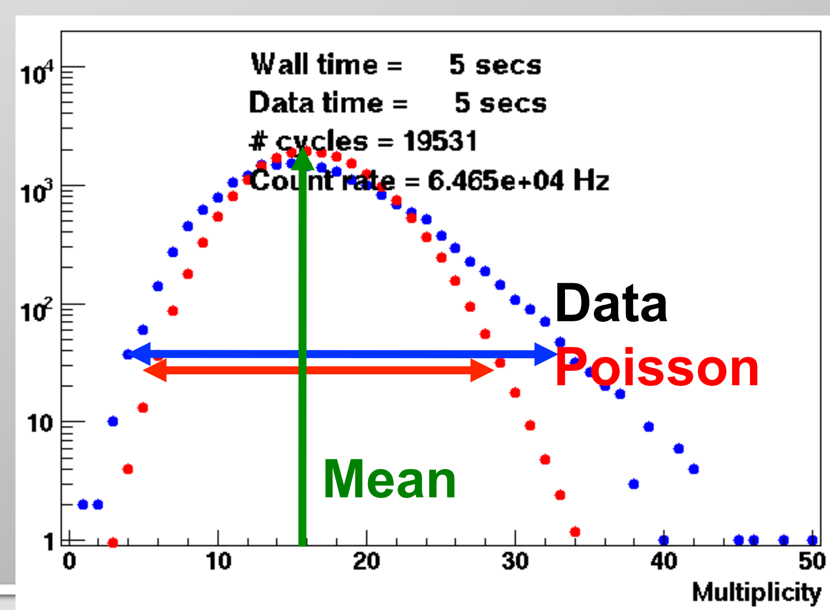
Counting Neutron Coincidences

Count neutron pairs within a time bin

- subtract random (Poisson) expectation
- divide by mean
- referred to as **Feynman Variance**

$$[\langle n(n-1)\rangle$$
$$- \langle n^2\rangle]$$
$$\div\langle n\rangle$$
$$= \mathbf{R2F}$$

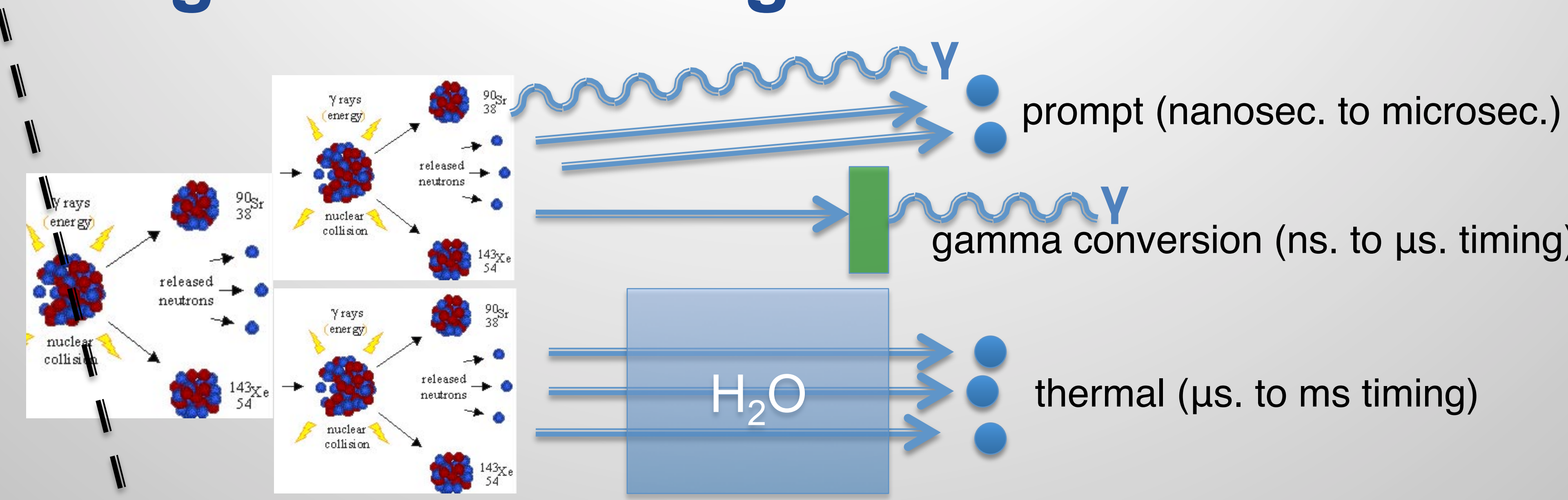


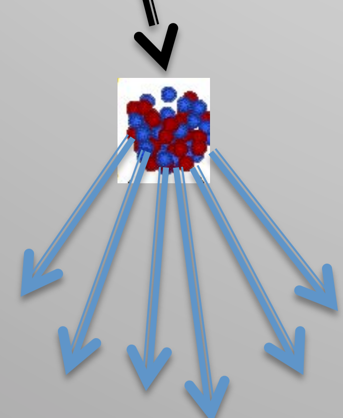


Neutron time correlations

- Return to idea developed by Feynman, extended by Prasad and Synderman
- Fission chains emit time-correlated neutrons
- Useful to measure object multiplication, but passive counting requires long integration time
- Explore photo-fission to boost production of time-correlated neutrons

Signals and Backgrounds





- n/γ scattering and conversions modify timing, but do not reduce signal
- random radiation from non-fissile sources is uncorrelated, does not contribute to signal
- Cosmic induced nuclear interactions

Conclusions

- Work in Nuclear Security remains challenging
- No silver bullet found, nor is one likely
- Achieving true nuclear security will require an array of approaches and coordination among departments and countries
- Detector R&D challenges have broad overlap with Nuclear Science needs