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Applications in Nuclear Non-proliferation

(and how radiation detection can help)

(especially radiation imaging)

(with neutrons?)

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Outline

1. Nuclear non-proliferation / nuclear security problem space
2. Radiation signatures
3. Radiation detectors/imagers
4. Examples: SNL neutron imaging systems

- NB: Acknowledged bias toward
  - Neutrons
  - Imaging
  - Arms control

EMB/SNL/NNSA/DOE

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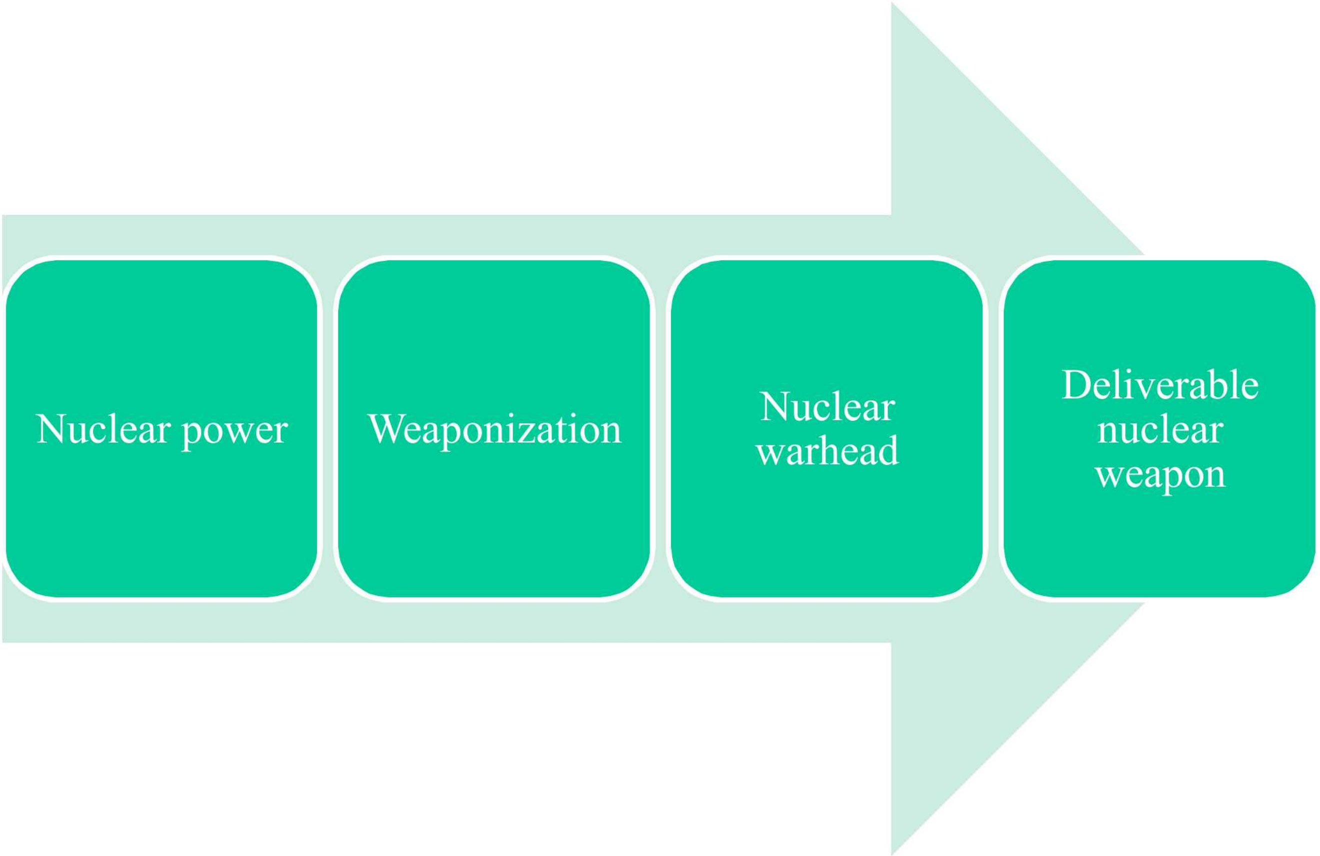
NNSA
National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

Nuclear non-proliferation problem space

Nuclear Proliferation



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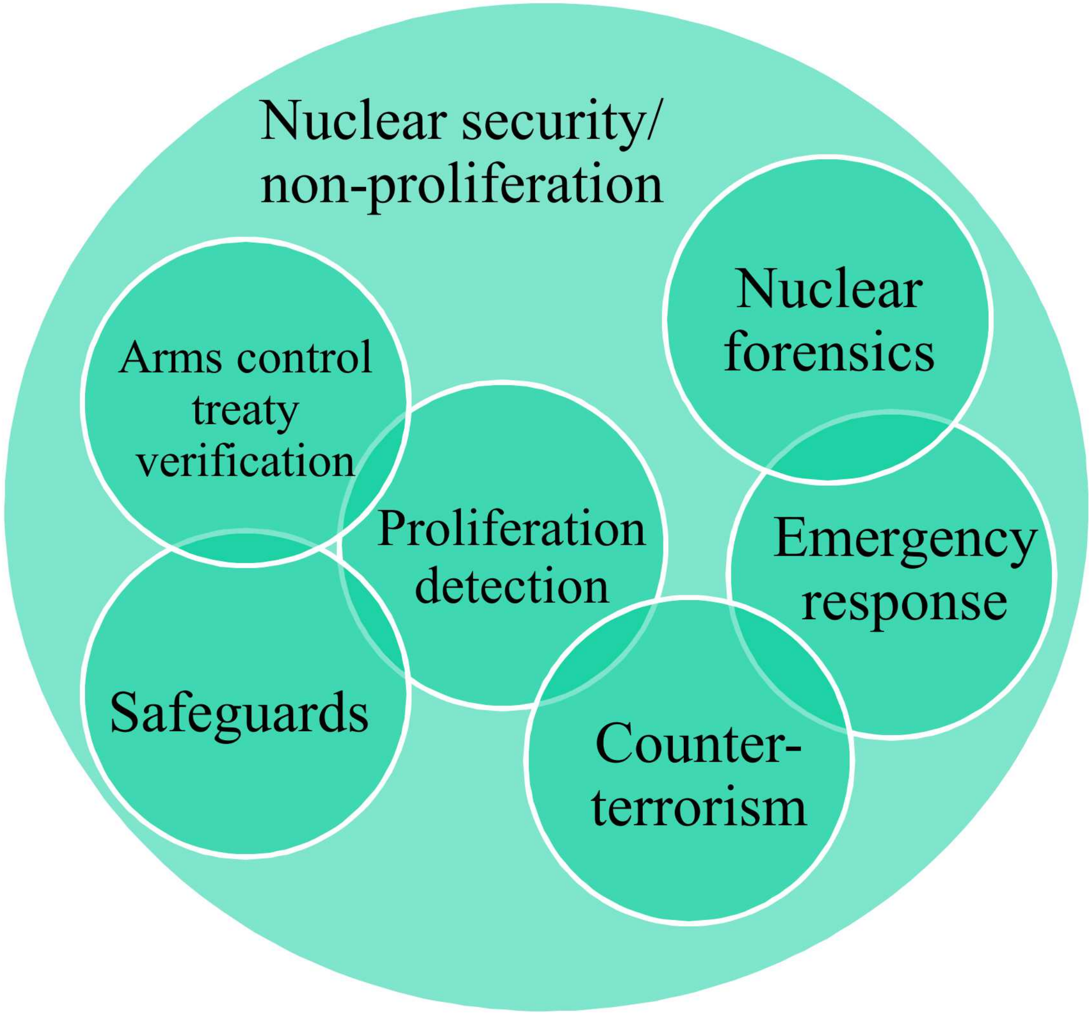
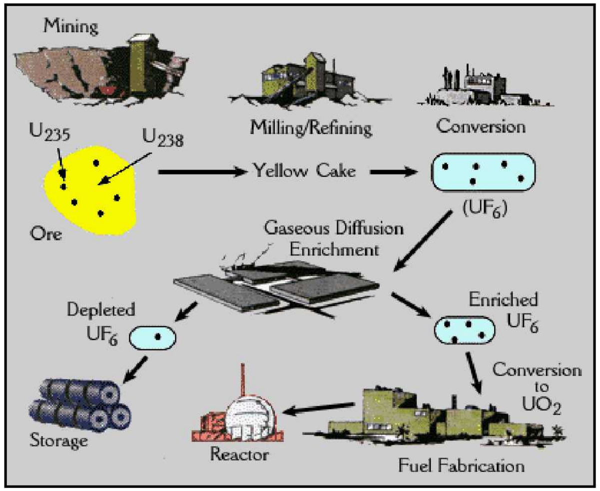
Some terminology



- Horizontal proliferation: new actors acquiring nuclear capabilities
- Vertical proliferation: existing NWS increasing nuclear capabilities
- Special nuclear material (SNM) is the common element.
  - Detect
  - Locate
  - Characterize
- Radiation detection can help!

Safeguards

- Nuclear power for peaceful use is acceptable under NPT
- Safeguards = monitor/verify that nuclear material is not diverted for weapon program
- Facilities, material balance
  - Enrichment
  - Power plants
  - Spent fuel
  - Reprocessing

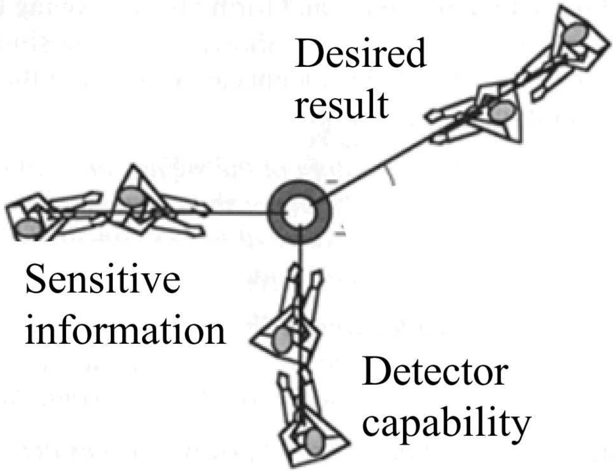


Proliferation Detection

- Detect/monitor state-level nuclear weapons programs
- Wide range of facilities & activities that could be relevant
  - Weaponization
  - Nuclear testing
  - Nuclear delivery systems

Arms control treaty verification

- **Treaty types**
- **Arms limitation/reduction treaty needs:**
  - Warhead counting
    - Verify declarations
  - Warhead confirmation
    - Verify it is a warhead
    - Verify warhead type
  - Chain of custody
    - Monitored storage
    - Spot check status
  - Dismantlement/disposition
    - Maintain perimeter
    - Track item through process



Three-way tug of war!

Counter-terrorism

- Non-state nuclear proliferation, theft, transport
- Material/device detection:
  - Urban search (backgrounds!)
  - Cargo screening
- Cargo screening
  - Extremely challenging problem!
    - Needle in a haystack
    - Flow of commerce
    - Potential for heavy shielding
    - Background variations
  - Primary screening, secondary, etc.

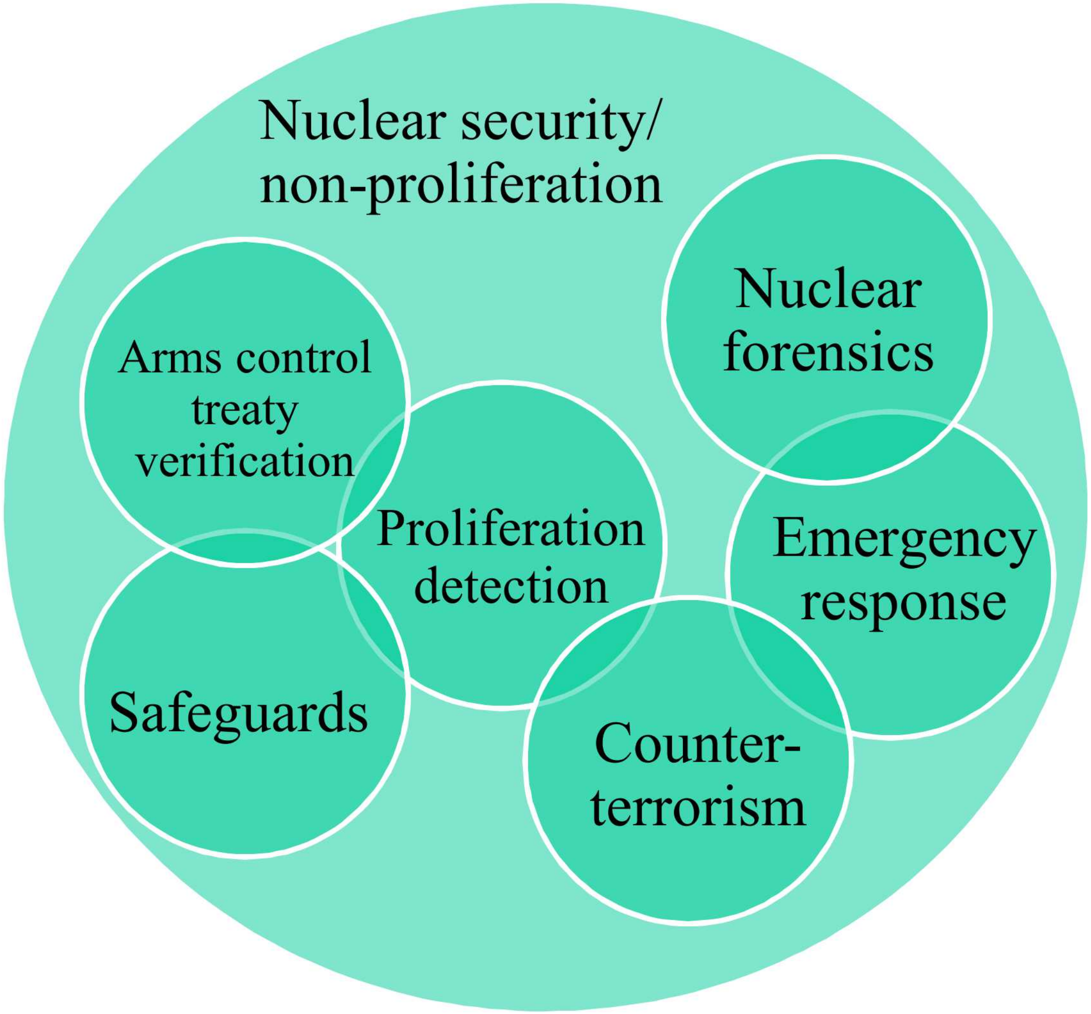
Emergency response

- Learn as much as possible, as quickly as possible, about a package containing SNM.
- All information is potentially useful.

Nuclear forensics

- After a nuclear detonation, what can we learn?
  - Attribution
  - Device design

Some terminology



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Radiation signatures for nuclear non-proliferation

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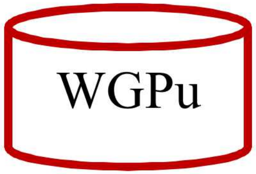
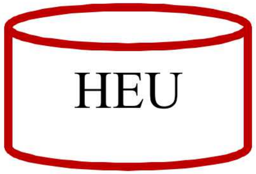
Special Nuclear Material





- What is it?
  - Plutonium, or
  - Uranium enriched in U-233 or U-235.
  - Sine qua non of a nuclear explosive.
- What does it look like?
  - Many different forms & colors.
- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
  - Only neutral particles (n,γ) useful in most cases

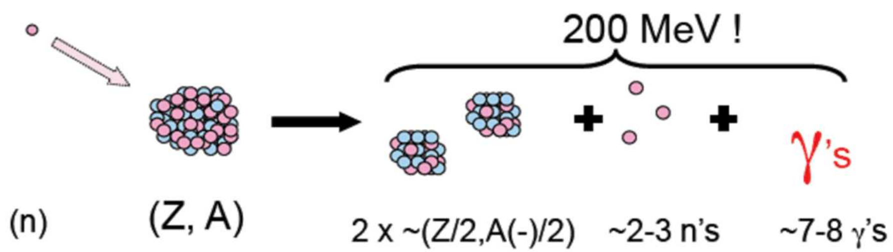
SNM radiation signatures

These physical processes…

- Spontaneous fission
- Induced fission
  - Self-interrogation
  - External interrogation
- Other radioactive decays
  - Gamma
  - (α,n)

… produce these signatures

- Gamma spectrum reflects isotopics
- Neutron fission spectrum
- Time correlations (multiplicity analysis)



Gamma signatures

The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	Mean Free Path (mm) (High-Z, ρ)	Mean Free Path (mm) (Low-Z, ρ)
^{234}U	120.9	9.35×10^{4}	0.23	69
^{235}U	143.8	8.40×10^{3}	0.36	73
	185.7	4.32×10^{4}	0.69	80
^{238}U	766.4	2.57×10^{1}	10.0	139
	1001.0	7.34×10^{1}	13.3	159
^{238}Pu	152.7	5.90×10^{6}	0.40	75
	766.4	1.387×10^{5}	9.5	139
^{239}Pu	129.3	1.436×10^{5}	0.27	71
	413.7	3.416×10^{4}	3.7	106
^{240}Pu	45.2	3.80×10^{6}	0.07	25
	160.3	3.37×10^{4}	0.45	76
	642.5	1.044×10^{3}	7.4	127
^{241}Pu	148.6	7.15×10^{6}	0.37	74
	208.0	2.041×10^{7}	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^{6}	0.26	70

These materials are dense; self-shielding is not negligible

Ref: "Panda Book"

Slide courtesy of David Chichester, INL

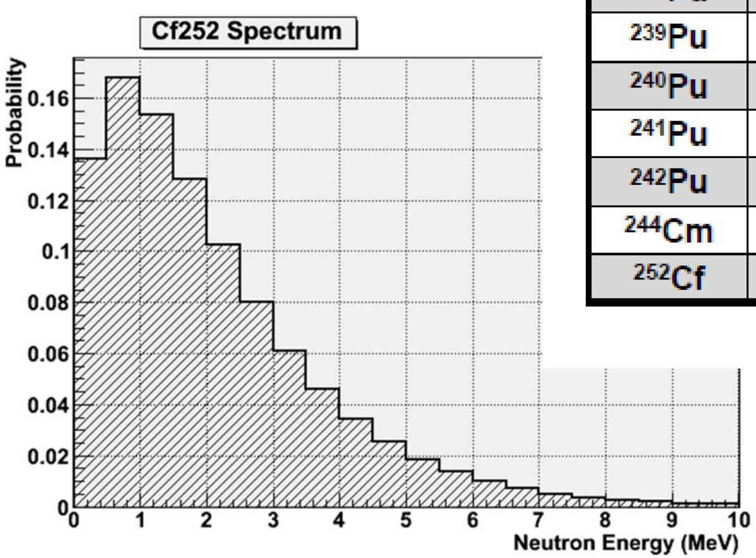
Neutron signatures

The Passive Neutron Signatures

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)	Spontaneous Fission Multiplicity ν	Induced Thermal Fission Multiplicity ν
^{232}U	71.7 yr	1,300	1.71	3.13
^{233}U	1.59×10^5 yr	0.86	1.76	2.4
^{234}U	2.45×10^5 yr	5.02	1.81	2.4
^{235}U	7.04×10^8 yr	0.299	1.86	2.41
^{236}U	2.34×10^6 yr	5.49	1.91	2.2
^{238}U	4.47×10^9 yr	13.6	2.01	2.3
^{237}Np	2.14×10^6 yr	0.114	2.05	2.70
^{238}Pu	87.7 yr	2.59×10^6	2.21	2.9
^{239}Pu	2.41×10^4 yr	21.8	2.16	2.88
^{240}Pu	6.56×10^3 yr	1.02×10^6	2.16	2.8
^{241}Pu	14.35 yr	50 ±	2.25	2.8
^{242}Pu	3.76×10^5 yr	1.72×10^6	2.15	2.81
^{244}Cm	18.1 yr	1.08×10^{10}	2.72	3.46
^{252}Cf	2.65 yr	2.34×10^{15}	3.757	4.06

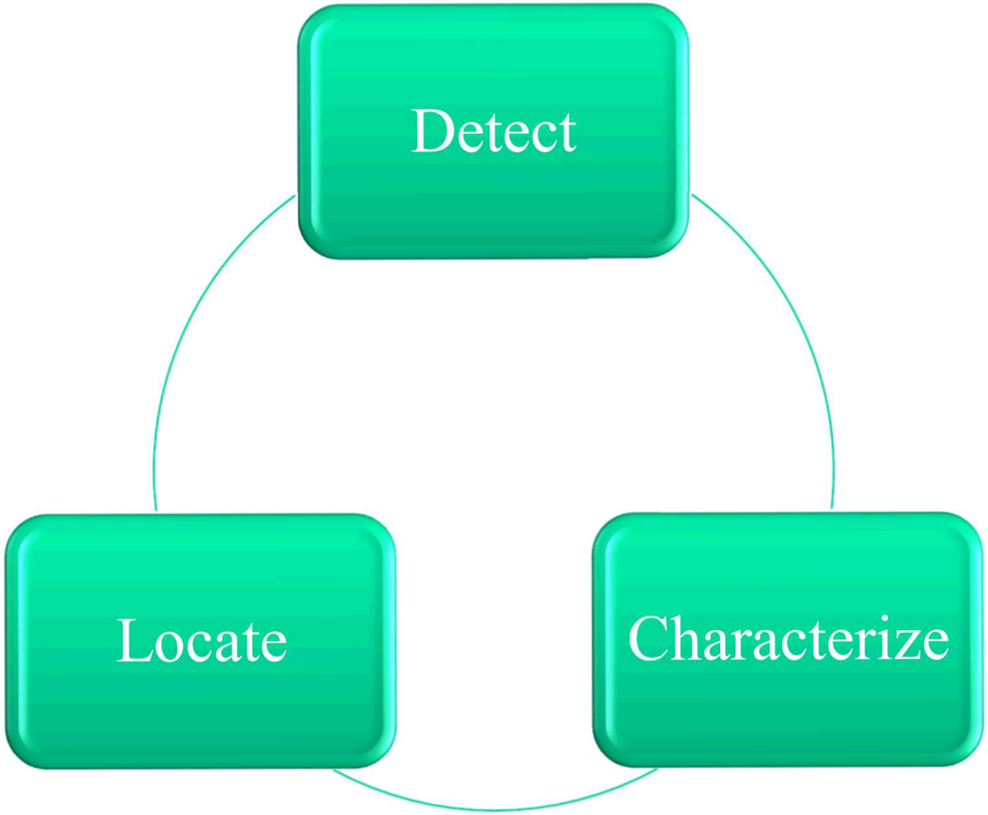
Ref: "Panda Book", values with ± have significant uncertainty

Table courtesy of David Chichester, INL



What about active signatures?

SNM tasks for rad detection



Rad detection for detecting SNM

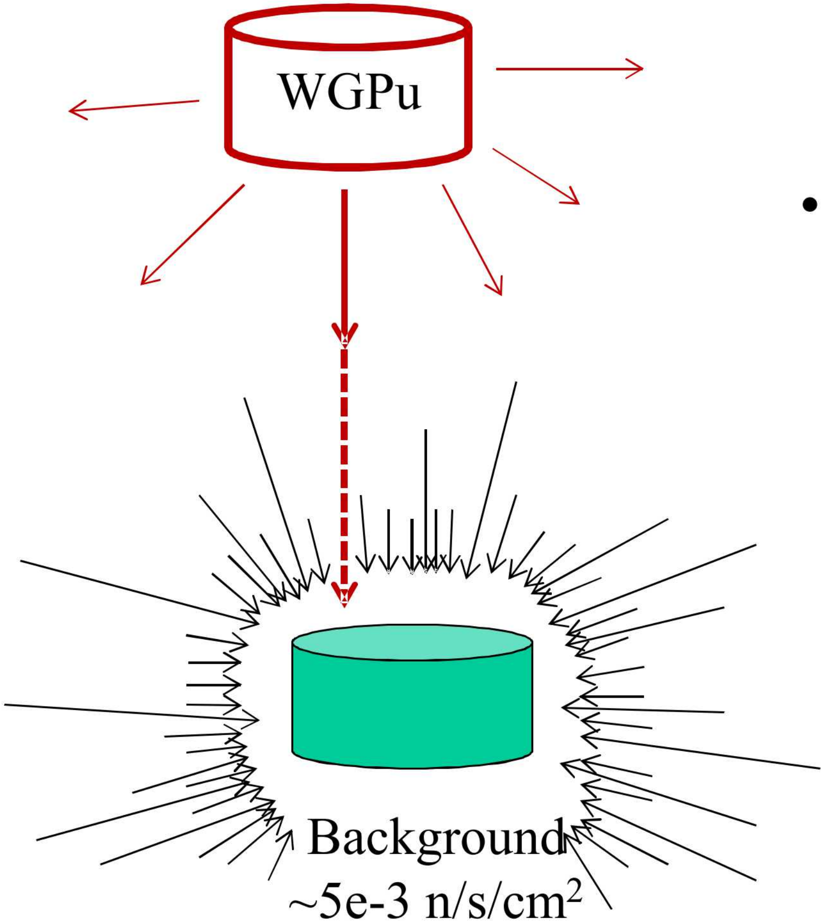
Notional scenarios:

- Sources indicate that a significant quantity of nuclear material is present in X neighborhood. Find it or provide all clear.
- Radiographic/active interrogation of rail cargo: scan rates of 8 to 24 km/h, scan lengths over one kilometer, and a penetration depth of 90 cm of steel

- By definition, interesting/difficult cases have low S:B.
- Active interrogation can increase signal at cost of more/different background
- Radiation detection needs:
  - High efficiency
  - Scalability
  - S:B discrimination

Standoff detection

~5.5e4 n/s/kg
IAEA sig = 8 kg



- Example: Large stand-off application (100 meters)
  - 8 kg WGPu = ~4.4e5 n/s → 4.4e5 *exp(-R/100)/4πR^2 ≈**1.3 n/s/m^2**
  - Background = ~**50 n/s/m^2** (at sea level)
  - 100% efficient, 1 m^2 detector → 5σ detection in **~13 minutes**
  - 10% efficient, 1 m^2 detector → 5σ detection in **~2 hours**
  - 10% efficient, 1 m^2 detector, 3% bg rate systematic → 5σ detection in **never**

Rad detection for locating SNM

Notional scenarios:

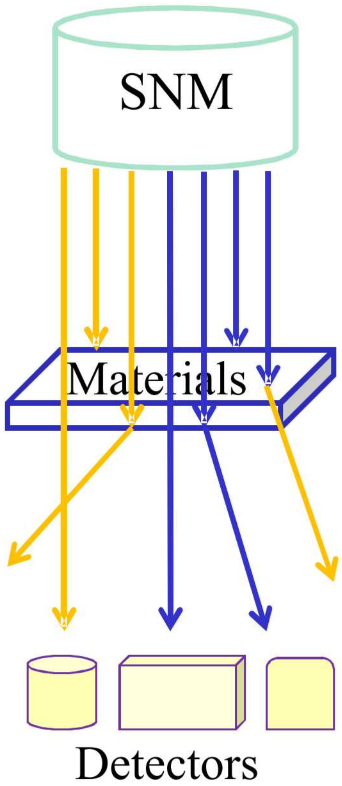
- Nuclear material is present in building X. Determine which floor/apartment.
- Count number of nuclear warheads on an ICBM without visual access.

- Radiation detection needs:
  - Directional information
  - Field of view depends on specific application

Rad detection for characterizing SNM

Signatures (physics)

- **SNM emits** γ, n radiation
  - {Spectrum, rate, vector field, correlations} determined by {SNM mass, isotopics, configuration}
- **Surrounding material** attenuates, scatters, modifies signature
- **Interactions** between SNM, surroundings



Detectors (technology)

- Typically optimized for measuring one aspect of the radiation signature, e.g.
  - Gamma spectrum → good energy resolution
  - Neutron timing correlations → Large effective area for n detection
  - SNM configuration → position, direction resolution
  - Low-rate processes → active stimulation

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Neutrinos

- Non-proliferation application of neutrino detection is to monitor or discover nuclear reactors.
  - Neutrino presence determines reactor on/off status
  - Neutrino spectrum sensitive to diversion (Pu/U ratio)
  - Neutrino direction improves detectability of weak sources relative to background
- Detection concepts not different from reactor neutrino physics experiments.
  - For ease of deployment, high desire for above-ground detection system → need exquisite background rejection.

Detect, Characterize

Radiation detectors for nuclear non-proliferation

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Signatures/detectors

- 0.1 MeV – 10 MeV gammas
  - High natural backgrounds, many NORM sources
  - Shielded by high-Z materials
  - Energy resolution key to determine isotopics
- 0.1 MeV – 10 MeV neutrons
  - Low natural backgrounds, few benign sources
  - Shielded by low-Z materials
  - Weak spectral information
  - Direct access to fission process: time correlations
- Directional information improves S:B, locates sources, measures spatial configuration of material
- Active interrogation, radiography are wild cards

Signatures/technologies

0.1 MeV – 10 MeV gammas • High natural backgrounds, many NORM sources • Shielded by high-Z materials • Energy resolution key to determine isotopics	• Plastic scintillator/PMT • Inorganic scintillators/PMT (NaI, CsI) • Semiconductors (HPGe, CZT) • Shaping/MCA electronics
0.1 MeV – 10 MeV neutrons • Low natural backgrounds, few benign sources • Shielded by low-Z materials • Weak spectral information • Direct access to fission process: time correlations	• Thermal neutron detectors (He-3 tubes) • Organic scintillators/PMT (plastic, liquid, crystalline) • Pulse height/shape discrimination • Multiplicity analysis
Directional information improves S:B, locates sources, measures spatial configuration of material	• More complex systems—high channel counts, calibrations, data processing, analysis, image reconstruction
Active interrogation, radiography are wild cards	• Gamma sources • Neutron sources

Radioisotope Identification Detectors (RIIDs)

- **RIIDs** are small radiation detectors that can be handheld, or transported in a bag or backpack.
  - Can identify gamma emitting radionuclides
  - Battery Powered
  - Built in spectral analysis software
  - GM tubes to indicate if the user is approaching a high radiation field
  - Visual and audible indicators
  - Operated in different modes: search, survey, ID, etc.

What are other fielded rad detectors?

SNL neutron imaging systems

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SNM detection/imaging

We develop systems for eventual application in a range of scenarios:

Standoff detection

Cargo screening

Arms control treaty verification

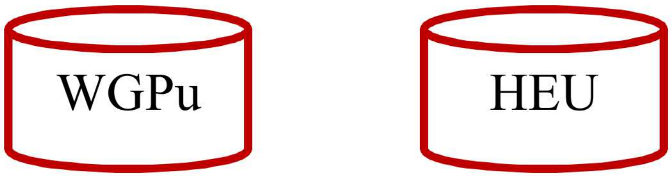
Emergency response

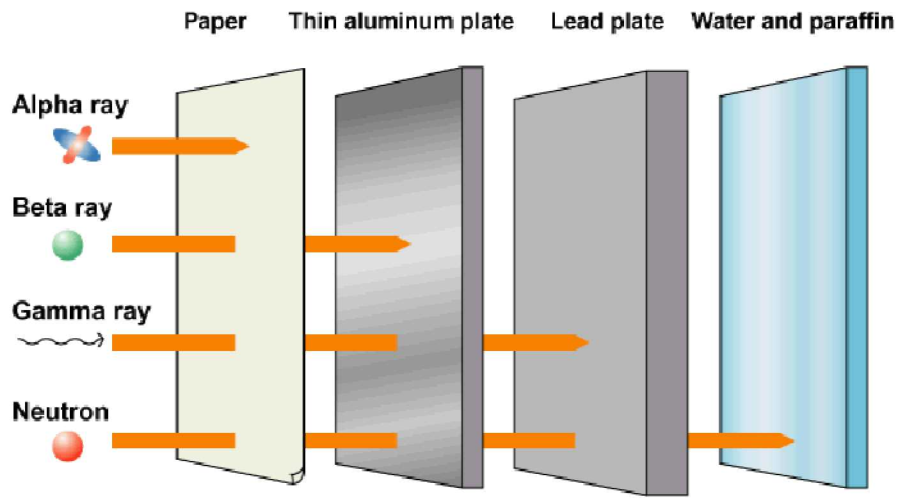
SNM detection applications
- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

SNM imaging applications
- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

Why neutrons?

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.
- Neutrons are more specific:
  - Lower natural backgrounds
  - Fewer benign neutron emitters

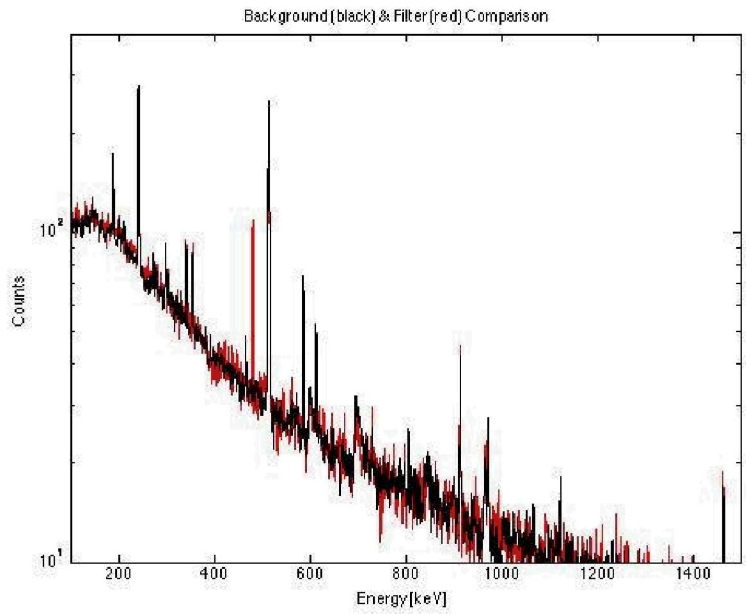




www.remnet.jp

Why imaging?

- Analogy to information from gamma spectrum.
  - Estimate background (systematic).
  - Ignore most background (statistical).



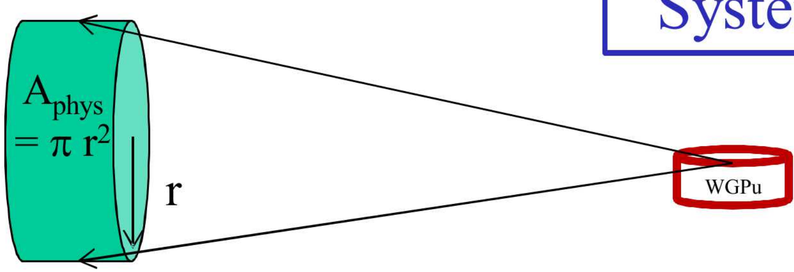
- Need imaging?
  - Imaging applications: **Yes**
    - ER diagnostics, AC
  - Localization: **Yes**
    - Direction to detected source
  - Detection, background unknown: **Probably**
    - Long-dwell standoff detection
  - Detection, background known: **Need very high quality imager**
    - Portal monitor, building monitoring

Fast neutron directional detectors

Common features

- N-P elastic scattering
- Sensitivity to direction
  - Event by event (kinematics)
  - Statistical (many events form a pattern)
- Liquid scintillator based.
  - Gamma discrimination
- Shielding is hydrogenous material.

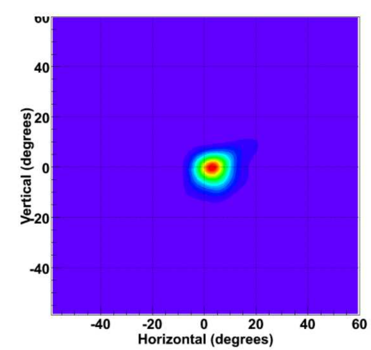
System attributes



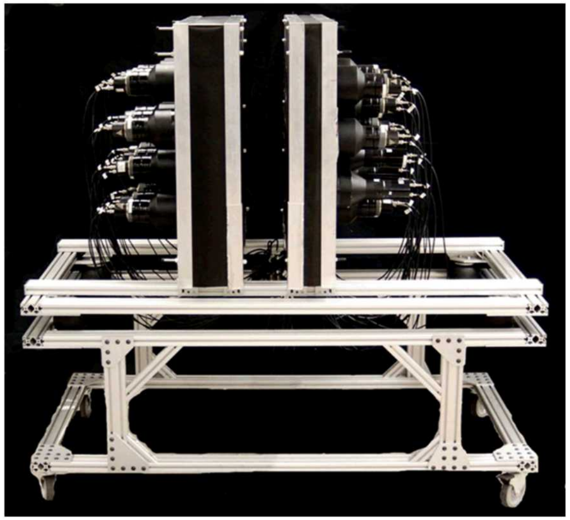
- ***Effective area***: area over which the detector would be 100% efficient.
  - Physical cross-sectional area times the detection efficiency.

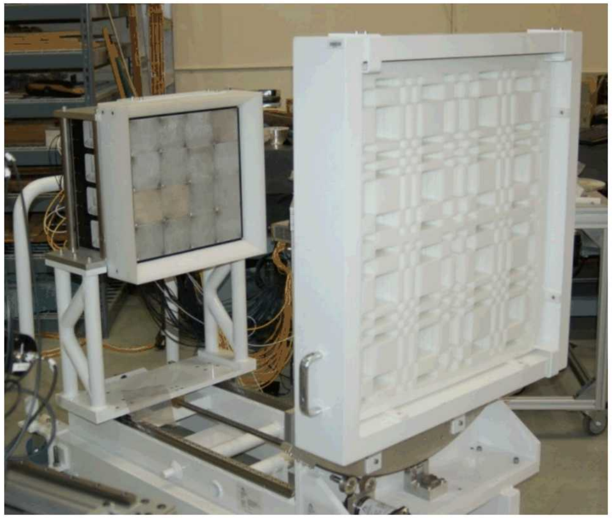
$$A_{eff} = A_{phys} * \varepsilon$$

- ***System angular resolution***: resolution of the reconstructed image in the far field.
- ***Event angular resolution:*** resolution on the direction of a single event.



Fast neutron imagers @ SNL/CA

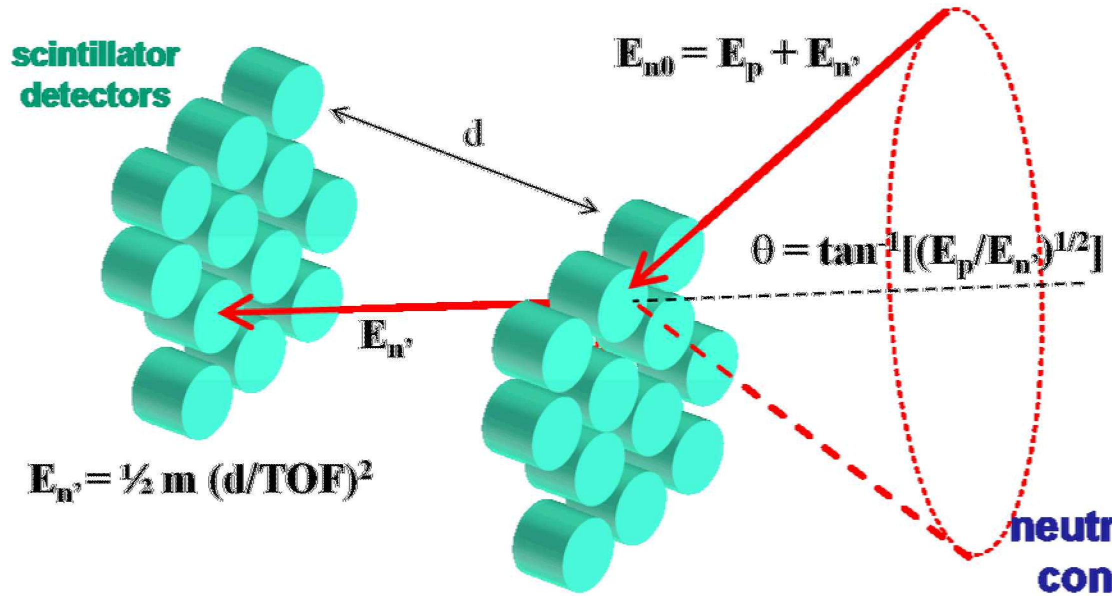




Neutron scatter camera

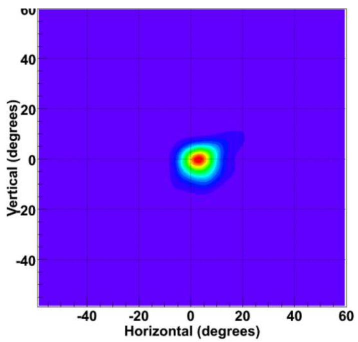
- Fast neutron imaging spectrometer
- Variable plane separation allows tradeoff of effective area, image resolution

Fast neutron directions and energies constrained by double scatter geometry



Multimode capability includes

- ***Neutron energy spectrum.***
- ***Compton imaging.***



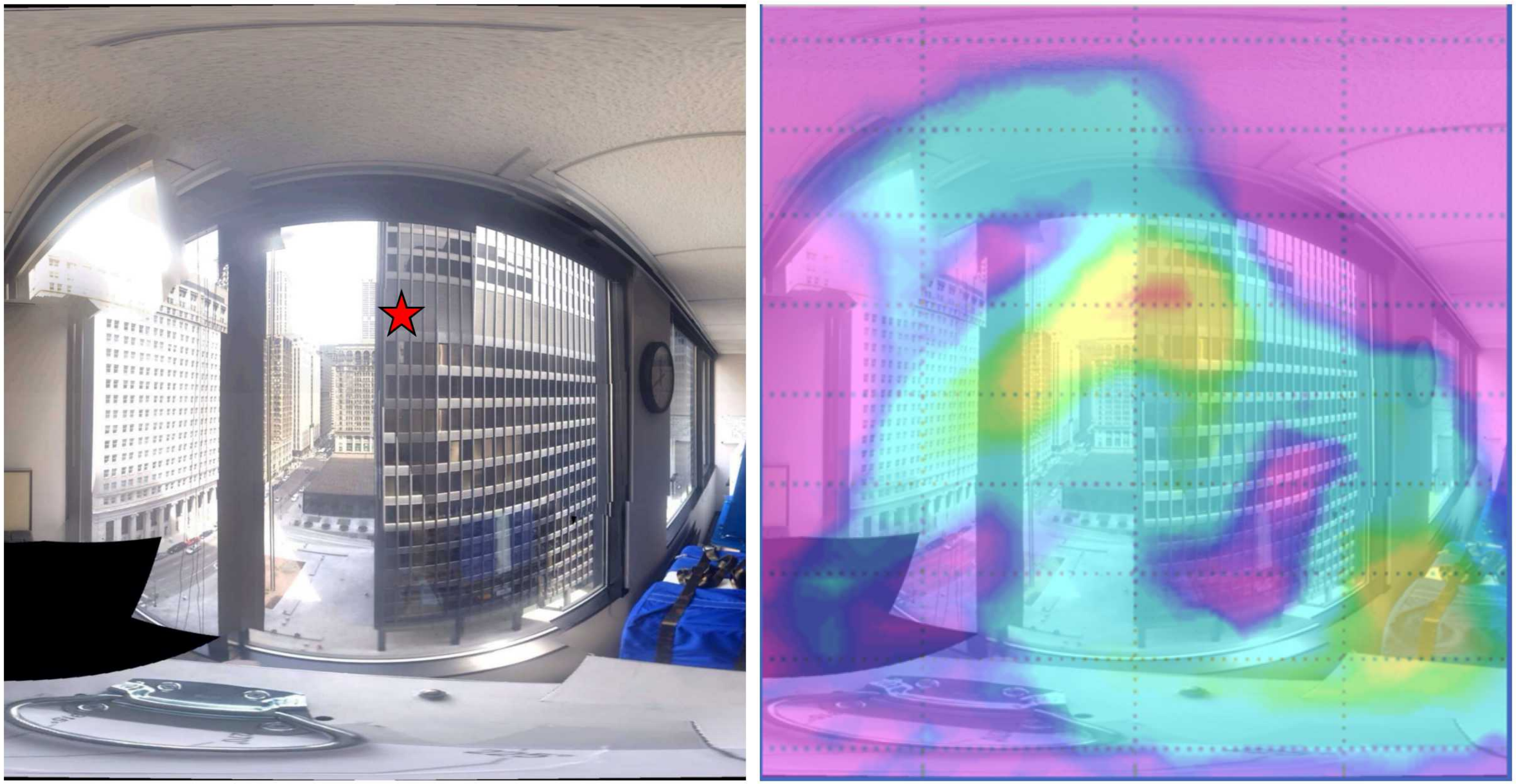
An MLEM-reconstructed neutron point source image.

Detect, Locate, Characterize

Neutron scatter camera

- Advantages:
  - Mature, proven detector system.
  - Excellent energy resolution.
  - Good event angular resolution.
  - Large LS volume for singles.
- Disadvantages:
  - Average system angular resolution.
  - Very low efficiency (double scatters).
- Potential use:
  - Neutron spectroscopy.
  - High background, low S:B environment.

MINER: Building to Building Imaging



Left: source location (red star) in adjacent high-rise (28 m distance).

Right: neutron image overlaid on photograph

Detect, Locate

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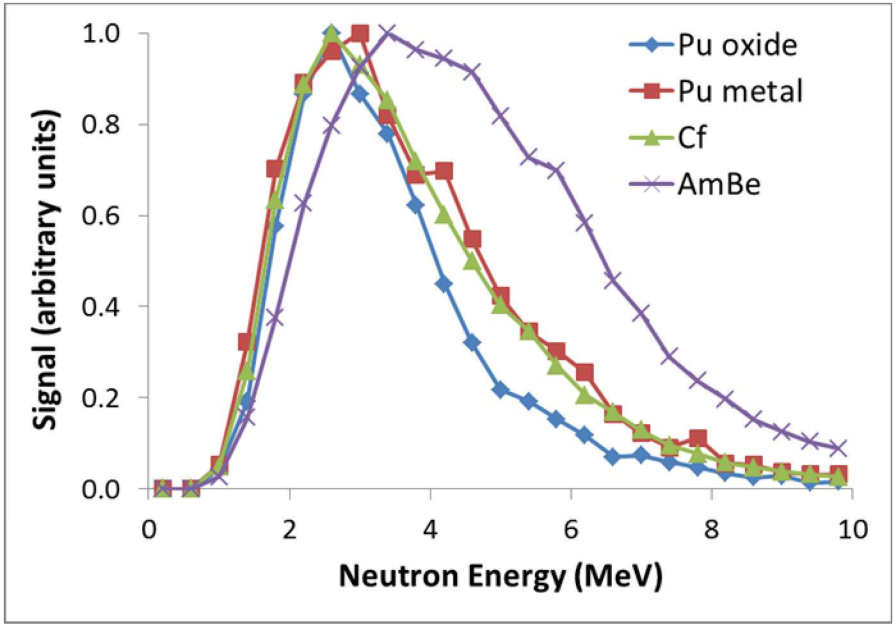
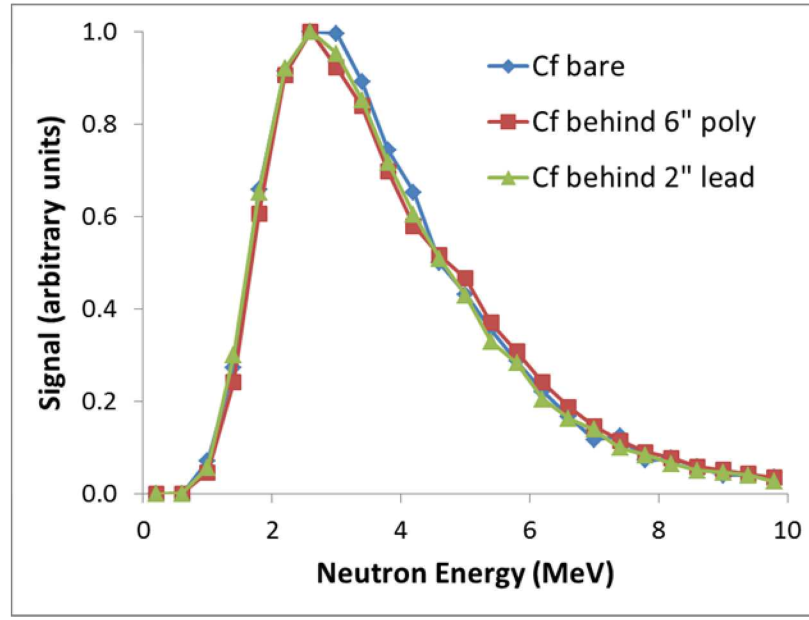
MINER: Neutron Spectroscopy



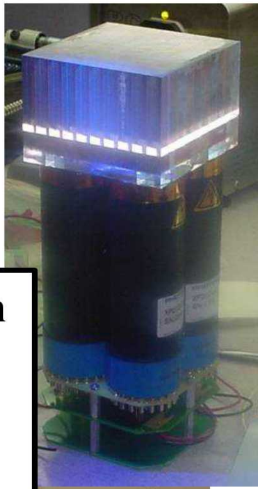


Left – peak-normalized spectra as measured using MINER. Right – insensitivity of Cf spectrum to intervening material as measured by MINER.

Characterize

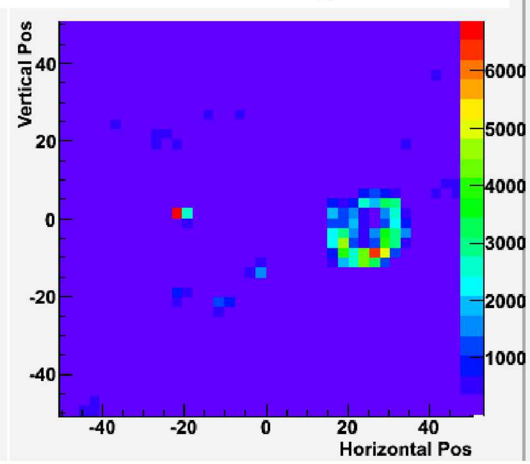
Neutron coded aperture imager

- Extension of pinhole with much higher effective area: signal modulated in unique 2-d patterns.
- ORNL/SNL fast neutron coded aperture imager being developed for arms control treaty verification.
- Image plane consists of 16 liquid organic scintillator pixilated block detectors
  - Each block consists of a 10x10 array of 1 cm. pixels.
  - PSD and pixel id accomplished by 4 photomultiplier tubes.
- Mask plane consists of 2.5 to 10 centimeters of HDPE.

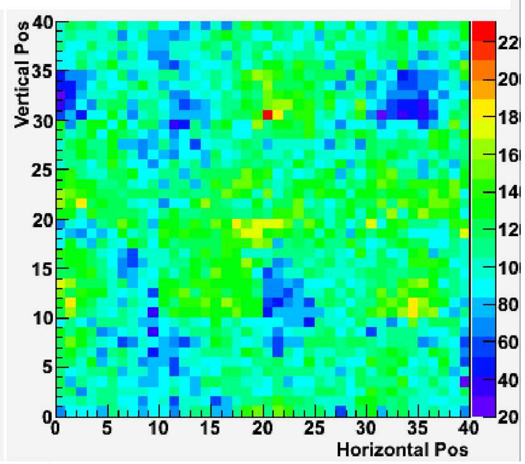


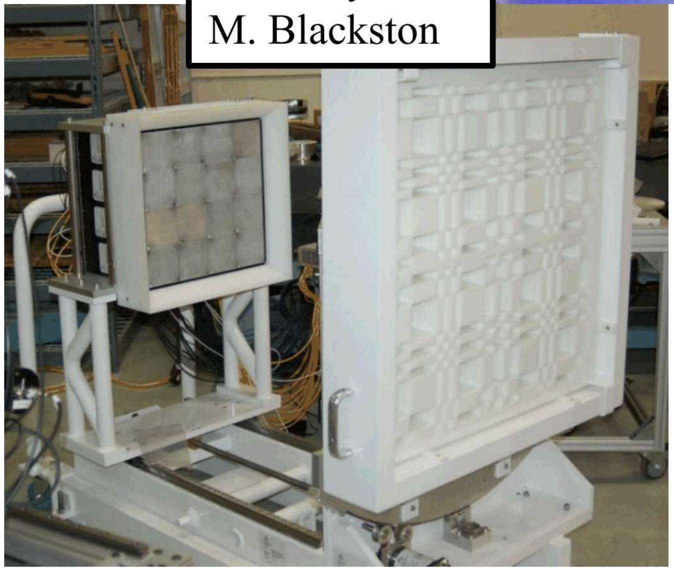
Collaboration with ORNL:
P. Hausladen
J. Newby
M. Blackston

Reconstructed image



Raw counts





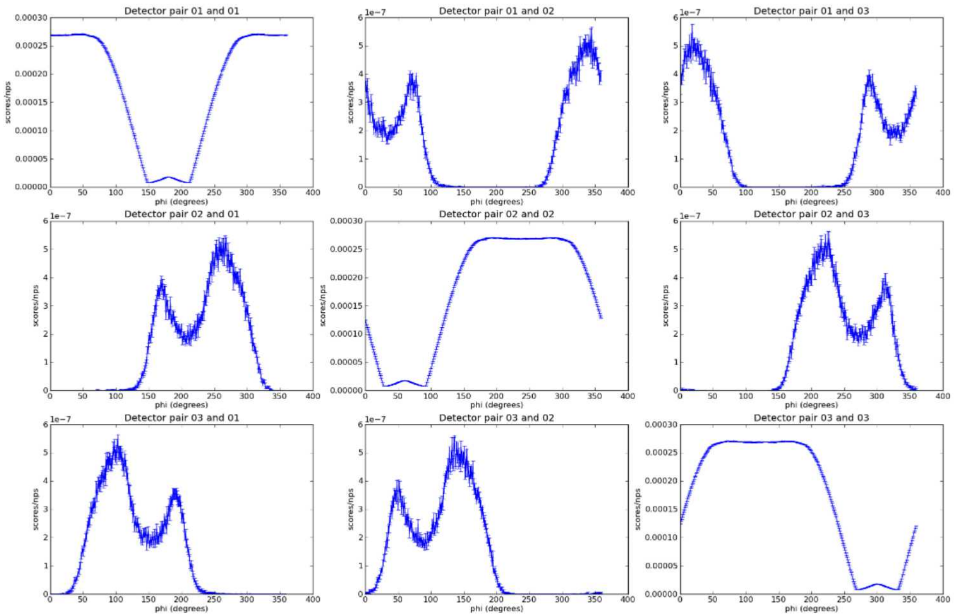
Locate, Characterize

Neutron coded aperture imager

- Advantages:
  - Excellent system angular resolution.
  - Good detection efficiency.
- Disadvantages:
  - Poor event angular resolution.
  - Complex detectors.
  - Performance degrades with multiple/extended sources.
- Potential use:
  - High-resolution, good S:B applications: arms control treaty verification, emergency response.

Rotational Self Modulation

PRISM



Response map vs rotation angle for a fixed source location

Detect, Locate

- More compact and more easily scalable at the cost of lower S/N

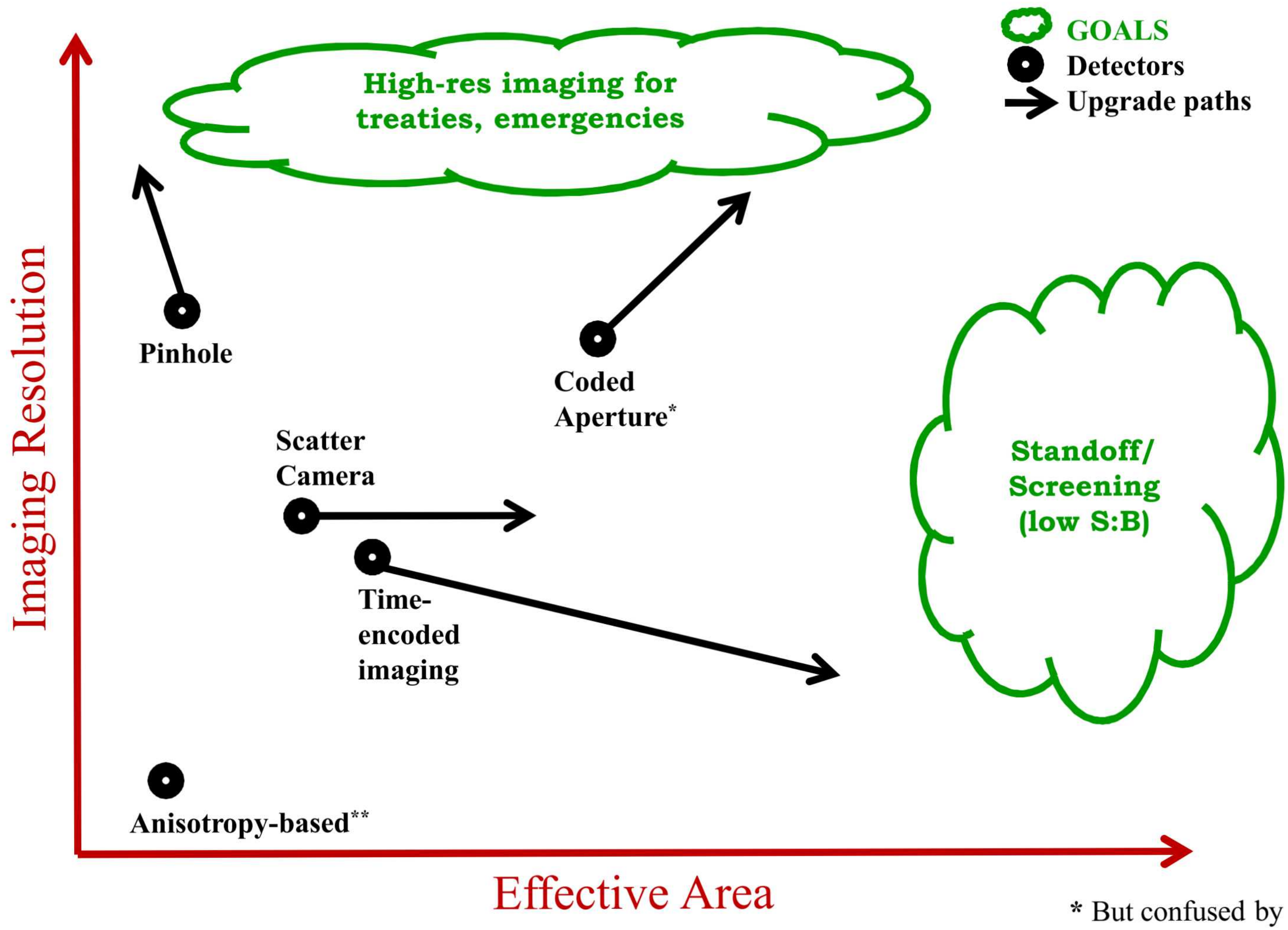
PRISM

- Advantages:
  - Scalable to large effective area at low cost.
  - Simple detector system.
- Disadvantages:
  - Low event and system angular resolution.
  - Poor energy resolution.
- Potential use:
  - Weak source detection with low S:B.

Conclusions

- Overview of non-proliferation application space
  - Safeguards, proliferation detection, counter-terrorism, emergency response, arms control treaty verification
  - Detect, locate, characterize SNM
- Radiation signatures for non-proliferation
  - 1-10 MeV gammas, neutrons
  - Counting, energy spectrum, imaging
- Radiation detectors/imagers for non-proliferation
  - Most valuable detectors are tailored to the application
  - Tradeoffs unavoidable; optimize carefully

The neutron imager zoo



* But confused by multiple/extended sources
** But compact