Fission Energy Neutron Imagers for Weak Source Detection

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Introduction

Standoff detection

Cargo Screening

SNM detection applications

- **Low signal rate**
  - Need large area detectors!
- **Low signal to background**
  - Need background discrimination!

Many applications in nuclear security fall under the general category of weak source detection, where a localized radiation source may or may not be present in some more diffuse background. Examples of such applications are large-area SNM search, where the signal may be weak due to distance from the detector, and cargo screening, where shielding and other cargo material may attenuate the signal.

Fast neutron imaging detector systems are well suited for the weak source SNM detection problem, due to the low natural neutron backgrounds, the relative paucity of benign neutron sources, and the ability to enhance signal significance using directional information.

We compare two fission-energy neutron imagers, the neutron scatter camera (NSC) and the portable rotational imager with self-modulation (PRISM) in terms of their suitability for weak source detection applications.

Example: Standoff Detection

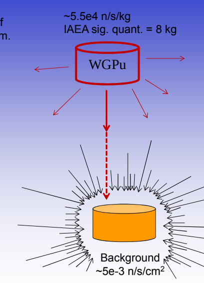
As an example, consider the problem of detection of an IAEA significant quantity (8 kg) of WGPu at 100 m.

- Neutrons emitted: **~4.4e5 n/s**
- Source neutrons reaching detector: **~1.3 n/s/m²**
  - Assumes 100 m attenuation length in air
- Background: **~50 n/s/m²**
  - At sea level

Clearly a large detector is needed for detection in reasonable times!

For a large counting detector with **1 m²** area:

- If 100% efficient + perfect bg estimate
  - 5σ detection in **~13 min**
- If 10% efficient + perfect bg estimate
  - 5σ detection in **~2 hr**
- If 100% efficient + 3% bg rate uncertainty
  - 5σ detection in **never**

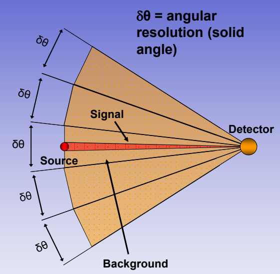


Fast neutron imaging for SNM detection

Weak source detection of special nuclear material is characterized by two features: low signal rates and low signal-to-background ratios (statistically **and** systematically speaking). Fission-energy neutrons are a prime signature for passive (or active) detection of special nuclear material (SNM), since natural cosmogenic backgrounds are low and there are few benign neutron-emitting sources. However, neutrons as a signature of SNM present certain challenges. One of these is the spectral similarity between sources of interest and typical backgrounds, which in contrast to gamma systems makes neutron energy measurements of limited utility in background discrimination. In order to improve signal-to-background metrics, therefore, we focus on directional information to isolate the SNM.

WHY FAST NEUTRON IMAGING?

- **Special nuclear material emits ionizing radiation.**
  - Sensitive and specific signature
- **Only neutral particles penetrate shielding.**
- **Neutrons are most specific:**
  - Lower natural backgrounds
  - Fewer benign neutron emitters
- **Fast neutrons likely have not scattered—retain directional history.**
- **Shielding turns fast neutrons into thermal neutrons—but also absorbs thermal neutrons.**
- **Directional information helps:**
  - Distinguish signal from background—isolate a point source.
  - Determine location of one or more point sources.



KEY CONSIDERATIONS

- **Scalability/size**
  - For interesting problems, must scale to O(1 m²).
- **Interaction length/cross-sections**
  - Reasonable efficiency dictates thickness of active medium and shielding > 2".
- **Robustness/fieldability**
  - Temperature sensitivity
  - Calibration issues

KEY METRICS

- ***Effective area***: area over which the detector would be 100% efficient.
- ***System angular resolution***: resolution of the reconstructed image in the far field.
- ***Event angular resolution:*** resolution on the direction of a single event.

Hypothesis test

In detection applications, the desired output is an alarm decision, not an image per se. Imaging can in fact be counter-productive, since it necessarily introduces noise and enhances statistical and systematic variations in the data. A more appropriate approach is task-based imaging, where the data as detected is mined for answers to specific questions. The hypothesis test is one task-based technique, developed to optimally detect the presence of a point source in a background field.

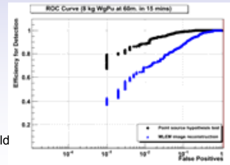
- **Theory:**
- **If signal and background behavior are known, the likelihood ratio is a sensitive test statistic to distinguish between them.**
- **By definition, encodes probability of statistical fluctuations.**
- **Systematic uncertainties can be accounted for as nuisance parameters.**
  - Integrate over them: Bayesian.
  - Fit for most likely (given constraints): Frequentist.

- **Procedure:**
- **Loop over possible point source locations (in field of view).**
- **For each source position, find LLR = Δ(ln L) between b-only and s+b hypotheses.**
  - Signal strength is unknown, so maximize LLR over signal fraction f:
  - $LLR = \max_f(\ln L(\text{data}|n_s=fN) - \ln L(\text{data}|n_s=0))$.
- **The largest LLR obtained from any potential source position is the test statistic.**
  - Effectively profile likelihood over source position, strength.

$$LLR = \ln \frac{L(\text{data} \mid s+b)}{L(\text{data} \mid b)}$$

Above: Log likelihood ratio to directly test consistency with a given signal hypothesis.

Right: ROC curve showing enhanced sensitivity using hypothesis test vs a threshold on the max bin content in an MLEM image.



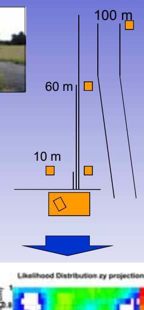
Neutron Scatter Camera

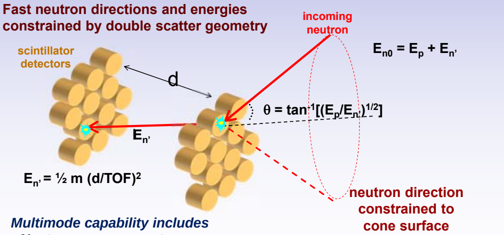
The neutron scatter camera (NSC) is a high-sensitivity fast neutron imaging spectrometer. The current instrument is a 32-element system utilizing liquid scintillator (EJ-309) in two planes of 16 cells each. The front plane cells are 13 cm dia. x 5 cm thick cylindrical cells while the rear cells are 13 cm thick. The liquid scintillator lends itself well to neutron-gamma discrimination and the two planes are mounted on a moveable track to provide a method of adjusting sensitivity and resolution. Source imaging and spectroscopy is performed using fast neutrons scattering elastically in the front and rear planes.

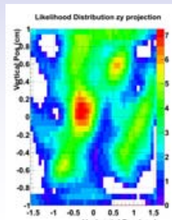
Neutron Scatter Camera

Field tests:

- **Cf-252 source at 10 m, 60 m, 100 m.**
- **~60 hr exposures @ 60 m, 100 m**





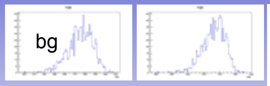


Multimode capability includes
- ***Neutron energy spectrum.***
- ***Compton imaging.***

POOR EFFECTIVE AREA, GOOD EVENT ANGULAR RESOLUTION.

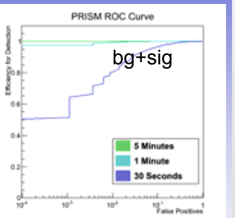
Time-Encoded Imaging: PRISM

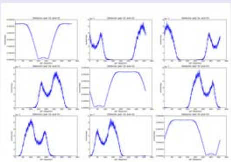
Time-encoding imagers (TEI) are a class of imagers based on the concept of modulating the neutron signal in time, and decoding the time modulations to determine the presence and location of a source in space. We have built two such systems, both of which are one-dimensional "images" intended primarily for high-sensitivity source detection. In one case, passive HDPE mask bars in a modified uniformly redundant array pattern rotate around a single central detector, providing the signal modulation. In the other case, several large detectors rotate around a common axis, each detector modulating the signal reaching the others.



Laboratory tests:

- **14.6 μCi Cf-252 @ 5 m.**
- **Single instrumented channel.**
- **Large datasets with/without source → build ROC curves.**
- **Hypothesis test; shape analysis only.**





VERY LARGE EFFECTIVE AREA; POOR EVENT & SYSTEM ANGULAR RESOLUTION

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