Fast Neutron Resonance Radiography for Explosives Detection

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Outline

- NRR technique
- NRR prototype
- Experimental results from elemental calibration and elemental mapping
- Applications

Results are from “NRR for explosives detection feasibility study” by L-3 Communications Security and Detection Systems, MIT Nuclear Science and Engineering, and MIT Bates Laboratory.
Neutron Resonance Radiography

- Make transmission images of objects using high energy (MeV) neutrons
- Attenuation by a particular element varies with energy in a manner unique to a given element
- Utilizes element specific resonances in energy to enhance the contrast
- Especially for imaging low Z elements such as carbon, oxygen and nitrogen, but can be extended to others
- Utilize this contrast enhancement mechanism to produce elementally resolved images of objects under inspection
Advantages Of Using Neutron Attenuation

Multiple Element (H, C, N, O +) Discrimination For 2-6 MeV Neutrons

- Proof Of Concept Application
  - Separation Of Diamonds (Carbon) From Kimberlite Rock.

- Sensitivity scales as $1/R^2$ rather than $1/R^4$
  - TNA or PFNA detect excited gammas which adds another factor of $1/R^2$ for overall scaling of $1/R^4$
NRR concept

- Like dual energy x-ray machines, NRR uses multiple neutron energies to extract information.
- Each energy produces its own equation.

Consider a simple set of linear equations:

\[
\begin{align*}
2H + 3C + N + 2O &= 8 \\
5H + 4C + 3N + O &= 13 \\
3H + C + 2N + 3O &= 9 \\
H + C + 2N + 3O &= 7
\end{align*}
\]

Solving the set of equations will tell how much of each element is present. A set of neutron attenuation images can be decomposed into contributions from each basis element.
NRR Advantages

- Why is NRR different
  - No Radioactive Source
    - Carbon Detection Demonstrated
    - H,C,N,O + Others Expected
  - No Nanosecond Neutron Pulse/TOF (time of flight)
    - Simple Accelerators Work
  - Simple attenuation \((1/R^2)\) vs. Neutrons In, Photons Out \((1/R^4)\).
  - No rotation or Reconstruction (CT)
Key NRR Challenges

- NRR requires a variable energy neutron source with minimal neutron energy spread at each setting.
- NRR requires good neutron detection and gamma rejection.
- In order to perform NRR measurements you must measure cross sections for all basis elements, and determine the number (> number basis elements) and neutron energies to use.
D(d,n)\(^3\)He Allows Production Of Variable Neutron Energy From a Single Deuteron Beam Energy.

- The Angle (Cone) With Respect to the Incoming Deuteron Beam Defines The Neutron Energy.
- Can Rotate Beam and Leave Target Fixed Or Fix Beam and Rotate Target.

Neutron energy as function of angle
NRR prototype concept: Rotate Accelerator to vary neutron energy.
System components

- Deuteron accelerator generates incoming $d^+$ beam
- Beam transport system focuses beam onto deuterium gas target to make neutrons.
- Rotation of accelerator and adjustable collimator allows variation of neutron energies
- Neutron detection via plastic scintillator and photomultiplier tube.
- Custom readout electronics / data acquisition provides experimental control and data recording.
- Prototype built in 2006 at MIT Bates Linear Accelerator Center in warehouse with minimal climate control (airport conditions).
NRR Prototype System - Side View
Detectors run in counting mode with gamma/neutron discrimination

150 elements: 2 cm x 2 cm x 10 cm plastic
Linear Detector Array
Experimental Results

- Cross section measurements
- Elemental composition
- Elemental maps
- Results generated by taking images at 7 neutron energies and fitting for basis elements Hydrogen, Carbon, Nitrogen, Oxygen, and Silicon.
Elemental Cross Sections: Monte Carlo vs. Measurement as a function of beam angle

- **Carbon**
  - Carbon Neutron Cross Section
  - Monte Carlo
  - Experimental Measurement

- **Nitrogen**
  - Nitrogen Neutron Cross Section
  - Monte Carlo
  - Experiment from LN (Scan-H)

- **Oxygen**
  - Oxygen Neutron Cross Section
  - Theory
  - Ex Oxygen from Gas Bottle (Scan-H)

- **Silicon**
  - Silicon Neutron Cross Section
  - Monte Carlo
  - Experiment from Silicon Crystal (Scan-H)
Elemental Calibrations - Measurement of Melamine chemical composition

Melamine

<table>
<thead>
<tr>
<th>Element</th>
<th>Experimental Determination</th>
<th>Expected Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>C</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>N</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>O</td>
<td>0.10</td>
<td>0.10</td>
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<tr>
<td>Si</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Al</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Fraction of Atoms in Molecule
Elemental Calibrations - Measurement of Ammonium Nitrate chemical composition

Ammonium Nitrate

- Reconstruction in Air
- Theoretical Prediction

H | C | N | O | Si
0.5 | 0.45 | 0.4 | 0.35 | 0.3 | 0.25 | 0.2 | 0.15 | 0.1 | 0.05 | 0
Elemental map, image view
Elemental map, Image view
Application:
Detection of explosives in air cargo

**LD3**
HALF SIZE LOWER DECK CONTAINER
FORKLIFTABLE
(AVE, AVN, AKE, AKN series)

- Rate Classification: 8
- Maximum Net Weight: 1490 kg (3285 lb)
- Tare Weight: 98 kg (215 lb)
- Maximum Gross Weight: 1588 kg (3500 lb)
- Approx. Internal Volume: 4.13 m³ (146 ft³)
- Floor Loading Limit: 977 kg/m² (200 lbs/ft²)
Automatic detection of Carbon target in typical air cargo background of flowers
Detection of Special Nuclear Materials Using NRR Facility

- Use fast neutrons from NRR to induce fission in SNM
- Detect fission neutrons and/or fission gammas
- Large area detectors located out of neutron beam
Which radiation to detect?

- Fission neutrons during RFQ pulse
  - Requires a “gamma-blind” detector
  - Possible candidate is large liquid scintillator
- Delayed fission neutrons
- Delayed (10’s of s) high energy γ’s > 3MeV
  - May be a unique signature for fission products of SNM
  - Great penetration of cargo for easier detection
  - Does not require good energy resolution
  - May be able to use liquid scintillator for both neutrons and γ’s
Neutron Penetration

Mean free path

Energy (MeV)

mfp (gm/cm²)

water
polyethylene
aluminum
iron
Total Cross Section

![Graph showing total cross section vs energy (eV). The graph includes multiple curves representing different elements, such as C, N, O, U238, and Pu239.](image)
Total Fission Cross Section

![Graph showing cross section vs energy for U235, U238, Pu239]
# Fission Products

<table>
<thead>
<tr>
<th></th>
<th>$^{235}$U thermal fission</th>
<th>$^{239}$Pu thermal fission</th>
<th>$^{238}$U fast fission</th>
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</thead>
<tbody>
<tr>
<td>Delayed neutrons[14]</td>
<td>0.015</td>
<td>0.0061</td>
<td>0.044</td>
</tr>
<tr>
<td>$\gamma$-rays[8] at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_\gamma &gt; 3$ MeV</td>
<td>0.127</td>
<td>0.065</td>
<td>0.11</td>
</tr>
<tr>
<td>$\gamma$-rays[8] at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_\gamma &gt; 4$ MeV</td>
<td>0.046</td>
<td>0.017</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Detection of Delayed $\gamma$'s

- **Large Plastic**
  - Can integrate with current NRR electronics
  - Set for $\gamma$'s and/or neutrons
  - Adjustable detection timing window synched to RFQ for delayed and/or prompts
  - Disadvantage
    - Poor energy resolution but can set for $>3$MeV

- **Liquid Scintillator**
  - Separates neutrons and $\gamma$'s
  - New electronics needed based on current low energy neutron interrogation project

- **NaI Scintillator**
  - Good energy resolution
  - Imaging using large array is possible
Imaging Issues

- Current imaging time is set by explosives detection time
- Absorption length
  - SNM $\sim 3 \text{ cm}^{-1}$
  - $C \sim 2 \text{ cm}^{-1}$
- Can image SNM as well as $C, N, O$
Advantages of this approach

- Container is imaged with existing NRR neutron beam
- Require relatively small add-on to current NRR system
- Present design allows increased interrogation time for suspicious regions
- Pulsed nature of RFQ allows for both prompt and delayed $\gamma$ and neutron detection
- Keeping neutron energy below 10 MeV avoids production of interfering 6.1 MeV $\gamma$ from $^{16}\text{O}(n,p)^{16}\text{N}$ and 7.1 s decay of $^{16}\text{N}$
Summary

- Measurements conducted on full scale NRR prototype conclusively show multi-element discrimination possible with NRR.
- Capability to measure rough chemical formulas demonstrated.
- Automated detection based on elemental maps in air cargo sized objects demonstrated.
- Dual use applications include special nuclear material detection, liquid explosives detection.
References

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