TWO-COLOR NEUTRON DETECTION FOR ZERO-KNOWLEDGE NUCLEAR WARHEAD VERIFICATION

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56th INMM Meeting, Indian Wells, California, July 2015
PREVENTING THE EXCHANGE OF SENSITIVE INFORMATION


**Trusted Information Barrier Protocol**
- Measure sensitive Information
- Hard to authenticate and certify
- Single-bit observation

**Interactive Zero-Knowledge Protocol**
- Never measure sensitive information
- Easier to authenticate and certify
- More complex observation
OUR GENERAL APPROACH

**TEMPLATE-MATCHING** (using active neutron interrogation)
More difficult to implement than attribute approach, but also more robust against important diversion scenarios
Generally requires “golden warhead” to generate template (reference signature)

**INTERACTIVE ZERO-KNOWLEDGE PROTOCOL**
Can prove that a statement is true without revealing why it is true
In contrast to “traditional approaches,” no requirement for trusted information barrier

**NON-ELECTRONIC DETECTORS**
Electronic hardware and software used for detectors and, especially, for information barriers are hard to certify and authenticate
Technologies based on “physical” detection may offer important advantages
“ONE-COLOR” RADIOGRAPHY

14 MeV Neutron source
(Thermo Scientific P 385)

Collimator

Collimator slot

Test object

Detector array

(coming up next)
PROOF THAT TWO RADIOGRAPHS ARE IDENTICAL

ITEM B IS EQUAL TO ITEM A
PROOF THAT TWO RADIOGRAPHS ARE IDENTICAL

RADIOGRAPH
ITEM A

+ COMPLEMENT
ITEM A

FLAT BACKGROUND

RADIOGRAPH
ITEM B

+ COMPLEMENT
ITEM A

RESIDUAL IMAGE

ITEM B IS NOT EQUAL TO ITEM A
ZERO-KNOWLEDGE VERIFICATION

RADIOGRAPHY WITH 14 MeV NEUTRONS

Simulated data from MCNP calculations; neutron detection energies > 10 MeV; N(max) = 5,000

FISSION CROSS SECTIONS
OF THE MAIN URANIUM AND PLUTONIUM ISOTOPES
FISSION CROSS SECTIONS
OF THE MAIN URANIUM AND PLUTONIUM ISOTOPES

Idea:
Let’s interrogate with neutrons in the 300-keV range and look for fission neutrons (> 1 MeV)

Source: Evaluated Nuclear Data File (ENDF), www-nds.iaea.org/exfor/endf.htm
“TWO-COLOR”
NEUTRON SETUP
POSSIBLE IMPLEMENTATIONS

“ONE-COLOR” AND “TWO-COLOR” SETUPS FOR ACTIVE NEUTRON INTERROGATION

14 MeV SOURCE vs. D_n > 10 MeV

14 MeV SOURCE vs. D_n > 500 keV

300 keV SOURCE vs. D_n > 500 keV
POSSIBLE IMPLEMENTATIONS
“ONE-COLOR” AND “TWO-COLOR” SETUPS FOR ACTIVE NEUTRON INTERROGATION

- **14 MeV SOURCE**
  - **TEST ITEM**
  - **D_n > 10 MeV**
  - **TRANSMISSION RADIOGRAPH**

- **14 MeV SOURCE**
  - **TEST ITEM**
  - **D_n > 500 keV**
  - **FISSION SIGNATURE**

- **14 MeV SOURCE**
  - **TEST ITEM**
  - **D_n > 500 keV**
  - **FISSION SIGNATURE (AND TRANSMISSION RADIOGRAPH)**

- **300 keV SOURCE**
  - **TEST ITEM**
  - **D_n > 500 keV**
  - **D_n > 10 MeV**
  - **FISSION SIGNATURE (AND TRANSMISSION RADIOGRAPH)**

- **300 keV SOURCE**
  - **TEST ITEM**
  - **D_n > 500 keV**
  - **(D_n > 150 keV)**
  - **FISSION SIGNATURE (AND TRANSMISSION RADIOGRAPH)**
Total neutron yield curves for several reactions. (The DD and DT data for this plot is derived from reference 24 and refers to a fully loaded titanium target with deuterons accelerated into TiD$_2$ for the $^2$H(d,n)$^3$He reaction and deuterons accelerated into TiT$_2$ for the $^3$H(d,n)$^4$He reaction. The solid plots refer to 100% atomic beams, except for the $^9$Be($\gamma$,n)$^8$Be reaction, while the two dashed plots refer to 100% molecular ion beams.)

Fig. 5

Using the DD fusion reaction is a straightforward and often used technique for neutron production with particle accelerators. The reaction is exothermic and its cross section yields a useful neutron production rate with accelerating energies of O(100) keV and modest beam currents of O(100) $\mu$A.

Neutrons from this reaction start at ~2.5 MeV, they are roughly monoenergetic at lower accelerating energies but less so at higher energies, as shown in Fig. 6.

The low Q value for the reaction results in a forward-directed anisotropic yield even at low accelerating potentials, with the relative yield from 0° to 90° decreasing by 4× for an accelerating potential 0.5 MeV.[19] The low yield of this reaction compared with the others described here limits its use in many applications.

David L. Chichester, Production and Applications of Neutrons Using Particle Accelerators INL/EXT-09-17312, Idaho National Laboratory, November 2009
OPEN-SOURCE MONTE CARLO SIMULATIONS

SimLiT + GEANT 4
MODELING APPROACH

**SIMLiT AND GEANT 4**

**SimLiT** ([shrek.phys.huji.ac.il/SimLiT](shrek.phys.huji.ac.il/SimLiT))

- Dedicated Monte Carlo code to simulate neutrons from $^7$Li(p,n) reaction
- Ability to couple to Geant 4
- Open source (designed as a C++ class)

**Geant 4** ([geant4.cern.ch](geant4.cern.ch))

- A Monte Carlo simulation toolkit for the simulation of the passage of particles through matter; used in many scientific fields
- Open source (C++)
SIMULATED p-Li NEUTRON SOURCE

SPECTRUM CAN BE TAILORED BY ADJUSTING THE INCIDENT PROTON ENERGY AND THE THICKNESS OF THE LITHIUM TARGET
SIMPLIFIED EXPERIMENTAL SETUP

NEUTRON SOURCE, TEST ITEM, AND DETECTOR ARRAY

- Neutron source (p-Li)
- Test item
- Neutron detector array (25 x 25)
NOTIONAL TEST ITEMS


**Fetter et al.’s Uranium Item (12 kg weapon-grade HEU)**

- Reference item: 14.0 cm OD, 12 kg of HEU; 93% U-235
- Modified isotopics
- Modified diameter: 15.0 cm OD (same mass)

**Fetter et al.’s Plutonium Item (4 kg weapon-grade Pu)**

- Reference item: 10.0 cm OD, 4 kg of WPu; 93% Pu-239
- Modified isotopics
- Modified diameter: 11.0 cm OD (same mass)
RESULTS
300-keV DRIVEN FISSION SIGNATURES

Invalid item (75% U-235)

Valid item (93% U-235)

Invalid item (85% U-235)

Small deviation from $N_{\text{max}}$

Significant deviation from $N_{\text{max}}$ (1.5, 2.0, 2.5, 3 Sigma)
300-keV DRIVEN FISSION SIGNATURES

- **Valid item (93% U-235)**
  - Bubble count distribution
  - Number of detectors
  - Detector index

- **Invalid item (larger diameter)**
  - Bubble count distribution
  - Number of detectors
  - Detector index

- **Number of detectors**
  - Small deviation from $N_{\text{max}}$
  - Significant deviation from $N_{\text{max}}$ (1.5, 2.0, 2.5, 3 Sigma)

- **Template**
  - Valid
  - 75% U-235
  - 85% U-235
  - Same Mass, Larger
"TRANSMISSION RADIOGRAPH"

Invalid item (75% U-235)

Valid item (93% U-235)

Invalid item (larger diameter)

Bubble counts (with preload):
- 4400 4600 4800 5000 5200 5400 5600

Number of detectors:
- Small deviation from $N_{\max}$
- Significant deviation from $N_{\max}$ (1.5, 2.0, 2.5, 3 Sigma)
ASSESSING THE RESULTS
USING THE KOLMOGOROV-SMIROV STATISTICAL TEST AS A PASS/FAIL CRITERION

<table>
<thead>
<tr>
<th></th>
<th>Uranium Item</th>
<th>Plutonium Item</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Radiograph</td>
<td>Fission signature</td>
</tr>
<tr>
<td>Valid item</td>
<td>0.988</td>
<td>0.987</td>
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<tr>
<td>75% U-235</td>
<td>0.872</td>
<td>0</td>
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<tr>
<td>85% U-235</td>
<td>0.986</td>
<td>0</td>
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<tr>
<td>Larger diameter</td>
<td>3.738E–05</td>
<td>0</td>
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</tbody>
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As expected, radiography (here: using 300-keV neutrons) is not very sensitive to isotopic changes. Fission signature is very clear for uranium and plutonium items.
CONCLUSION AND OUTLOOK

“ONE-COLOR” SETUP

Neutron transmission radiography using high-energy (14 MeV) neutrons is effective in detecting geometric and elemental differences.

Distinguishing isotopic differences can be more challenging because relevant 14-MeV fission cross sections can be similar for some elements (esp. for Pu-239 vs Pu-240).

“TWO-COLOR” SETUP

Fission signatures triggered by ~ 300-keV neutrons are extremely sensitive to isotopic differences (and also to differences in geometry).

Combine with 14-MeV (and ~150-keV) transmission radiography.

Needed for experimental demonstration: Intense 2-MeV proton source.