Experimental demonstration of a physical cryptographic warhead verification protocol using nuclear resonance fluorescence

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How can an inspector verify a warhead is real without revealing classified information?
We use nuclear resonance fluorescence (NRF) to make isotope-specific measurements. Different line spectra for U-235, U-238, Pu-239, Pu-240... other resonant processes?...
The inspector can only compare NRF signatures.

Encryption (‘hashing’) by a physics process, not electronics.
Multi-line inference, cryptographic filters

- First layer of security: foil thickness $X$ and warhead thickness $D$ are both unknown and both affect the NRF rate
  - One equation, two unknowns
  - Problem: build a system of equations, use neighboring lines, take ratios to cancel systematics, make some approximations
    $\Rightarrow$ infer foil $X$ $\Rightarrow$ infer warhead $D$

- Solution: introduce a cryptographic filter of warhead isotopes
  $\Rightarrow$ at most, can infer $D + \Delta D$
  $\Rightarrow$ bonus: inspector can bring the foil, and it can be thick to maximize stats
Simulations showed strong hoax resistance

<table>
<thead>
<tr>
<th>Hoax scenario</th>
<th>Strongest discrepancy (st. dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WGPu → U-238</td>
<td>107 σ</td>
</tr>
<tr>
<td>WGPu → FGPu</td>
<td>14.6 σ</td>
</tr>
<tr>
<td>Geometric hoax, 0°</td>
<td>1.16 σ</td>
</tr>
<tr>
<td>Geometric hoax, 10°</td>
<td>6.38 σ</td>
</tr>
<tr>
<td>Geometric hoax, 30°</td>
<td>49.7 σ</td>
</tr>
</tbody>
</table>

Fall 2017 experiments at MIT HVRL

- **~2.6 MeV e\(^{-}\)**
- **Radiator (Cu + Au)**
  - Warhead proxy
    - Genuine: DU + plastic
    - Hoax: Pb + plastic
- **Encrypting foil (DU + Al)**
- **HPGe**
- **Brems**
- **NRF**
- **LaBr downbeam**
The spectra appear to match remarkably well...

- template (DU) spectrum
- hoax (Pb) spectrum
...but let’s zoom into the NRF region...

[Graph showing energy spectra with peaks at Al-27, U-238, and U-238 labeled.]
Template (DU) vs hoax (Pb)

Target: Plastic, DU or Pb

U-238 lines indicate DU diversion
Al-27 line indicates Al consistency
Template (DU) vs genuine candidate (DU)

Target:
Plastic
DU

Interp. counts per 1.00 keV per μA⋅s (live)

Energy E [MeV]

Template (DU) spectrum
Candidate (DU) spectrum
Template (DU) fit
Candidate (DU) fit
Discrepancy = 1.74 σ
Template II (DU) vs hoax (Pb)

Target: Plastic 2x DU or Pb

interp. counts per 1.00 keV per µA·s (live)

- template (DU) spectrum
- hoax (Pb) spectrum
- template (DU) fit
- hoax (Pb) fit

discrepancy = 10.69 σ
Template II (DU) vs partial hoax (Pb/DU)

Target: Plastic, DU, DU or Pb

interp. counts per 1.00 keV per \( \mu \)A-s (live)

- template (DU) spectrum
- hoax (Pb) spectrum
- template (DU) fit
- hoax (Pb) fit

\[ \sigma \text{ discrepancy} = 4.57 \sigma \]
What could we achieve with a dedicated verification facility?

5-10 $\sigma$ in a (1+1)-hour proof-of-concept:
- How long for realistic (thicker) designs?
- Weaker NRF lines of fissile U-235, Pu-239?

25 $\mu$A $\rightarrow$ 5 mA beam current:
- 200x rate increase

3 $\rightarrow$ 30 HPGe detectors:
- 10x rate increase
- Measurement times on the order of 20 minutes
- $O(5 \text{ M})$ for full system

IFA Rhodotron

GammaSphere
Future work

1. Continue investigations of information security
   – Multi-line inference
   – Continuum background

2. Investigate combined verification measurements
   – Neutrons (Princeton) \textit{and} photons (MIT)
   – Secure ADCs (Umich)

3. Conduct further experiments
   – Reciprocals?
   – Other resonant processes
Disarmament verification with epithermal neutron resonances

Areg Danagoulian, Ezra Engel, Jake Hecla
Basic Concept

+ Epithermal neutrons in the 1-10 eV also have resonances.
+ Perform direct transmission, use TOF to reconstruct energy: transmitted spectrum will have both geometric and isotopic sensitivity.
+ Use the “reciprocal” mask to achieve a true Zero Knowledge verification
WGPu pit vs. a hoax (Reactor Grade) → isotopic hoax resistance

+ Different isotopics result in different transmission spectra
+ Only ~100k incident counts necessary for a 5σ detection
  - Use accelerator, p + 7Li → minutes
  - Use LANL spallation source
  - MIT reactor

Slide: Areg Danagoulian
Geometric hoax resistance

Slide: Areg Danagoulian
Status


→ collaborate with the labs (Lujan Center, LANL?) for a proof-of-concept

- Students: Ezra Engel (MIT), Jake Hecla (now at Berkeley)

+ J. Vavrek, B. Henderson, A. Danagoulian, “Experimental implementation of a warhead verification protocol using nuclear resonance fluorescence,” in preparation

Slide: Areg Danagoulian
Conclusions

We have completed proof-of-concept, isotope-sensitive warhead verification measurements using NRF.

We have developed and simulated a new verification measurement using epithermal neutron radiography.

Resonant phenomena provide promising warhead verification techniques.
Physical cryptography collaboration

Faculty:

Prof. Areg Danagoulian
Prof. Scott Kemp
Dr. Richard Lanza

Stanton post-doctoral fellow:

Brian Henderson

Graduate students:

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Ruaridh Macdonald
S Jeremiah Collins
Jake Hecla
BACKUP
Geometric Information Security

+ Compare the transmission image of the pit+reciprocal to that of a flat plate of the same total thickness
+ Images and spectra are identical – can’t differentiate, thus cannot infer any geometric information \( \rightarrow \) geometric ZK!
Isotopic Information Security

+ Protect isotopes of their weapons
+ MC simulations of three scenarios:
  - 70% 239Pu enriched pit, 98% enriched extension
  - 78% enriched pit and extension
  - 93% pit, 71% extension
  ➔ the transmitted spectra are identical: isotopic ZK
The Goldston filter

- A nefarious host could place a layer of Pb directly upstream of the filter to induce notch refill and lower sensitivity of NRF
- For a 2.6 MeV endpoint beam, the Goldston filter will induce ~3x as much notch refill than expected from standard geometries
  - Modest reduction in sensitivity
  - Could be caught by other spectral changes
  - Can enforce minimum SNRs
The glass equation

Semi*-analytical model for NRF count rates, single isotope:

\[
\frac{d^3 n}{dE d\Omega dx} = \phi_t(E) b \mu_{NRF}(E) \frac{W(\theta)}{4\pi} \exp \left\{ -x \left[ \mu_{NRF}(E) + \mu_{nr}(E) + \frac{\mu_{nr}(E')}{\cos \theta} \right] \right\} \epsilon_{int}(E') P_f(E')
\]

* Initial bremsstrahlung flux is often computed via MC

count rate = transmitted flux
production in foil
anisotropy
attenuation in foil
detector losses
April 2017 direct NRF data

HVRL 04/28/2017 NRF spectrum

34.0 uA.h (live)
20-parameter background + peak fit

counts per 1.53 keV

energy E [MeV]

0 100 200 300 400 500 600

2.05 2.10 2.15 2.20 2.25 2.30 2.35