CVT Workshop

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Absolute nuclear resonance fluorescence experiments for physics and security

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Goal: improved NRF cross section data for physics and security

NRF for security
- warhead verification
- nuclear structure
- cargo scanning
- energy selection (e.g. Pound-Rebka, Goldhaber expts)

NRF for physics
- Yoshimi et al, PRC (2008)
Mission Relevance and Outline

1. CVT Thrust Area 5: Disarmament Verification
   – Performed proof-of-concept warhead verification experiments with NRF

2. CVT Thrust Area 2: Physics
   – Validated U-238 and Al-27 NRF cross sections to within ~10% in an absolute measurement
   – Beginning MIT/LLNL/TUNL collaboration on absolute measurement of Pu-239 NRF cross sections
Template verification preserves security

Authenticated template “golden copy” of a warhead

Picked from a randomly selected ICBM

Candidate warheads

Is $A_0 = A_1$ ? ✓
$A_0 = A_2$ ? ✓
$A_0 = A_3$ ? ✓

Challenge:
1. Catch hoaxes
2. Identify all real warheads
3. Reveal no additional info

→ need physical cryptography
→ Use nuclear resonance fluorescence (NRF)!

Figure: Areg Danagoulian
NRF provides isotope-specific warhead measurements

Compare NRF signatures:
(candidate) + (encryption foil) vs
(genuine) + (encryption foil)

→ encryption of sensitive design information via physics
→ only check if results match
→ “physical cryptography”

different line spectra for U-235, U-238, Pu-239, Pu-240…

U-235 NRF spectrum
Information security challenges

1. 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 $D$

1. 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

2. Other options: monochromatic beams or UMich ADCs
Verification setup at MIT HVRL

![Diagram of verification setup at MIT HVRL](image)

- **Radiator**
- **Collimator**
- **Proxy Warhead**
- **Optional Encryption Plates**
- **Cu**
- **Au**
- **DU, Al**
- **Pb**
- **LaBr₃**
- **2 × HPGe**
- **NRF γ**
- **DU/Al Encryption Foil**

*(top view, not to scale)*
Verification experiments

- Radiator (Cu + Au)
- Warhead proxy
  - Genuine: DU + plastic
  - Hoax: Pb + plastic
- Encrypting foil (DU + Al)

Consortium for Verification Technology
NRF measurements catch DU/Pb hoaxes

JR Vavrek, BS Henderson, A Danagoulian, PNAS 115 (17) 4363-4368, 2018
(See also Kemp et al, PNAS 113 (31) 8618-8623, 2016)
Diagnostics allow cross section extraction

• Multiple additional diagnostics from verification measurements:
  – Accelerator current readout
  – Downbeam bremsstrahlung flux monitor (LaBr$_3$)

• Systematics across different:
  – Detectors
  – Energies
  – Proxy warheads

Can use verification data to make absolute NRF cross section measurements!
Example model for extraction

Semi-analytical model ("Model 0"):

Data extraction:

Model:

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

- really $\Gamma$, not $\mu$
- ‘model’ can be Geant4
First, compare **forward** models to data

Ratios of absolute NRF count rates, model over data:

<table>
<thead>
<tr>
<th>NRF line</th>
<th>Avg model/obs ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238 2.176 MeV</td>
<td>1.22 ± 0.03</td>
</tr>
<tr>
<td>U-238 2.245 MeV</td>
<td>1.18 ± 0.04</td>
</tr>
<tr>
<td>Al-27 2.212 MeV</td>
<td>1.09 ± 0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model #</th>
<th>Avg model/obs ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 0</td>
<td>1.20 ± 0.01</td>
</tr>
<tr>
<td>Model 1</td>
<td>1.11 ± 0.01</td>
</tr>
<tr>
<td>Model 2</td>
<td>1.11 ± 0.01</td>
</tr>
<tr>
<td>Model 3</td>
<td>1.14 ± 0.02</td>
</tr>
</tbody>
</table>

More Geant4-reliant

**Average:** 1.14 ± 0.02 (stat) ± 0.06 (sys)

Predicted absolute NRF count rates agree with data to ~15%!
Then, invert the model to find cross sections

(really level widths $\Gamma_r$)

<table>
<thead>
<tr>
<th>NRF line</th>
<th>Extracted level width $\Gamma_r$ [meV]</th>
<th>Approx. level width ratio, data/literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238 2.176 MeV</td>
<td>37 ± 1 ± 3</td>
<td>0.65</td>
</tr>
<tr>
<td>U-238 2.245 MeV</td>
<td>23 ± 1 ± 2</td>
<td>0.78</td>
</tr>
<tr>
<td>Al-27 2.212 MeV</td>
<td>15 ± 0.3 ± 1</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Non-linear dependence of NRF count rate on $\Gamma_r$
- makes NRF cross section extraction harder (more sensitive to error)
- makes NRF count rate prediction easier (less sensitive to error)

Approximate validation, derived from absolute measurements
(under review at Phys Rev C)
MIT/LLNL/TUNL Pu-239 NRF analysis

• Pu-239 direct NRF experiments at HiγS in 2010-11
  – specifically designed for absolute cross section measurements
  – aim for < 5 % cross section uncertainty
  – also extract level spin and parity $J^\pi$

• Aims to improve on existing data (Bertozzi et al, PRC 2008):
  – cross section uncertainties of 15-75%
  – no $J^\pi$ determined
  – normalized against Al-27 2.212 MeV NRF line
HlγS facility at Duke

- laser Compton backscatter from ~300 MeV, 75 mA e⁻ beam and ~1000 nm free electron laser
- produces ~2 MeV quasi-monoenergetic photon beam (~1% FWHM, $10^7$/s, quasi-CW, linearly polarized)
CVT Impact

• Pu-239 collaboration with LLNL/TUNL made possible by CVT

• Warhead verification project red-teamed by PNNL

• Possible future collaboration through postdoc positions
Conclusions

1. Developed an NRF-based warhead verification technique with high (> 5 σ) hoax-resistance

2. Validated and measured literature NRF cross sections for U-238 and Al-27 in an approximate but absolute sense

3. Working on analyzing Pu-239 NRF cross sections using a dedicated absolute measurement
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