Nuclear Arms Control with Nuclear Resonances
Introduction

• **The bomb**: what is it?

• **Policy**: Nuclear Arms Control, how is it (not) verified?

• **Information**: Physical Cryptography and Zero Knowledge

• **Physics**:
  - Resonances and nuclei
  - Resonance Experimental Physics with physical cryptography

• **Engineering**:
  - Compact verification devices
How does the bomb work?

Explosive “lenses”

Plutonium “pit”

To learn more: “Los Alamos Primer”

(source: wikipedia.org)
How Big? – then

First nuclear bomb
“Fat Man”, ~5 tones

First US thermonuclear bomb
“Castle Bravo,” ~10 tones
How Small? -- now

Special Atomic Demolition Munition

(I. Jovanovich)

40 cm

~ 20 kg
How Small? -- now

W80 thermonuclear warhead, 150 000 tones of TNT equivalent
- 100 kg

→ very small
Delivery

Intercontinental Ballistic Missiles (ICBM)

Strategic Bombers

- Delivery times – 15-30 minutes
- Early warning systems → the president has 10 minutes to make a decision.

Possibility of accidental nuclear war. Many close calls in the past (we are all very lucky).
Source: https://en.wikipedia.org/wiki/Ballistic_missile
Estimated Global Nuclear Warhead Inventories, 2022

Significant reduction from Cold War era


(from https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/)
Technology is Critical

- First attempts at a Comprehensive Test Ban Treaty (CTBT) – 1958
- Glenn Seaborg’s account of the negotiations (pp. 15-19)

The Berkner Panel’s report also had a more somber side. This concerned techniques of evasion. Following the Conference of Experts, Edward Teller had asked Livermore and Rand Corporation scientists to consider ways in which the Geneva System might be evaded by a clever violator. Albert Latter of the Rand Corporation turned his attention to “decoupling,” a technique for reducing the seismic impact of an explosion by detonating it in the center of a large underground chamber so that the surrounding earth would not be forcefully impacted by the explosion. Latter’s analysis indicated that it was possible to decouple to such an extent that a 300-kiloton explosion would register on seismographs as though it were only one kiloton. While there was doubt that yields as high as 300 kilotons could be decoupled because of the difficulty and costs involved in building so large a chamber, even scientists friendly to a test ban, such as Hans Bethe, conceded that Latter’s analysis was, in general, valid. These findings seemed to have a devastating effect on the Geneva System since they implied that some underground tests could be concealed and that seismograph readings would not necessarily provide a reliable indication of the size of an explosion.

- Result: only Limited Test Ban
- Another ~40 years before technology caught up and CTBT was agreed upon
How do treaty partners verify that the other side is dismantling actual warheads and not fakes? They don’t.

Verification: delivery vehicles – easier to verify.

Problems: large leftover of non-deployed warheads
• theft → nuclear terrorism, nuclear proliferation

Authenticate warheads, without revealing secret information
Past approaches to warhead verification: attribute measurements with information barrier

Attribute problems:
1. Risk of hoaxes
2. Attributes aren’t unique (and may be classified)
3. Hard to ensure barrier doesn’t leak information or provide false results
What can be trusted to be both accurate and secure?

- software encryption?
- electronic barriers?
- physics

(Jayson Vavrek)
Our Research: physics-based cryptography, template verification

Authenticated template “golden copy” of W88
Picked from a randomly selected ICBM

Candidate copies, W88

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

Challenge: perform checks while

- protecting secrets $\rightarrow$ physical cryptography
- isotopic specificity $\rightarrow$ resonances!

To dismantlement
But how do you find a "golden copy?" Radom, unannounced visits by inspectors.

(Jayson Vavrek)
templates...attributes...IB...Physical Crypto/ZK...active...passive

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<td>Information Barriers</td>
<td>TRIS, NG-TRIS</td>
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<td>MeV Neutrons (Princeton/PPPL)</td>
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<td>Epithermal neutrons (MIT)</td>
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<td>NRF (MIT)</td>
<td>Neutrons</td>
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Others: NMIS (ORNL)

Resonances: unique fingerprint of nuclear structure

Photons: Nuclear Resonance Fluorescence (NRF)

Analogy: atomic fluorescence

Neutrons

If \( E_n \neq E_r \)

Potential (hard sphere) scattering

If \( E_n = E_r \)

\[
\sigma_T(E) = 4\pi R^2 + \pi\lambda^2 g \left( \frac{4\Gamma_n(E - E_0)R' / \lambda + \Gamma_n^2 + \Gamma_n \Gamma + \Gamma_n \Gamma_f}{(E - E_0)^2 + (\Gamma_n + \Gamma + \Gamma_f)^2 / 4} \right)
\]

Laboratory for Applied Nuclear Physics

Areg Danagoulian
Neutrons

Energy going in: eV
Energy going out: MeV!
How does an eV neutron access an MeV level?

Remember, energy is conserved: kinetic + internal/potential

The reaction is exothermic – releases energy.

This is why an eV neutron can access an MeV nuclear state!

\[ E_n = E_r \]

\[
\sigma_T(E) = 4\pi R^2 + \pi\lambda^2 \left( \frac{4\Gamma_n(E - E_0)R'}{E - E_0\lambda + \Gamma_n + \Gamma_r + \Gamma_\gamma + \Gamma_\omega} \right) \left( \frac{(E - E_0)^2 + (\Gamma_n + \Gamma_\gamma + \Gamma_f + \Gamma_\omega)^2}{4} \right)
\]
Verification with Epithermal Resonant Analysis (VERA)
Neutrons: Epithermal Resonant Cryptographic Radiography

- Epithermal neutron resonances in the 1-100 eV
- Neutron Resonance Transmission Analysis (NRTA)

- choose a resonance
- \( \rightarrow \) isotopic image
Epithermal Resonant Cryptographic Radiography: verification

\[ \ln(\text{signal}) = (\text{object}) \times (\text{reciprocal}) \]

\[ ? = \text{SIGNAL}_{\text{golden}} = \text{SIGNAL}_{\text{candidate}} \]
Physical cryptography vs naïve template verification

Analogy with underdefined system of equations:

\[ X + Y = 10 \pm 0.1 \]

- encrypting mask
- “golden copy” weapon

\[ X' + Y = 10 \pm 0.1 \]

- candidate weapon

Verification:

\[ X' - X = 0 \pm 0.14 \implies X' \approx X \]

Privacy: \( X \) can be anything between 0 to 10.
Experiments: Rensselaer Polytechnic Institute

- Can we avoid simple imaging? Yes – single pixel tomography
  - no need for complicated reciprocals
  - simple detectors

- Experimentally prove the feasibility of the concept

- Proxies for honest “golden” copy pit and “hoax” pit:
  - honest: 90% Mo / 10% W (Mo $\leftrightarrow$ $^{239}$Pu : W $\leftrightarrow$ $^{240}$Pu)

- Measurements: single pixel detector, 6Li glass, TOF

![Diagram of neutron beam, Mo/W object, encrypting foil, and Li glass detector with TOF and energy measurement.]
The Experiment - beamline
Signal: W and Mo

(Ezra Engel)
Hoaxes

Golden copy:

Isotopic Hoax:

Geometric hoax:

System only sensitive along Z-axis. Rotations!
Isotopic Hoaxes

Mo/W:90/10 template vs. 50/50 hoax

Mo/W:90/10 template vs. 10/90 hoax
Geometric Hoaxes: cylinder vs. cube

(Ezra Engêl)
Honest Candidates

(Ezra Engel)
## Summary

<table>
<thead>
<tr>
<th>candidate object Mo/W composition and shape</th>
<th>rotation (degrees)</th>
<th>$\chi^2$/ndf</th>
<th>p value</th>
<th>decision</th>
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<td>90</td>
<td>589 / 588</td>
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Information Security

Does signal depend only on the **total areal density** and the **average enrichment** observed by the beam?

Same areal density $\rightarrow$ same signal?

If so, inspector can’t tell between

and
Information Security: geometry

Geant4 simulations for an actual “pit”. Combined pit+mask thickness: \( = 6.86 \text{cm} \)

Identical signals. Inspector can’t distinguish between no pit and 9.78/10cm pit (>> critical mass!)
Identical signals. Inspector can’t distinguish between 75% and 98%.

Inspector inferences:
- The pit mass is $0 < M < 40$ kg
- The pit enrichment is $75% < r < 98%$
  $\rightarrow$ **no new information**
- Measurement times -- $< hr$

Ezra M. Engel, Areg Danagoulian, “A physically cryptographic warhead verification system using neutron induced nuclear resonances,” *Nature Communications*, vol. 10 (2019) 1
Current Facilities

**RPI:**

**Los Alamos:** Instrument size: **mesa-scale!**
Experiments with Epithermals: MIT

2.6 m

- Borated poly
- DT tube
- moderator
- W
- B4C
- Pb shielding

6Li glass scintillator
Results

Main DT pulse, ~ 1.5 us

Epithermal neutrons, delayed

<table>
<thead>
<tr>
<th>dt</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
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<td>51140</td>
<td>45.2</td>
<td>54.83</td>
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</tbody>
</table>
Results (preliminary)

(Farheen Naqvi, Ethan Klein)

Time: 2 hrs
Distance: 2.6 m
Target: W+In+Ag+Cd
Why are we doing this?

~ $1\text{bln}$

~ $1000$ m

~ $100k$

~ $1$m

Need to go from **mesa-scale** to **table-scale**!
Conclusions and The Future

• NRF / photon probes ✓
• Neutron probes ✓

• DT generator, compact epithermal probes
  • Preliminary experimental results highly encouraging, can see resonances 1 to ~180 eV ✓

• Other applications:
  • Archaeology (<250 eV resonances for tin, copper, gold, silver)
  • NRF, epithermal NRTA: materials analysis, fuel enrichment

• Collaborate on arms control with
  • national labs (PPPL, PNNL, LLNL)
  • Russia (NAS Joint U.S./Russia Project on Monitoring and Verification)
  • Korea (KINAC, KAERI, KAIST)

• Need technological solutions for treaty verification → more ambitious, far reaching treaties
The Team

Research Scientists and postdocs:

Dr. Farheen Naqvi
Dr. Ruaridh Macdonald

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Ethan  Will  Peter

S.M.
Jacob  Chaney  Nina

Undergraduate

Alumni:

Dr. Hin Lee  Dr. B. O’Day  Dr. J. Vavrek
Dr. Brian Henderson (postdoc)  E. Engel  Jill Rahon  R. Nelson  J. Collins
Jake Miske  Jake Hecla

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