CVT Workshop

October 31 – November 1, 2018

Absolute nuclear resonance fluorescence experiments for physics and security

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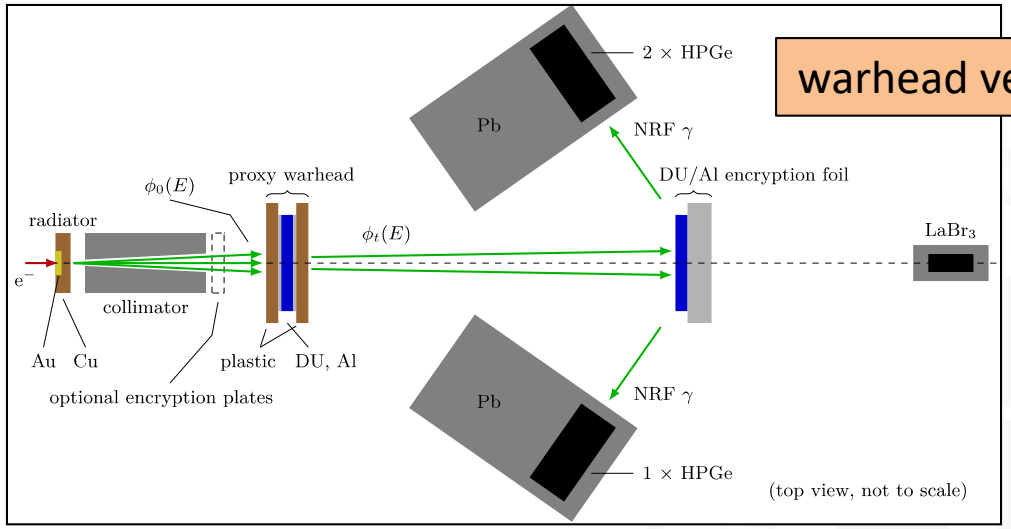
MIT, LLNL, TUNL

11/01/2018

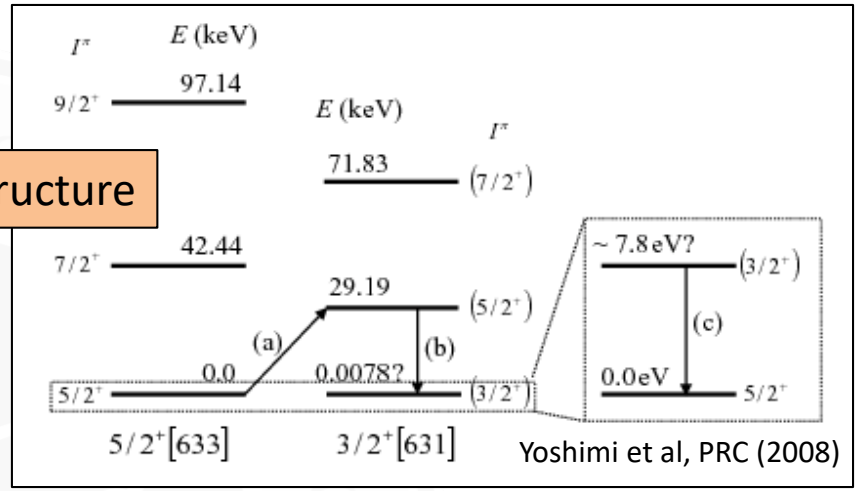
Goal: improved NRF cross section data for physics and security

NRF for security



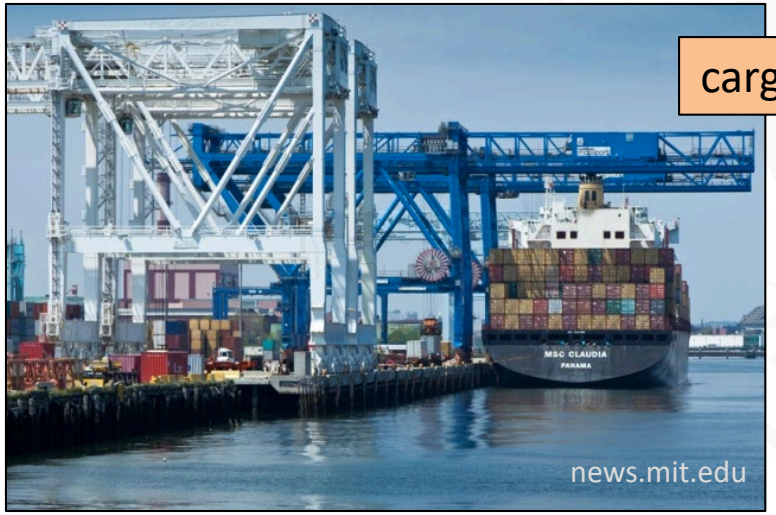
warhead verification

NRF for physics

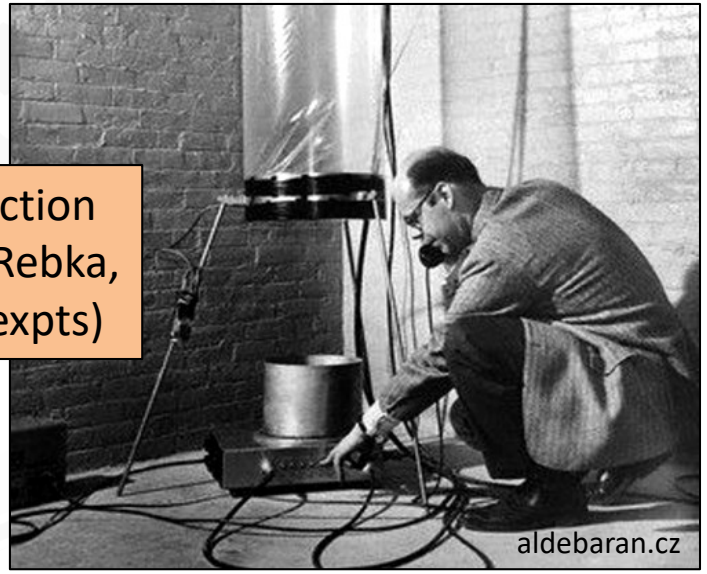


Yoshimi et al, PRC (2008)

nuclear structure



cargo scanning



energy selection (e.g. Pound-Rebka, Goldhaber expts)

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

Figure: Areg Danagoulian

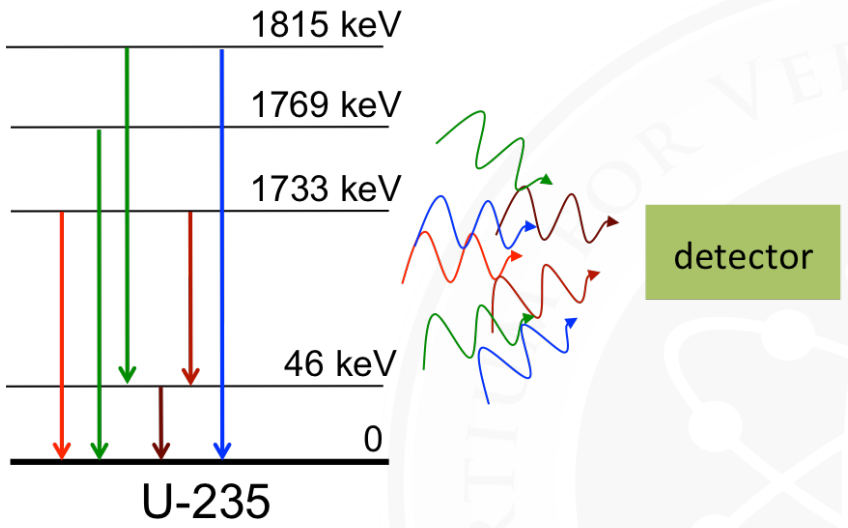
Candidate warheads

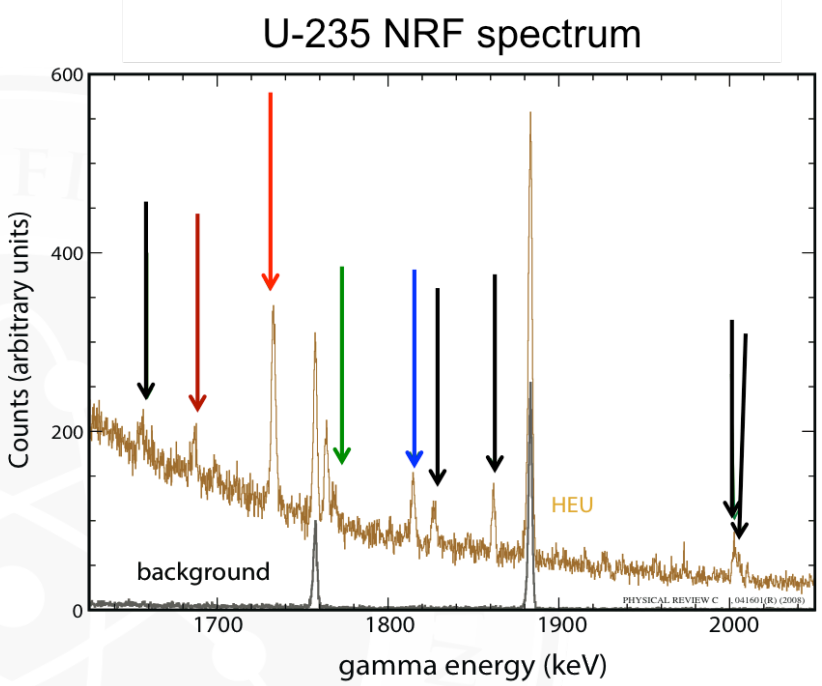
Is $A_0 = A_1$? ✓
$A_0 = A_2$? ✓
$A_0 = A_3$? ✓
⋮

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

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

NRF provides isotope-specific warhead measurements





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

<u>Compare NRF signatures:</u>
(candidate) + (encryption foil)
vs
(genuine) + (encryption foil)

➔ encryption of sensitive design information via physics
➔ only check if results match
➔ "physical cryptography"

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

     → infer foil *X* → infer warhead *D*

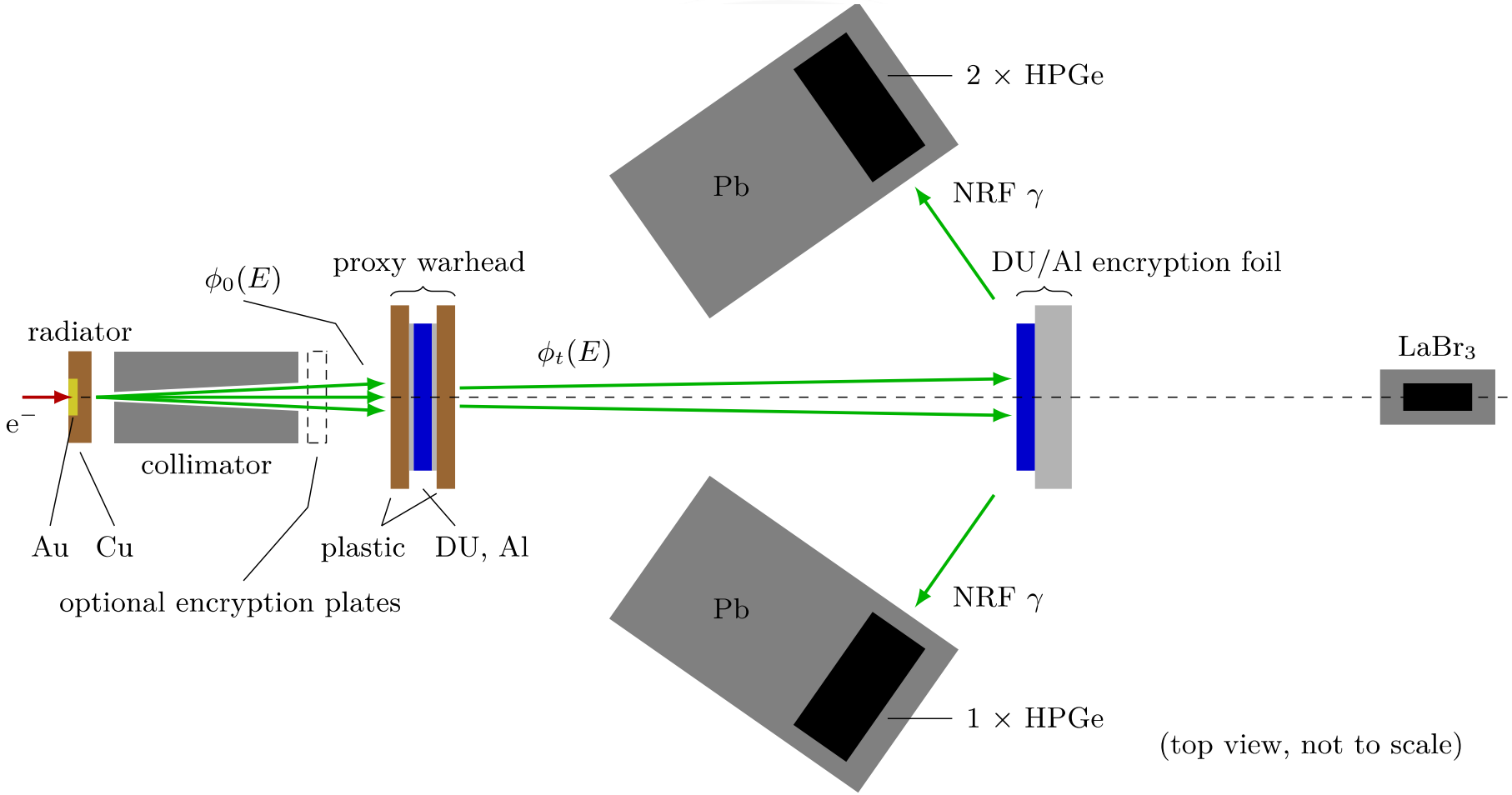
1. Solution: introduce a cryptographic filter of warhead isotopes

   → at most, can infer $D + \Delta D$

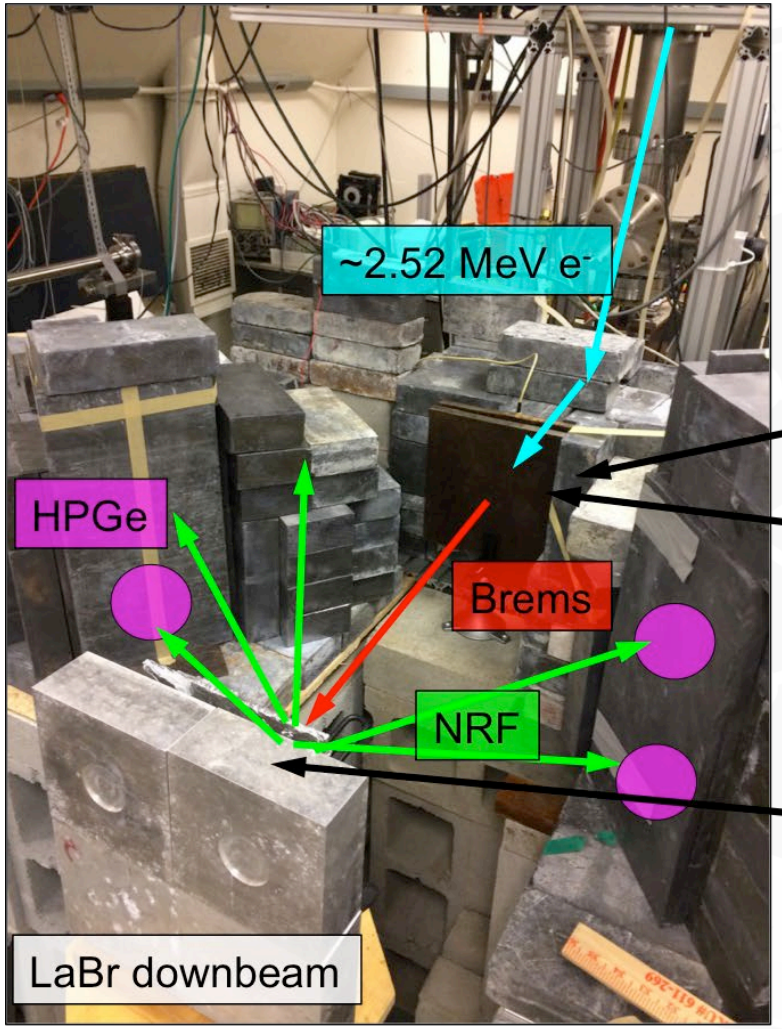
   → bonus: inspector can bring the foil, and it can be thick to maximize stats

2. Other options: monochromatic beams or UMich ADCs

Verification setup at MIT HVRL



Verification experiments



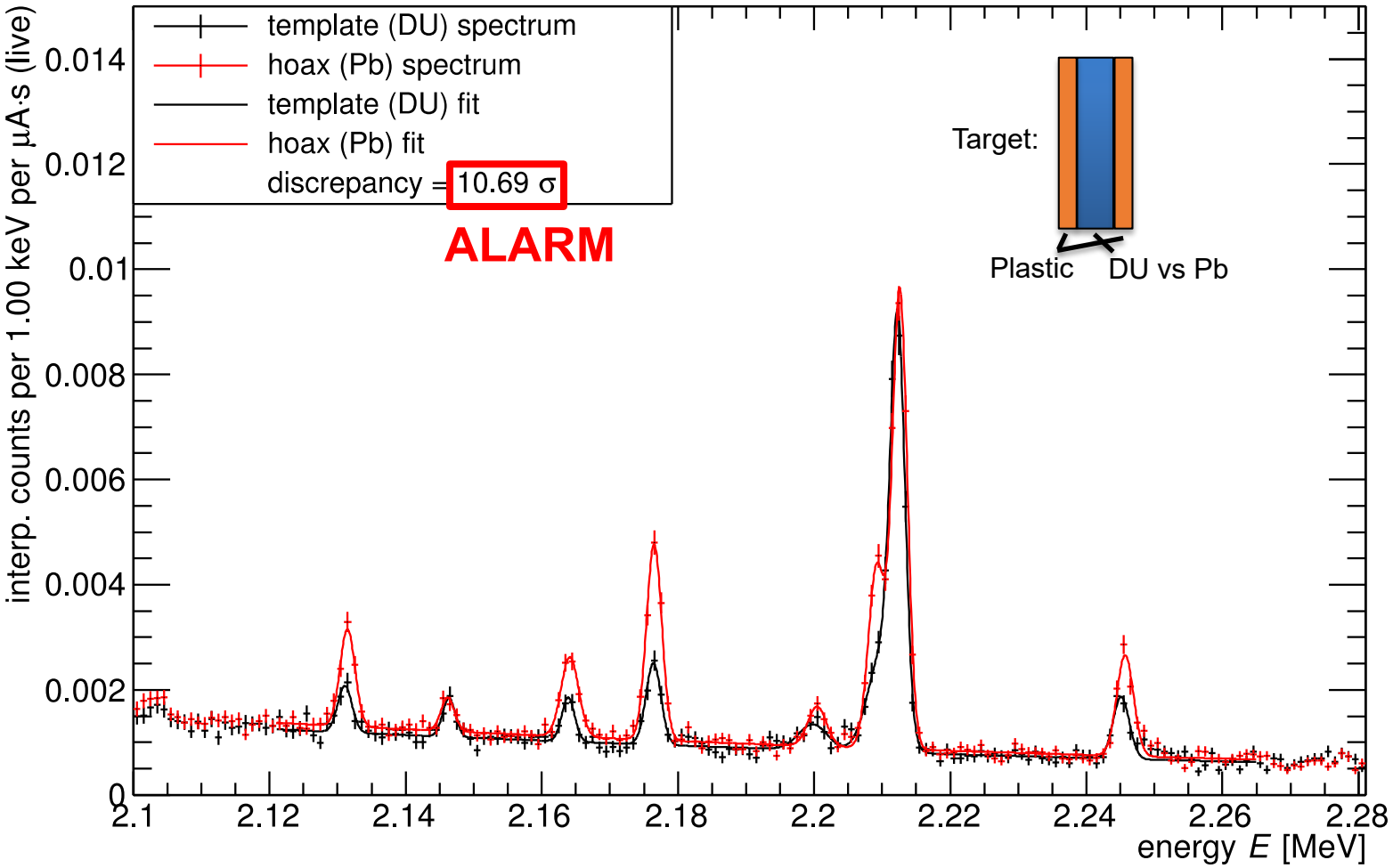
Radiator
(Cu + Au)

Warhead proxy

- Genuine: DU + plastic
- Hoax: Pb + plastic

Encrypting foil
(DU + Al)

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)

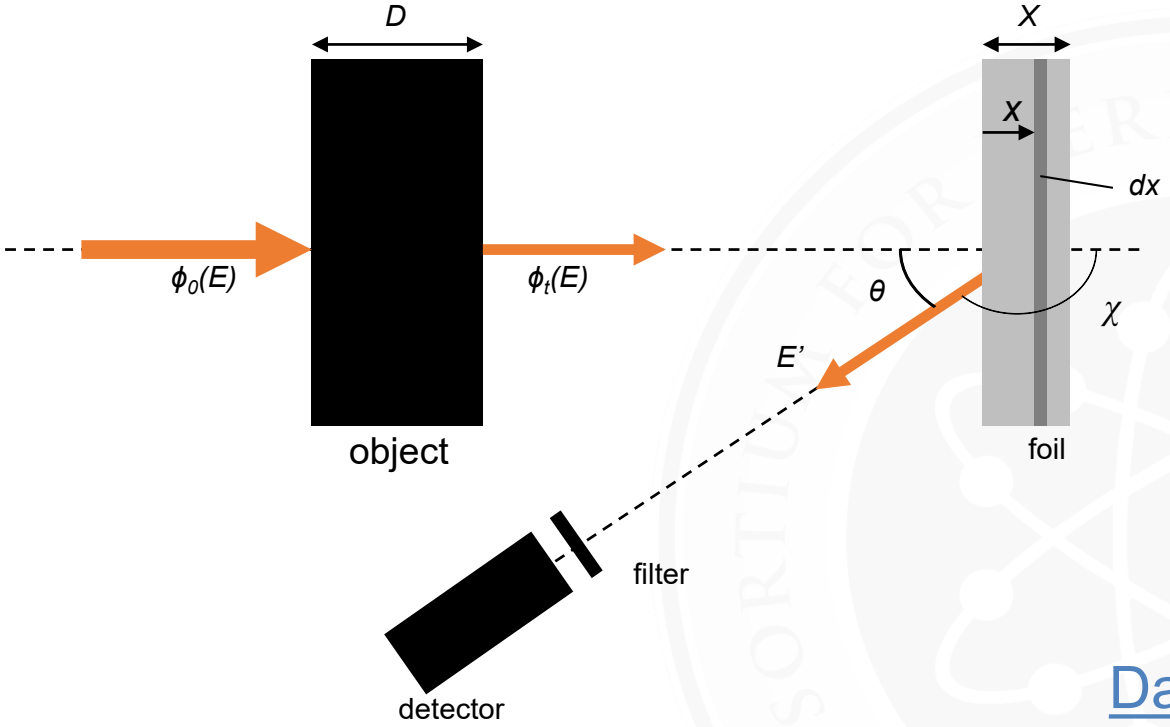
Diagnostics allow cross section extraction

- Multiple additional diagnostics from verification measurements:
  - Accelerator current readout
  - Downbeam bremsstrahlung flux monitor ($LaBr_3$)
- Systematics across different:
  - Detectors
  - Energies
  - Proxy warheads

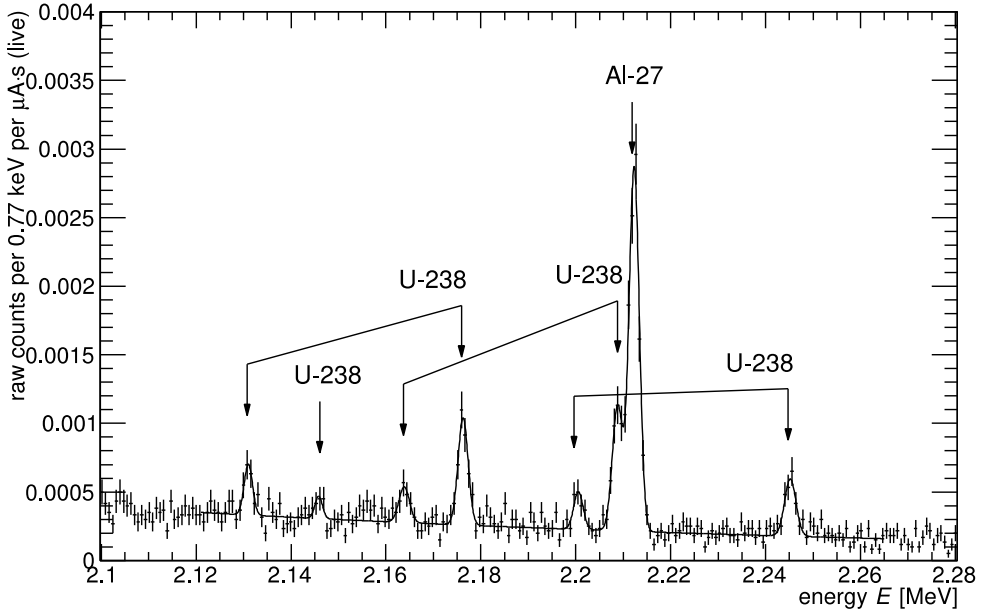
Can use verification data to make absolute NRF cross section measurements!

Example model for extraction

Semi-analytical model ("Model 0"):



Data extraction:



Data:

$$f(E) = \exp(c_1 + c_2 E) + \sum_{k=1}^{8} \frac{a_k}{\sqrt{2\pi}\sigma_k} \exp\left[-\frac{(E-E_k)^2}{2\sigma_k^2}\right]$$

Model:

$$\underbrace{\frac{d^3 n}{dE\, d\Omega\, dx}}_{\text{count rate}} = \underbrace{\phi_t(E)}_{\text{transmitted flux}} \underbrace{b\, \mu_{\mathrm{NRF}}(E)}_{\text{production in foil}} \underbrace{\frac{W(\theta)}{4\pi}}_{\text{anisotropy}} \underbrace{\exp\left\{-x\left[\mu_{\mathrm{NRF}}(E) + \mu_{\mathrm{nr}}(E) + \frac{\mu_{\mathrm{nr}}(E')}{\cos\theta}\right]\right\}}_{\text{attenuation in foil}} \underbrace{\epsilon_{\mathrm{int}}(E') P_f(E')}_{\text{detector losses}}$$

- really Γ, not μ
- 'model' can be Geant4

First, compare forward models to data

Ratios of absolute NRF count rates, model over data:

NRF line	Avg model/obs ratio
U-238 2.176 MeV	1.22 ± 0.03
U-238 2.245 MeV	1.18 ± 0.04
Al-27 2.212 MeV	1.09 ± 0.02

Model #	Avg model/obs ratio
Model 0	1.20 ± 0.01
Model 1	1.11 ± 0.01
Model 2	1.11 ± 0.01
Model 3	1.14 ± 0.02

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 Γ_r)

NRF line	Extracted level width Γ_r [meV]	Approx. level width ratio, data/literature
U-238 2.176 MeV	37 ± 1 ± 3	0.65
U-238 2.245 MeV	23 ± 1 ± 2	0.78
Al-27 2.212 MeV	15 ± 0.3 ± 1	0.85

Non-linear dependence of NRF count rate on Γ_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

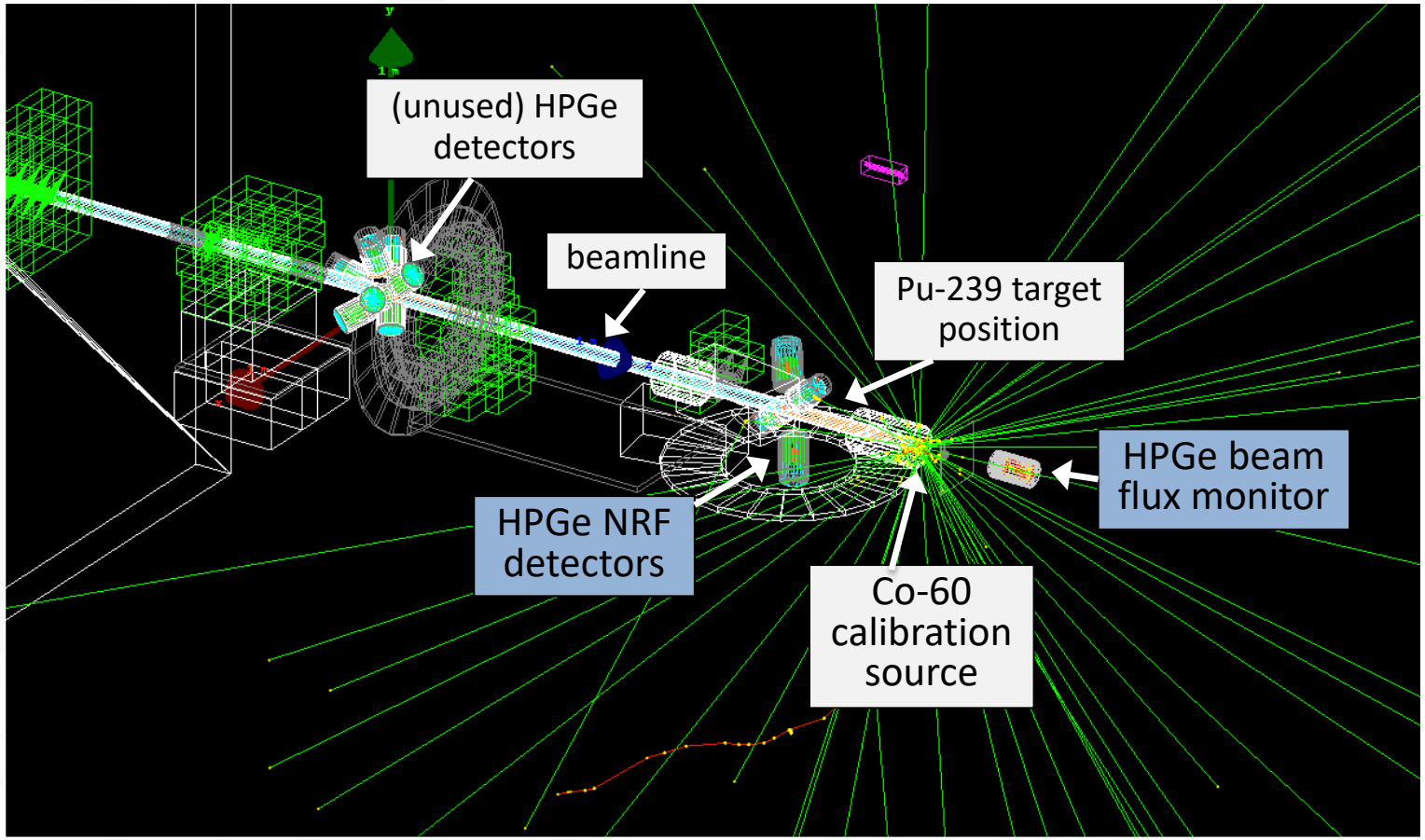
- Pu-239 direct NRF experiments at HIγS in 2010-11
  - specifically designed for absolute cross section measurements
  - aim for < 5 % cross section uncertainty
  - also extract level spin and parity J^{π}

- Aims to improve on existing data (Bertozzi et al, PRC 2008):
  - cross section uncertainties of 15-75%
  - no J^{π} determined
  - normalized against Al-27 2.212 MeV NRF line

MIT/LLNL/TUNL Pu-239 NRF analysis

HIγS 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

Acknowledgements

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