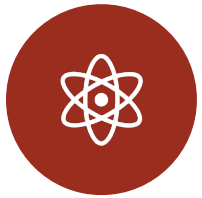
DEVELOPMENT OF A PORTABLE SYSTEM FOR EPITHERMAL NEUTRON RESONANCE ANALYSIS

ETHAN KLEIN*, AREG DANAGOULIAN

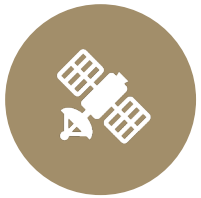
2020 MTV Conference
University of Michigan | Ann Arbor, MI

LABORATORY FOR NUCLEAR SECURITY AND POLICY

OUTLINE



OVERVIEW OF NEUTRON RESONANCE-BASED TECHNIQUES



APPLICATIONS OF EPITHERMAL NEUTRON RESONANCE-BASED TECHNIQUES

MONTE CARLO OPTIMIZATION OF MOBILE SYSTEM

EXPERIMENTAL RESULTS

CONCLUSION & NEXT STEPS

NEUTRON IMAGING FOR NUCLEAR SECURITY

"The United States will continue its efforts to…seek arms control agreements that enhance security, and are ***verifiable and enforceable.***"

"Further, the United States remains committed to finding ***long-term solutions to the technical challenges of verifying nuclear reductions***, and therefore will explore new concepts and approaches for this goal."

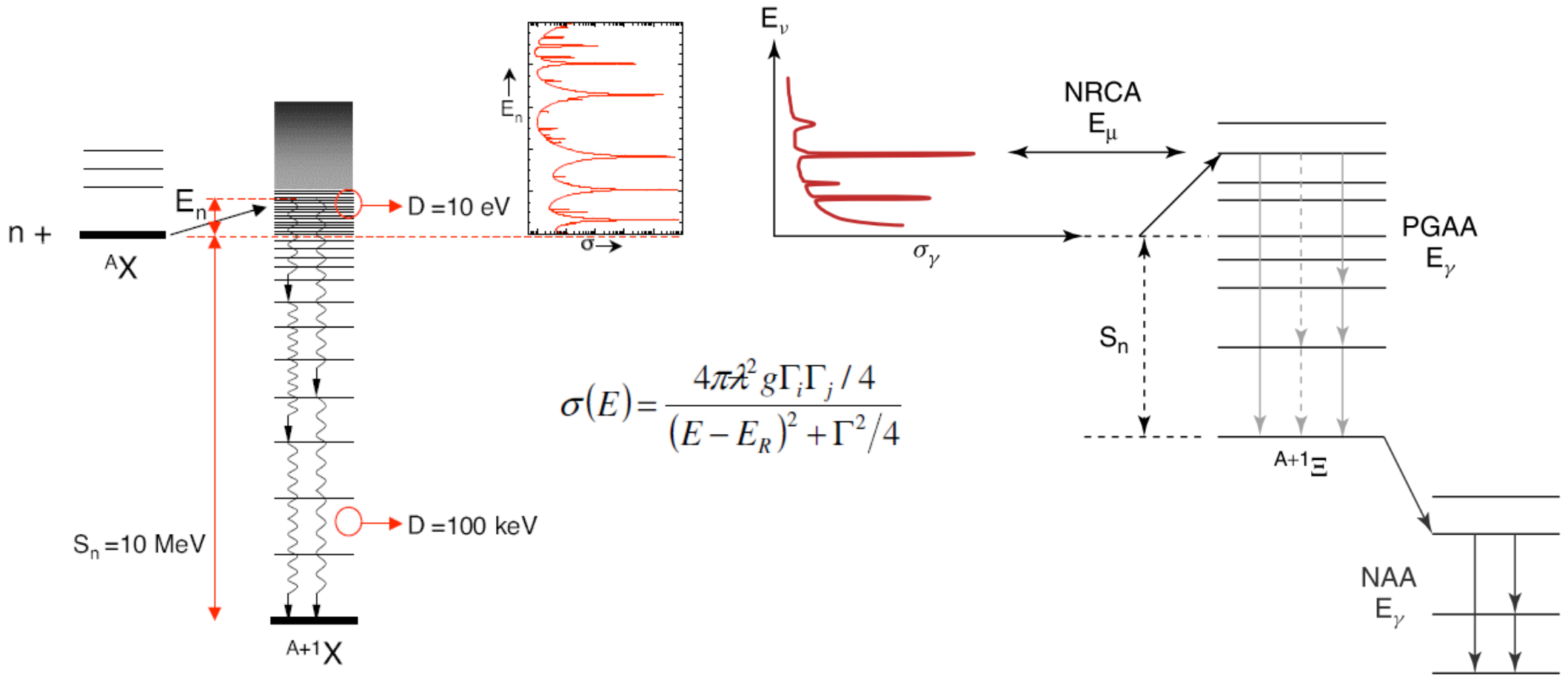
- U.S. Nuclear Posture Review (2018)

"R&D Needs: Enhance the set of expert tools necessary to process the variety of safeguards-relevant information and implement them, with ***emphasis on timely responses and cost-effectiveness***."

"***Improve analytical timeliness*** of dealing with special and high priority demands for analysis by means of the reduction of sample size, the ***application of in-situ analysis*** and by strengthening the response regime"

- IAEA Safeguards R&D Plan (2018)

THEORY OF NEUTRON RESONANCES

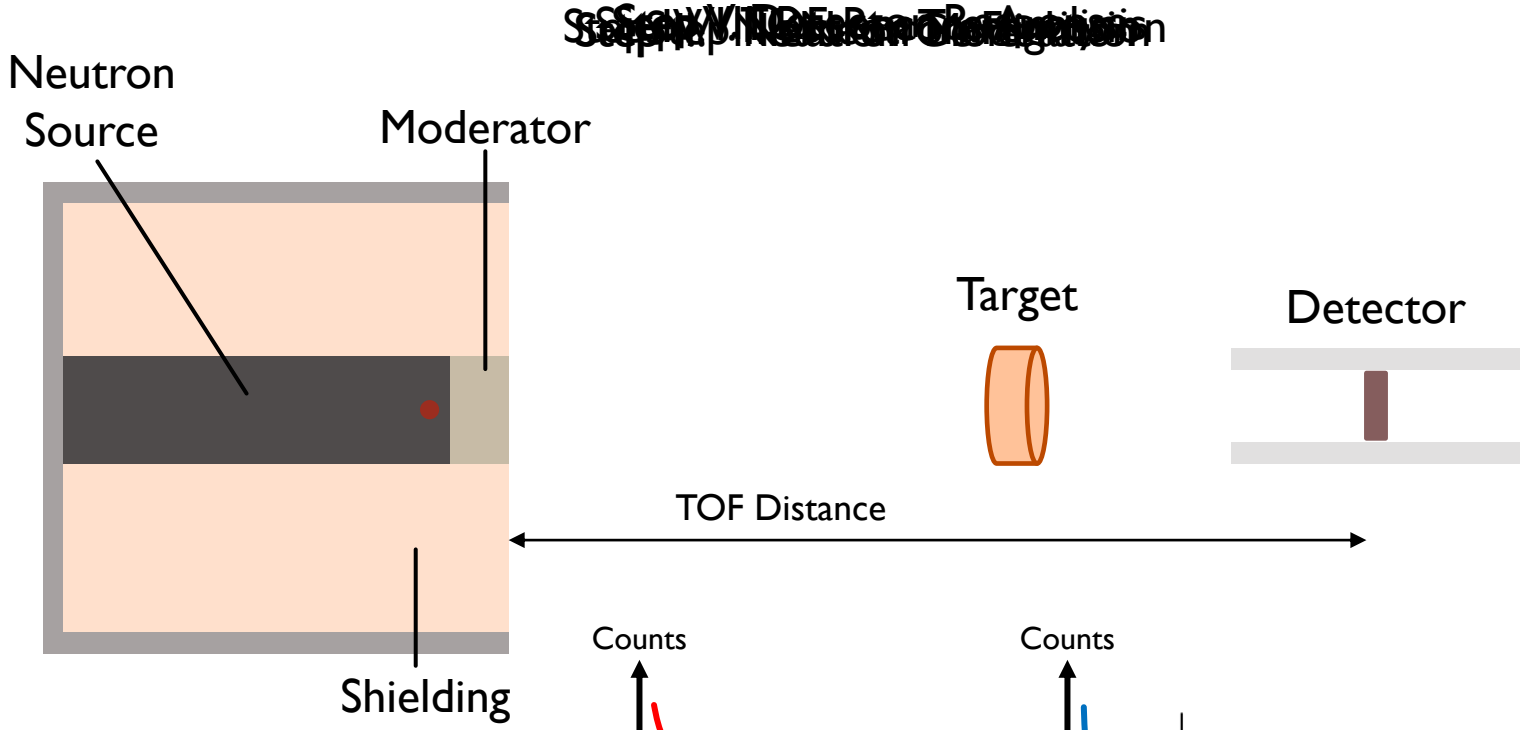


$$\sigma(E) = \frac{4\pi\lambda^2 g\Gamma_i\Gamma_j / 4}{(E - E_R)^2 + \Gamma^2/4}$$

Source: Neutron Resonance Spectroscopy, Frank Gunsing, 2005.

Source: Postma and Schillebeeckx (2009)

NEUTRON RESONANCE TRANSMISSION ANALYSIS



Time-of-Flight Energy Reconstruction:

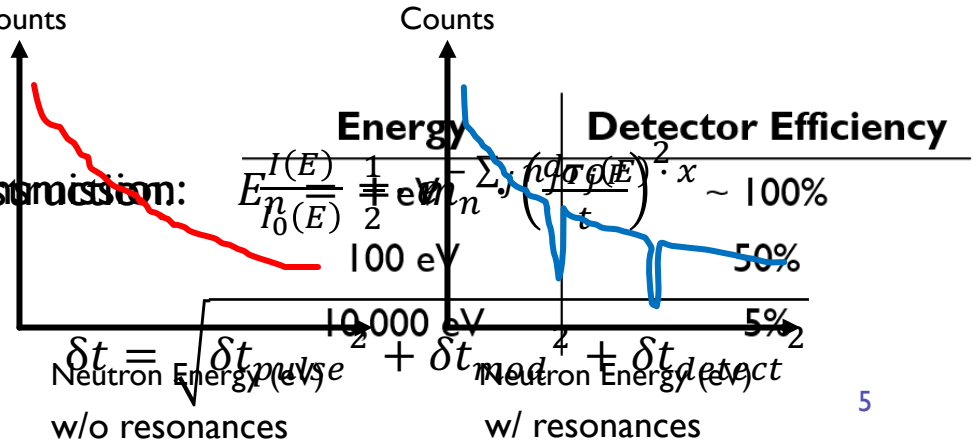
$$E_n = \frac{1}{2} m_n \left(\frac{L}{t}\right)^2$$

Neutron Transmission:

$$\frac{I(E)}{I_0(E)} = e^{-\sum_j \left(n_j \sigma_j(E)\right) \cdot x}$$

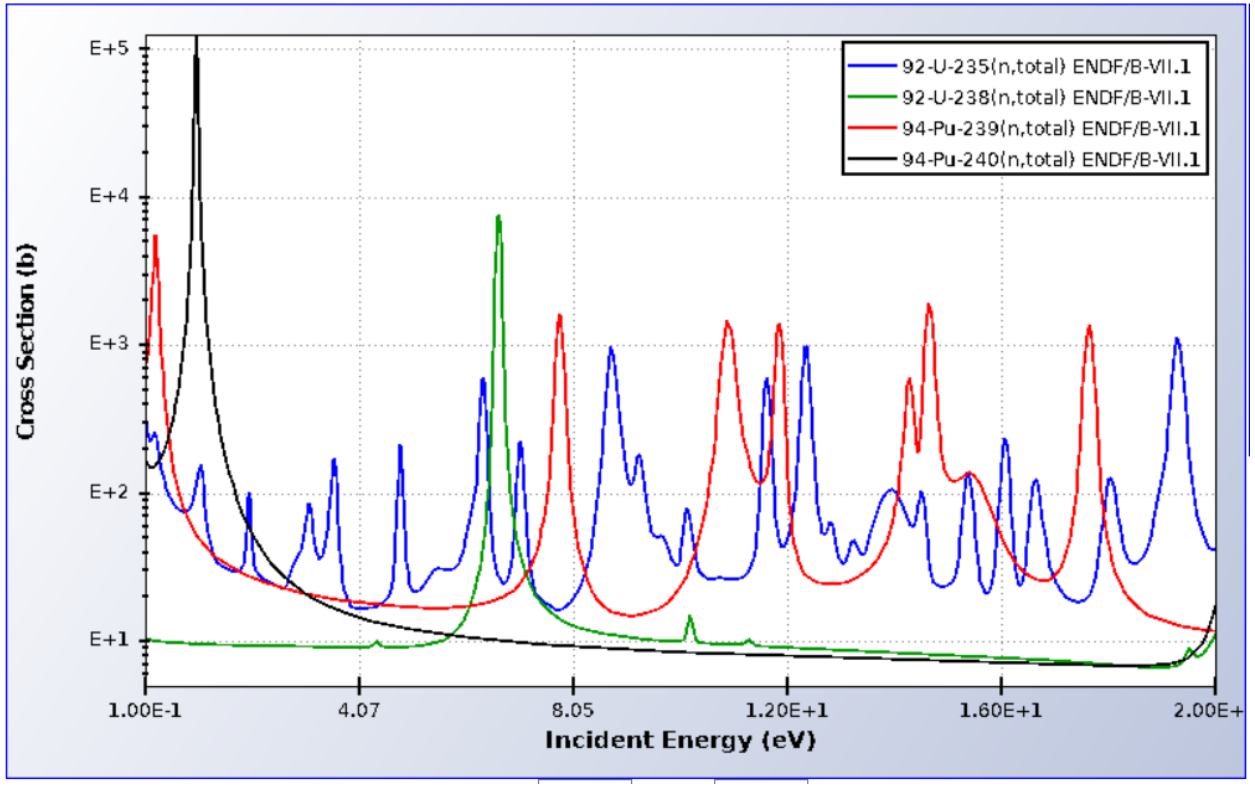
Uncertainty in Time-of-Flight:

$$\delta t = \sqrt{\delta t_{pulse}^2 + \delta t_{mod}^2 + \delta t_{detect}^2}$$



FEATURES OF EPITHERMAL NRTA

- **Isotopic signatures for Special Nuclear Material (U-235, U-238, Pu-239, Pu-240)**
- No epithermal resonances for common shielding materials (H, C, O, Al, Fe, Pb) – reasonable penetration
- Induced nuclear reactions, e.g. (n, γ), can provide additional information for material identification



Source: National Nuclear Data Center

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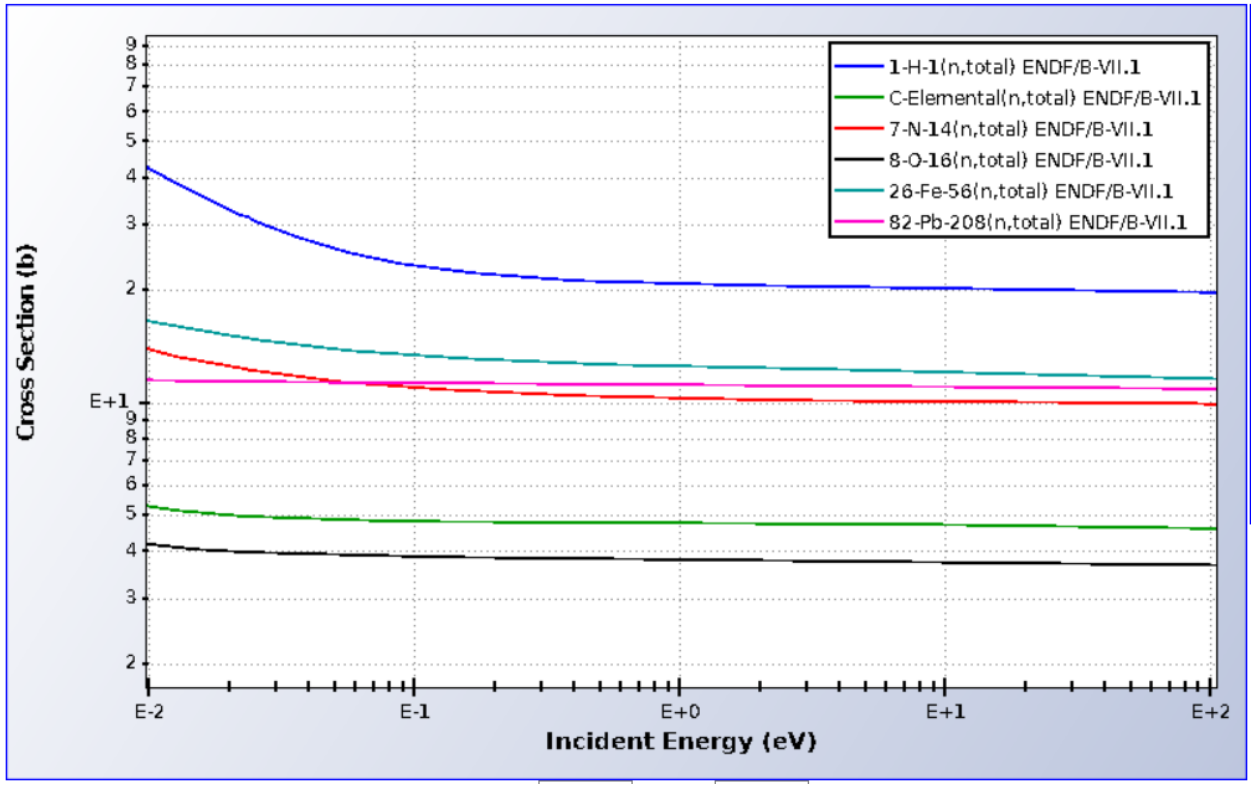

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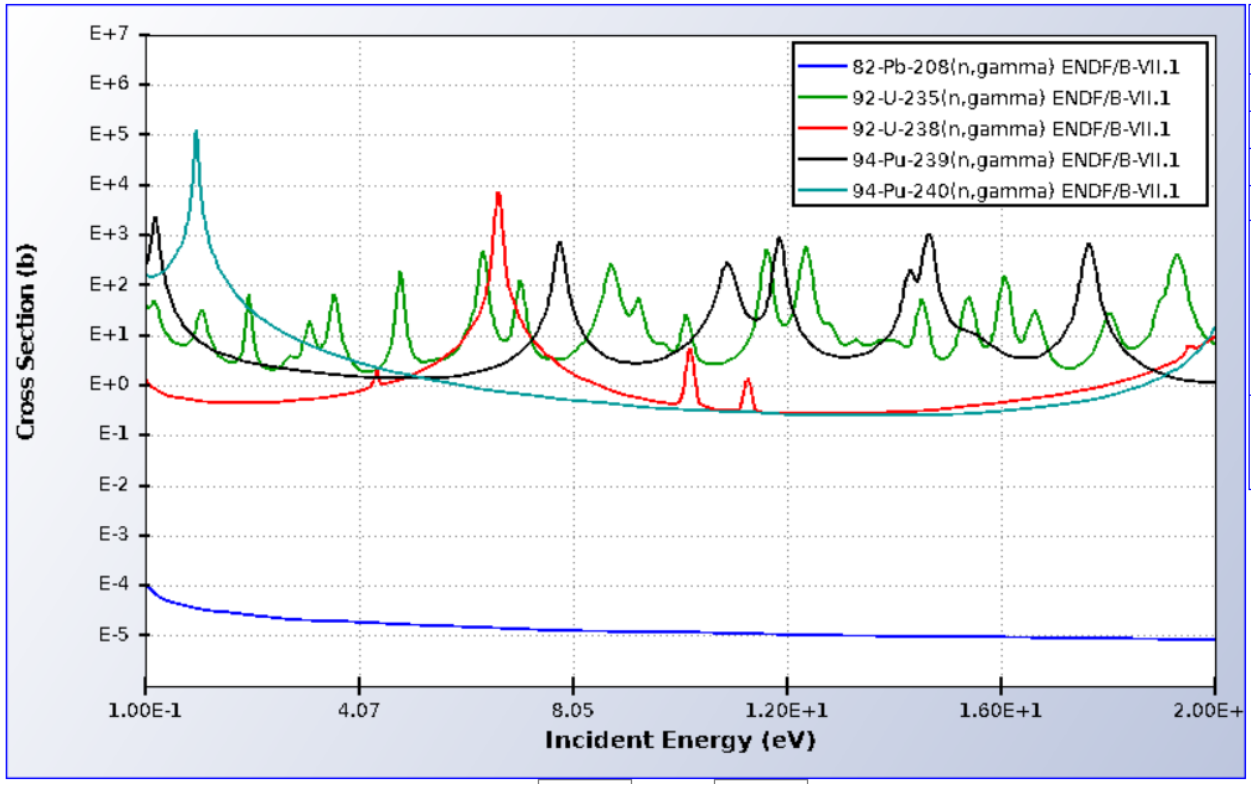
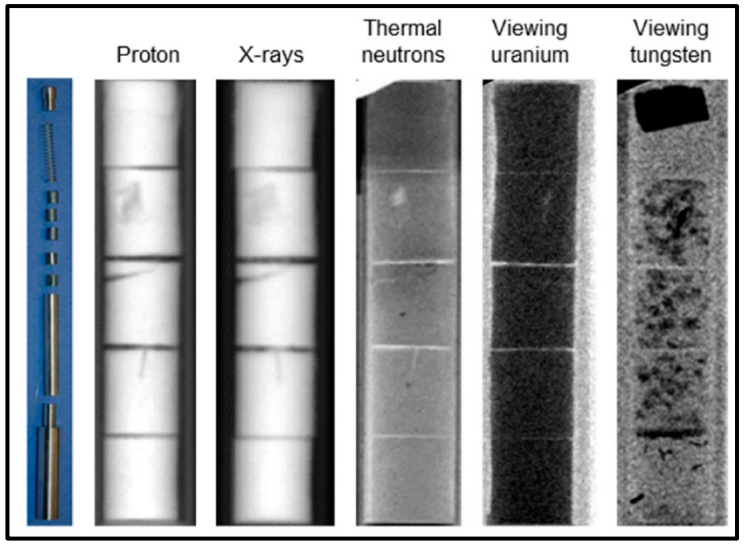


Source: National Nuclear Data Center

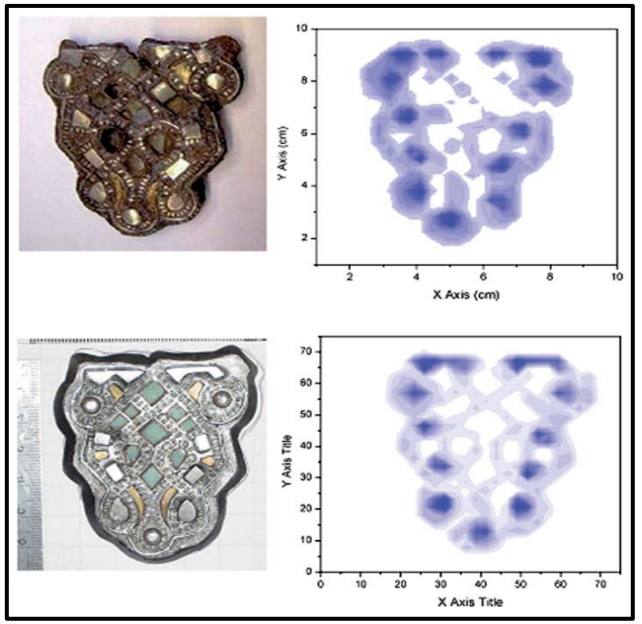
CURRENT STATE OF AFFAIRS

- Epithermal NRTA demonstrated for applications requiring isotopic sensitivity of high-Z materials (e.g. Ag, W)
- Experiments conducted at large-scale user facilities (TOF distances ~ 25m) to maximize energy resolution and neutron flux
- Improvements in portable neutron generators and position-sensitive neutron detectors



Quality Analysis of Nuclear Fuel Pellets

Nelson, R. O. et al. 2018. "Neutron Imaging at LANSCE -- From Cold to Ultrafast." *Journal of Imaging* 4 (2): 45.



Isotopic Imaging of Archaeological Objects

Cippo, E.P., et al. 2011. "Imaging of Cultural Heritage Objects Using Neutron Resonances." *J. Anal. At. Spectrom.* 26 (5): 992–99.

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NIST Center for Neutron Research

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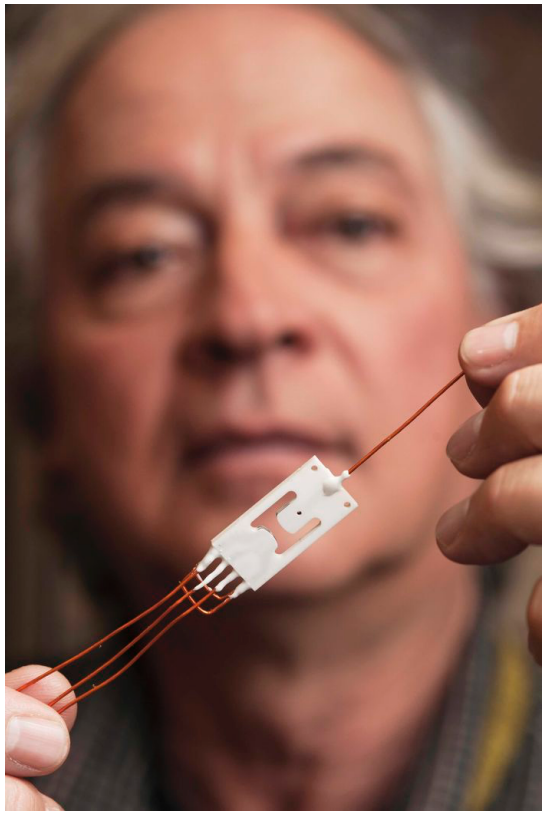
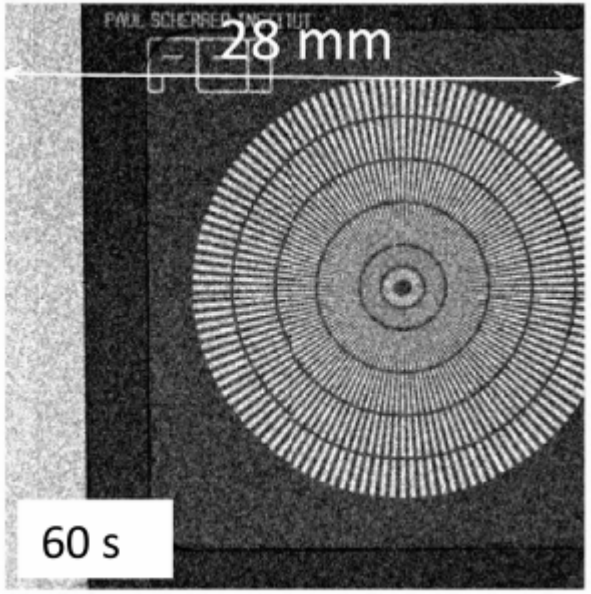


Source: Sandia National Laboratories



Tremsin, A.S., et al. 2018. "Digital Neutron and Gamma-Ray Radiography in High Radiation Environments with an MCP/Timepix Detector." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 902 (September): 110–16.

DEVELOPING A MOBILE EPITHERMAL NRTA SYSTEM

- Experimental Challenges
  - Decreased neutron flux
    (longer measurement times)
  - Limitations on neutron shielding
  - Environmental variations
  - Limitations on time-of-flight distance

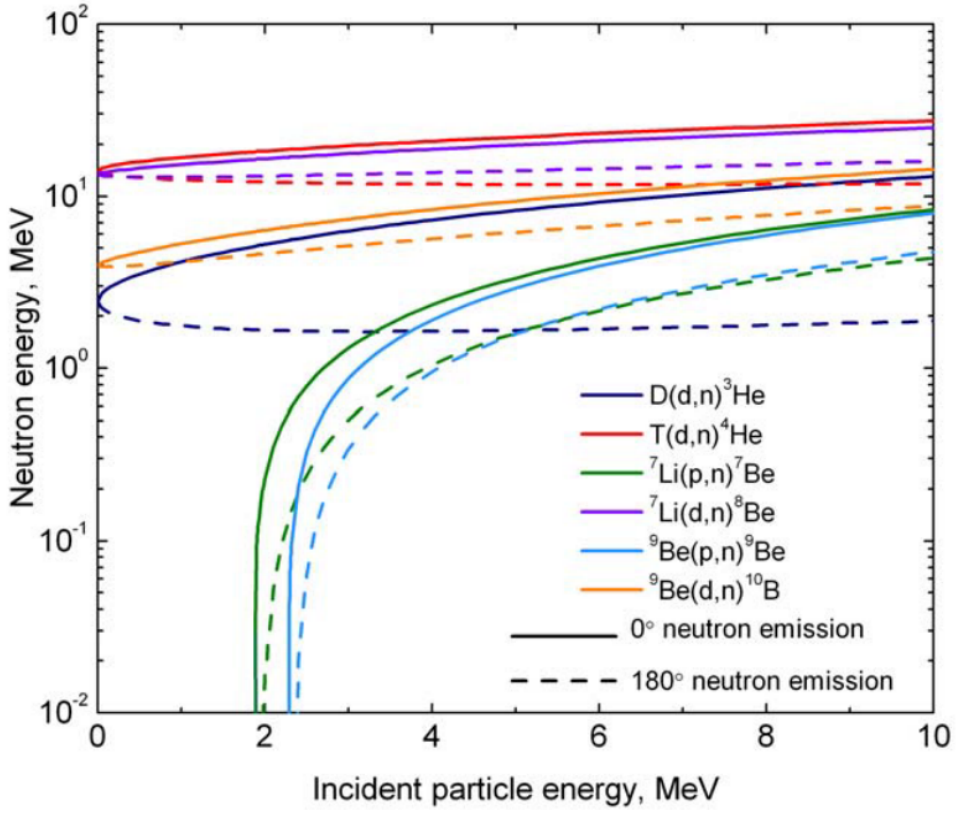
Biggest challenge for in-situ epithermal neutron imaging is **developing a mobile, collimated epithermal neutron beam!**

NEUTRON GENERATION

Table 2 Common nuclear reactions particle accelerators use to produce neutrons.

Reaction	Shorthand	Q Value [MeV]	Threshold Energy [MeV]	Minimum Product Energies [MeV]	
$^{2}H + {}^{2}H \rightarrow {}^{3}He + n$	$^{2}H(d,n)^{3}He$	+3.269	NA	^{3}He: 0.82	n: 2.45 *
$^{2}H + {}^{3}H \rightarrow {}^{4}He + n$	$^{3}H(d,n)^{4}He$	+17.589	NA	^{4}He: 3.54	n: 14.05
$^{1}H + {}^{7}Li \rightarrow {}^{7}Be + n$	$^{7}Li(p,n)^{7}Be^{\dagger}$	-1.644	1.880	^{7}Be: 0.21	n: 0.03
	$^{1}H(^{7}Li,n)^{7}Be^{\dagger}$	-1.644	13.094	^{7}Be: 10.0	n: 1.44
$^{2}H + {}^{7}Li \rightarrow {}^{8}Be + n$	$^{7}Li(d,n)^{8}Be$	+15.031	NA	^{8}Be: 1.68	n: 13.35
$^{1}H + {}^{9}Be \rightarrow {}^{9}B + n$	$^{9}Be(p,n)^{9}B$	-1.850	2.057	^{9}B: 0.18	n: 0.023
$^{2}H + {}^{9}Be \rightarrow {}^{10}Be + n$	$^{9}Be(d,n)^{10}B$	+4.361	NA	^{10}B: 0.40	n: 3.96

Notes: * The probability that the $^{2}H + {}^{2}H$ (DD) reaction produces a neutron is roughly equal to the probability that the reaction results in ^{3}H + a proton.
† There are competing end products for this reaction



Source: Chichester, D. L. 2012. "Production and Applications of Neutrons Using Particle Accelerators." In *Industrial Accelerators and Their Applications*, 243–305. World Scientific.

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D-T Fusion-Based

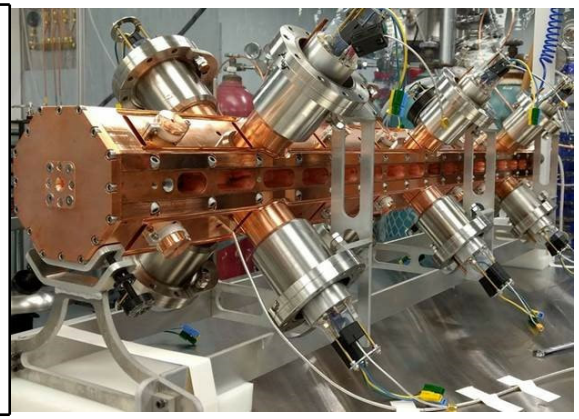
- Yield: 5.0 E+08 n/s
- Min. Pulse Width: 5 us
- Energy: ~14 MeV
- Weight: 12kg

p-Li Reaction-Based

- Yield: 5.0 E+08 n/s
- Min. Pulse Width: 5 us
- Energy: ~50 keV
- Weight: 350kg

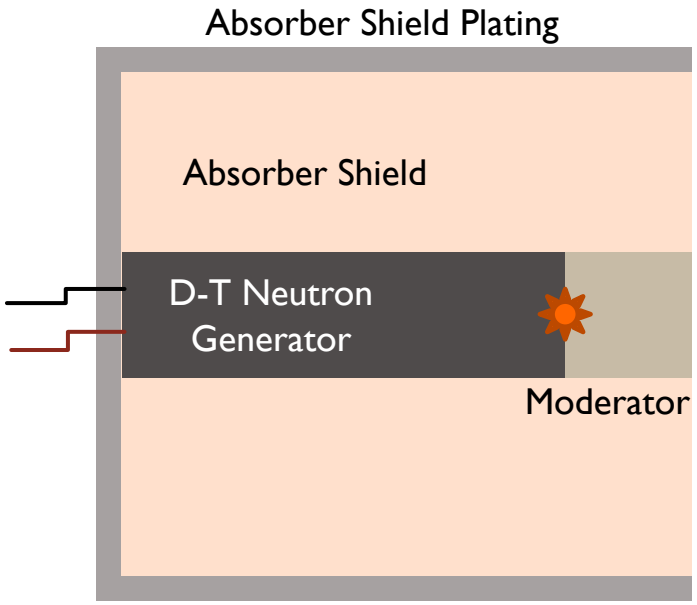
The picture can't be displayed.

Source: ThermoFisher Scientific

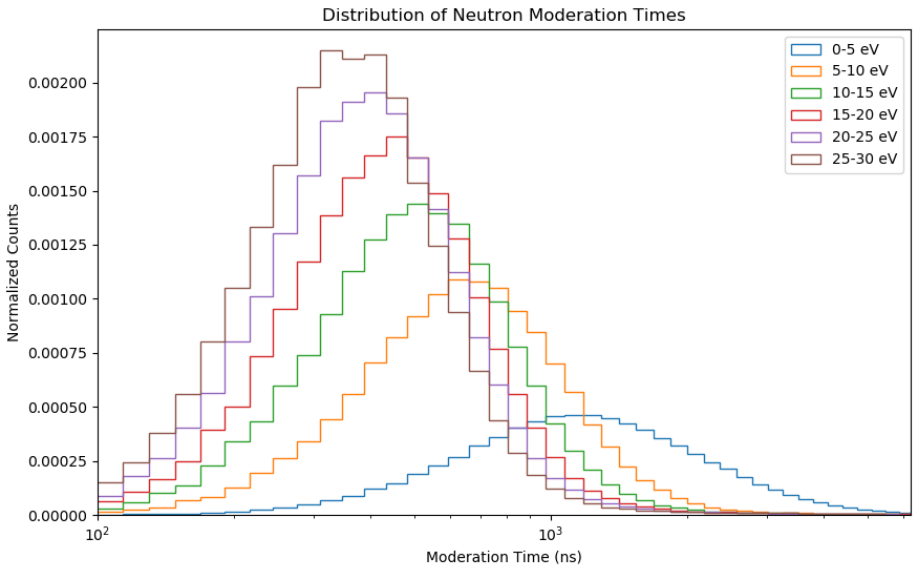


Source: Starfire Industries

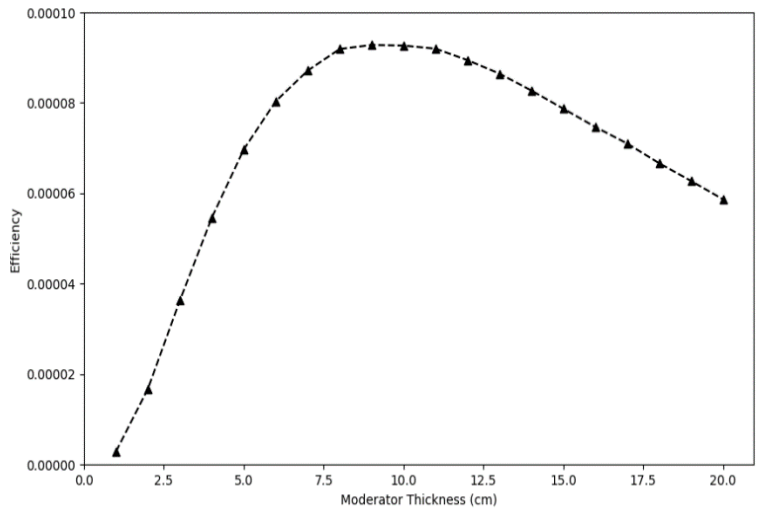
CONSTRUCTION OF AN EPITHERMAL NEUTRON BEAM



HDPE is moderator of choice, but other options are available



Δt_{MOD} increases for decreasing energy, $\boldsymbol{\mathcal{O}}(100ns - 1\mu s)$



$\epsilon_{epi}\ peaks\ at \sim 0.0001$

Neutron flux $\propto \frac{1}{r^2}$

TARGET TRANSMISSION

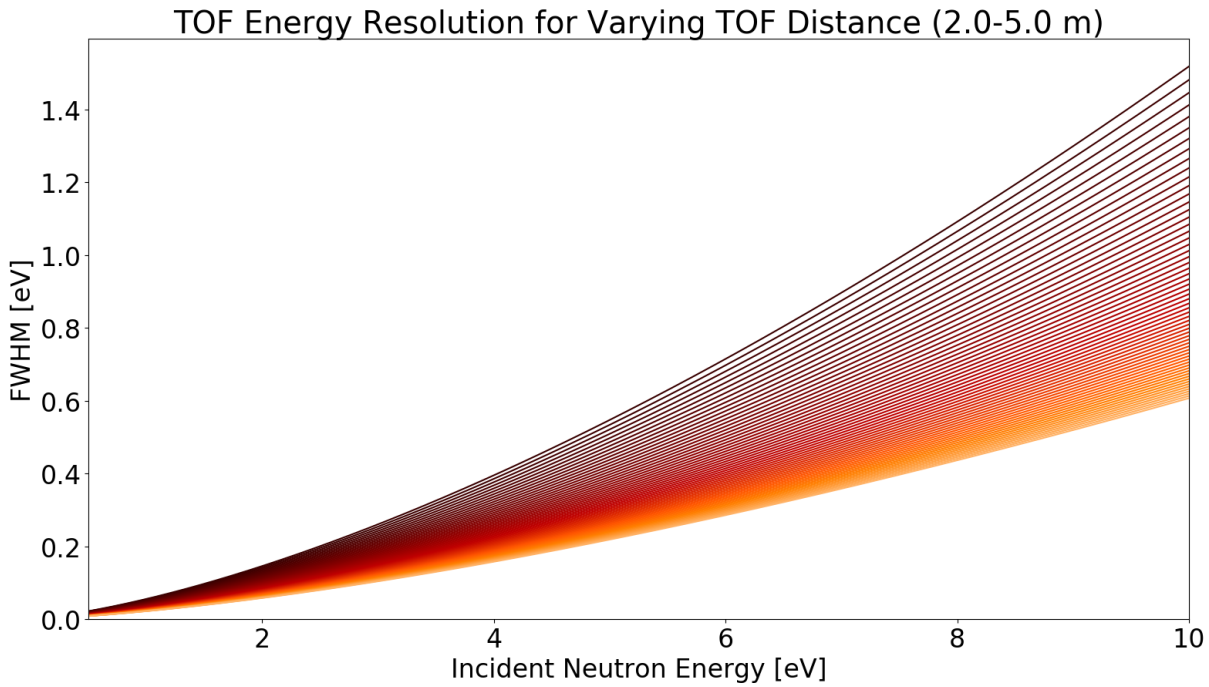
- Given parameters of experimental apparatus, for a given E_n , ΔE_n is a function of l_{TOF} :

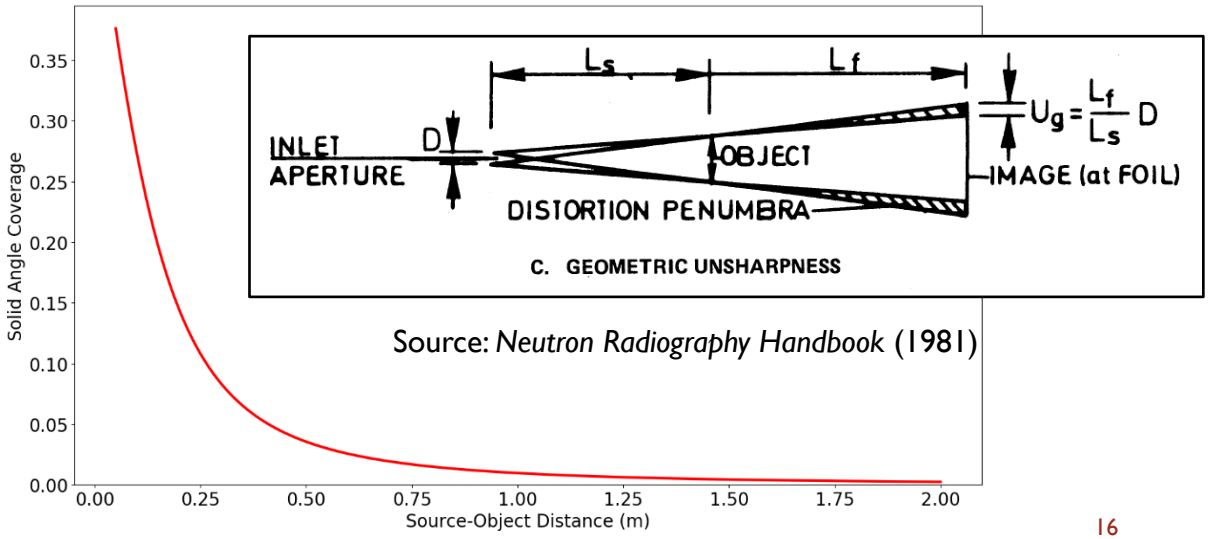
$$\frac{\Delta E_n}{E_n} = \frac{2}{l_{TOF}} \sqrt{\frac{E}{\alpha^2} \Delta t_{TOF}{}^2 + \Delta l_{TOF}{}^2}$$

- Choice of l_{TOF} fixes sum of Source-Object distance (l_s) and Object-Detector distance (l_f) :

$$l_{TOF} = l_s + l_f$$

- Choice of $\frac{l_s}{l_f}$ ratio determines trade-off between Φ_n incident on object and unsharpness, U_g of isotopic image





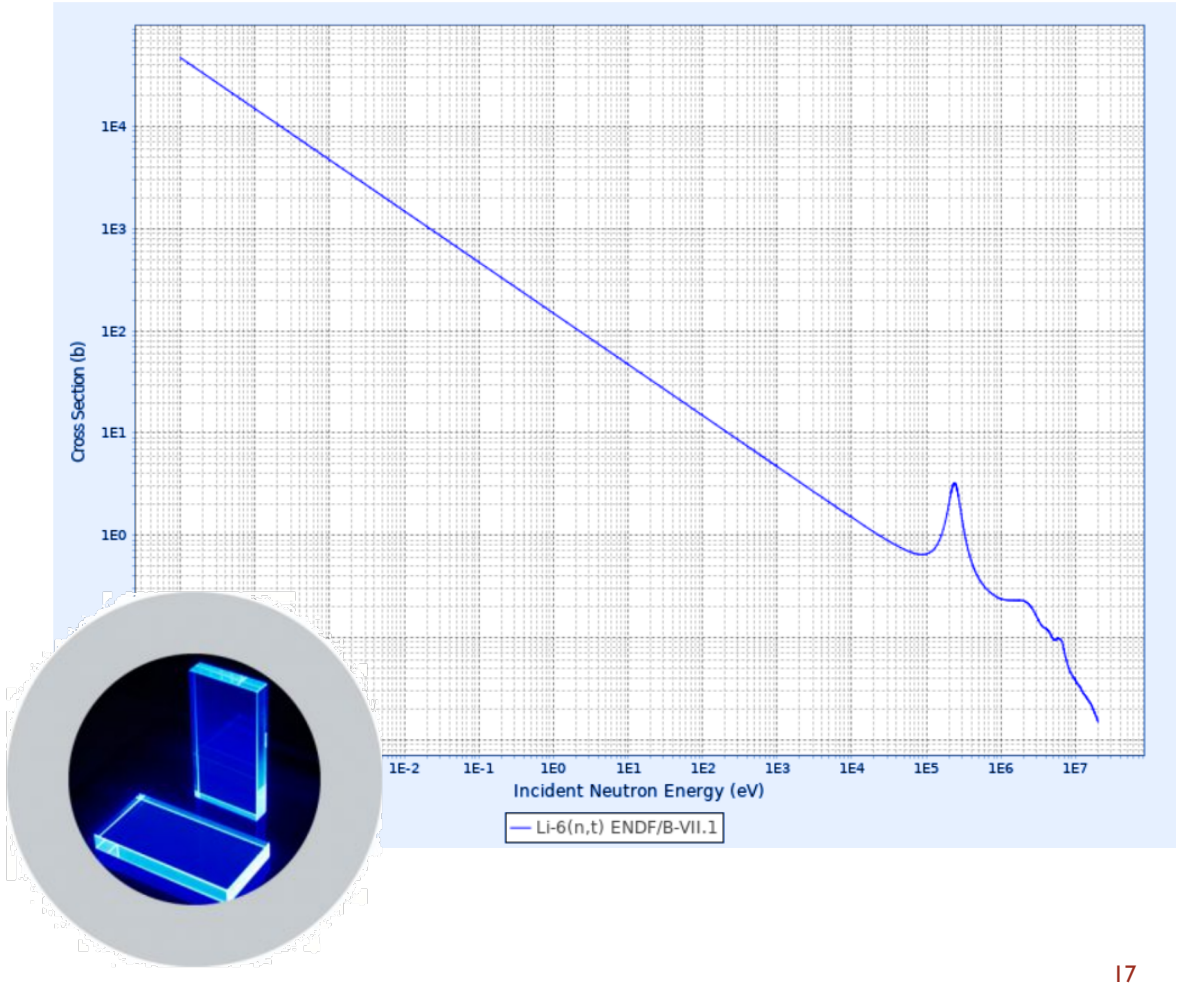
Source: *Neutron Radiography Handbook* (1981)

EPITHERMAL NEUTRON DETECTION

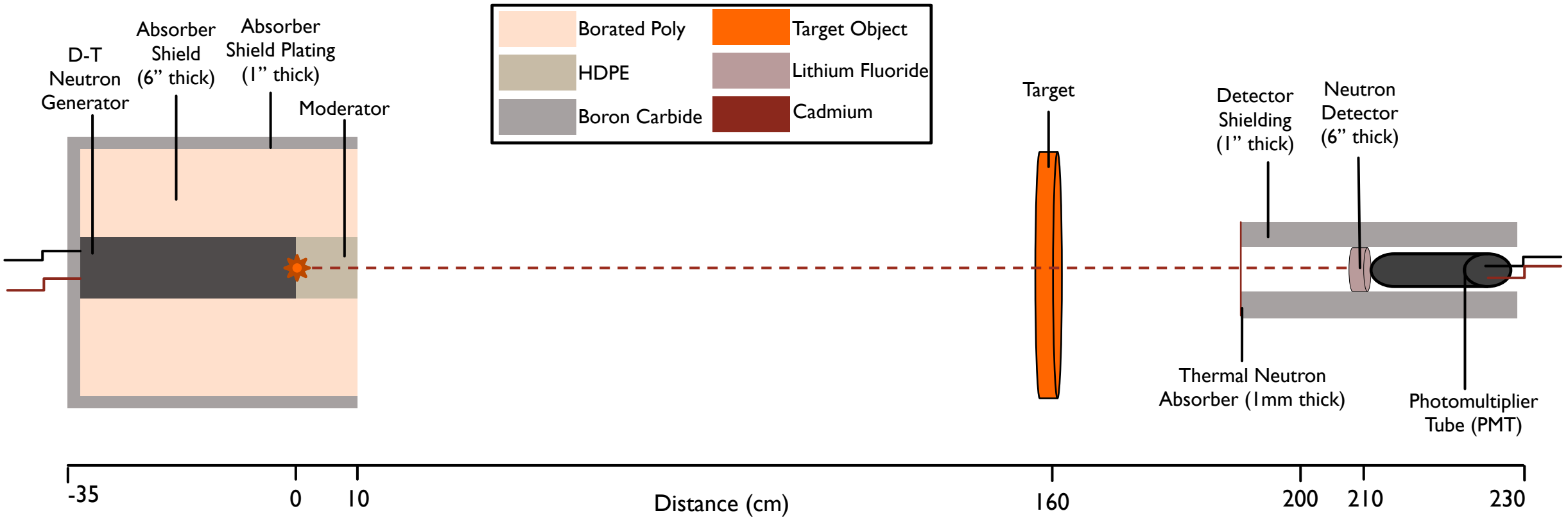
^{6}Li-doped, Ce-activated aluminosilicate glass

$$^{6}\mathrm{Li} + \mathrm{n} \longrightarrow \alpha + {}^{3}\mathrm{H} \quad Q = 4.78\ MeV$$

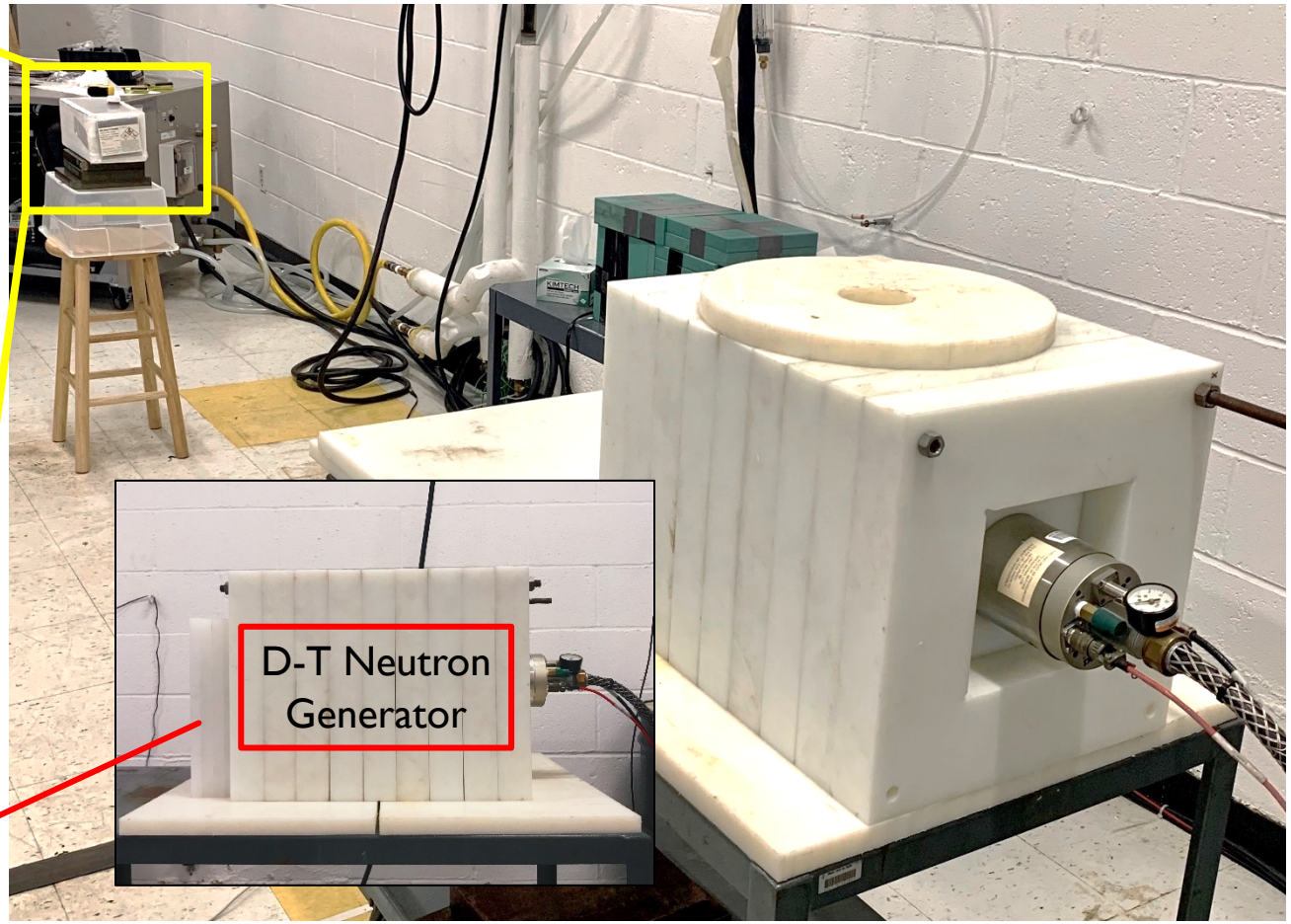
Properties	GS20*
Light output relative to anthracene*	20-30%
Decay times†, neutron excitation, ns	18, 57 & 98
Decay times†, alpha excitation, ns	16, 49 & 78
Decay times†, beta excitation, ns	20, 58 & 105
Alpha/beta ratio	0.23
Wavelength of emission max [nm]	395
Refractive index at emission maximum	1.55
Resolution on the thermal neutron "peak" obtained with moderated Po/Be neutrons	15-28%
Peak/through ratio of above "peak" (range)	10:1 - 40:1



MONTE CARLO OPTIMIZED EPITHERMAL NRTA APPARATUS



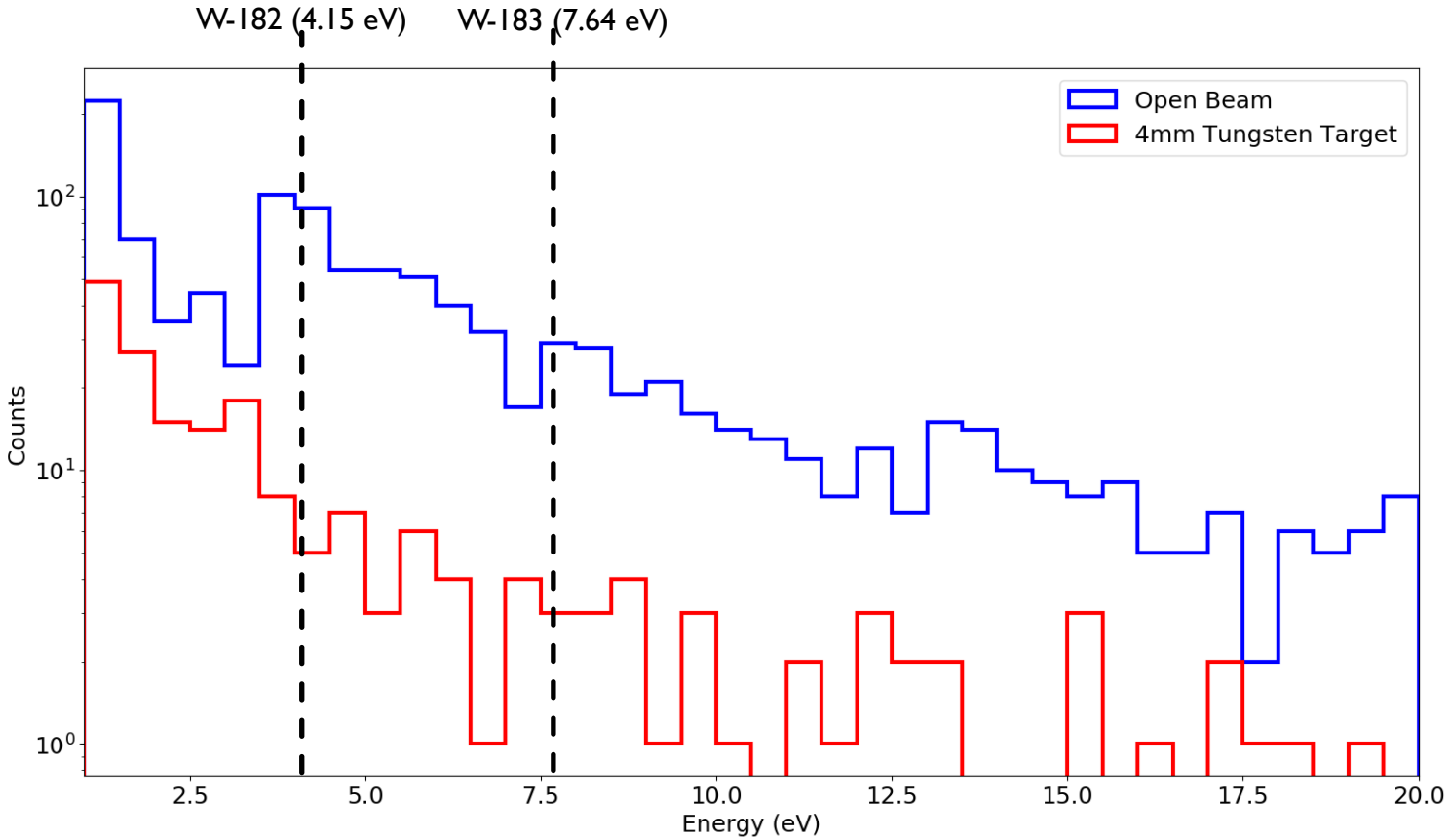
CURRENT EXPERIMENTAL SETUP

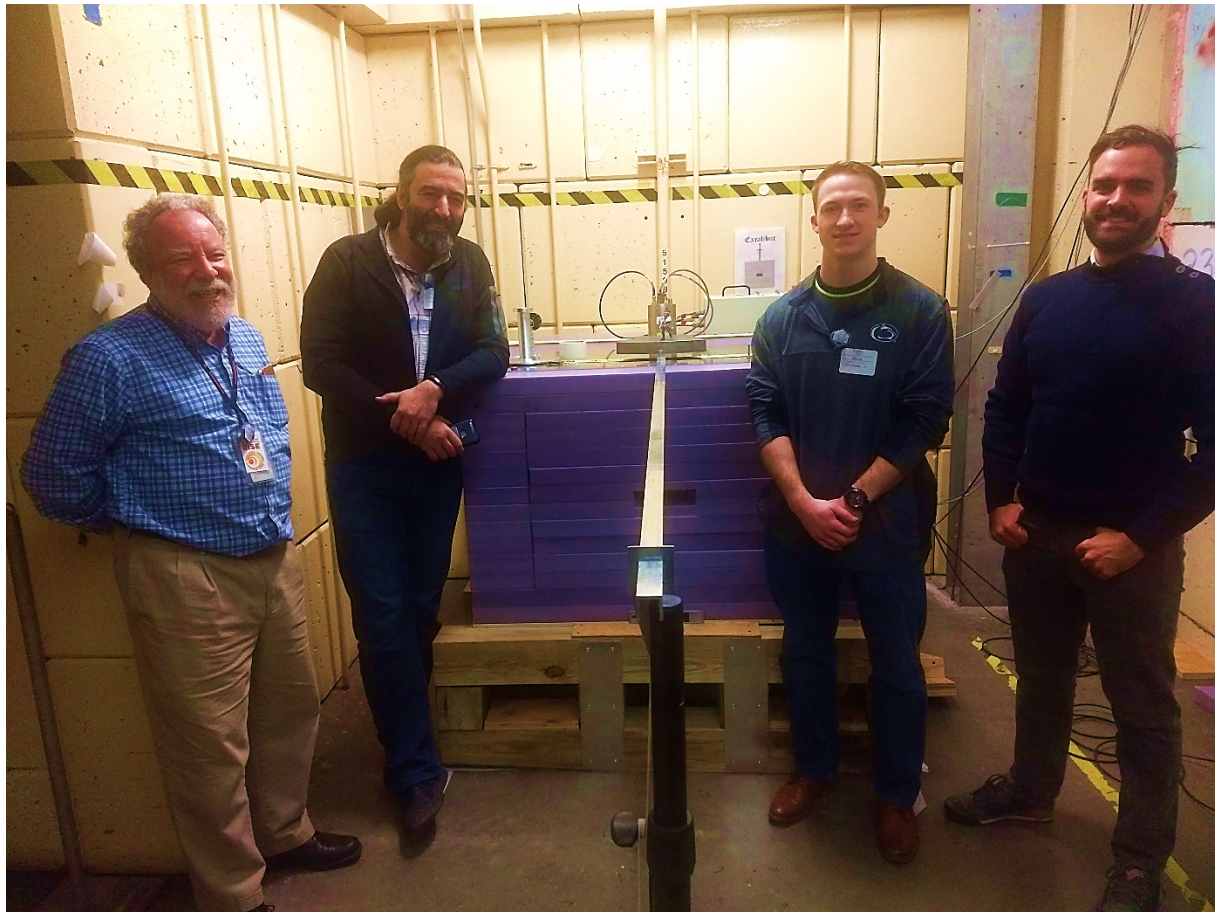


EXPERIMENTAL RESULTS USING A325 D-T GENERATOR

Experimental Parameters:

- TOF Distance: $2.00\ m$
- D-T Pulse Rate: $5\ kHz$
- D-T Duty Cycle: 5%
- D-T Pulse Width: $10\ \mu s$
- Run Time: $30\ min$



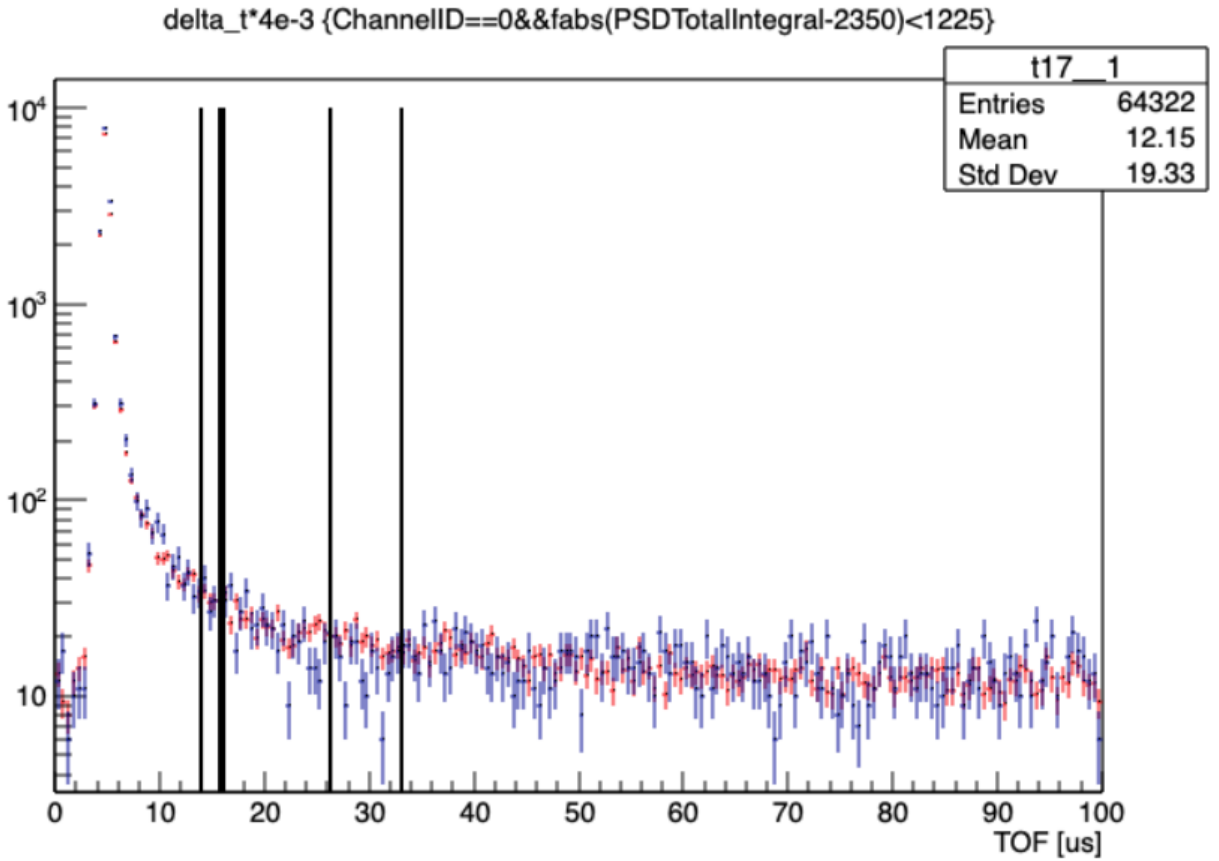


MIT VISIT TO PRINCETON (PPPL)

JANUARY 2020

EXPERIMENTAL RESULTS FROM PPPL VISIT

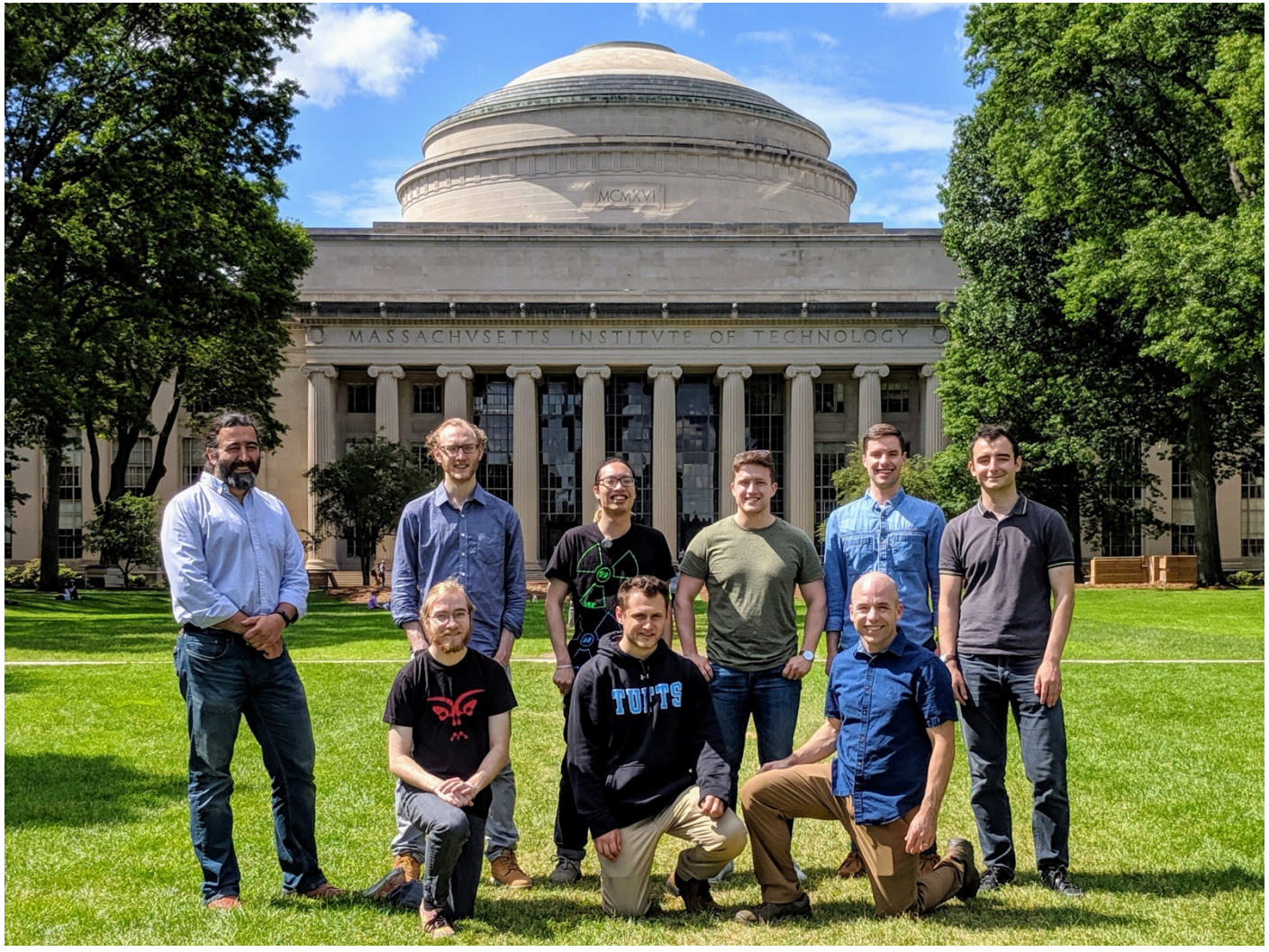
- Red spectrum is open beam
  Blue spectrum is 1.5cm tungsten (W) target
- Majority of counts likely γ rays produced via (n, γ) reactions on surrounding steel
- Statistically significant deviation between the two spectra in $24 - 32\ \mu s$ TOF region, approximately corresponding to the combination of the 4.2 and $7.6\ eV$ resonances of the W target



CONCLUSIONS

- Epithermal neutron imaging is an isotopically sensitive technique with significant potential for nuclear security applications
- Monte Carlo simulations demonstrate feasibility of a mobile epithermal NRTA system for isotopic characterization of high-Z composite materials
- Preliminary experimental results indicate that commercial D-T portable neutron generators are insufficient for epithermal NRTA operational requirements
- Portable accelerators for near-threshold reactions (e.g. $^{7}Li(p,n)^{7}Be$) show significant promise for this technique and require further study

ACKNOWLEDGEMENTS

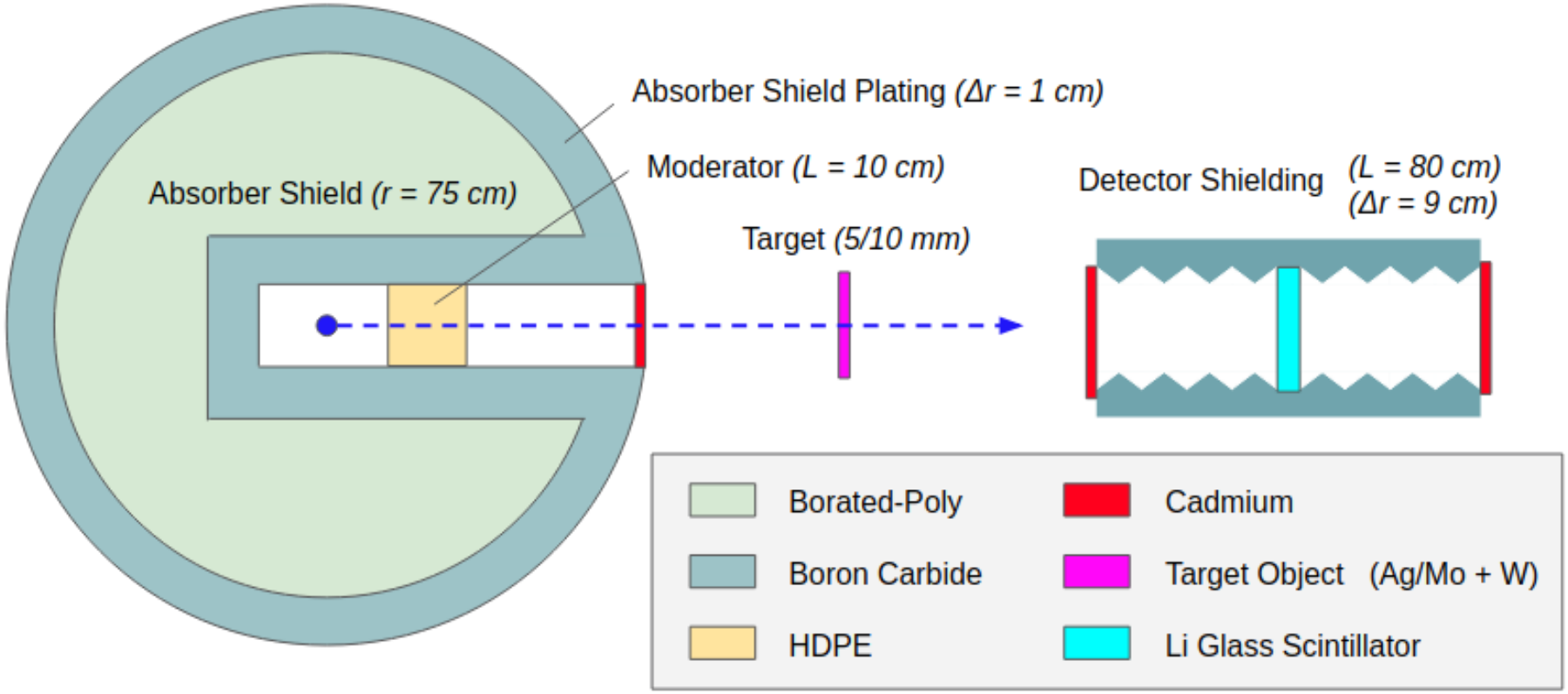


NSE
Nuclear Science & Engineering at MIT
SCIENCE : SYSTEMS : SOCIETY

National Nuclear Security Administration

CONSORTIUM FOR MONITORING TECHNOLOGY AND VERIFICATION

BACKUP SLIDES



MONTE CARLO OPTIMIZED EPITHERMAL NRTA APPARATUS

(NOTE: NOT DRAWN TO SCALE)