COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Norfolk, Virginia
AccelApp'24

New Applications of Compact Accelerators in Security and Nonproliferation

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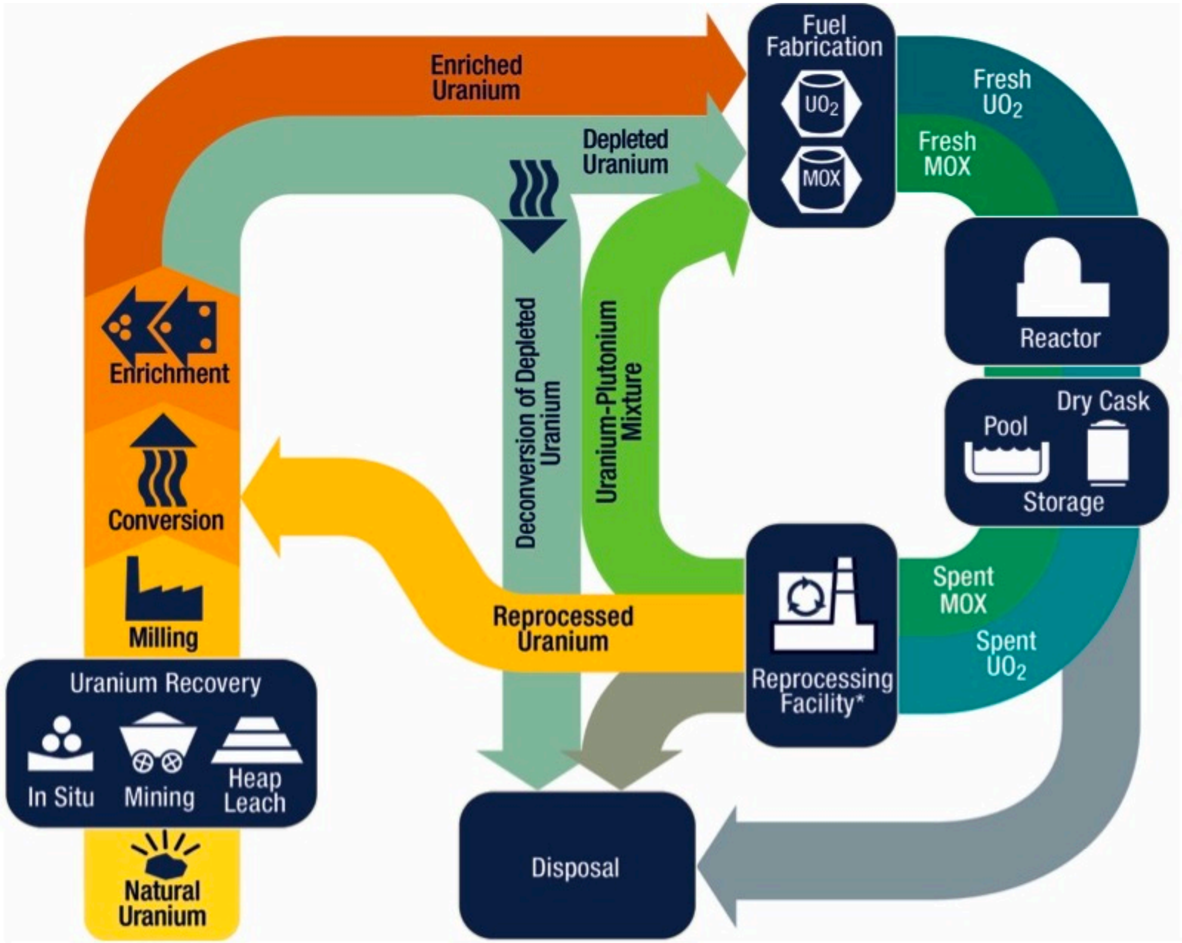
Overview

- The nuclear security and nonproliferation context
- RFQs / cyclotrons → dual-particle multiple-monoenergetic radiography
- Compact neutron generators → neutron die-away and delayed neutrons
- Linacs / laser-driven sources → detection of photofission

Aspects of nuclear security and nonproliferation

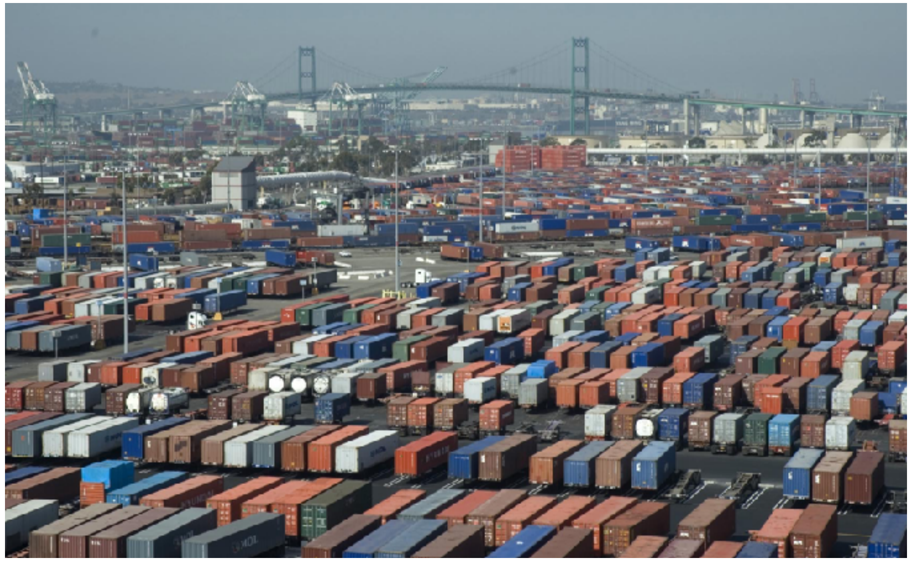


Monitoring of nuclear fuel cycle

Monitoring nuclear treaty compliance

Arms control

Aspects of nuclear security and nonproliferation

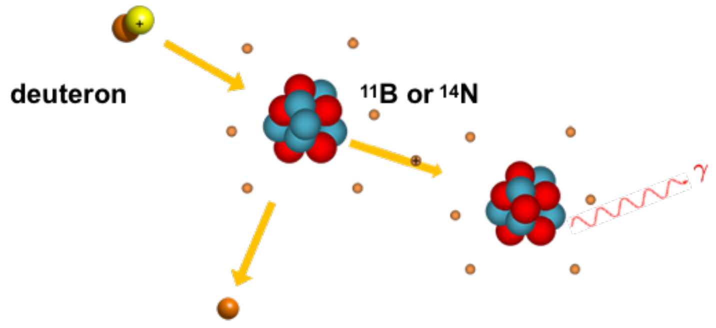


Cargo screening / detection of concealed SNM

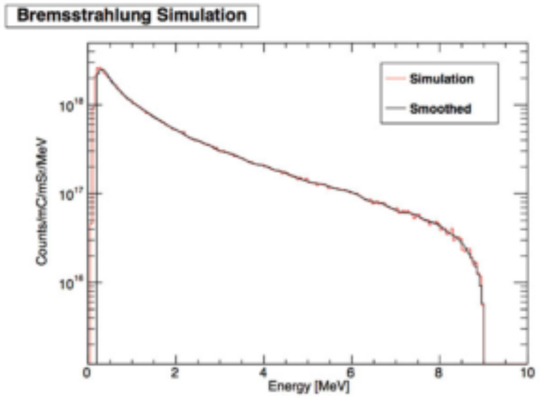
Nuclear forensics

Active interrogation sources based on compact accelerators

Ion-driven nuclear reactions

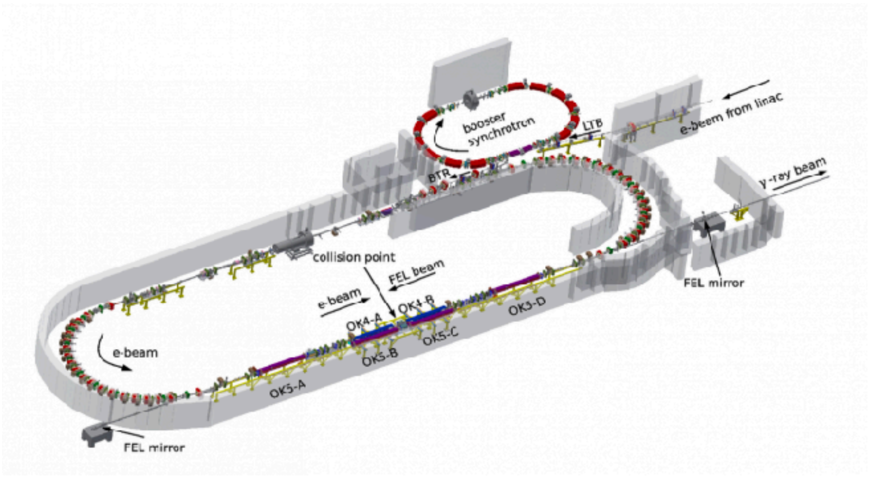


Bremsstrahlung sources



Neutron generators

Compton scattering sources



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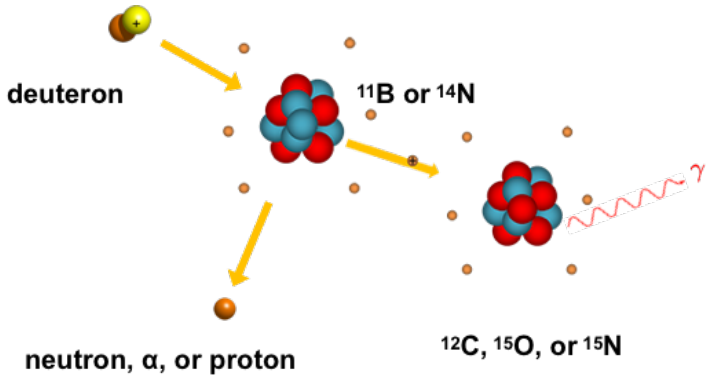
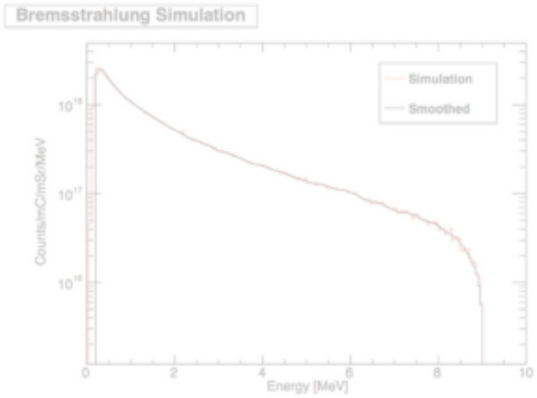
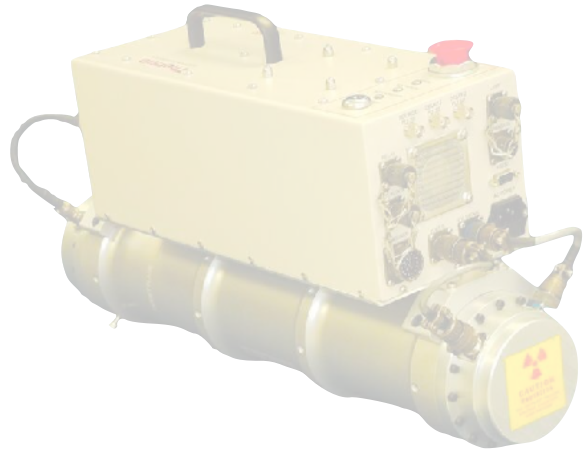


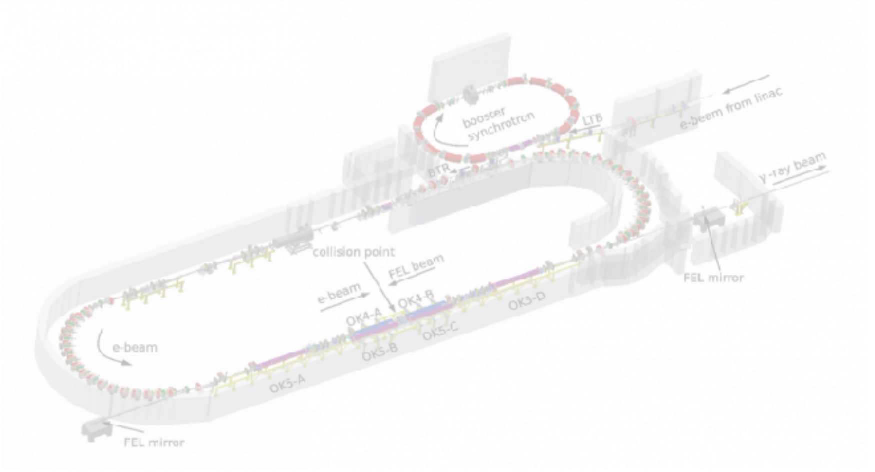
Bremsstrahlung sources



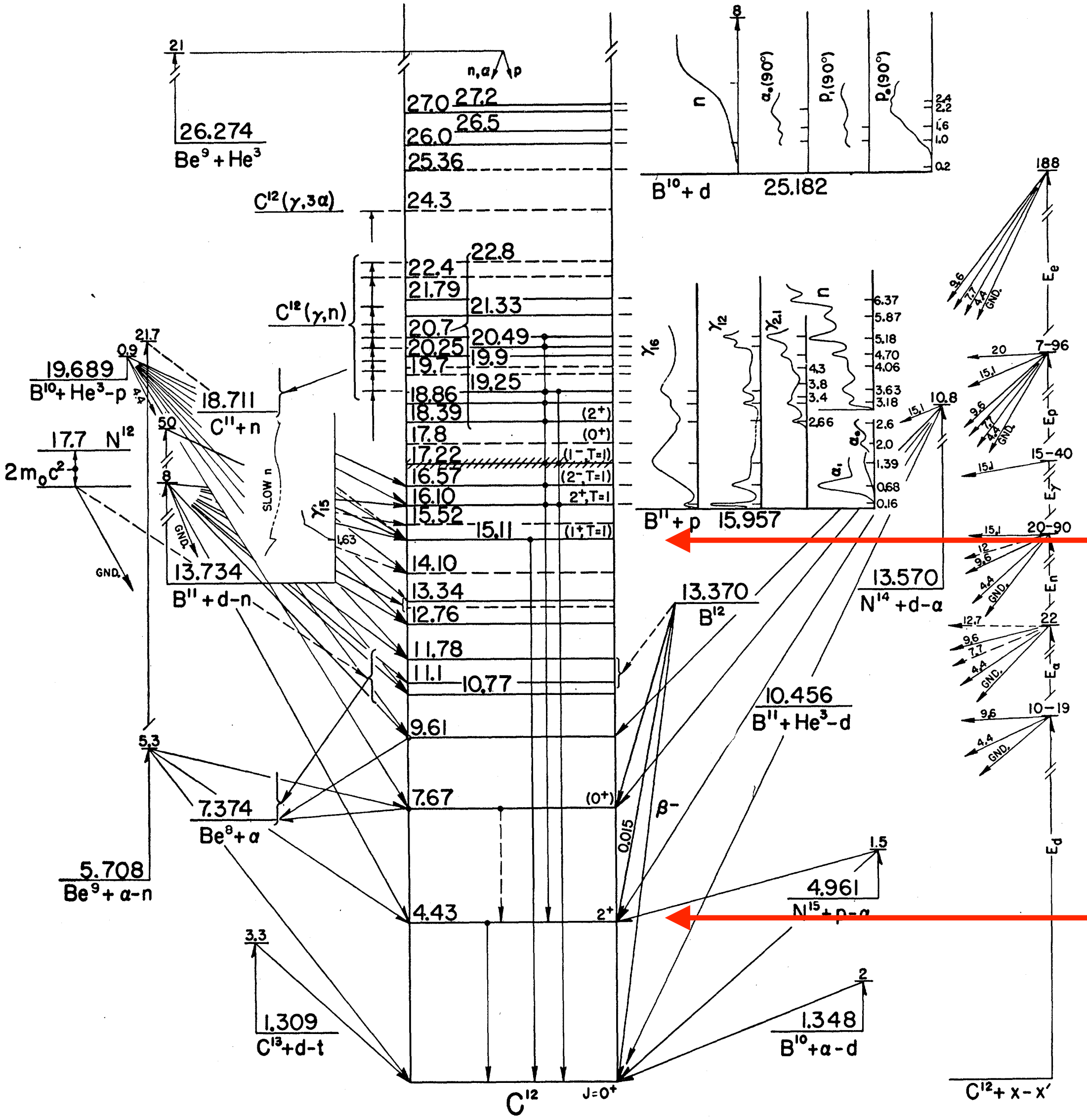
Neutron generators



Compton scattering sources



Ion-driven nuclear reactions can be used to efficiently produce characteristic gamma rays

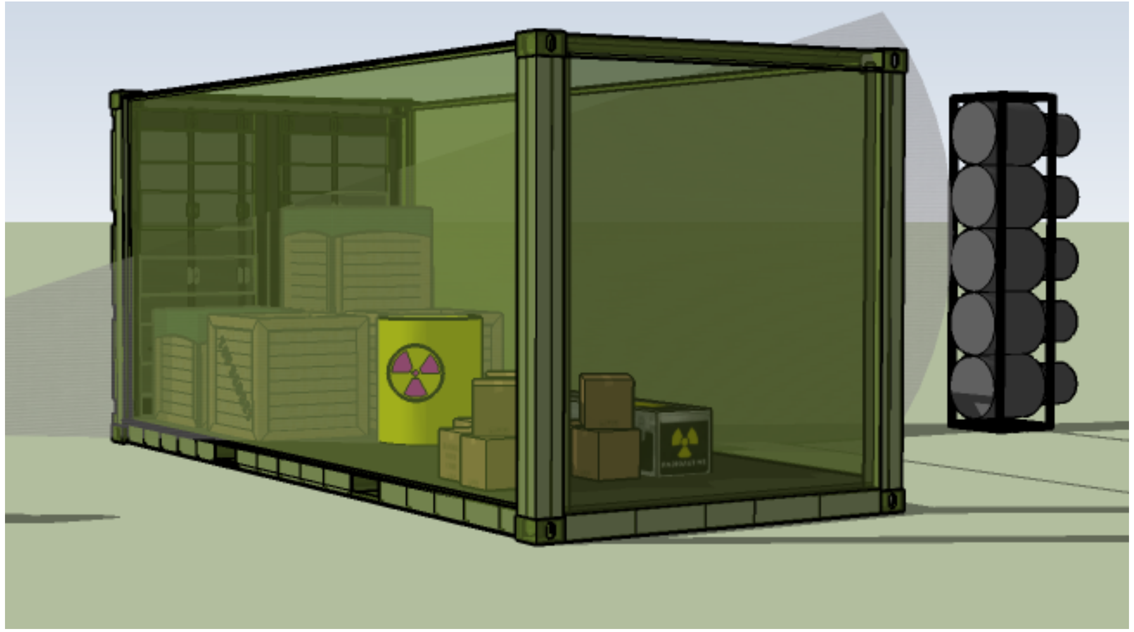


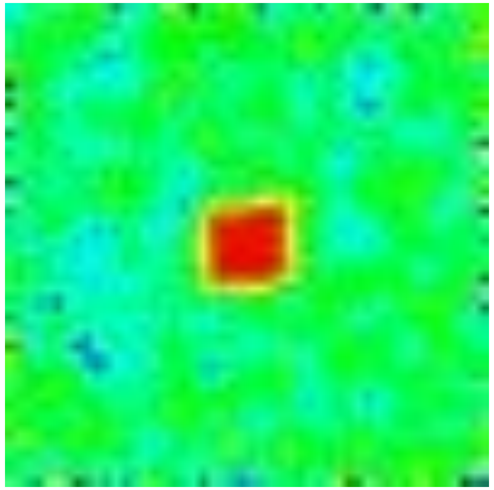
15.1 MeV - M1 (1⁺ → 0⁺)

4.438 MeV - E2 (2⁺ → 0⁺)

^{11}B(d,n)^{12}C
Q = 13.73 MeV
E_{thr} = 1.63 MeV

Ion-driven nuclear reaction-based sources for active interrogation





100 cc U cube in 40 cm Fe block imaged with 15.1 MeV gammas (MCNPX simulation)

Multi-particle multiple-monoenergetic source

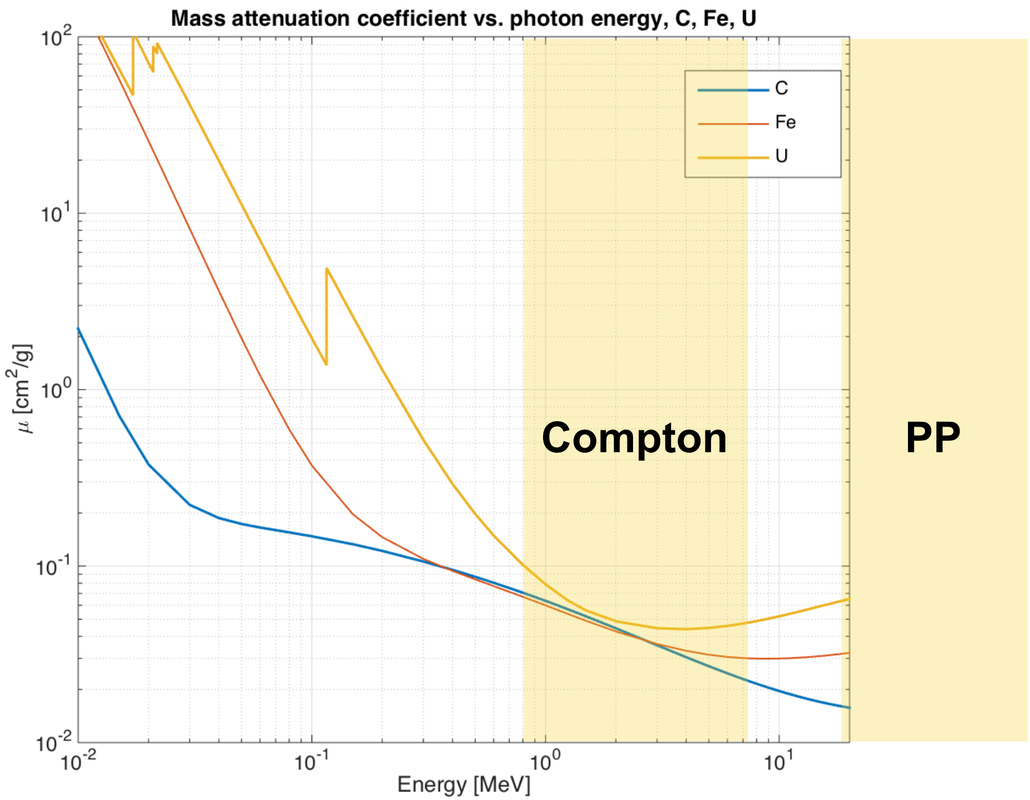
Multi-particle spectroscopic detectors

Dual-energy gamma transmission radiography → effective atomic number and areal density

$$\underbrace{\frac{\ln\left[I(E_1)/I_0(E_1)\right]}{\ln\left[I(E_2)/I_0(E_2)\right]}}_{\text{measured}} = \underbrace{\frac{\mu(E_1)}{\mu(E_2)}}_{\text{known nuclear data}}$$

measured

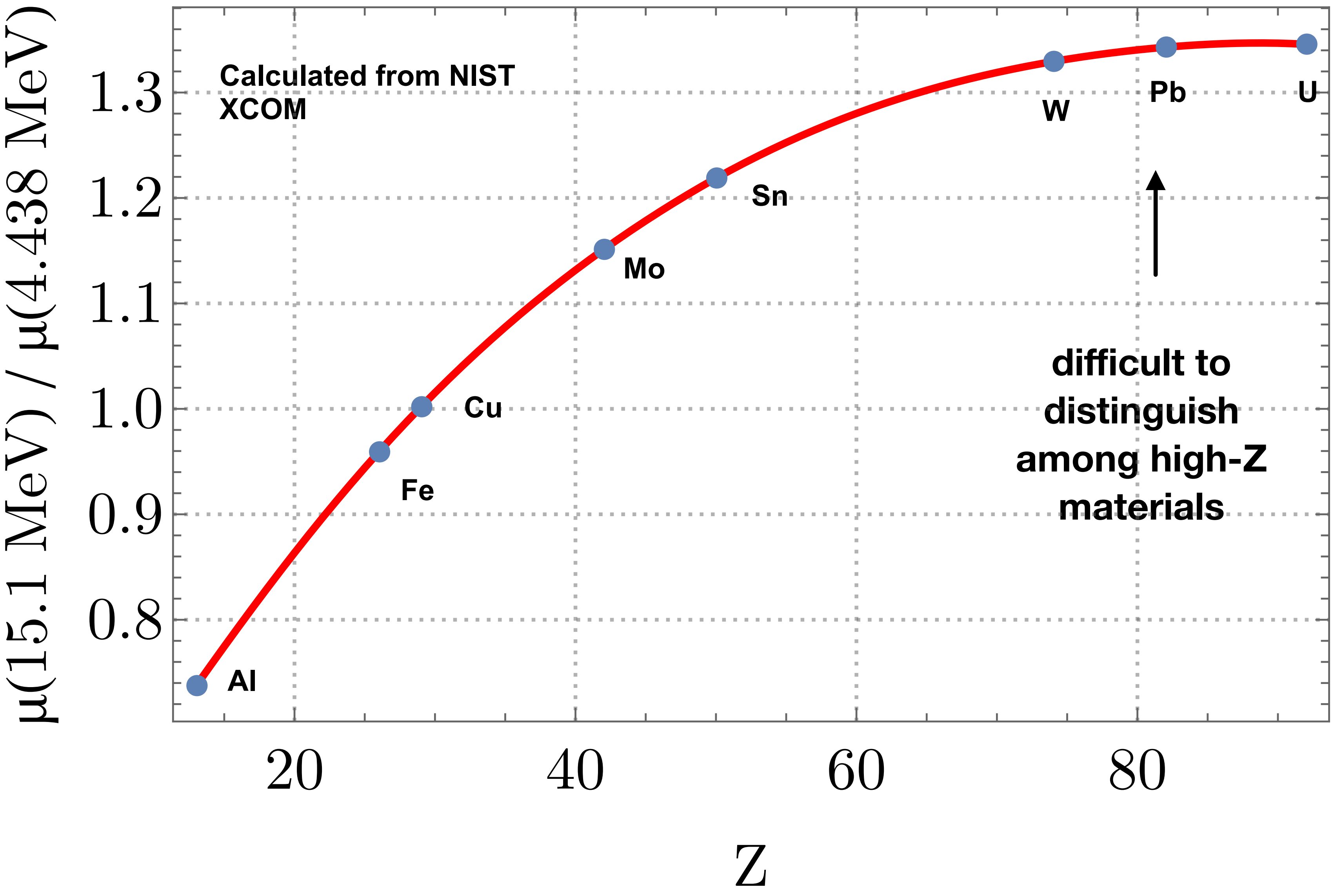
known nuclear data



Measurement 1: Compton dominant (4.4 MeV)

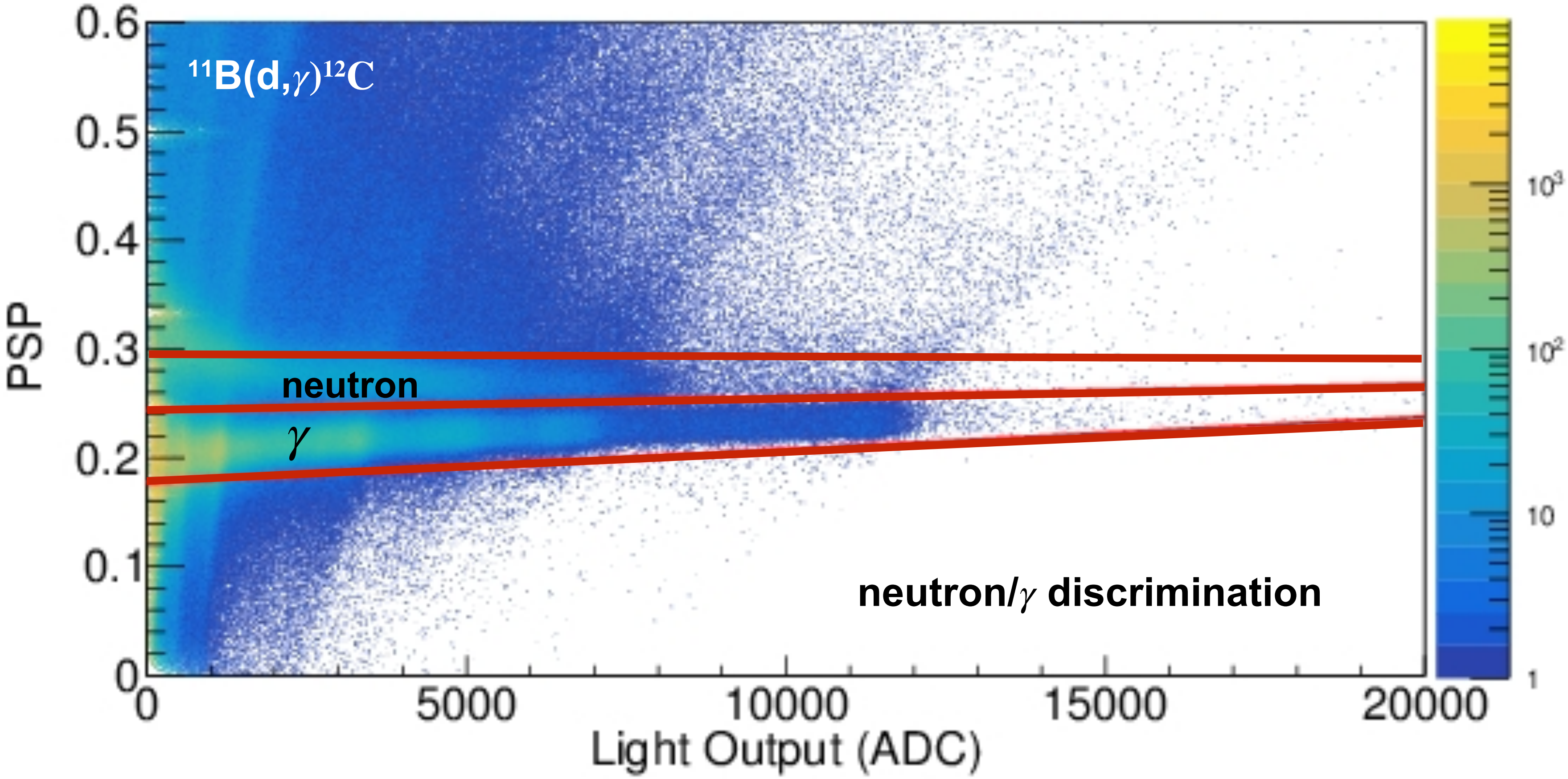
Measurement 2: PP dominant (15.1 MeV)

Dual-energy elemental discrimination

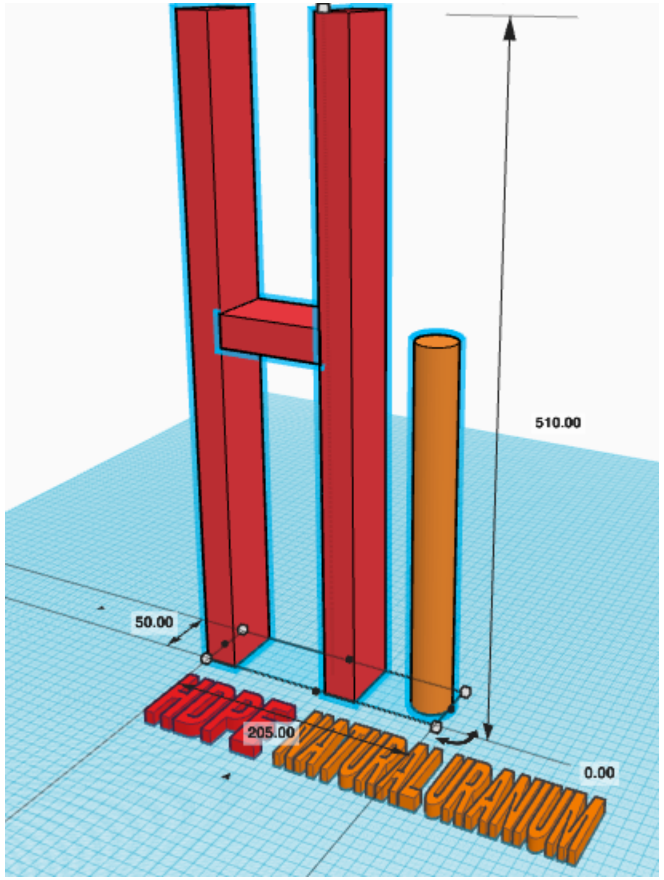


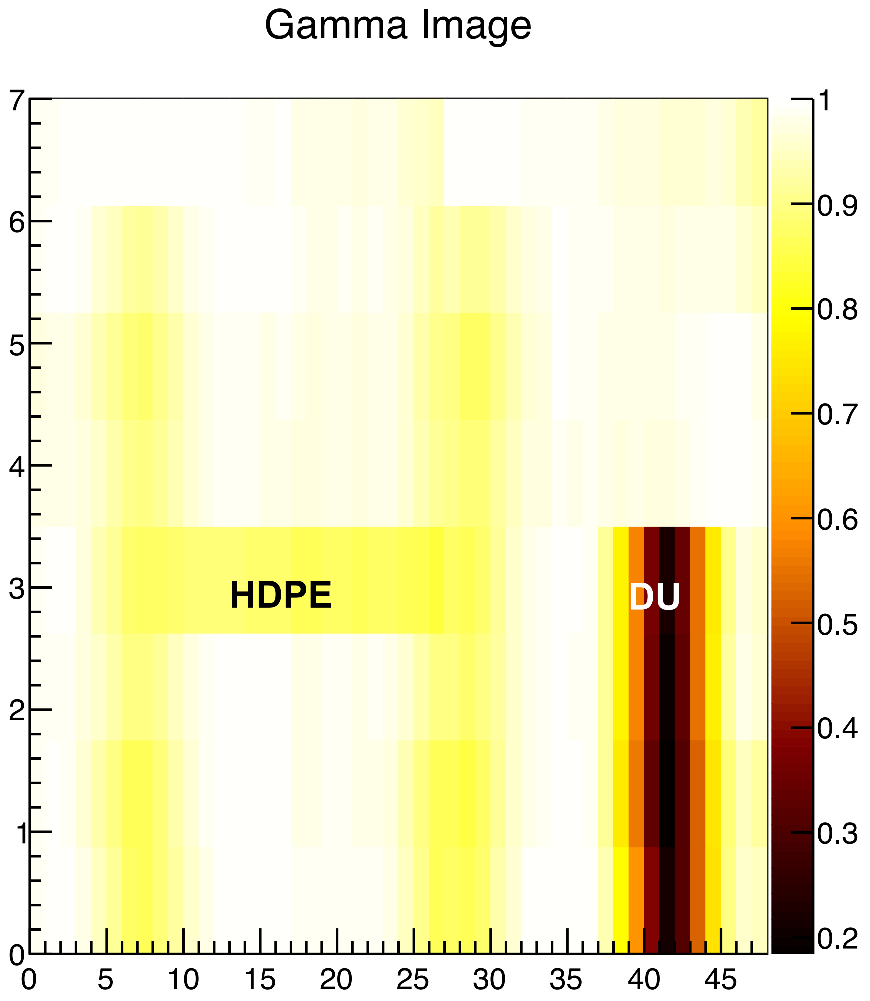
Dual-particle spectroscopic transmission radiography

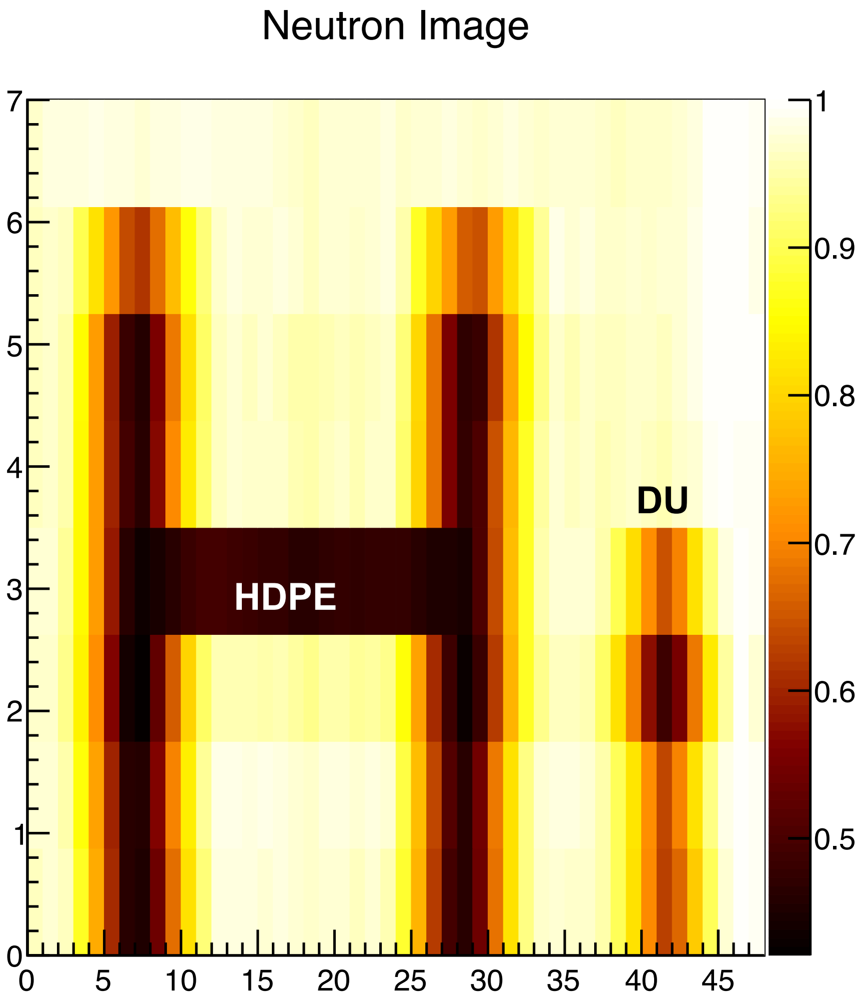
- One could use two sets of detectors optimized for each particle
- Alternative: use the same detector for both particles
- Basic requirement: neutron-gamma discrimination



Dual-particle transmission radiography

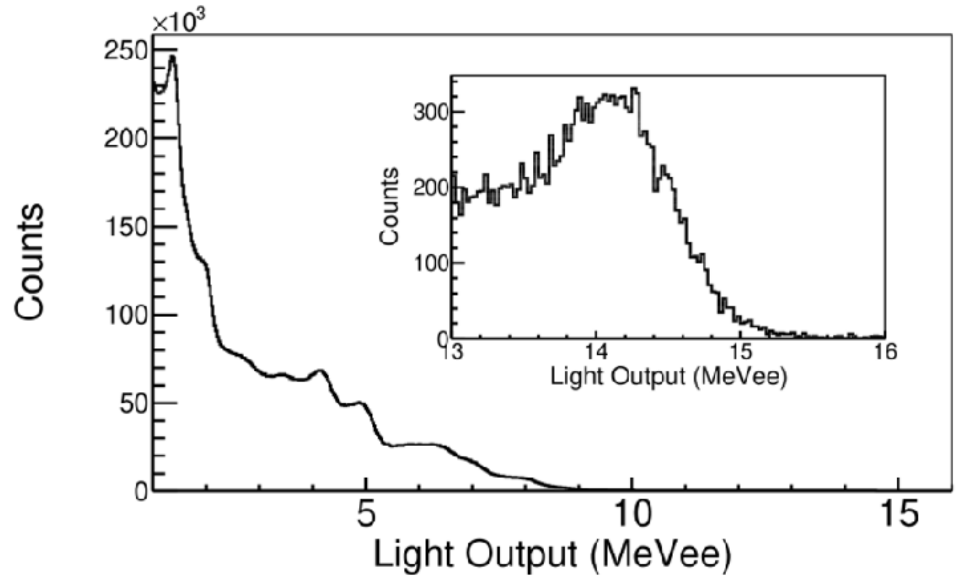






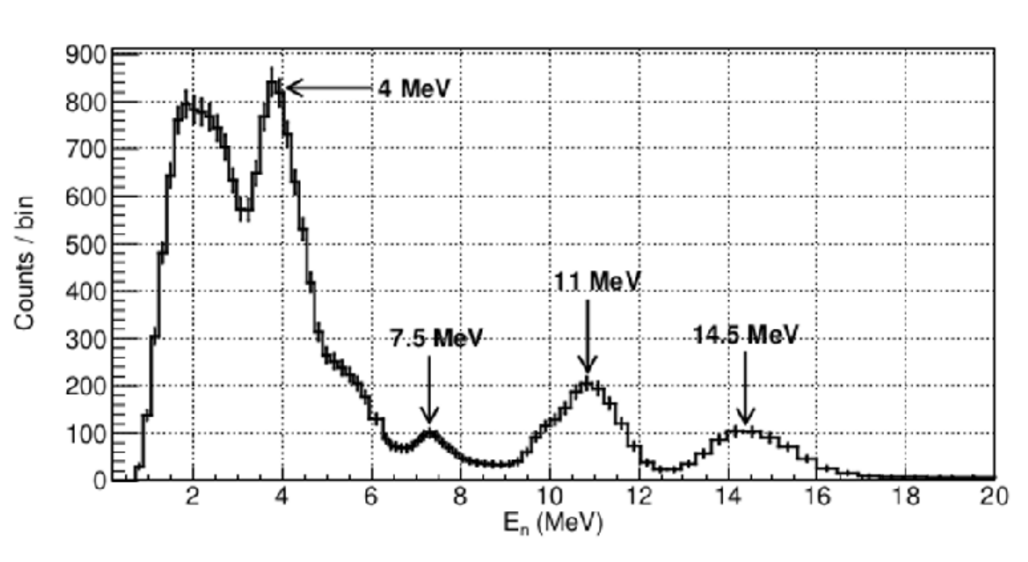
P. Rose, A. Erickson, M. Mayer, J. Nattress, and I. Jovanovic, Sci. Reports 6, 24388 (2016)

Multi-particle, multiple-monoenergetic radiation source

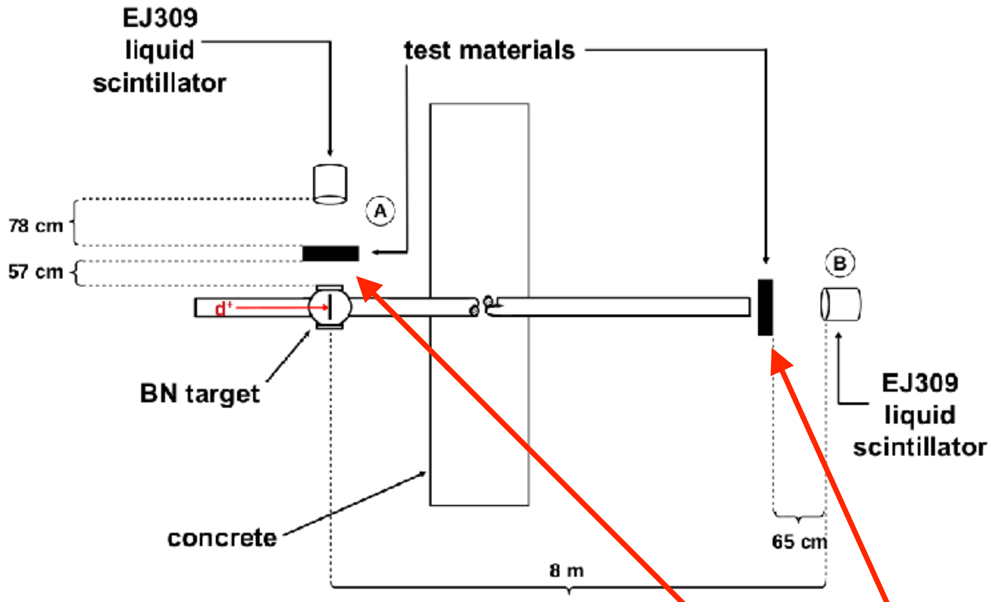


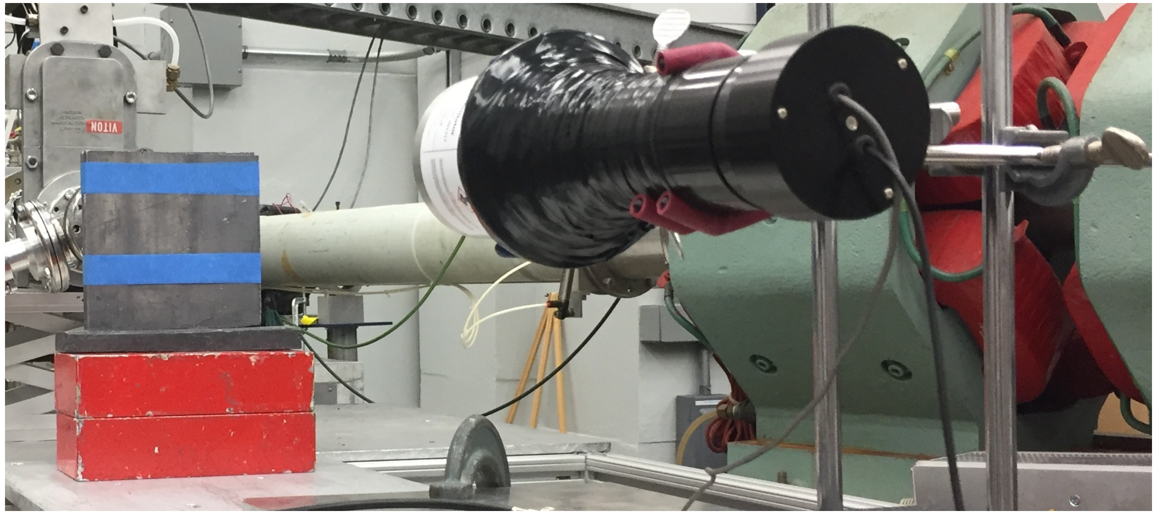
Multi-monoenergetic gamma-ray source

Multiple-monoenergetic <u>tunable</u> neutron source



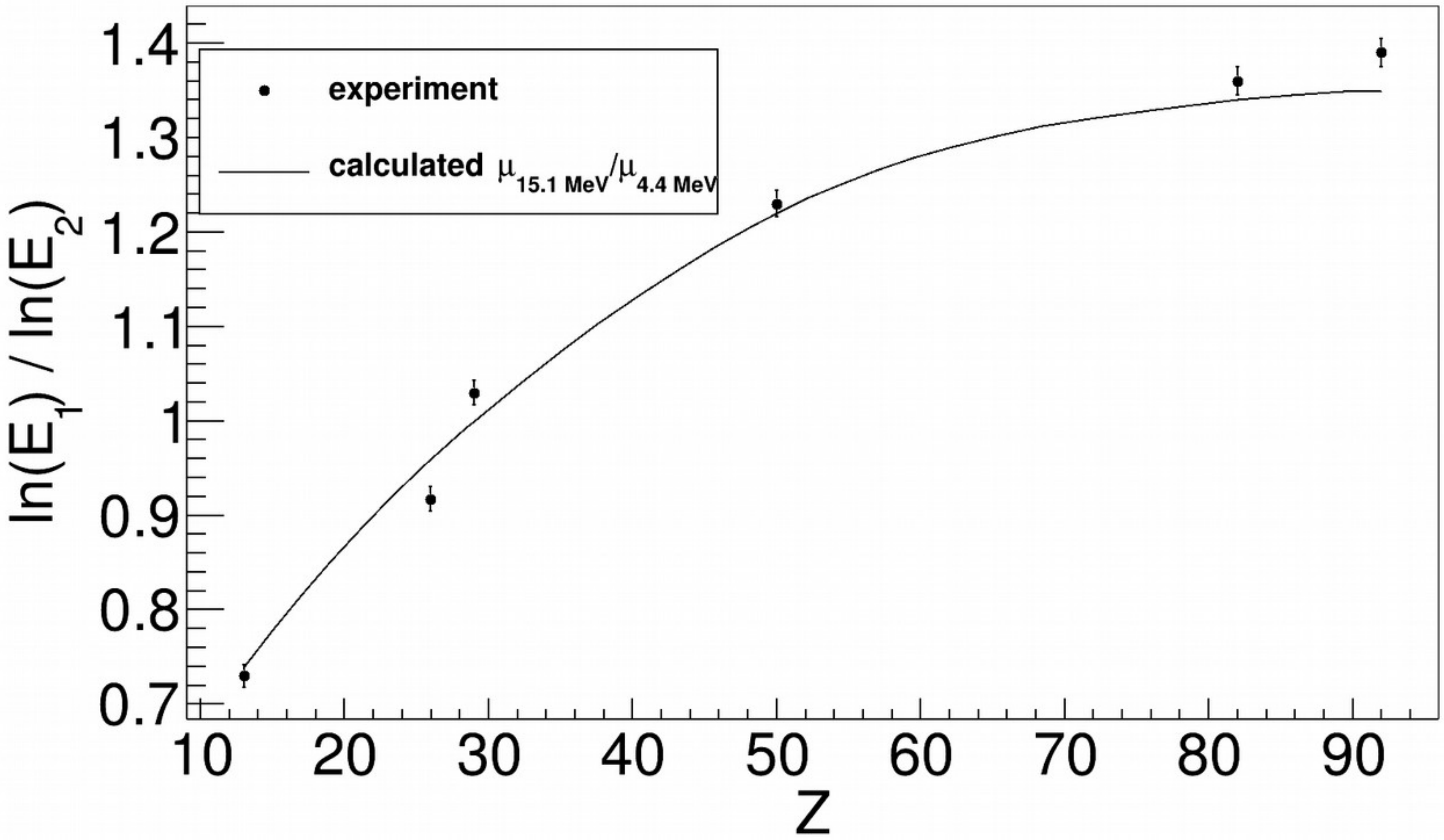
Testing of objects composed of various materials





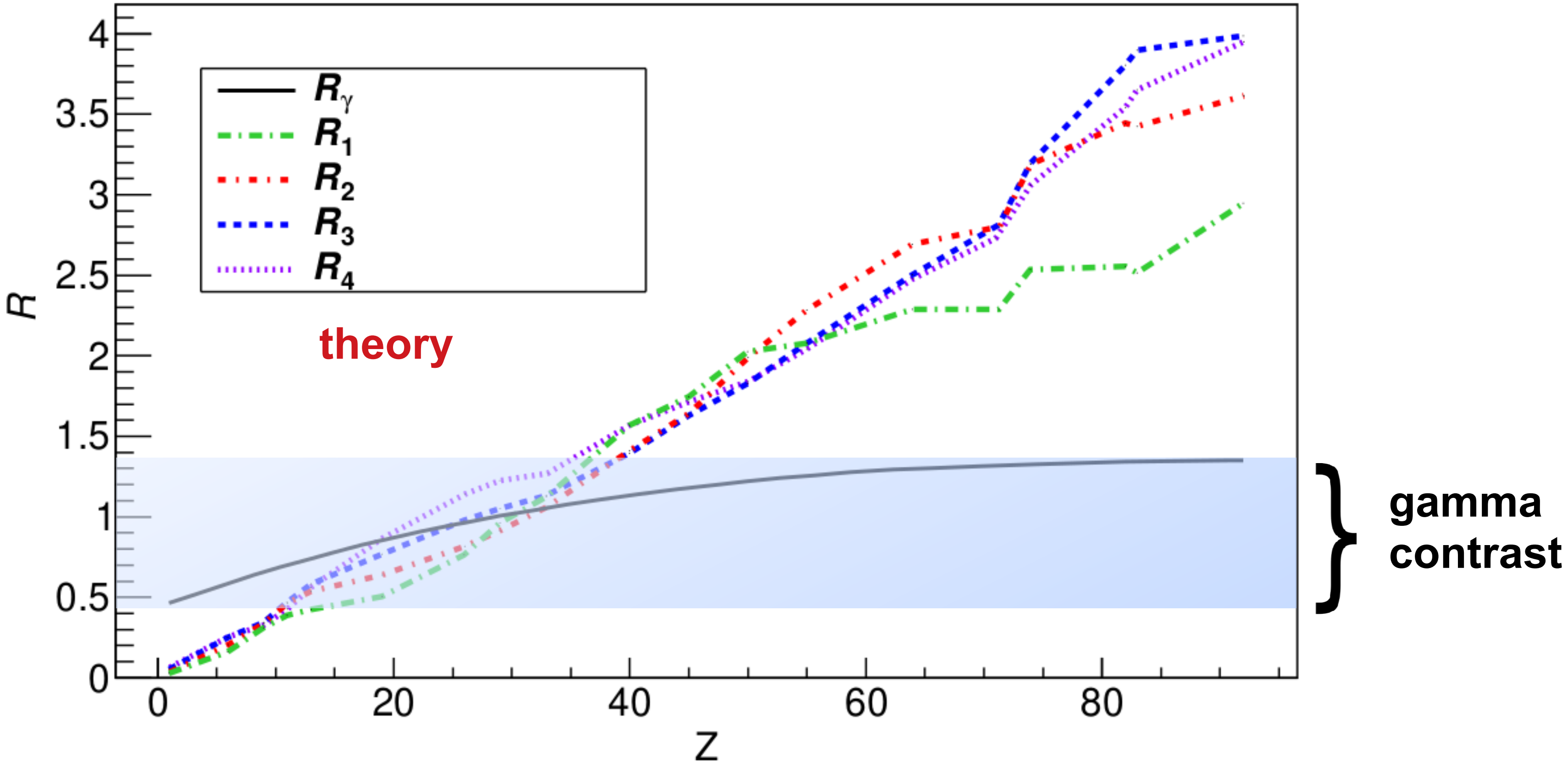
Material	Z	Areal Density (g/cm^3)
Al	13	18.1
Cu	29	17.1
Sn	50	25.1
W alloy	64.7	25.3
Pb	82	22.5
Bi	83	30.3

Experimental results: material ID based on photon/photon transmission



J. Nattress et al., Phys. Rev. Applied 11, 044085 (2019)

Neutron + gamma transmission discriminants → greater material contrast

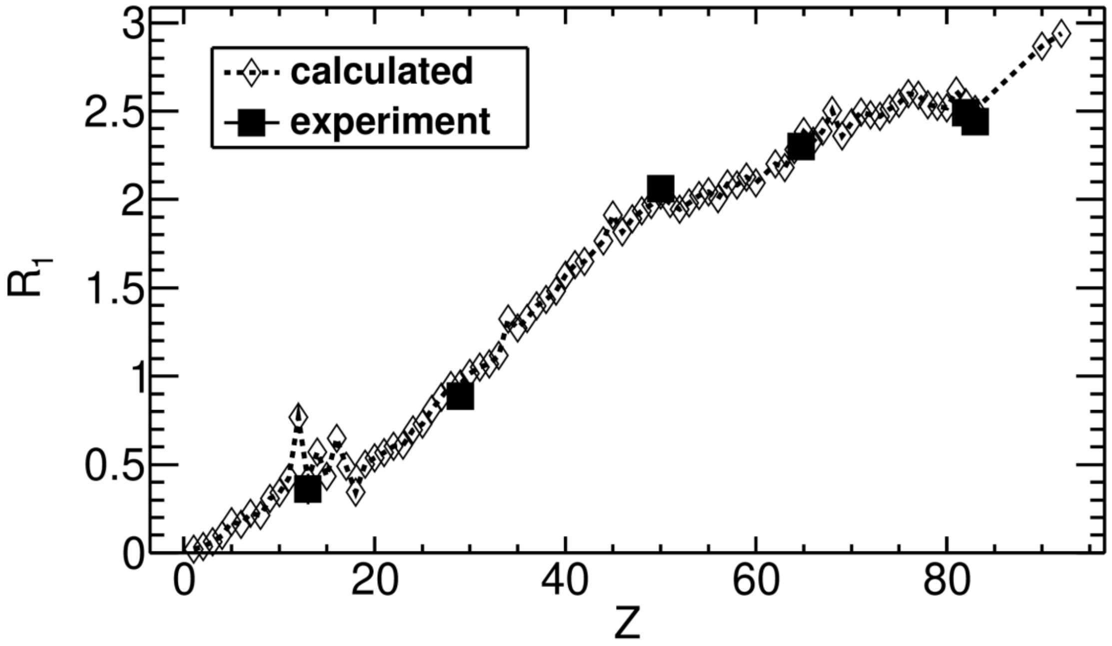


R-value	μ/Σ
R_1	15.1 MeV/4 MeV
R_2	15.1 MeV/7.5 MeV
R_3	15.1 MeV/11 MeV
R_4	15.1 MeV/14.5 MeV

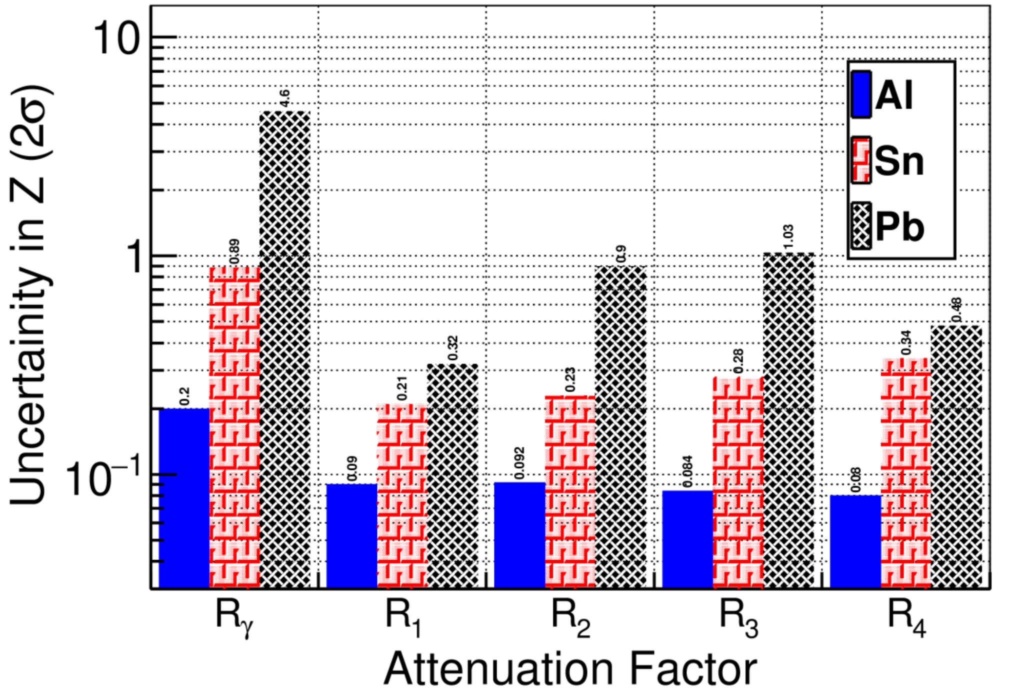
$$R = \frac{\ln\left(I^{\alpha}(E_1)/I_0^{\alpha}(E_1)\right)}{\ln\left(I^{\beta}(E_2)/I_0^{\beta}(E_2)\right)}$$

J. Nattress et al., Phys. Rev. Applied 11, 044085 (2019)

Combining gamma and neutron spectroscopic radiography



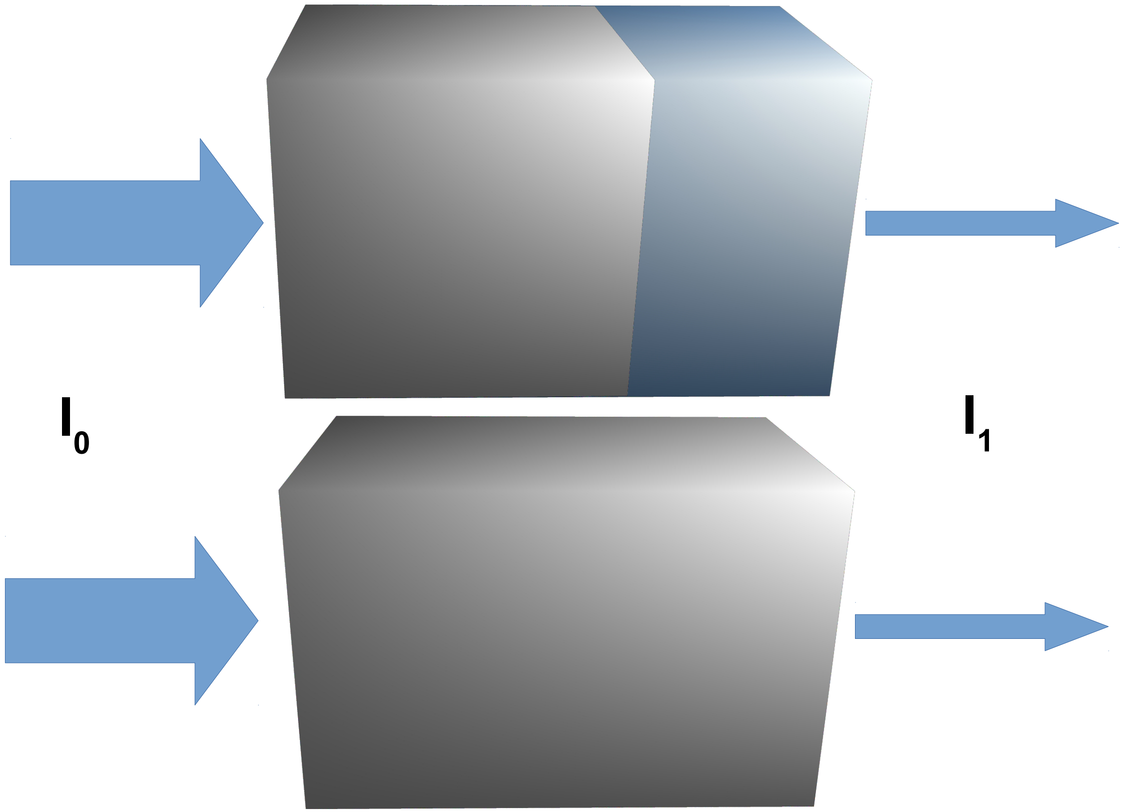
Element	True Z	$Z(R_1)$	$Z(R_2)$	$Z(R_3)$	$Z(R_4)$
Al	13	12.8±4.0	17.4±5.8	11.9±3.2	14.7±3.2
Cu	29	27.3±1.2	26.8±4.5	28.6±2.9	30.1±6.0
Sn	50	53.7±3.2	52.3±2.4	54.0±1.7	55.8±3.0
W alloy	64.7	63.6±2.4	67.4±3.7	69.6±1.9	70.0±2.2
Pb	82	77.4±4.5	78.6±2.7	77.3±4.9	81.4 ±1.8
Bi	83	71.1±4.7	77.9±5.7	90.1±3.6	79.3±3.0



J. Nattress et al., Phys. Rev. Applied 11, 044085 (2019)

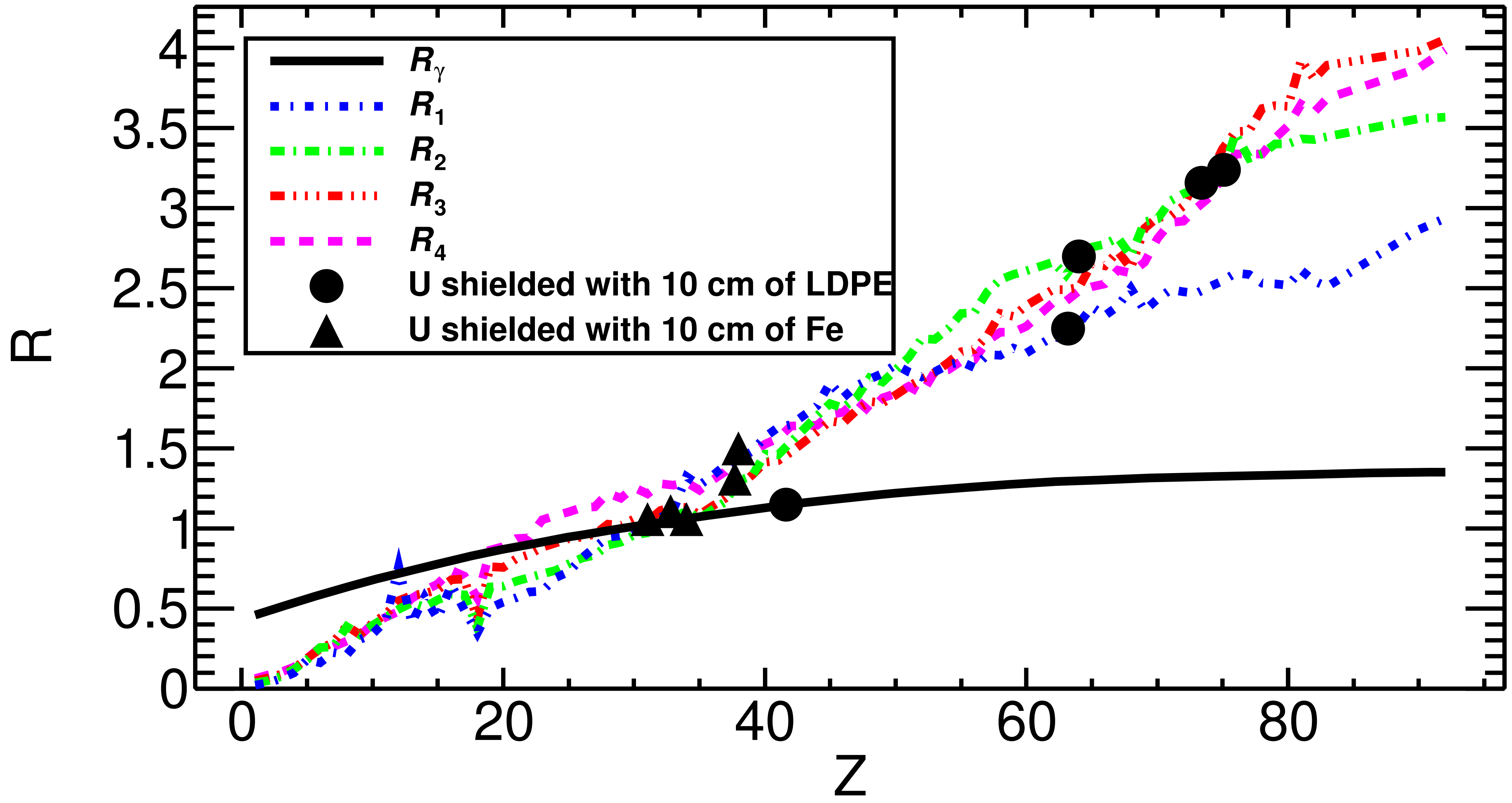
Mixed-material objects and shielding

Z_{eff} or the effective element is a function of energy and particle



$$T = \Pi_i \exp(-\mu_i/\rho_i \kappa)_i = \exp(-\Sigma_i \mu_i/\rho_i \kappa_i) = \exp\left(-\left(\frac{\mu}{\rho}\right)_{eff} \kappa\right)$$

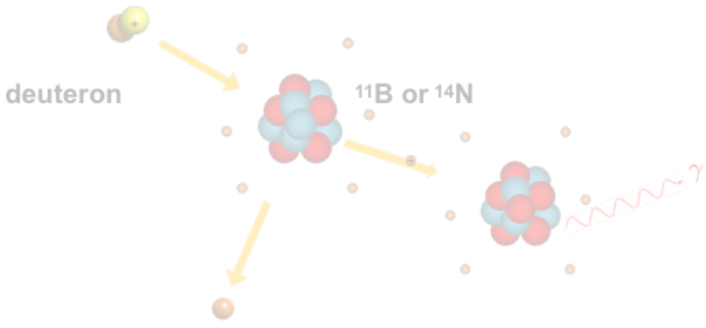
Inconsistency in multimodal Z-reconstruction → mixed elemental or non-natural isotope composition



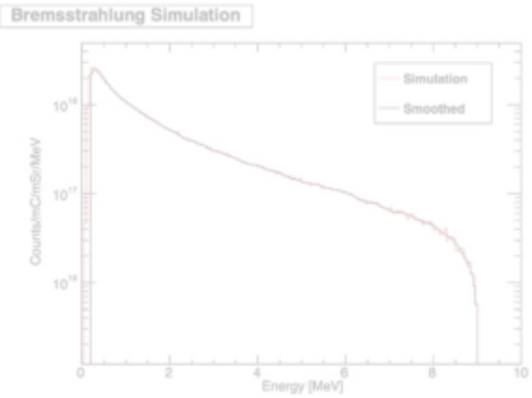
J. Nattress et al., Phys. Rev. Applied 11, 044085 (2019)

Active interrogation sources based on compact accelerators

Ion-driven nuclear reactions

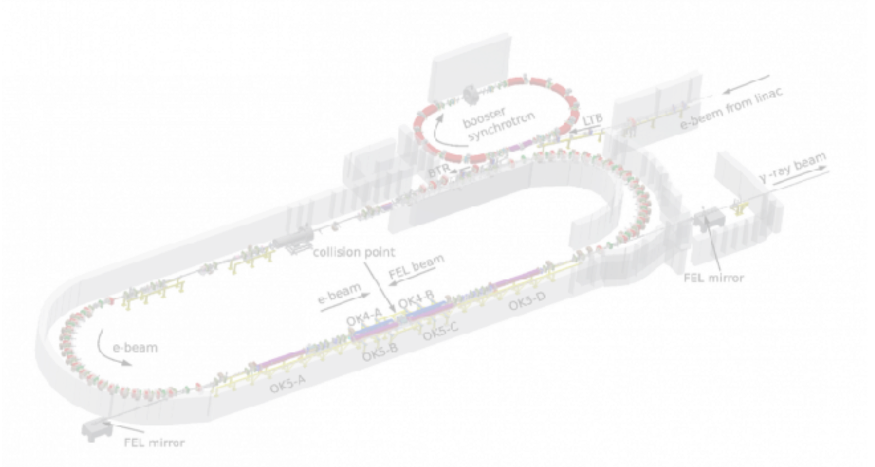


Bremsstrahlung sources

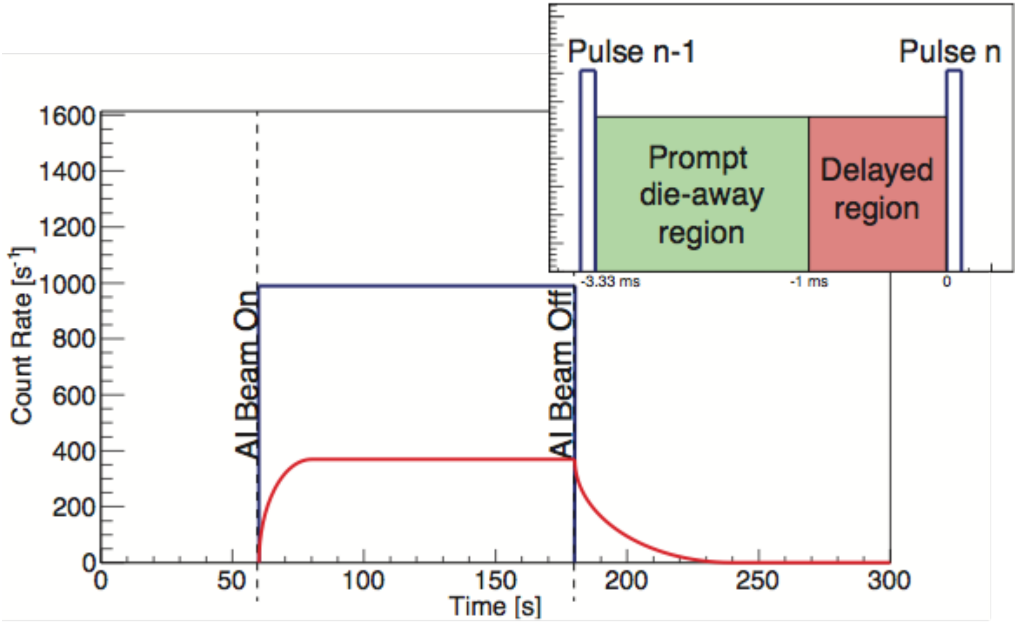


Neutron generators

Compton scattering sources

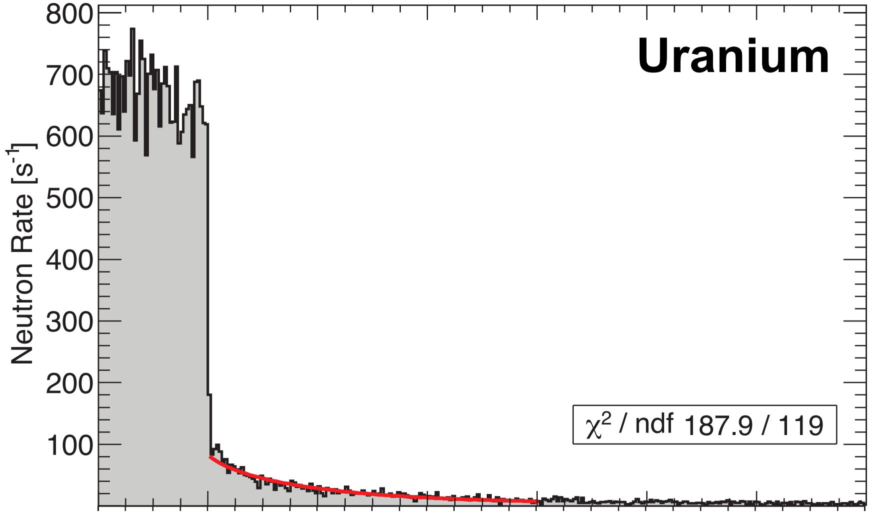


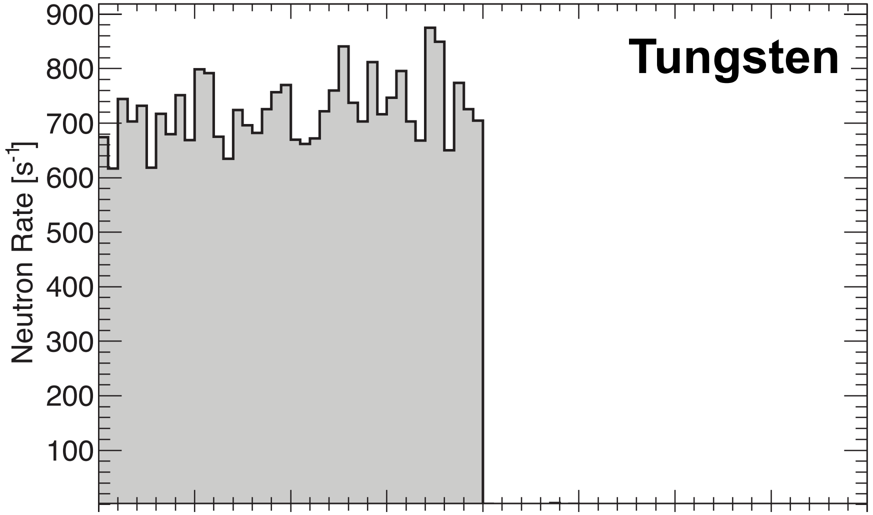
Detection of delayed neutrons from fission



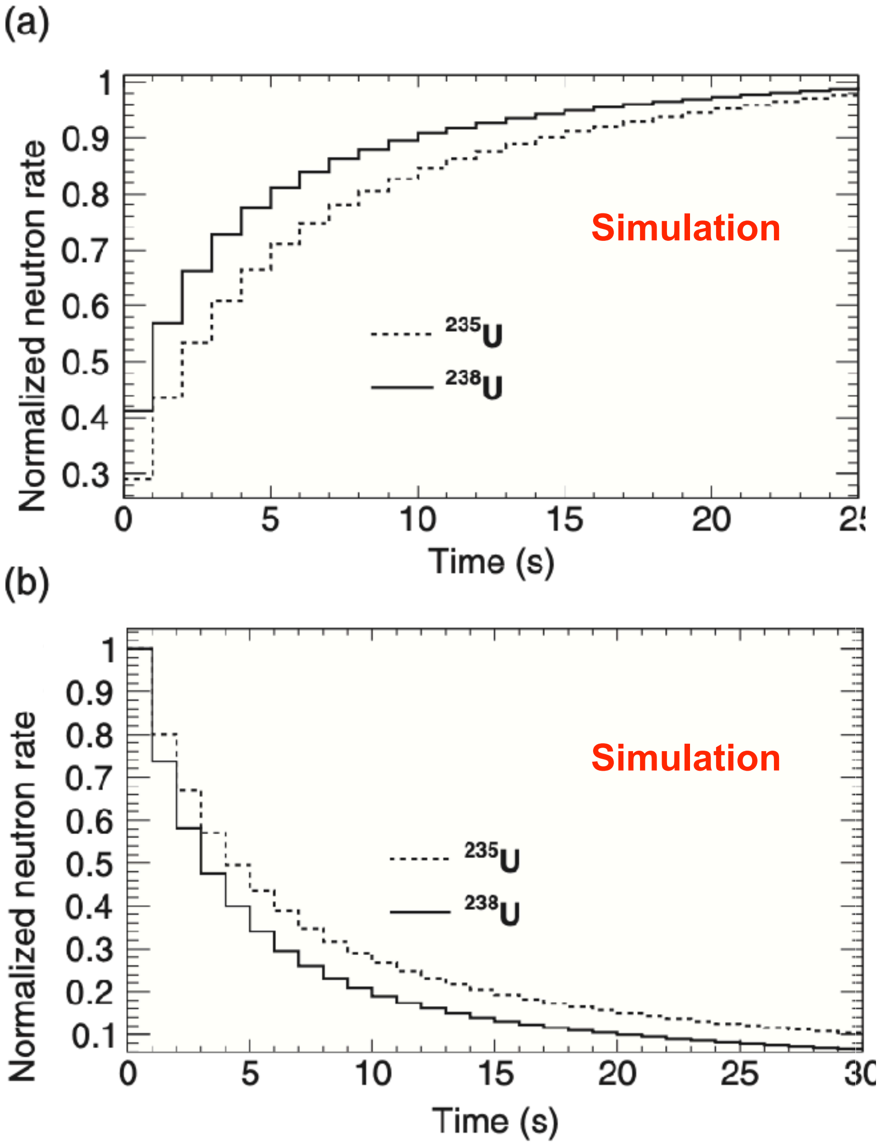
M. Mayer, J. Nattress, and I. Jovanovic, Appl. Phys. Lett. 108, 264102 (2016)

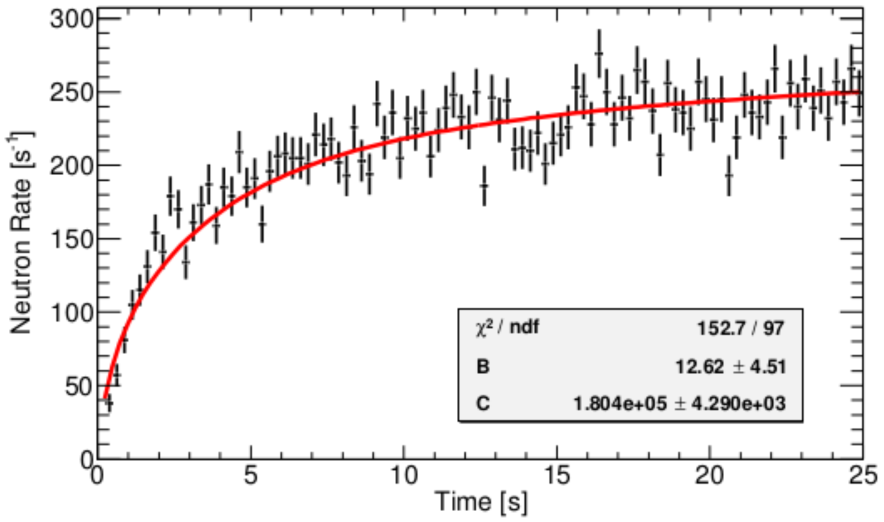
F. Sutanto, J. Nattress, and I. Jovanovic, J. Appl. Phys. 122, 054901 (2017)

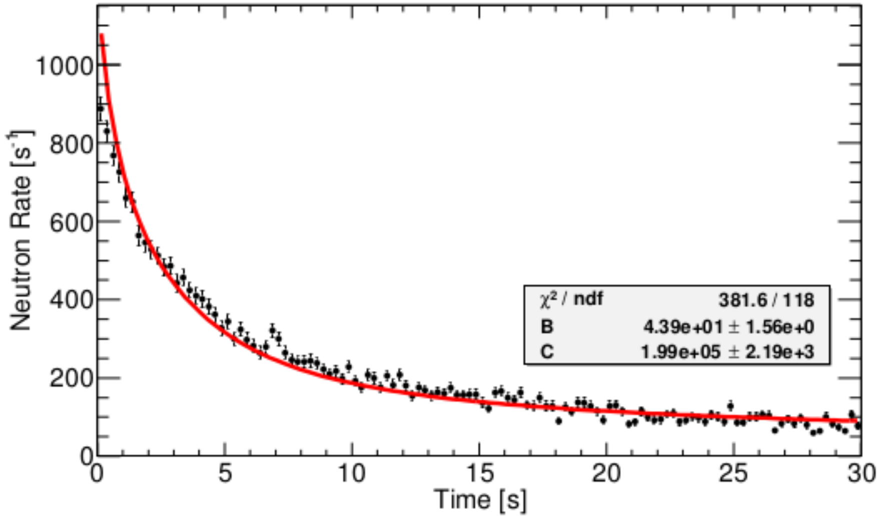




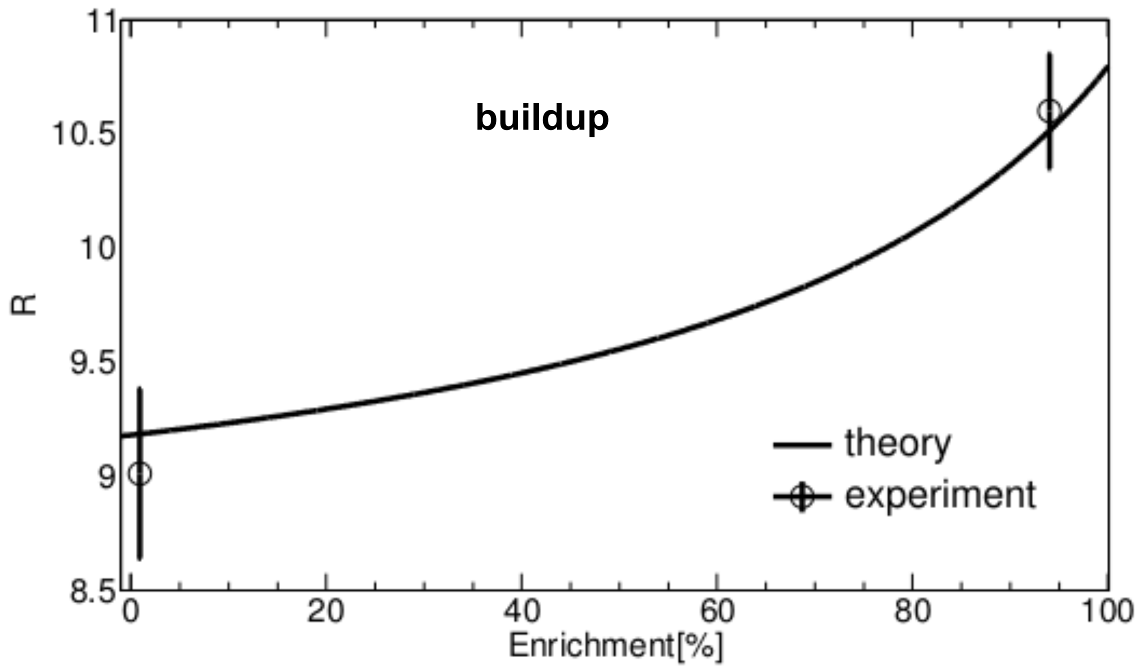
^{235}U and ^{238}U have unique delayed neutron time profiles → isotopic discrimination

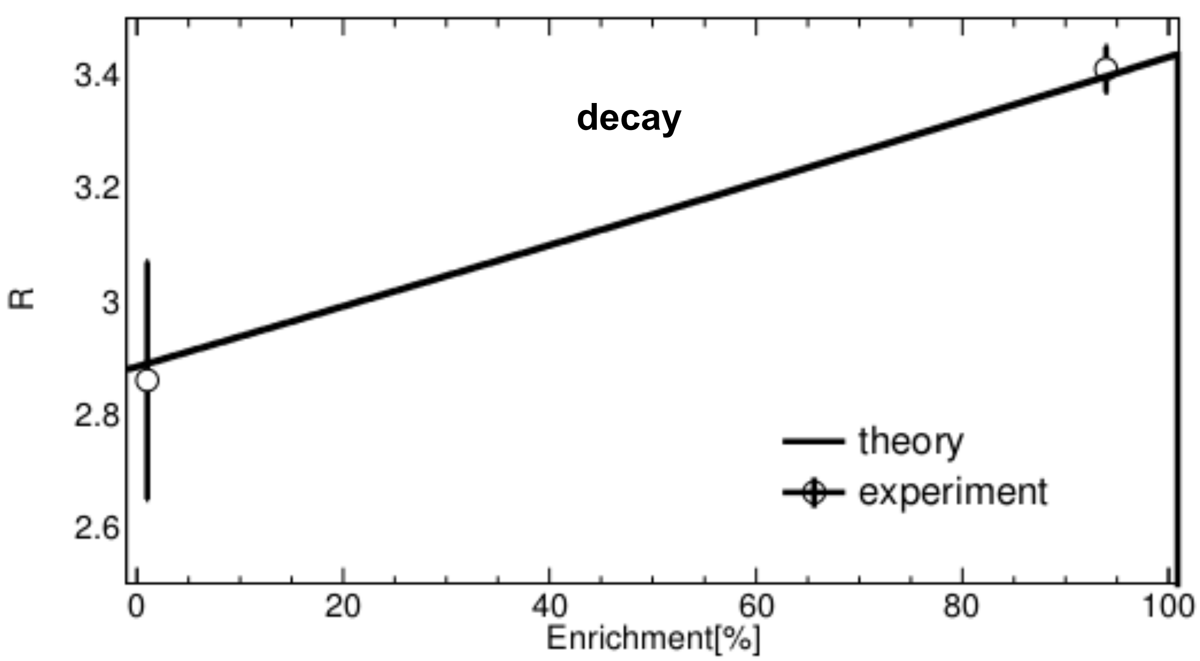






^{238}U / ^{235}U differentiation using buildup and decay of delayed neutrons

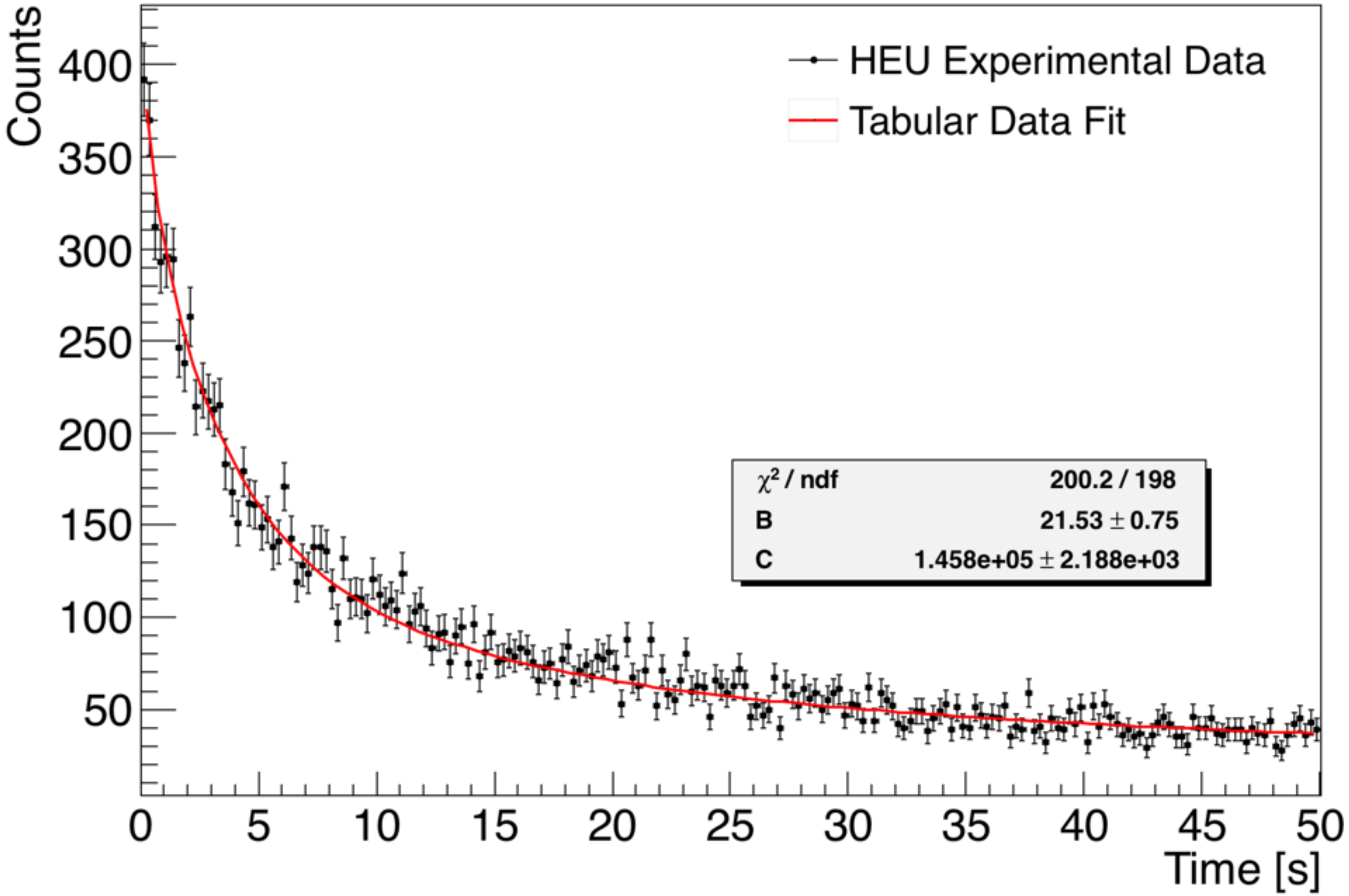




J. Nattress, K. Ogren, A. Foster, A. Meddeb, Z. Ounaies, and I. Jovanovic, Phys. Rev. Applied, 10, 024049 (2018)

K. Ogren, J. Nattress, and I. Jovanovic, Phys. Rev. Applied 14, 014033 (2020)

Multi-generation delayed neutron profile from HEU



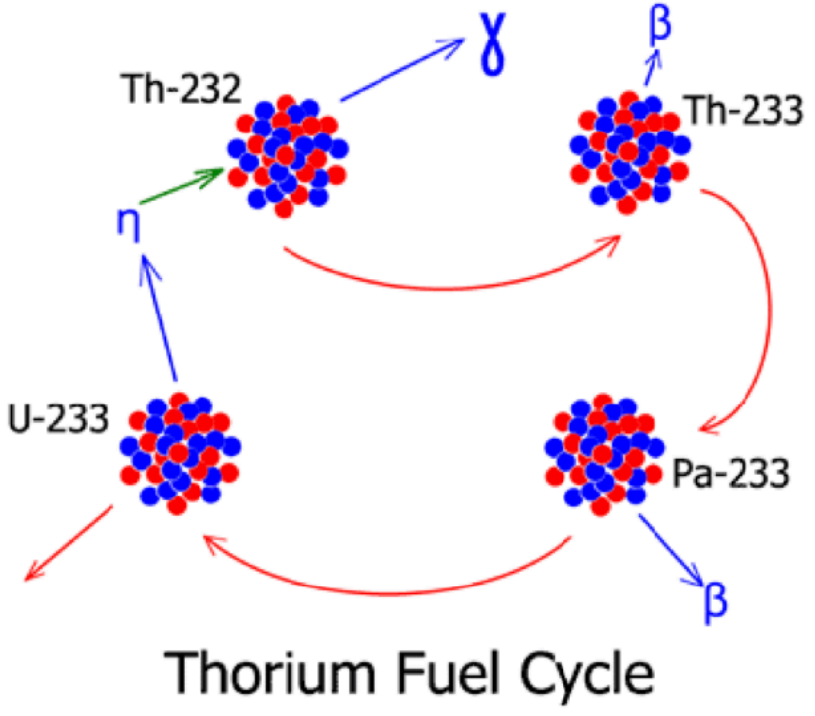
This is a **calibration-free** measurement, where the shape of delayed emission is predicted solely from nuclear data and is **isotope-specific**.

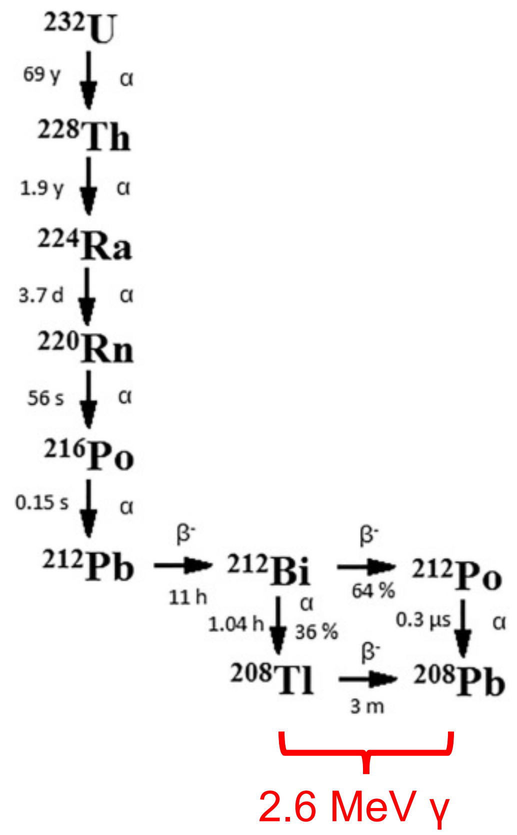
J. Nattress et al., Phys. Rev. Applied, 10, 024049 (2018)

K. Ogren et al., Phys. Rev. Applied 14, 014033 (2020)

The time signature is **immune to shielding.**

K. Ogren et al., NIMA 1019, 165847 (2021)





IAEA SQ

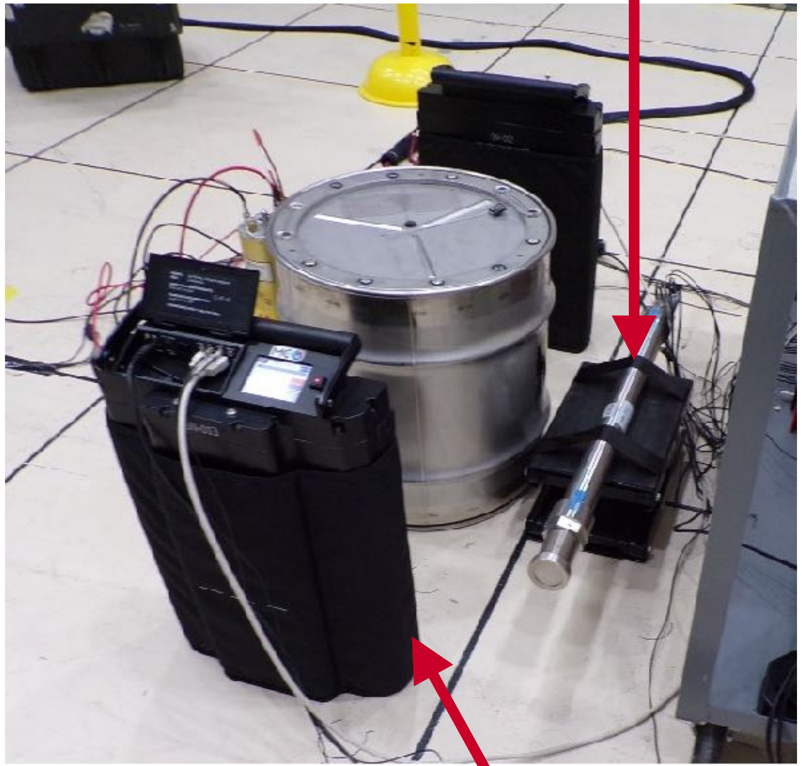
- 8 kg for ^{233}U vs. 25 kg for ^{235}U
- Th fuel cycle designs – $^{233}U/^{235}U$ mixtures
- ^{233}U & ^{235}U must be quantified *separately*

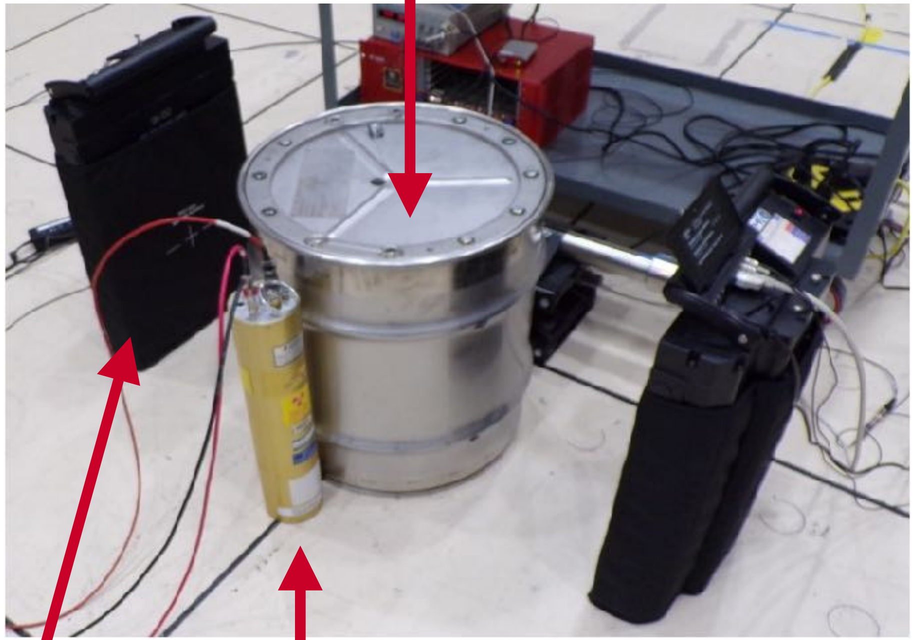
- Typical concentration or ^{232}U in ^{233}U: 100–2000 ppm
- Extreme γ environment – 6.04 Ci/SQ @ 100 ppm

Experiments with $^{233}U_3O_8$ Zero Power Reactor Fuel Elements Plates

S670 ^{4}He detector

1188 g $^{233}U_3O_8$

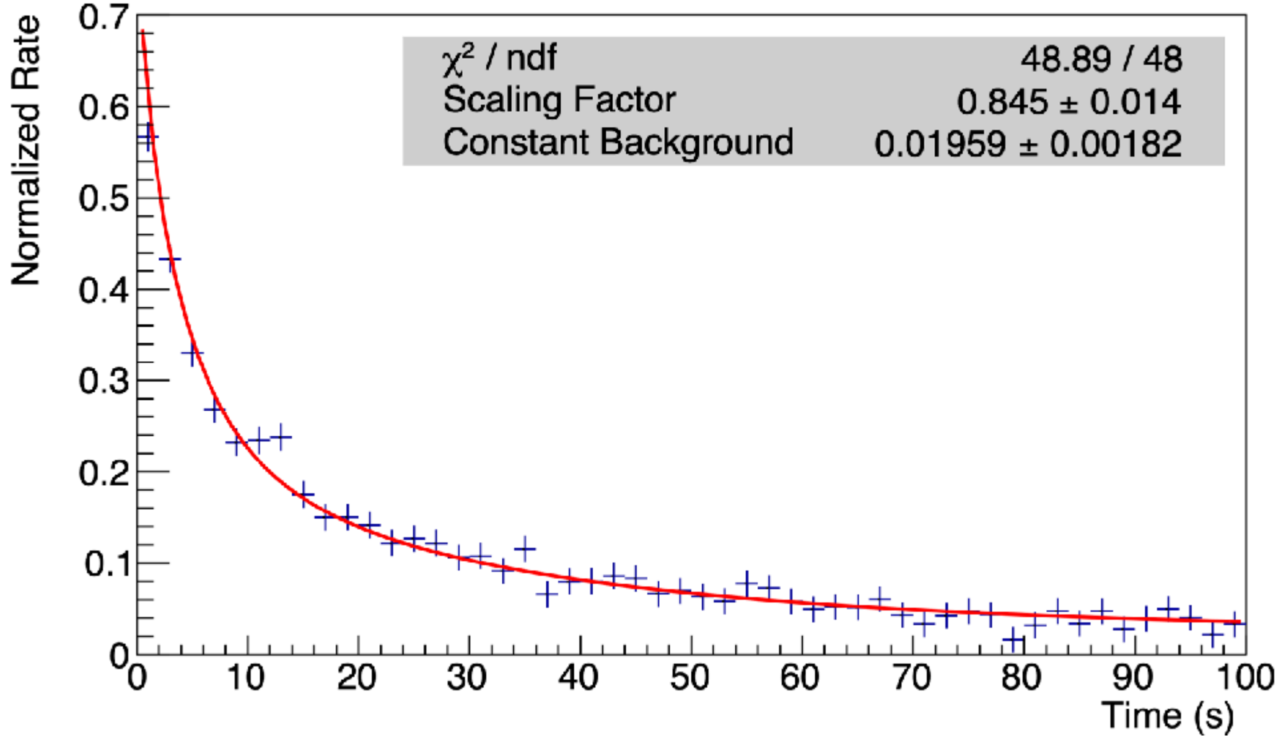


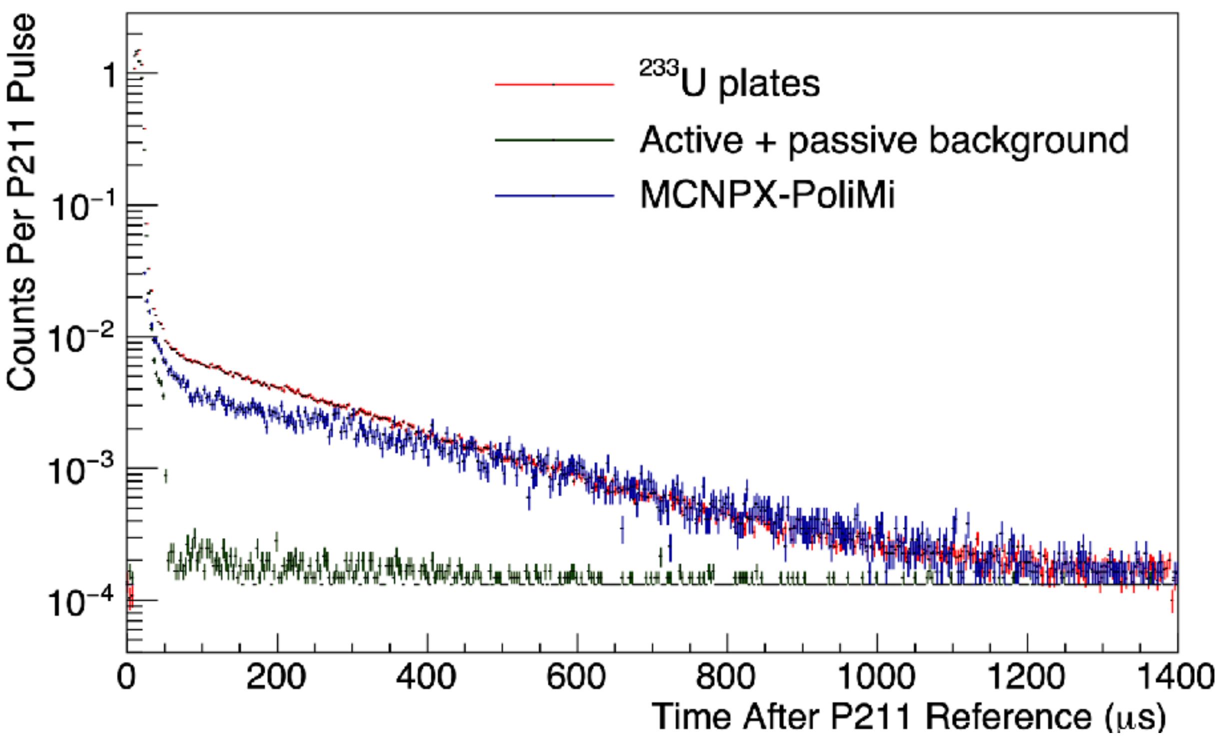


MC-15 ^{3}He detectors

P211 Neutron Generator

First demonstration of ^{233}U delayed neutron and differential die-away measurement with industrial-scale quantity, using active interrogation

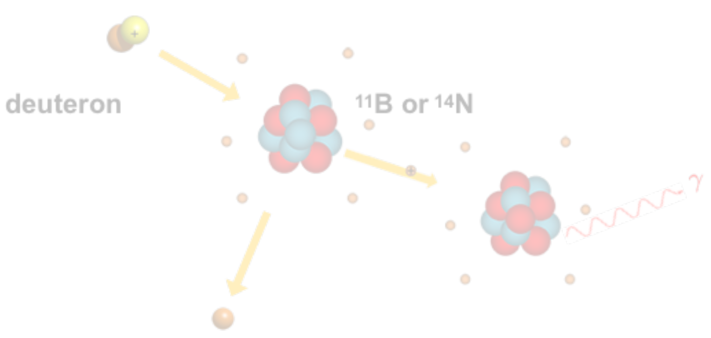




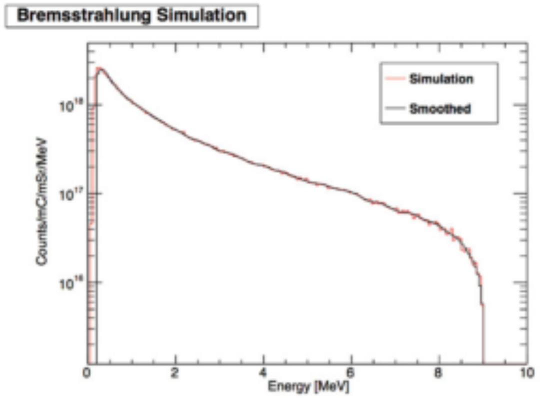
O. Searfus, P. Marleau, E. Uribe, H. Reedy, and I. Jovanovic, Phys. Rev. Applied 20, 064038 (2023)

Active interrogation sources based on compact accelerators

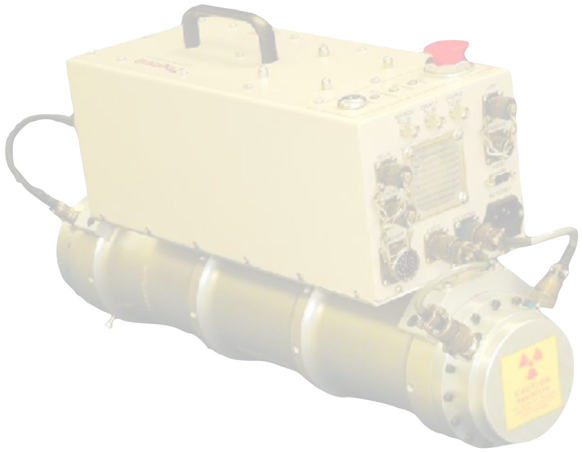
Ion-driven nuclear reactions



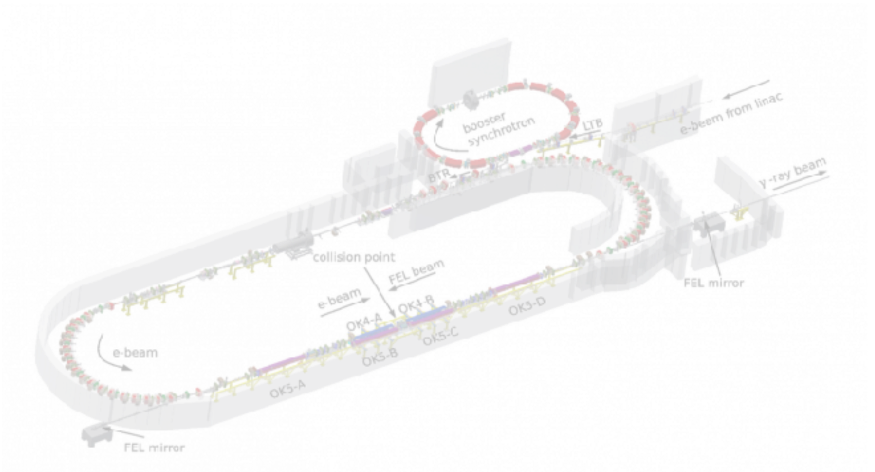
Bremsstrahlung sources



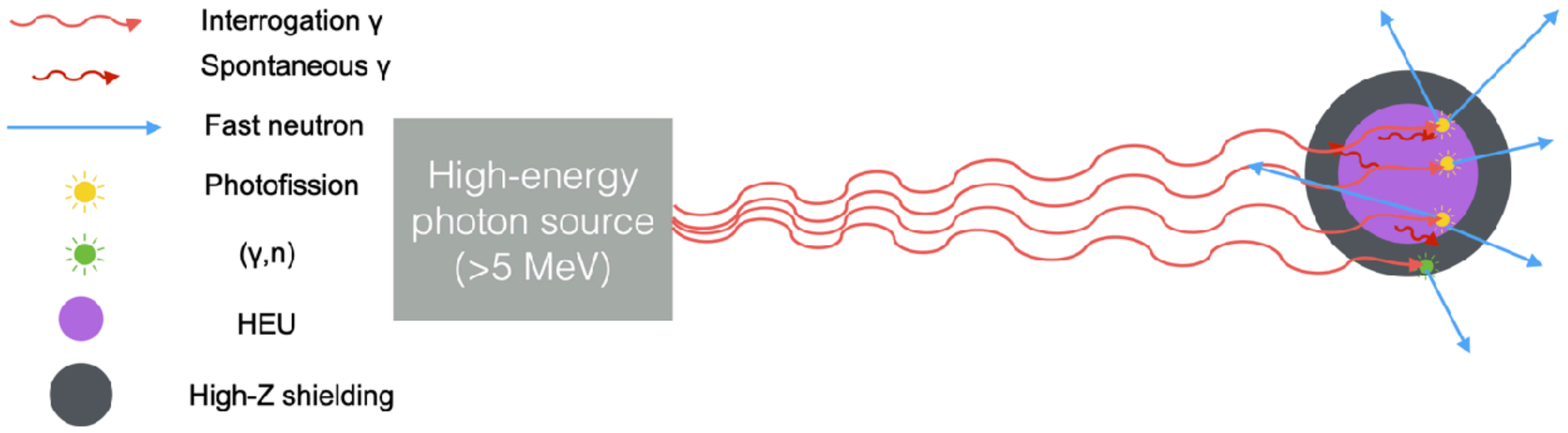
Neutron generators

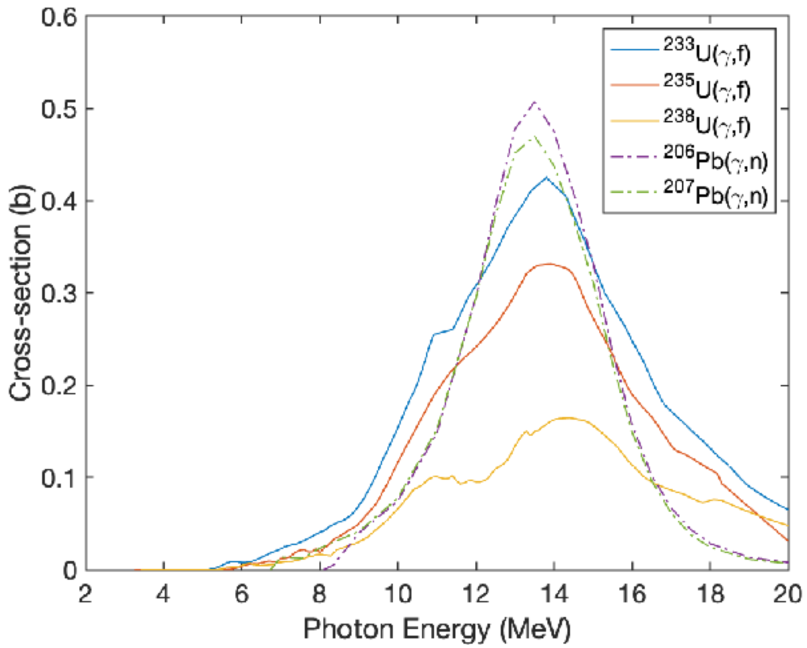


Compton scattering sources



Detection of prompt photofission neutrons





- reduced dose
- adjustable fission threshold
- detect fission neutrons

Prompt neutrons

- more abundant than delayed neutrons
- different spectrum from photoneutrons

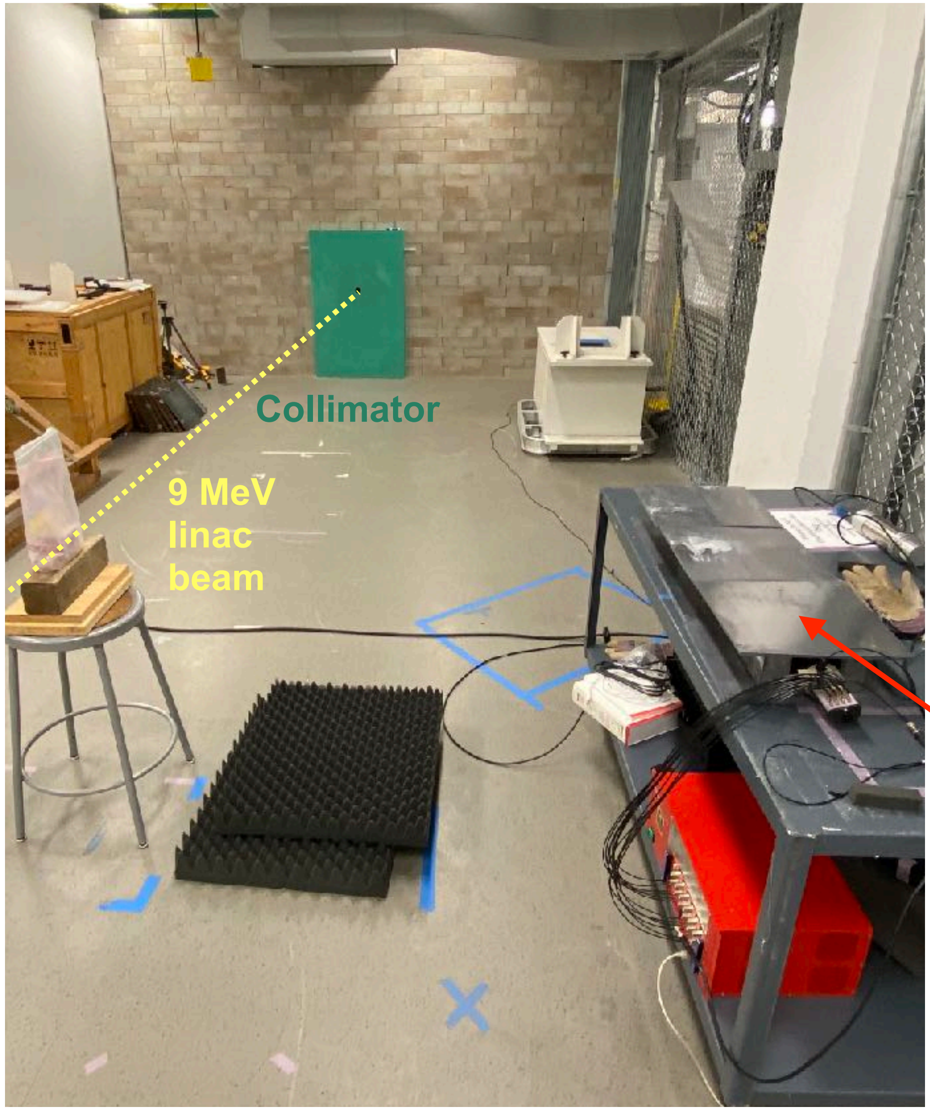
but: coincident with high gamma flux

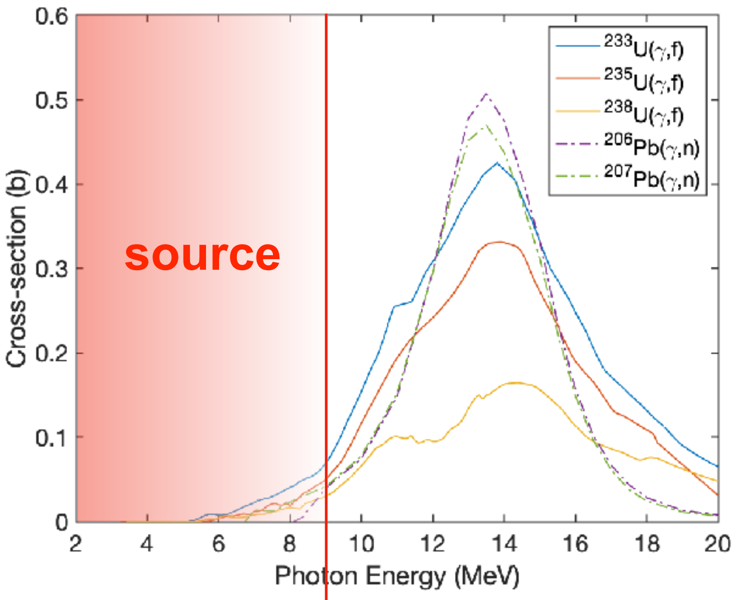
Detection of prompt photofission neutrons with a 9 MeV linac and ^{4}He detector

2.7 kg DU

3 kg PbO

3 kg Fe



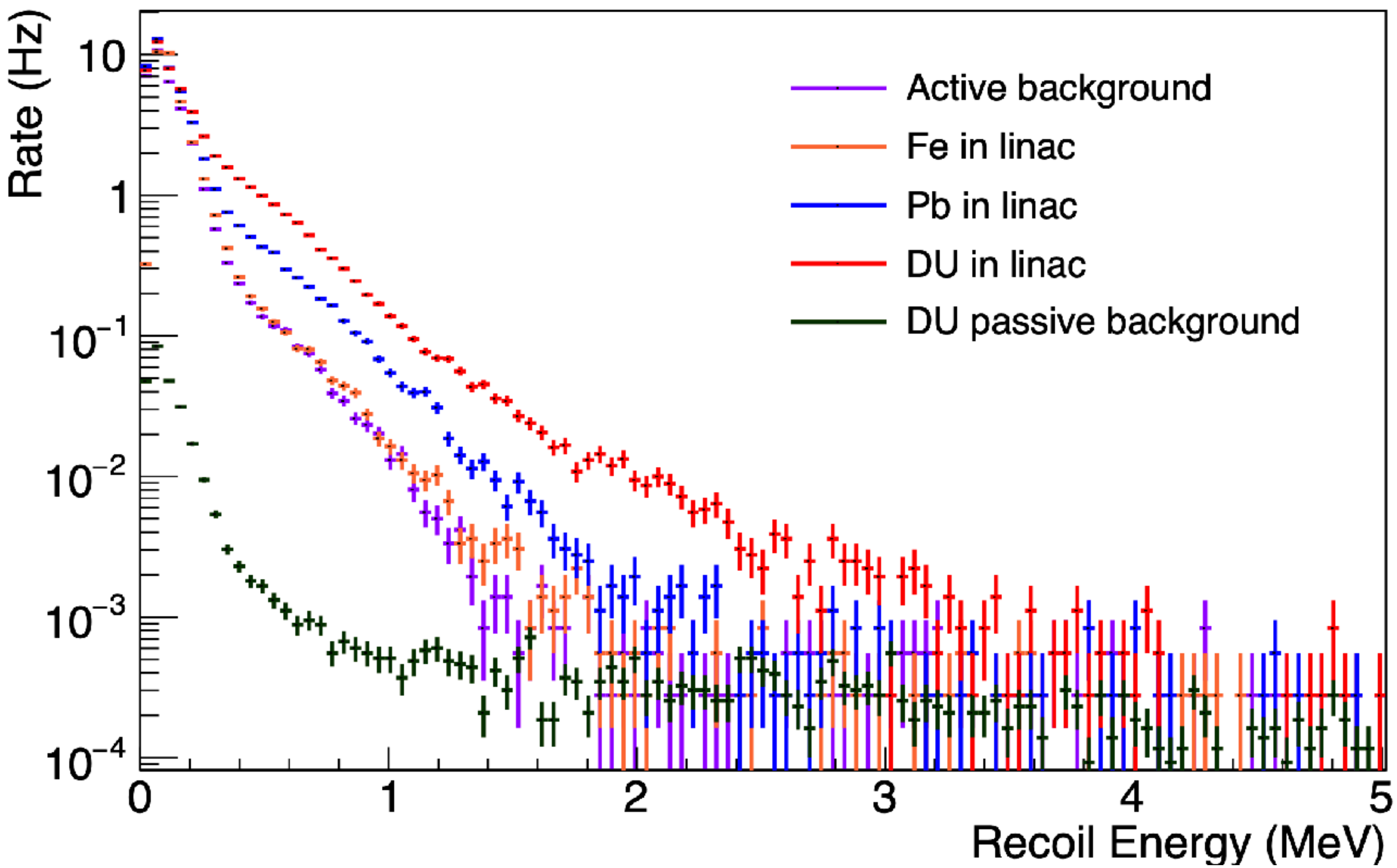


bremsstrahlung endpoint

^{4}He detector
poor sensitivity to gammas!

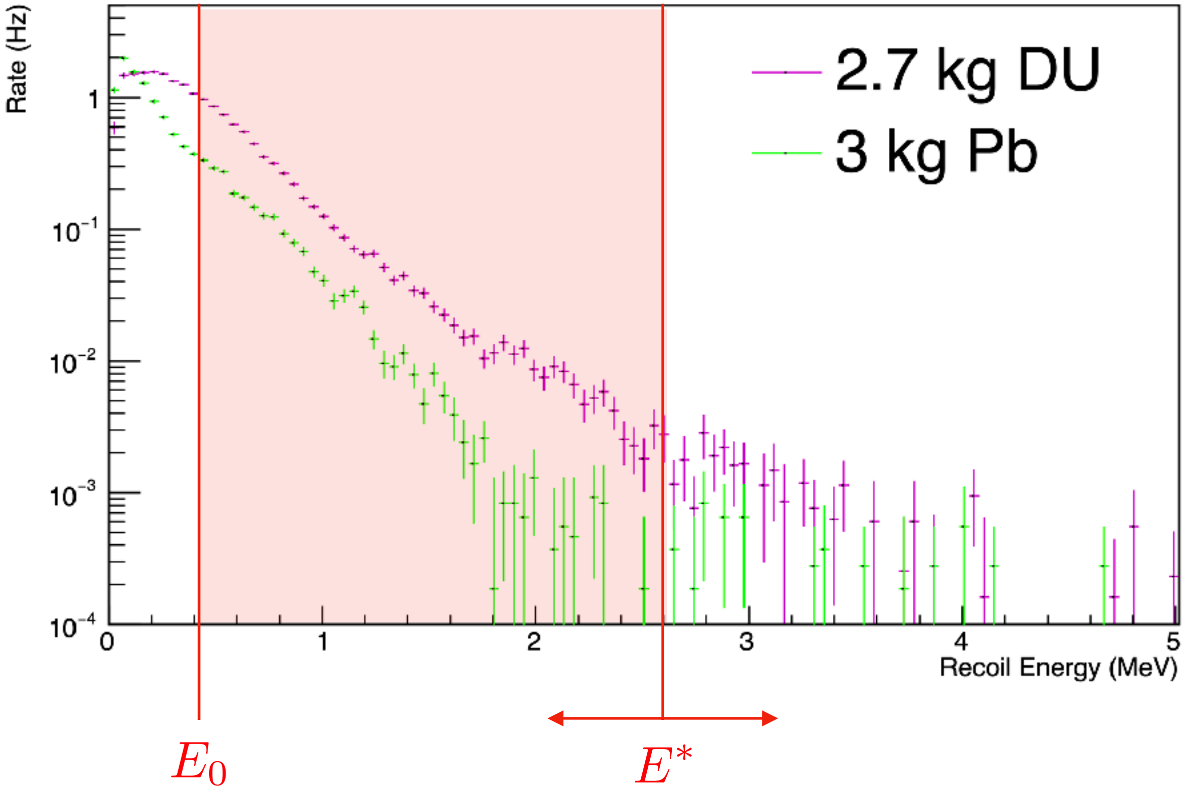
Active background: (γ,n) neutrons from collimator

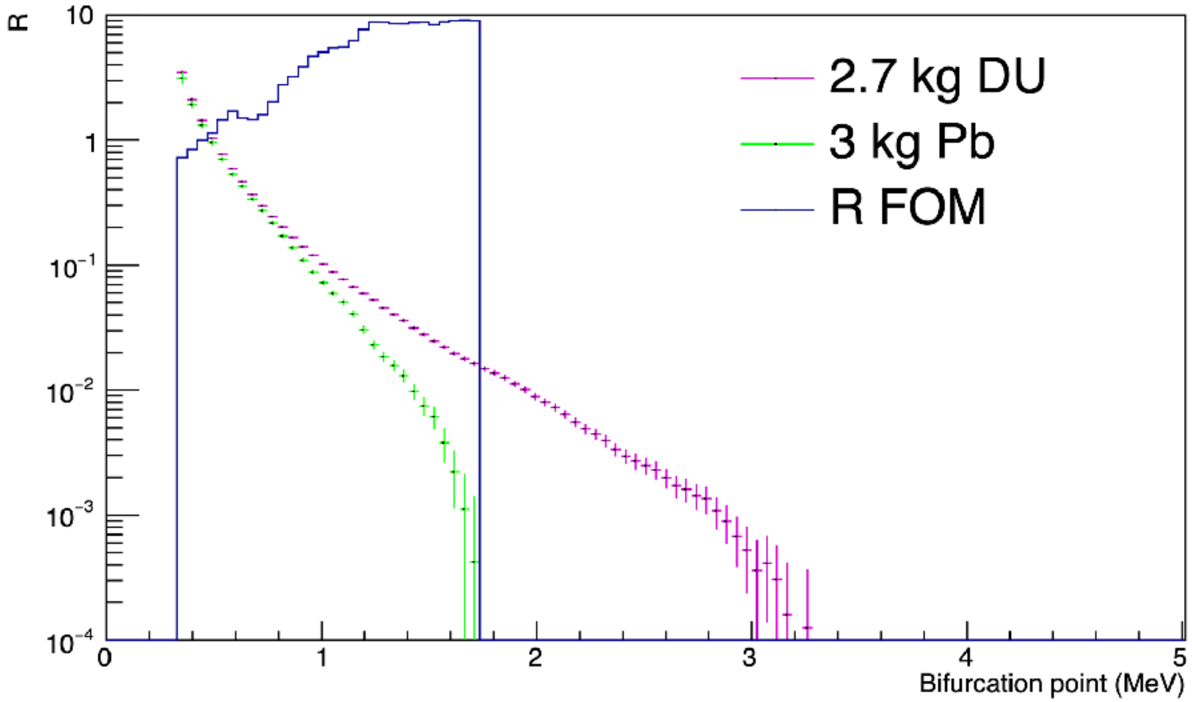
Prompt photofission neutrons isolated via spectroscopy



Detector insensitive to gammas – no PSD analysis needed!

Optimization of uranium-lead discrimination

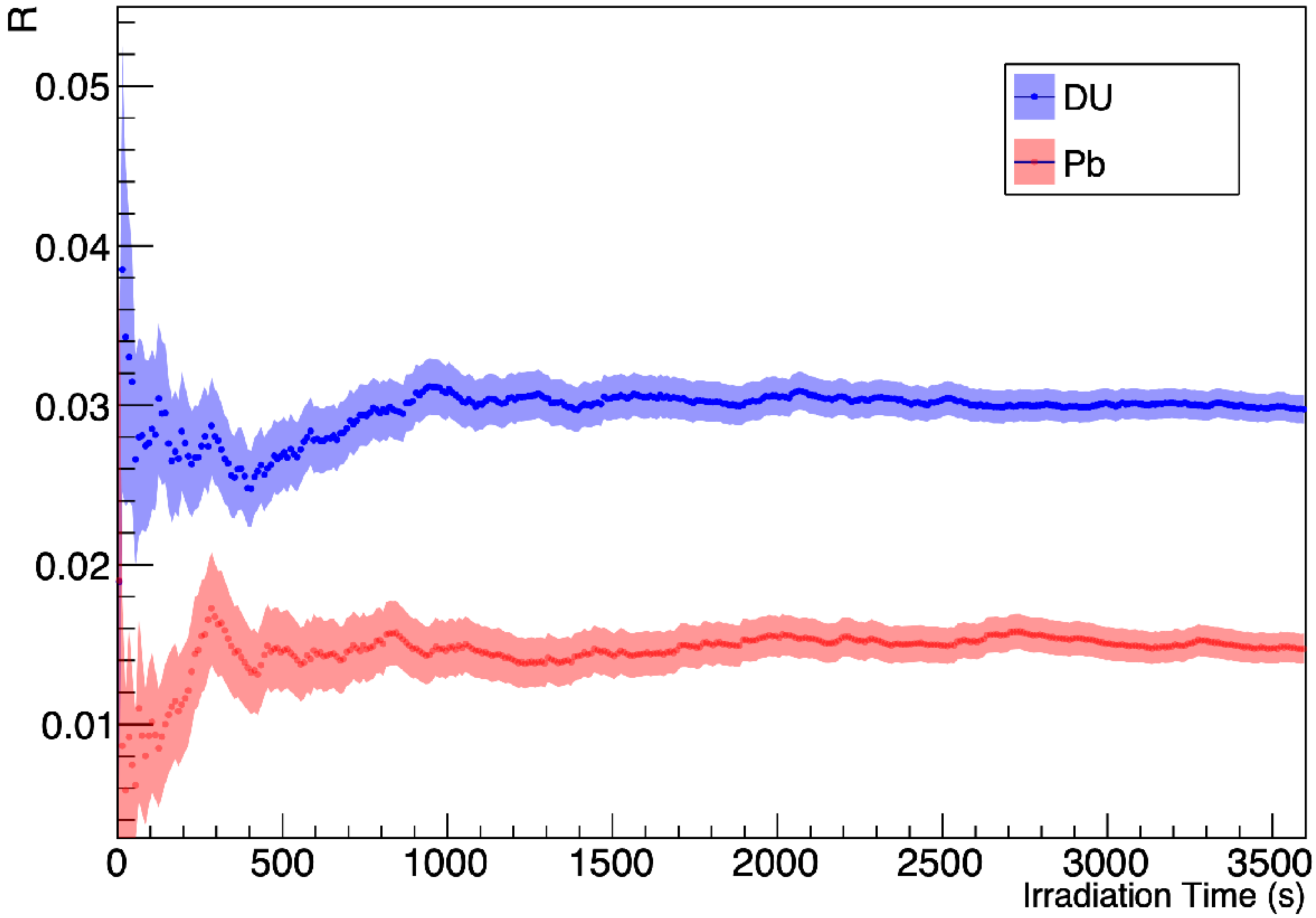




$$R = \frac{\int_{E^*}^{\infty} S\,dE}{\int_{E_0}^{E^*} S\,dE}$$

$$FOM_R = \frac{R_{DU} - R_{Pb}}{\sigma_{R_{DU}} + \sigma_{R_{Pb}}}$$

Spectral discrimination over time



Using the spectral ratio, Pb and DU are distinguishable with >3σ separation within minutes of irradiation.

Conclusion

Nuclear security and nonproliferation continue to be a major challenge that continues to drive technological innovation in nuclear instrumentation and nuclear analytical methods.

Compact accelerators play a critical role in supporting those applications.

- **dual-particle multiple-monoenergetic radiography**
- **neutron die-away and delayed neutrons**
- **detection of photofission**