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# Characterization of the Neutron Pulse Time Profile from a Deuterium-Tritium Neutron Generator

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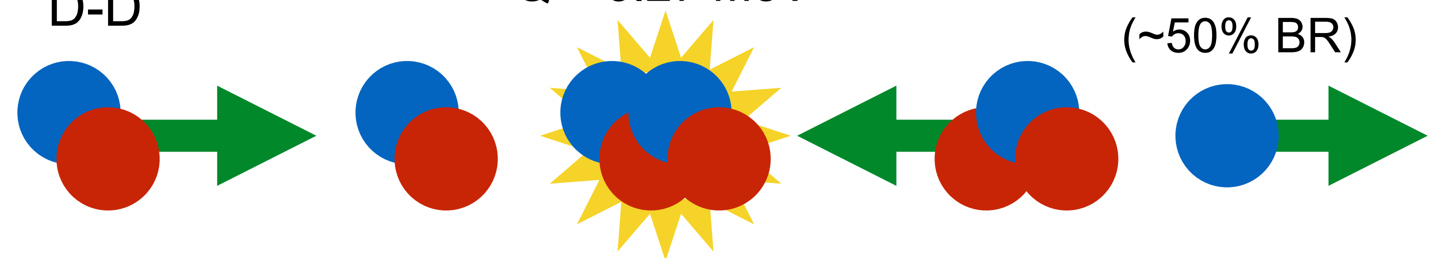
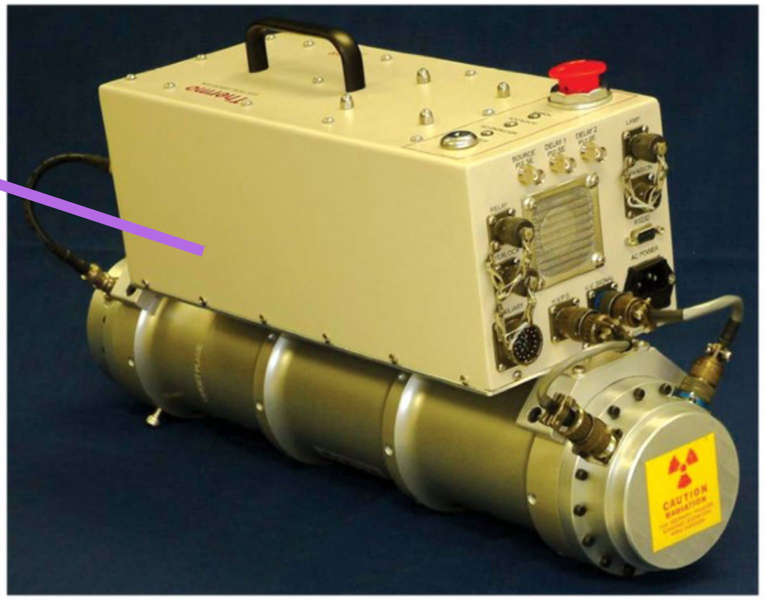
# Background: Pulsed Neutron Generators

Neutron generators (NG): compact linear accelerators to produce neutrons via fusion reaction (D-D or D-T):

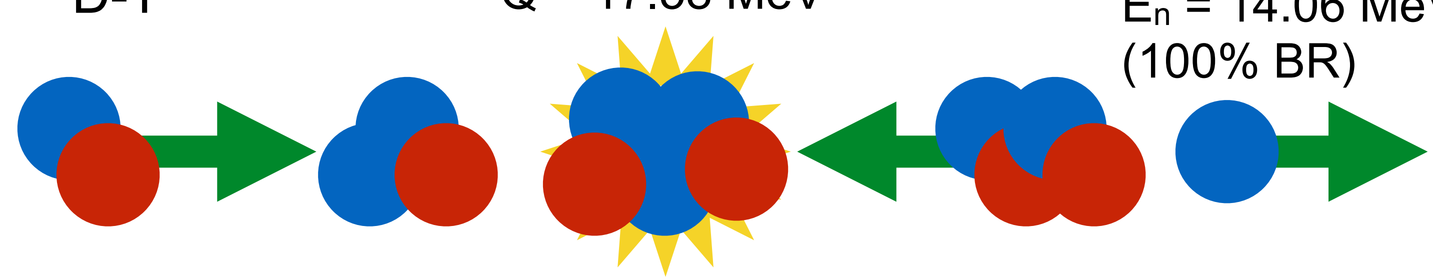
- Typically 100-500 kV acceleration potential
- Yield: $10^5$ to $10^{11}$ n/s
- Pulse lengths: ~5 μs to CW
- Quasi-isotropic
- Neutron emission time and momentum may be tagged using the associated alpha




Thermo Scientific MP320
$10^6$ n/s (D-D)
1000 Hz, ~100 μs pulse



Thermo Scientific P211
$10^8$ n/s (D-T)
100 Hz, ~10 μs pulse




Technical applications of neutron generators are diverse:

- Neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA)
- Prompt fission neutron active interrogation (PFNAI) (D-D only)
- Delayed neutron active interrogation (DNAI)
- Neutron resonance transmission analysis (NRTA)
- Differential die-away analysis (DDAA)

# Primary NG-based Technologies of Interest

NAA:

- Sample irradiated with neutrons; activation products measured *after irradiation* (typical)
- $\beta$ and/or $\gamma$ measurement

PGNAA:

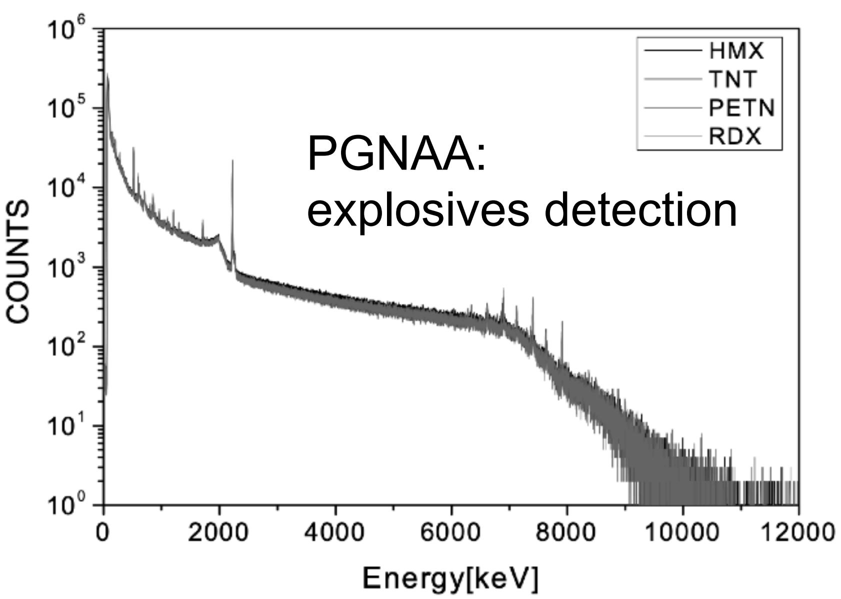
- Signature is *prompt* $\gamma$-ray emission measured *during* irradiation

PFNAI:

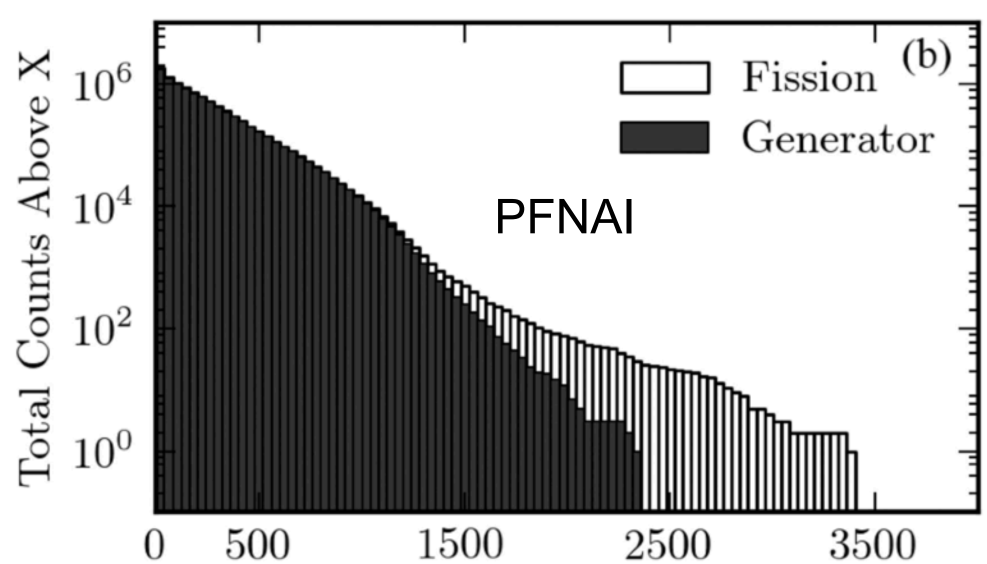
- SNM interrogated w/ neutrons having energy lower than fission neutron end-point
- Presence of high-energy fission neutrons indicates SNM

DDAA:

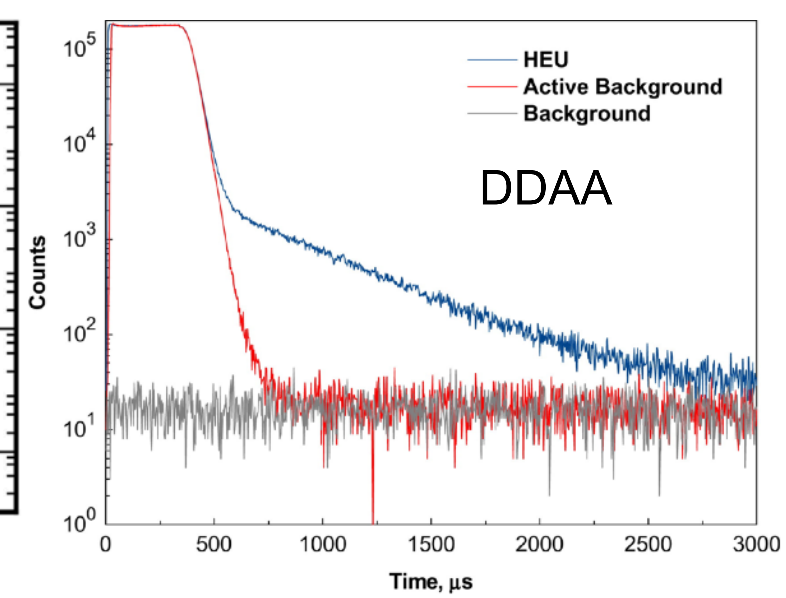
- SNM interrogated w/ pulsed NG, neutrons detected after pulse exponentially "die away," indicates fission chains → multiplicative SNM mass



Im et al. JNST 2014



Lewis et al. Appl. Phys. Lett. 2014

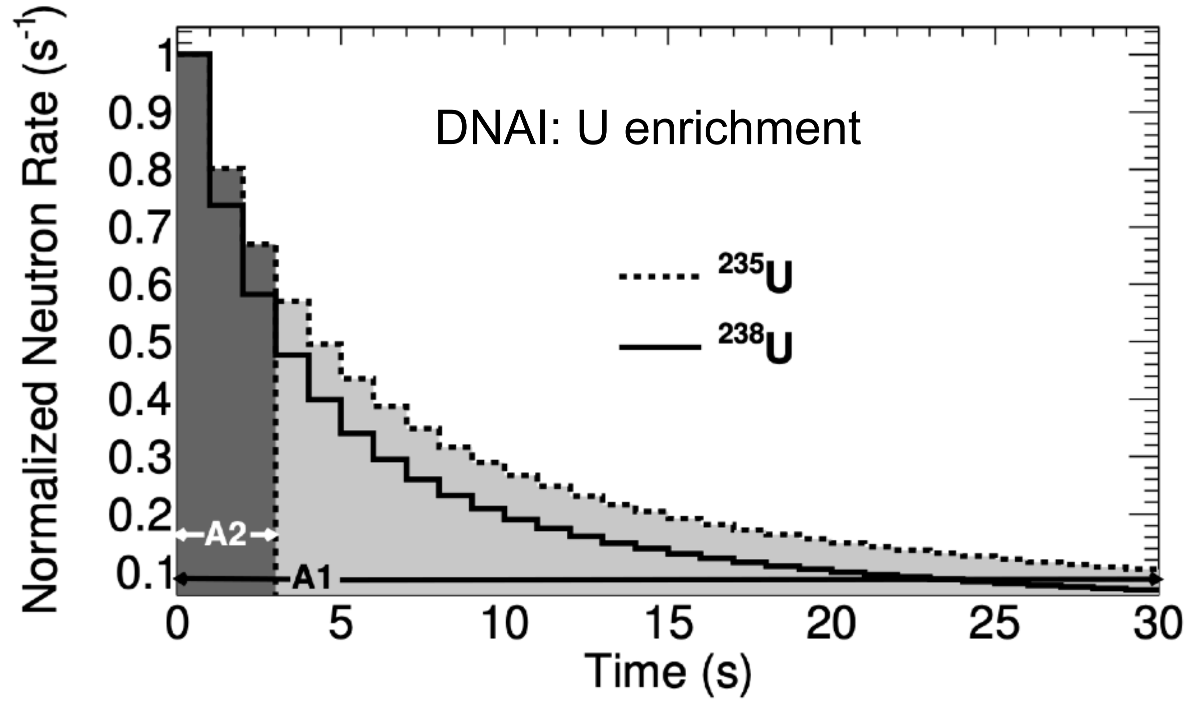


Runkle et al. NIMA 2012

# NG-based Technology Relevance

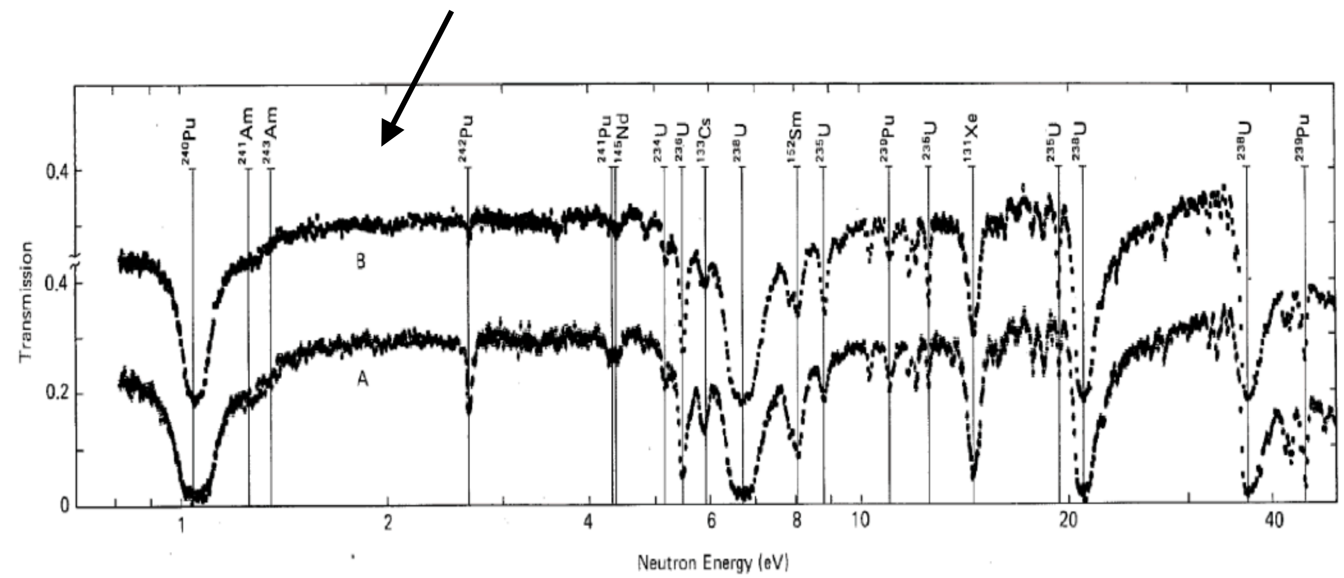
NG-based technology discussed here primarily applied to *nuclear nonproliferation, safeguards, and security:*

- DNAI:
  - proven capability to measure uranium enrichment of thick/ shielded objects (safeguards)
- PFNAI/DDAA:
  - capability to detect attribute of shielded fissile material (nonproliferation, security)
  - may be developed for uranium assay (safeguards)
- NRTA:
  - capability to quantify actinide isotope composition (nonproliferation, safeguards, and security/arms control)




J. Nattress et al. Phys. Rev. Applied 2018

NRTA: spent fuel characterization



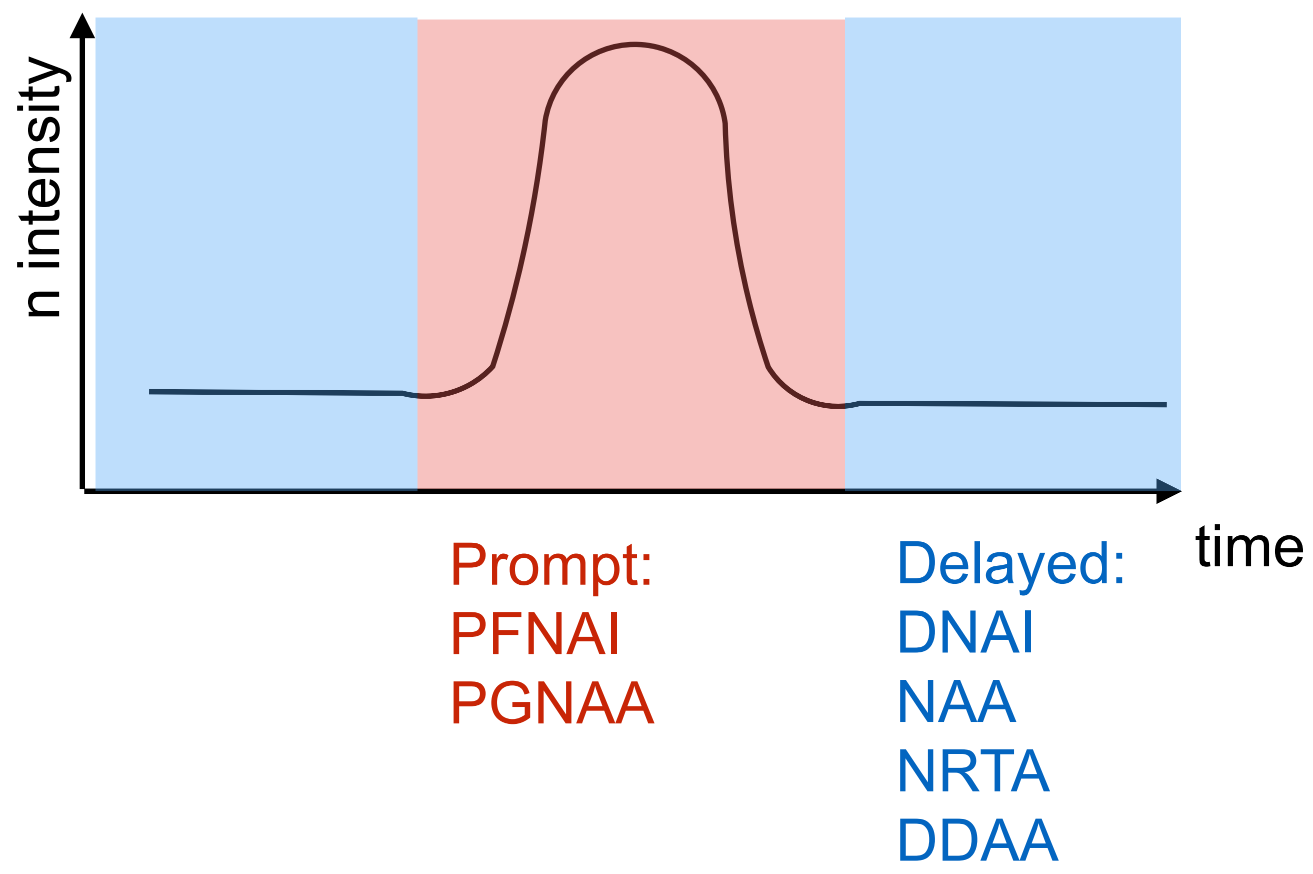

Sterbentz & Chichester, INL Tech. Rep. 2010

# Traditional Temporal Analysis

- Traditionally, these analyses categorize events as prompt or delayed
- Conservative bound is used to exclude the category not desired

- Binary categorization loses valuable timing data
- Time profile of induced radiation unique to production pathway and/or half-life of induced species
- Event timestamp and energy orthogonally measured; combination theoretically improves sensitivity

- Finer analysis requires detailed knowledge of primary generator radiation time profile



# Pulse Time Profiles of Neutron Generators

- Ion source tightly controlled to produce quasi-square pulse
- Most neutron generators achieve high output by utilizing high duty factor/pulse rate, yields low peak output
  - Major drawback for DNAI, DDAA

- For high peak output, quasi-square pulse shape sacrificed, complex pulse shape arises
- Thermo Scientific P211:
  - 100 Hz, 10 μs pulse: 0.1% duty cycle!
  - avg. output $10^8$/s, peak **>$10^{11}$/s**
  - **Excellent for DNAI, DDAA, PGNAA**
  - Challenge: pulse profile is non-trivial

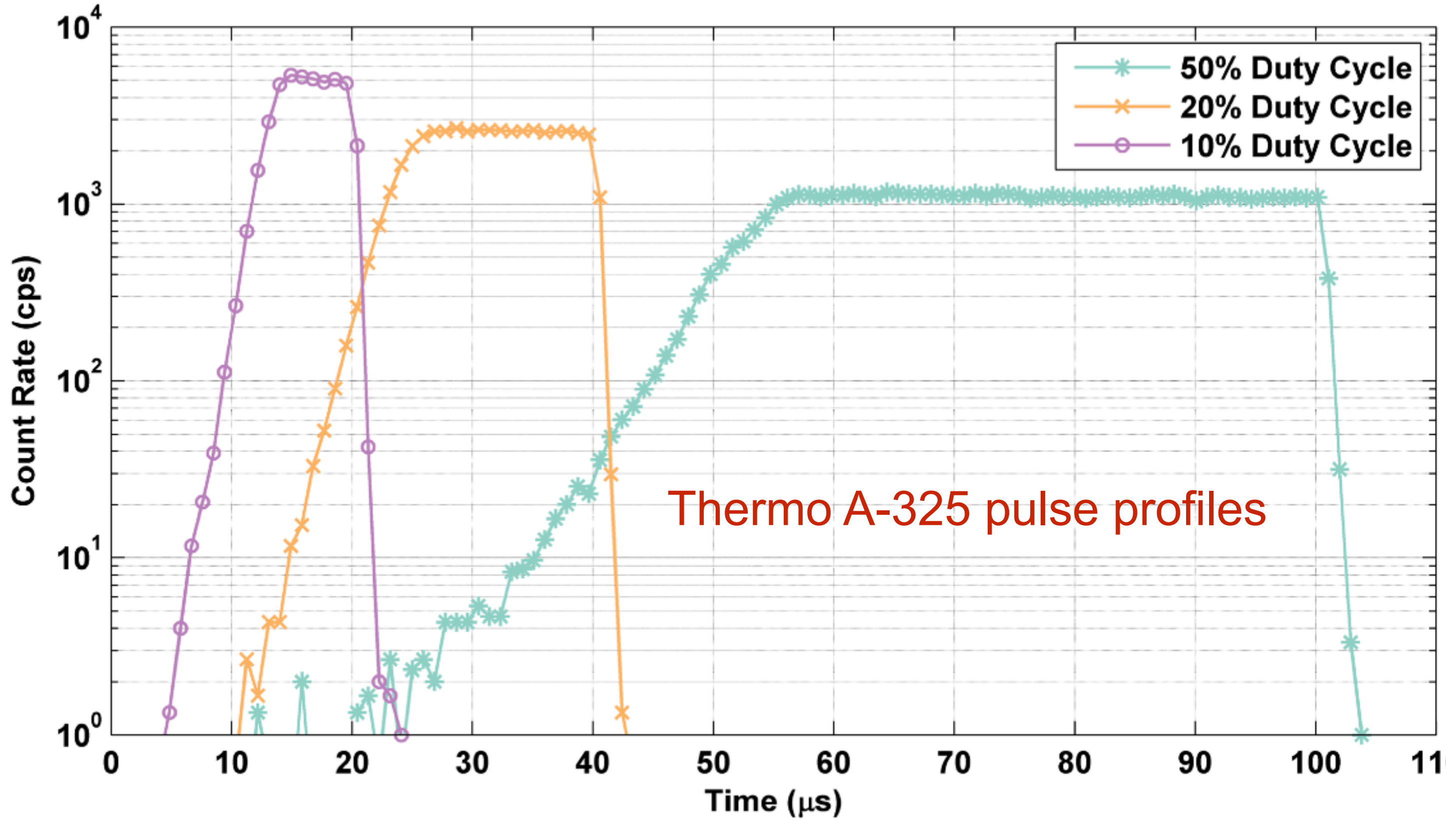
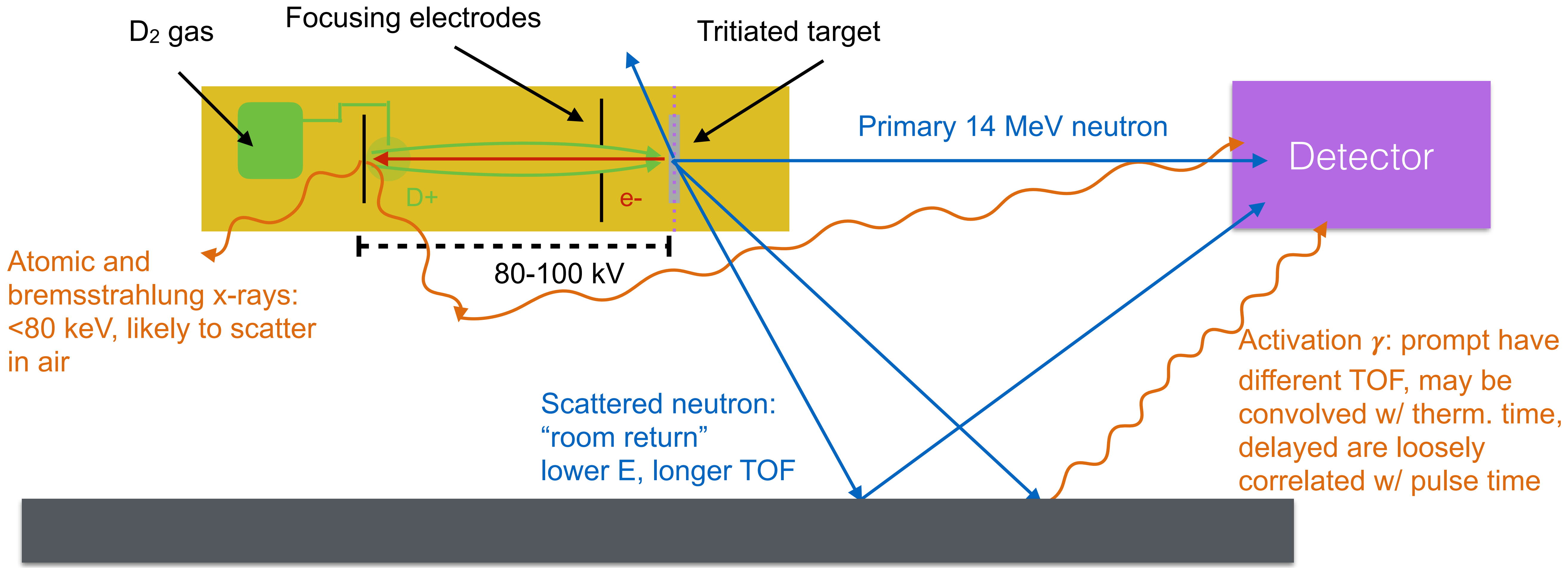


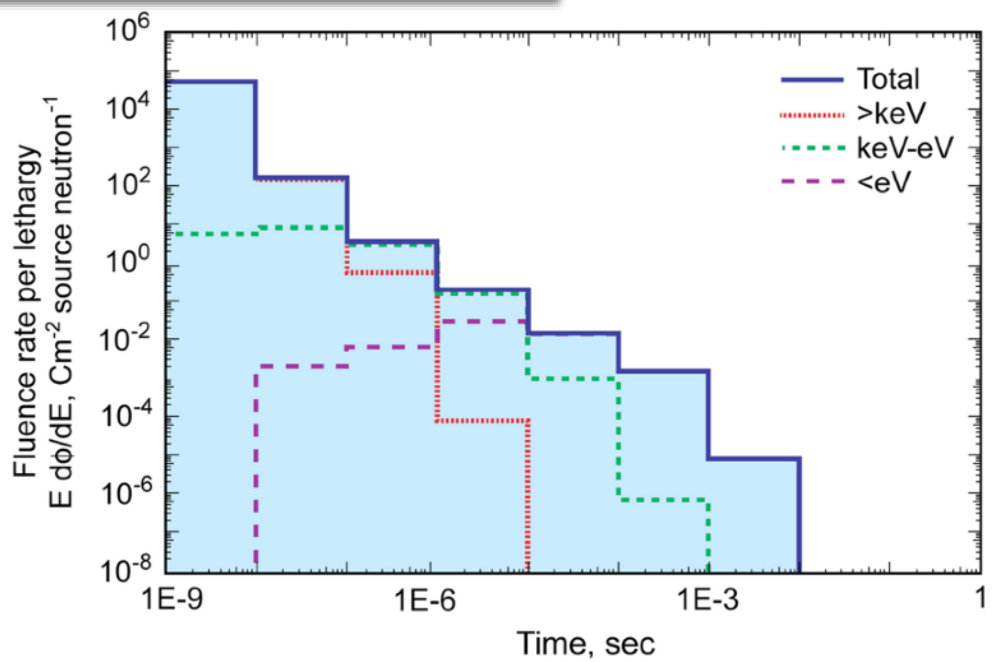

Figure 7: Neutron output profiles at a 5 kHz pulse rate with various duty cycles.

Preston et al. J. of Instr. 2013

# Challenges in Measuring NG Primary Time Profile

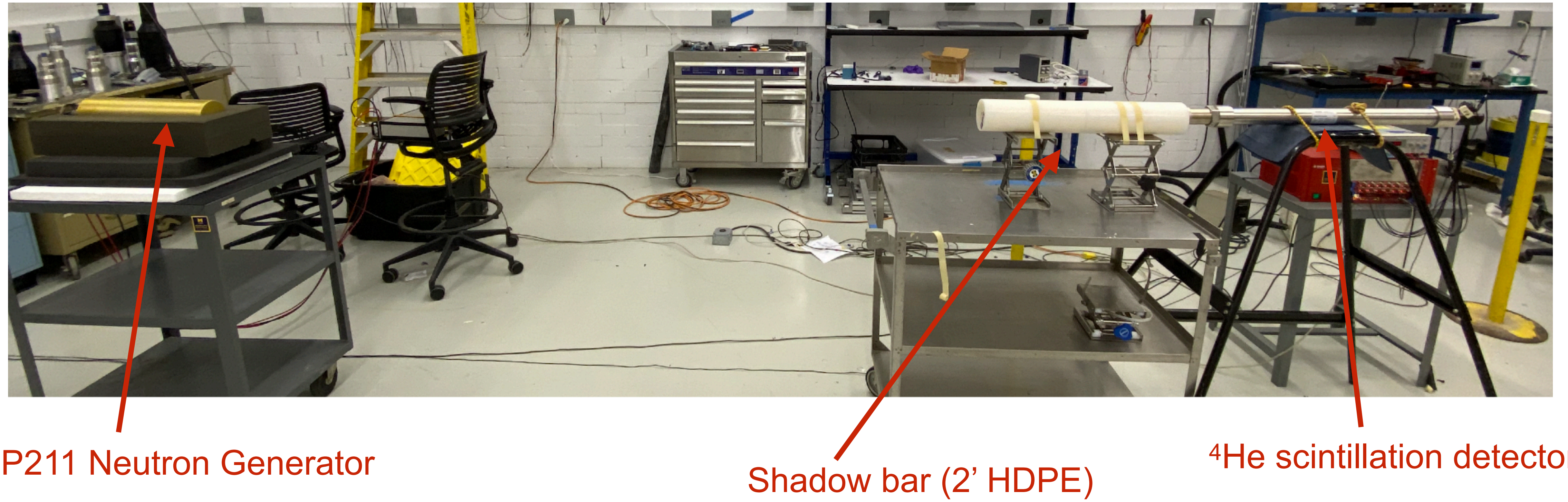



Secondary interactions can distort the measured time profile *and* spectrum, must be accounted for.



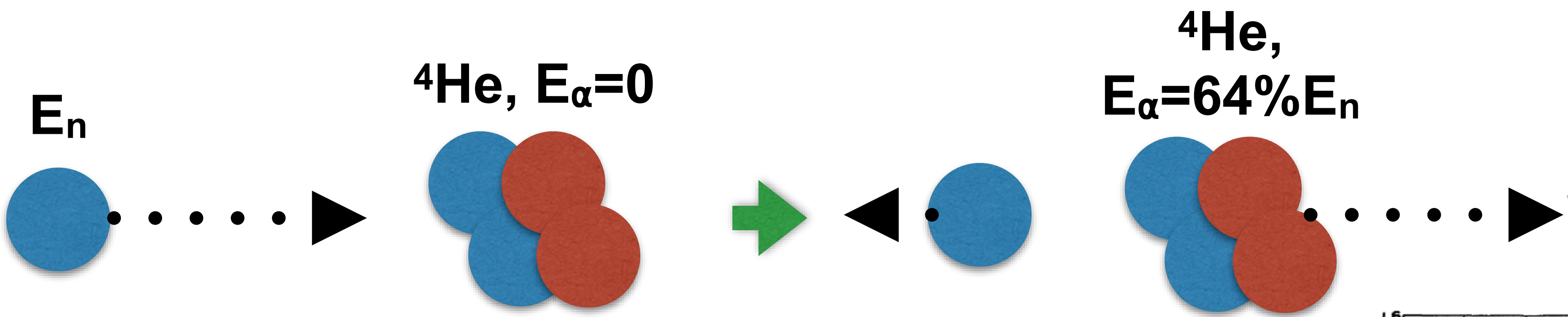

Runkle et al. NIMA 2012

# Primary Method for Measuring Time Profile: $^4$He detector




- $^4$He detector a strong candidate for pulse shape characterization:
  - intrinsic low sensitivity to photons and electrons
  - recoil-based detector to measure D-T neutron spectrum
- P211 NG measured with and without shadow bar to isolate the room return effects
  - Shadow bar results identify portion of measured spectrum not impacted by room return
- P211 reference signal ~10 μs before radiation is emitted, digitized in same DAQ and compared against detector signal

# $^4$He Detector Fundamentals



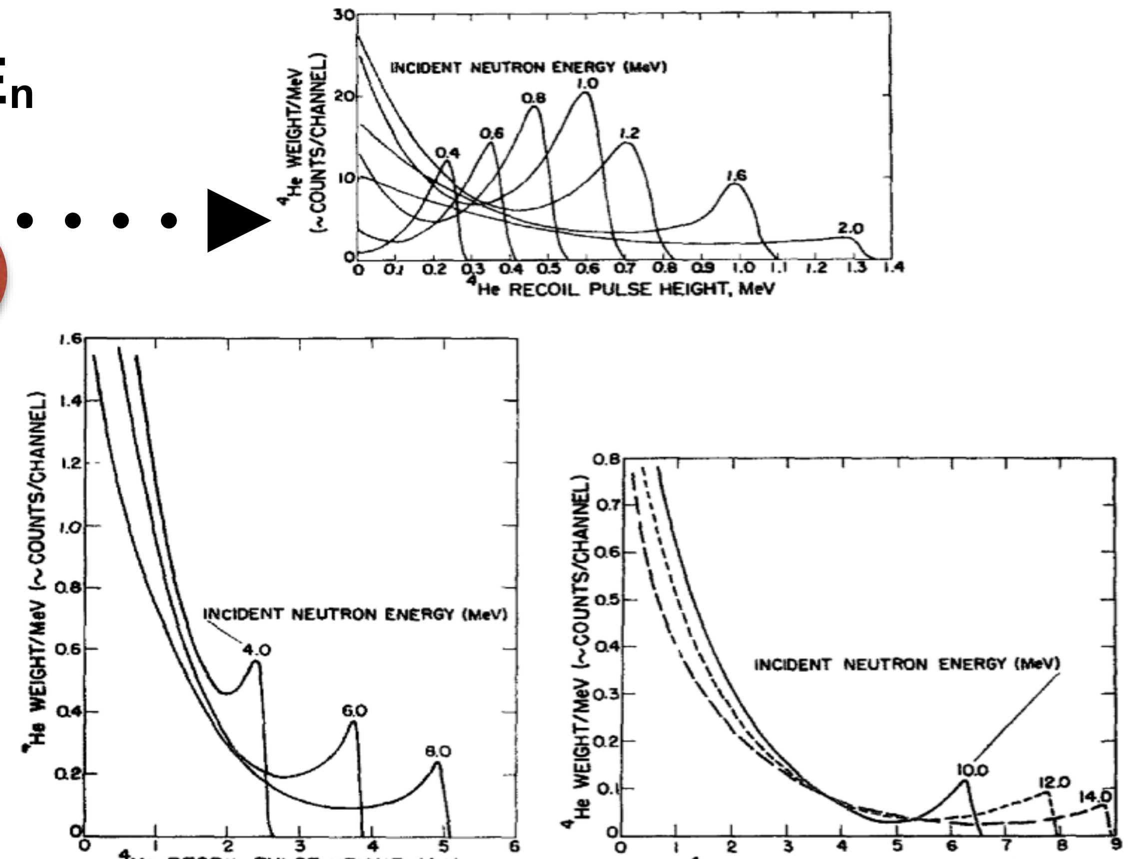
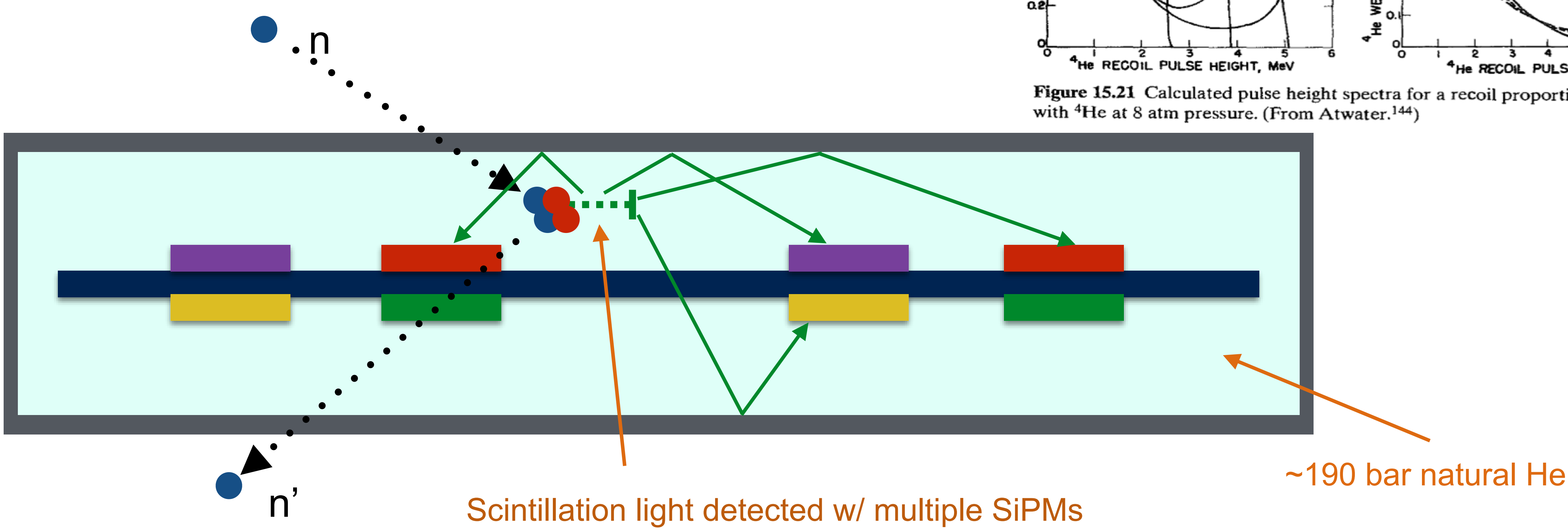



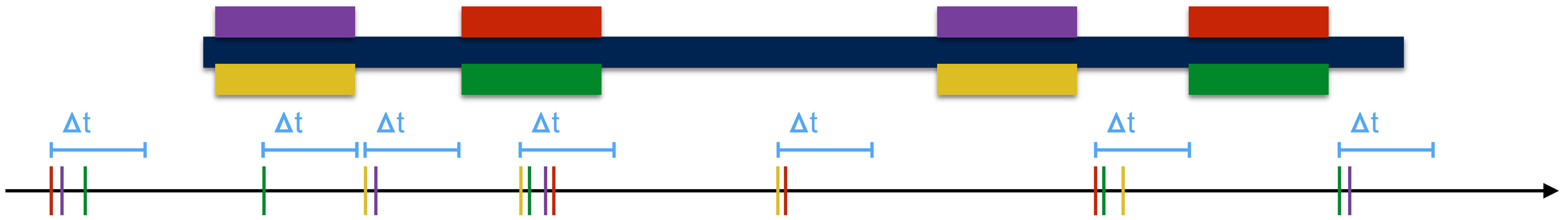

**Figure 15.21** Calculated pulse height spectra for a recoil proportional counter filled with $^4$He at 8 atm pressure. (From Atwater.[144])

Scattering kinematics allow maximum energy transfer of 64% from neutron to $^4$He nucleus, which generates scintillation signal

Intrinsically low sensitivity to $\gamma$-rays, no PSD required



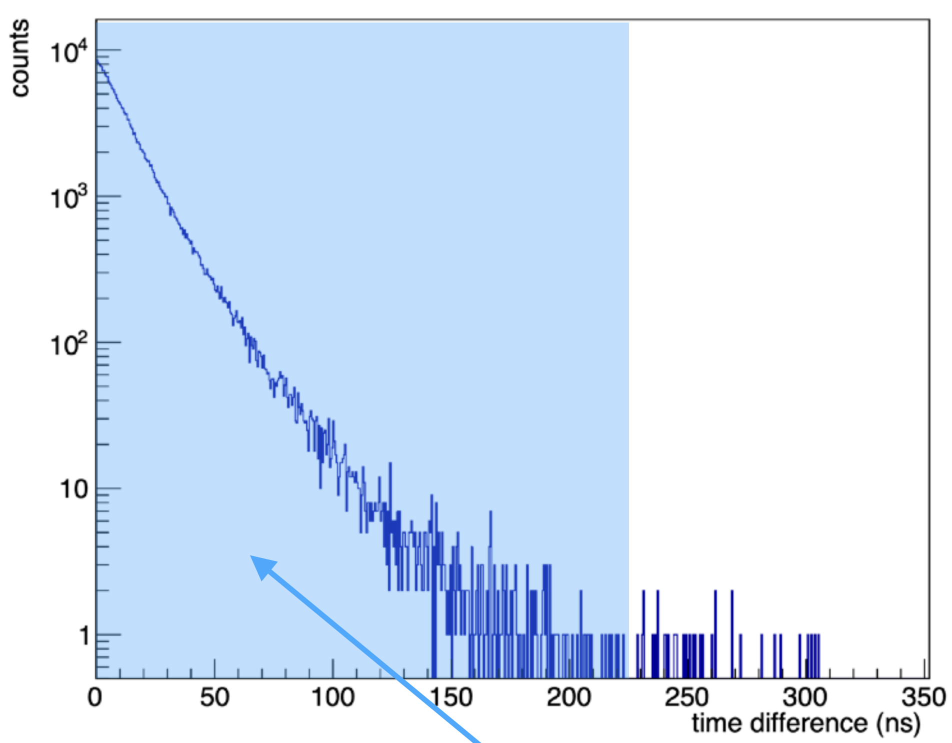
# Generation of $^4$He Spectral and Temporal Data




For each set of pulses within a 225 ns window:

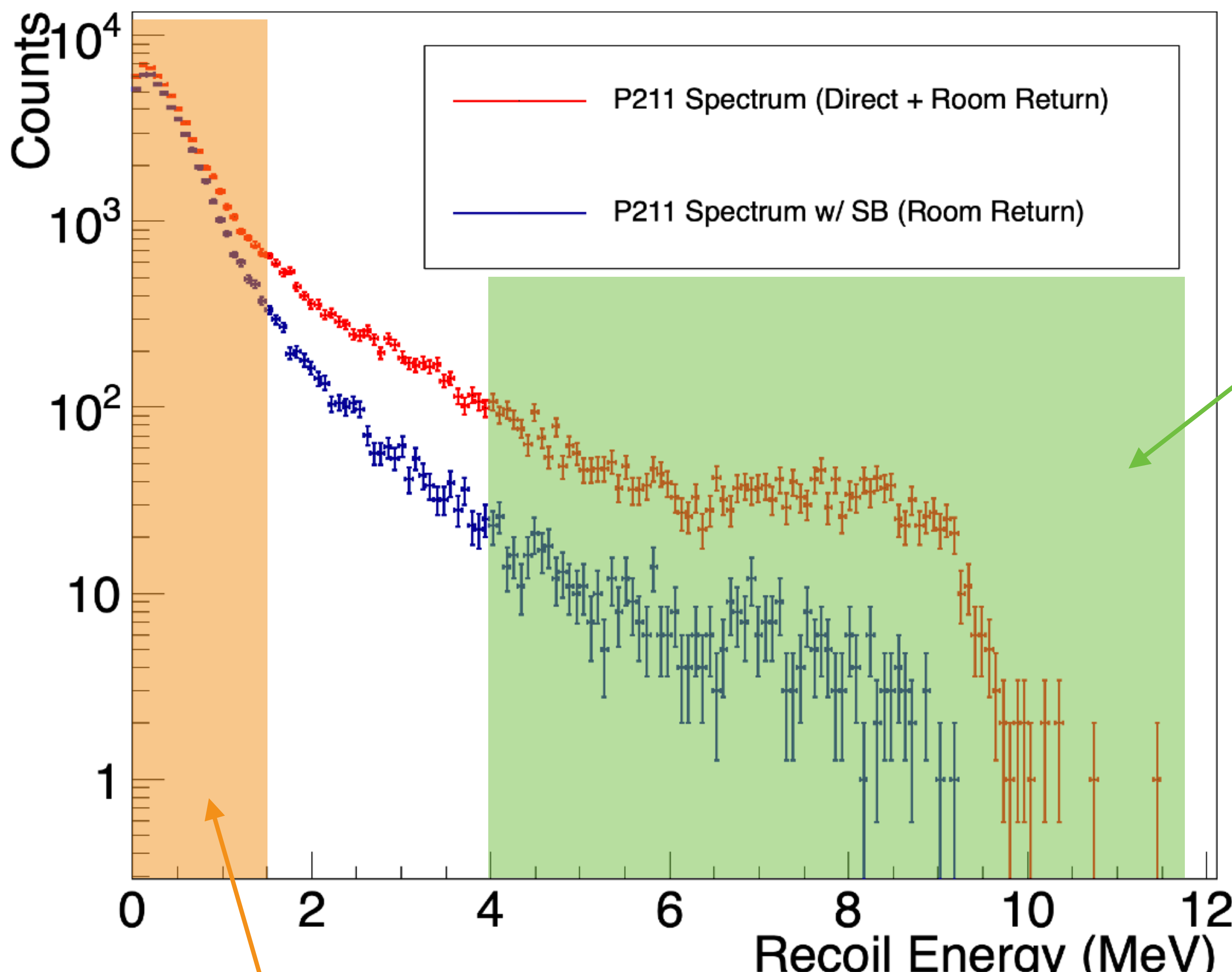
$$PH_{seg} = \sum_{ch=1}^{n_{ch}} PH_{channel}$$

$$t_{seg} = \frac{\sum_{ch=1}^{n_{ch}} t_{channel}}{n_{ch}}$$




Accept these inter-pulse times Δt = 225 ns

# Results: Shadow Bar Characterization




At recoil energies above 4 MeV, >90% of the measured signal is direct signal from generator

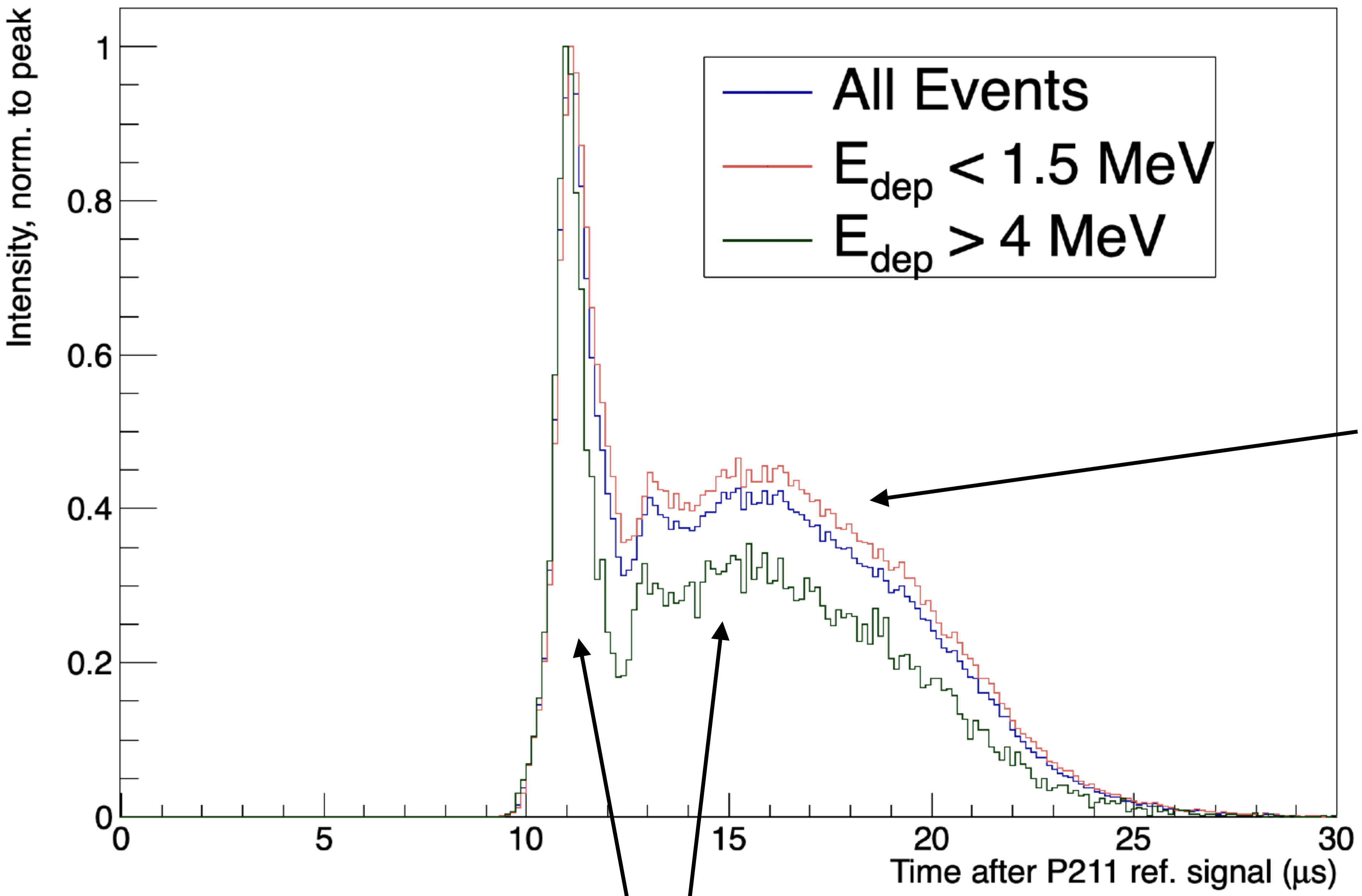
At recoil energies below 1.5 MeV, >90% of the measured signal is **room return**

Performing measurements with and without SB is impractical for realistic applications.

Using a 4 MeV energy deposition requirement is a simpler alternative to measure the time profile in a single measurement

$E_{dep} = 4$ MeV $\rightarrow E_n > 6.25$ MeV

# Results: Time Profile Measurement




Low-energy events overestimate prominence of second feature: impact of secondary radiation from first feature

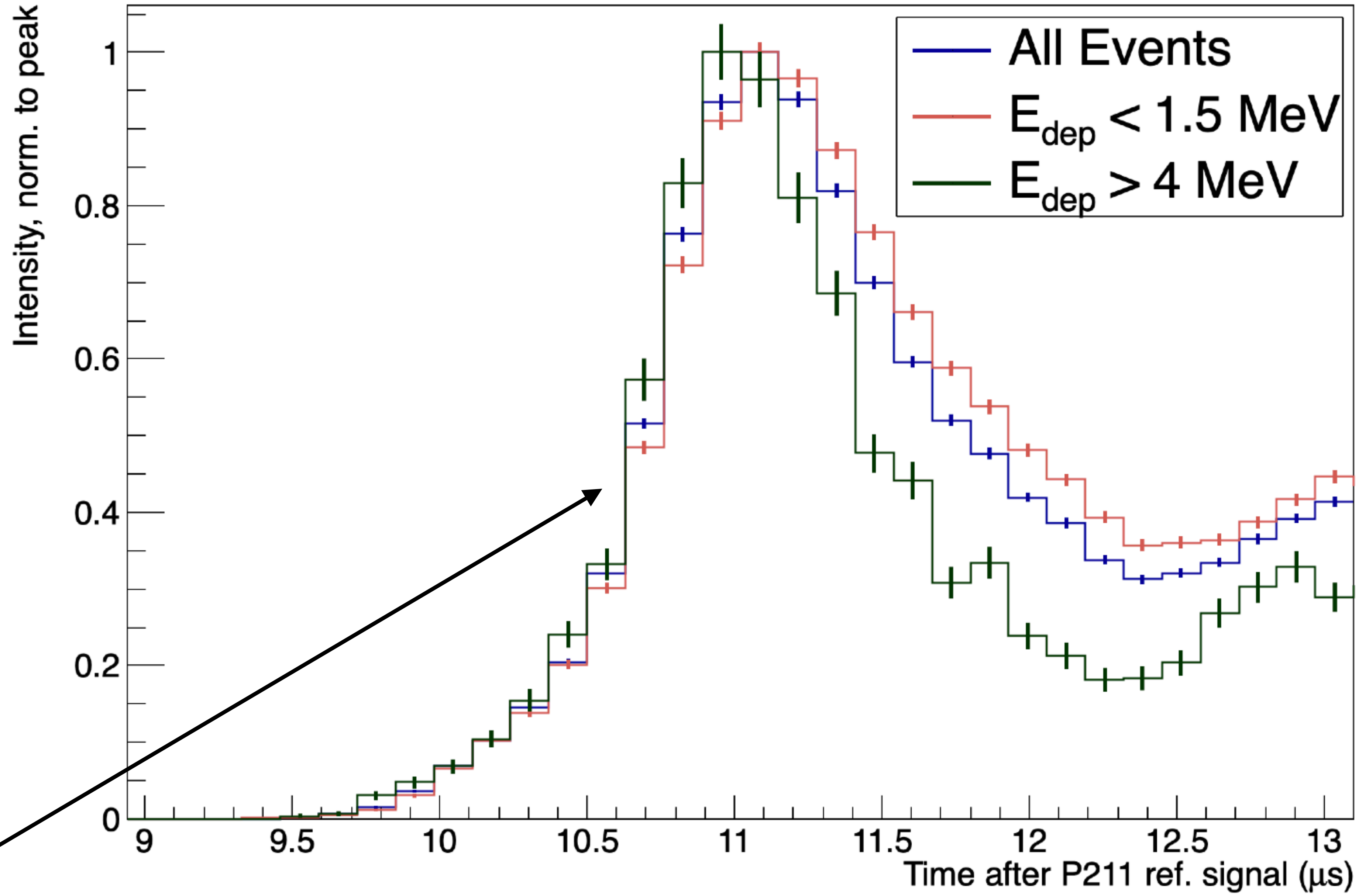
Pulse appears as superposition of two distinct pulses

# Results: Time Profile Measurement

Initial peak illustrates impact of room return:

- High energy: ~1 μs FWHM, peak @ 11.0 μs
- Low energy: ~1.5 μs FWHM, peak @ 11.2 μs

Rising edge is also clearly slower for low energy: room return has longer flight path/response time

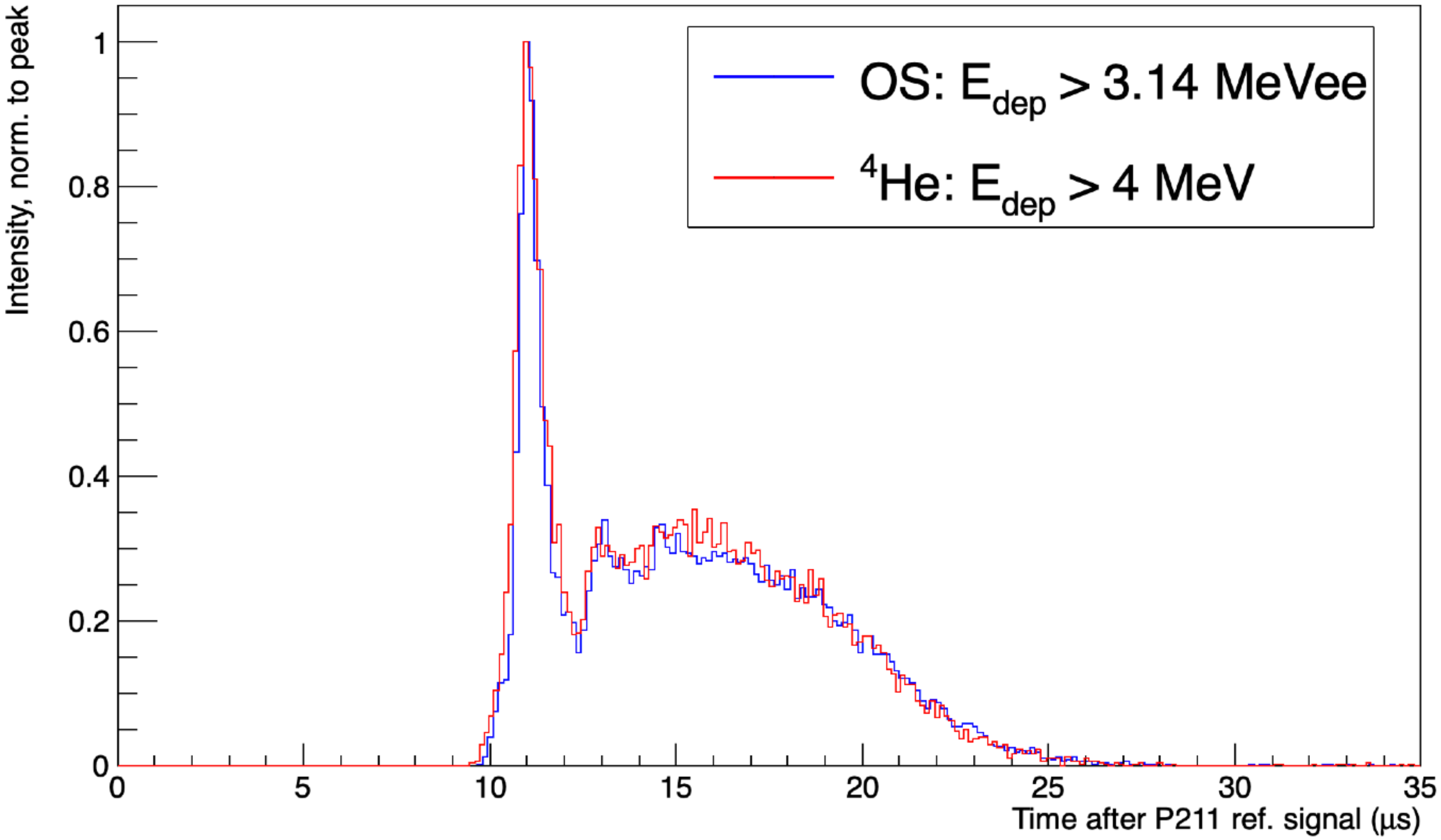


# Result Confirmation: Organic Scintillator

Same measurement conducted w/ organic scintillator:

- 3.14 MeVee threshold:
  - LO corresponding to 6.25 MeV proton recoil (Enqvist et al., NIMA 2013)
- Pile-up rejected
- Pulse shape discrimination applied to reject $\gamma$-rays

OS time-profile showed visually good agreement w/ $^4$He results



# Conclusions and Further Work

- **The direct, primary P211 neutron time profile was isolated from room return and measured with a $^4He$ detector**
  - **$^4He$ detector validated for use as diagnostic of NG spectrum/time profile**
  - **Allows for rapid characterization w/ no shadow bar measurement or PSD required**
  - **P211 initial peak > 3x more intense than secondary peak, indicating peak output of > $10^{11}$ n/s. Fast falling edge of initial peak may be useful for intra-pulse DDAA and NAA.**

- With time profile characterized, work can move to developing advanced temporal analysis of neutron active interrogation signatures
  - Deconvolution of measured signature time profile and measured direct time profile
  - Spectral "weighting" of measured signature based on measured direct time profile

# Acknowledgements

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