Nuclear Resonance Fluorescence and Potential Uses in Active Inspection Technologies

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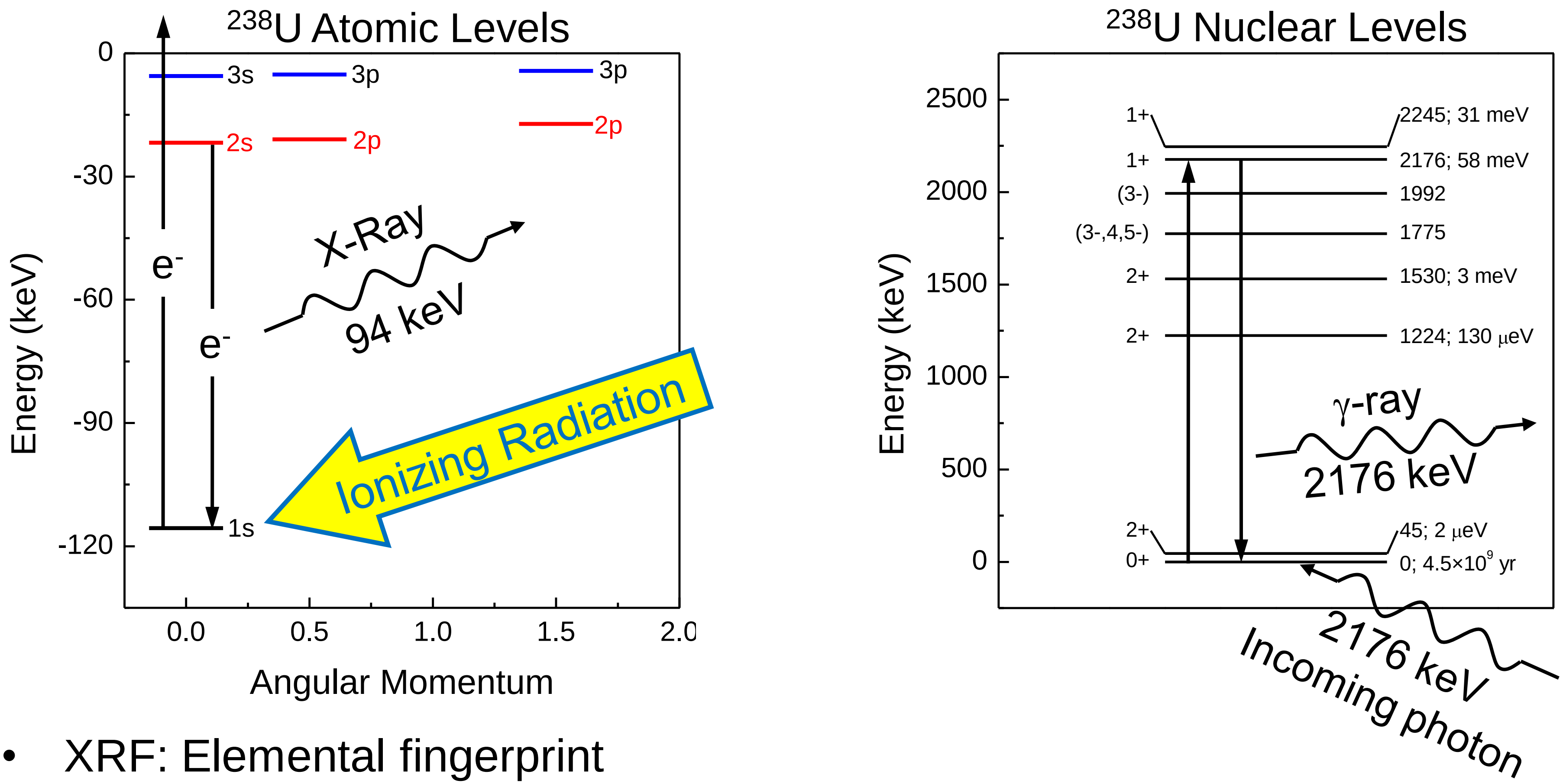
Idaho Accelerator Center — Idaho National Laboratory — Pacific Northwest National Laboratory

NRF is Fluorescence Process Similar to XRF



- XRF: Elemental fingerprint
- NRF: Isotopic fingerprint

- Nuclear resonance fluorescence
  - High-energies 100's of keV to ~MeV
  - Probe photon must be on resonance

NRF Cross Section are Large and Narrow

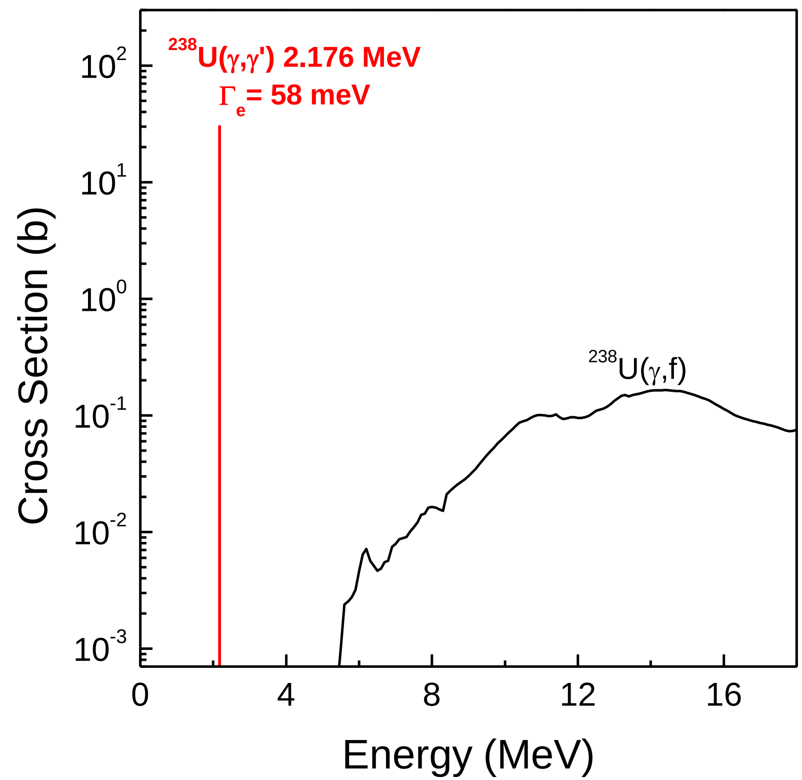
- NRF cross section is simple Lorentzian
  - $$\sigma_{nrf}(E_\gamma) = \left(\frac{c\hbar}{E_e}\right)^2 \cdot \frac{2J_e+1}{2(2J_o+1)} \cdot \frac{\Gamma_{eo}^2}{(E_\gamma - E_e)^2 + \frac{1}{4}\Gamma_e^2}$$

Partial Width

Total Width

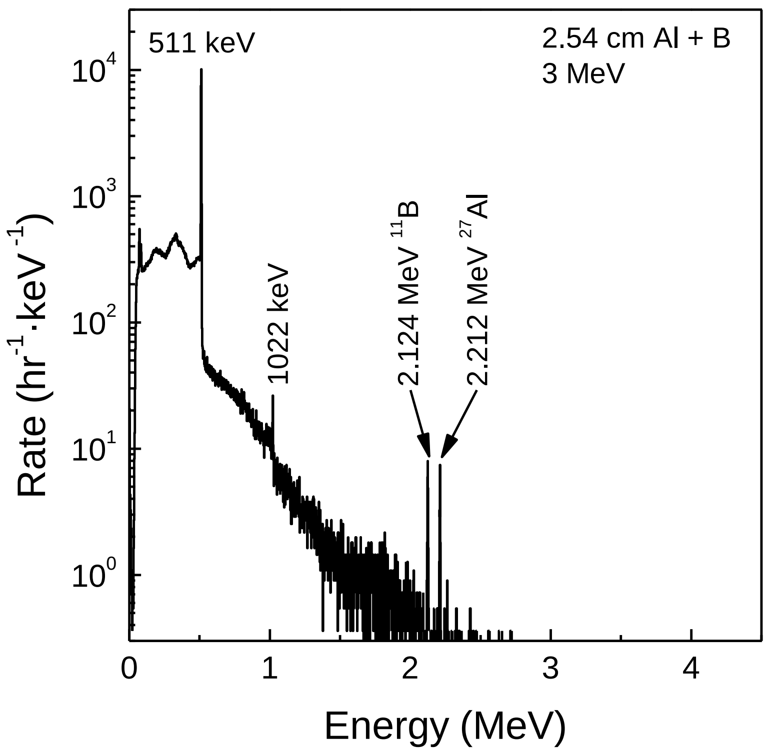
Excitation Energy

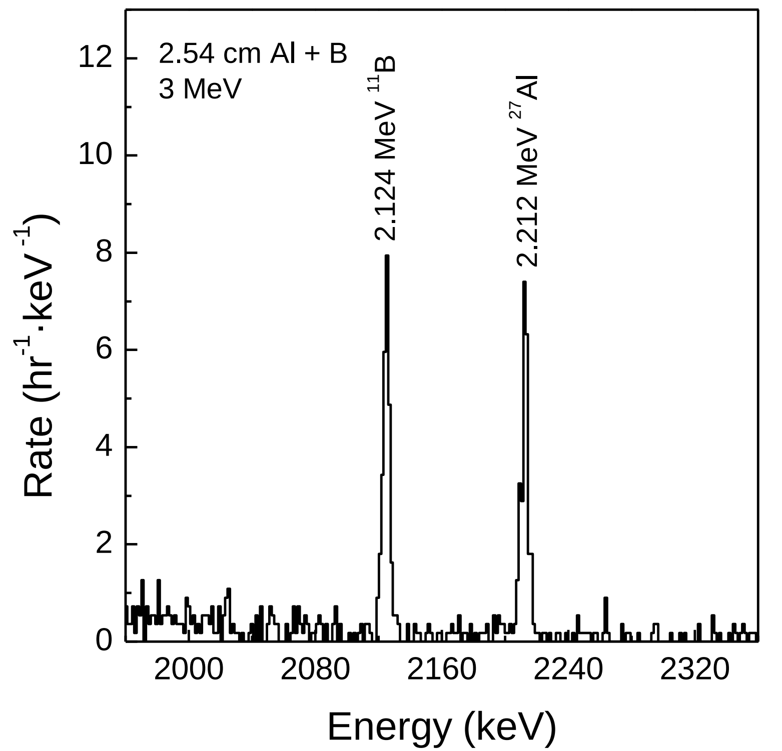
  - Large widths → big cross sections
  - Typical widths μeV, meV, eV
  - Thermal motion broadening important
  - Typical peak cross section
    - ^{208}Pb: 263 b, ^{238}U: 30 b, ^{11}B: 6.0 b



- Broad band probe source (i.e. brems)
  - Flux constant across width
  - Integrated cross section more relevant
    - ^{238}U: 58 b·eV, ^{11}B: 51 b·eV
  - Integrated fission σ: 1.1×10^6 b·eV

NRF Isotopic Fingerprints are Unique: B + ^{27}Al

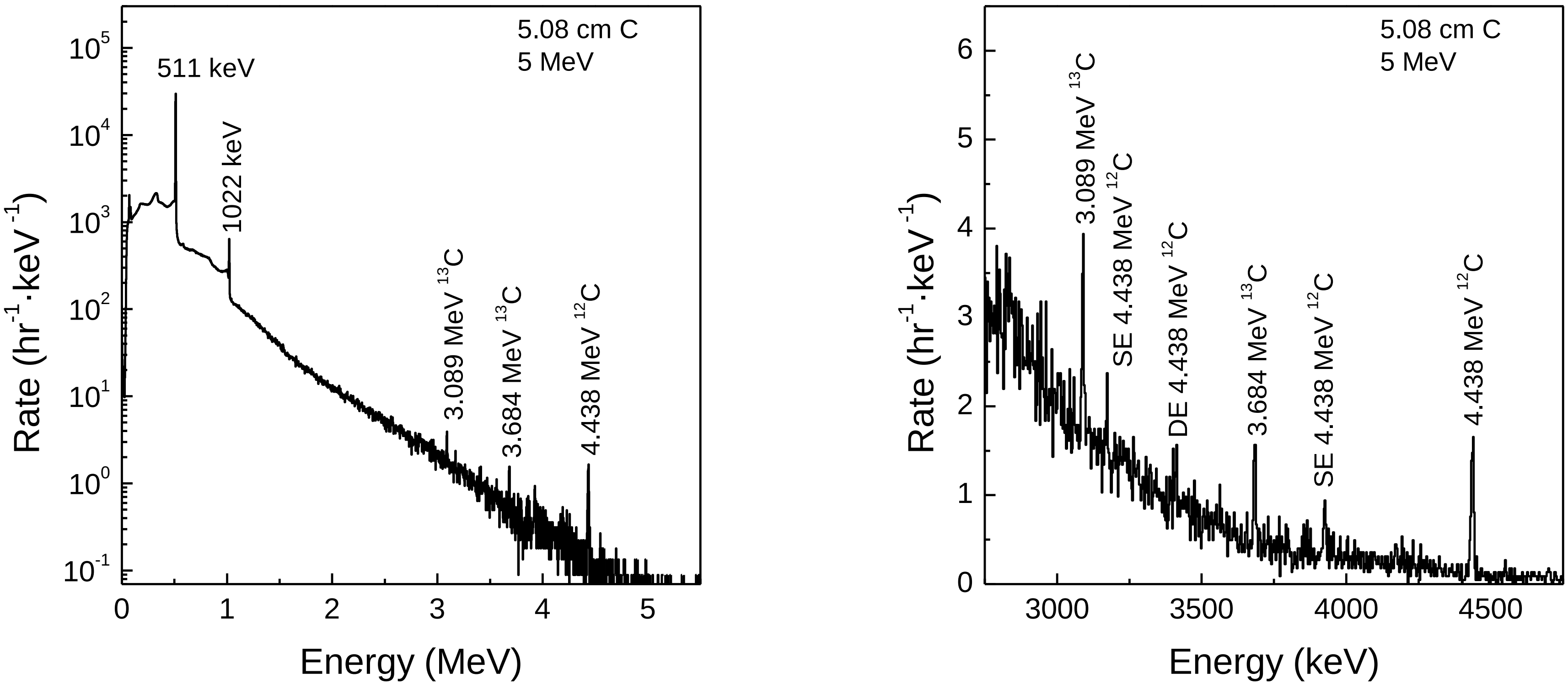




- 3 MeV bremsstrahlung
  - 3 kHz pulsed accelerator; ~15 μA e^-
- Low-Z targets little background

- Cross sections
  - ^{11}B$_{(80\%)}$ 51 b·eV
  - ^{27}Al$_{(100\%)}$ 18 b·eV

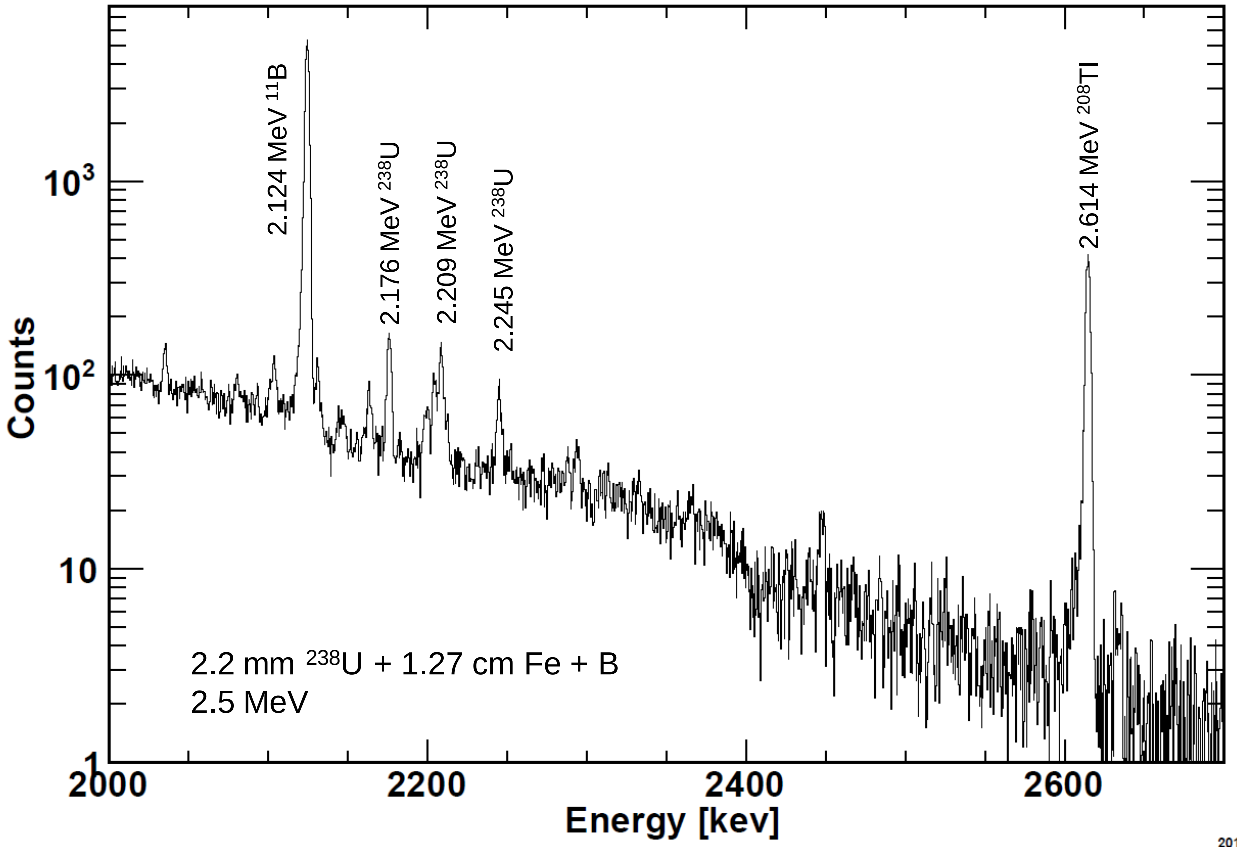
NRF Isotopic Fingerprints are Unique: C



- 5 MeV bremsstrahlung
  - 3 kHz pulsed accelerator; ~8 μA e^-
- Higher-energy + thick target → background

- Cross sections
  - ^{12}C(98.9%) 10 b·eV
  - ^{13}C(1.1%) 235 b·eV

NRF Isotopic Fingerprints are Unique: $^{238}U + Fe + B$



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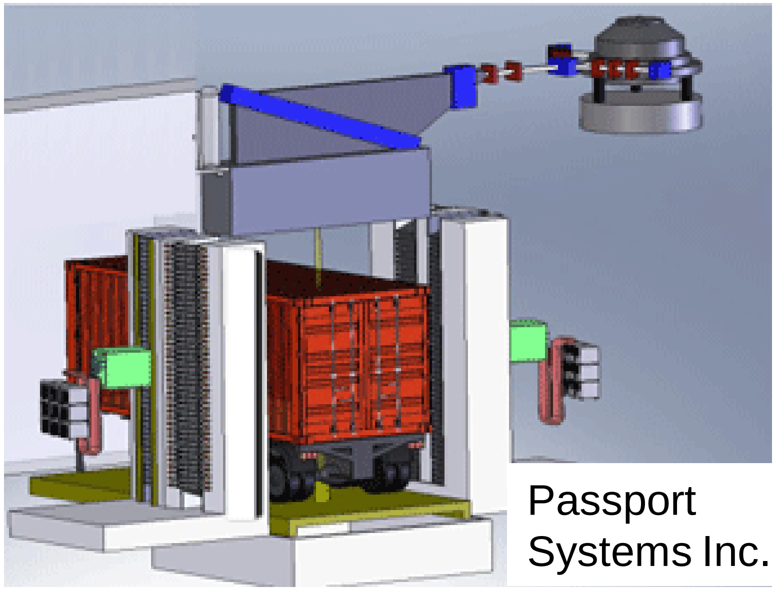
- 2.5 MeV bremsstrahlung
  - CW accelerator; ~27 μA e^-
- High-Z + shielding → background

- Cross sections
  - $^{11}B_{(80\%)}$ 51 b·eV
  - $^{238}U_{(99.8\%)}$ 58 b·eV

Isotope Identification Key to Potential Applications

- **Safeguards**
  - **Nuclear energy**
  - **Specificity, accuracy, speed**
- **Nuclear Forensics**
  - **Military, law enforcement**
  - **Specificity, speed, accuracy**
- **Waste Assaying**
  - **Nuclear energy**
  - **Sensitivity, specificity, accuracy**
- **Cargo Screening**
  - **Security, customs**
  - **Sensitivity, speed, environment**
- Treaty Verification
  - Nonproliferation, Diplomacy
  - Sensitivity, specificity
- Long Standoff
  - Military
  - Sensitivity, speed, environment



Passport Systems Inc.

Nondestructive Key!

- Sensitivity – Minimal detectable mass
- Accuracy – Mass determination
- Speed – How fast is inspection
- Specificity – Isotope identification
- Environment – How much dose

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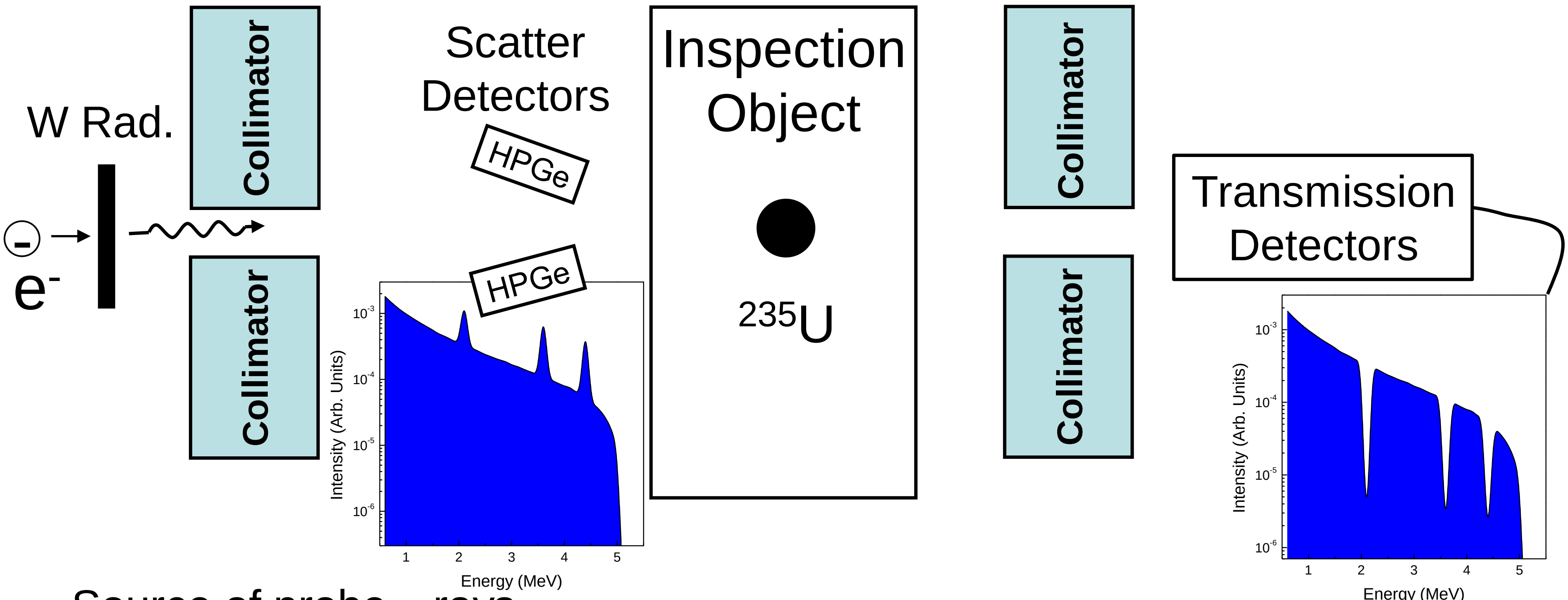
Experiment or Inspection Setup Straightforward



- Source of probe γ-rays
  - Bremsstrahlung: Look for many NRF lines, majority of beam “unused”
  - Monoenergetic (e.g. LCS): Majority of beam “used”, observe a single NRF line
- Collimation and Shielding (probe beam and detectors)
- Detectors
  - Scatter: Observe transition
  - Transmission: Measure absorption of probe beam (tuned to specific NRF lines)

Messy when Schematic Meets Experimental Reality

Collimator

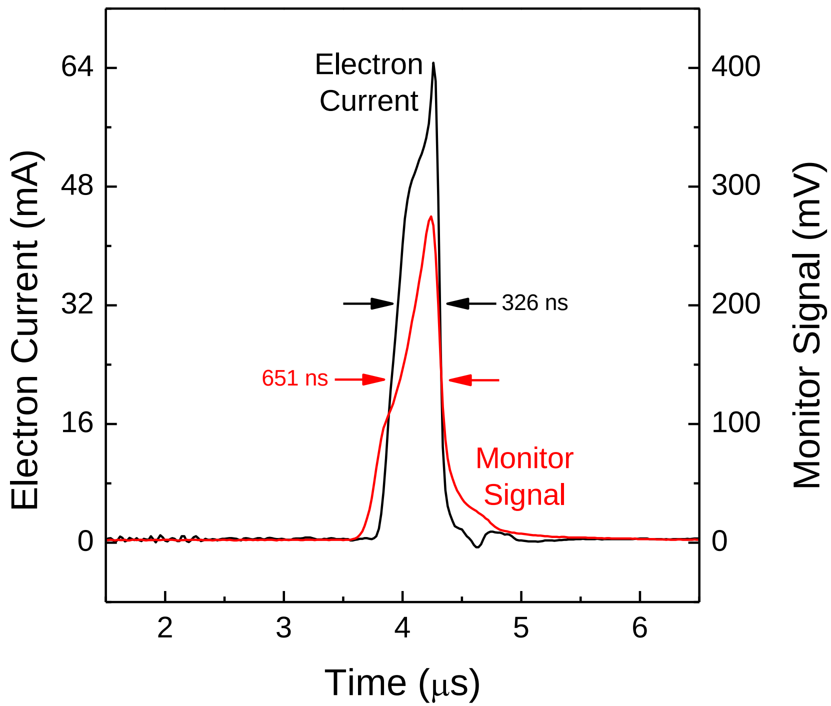
90% HPGe Detector

^{238}U Target

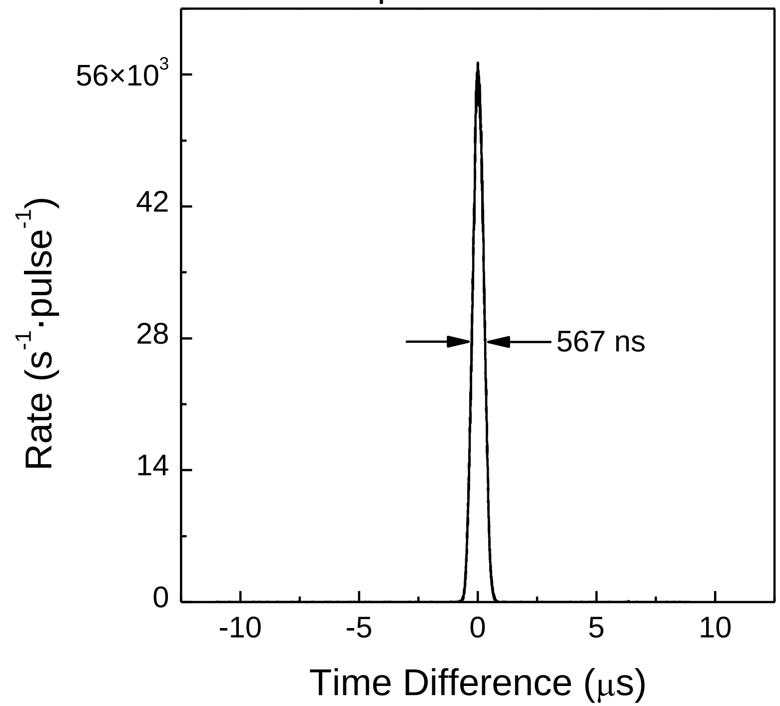
Beam Monitor

Pulsed Linacs are "Off" Most of the Time

Electron and Beam Monitors



Coincidence Spectrum HPGe vs. Brem.



- Repetition rates are low
  - Typical linac (i.e. medical): 300 Hz
  - Enhanced medical: 1 to 3 kHz
- IAC linac "on" 0.059% to 0.195% of time
- Must avoid pulse pileup in HPGe
  - Detector rate ~100 to 300 Hz
- CW Accelerator
  - Detector rate ~15 kHz
  - Can this be pushed higher?
- Do not use pulsed linacs?

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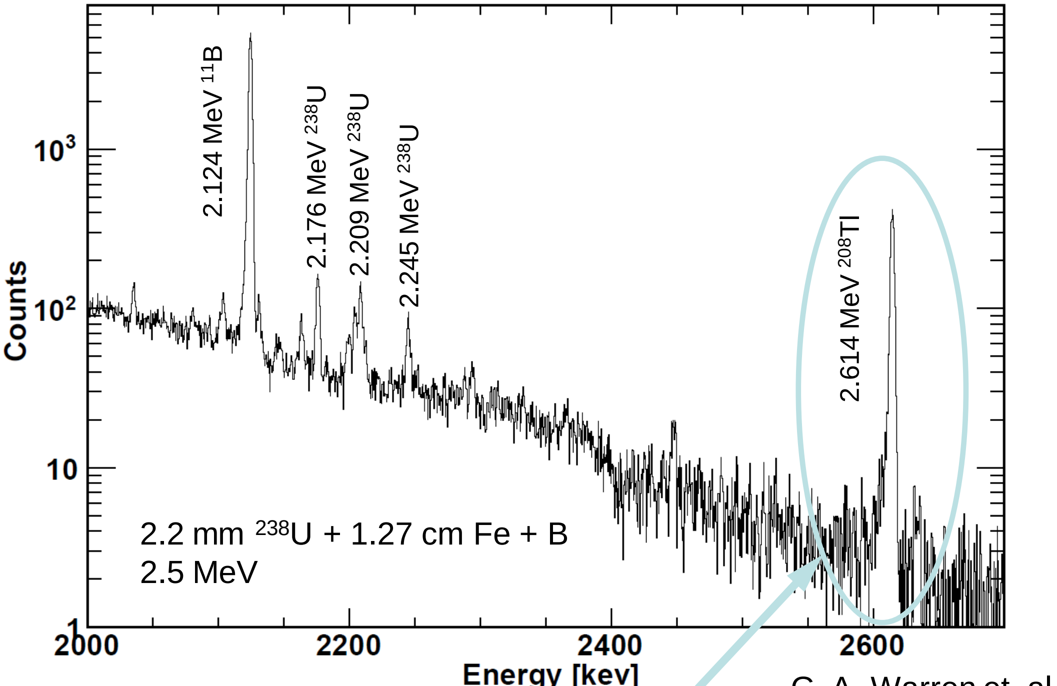
Low Rep. Rate → Statistically Starved Spectra

CW Accelerator NRF Spectrum



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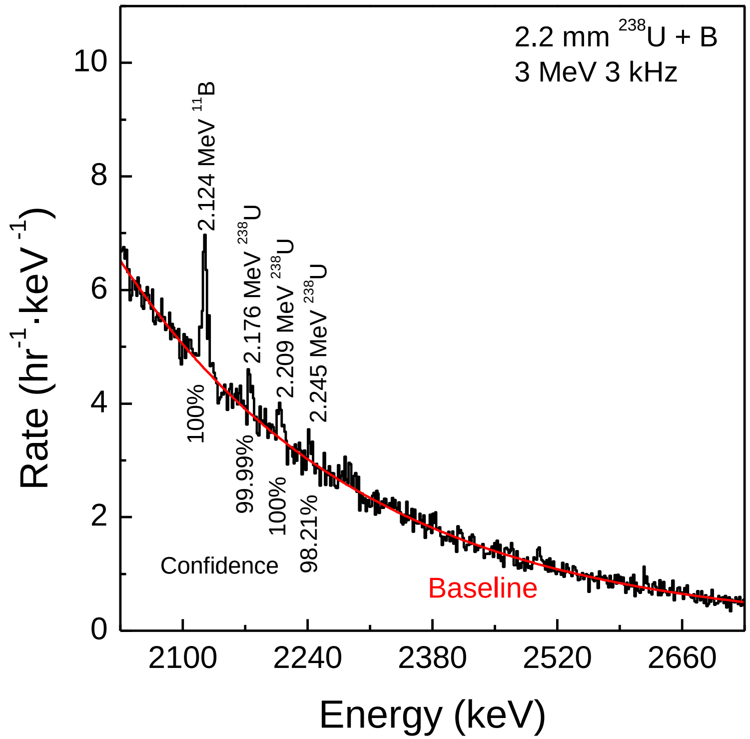
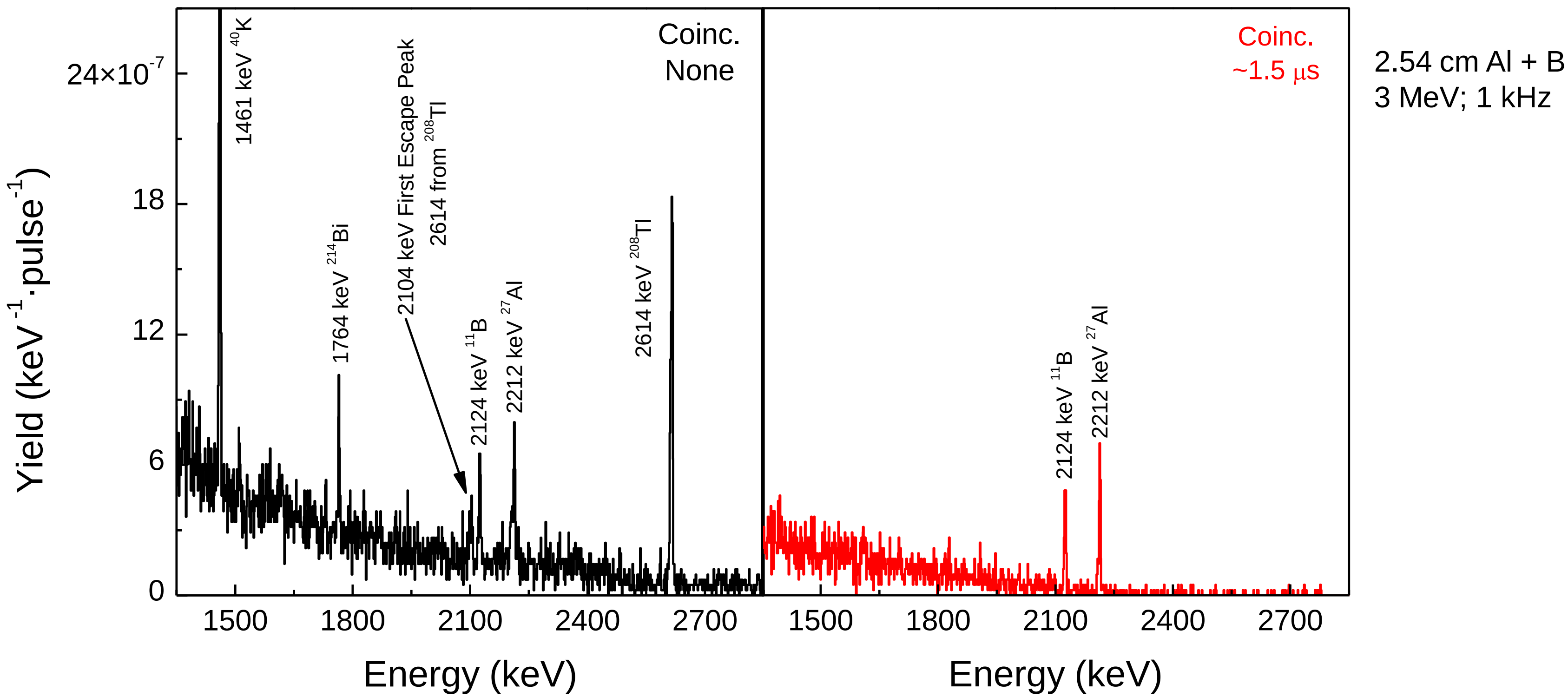
Passive Background

Pulsed Linac NRF Spectrum



- CW Experiment
  - Shielded ^{238}U plate
  - 27 μA e^- current
  - Detector rate ~15 kHz
- Pulsed Experiment
  - Bare ^{238}U plate (same as in CW)
  - 14 μA e^- current
  - Detector rate ~300 Hz

Pulsed Brems Eliminates Natural Background



- Without coincidence requirement
  - Passive background: ~10^{-5} pulse^{-1}
  - NRF yield: (5.2±0.6)×10^{-6} pulse^{-1}
- 1.5 μs coincidence requirement
  - Passive background: ~10^{-8} pulse^{-1}
  - NRF yield: (3.4±0.4)×10^{-6} pulse^{-1}

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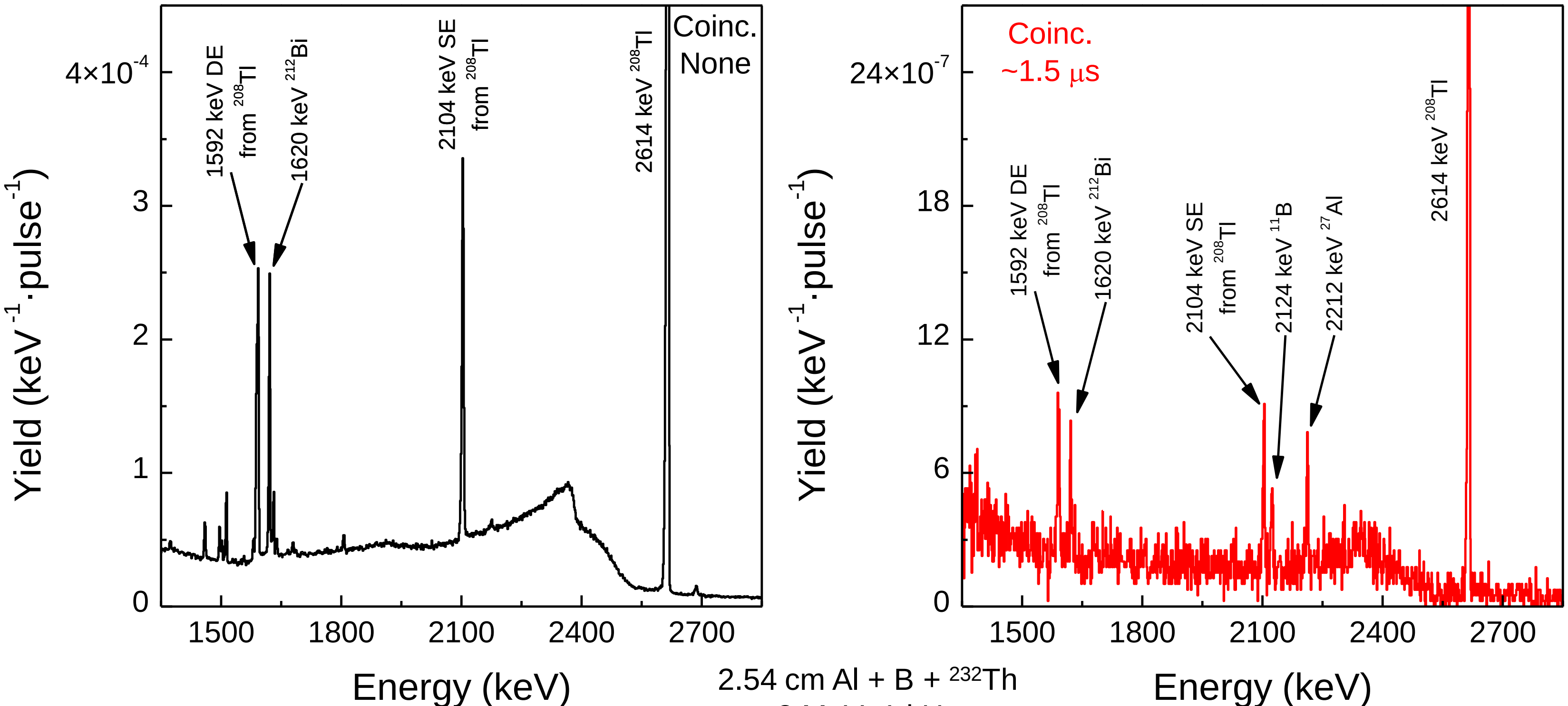
Important to Minimize Passive Background

- Low mass or shielded materials
  - Natural background is significant
  - Nuclear forensics
  - Waste assaying
  - Cargo screening

- High passive backgrounds
  - Passive background obscures NRF transitions
  - Safeguards
    - Assaying of spent fuel for ^{239}Pu (UCB + LBL currently investigating)
    - Reprocessing monitor
  - Waste assaying
    - Fissile content assay for waste classification

- Minimized background → Maximized sensitivity

Coinc. to Minimize Large Passive Background



2.54 cm Al + B + ^{232}Th
3 MeV; 1 kHz

Additional ^{232}Th increased 2614 keV rate by 10^3

- Without coincidence requirement
  - Passive: ~10^{-2} pulse^{-1}
  - NRF yield: Unmeasurable
- 1.5 μs coincidence requirement
  - Passive: ~10^{-5} pulse^{-1}
  - NRF yield: $(2.9\pm0.6)\times10^{-6}$ pulse^{-1}

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Conclusions

- NRF provides isotopic fingerprint
  - Applications requiring isotope specificity

- NRF cross sections are large and narrow
  - Broad energy probe beam: Identify many isotopes; Majority of beam “unused”
  - Monoenergetic probe beam: Identify single isotope; Majority of beam “used”

- Advantages of pulsed bremsstrahlung
  - Minimize passive background by 10^3
  - Maximize sensitivity

- Issues with pulsed bremsstrahlung sources
  - Low repetition rates → small NRF rates
    - Need high rate accelerator
  - Enhanced pulse pile up
    - Need deconvolution algorithms (exploit time information)

Path Forward for Pulsed Bremsstrahlung

- Current CW experiments
  - 15 kHz detector rate
- Desired pulsed accelerator
  - Repetition rate: 150 kHz
  - Charge in pulse: Match 15 kHz detector rate
  - Pulse width: ~10 ns take full advantage of coincidence timing
- Capabilities of pulsed NRF system
  - NRF intensities matching current CW experiments
  - ~10^3 passive background reduction
- Higher detector rate?
  - Increase repetition rate → decrease passive background reduction
  - Increase hit fraction → increased pulse pileup