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Contraband Detection using Materials Identification by Resonance Attenuation (MIRA)

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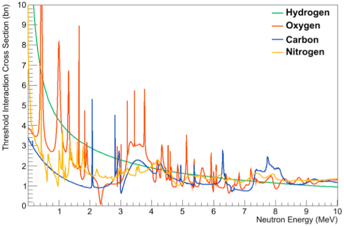
Outline

- Explosives Detection with Fast Neutrons - Summary
- Material Identification through Resonant Attenuation - Overview and Methods
- Prototype results with two block setup
- Detector development for six block setup
- Simulation and algorithm development
- Path forward

Explosives Detection Methods

- X-ray screenings only sensitive to variations in density
- Techniques based on neutrons are sensitive to nuclear structure
  - Thermal Neutron Analysis looks at gamma particles resulting from thermal neutron capture (e.g. 2.2 MeV gamma from capture on Hydrogen, 10.8 MeV from capture on Nitrogen-14)
  - Fast Neutron Analysis techniques use neutron attenuation to do tomographic imaging and look at resonance absorptions



The Time-Resolved Integrative Optical Neutron (TRION) Detector

- Fast Neutron Analysis technique, looking at resonances in neutron absorption and doing tomographic imaging
- Interrogates sample with 1-2 MHz pulse neutron beam
- Uses TOF to determine energies in 1-10 MeV range
- Scintillation light focused onto time gated optics: gate only allows certain energies to pass
- Drawbacks are complexities of pulsed neutron beam and only discrete energy measurements

Fig. 28c Camera 2, E_n = 7.3 MeV

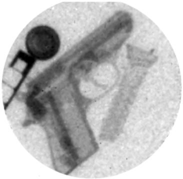
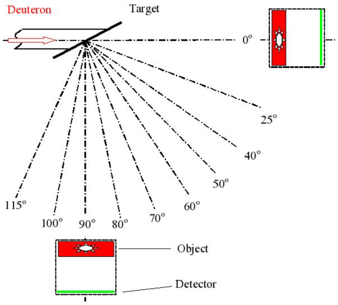


Fig. 28d Camera 3, E_n = 3.1 MeV

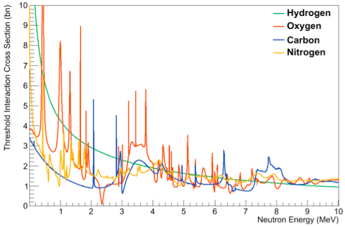
G. Chen and R. Lanza's Method

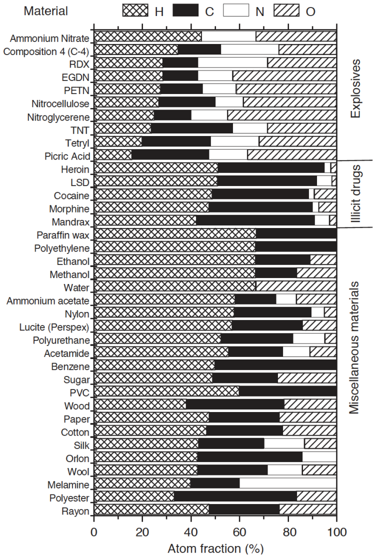
- Similar to TRION detector, but does not use TOF to determine neutron energy
- Accelerate deuterium/protons onto a deuterium/Lithium target $\rightarrow$ neutrons with energies dependent on the angle between the beam and detector
- Similar drawbacks to TRION



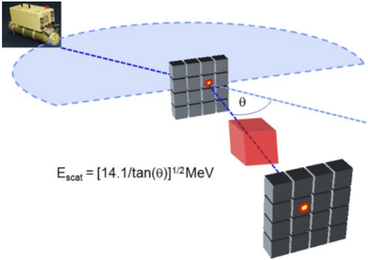
Contraband Detection with MIRA

- Light elements such as O, C, N have resonant features in the neutron cross section
- The energy-dependent attenuation of 1-10 MeV neutrons leaves a "fingerprint" of the material's elemental composition





Why is MIRA Different

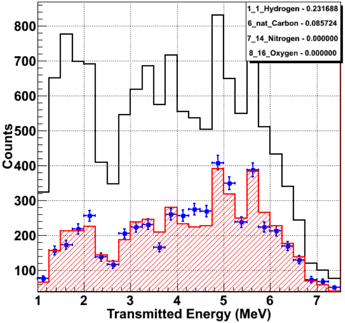


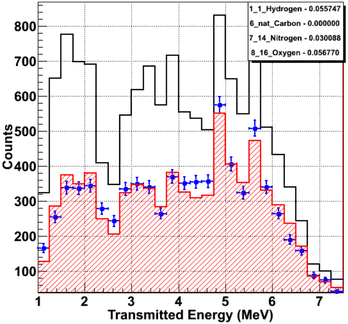
- Down scatter in first detector provides range of energies in one scan
- Down scatter in first detector provides time tag for TOF energy measurement/windowing to reject backgrounds
- Competitors often have schemes involving one energy per scan
  - Gated electronics coupled with pulsed neutron accelerator for TOF measurement
  - Angular dependent neutron generator (deuterium/protons on deuterium/lithium target) with sample and detector rotating with respect to beam

Two Methods of Energy Calculation - TOF Method

- $E_i = \frac{m}{2}\left(\frac{d}{t}\right)^2$ where
  - E_i is the energy before passing through the sample
  - d is the distance between two detectors on either side of the object to be interrogated,
  - t is the time-of-flight
  - m is the mass of the neutron
- $\sigma_{E_i} = \sqrt{\left(\frac{\partial E_i}{\partial d}\right)^2 \sigma_d^2 + \left(\frac{\partial E_i}{\partial t}\right)^2 \sigma_t^2} = 2E_i\sqrt{\frac{\sigma_d^2}{d^2} + \frac{\sigma_t^2}{t^2}}$
- With 1 ns timing resolution and 1 cm depth resolution, we can expect 7% energy resolution at 3 MeV (1 ns requires a change in scintillator/electronics)

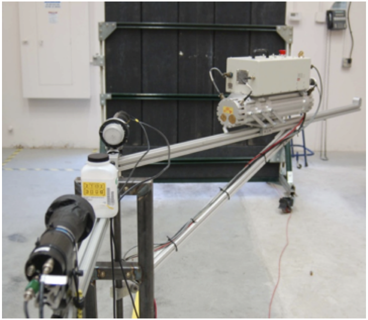
Previous Results - 2 Block Setup





Sample	H (M/cc)		C (M/cc)		N (M/cc)		O (M/cc)	
	exp.	mea.	exp.	mea.	exp.	mea.	exp.	mea.
HDPE	0.23	0.23	0.11	0.09	0.00	0.00	0.00	0.00
Water	0.22	0.22	0.00	0.04	0.00	0.02	0.11	0.10
AN	0.06	0.08	0.00	0.00	0.03	0.03	0.05	0.04

Lessons Learned

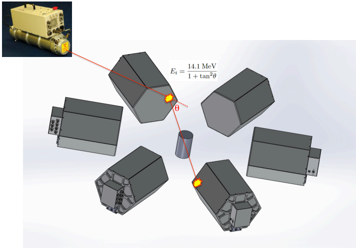


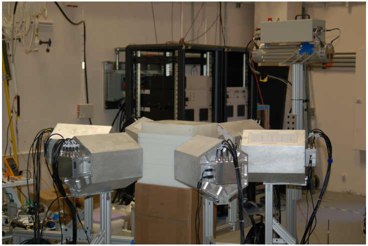
- Resolution Matters! - both timing and position
- Scan time matters - more blocks allow for only one scan, and a faster one
- With more blocks we have bonus information on scattered neutrons (more on that in a bit)

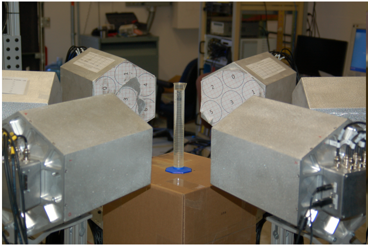
Two Methods of Energy Calculation - Trajectory Method

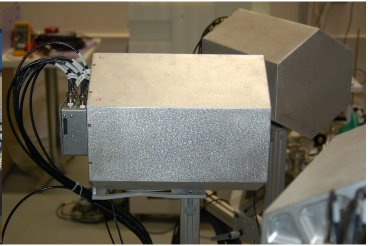
- $E_i = \frac{14.1 \text{ MeV}}{1+\tan^2\theta}$ where
  - E_i is the energy before passing through the sample
  - $\theta = \tan^{-1}(\frac{z}{x})$ is the deflection angle
  - α is the angle defined by the angular extent of the (d-T) generator's emission region
- $\sigma_{E_i} = \sqrt{\left(\frac{\partial E_i}{\partial \theta}\right)^2 \sigma_\theta^2 + \left(\frac{\partial E_i}{\partial \alpha}\right)^2 \sigma_\alpha^2}$
  $= 2\sqrt{2} E_i \tan\theta \sqrt{\left(\frac{z}{x^2+z^2}\right)^2 \sigma_x^2 + \left(\frac{-x}{x^2+z^2}\right)^2 \sigma_z^2 + \sigma_\alpha^2}$
- With 5 mm spatial resolution, we can expect 5% energy resolution at 3 MeV

Current Detector - Six Block Setup

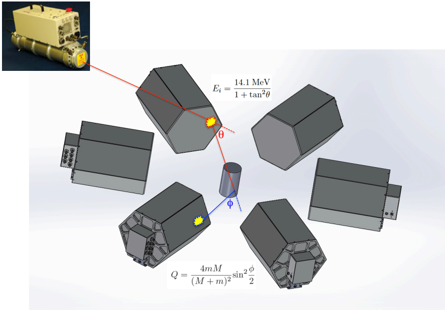








Bonus Mode of Operation - Elastic Scattering

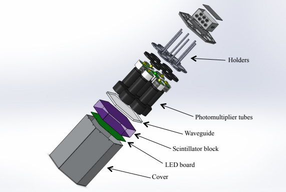


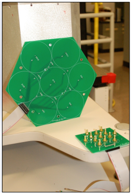
- Assuming $m << M$[1] the neutron energy lost in collision with sample nuclei is $Q = \frac{4mM}{(M+m)^2}\sin^2\frac{\phi}{2}$
- If we get the energy before and after a collision, Q, along with the trajectory information, the mass of the nuclei, M, in the sample is uniquely determined:

$$M = \frac{2m}{Q}\sin^2\frac{\phi}{2}\left(1 \pm \sqrt{1 - \frac{Q}{\sin^2\frac{\phi}{2}}}\right) - m$$

[1] For the special case of m=M (i.e. scattering on Hydrogen), the two particles scatter at right angles to each other and the energy loss is $Q = E_0\cos^2\phi$

The Block Detectors

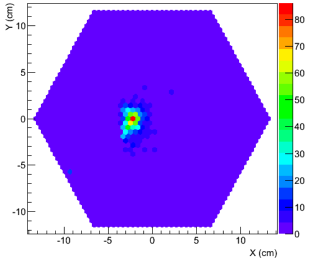




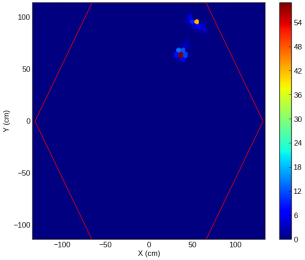
- Designed to be fast: EJ-200 plastic scintillator, ET model 9821KB PMTs
- Digitized by Struck SIS3320 eight-channel 250 MHz digitizers

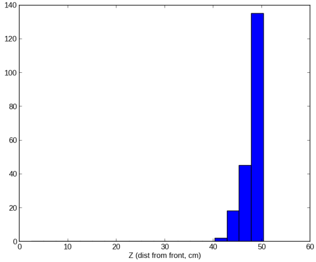
- LED board for calibration: intended to use ^{60}Co calibration for center tubes, then use equidistant LEDs to gain match
- Wave guide is there for better position reconstruction (failure at recoils close to PMT faces)
- White paint on front of scintillator, black on sides for better position reconstruction

Position Reconstruction

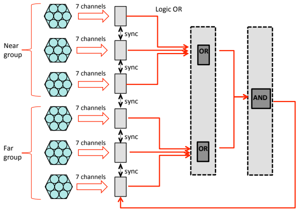


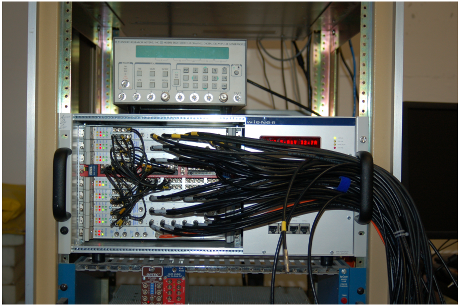
- Maximum-likelihood with optical transport model
- Model has some regions where position is ambiguous, getting worse at positions closer to PMT faces
- Outside this region, position is reconstructed with $\sim$ 5 mm resolution





Trigger Scheme



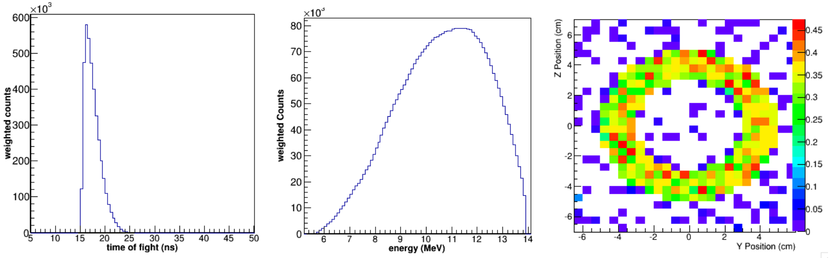


- Looking for 250 ns coincidence between front and back block groups
- Not set up to take advantage of elastic scattering

Algorithm Development

- In order to reconstruct the material distribution and elemental composition, we need the attenuation at every
  - (x,y,z) position and every detector combination
  - for every element (HCNO)
  - and every target voxel
  - for a range of energies
- Due to memory and CPU restrictions
  - (x,y) position broken into $\sim$1 inch bins, z position 1 cm bins
  - either assume material and reconstruct image or
  - assume sample spatial extent and reconstruct material

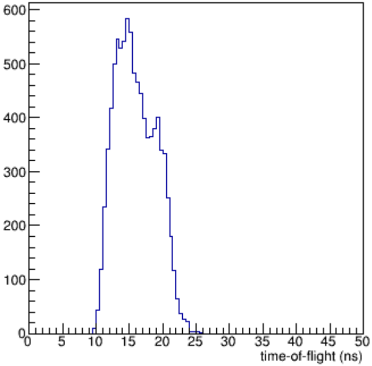
Algorithm Development - Polyethylene test object, 2 blocks

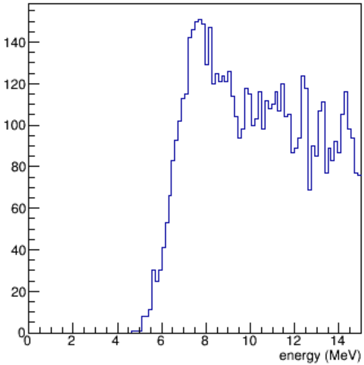


- Position, time, energy of each detector hit is smeared, assigned pixel and detector ID
- Time-of-flight is calculated, required to be within 5 ns of the expected for that pixel/detector ID
- Energy is calculated from trajectory method
- Maximum-likelihood expectation maximization (MLEM) algorithm is used against Hydrogen and Carbon elemental attenuation lengths to reconstruct image

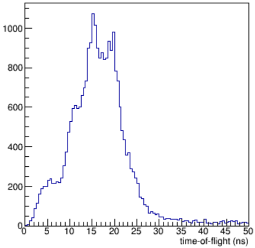
Status

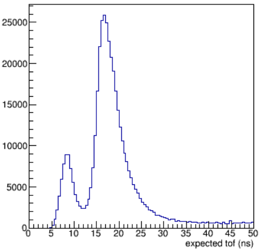
- We have a couple of scans with nothing, a polyethylene block, water, hydrogen peroxide, and polyethylene comb-like test object (imaging)
- The scans might not be enough stats
- Backgrounds are high (better timing resolution could solve this)

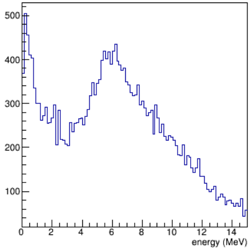




Status


1000
800
600
400
200
0
0 5 10 15 20 25 30 35 40 45 50
time-of-flight (ns)


25000
20000
15000
10000
5000
0
0 5 10 15 20 25 30 35 40 45 50
expected tof (ns)


500
400
300
200
100
0 2 4 6 8 10 12 14
energy (MeV)

Path Forward - Detector Upgrades

- Modifications to detectors:
  - PSD plastic or liquid scintillator - background discrimination and improved timing resolution
  - Improved calibration scheme
  - Improved position reconstruction - thicker light guide or change in PMT placement
  - New enclosure or modifications to existing (thicker light guide will require more room than is available)
- Alternative to hardware modifications:
  - Attempt to reject events that reconstruct a small depths
  - Re-bin the pixelization such that we have fine resolution toward the center and coarse resolution on the outer layers (each depth could be different guided by optical simulation)

Path Forward - Simulations

- Geant4 simulations to explore effect on observation space (will scattering be a problem?)
- Optics simulation (what is the optimum thickness? Does it improve small depth ambiguities?)
  - Better understanding of the optical model with LED scan along PMT faces for each block
- Use MC simulated data to bypass difficulties in position reconstruction and test ResponseBuilder model and unfolding
- Make predictions about minimum detectable quantities and time to detection
- Scaling study to larger system

Path Forward - Algorithm Development and Data Taking

- Algorithm Development
  - How do we handle large detector response matrices? Borrow from medical imaging?
  - How do we speed up the analysis? GPUs?
- Data taking
  - PMT angular and position dependence
  - Lab tests at SNLL
  - Field tests at SNLA with real explosives