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Title: A Passive Method for Identifying and Locating Fissile Materials Using Cosmic-Ray Muons

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Form 836 (7/06)

A Passive Method for Identifying and Locating Fissile Materials Using Cosmic-Ray Muons

Randy J. Spaulding
Los Alamos National Laboratory
Presented at University of New Mexico
NUPAC Series, Sep 21, 2010

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Overview

- A brief history of the worldwide nuclear arms control effort
- Charged Particle Radiography and Tomography
  - Cosmic-Ray Muons
- Our proposed system:
  - System overview
  - Tracking muons
  - Fissile material identification: potential signatures
- Exploratory experiments and results
- Conclusion

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A Brief History of Worldwide Arms Control

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Major Moments in Arms Control

- 1960's: Nuclear arms race → Mutually Assured Destruction (MAD)
- 1962: Cuban Missile Crisis
- 1963: Limited Test Ban Treaty
- 1968: Nuclear Non-proliferation
- Strategic Arms Limitation Talks
  - 1969: SALT I, interim arms limitation treaty
  - 1972: ABM treaty
  - 1979: SALT II set first concrete limits
- 1970's: MIRVs reduce efficacy of MAD

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Major Moments in Arms Control

- 1980's: Mistrust leads to mounting pressure
  - 1983: Reagan presents Strategic Defense Initiative
  - 1986: USA violates SALT II
- 1987: INF Treaty signed by Reagan, Gorbachev
  - First actual reduction in nuclear arsenals
- START I
  - 1982: Proposed by USA (Reagan)
  - 1991: Signed by Bush, Gorbachev
  - Reduced arsenals back to 1982 levels

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Major Moments in Arms Control

- START II
  - Signed in 1993 by Bush, Yeltsin, never ratified
  - Would have eliminated ICBM-based MIRVs and reduced arsenals
- START III
  - Agreed to in principle by Clinton, Yeltsin
  - Never negotiated
- 2002: SORT signed by Bush, Putin
  - Further reduction to 1700-2200 warheads
  - Never ratified by either party

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START 2010

- Signed April 8, 2010 by President Obama and President Medvedev of Russia
- Massive reduction slated over 7 years:
  - 700 deployed launchers (ICBMs, SLBMs, bombers)
  - 800 total launchers
  - 1550 total warheads
- Most stringent protocols for verification and inspection to date
  - Allows both parties to quantify warheads within deployed launchers

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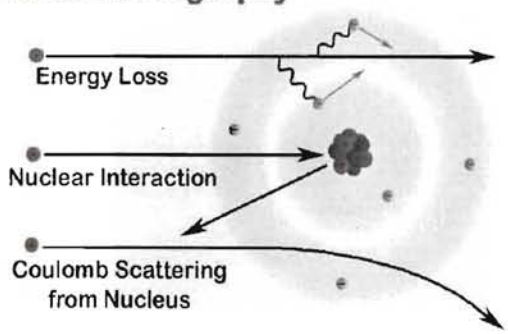
Charged Particle Radiography

Proton Radiography



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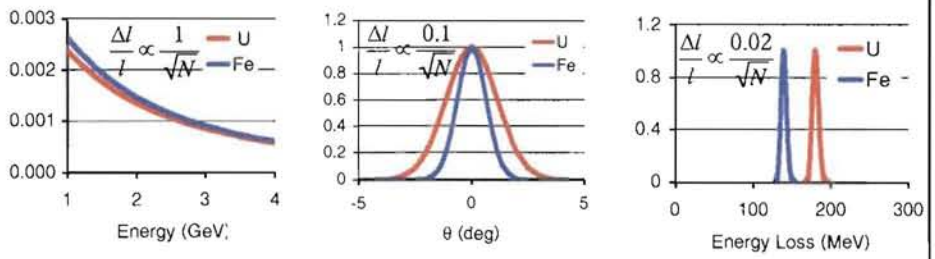
Three Sources of Information in Charged Particle Radiography

Example: how to distinguish 10 cm of Fe from 10 cm of U



Attenuation	Scattering	Energy Loss
(photons, cosmic rays)	(protons, muons)	(protons, muons)
~10,000 particles for 1% accuracy	~100 particles	~4 particles

Capability to measure energy loss creates high information content and enables low dose radiography. Other interactions add dimensions to the decision matrix.

K. Borozdin, Los Alamos P-25 Seminar, Nov 23, 2009

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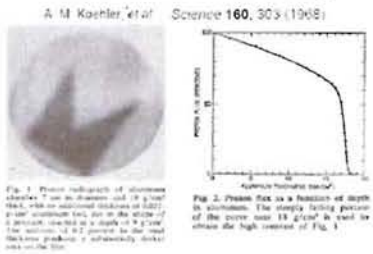
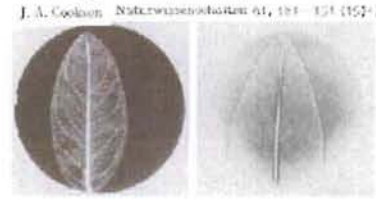
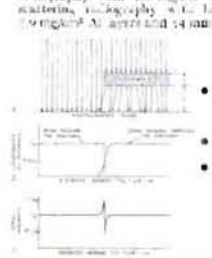
Proton Range Radiography

A. M. Koehler, et al. Science 160, 303 (1968)



J. A. Cookson





Marginal Range Radiography

- Reduce proton beam energy to near end of range.
- Use steep portion of transmission curve to enhance sensitivity to areal density variations.
- Coulomb scattering at low energy results in poor resolution >1.5 mm.
- Contrast generated through proton absorption.

- Edge enhancement by scattering
- Limited to thin objects
- Contrast generated through position dependent scattering

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Muon Attenuation Radiography

Searching for Hidden Chambers in Pyramids

Luis Alvarez, et. al.
Science **167**, 832 (1970)

Arturo Menchaca, et. al.
current effort, see
http://www.msnbc.msn.com/id/4540266/

Predicting Volcanic Eruptions

Tanaka, Nagamine, et. al.
Nuclear Instruments and Methods A
507:3, 657 (2003)

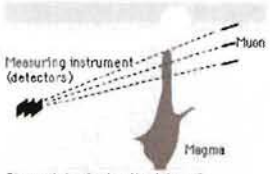

Figure 4. Analyzing the internal structure of a volcanic zone using muons

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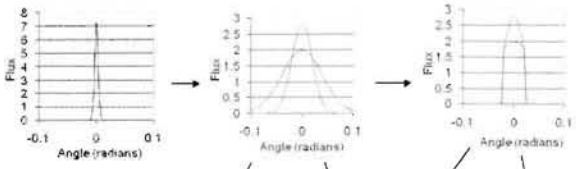
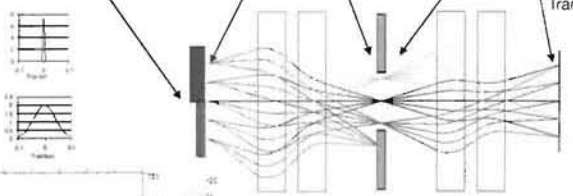
Dynamic Proton Radiography

Incident Beam | After Object | After Collimator



Measured transmission provides information of object thickness



$$T = e^{-x/\lambda_i}\left(1 - e^{-\left(\frac{\theta_0 p\beta}{4.1\,MeV}\right)\frac{x_{\alpha}}{2x}}\right)$$

Morris, C. M., et al. 2006, Proton Radiography. Los Alamos Science, 30, 2006
Merrill, F. Proton Radiography Primer

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Cosmic Rays

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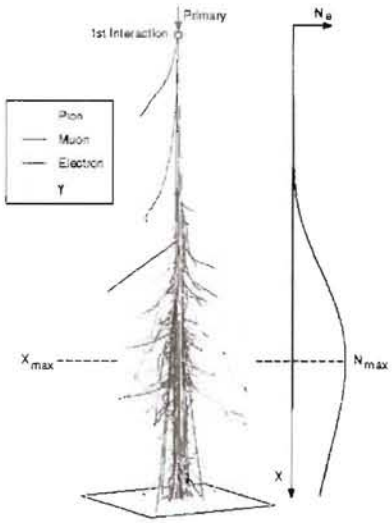
Surface Radiation Produced from Cosmic Rays

- Cosmic rays (mostly protons) interact in the upper atmosphere, creating showers of particles such as pions
  - Favors positive particles
- Pions (t1/2 = 26ns) quickly decay into highly-relativistic muons (~70%)
- Full electromagnetic shower also includes electrons (~30%), gammas (<1%), neutrons (<1%), etc.



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Cosmic-Ray Muons

- 60% positive, 40% negative
- Muons decay into electrons (+neutrinos) with a half-life (at rest) of $\tau_{1/2} = 2.2\mu s$
  - Atmospheric penetration requires $\gamma > 30$ (~20km)
    - Muons reaching surface were created having energy in excess of 3 GeV
- Muons very attractive for radiography, passive interrogation, etc
  - Highly penetrating
  - No increased radiation exposure
  - Free!

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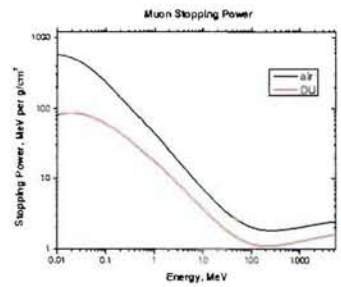
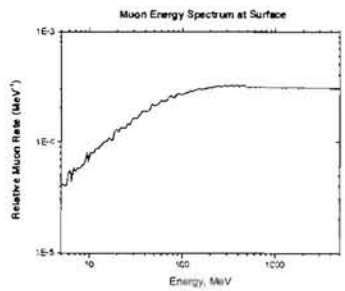
Muon Energy Spectrum

- Muon spectrum comes to equilibrium with low energies exponentially damped
- ~4% of muons fall into our stopping window E<400 MeV
  - 15 cm Uranium + other stuff





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Charged-Particle Tomography

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A New Kind of Tomography

- Computed Tomography (CT) generates 3-D voxelized images by taking multiple radiographs at different angles and unfolding cylindrical density map
- Tracking Tomography reconstructs rectangular scattering density map based on multiple scattering

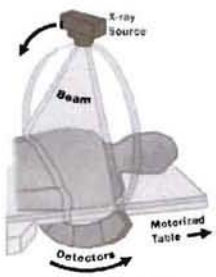

Image source: www.fda.gov

K. N. Borozdin, et al, Nature, March 20, 2003

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Tracking System Synopsis

- Cylindrical drift tubes measure radial position of charged particles passing through
- Yields intercept and angle in two dimensions by interleaving tubes having axis oriented in x- and y-directions
- For tomography, banks of tubes are located above and below object to measure scattering angle (average scattering density)
- In this application, lower position is blocked
  - Only incoming coordinates are measured

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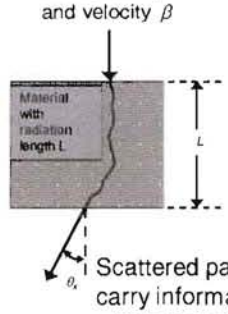
Physics of Multiple Scattering

Incoming particle with momentum p and velocity β



Scattered particles carry information from which material may be identified.

Scattering distribution is approximately Gaussian

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

The spread is related to the radiation length in the material, λ:

$$\theta_0 = \frac{13.6}{p\beta}\sqrt{\frac{L}{\lambda}}$$

Material	λ, cm	θ_0, mrad*
Water	36	2.3
Iron	1.76	11.1
Lead	.56	20.1
*10 cm of material, 3 Gev muons		

K. Borozdin, Los Alamos P-25 Seminar, Nov 23, 2009

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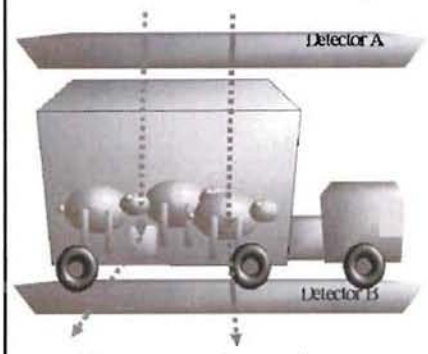
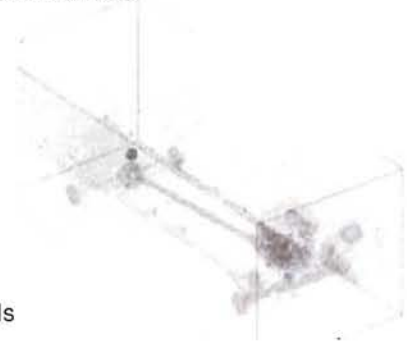
Cosmic-Ray Muon Tomography



- Highly penetrating probe
- Ubiquitous source
- No artificial dose



- Allows covert inspection
- Provides 3D imaging
- Sensitive to high-density, high-Z materials
- Measures scattering density

2007: ML/EM reconstruction(Schultz)

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Early Demonstrations Successful

- **896 channels**
- **Drift gas: 60% Ar/ 40% Isobutane**
- **~100 Hz trigger rate at current geometry**
- **1.5 m tall sample area**

2010: Chris L. Morris, "Looking Inside Explosions and Other Stuff"

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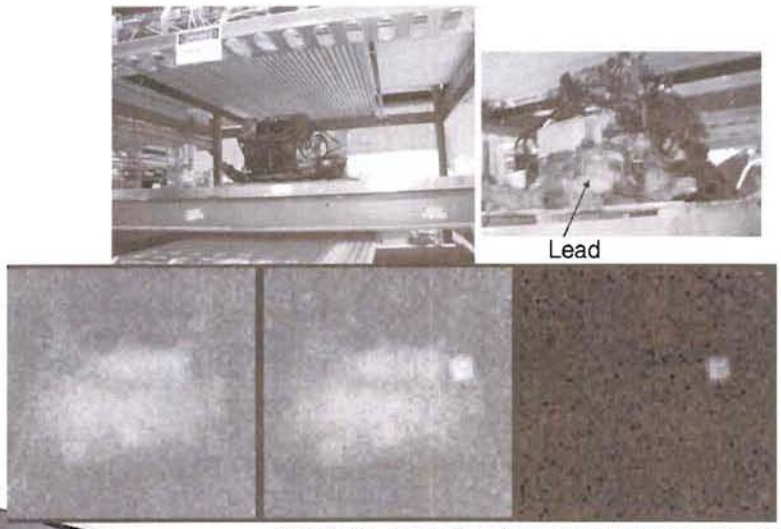
Early Demonstrations Successful



2010: Chris L. Morris, "Looking Inside Explosions and Other Stuff"

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GMT Scanner, DSC Corp.

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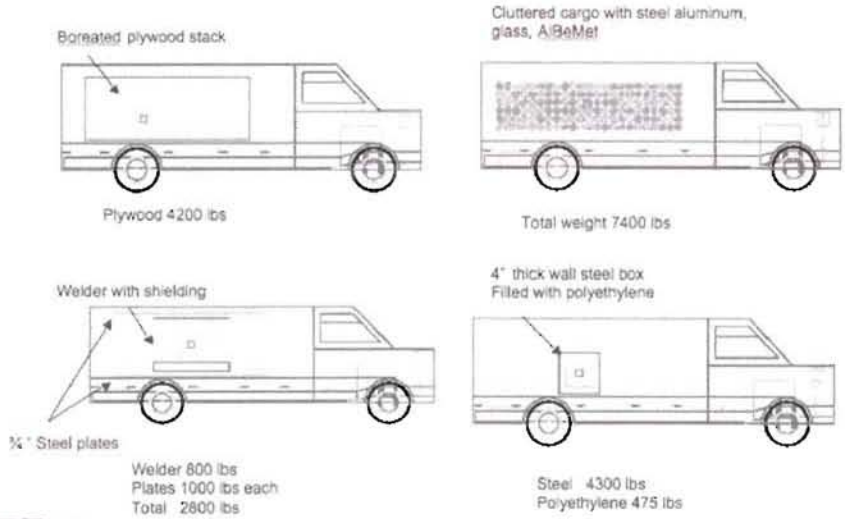
Clutter Discimination in Cargo



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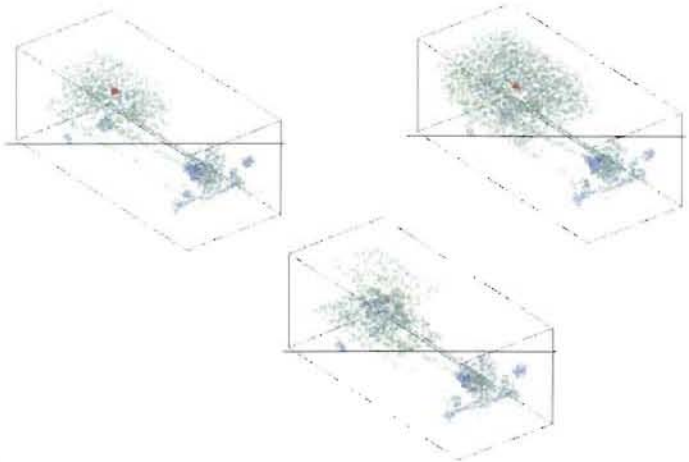
60-Second Cargo Reconstructions



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Final Words on Tracking

- Robust
  - Tubes have been in operation for >3 years with minimal failures
- Flexible
  - Simple technology scales easily
  - We have demonstrated the addition of Helium-3 for neutron detection
- Successful
  - Decision Sciences, Corp. (San Diego, CA) presently designing three 24' x 72' systems for immediate deployment

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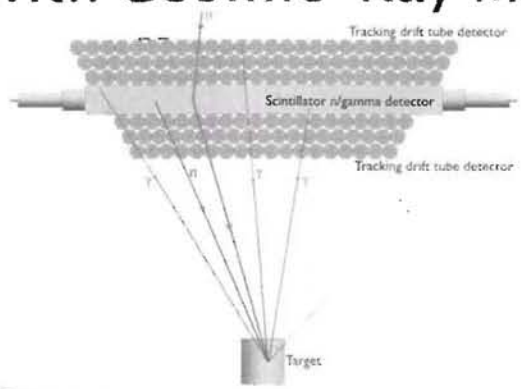
Detecting Fissile Materials with Cosmic-Ray Muons



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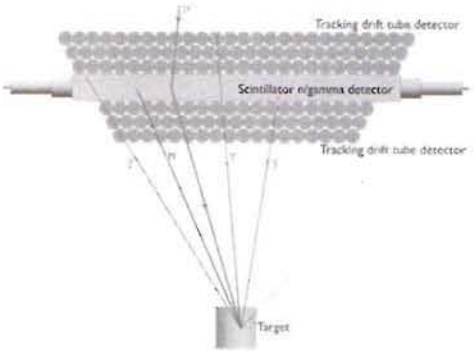
Detection System

- Comprised of two components:
  - Drift-tube based muon tracker (upper section only)
  - Plastic and/or liquid scintillator for detecting secondaries
    - gamma, neutron



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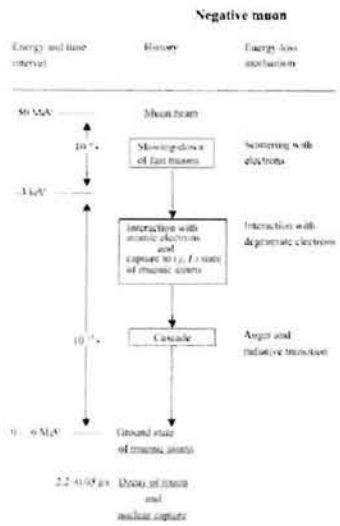
Detection System Physics

- Low-energy muons (< 300-500 MeV) are stopped in the interrogation object
- Thermalized negative muons are captured into highly excited electron-like orbits
- Multiple secondary particles emitted per captured muon, including muonic x-rays, gammas, neutrons
- Greatly enhanced fission probability for fissile materials



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Location of Objects Using Ray-Tracing Tomography

- Voxelized geometry
- Each time a stopped muon is detected, a "hit" is recorded in each voxel along the muon's projected path
- Normalized image reveals location of heavy objects
  - Recording fraction of stopped particles yields density information
  - More sophisticated detector systems that include species and energy tagging can specifically identify fissile materials

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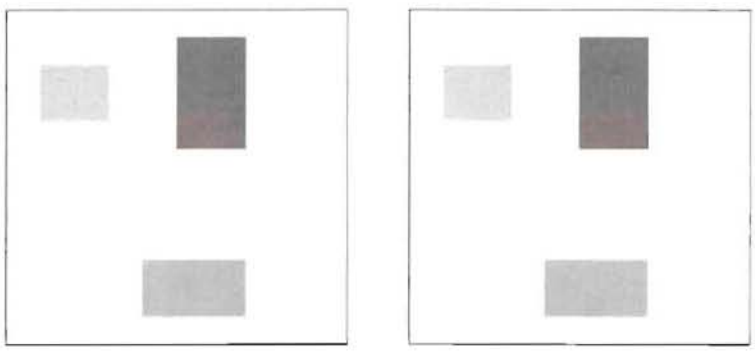
Ray-Tracing Tomography Example



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Detecting Fissile Material: Potential Signatures

- Some signatures stand alone, some enhance density tomograph (in red)
- Count Rate
  - Gross Rate - difficult - requires very high SNR
  - Neutron Rate - enhanced in fissile materials
- Time separation
  - Delayed fission
  - Neutron Time-of-Flight
- Multiplicity
- Others??

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Muon-Induced Fission Neutrons

- Fission yield per neutron stop = 0.068 ± 0.013 for ^{238}U and 0.142 ± 0.023 for ^{235}U
  - Multiplication via k-eff further enhances ^{235}U signal
  - Difficult to separate from evaporation neutrons
- Delayed component accounts for 91% of fissions in ^{238}U and 88% in ^{235}U
- Mean lifetime = 77.2 ± 0.4 ns for ^{238}U and 71.6 ± 0.6 ns for ^{235}U
  - Easily separable from neutron time-of-flight signal
- 4" x 4" DU Target @ LANL: 14 stops per minute = 1.0 fissions per minute

S. Ahmad, et al, TRIUMF, Canadian Journal of Physics Aug 1985

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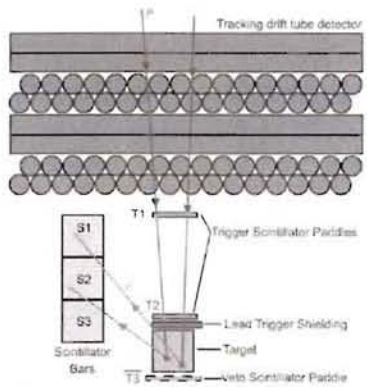
Exploratory Studies and Initial Results



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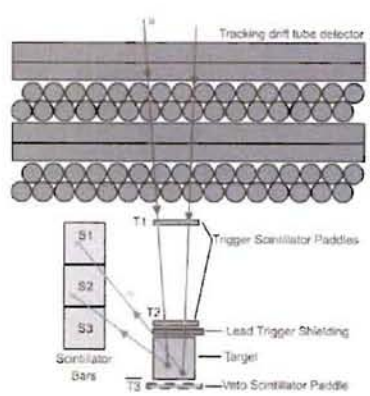
Testbed Setup

- Trigger scintillator "telescope" constrains directionality of incoming muons
- Large scintillator bars S1, S2, S3, detect secondary neutrons, gammas, etc. produced from muons stopping in target
- High multiplicity of secondary particles →nearly 100% efficiency even for small ($\sim\pi/2$) solid angle
- Pb shielding prevents natural target radiation from causing spurious triggers
- Tracker not yet integrated



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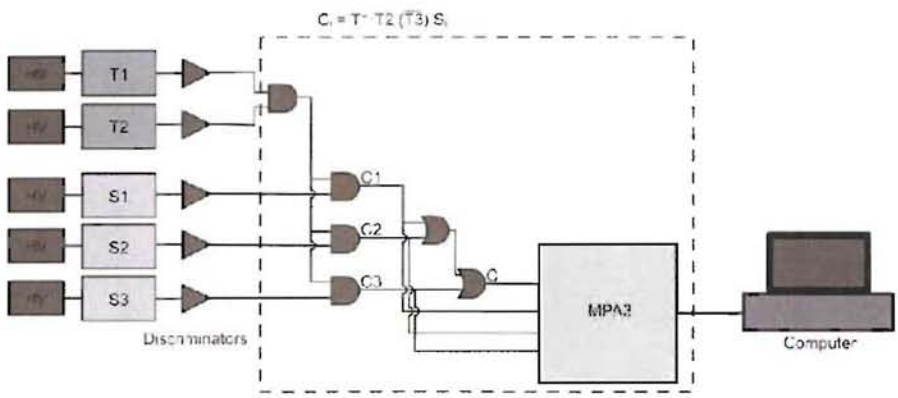
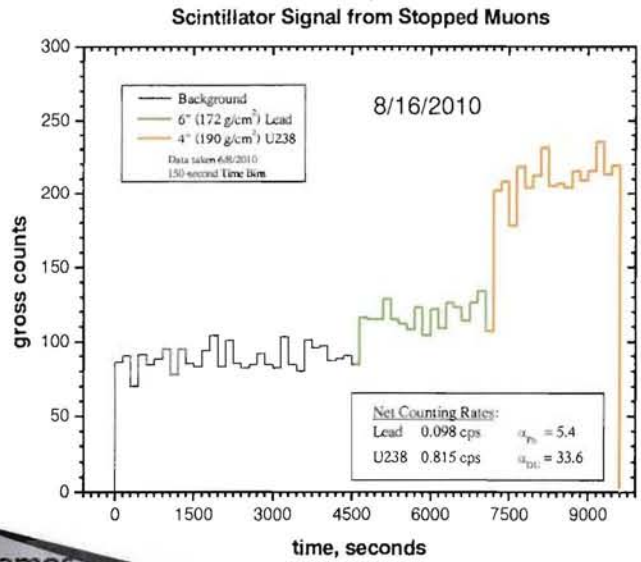
Testbed/Demo DAQ



Proof-of-Concept Demo



Muon Removal Rates

- Number of stopped muons can be measured as $R = 1 - \frac{T}{T \cdot V}$, where $T \equiv T_0 \cdot T_1 \cdot T_2$ is the telescope trigger rate and $V \equiv \overline{T_3}$ is the veto signal
- Expected to be linear with thickness
- Expected to increase with Z, density
- Good benchmark, easy to model

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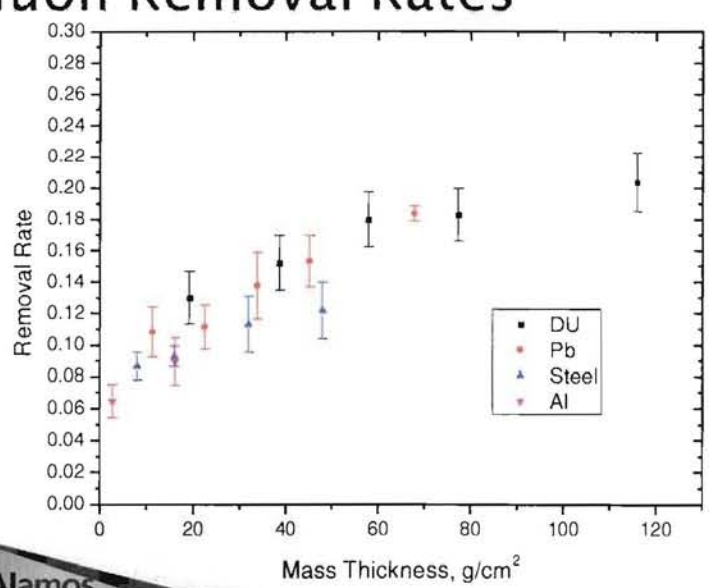
Muon Removal Rates



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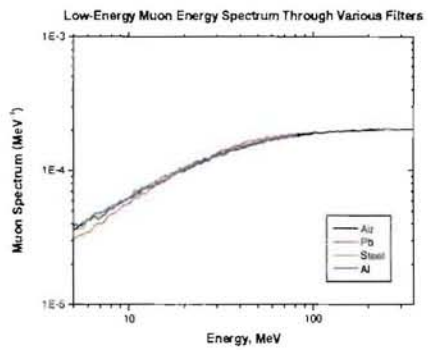
Filter Removal Rates

- 10-cm DU cube with 2" filters above
- Use of different filters upsets equilibrium of muon spectrum
  - Allows us to probe different regions of low-energy muon flux
  - Fissionable/fissile materials and structural materials respond differently!



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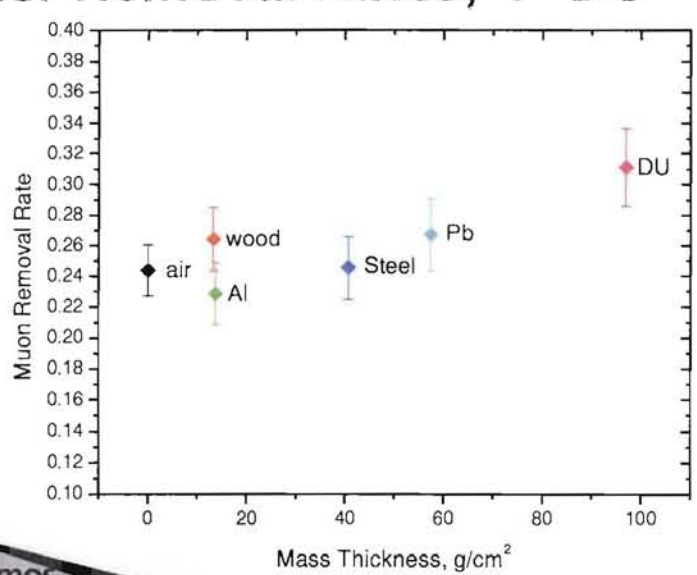
Filter Removal Rates, 4" DU



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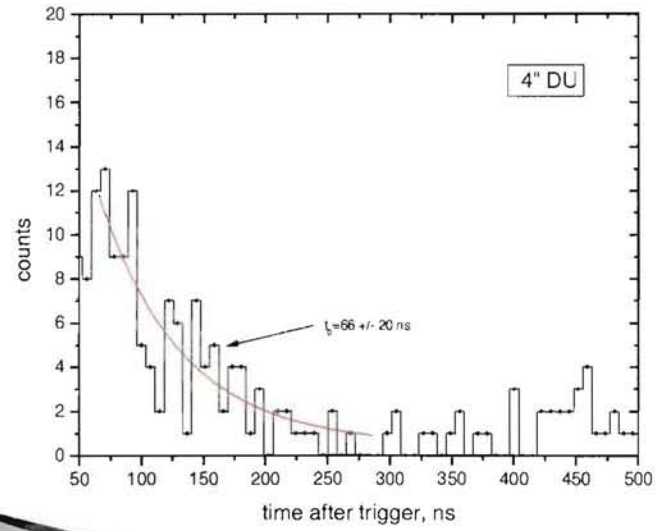
Timing Measurement



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Conclusion and Future Work

- Passive interrogation is *tough*
  - Potential demonstrated but will it be feasible?
- Detectors and DAQ need vast improvement
  - Include neutron detectors (He-3)
  - Include energy measurement
  - More complete and robust timing
  - Integrate Muon Tracking
- Development timescale: 2-3 years to reach prototype
  - Thesis potential...?

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Acknowledgements

Chris L. Morris, Konstantin N. Borozdin, Larry Schultz, Andy Fraser, Fesseha Mariam, Andrew Green, Nicolas Hengartner, Bill Priedhorsky, Frank Merrill, Alexei Klimenko, Leticia Cuellar, Richard Schirato, Andy Saunders, Debbie Clark, Michael Brockwell, Jeff Bacon, Margaret Teasdale, Rick Chartrand, Gary Hogan, Mark Galassi, Kiwhan Chung, Jeff Wang, Peter Walstrom, Steve Greene, Pat McGaughey, Rich Sheffield, Haruo Miyadera, Andy Jason, Mark Makela, Bethany Brooks, Fawn Pazuchanics, Camillo Espinoza, Gary Blanpied, John Lestone, Michael Sossong, Chris Ormes, John Ramsey, Mark Saltus, Kolo Wamba, Neel Gupta, Jonathan Roybal, Matthew Murray, and everybody else we forgot!

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