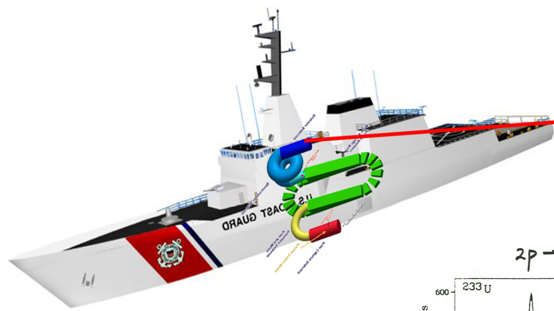
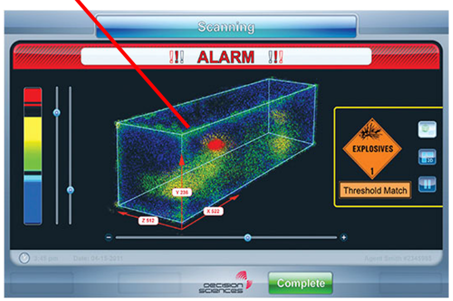
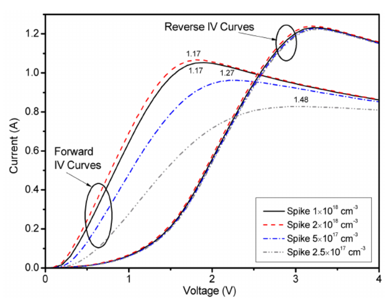
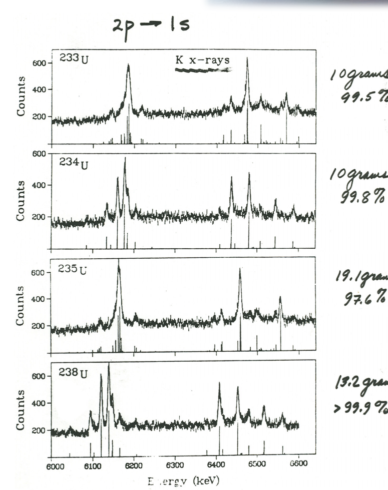
Game changing muon applications:

beyond the high energy physics window









Zack Sullivan

May 3, 2016

w/ Adam Hock, Dan Kaplan, Jeff Terry

Fermilab is part of this BIG IDEA

SOLVING BIG PROBLEMS WITH SMALL ACCELERATORS

S. HENDERSON
Argonne National Laboratory

W. LEEMANS
Lawrence Berkeley National Laboratory

April 21, 2016

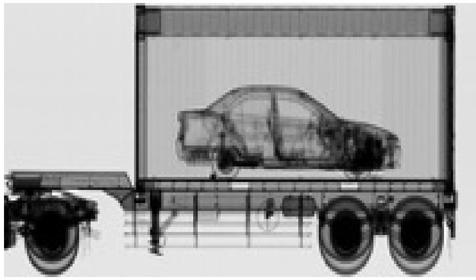
U.S. DEPARTMENT OF ENERGY | Office of

ACCELERATORS ARE ESSENTIAL TOOLS IN MODERN LIFE

Discovery Science

Groundbreaking, Nobel prize winning science

National Security



Securing dozens of border crossings, ports and airports

Industry

$500B/year in products

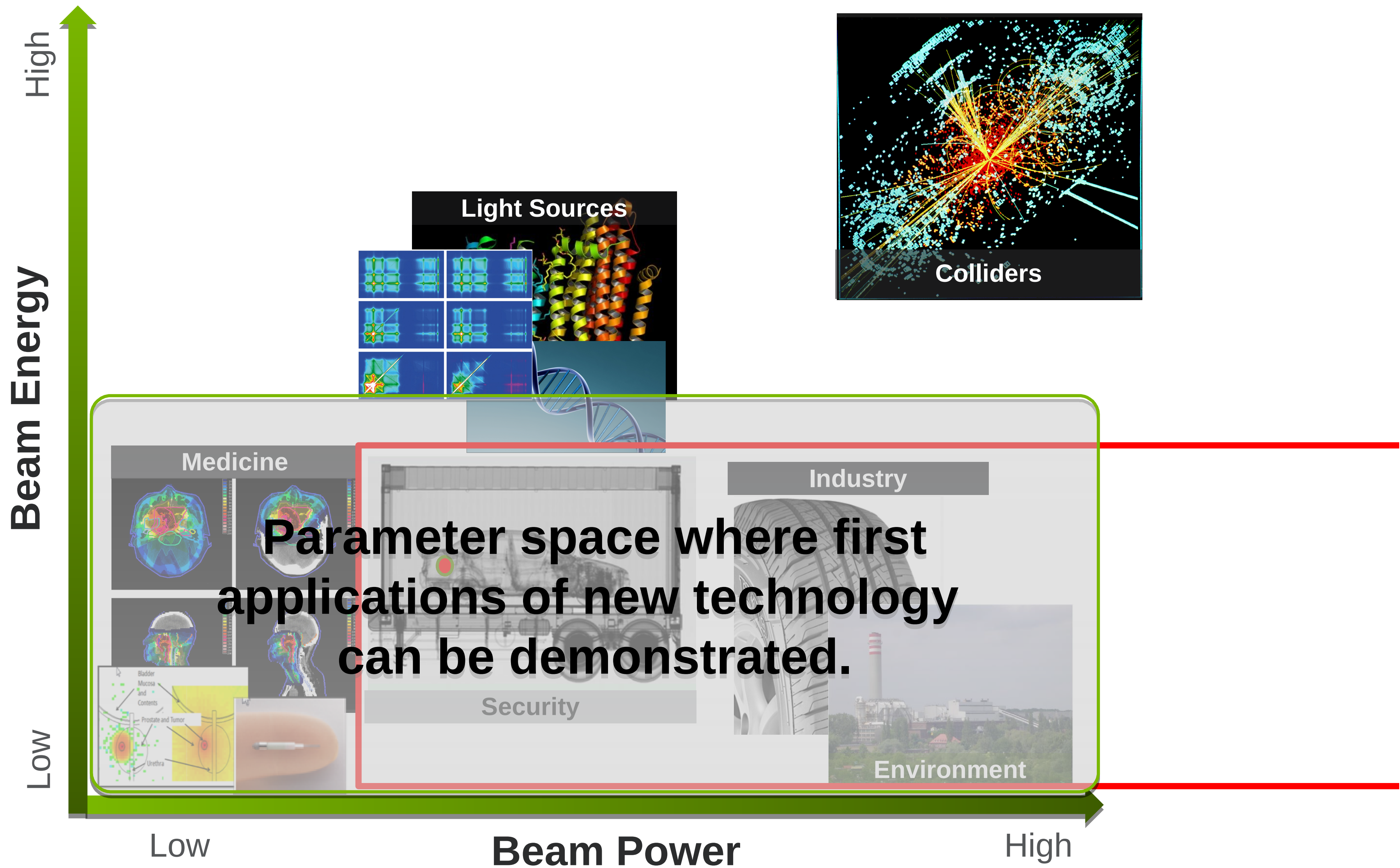
Medicine

10's of millions of patients treated with accelerators each year

The development of accelerator technology in the 20th century is a tremendous success story.

- However, the reach of accelerators is more and more limited by size, cost, and performance.
- But, new techniques can make accelerators more compact, more powerful, more energy-efficient, and can solve a wider range of problems

DIFFERENT APPLICATIONS REQUIRE DIFFERENT ACCELERATOR PERFORMANCE



Some applications for today

1) Muons for security
   - A nuclear security challenge
   - Muon tomography
   - Muon-induced gamma spectroscopy
   - What needs to be done
2) Muons for radiation damaged materials (Terry)
3) Muons for lightly doped semiconductors (Hock)

IPRO 497-209
Developing a New Strategy to Detect Smuggled Nuclear Material

with Profs. Sullivan and Kaplan
Held Fall 2015, 2016

Life cycle of a cargo container

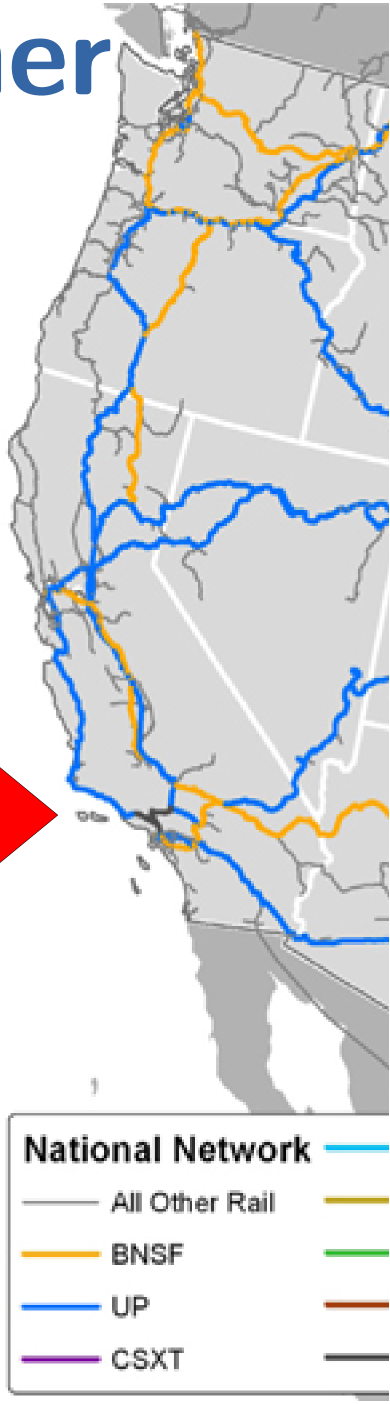
Somewhere in the world...

A container is filled

and loaded onto a ship.

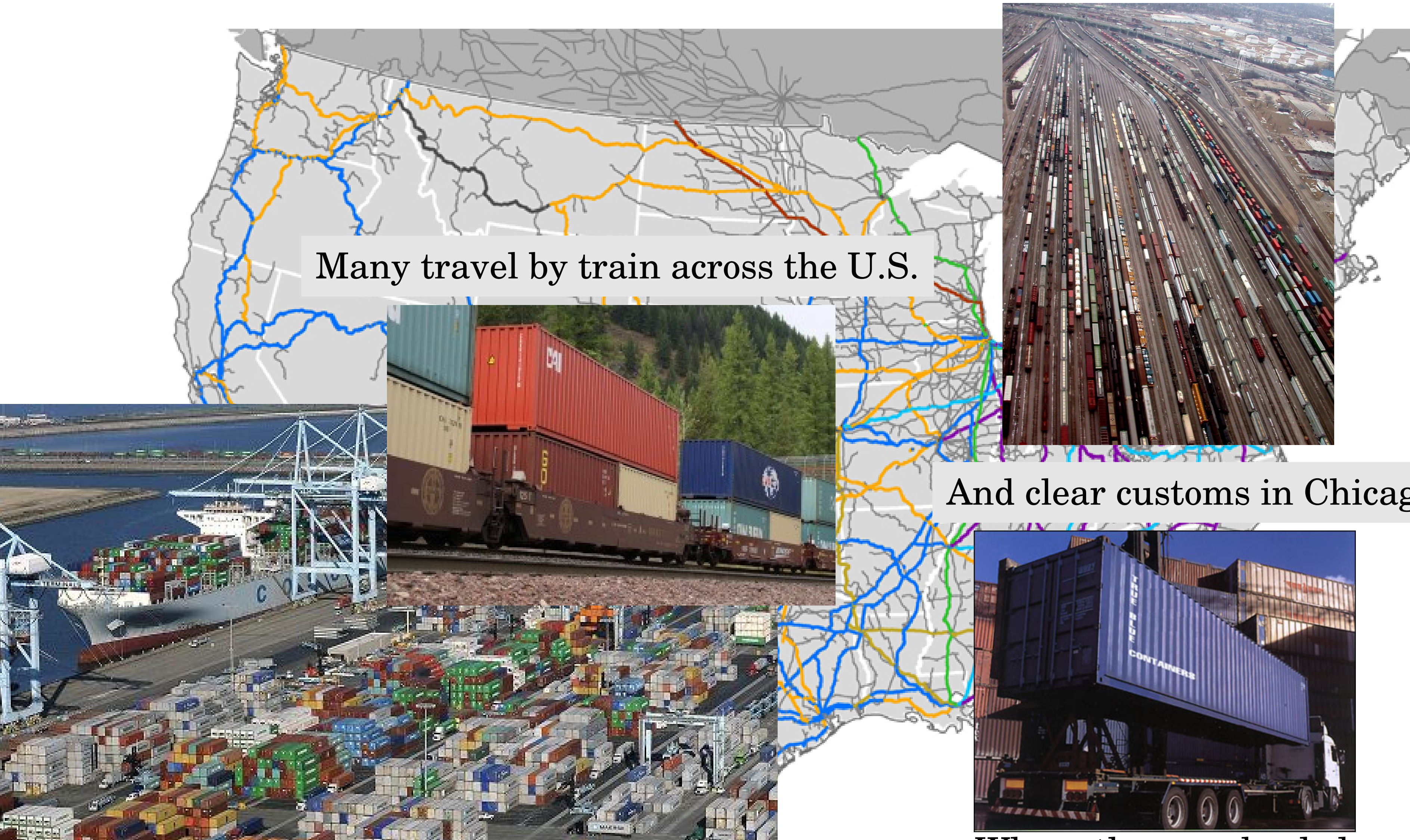
The U.S. cannot secure these points.

Life cycle of a cargo container



The first interaction might be just offshore before entering port, but boarding all ships is impractical.

Life cycle of a cargo container



Many travel by train across the U.S.

And clear customs in Chicago...

10+ million containers unloaded in ports each year

Where they are loaded on trucks and disperse everywhere

The Washington Post

National Security

Port security: U.S. fails to meet deadline for scanning of cargo containers

By Douglas Frantz July 15, 2012

The Obama administration has failed to meet a legal deadline for scanning all shipping containers for radioactive material before they reach the United States, a requirement aimed at strengthening maritime security and preventing terrorists from smuggling a nuclear device into any of the nation's 300 sea and river ports.

The Department of Homeland Security was given until this month to ensure that 100 percent of inbound shipping containers are screened at foreign ports.

But the department's secretary, Janet Napolitano, informed Congress in May that she was extending a two-year blanket exemption to foreign ports because the screening is proving too costly and cumbersome. She said it would cost $16 billion to implement scanning measures at the nearly 700 ports worldwide that ship to the United States.

Further into the article

The DHS says monitors scan 99 percent of the containers for radiation after they arrive at U.S. ports. But experts say the monitors at U.S. ports are not sophisticated enough to detect nuclear devices or highly enriched uranium, which emit low levels of radiation.

The Government Accountability Office has warned that a nuclear device could be detonated while at a port — containers often sit for days awaiting radiation checks — causing billions of dollars in damage in addition to the loss of life. Estimates of damage caused by a nuclear detonation at a major port range from tens of billions of dollars to $1 trillion.

Shipping containers are potentially ideal for smuggling weapons, people and other illicit cargo; ensuring the integrity of the contents is difficult and costly. The standard container is 40 feet long and 8 feet high and holds more than 30 tons of cargo. A large vessel carries 3,000 or more containers from hundreds of different shippers and many ports. And a single container can hold cargo from many customers.

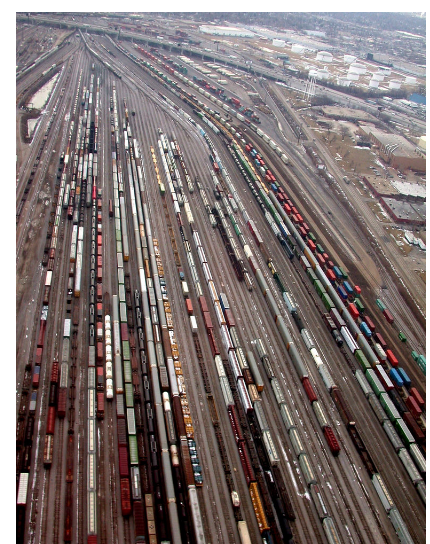
Where can we stop the threat?

- Follow the law and check at a foreign port?
  Not realistic...

- Scan trucks/trains in U.S. ports?
  This is the most common focus.

- Scan ships while at sea?
  This is ideal, but technically challenging.

- Check in Chicago with a Geiger counter?
  This is done now, but not really effective...



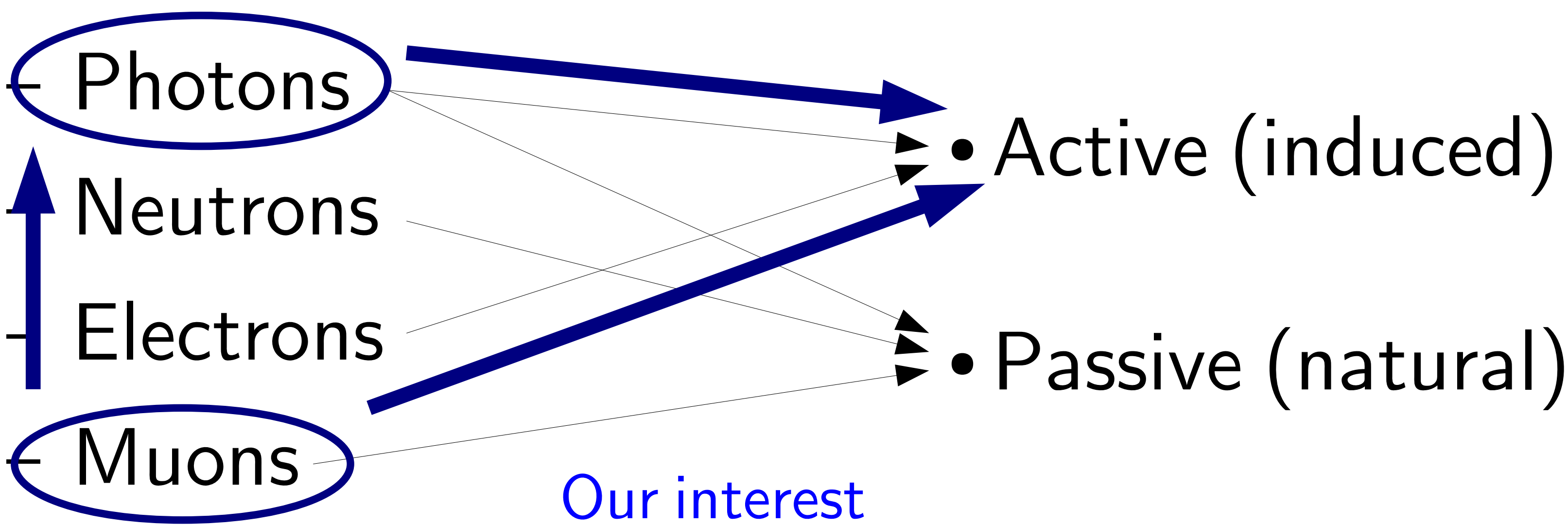
Congressional Research Service

Detection of Nuclear Weapons and Materials: Science, Technologies, Observations

Jonathan Medalia
Specialist in Nuclear Weapons Policy

June 4, 2010

- Compares scanning technologies using particles:



Congressional Research Service
7-5700
www.crs.gov
R40154

CRS Report for Congress
Prepared for Members and Committees of Congress

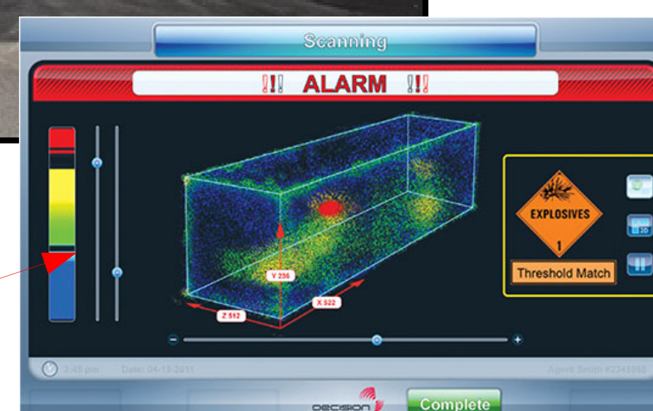
Overview

- National security problem
  - Life cycle of a cargo container
- What can we do with μ?
  - Tomography
  - Isotope fingerprinting
- Health Physics (an aside on "how not to die")
- What do we need?

What can we do with μ?

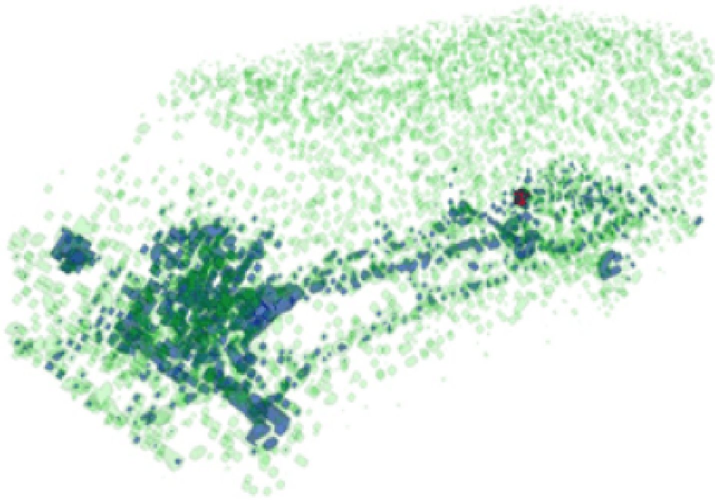
- Tomography (fancy word for picture taking)
  - Find the really dense materials, like Uranium, via scattering, though lead, tin, etc. scatter too
- Isotope fingerprinting
  - Uniquely identify higher than trace amounts of "interesting" materials, e.g., ^{235}U vs. ^{238}U vs. ^{208}Pb etc.

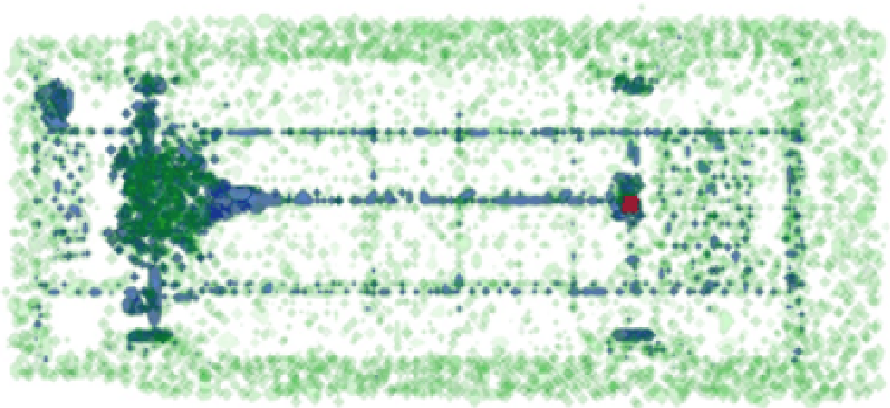
Decision sciences uses atmospheric muons for tomography (passive)



Promotional picture

Simulations for imaging a car...





90 seconds
to find the red dot?

Source: Decision Sciences International Corporation.

Notes: This figure shows one simulated scan at 90 seconds of side-angle and top views using simulated data. The dark spot above the rear axle represents SNM and is highlighted in red.

How does tomography work?

- High-Z (proton number) materials scatter more than low-Z, so measure angles.
- High-Z materials capture muons at a rate that goes like Z^2, so look for muons that go in but don't come out.
- Existing test facility uses both methods.

- Remembering our chemistry, what we are mostly interested in are the Actinides.

Periodic Table of Elements

C Solid | Hg Liquid | H Gas | Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals
Nonmetals: Other nonmetals, Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794	Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 La Lanthanum 138.90547	58 Ce Cerium 140.1[illegible]	59 Pr Praseodymium	60 Nd Neodymium 144.242	61 Pm Promethium	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
Ac Actinium	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	Am	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

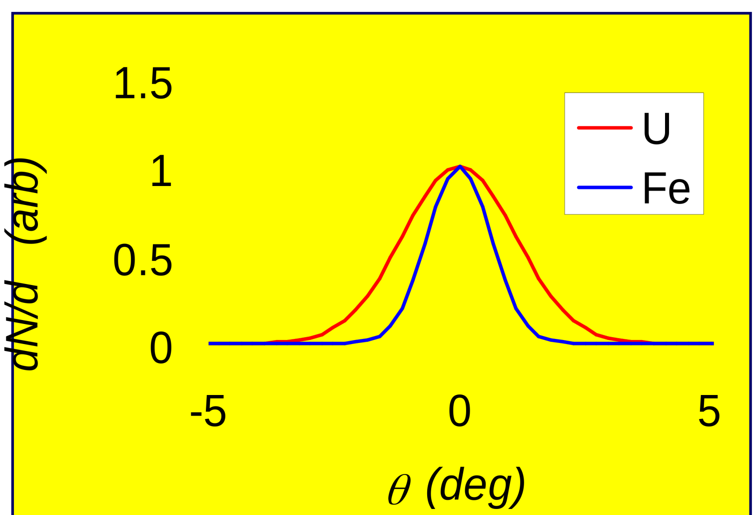
Ptable.com

Multiple Coulomb Scattering

decision sciences
Security Solutions

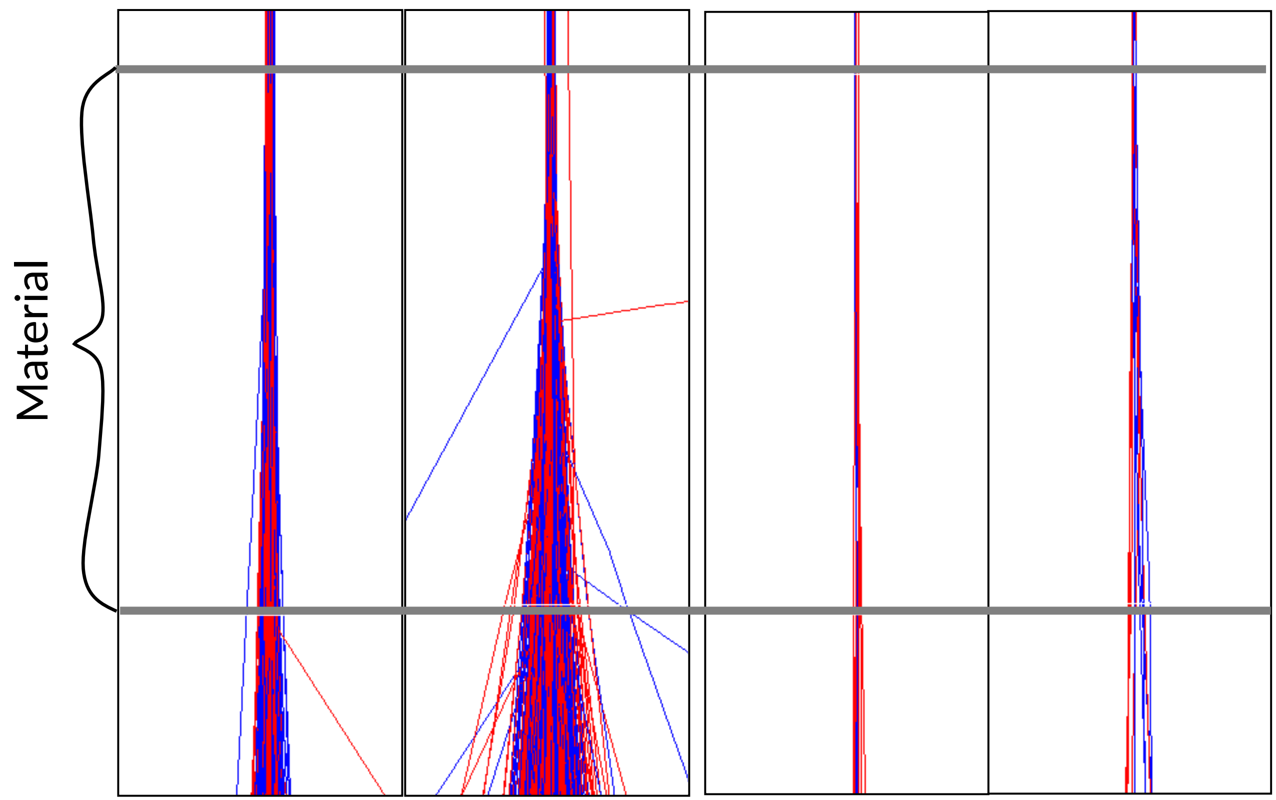
$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

$$\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{x}{X_0}}$$



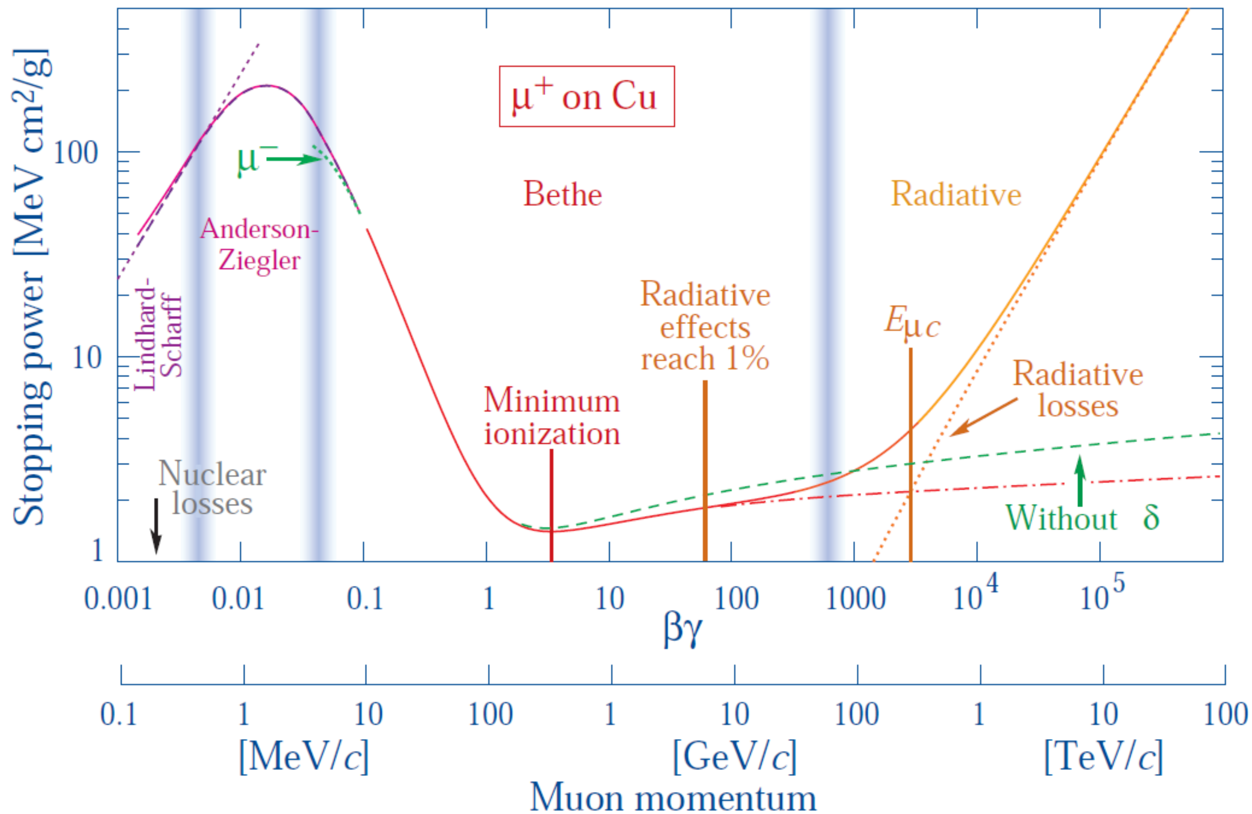
DSIC Cosmic Ray Scanning

GEANT simulation of Iron and Uranium Plates			
1000 Muons		10 Muons	
Iron	Uranium	Iron	Uranium



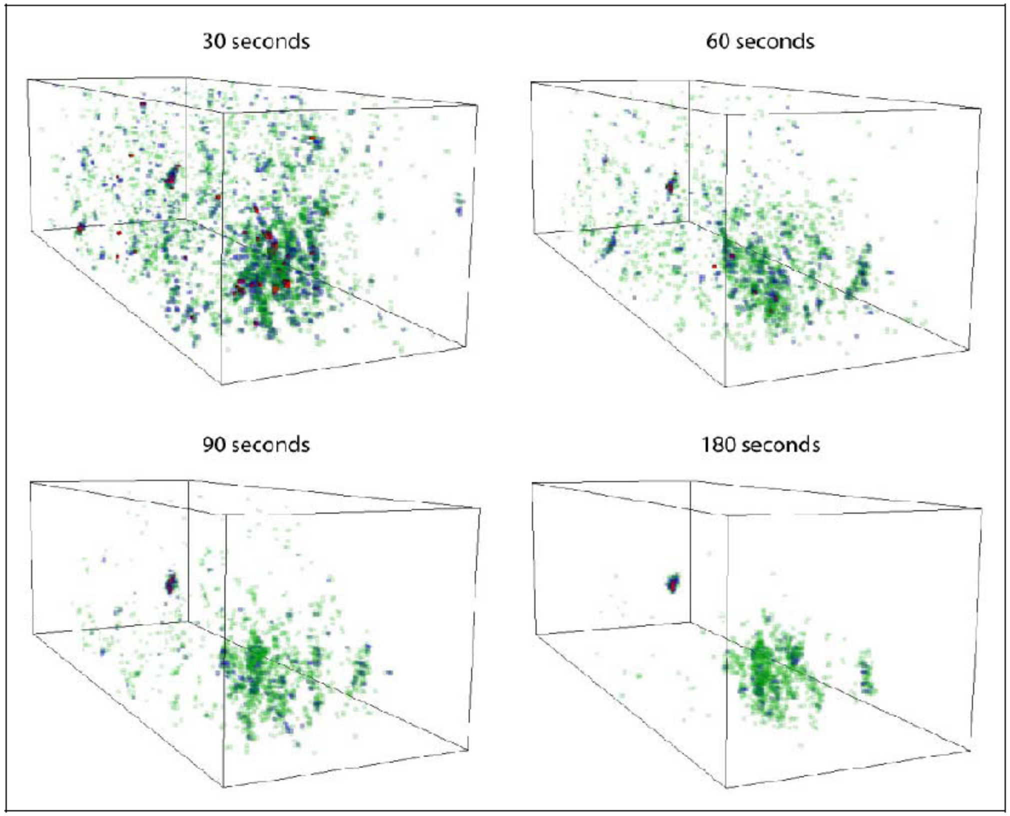
As few as 10 Muons Provides 95% Discrimination (known momentum)

Muons passing through (or stopping) in matter



Energy loss $$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Actual imaging data (how they really do)



Source: Decision Sciences International Corporation, April 2010

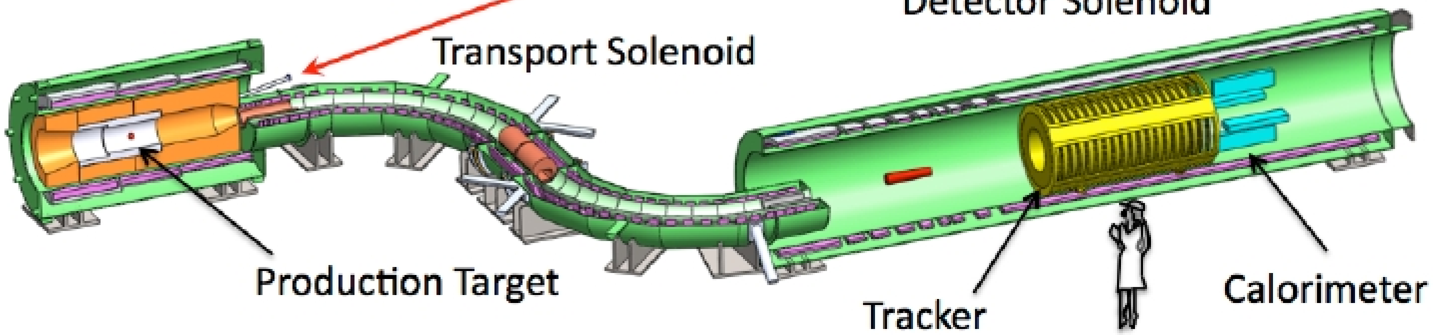
Notes: This figure shows scans of a car at various times using actual data. The dark spot "floating" at the back of the image is high-Z material and is highlighted in red.

- Clearly the longer the exposure the better, but a container full of rock needs to be scanned quickly.
- Realistically, this takes 10+ min for a loaded vehicle – a few percent false positives are not acceptable.

Using beams of muons we can have roughly any intensity we need

- Key observation: time ~ 1/intensity$^{\delta}$

  (note δ is some power likely between 1/2 and 1)



- So use a muon accelerator to turn up intensity

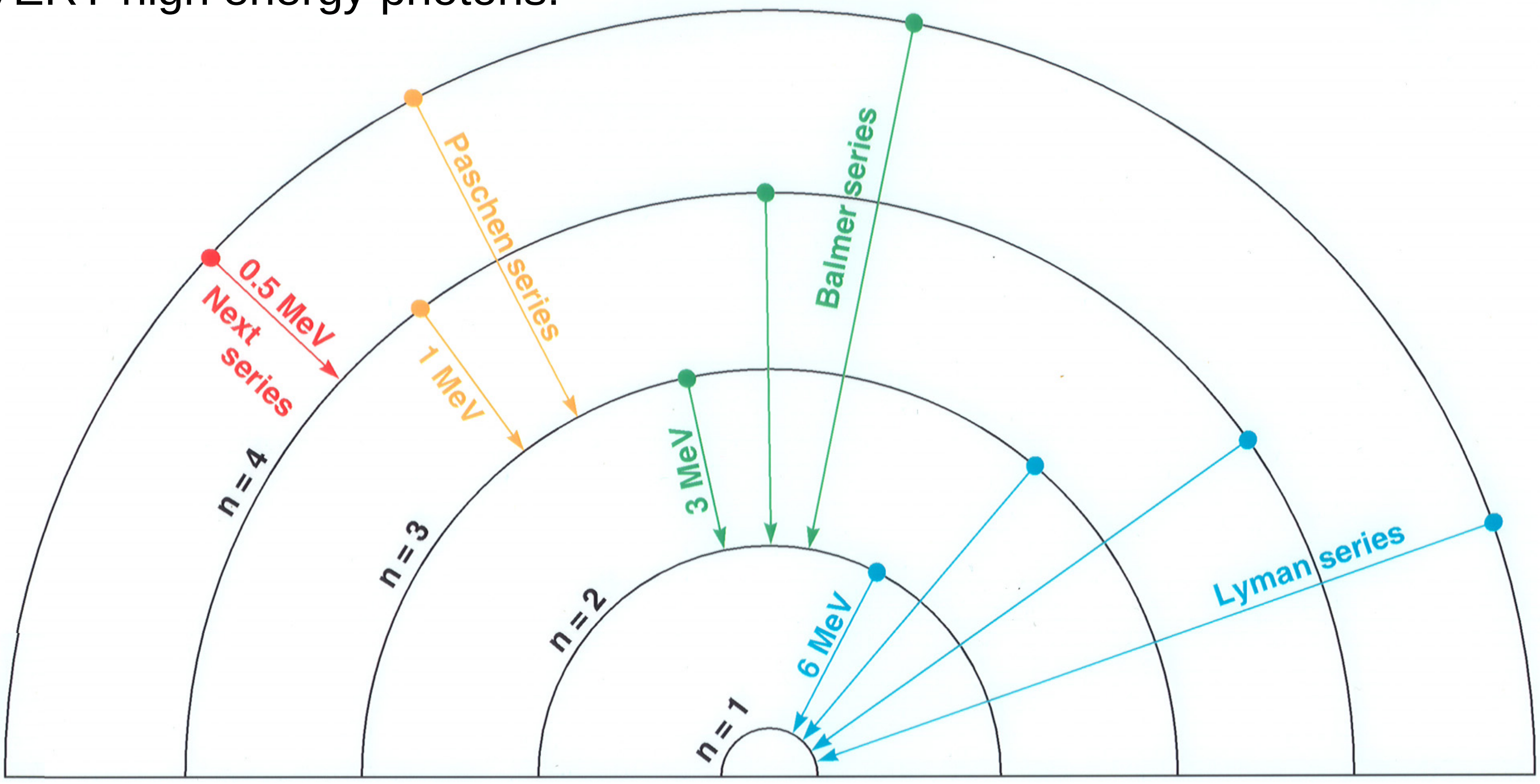
  (ultimately will want to design smaller muon sources)

What can we do with μ?

- Tomography (fancy word for picture taking)
  - Find the really dense materials, like Uranium, via scattering, though also lead, tin, etc. scatter too
- Isotope fingerprinting
  - Uniquely identify higher than trace amounts of "interesting" materials, e.g., ^{235}U vs. ^{238}U vs. ^{208}Pb etc.
  - When muons capture they induce characteristic photon emission energies (from "atomic levels")
  - They also fall into the nucleus, emitting more photons
  - High-Z materials also fission (don't turn up the intensity too high! Something we'll have to watch out for…)

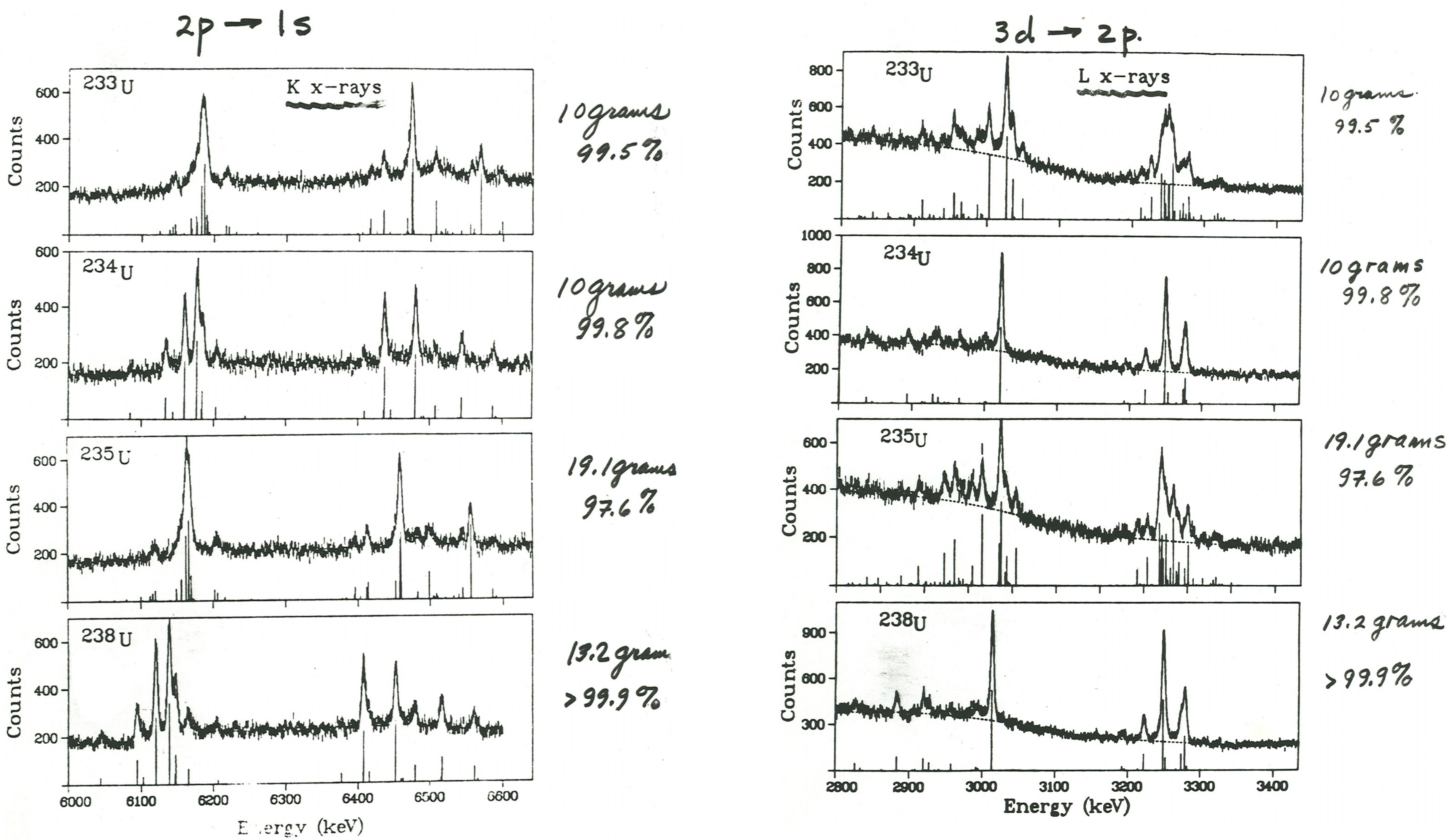
Muons for isotope fingerprinting

VERY high energy photons!



Muon mass multiplies energy levels by a factor of 207!

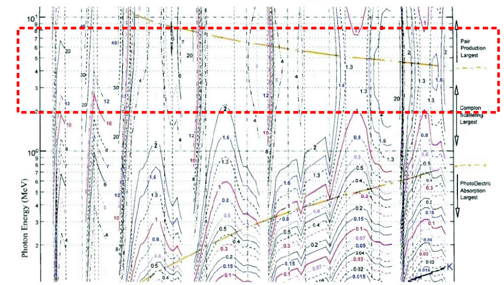
U spectra measured in 1984 by John Zumbro w/ LANSE



Ge detector

2 modes of operation: fingerprinting or faster tomography

- Needed:
  - Accelerator parameters (muon energies, timing, etc.)
  - Detector ideas (large scale, 100 keV resolution for 6 MeV photons)
    - George Chapline (LLNL) looking at NaI at RAL
    - Would like to move to LaBr, SiI
  - Materials database (for fingerprinting)
    - Essential for real applications
    - Need U, Pu, U_xO_y, UZr, etc.
    - Also need Pb, W, PbO, high-W steel, and everything else
  - HEALTH PHYSICS – will the needed intensity kill you?



6 MeV has reduced γ absorption so signal may escape shielding

Health Physics: radiation safety

- What happens to someone if they are hiding in the container?
- The answer to this question is a clear go/no go point.
  - If we cannot raise the intensity high enough to beat the use of natural atmospheric muons, then this program will never start
- A good solution here is a dual-mode system using tomography for bulk pointing, and concentrated muon capture for fingerprinting in volumes w/ high-Z material.

What we need 1st

- Low energy muons (what can we get E vs. $\mathcal{L}$?)
  - What really matters is captured μ/s across various high-Z materials
  - Minimum interesting 10^5/s, want 10^7-10^8/s
- Confirm muon atomic spectra on "interesting" materials
  - Starting with Pb, W, ^{238}U
  - Begin to build a database of materials
  - Test detector technologies for 1-10 MeV gammas

Some applications for today

1) Muons for security

- A nuclear security challenge
- Muon tomography
- Muon-induced gamma spectroscopy
- What needs to be done

2) Muons for radiation damaged materials (Terry)

3) Muons for lightly doped semiconductors (Hock)

Nuclear Materials

- Fuel
  - Radiation Damage
  - Corrosion
  - Pellet Cladding Interaction
  - Fission gas release and swelling
- Beyond Design Basis Accidents
  - High Temperature
  - Fuel Cladding Reactions
  - Hydrogen Generation

Problems

- Radiation Effects Play a Major Role in Defining the Physicochemical Properties of Nuclear Fuels
- Incredibly Difficult To Irradiate Nuclear Fuels In a Controlled Manner
- In Reactor
  - Research Reactors Do Not Run 24/7
- Rabbits
  - Short Exposures

In Reactor Irradiation

Cycle #	Cycle Start Date	Outage Days	Operating Days	Lobe Powers[a]			
				NW	NE	SW	SE
140A	9/29/07	14	49	18.0	18.0	23.0	23.0
140B	12/1/07	20.5	35.6	18.0	17.7	23.7	23.0
141A	1/26/08	9.6	32.4	18.0	18.0	23.0	23.0
142A	3/8/08	57	48	23.0	18.0	24.8	23.0
142B	6/21/08	18	52	23.0	18.0	25.0	25.0
143A	8/30/08	21	56	18.0	18.0	25.0	25.0
143B	11/15/08	21	56	18.0	18.0	25.0	25.0
144A	1/31/09	14	49	18.0	18.0	23.0	25.0
144B	4/4/09	14	49	18.0	18.0	23.0	23.0
145A	6/6/09	56	56	18.0	18.0	23.0	25.0
145B	9/26/08	14	49	18.0	18.0	23.0	25.0
146A	11/28/09	14	56	18.0	18.0	23.0	25.0
146B	2/6/10	14	49	23.0	18.0	23.0	25.0
147A	4/10/10	49	49	23.0	18.0	23.0	23.0
147B	7/17/10	14	14	18.0	18.0	50.0	30.0
148A	8/14/10	7	56	18.0	18.0	23.0	23.0
148B	10/16/10	14	49	18.0	18.0	23.0	23.0
149A	12/18/10	14	56	18.0	18.0	23.0	23.0

a. Powers listed for Northwest (NW), Northeast (NE), Southwest (SW), and Southeast (SE) reactor lobes

- Research reactors have a short cyclic schedule

In Reactor Irradiaton

- Temperature and Irradiation Cycles Vary
  - Samples Undergo Thermal Cycling
  - Some Instrumented Capsules That Attempt to Control or Measure Temperature
  - Big Advantage Higher Flux
    - 4.4×10^{14} n/cm^2-s
  - Long Irradiation Times

Rabbit

- Pneumatic Tubes
  - Short Irradiation Times (3600 s)
  - No Temperature Control
  - Rudimentary Instrumentation
  - Lower Flux
    - 10^{12} - 10^{14} n/cm^{2}-s

Why Muons

- Controlled Experiments
  - Put an Advanced Fuel in a Temperature Controlled System
  - Irradiate With Muons
  - Observe Damage From Fission

Muon-induced Fission

- Fission Probability
  - Fission Yield 0.142 per muon
  - Comparable to 0.1 per thermal neutron

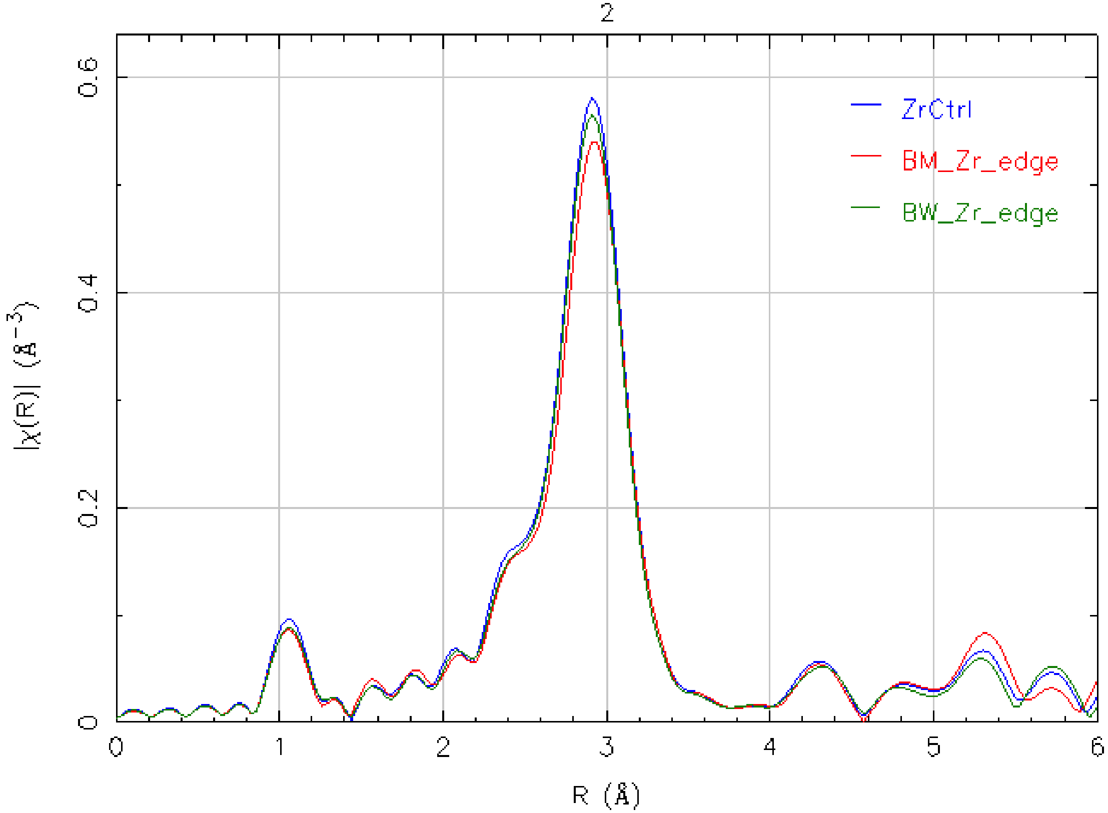
S. Ahmad, et al, Physics Letters 92B, 83 (1980).

Table 4.15
Basic parameters for fission and Auger events for muon stops in heavy atoms

Nuclide	Lifetime (ns)	Prompt/ delayed fission	Total fissions per μ stop	Prompt/ delayed neutrons	ν_p (prompt fission)	ν_d (delayed fission)	Auger neutrons (%, per stop)
^{207}Pb	75.4 (10)						$\sim 5^a$
^{209}Bi	73.5 (4)		0.000042 (7)				7 (2)^a
^{232}Th	77.3 (3)	0.05 (1)	0.02 (1)	0.056 (10)	2.4	3.6	10 (2)^b
^{233}U	68.9 (3)	0.201 (1)	0.48 (13)		2.4	3.6	
^{234}U	70.6 (2)	0.177 (1)	0.31 (8)		2.5	3.7	
^{235}U	72.2 (2)	0.125 (1)	0.31 (8)	0.11	2.5	3.7	18 (6)^b
^{236}U	74.3 (3)	0.186 (2)	0.20 (5)		2.6	3.8	
^{237}U			0.17 (5)^c		2.9	4.1	
^{238}U	77.1 (3)	0.088 (1)	0.14 (4)	0.08	3.1	4.3	15.4 (17)^b
^{237}Np	69.8 (2)	0.281 (1)	0.54 (17)		2.9	4.1	
^{239}Pu	70.1 (7)	0.20 (5)	0.8 (3)	0.16 (2)	3.2	4.4	$\sim 5^b$
^{242}Pu	75.4 (9)	0.21 (1)	0.6 (2)	0.17	3.4	4.6	
^{244}Pu	78.2 (4)	0.26 (1)	0.6 (2)		3.4	4.6	

Uranium Metal Fuels: UZr

- Higher Thermal Conductivity
  - Reduces likelihood of meltdown



- 10^{13} n/cm^2-s for 1800 s (Rabbit)
- Expect loss of coordination due to radiation damage

Damage Mechanisms

- Goal is to understand the damage mechanisms
  - Too many confounding factors
- Muon Irradiation Can Provide Better Control of Parameters
  - Muon Flux of 10^8-10^{10} muons/cm^2-s Would Provide Useful Information With Month to Year Exposures

What we need 1st

- Low energy muons (what can we get E vs. $\mathcal{L}$?)
  - What really matters is captured μ/s in U
  - Minimum interesting 10^5/s, want 10^7-10^8/s or more
- Low temperature controlled exposures
  - Distinguish temperature vs. radiation effects
  - Rate effects on stress formation (controlled by exposure)
- Then move on to cladding materials, structural steel for core supports, etc.

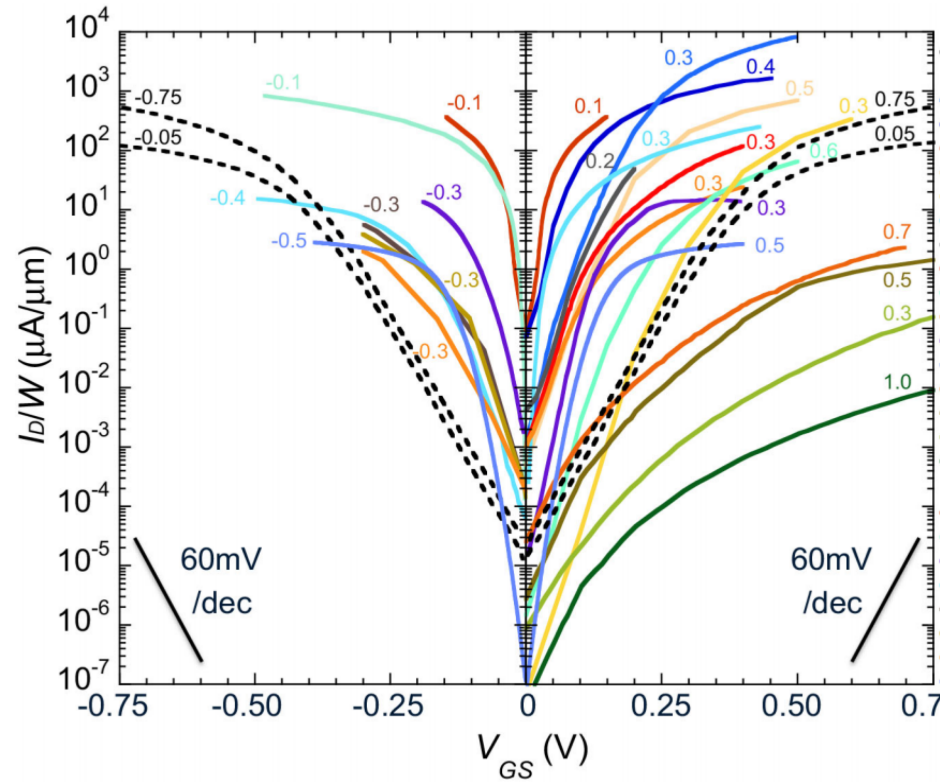
Some applications for today

1) Muons for security
   - A nuclear security challenge
   - Muon tomography
   - Muon-induced gamma spectroscopy
   - What needs to be done
2) Muons for radiation damaged materials (Terry)
3) Muons for lightly doped semiconductors (Hock)

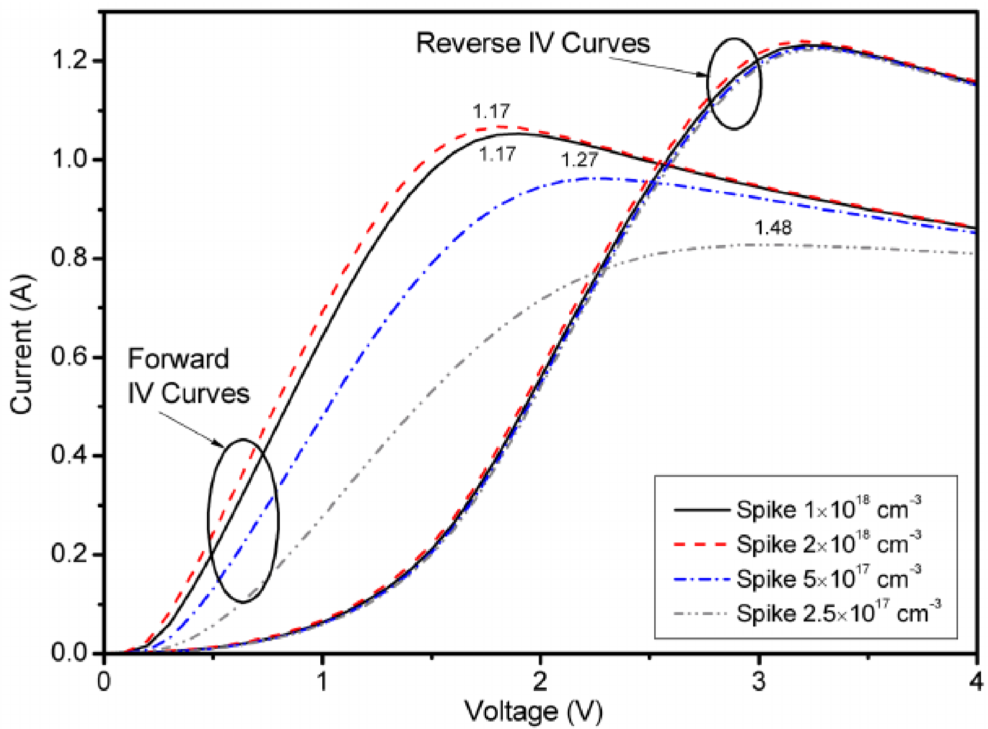
- What effect would captured muons have on semiconductor devices doped with a few mid to high-Z atoms?
  - The muons should neutralize hole carriers (at least partially), but will not change the crystalline structure.
  - What does that do to electrical properties?
- Can we use these temporary muon captures to learn about inner band gaps structures?

Electrical Devices Intro

Response per $\Delta V = 1$ V can be > 10^9
- Over a huge variety of material compositions
- Similar device performance
- Robust devices=many I-V other cycles
  - High reproducibility



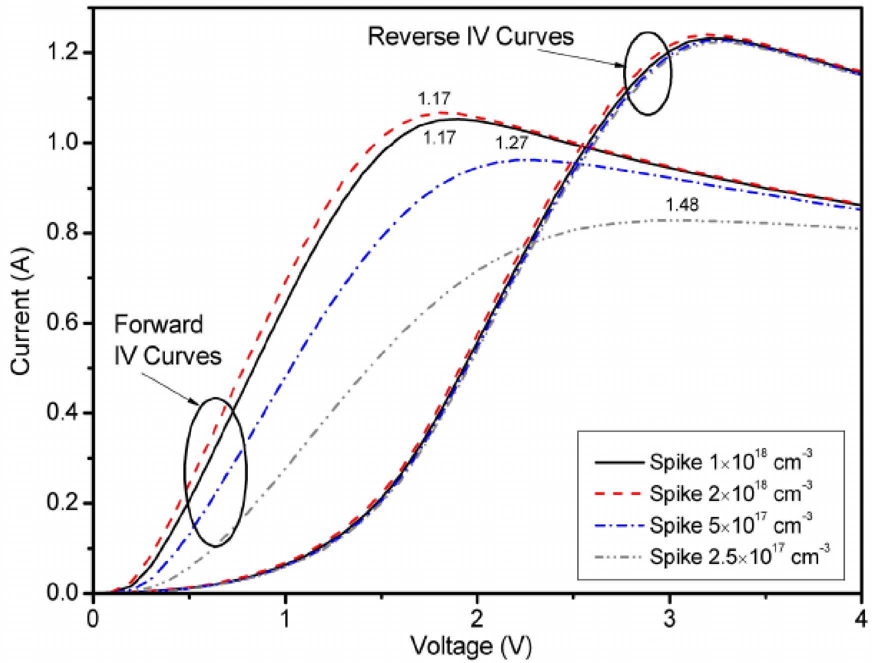
Lu and Seabaugh, *J. Electron. Dev. Soc.* 2014, 10.1109/JEDS.2014.2326622



Typical response to dopant concentrations
- Change in mobility
- I-V and C-V curves *very* sensitive to change in dopant concentrations

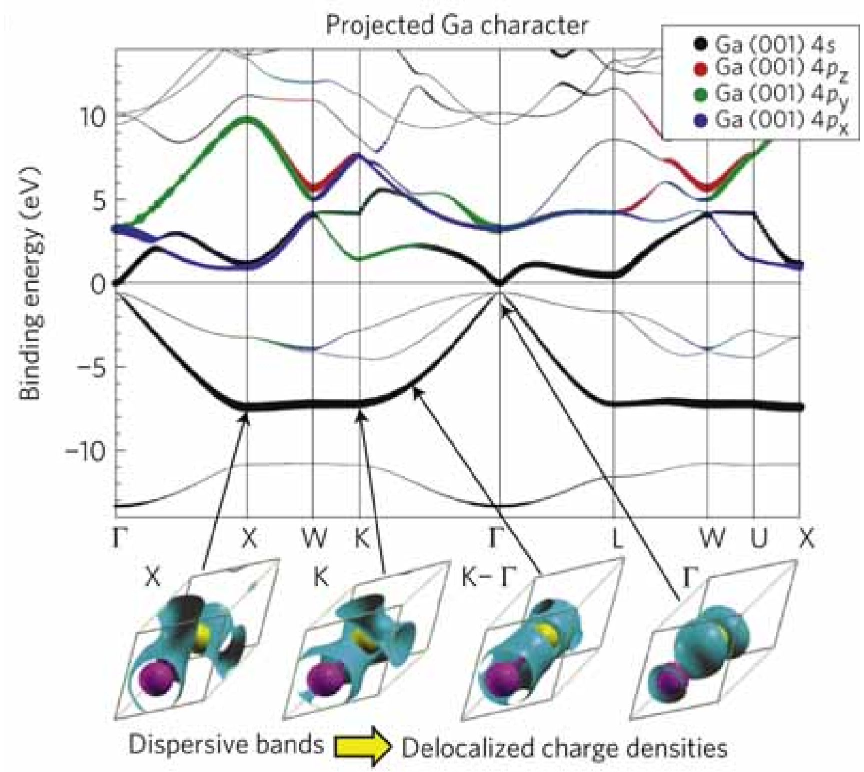
10.1117/12.830296

Electrical Devices, continued



In GaAs material

- Heavy Z elements
- Can we use muons to change dopant concentration?
- Effect on dopant levels, carrier mobility, etc?



Nature Mat. 2011, 10.1038/nmat3089

Can muon irradiation experimentally modify dopant concentrations?

- Quench p-doped sites?
- ‘extra’ n-dopants?

Initial Experiment, controls

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1e15 acceptors per cm^3 to 1e17 acceptors per cm^3 in lightly doped semiconductor
1e-15 cm^3, in $100nm^2$ by 40nm single device
= 4 dopant atoms in a device

It is now possible to fabricate devices with 1-1000 atoms as dopants.

Possible initial experiment:
verify effect as a function of Z (capture probability)

- Equal doping level with high and low-z dopants
- High Z devices with multiple doping concentrations

'Broader Impact'

- What do muons do to electrical properties?
  - Carrier concentration
  - Carrier mobility
  - Interaction with 2-D electron gasses(?)
- New tool for characterizing materials/devices?

Aside: These 100x100 nm devices fit in an array on a single chip, so really you do $10^4 – 10^6$ experiments simultaneously.

Up to tera-HZ switching can be used to observe turn off/on of dopant effect while muon is in place/decays.

What we need 1st

- Low energy muons (what can we get E vs. $\mathcal{L}$?)
  - What really matters is captured μ/s for a wide range of Z (from $_{92}$Pb down to $_{14}$Si)
  - Minimum interesting 10^5/s, want 10^7-10^8/s or more
  - Nearly continuous exposure desirable
- Higher beam density pays large dividends
  - Semiconductor devices are small → activate as many as possible
  - 1 cm^2 is OK, but < 1 mm^2 or smaller beams allows for much broader range of device applications
  - Ultimately want to aim toward few μm-sized concentrated beams to activate more sites/device.

Conclusions

- There a push to address broad accelerator applications across the DOE lab complex.
- Muons can address national needs in:
  - Nuclear security
  - Nuclear reactor materials improvements
  - New semiconductor materials
- All of these are best served by high-intensity (10^8/s), low-energy ($<$100 MeV?), focused (μm) muon sources.
- All would benefit from initial lower-luminosity (10^6/s) demonstration experiments.