Chadwick's Neutron and the Role of New Particles in Accelerator Health Physics

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Theme: Accelerators and New Particles

- Valentine Telegdi (1922-2006) may have stated a key theme of accelerator health physics: “Yesterday's sensation is today's calibration and tomorrow's background.”
- Paraphrased by Fermilab’s Andy Van Ginneken (ca. 1996): “Yesterday's sensation is today's radiation.”
- NEUTRONS AND OTHER “NEW” PARTICLES HAVE BEEN A MAJOR THEME OF CHALLENGES IN ACCELERATOR HEALTH PHYSICS (AHP).

The Neutron - Discovery

- Sir James Chadwick (1891-1974)
  - Discovered the neutron in 1932.
  - Produced neutrons with radioactive decay α-particles absorbed by Be, not with an accelerator.
  - First of several "new" particles that have challenged accelerator health physics (AHP)
  - Neutrons still vex us!

Neutron: Basic Properties*

* Ref. for "basic properties": Particle Data Group, "Review of Particle Properties", Journal of Physics G 37 , #7A, July 2010.

n: 3 quarks, a baryon hadron => nuclear force

Mass (Rest energy) = 939.565346 MeV.

Spin = ½ (Fermi-Dirac quantum statistics).

Mean life (at rest) τ = 885.7 s.

Moving particles makes $c\tau$ a useful quantity.

For neutrons $c\tau = 2.655 \times 10^8$ km.

Neutron: Basic Properties

Relativistic time dilation:

Multiply τ by $\gamma = \dfrac{\text{(kinetic energy + rest energy)}}{\text{rest energy}} = \sqrt{1-\left(\dfrac{v}{c}\right)^2}$

γ	v/c	Neutron Kinetic Energy (MeV)
1.0	0.000	0.0
1.2	0.553	188
1.5	0.745	470
2.0	0.866	939
5.0	0.980	3760
10	0.994	8456

Neutron: Basic Properties

Charge = 0, => No Coulomb forces.

Magnetic dipole moment = -1.9130427 μ_{n},

$$\mu_n = \frac{e\hbar}{2m_p} =$$ "the nuclear magneton".

Electric dipole moment < 0.28 x 10^{-25} e cm.

Small! Nonzero electic dipole moment violates time reversal symmetry!

$m_n - m_p$ =1.2933321 MeV, neutrons decay!

Main decay mode: $n \to p + e^- + \overline{\nu}_e$

Minor decay mode (0.3 %): $n \to p + e^- + \overline{\nu}_e + \gamma$

Major AHP “Gripes” with the Neutron

- There is no ionization range-out.
- Magnetic deflection does not help.
- Produced copiously at all accelerators (proton, electron, or ion) having (kinetic) energies > 10 MeV.
- Produced at large production angles relative to the beam.
- Major player in hadronic cascades that can drive shielding size and bulk
- All energies typically seen, thermal up to the nearly the energy of the beam.

Major AHP “Gripes” with the Neutron

- Readily creates radioactive materials with residual activity hazards.
- Radionuclides produced can span the periodic table up to the atomic mass of the irradiated materials at high energy accelerators.
- Instrumentation needed to assess dose, dose equivalent, equivalent dose, effective dose, etc. over energy domain is difficult to make or does not exist for required dosimetric quantities!
- Determining the dose/fluence is difficult.

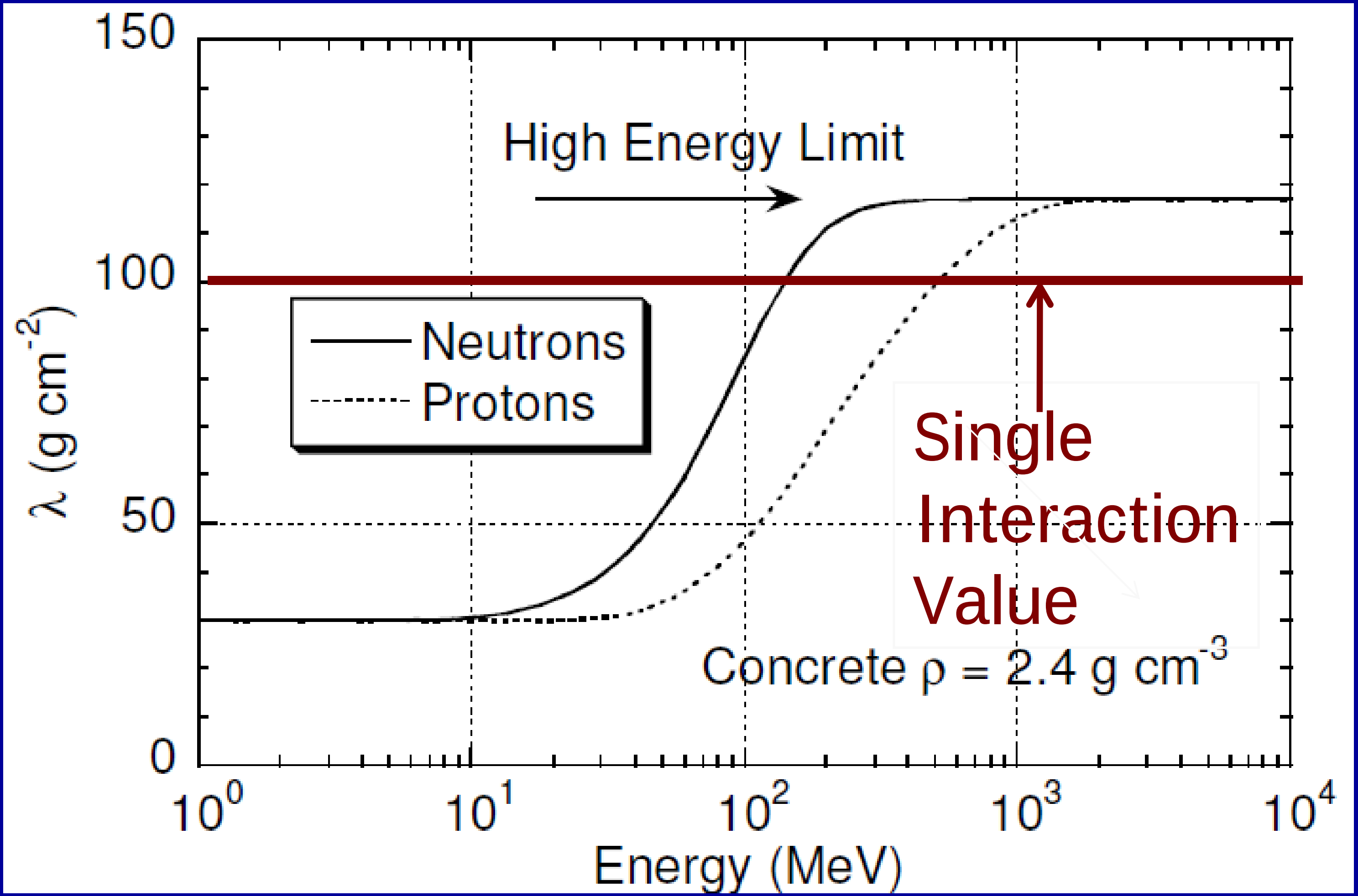
Neutron Special Problem 1: Large λ

- Neutrons at high energies have large mean free paths (λ) in materials.
- Here are high energy (HE) values of λ for a few common shielding materials:

MATERIAL	λ (g cm^{-2})	λ (cm)
Concrete (ρ=2.5 g cm^3)	99.9	40.0
Carbon (graphite)	86.3	38.1
Aluminum	106.4	39.4
Iron (textbook density)	131.9	16.8
Lead	194.0	17.1

Neutron Special Problem 1: Large λ

λ in hadronic cascades becomes even larger.



Neutron Special Problem 1: Large λ

- Makes shields massive.
- Results in the need for
  - Penetrations and labyrinths, big shield doors
  - Expensive structures to support massive roofs
  - Thin roofs that can lead to skyshine.
- Costly! Mostly use the 3 “cheap” shields
  - Earth
  - Concrete
  - Iron (but see Neutron Special Problem 2)

Neutron Special Problem 2: Low Energy Buildup in Shielding

- Most energy loss by neutrons in a shield is by inelastic scattering.
  - Energy removed through excitation of nuclear states, emission of photons and, sometimes, charged particles
  - Non-relativistic elastic scattering transfers energy according to:

$$\frac{\Delta E}{E_o} = \frac{4\frac{M}{m_n}\cos^2\theta}{\left(1+\frac{M}{m_n}\right)^2}$$

  - Let’s play billiards!

Neutron Special Problem 2: Low Energy Buildup in Shielding

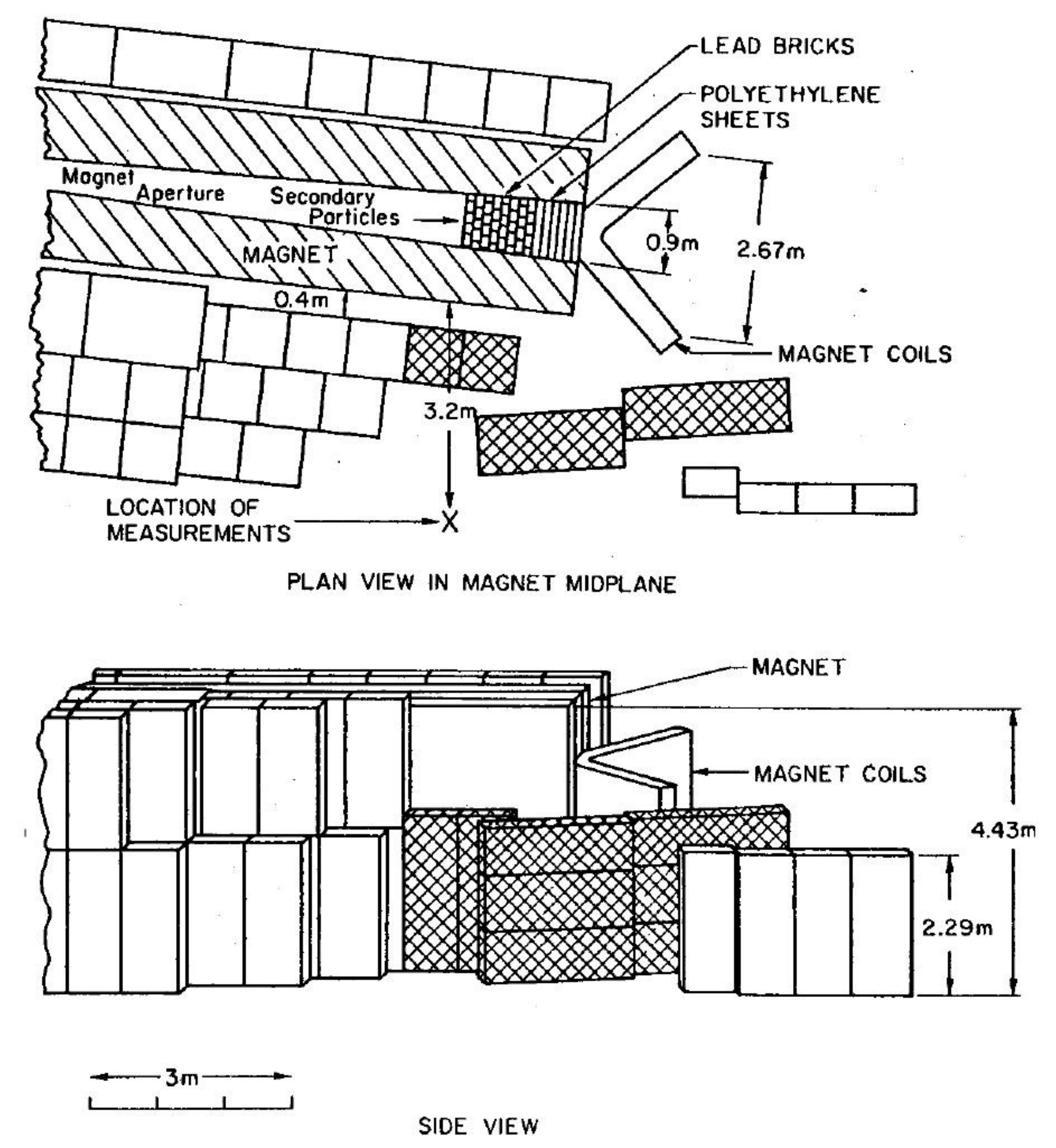
- Once lower energies are reached, elastic scattering on hydrogen transfers much energy to protons.
- The protons lose energy by ionization.
- Elastic scattering on heavy elements transfers very little energy.
- Hydrogen also can capture thermal neutrons.
- Therefore: Moderation by hydrogenous materials is very important!
- We are all glad earth & concrete contain water!

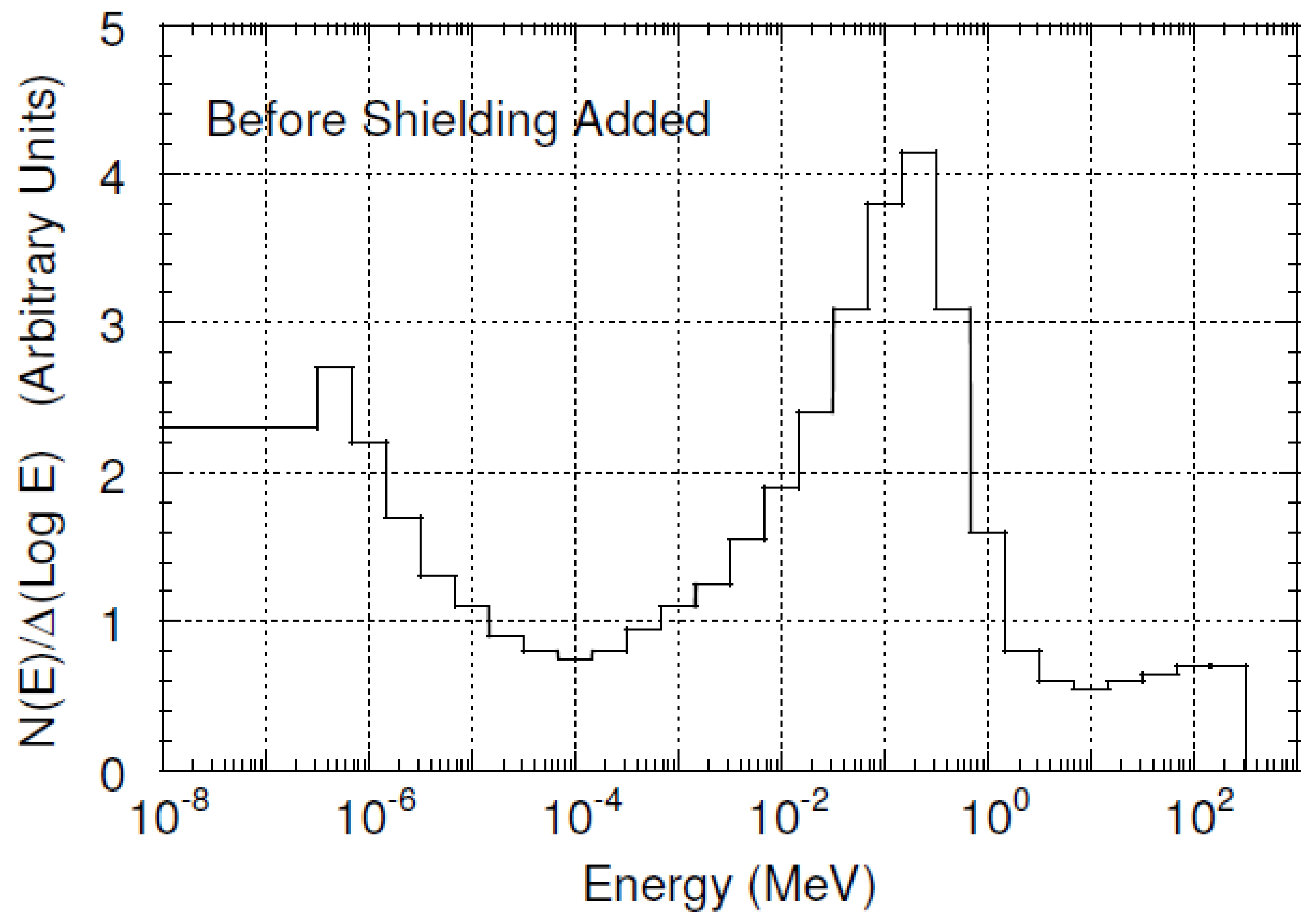
Neutron Special Problem 2:

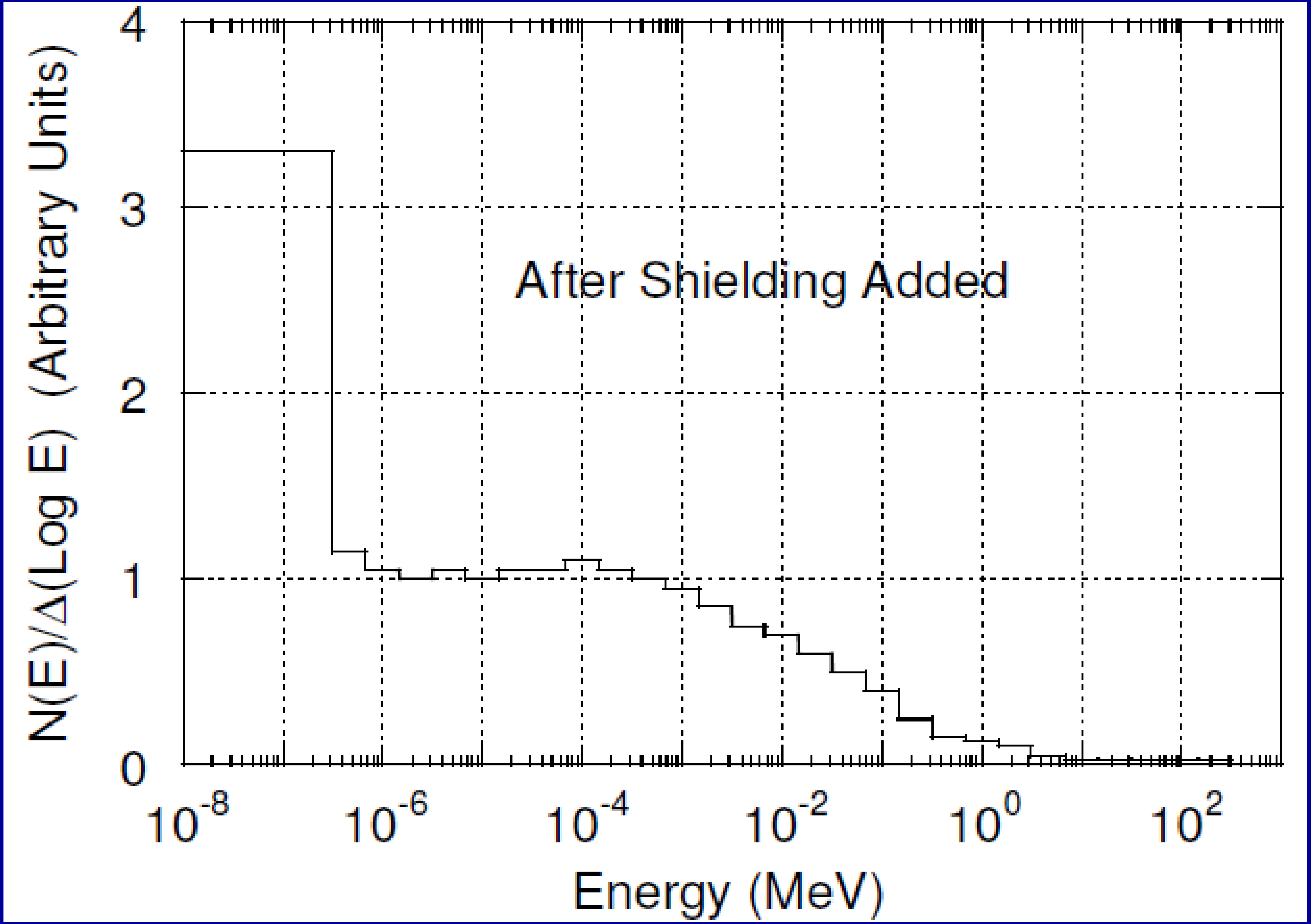
- Seen most readily in iron; applies to other materials.
  - 1^{st} nuclear excited state in ^{56}Fe is at 847 keV.
  - In high energy cascade, get buildup of neutrons near that energy.
- Phenomenon has long been known.
- Often comes up when designers want to "try to help and fix a shielding problem".
- Had a graphic example at Fermilab.
- Lesson: Use iron capped with > 60 cm of earth or concrete on the outside of the shield.

Fermilab E605 Example

[Elwyn & Cossairt, HP 51 (1986) 723]




Before Shielding Added
N(E)/Δ(Log E) (Arbitrary Units)
Energy (MeV)
0
1
2
3
4
5
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}


After Shielding Added
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Energy (MeV)
0
1
2
3
4
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}

Neutron Special Problem 3: Time, ~~Distance, and Shielding~~

- Recall the *mantra,* "Time, distance, and shielding" as a way of keeping doses ALARA.
- It is a well-known that an enclosure with fast neutrons WILL get filled nearly uniformly with slow & thermal neutrons.
  - Walls can get activated nearly uniformly.
- Result: Residual dose rate inside the room due to the a uniformly activated wall will be uniform.
- Demonstrated for cylinders [Armstrong and Barish, Nucl. Sci. & Eng. 38 (1969) 373.].

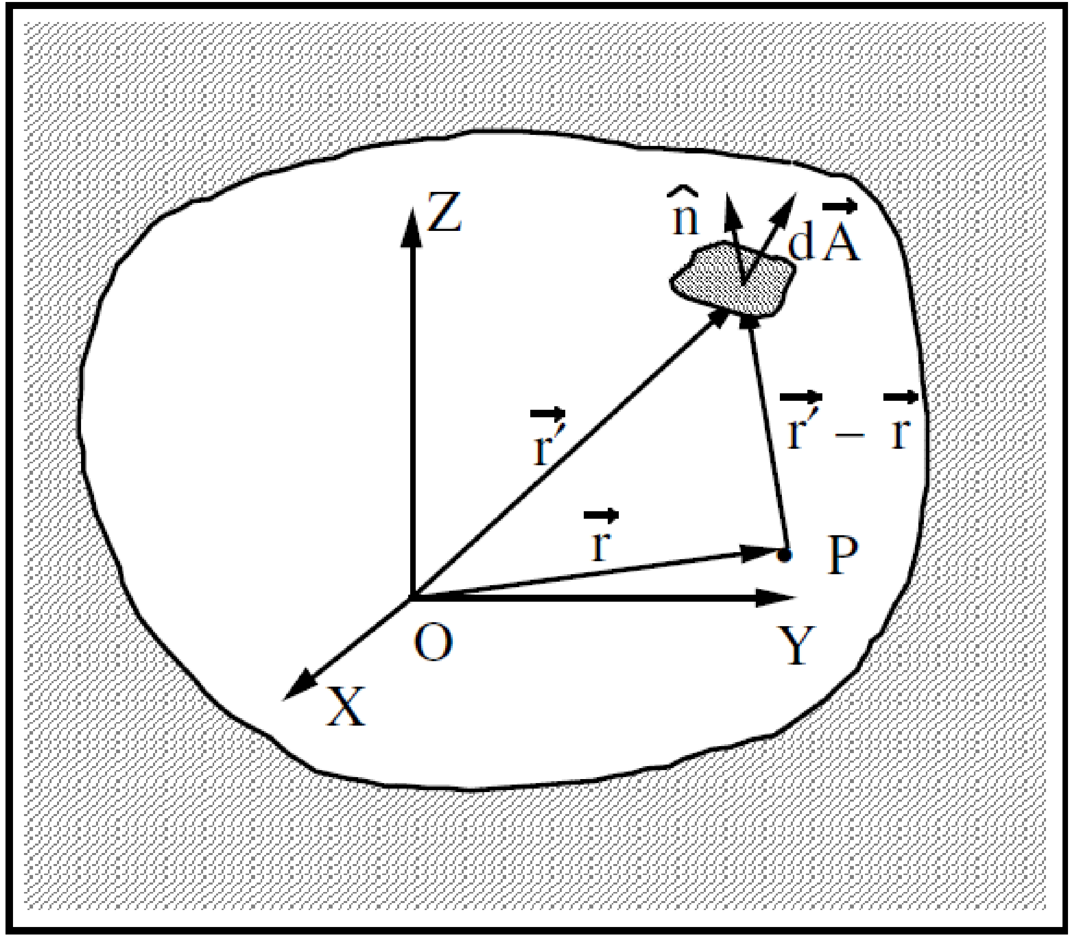
Neutron Special Problem 3: Time, ~~Distance, and Shielding~~

True in general, not just for cylinders [Cossait, HP 71 (1996) 315].

The flux density at point P due to $d\vec{A}$ is:

$$d\phi = \frac{\phi_o}{4\pi} \frac{d\vec{A} \bullet \hat{n}}{\left|\vec{r}' - \vec{r}\right|^2};$$

$$\hat{n} = \frac{\vec{r}' - \vec{r}}{\left|\vec{r}' - \vec{r}\right|}.$$



$\int_{4\pi}\frac{\phi_o}{4\pi}d\Omega=\phi_o$

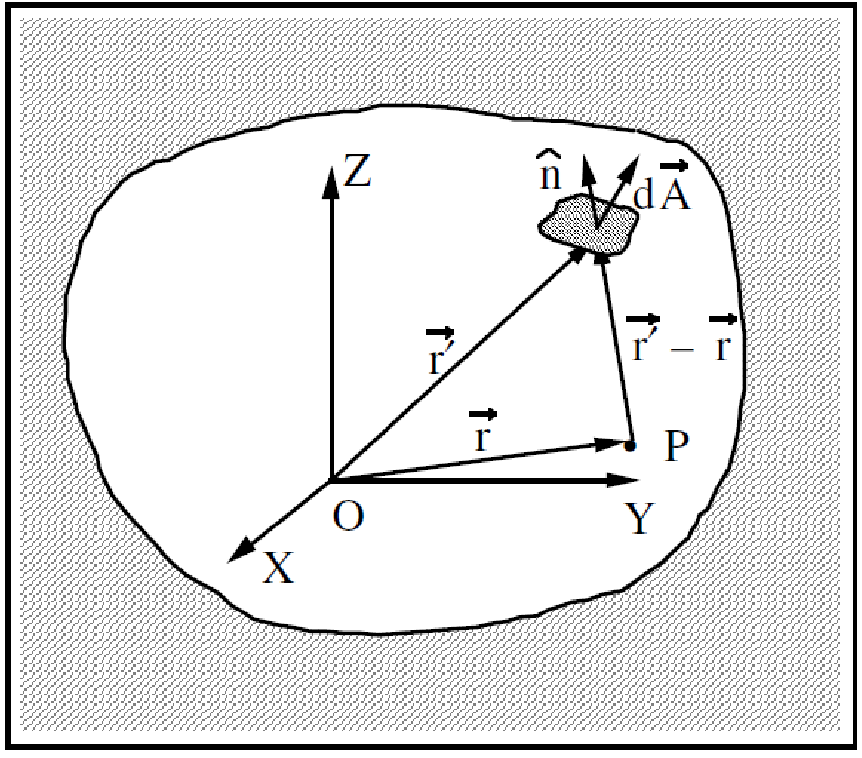
Neutron Special Problem 3: Time, ~~Distance, and Shielding~~

But the solid angle at P Of $d\vec{A}$ is:

$$d\Omega=\frac{d\vec{A}\bullet\hat{n}}{\left|\vec{r}'-\vec{r}\right|^2}$$

$$d\phi=\frac{\phi_o}{4\pi}\frac{d\vec{A}\bullet\hat{n}}{\left|\vec{r}'-\vec{r}\right|^2}=\frac{\phi_o}{4\pi}d\Omega;$$

$$\phi=\int_{4\pi}\frac{\phi_o}{4\pi}d\Omega=\phi_o$$



Neutron Special Problem 3: Time, ~~Distance, and Shielding~~

- Problem exacerbated with concrete walls due
  - ^{24}Na production by thermal capture
  - ^{24}Na emits 1.37 & 2.75 MeV photons.
- Removing beamline parts does not help.
- Moving away from beamline does not help.
- Aside from wearing suits of lead armor, shielding does not help.

The Charged Pion - Discovery

- Cecil Frank Powell, among others (1903 – 1969)
  - Discovered the charged pion in 1947.
  - Done with cosmic rays, before accelerators had sufficient energy
- Pion’s existence predicted by Hideki Yukawa (1907-1981) in 1935.
- Much longer-lived “daughter” muon discovered first, in 1936 – confusion reigned!

Charged Pion: Basic Properties

π^+: 2 quarks, a meson hadron

Mass = 139.57018 MeV.

Spin = 0 (Bose-Einstein quantum statistics).

Mean life τ = 2.6033 x 10^{-8} s.

$c\tau$ = 7.8045 m.

Decay modes: 99.98770 % $\pi^+ \to \mu^+ + \nu_\mu$

0.0200 % $\pi^+ \to \mu^+ + \nu_\mu + \gamma$

0.0123 % $\pi^+ \to e^+ + \nu_e$

Charged Pion: Basic Properties

Special AHP problem:

They end up as muons!

Since $c\tau$ = 7.8045 m,

Can decay into muons in decay paths of “finite” lengths.

The Neutral Pion - Discovery

- Jack Steinberger (1921 – present), among others
  - Discovered the neutral pion in 1949.
  - Done at Berkeley using an accelerator.
  - Others confirmed it in cosmic rays.

Neutral Pion: Basic Properties

π^o : 2 quarks, a meson hadron

Mass = 134.9766 MeV.

Spin = 0 (Bose-Einstein quantum statistics).

Mean life τ = 8.4 x 10^{-17} s.

$c\tau$ = 25.1 nm.

Decay modes: 99.823 % $\pi^o \rightarrow \gamma + \gamma$

1.174 % $\pi^o \rightarrow e^+ + e^- + \gamma$

Neutral Pion: Basic Properties

Special AHP Problem:

Initiate electromagnetic cascades and <u>much</u> of component radiation damage, heating, & failures and dose for repairs.

$$\pi^o \rightarrow e^+ + e^- + \gamma$$

The Charged Kaon - Discovery

George Dixon Rochester (1908 - 2001)
&
Clifford Charles Butler (1922 – 1999)

- Discovered charged kaons in 1947.
- Originally found in cosmic rays.

Charged Kaon: Basic Properties

K^+ : 2 quarks, a meson hadron

Mass = 493.677 MeV.

Spin = 0 (Bose-Einstein quantum statistics).

Mean life $\tau = 1.2380 \times 10^{-8}$ s.

$c\tau = 3.712$ m (similar to that of π^+).

Decay modes: 63.55 % $K^+ \rightarrow \mu^+ + \nu_\mu$

20.66 % $K^+ \rightarrow \pi^+ + \pi^o$

5.59 % $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$

5.07 % $K^+ \rightarrow \pi^o + e^+ + \nu_e$

Neutral Kaon: Basic Properties

K^o : 2 quarks, a meson hadron

Mass = 497.614 MeV.

Spin = 0 Two kinds!: $K^o_{short,}$ and $K^o_{long.}$

Mean life τ (K^o_{short})= 8.953 x 10^{-11} s.

$c\tau$ = 2.6842 cm.

Decay modes: 69.20 % $K_S^o \to \pi^+ + \pi^-$

30.69 % $K_S^o \to \pi^o + \pi^o$

Neutral Kaon: Basic Properties

Mean life τ ($K^o_{long,}$)= 5.116 x 10^{-8} s.

$c\tau$ = 15.34 m.

Decay modes: 40.55 % $K^o_L \rightarrow \pi^+ + e^- + \nu_e$

27.04 % $K^o_L \rightarrow \pi^+ + \mu^- + \nu_\mu$

AHP Problem: Nearly all Kaons either decay to muons or pions that then decay to muons.

Muons, Muons, Muons!

The Muon - Discovery

- Discovered by Carl D. Anderson (1905 - 1991) and Seth Neddermeyer (1907 - 1988) in 1936 in cosmic rays.
- Initial confused with pions. [Old books call them “mu-mesons”. This is incorrect; they are not hadrons.]
- Turned out to be a “heavy electron”, not the expected nuclear force mediator.
- Isidor Isaac Rabi (1898 – 1988) remarked, “Who ordered that?”

Muon: Basic Properties

- The $\mu^{\pm}$: A charged lepton, very much like a heavy electron
- Mass = 105.658367 MeV.
- Spin = ½ (Fermi-Dirac quantum statistics).
- Mean life τ = 2.197034 x 10^{-6} s.

  $c\tau$ = 658.654 m.
- Decay modes: 100.0 % $\mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu}$

  1.4 % $\mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu} + \gamma$

Muon: Basic Properties

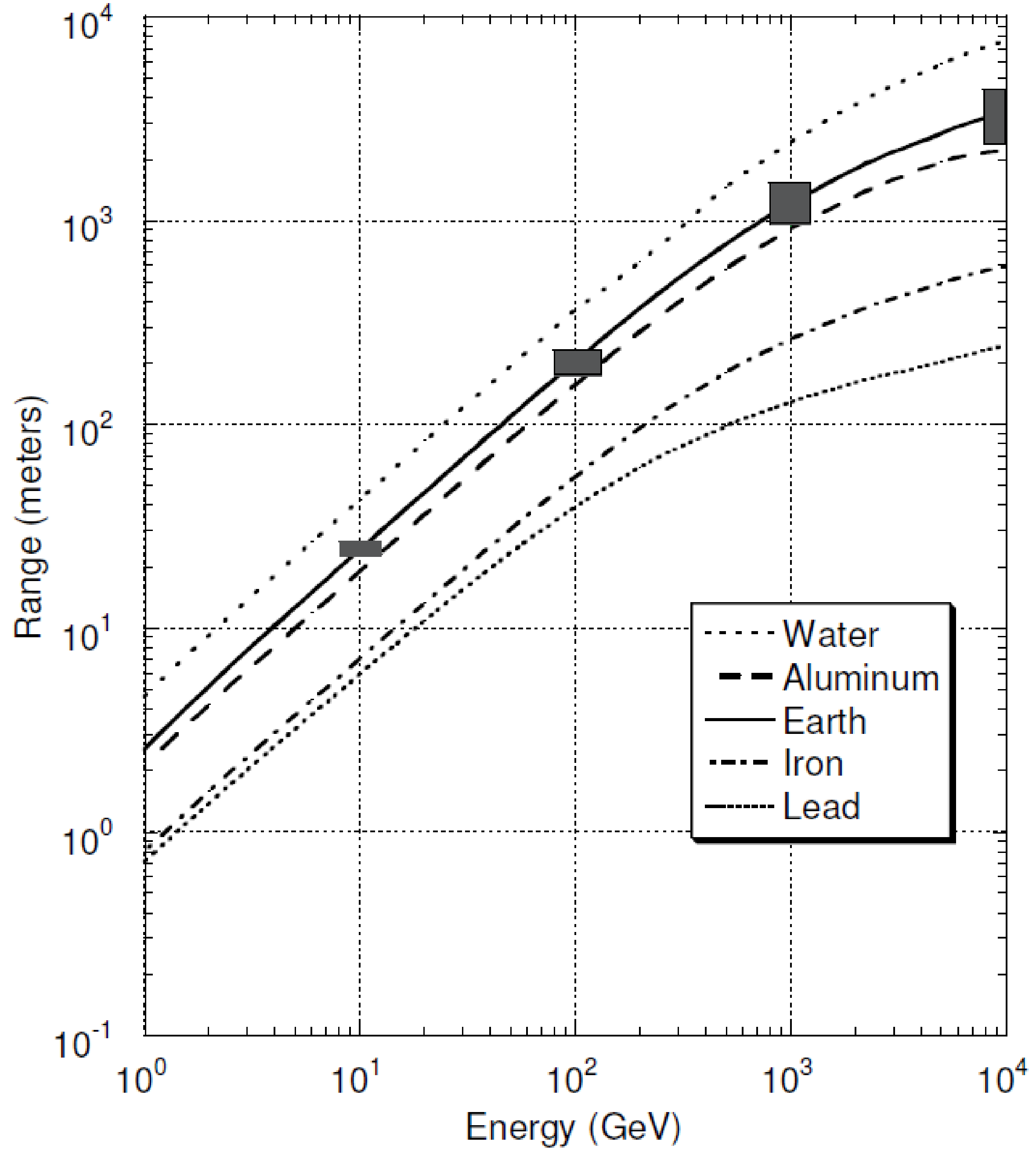
- Produced by:
  - Pair production at electron accelerators
  - Pion and Kaon decay at hadron accelerators
    - Long decay paths promote production.
  - Both mechanisms result in strong forward-peaking.
- Subject to deflection by magnetic fields.
- <u>Both</u> signs of electric charge are often present.
- Attenuation “straight-ahead” is most important.

Muon: Special Problem - Long Ionization Ranges and Forward Peaking

- Predominant energy loss is by ionization (low linear energy transfer or “LET”).
- Makes the dose/fluence easy to calculate!
- Unlike electrons, not scattered much by atomic electrons but are dispersed by multiple Coulomb scattering.
- To remove, must range them out.
- Ionization ranges grow large with energy.
- Need “cheap” shielding, usually earth or iron

Muon: Special Problem

Range-Energy relation

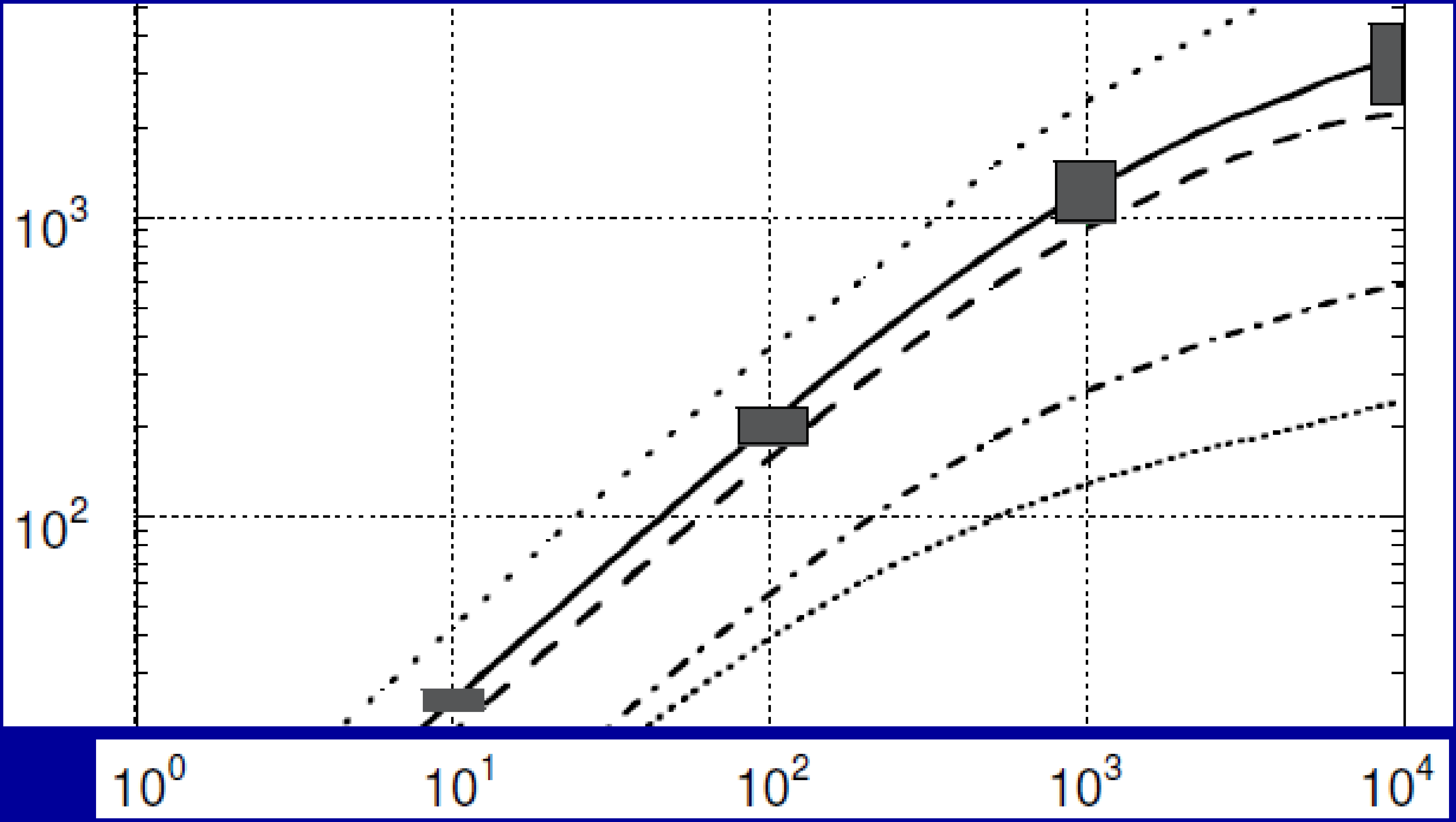


Muon: Special Problem - Long Ionization Ranges and Forward Peaking

- At high energies, range-energy straggling is very significant.
- Straggling results from
  - e^+e^- pair production
  - Bremsstrahlung, dominant above a critical energy E_c for muons in solids given by:

$$E_{c,muon} = \frac{5700\ \mathrm{GeV}}{\left(\mathrm{Z} + 1.47\right)^{0.838}}$$

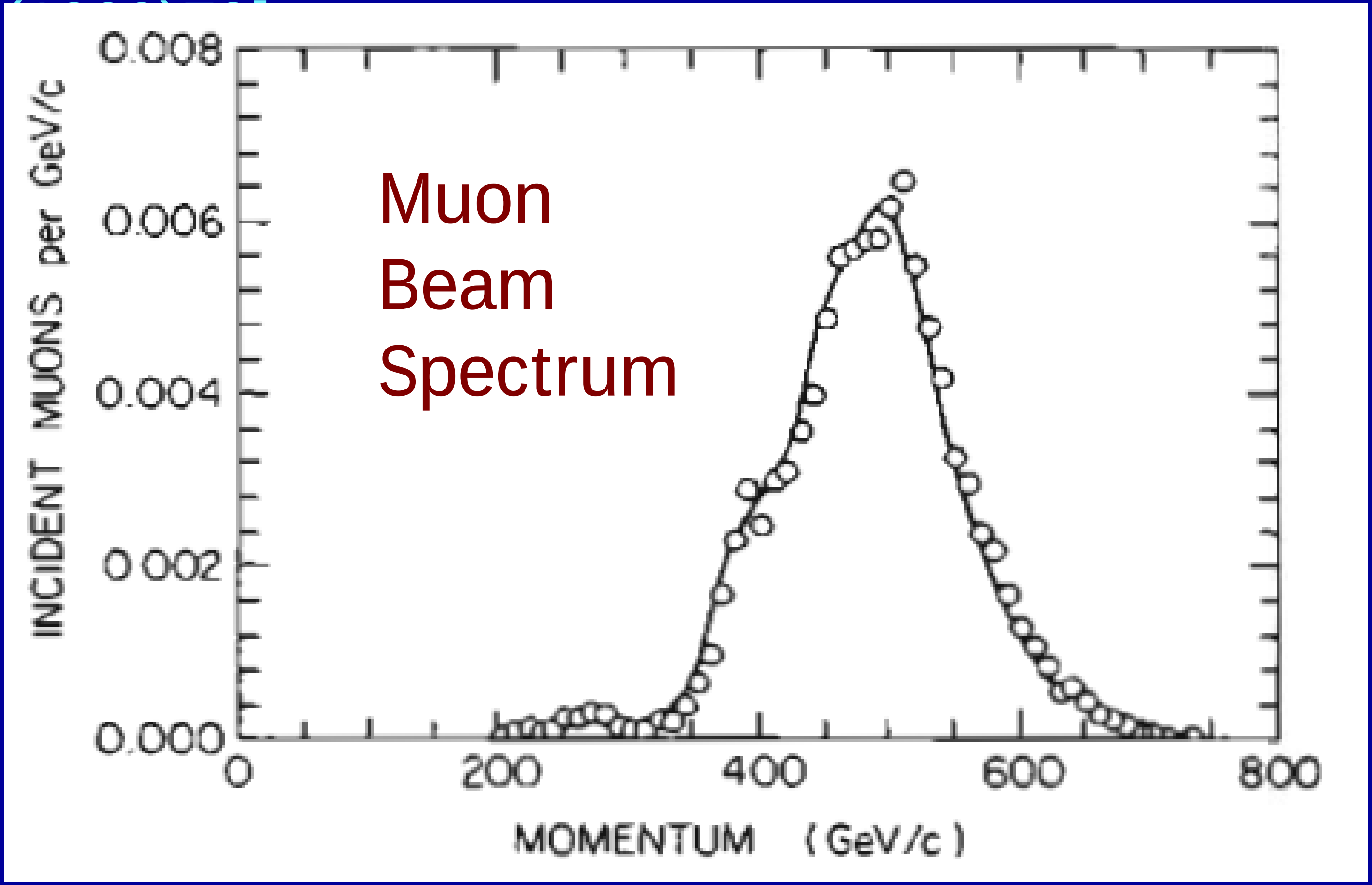
Muon: Special Problem



Note the straggling as % of the range!

Muon: Special Problem

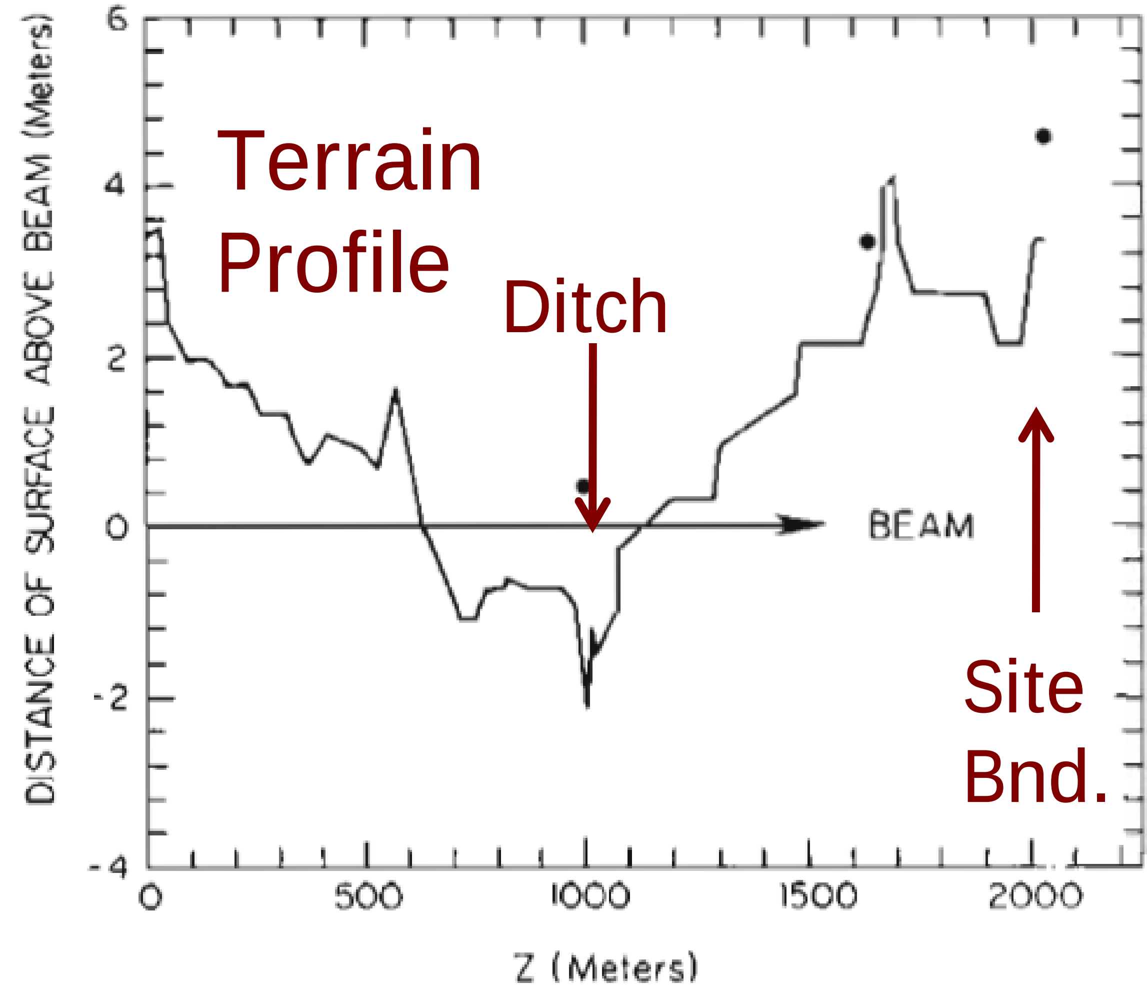
Fermilab E665 (late 1980s), horizontal muon beam below grade: [Cossairt et al. NIM A276



Muon Beam Spectrum

Muon: Special Problem

- Designers used 26 GeV shielding code
  - Missed the dip.
  - Straggling not included.
- Result: Unacceptable Site Boundary Dose

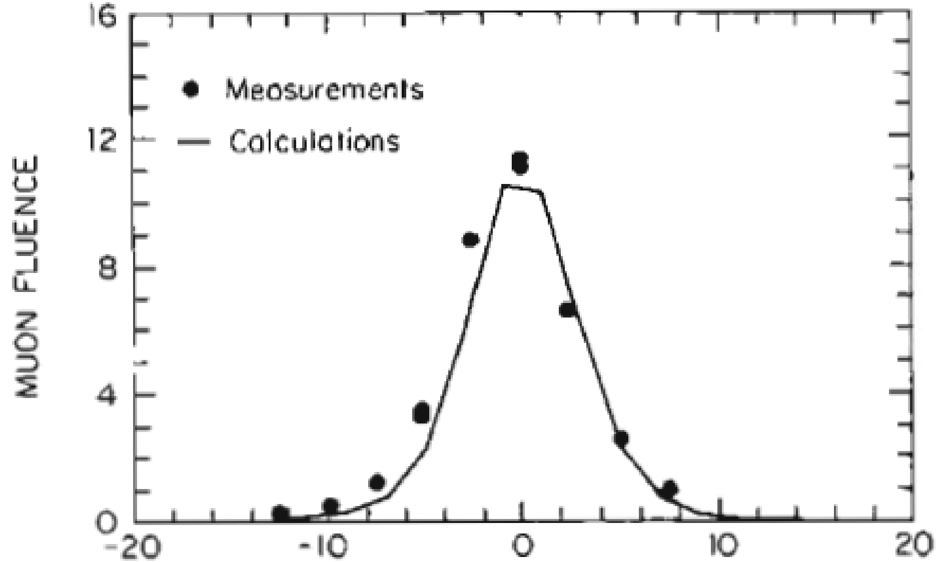


Muon: Special Problem

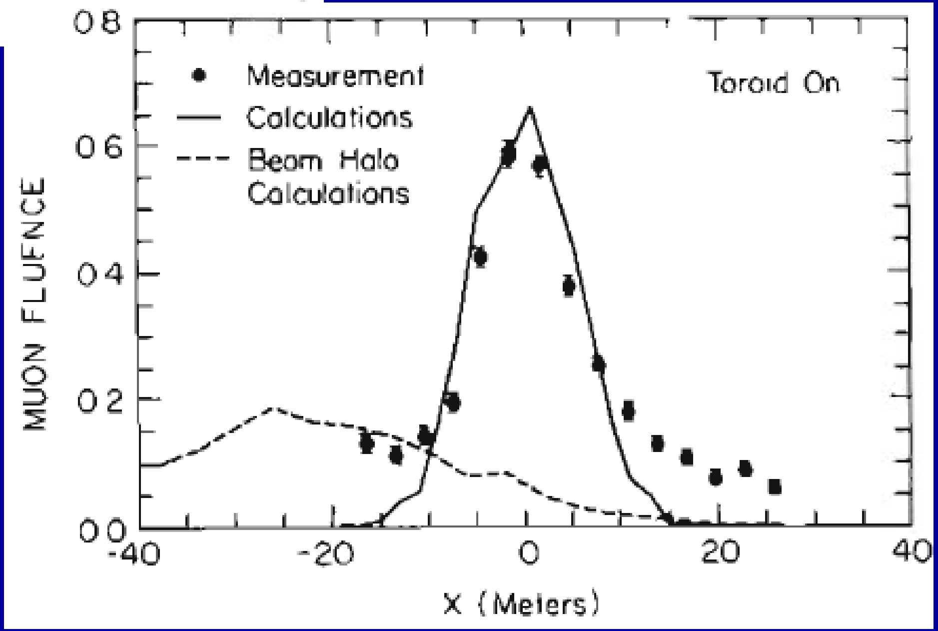
- Remedy: Intercept with magnetized iron “spoilers” set to bend μ^+s DOWN.
- All muons were μ^+s. Solution would not have worked for mixed-sign muons.
- Beam center for 500 GeV/c muons moved 6 m lower at Z = 1000 m. (2.75 GeV/c down)
- Peak site boundary dose/muon reduced by a factor of 14.

Muon: Special Problem

Undeflected Transverse Distribution at Ditch



Deflected Transverse Distribution At Ditch



The Neutrino - Discovery

- Postulated by Wolfgang Pauli (1900 – 1958) in 1930. [Pauli called it the neutron!]
- The neutrino was needed as the 3rd body in nuclear β-decay.
- 1934: Naming problem solved by Enrico Fermi (1901 – 1954) (neutrino = “little neutral one”).
- 1956: Clyde Cohen (1919 - 1974) and Frederick Reines (1918 - 1998)

first detected reactor neutrinos.

Neutrino: Basic Properties

ν: A neutral lepton (very weakly interacting)

> 3 kinds (flavors), ν_e, ν_μ, ν_τ; they mix!

Mass < 2 eV (now known to be nonzero).

Spin = ½ (Fermi-Dirac quantum statistics).

Mean life $>$ 7 x 10^9 s/eV of Mass.

Decay modes: “Oscillate” from one flavor to another – a matter of current frontier research, now verified by experiment.

Neutrino: Dose Per Fluence

- Remember A. Van Ginneken: “Yesterday's sensation is today's radiation.”
- High intensity neutrino experiments are currently of prominent scientific interest.
- We needed values of dose per fluence for environmental assessments .
- Included effects at all energies [Cossairt, et al., HP 73 (1997) 894; Mokhov & Van Ginneken, Fermilab Report Conf-99/067 (1999)]
- Most important need: For neutrinos emerging “straight ahead” from very thick earth shields.

Neutrino: Dose Per Fluence

- Neutrinos DO interact with matter!
- Four processes, start with cross sections:

A. Scattering from atomic electrons

$$\sigma_{\nu-\text{electron}} = CE_{\nu}\,(\text{MeV}) \times 10^{-45}\ (\text{cm}^2)$$

C is dependent upon neutrino flavor.

B. Scattering from nuclei

$$\sigma_{\nu-\text{nucleus}} = 4.2 \times 10^{-45}\, N^2 E_{\nu}^2 (\text{MeV})\ (\text{cm}^2)$$

N is neutron number of the absorbing material.

Neutrino: Dose Per Fluence

C. Scattering from individual nucleons

$$\sigma_{\nu-\text{nucleon}} = 6.7\times10^{-39} E_\nu\,(\text{GeV})\ (\text{cm}^2)$$

"6.7" becomes 3.4 for antineutrinos.

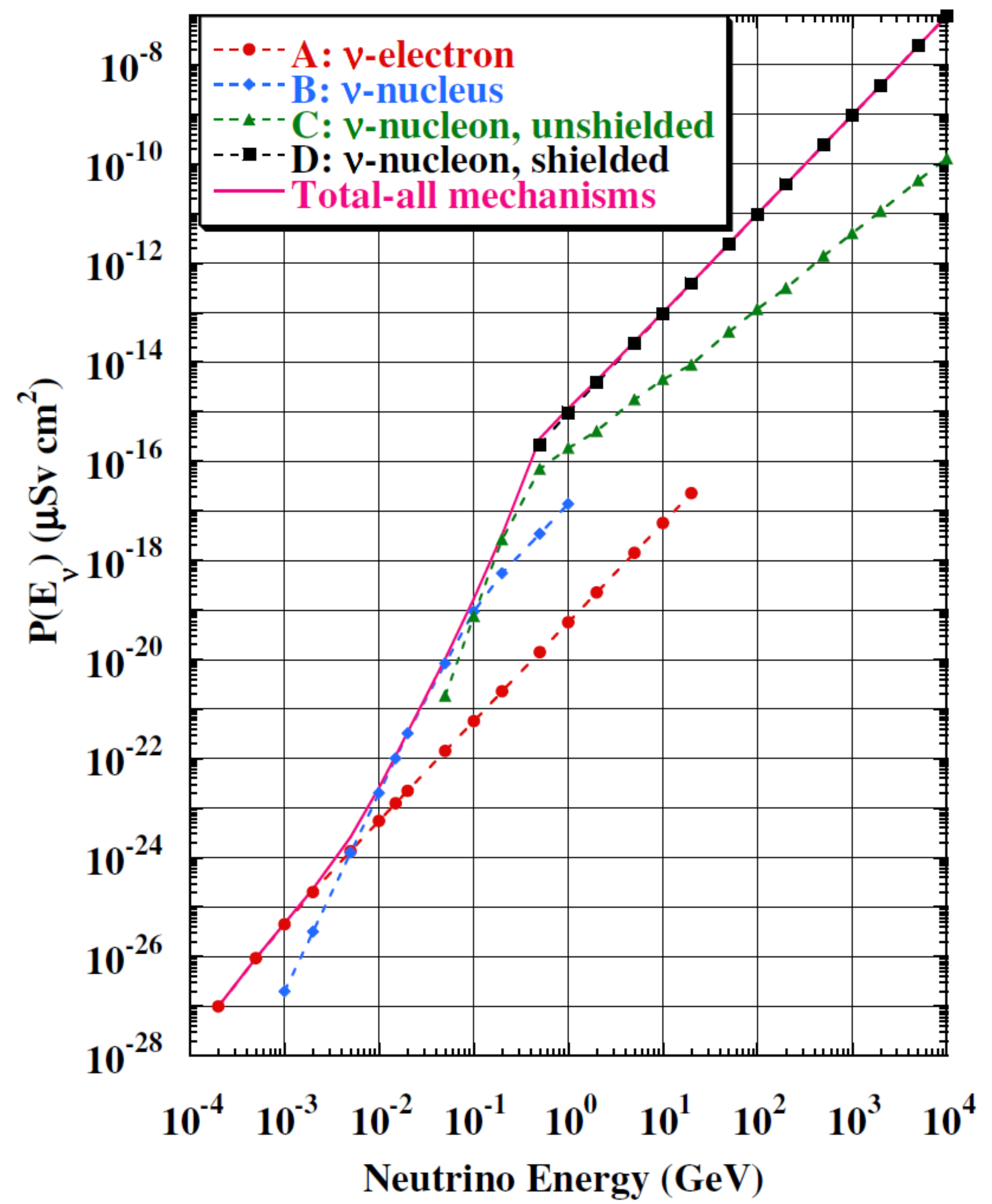
D. Buildup of "equilibrium" radiation from neutrino interactions far upstream in a long earth shield (delivered mostly by muons), the dominant process above about 10 GeV; Get dose/fluence equation:

$$P(E_\nu) = 0.16\sigma_{\nu-\text{nucleon}} E_\nu\,(\text{GeV}) N_A Q\ (\mu\text{Sv cm}^2)$$

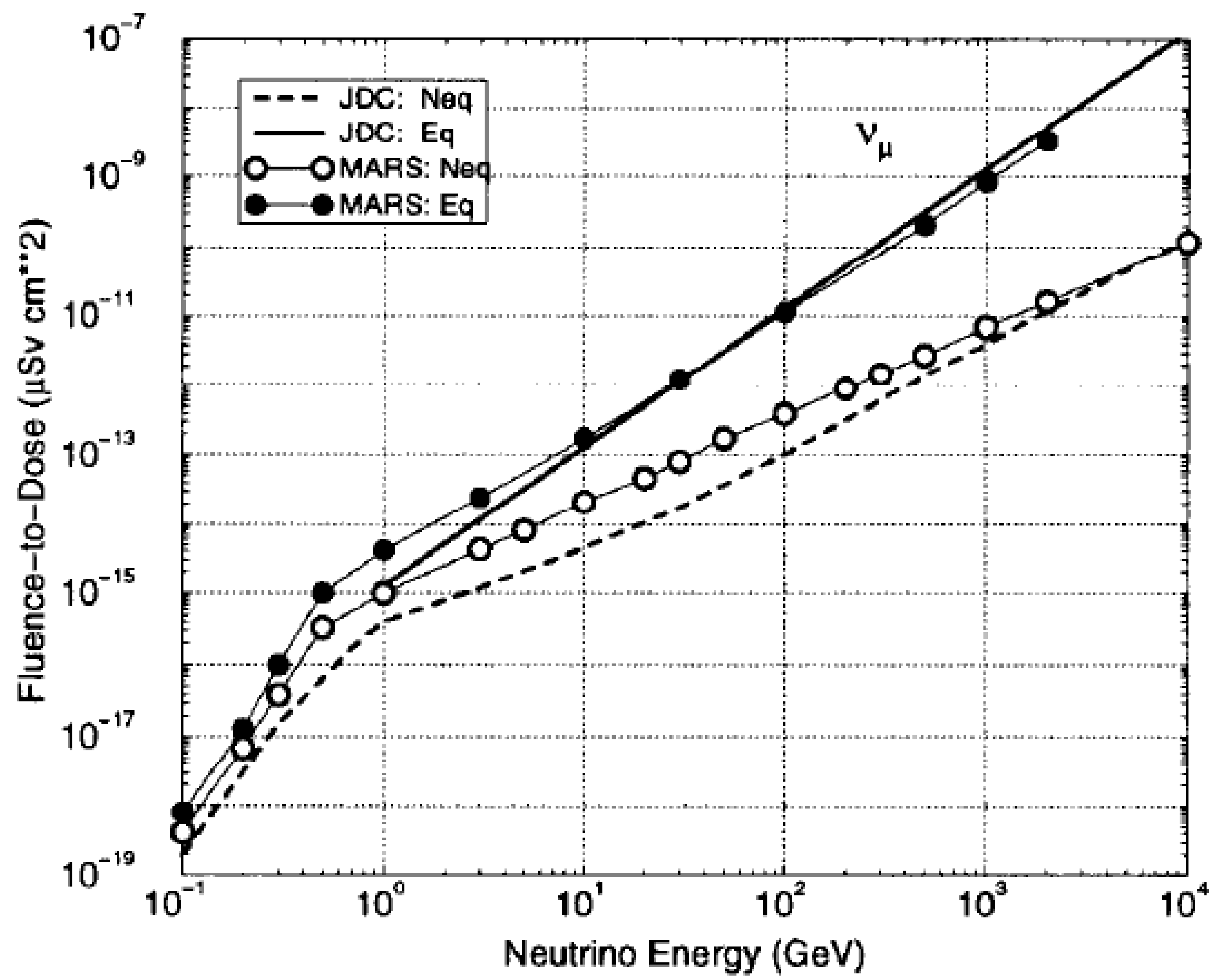
N_A = Avogadro's #, Q = 1.3, est. quality factor.

Neutrino: Dose Per Fluence

for All 4 processes for ν_μ's, and sum, [Cossairt et al.]



Two Results Beat 1! [Mokhov & Van Ginneken]



Neutrino: Dose Per Fluence

- H. Wade Patterson's (1924 -1997) last words to me [at the San Jose HPS Midyear in 1997], "Don, you have published the smallest dose coefficients in the history of health physics!"
- Fermilab "Neutrinos at the Main Injector" (NuMI) experiment doses using these results:
  - "Near" detector @ Fermilab (1 km from target): 12 μSv y^{-1}
  - "Far" Detector @ Soudan, MN (730 km):
    8.5 X 10^{-6} μSv y^{-1}
- Not a big deal now, but...

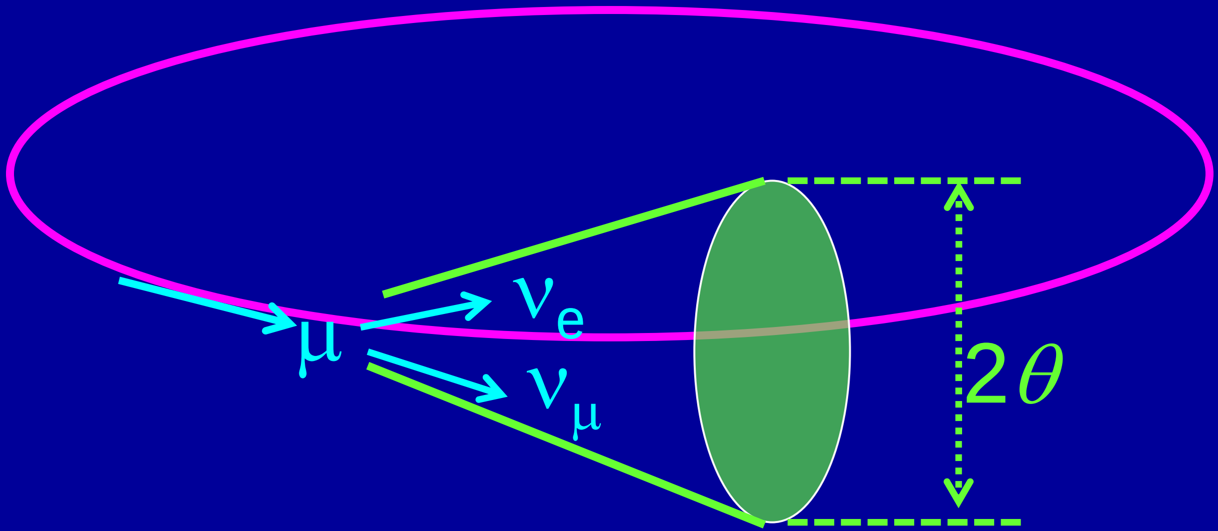
Neutrino: Special Problem

- Scientists want to use muons as a physics probe.
- Also want to make “neutrino factories”.
- Want lots of beam intensity in storage rings
- Want lots of luminosity (beam x beam/area) in collider rings
- Cannot do “single pass” because many muons are needed hence want storage rings
- Naturally, want highest energy possible!
- Muons will continuously decay to neutrinos via

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \text{ etc.}$$

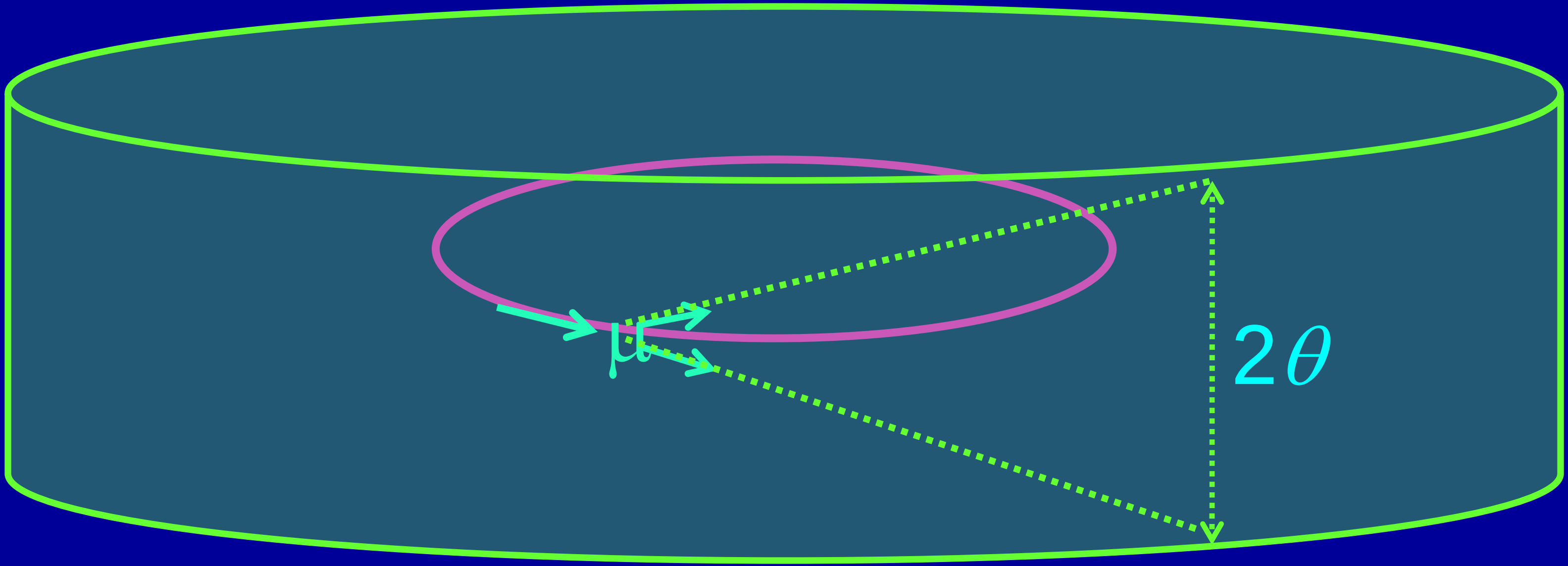
Neutrino: Special Problem

- There are always 2 neutrinos per decay.
- The decay neutrinos will sweep out like a searchlight beam in a vertically narrow disk.
- Decays confined to a cone of $\theta = m_{\mathrm{muon}}/E_{\mathrm{beam}} = 1/\gamma$ radians due to special relativity at work!



Neutrino: Special Problem

- The fact that $\theta = m_{\text{muon}}/E_{\text{beam}} = 1/\gamma$ => neutrino fluence is proportional to E_{beam}.
- Get thin donut-shaped radiation zone
- Mostly no "neutrino" radiation inside ring.

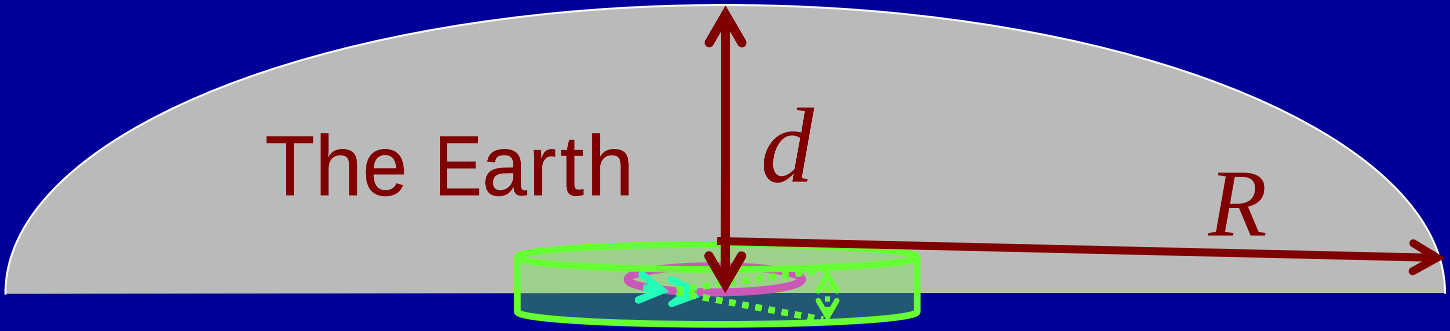


Neutrino: Special Problem

- "Ring Trouble" comes in 3's!"
  - Neutrino fluence is proportional to E_{beam} (1/γ)
  - Recall $\sigma_{\nu-\text{nucleon}} = 6.7\times10^{-39} N^2 E_\nu\,(\text{GeV})\ \text{cm}^2$

    and $P(E_\nu) = 0.16\sigma_{\nu-\text{nucleon}} E_\nu\,(\text{GeV}) N_A Q\ (\mu\text{Sv cm}^2)$
  - Get dose proportional to E_ν^3!
  - Get E_ν^4 for straight sections (two 1/γ factors), thus worse.
  - Collider: Radiation from both directions

Neutrino: Special Problem



- Only distance, not shielding helps!
- Need to bury deep so dose disk emerges from the spherical Earth sufficiently spread out.
- One early realistic design for 1 TeV on 1 TeV; $R = 23$ km to get < 100 μSv y^{-1} [Mokhov & Van Ginneken]
- Implies $d = 42$ m and height of pancake at surface at $R = 23$ km is 1.6 m.

Neutrino: Special Problem

- Fact: Realistic beams get to doses of concern.
- Discovered & understood by proponents!
- Possible remedies:
  - Collider: get desired luminosity with less muons.
  - "Costs" may drive toward lower energies
  - "Smear" beams vertically in horizontal ring
  - Aim straight sections and rings downward

Recent reference on muon colliders: S. Geer, Ann. Rev. Nucl. Part. Sci. 59 (2009) 347.

Conclusions

- Developments in nuclear and particle physics lead to new phenomena affecting AHP.
- Accelerator health physicists need to keep with them.
- Basic understanding of the physical phenomena is crucial to this.
- It’s never boring!

Thanking My Supporters!

- My nomination by the HPS Accelerator Section
- Fermilab supportive “bosses”: Lincoln Read, Larry Coulson, Ken Stanfield, Peter Garbincius, John Peoples, Bill Griffing, & Nancy Grossman
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- All Radiation Protection personnel at Fermilab.
- My family; wife Claudia; children Joe & Sally; grandchildren Jack, Laura, Charlie, Jessica, & Alexander