PHYS 575A/B/C

Autumn 2015

Radiation and Radiation Detectors

Course home page:

http://depts.washington.edu/physcert/radcert/575website/

4: Scintillator counters; interactions of particles in matter

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Course calendar

Tonight

week	date	day	topic	text
1	10/1/15	Thurs	Introduction, review of basics, radioactivity, units for radiation and dosimetry	Ch. 1, notes
2	10/6/15	Tues	Radioactive sources; decay processes;	Ch. 1, notes
3	10/13/15	Tues	Photomultiplier tubes and scintillation counters; Counting statistics	Chs. 3, 8, 9 (I-V)
3	10/15/15	Thurs	**LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules	Chs. 4, 9, 16, 17
4	10/20/15	Tues	Overview of charged particle detectors	Ch. 4
4	10/22/15	Thurs	**LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area	Chs. 17, 18
5	10/27/15	Tues	Interaction of charged particles and photons with matter	Ch. 2
6	11/3/15	Tues	Other photodetectors; gas and solid-state detectors	Chs. 5, 6, 7 Chs. 11, 12, 13
7	11/10/15	Tues	Detecting neutral particles; Data acquisition methods	Ch. 14, 15, 18
8	11/17/15	Tues	Cherenkov detectors; Case studies: neutrino detectors (Super-K)	Ch. 19, Notes
9	11/24/15	Tues	Case studies: classic detectors (cloud and bubble chambers, nuclear emulsion), high energy accelerators	Ch. 19
10	12/1/15	Tues	Case studies: contemporary leading-edge detectors (ATLAS, Auger)	Notes
11	12/8/15	Tues	Student presentations	-
11	12/10/15	Thurs	Student presentations	

LAB session **this Thursday**

- Meet in room B-248, not here
- 6:30 to 9pm
- BEFORE class, read handouts posted on website:

"Documents for lab sessions (writeups and handouts)"
http://depts.washington.edu/physcert/radcert/575website/lab_documents/Lab_2/

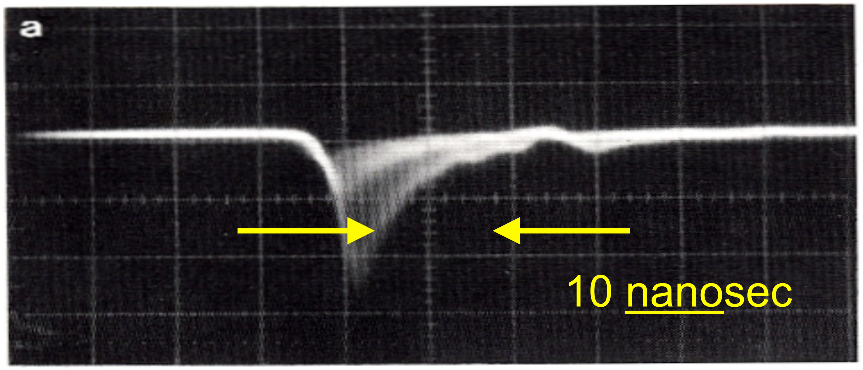
1. Procedures for Lab 2: Energy Measurement Using PMTs and PHAs
2. Labview pulse height analyzer software documentation

- Tonight:

1. How scintillators work
2. "Interactions of charged particles with matter" (energy loss processes in detectors and shielding)

Last time

Oscilloscope Traces from Scintillation Counters



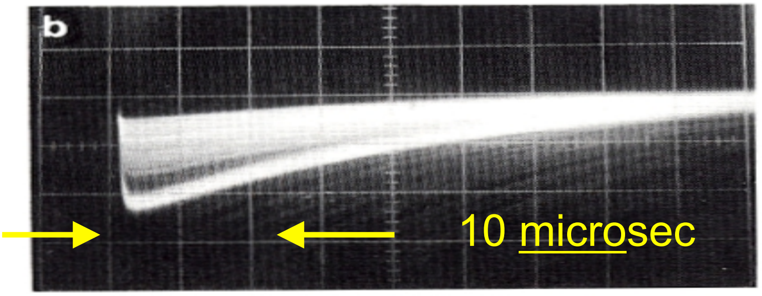
10 nanosec

Plastic scintillator

Plastic

Vert. scale : 0.2 V/cm
Hor. scale : 10 ns/cm
Source : ^{207}Bi 10μCi

10 nsec / division



10 microsec

Inorganic crystal, NaI

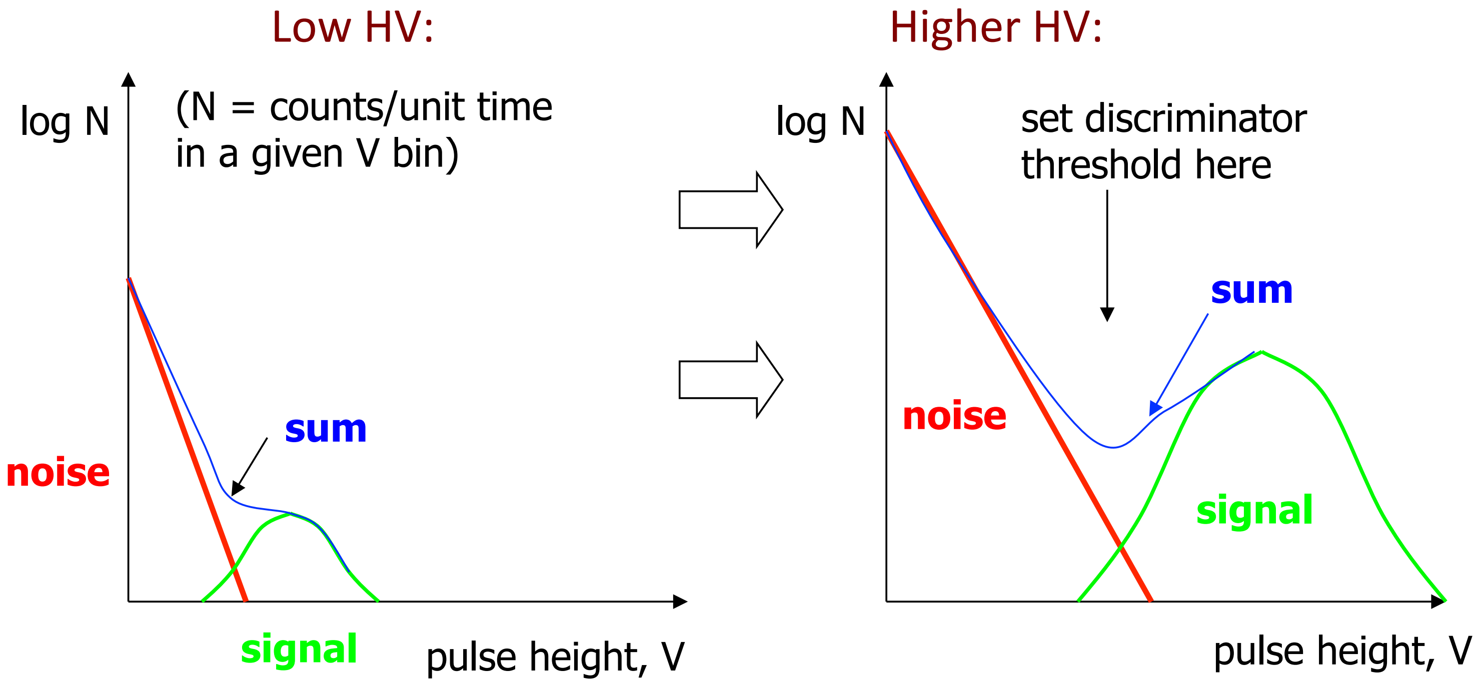
NaI

Vert. scale : 0.2 V/cm
Hor. scale : 5μs/cm
Source : ^{137}Cs 10μCi

5000 nsec / division
(Longer time scale for
fluorescence to occur)

Pulse height spectrum = histogram of pulse sizes

- Low amplitude pulses = (exponential) noise spectrum from PMT
  - Slope varies with temperature, photocathode material, tube gain
- Signal peak is at higher amplitude (pulse "height" = *area*)
- Whole pattern expands as V_{HV} is increased
- Goal: set discriminator threshold at "notch" between noise and signal.



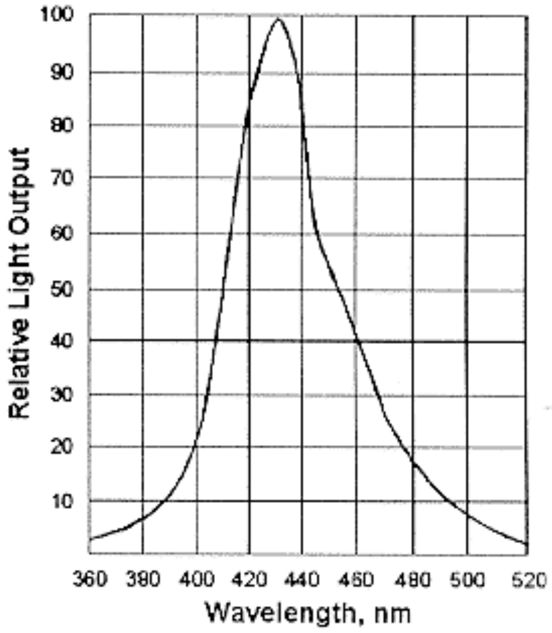
Device to make these plots: Pulse Height Analyzer (PHA)

Charged particle detectors: (1) scintillation counters

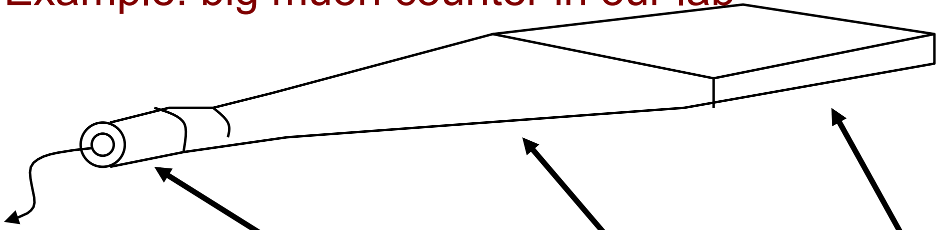
- Scintillators - features
  - Fast light pulses (nsec),
  - high yield (~10K photons per MeV of particle energy deposited),
  - emission at UV~blue wavelengths (400~450 nm)
    - Plastic scintillator = transparent styrene doped with fluorescent material
    - NaI = natural crystal with fluorescent behavior

Used in the form of strips, slabs, or fibers, with photons propagated by total internal reflection

Typical photon spectrum
(Bicron Type 408)
see http://www.bicron.com/



Example: big muon counter in our lab



To analog electronics

Photomultiplier Tube (PMT)

Acrylic Light Pipe

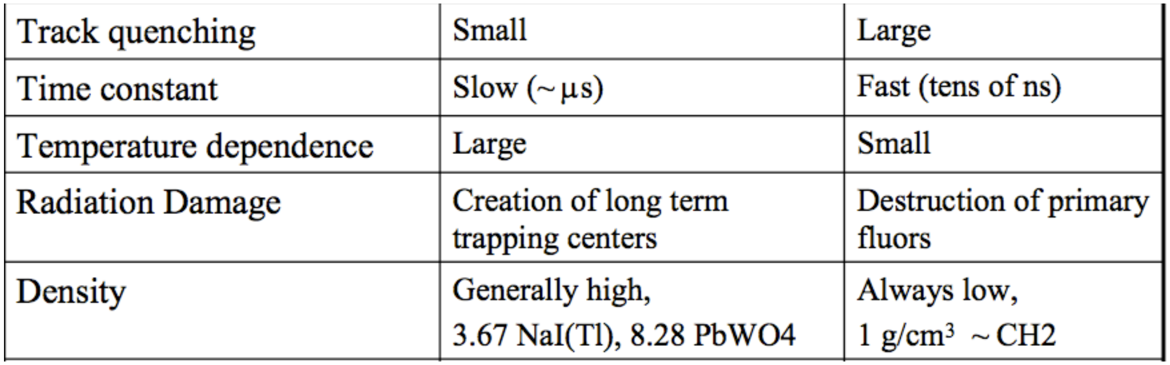
Plastic Scintillator

Scintillator examples

- Applications in Nuclear and Particle Physics experiments
  - Telescope or trigger
    - Defines trajectory of charged particles
    - Defines time when particle passed through scintillator and therefore can be used to start a clock for other detector elements
  - Total Energy Measurements
    - Particle stops in scintillator and deposits all of its energy
    - Use in sampling calorimeters where absorber is placed between scintillator planes, and charged particles created in the absorber deposit energy in the scintillator.
- Basic scintillation counter detector
  - Scintillating substance that emits light (solid, liquid, gas..)
    - Must be transparent to scintillation photons, and relatively inexpensive
    - Inorganic (crystals like NaI) or organic (plastic or mineral oil, with fluor)
  - Sensitive light detector
    - Photomultiplier (PM) tubes widely used
    - Silicon photodiodes (“solid state PMTs”)

Scintillators: how they work

- Radiation interacts with atoms/molecules by ionization
  - leaves ionization trail that excites fluor atoms
- Light is emitted when atoms relax to ground states
- Light is collected and led to a photosensor
  - Photomultiplier tube
  - “solid state PMT” (SSPMT) = photodiode array with 1-photon sensitivity
- Scintillator counter can be used to measure energy loss
  - Energy loss by particle → light produced - almost linear response
- Fast response time – can be picosec, depending on material



Property	Inorganic (crystal)	Organic (doped plastic)
Track quenching	Small	Large
Time constant	Slow (~ μs)	Fast (tens of ns)
Temperature dependence	Large	Small
Radiation Damage	Creation of long term trapping centers	Destruction of primary fluors
Density	Generally high, 3.67 NaI(Tl), 8.28 PbWO4	Always low, 1 g/cm^3 ~ CH2

Scintillator materials

- Luminescence – absorbs energy and emits light in the visible spectrum
  - *Fluorescence* when emission occurs within 10^{-8} s or so
  - Metastable states delay light emission leading to *phosphorescence* (light emission persists for 10^{-4} s or more)
- Light emission often has two time constants, fast and slow
  - The number of photons can be described by sum of exponentials: $N = N_0(e^{-t/\tau 1} + e^{-t/\tau 2})$ where τ_1 and τ_2 are the fast and slow components
    - Example: in BaF, γ rays excite the fast component, while α particles excite the slow component: can identify them from the PMT signal.
- Organic Scintillator
  - Hydrocarbon compounds - nanosecond decay times
  - Organic crystals such as naphthalene ($C_{10}H_8$) in a liquid organic solvent or a solid plastic solvent
  - Styrene with POPOP = 1, 4-bis(5-phenyloxazole-2-yl)benzene

Desired attributes

- High efficiency to convert ionization energy to fluorescence
- Long attenuation length for emitted light
- Emitted light well matched to spectral response of photosensor, usually a PMT
- Fast decay time needed, when timing data is desired

- Average energy required per photon produced
  - NaI(Tl) – 25 eV/photon
  - Anthracene ($C_{14}H_{10}$) – 60 eV/photon
  - Plastic + POPOP – 100 eV/photon
  - BGO ($Be_4Ge_3O_{12}$) – 300 eV/photon

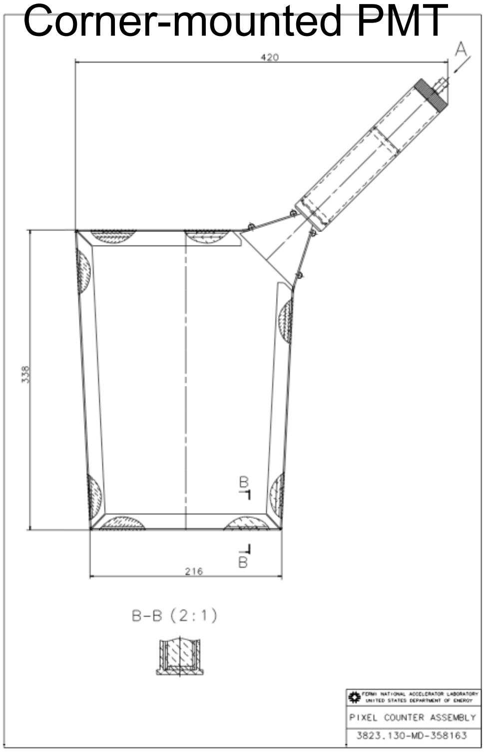
Plastic scintillator is most common

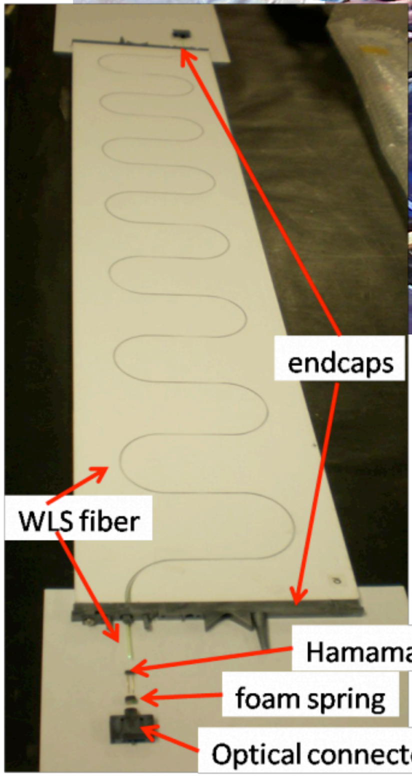
- Easy to work with
  - Can be cut to any shape
  - Can be bent into curves using solvents
  - Material not expensive
  - Can form by extrusion
  - Can machine plastic to achieve desired shape
- Fast signal (short decay time)
- Plastic light guides are easy to shape and attach by gluing with a plastic solvent; match optical properties
- Wave-length shifter can be added to plastic to shift the spectrum to longer wavelengths for more efficient response from silicon photosensors

Different ways to get light out of a scintillator

Gluing PMTs onto scintillator faces

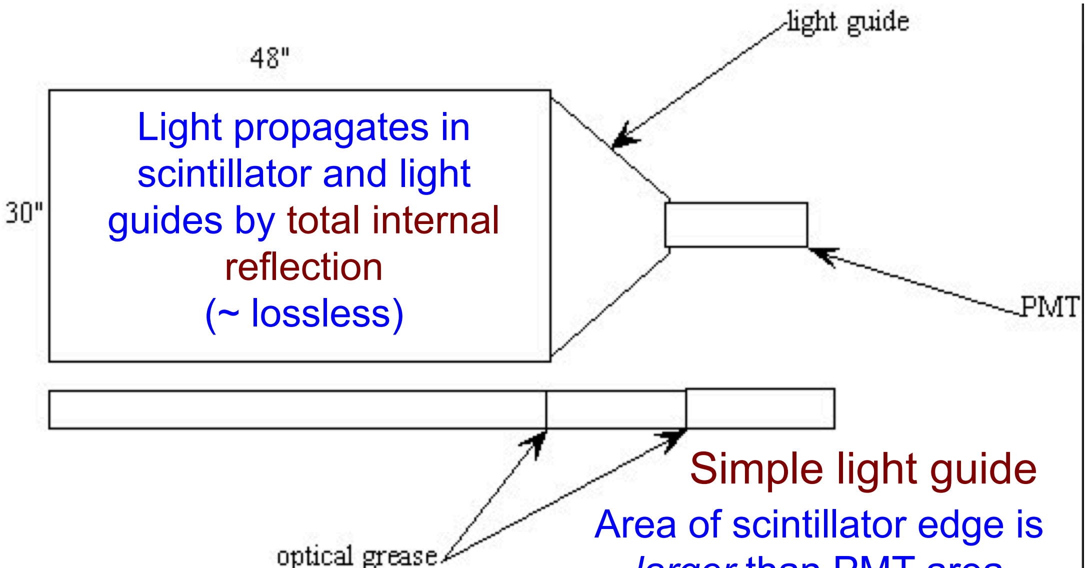
Corner-mounted PMT





Scintillator with Wavelength Shifting (WLS) optical fiber to collect and transport light to a photodiode

Lightproofing counters



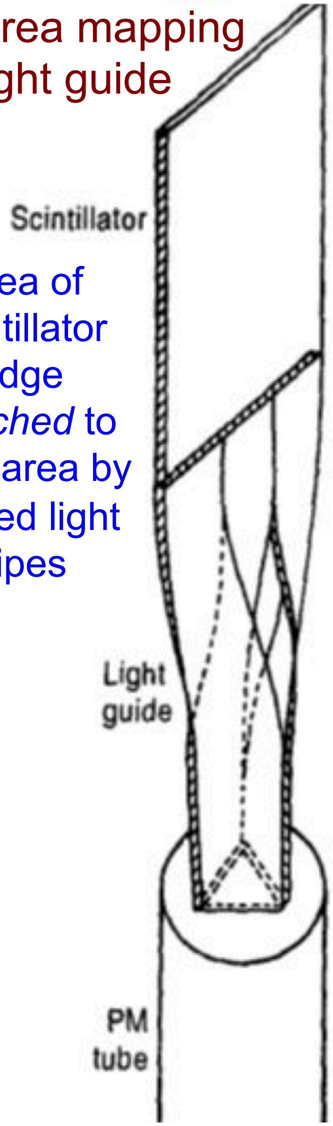
Light propagates in scintillator and light guides by total internal reflection
(~ lossless)

(index of refraction matches plastic)

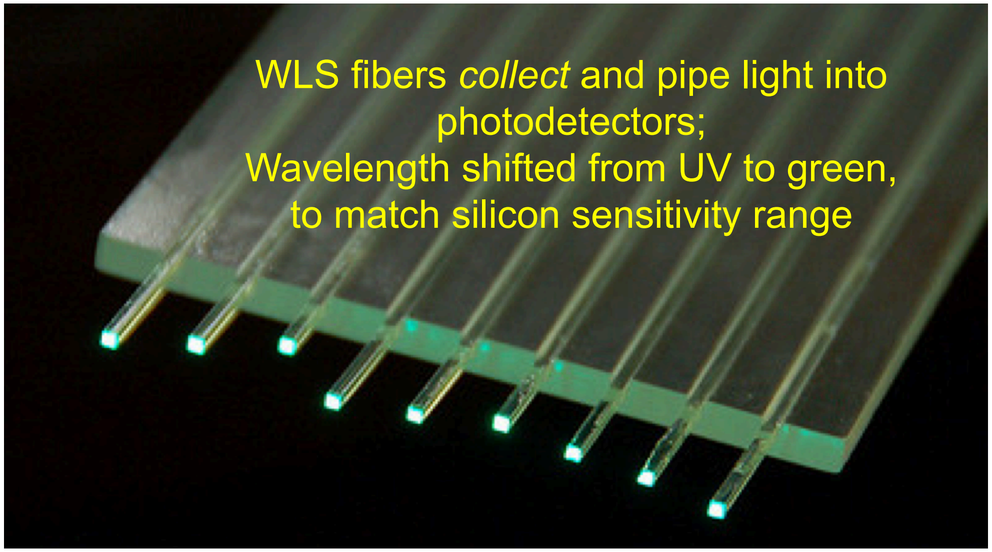
Simple light guide

Area of scintillator edge is *larger* than PMT area

Area mapping light guide



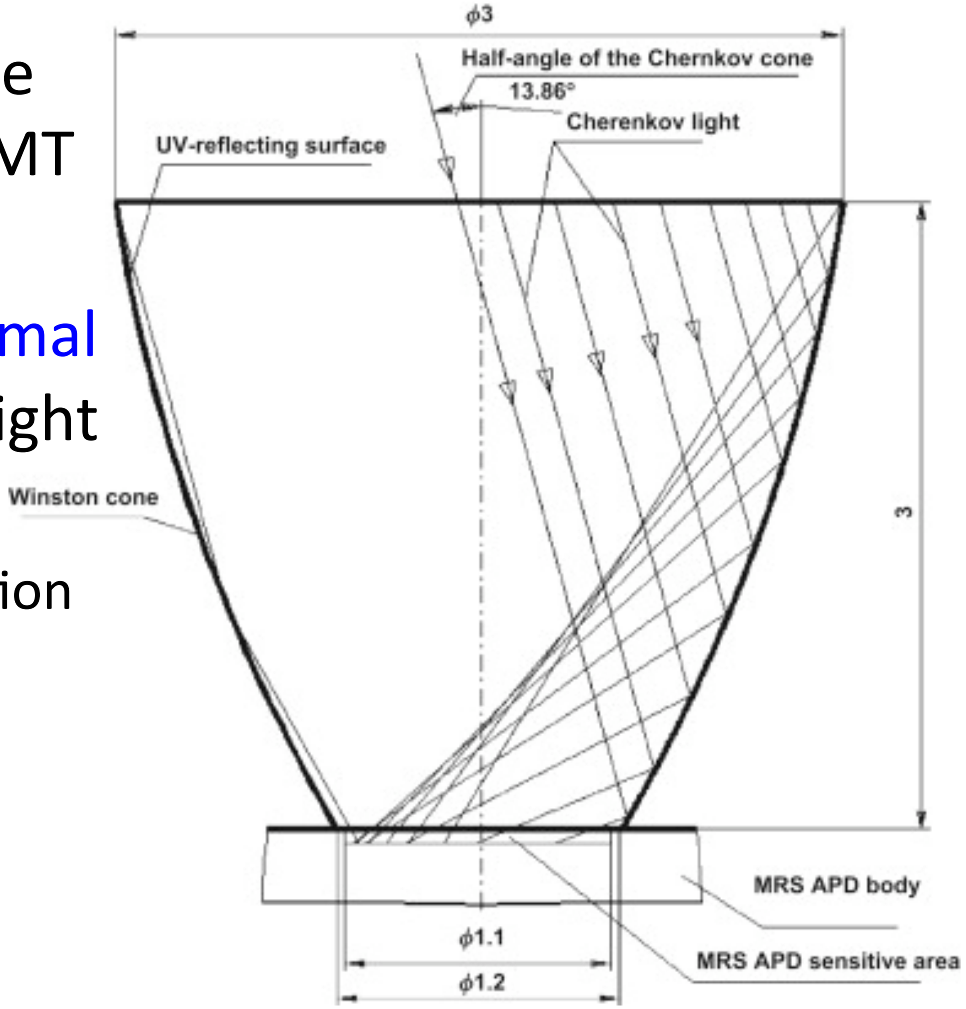
Area of scintillator edge *matched* to PMT area by curved light pipes



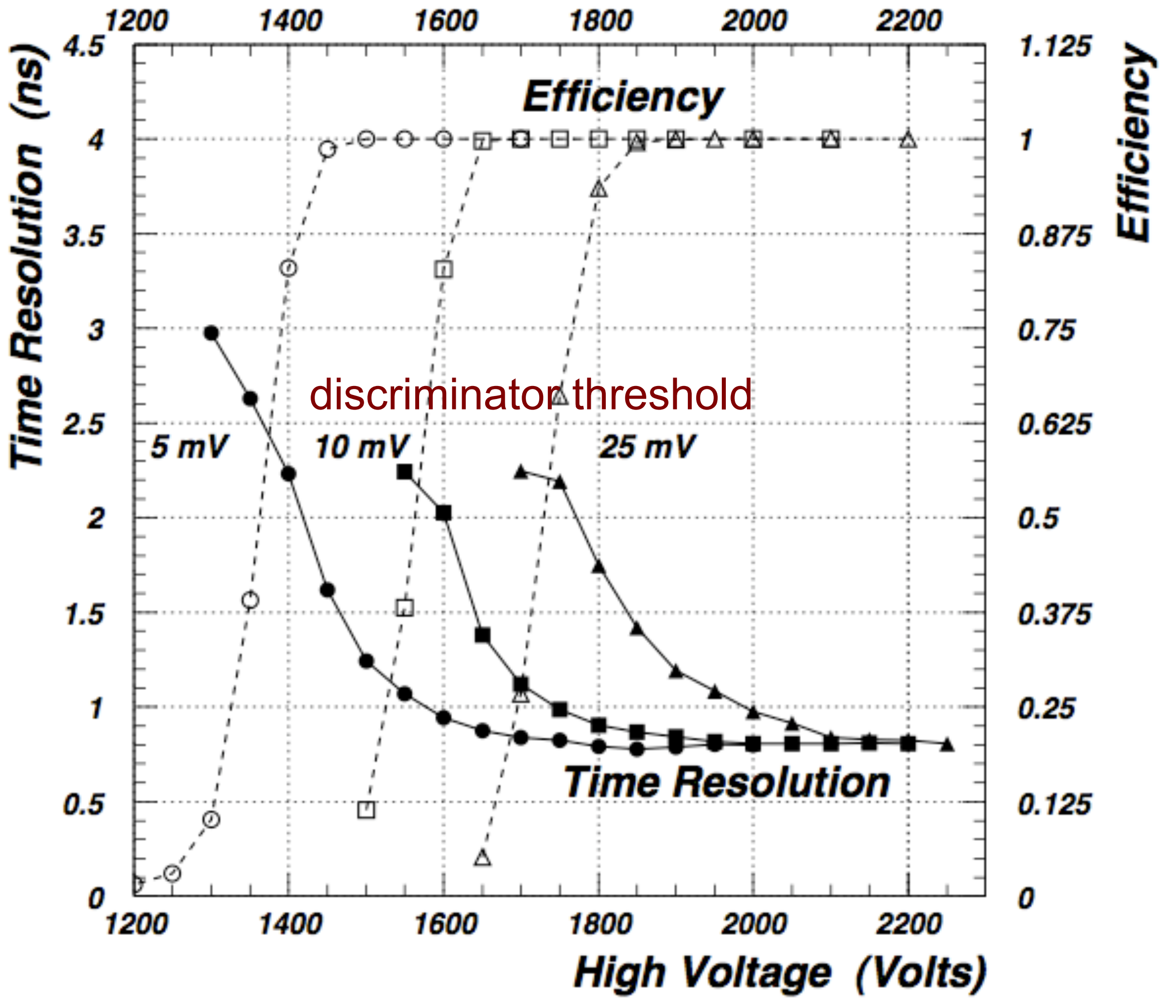
WLS fibers *collect* and pipe light into photodetectors;
Wavelength shifted from UV to green, to match silicon sensitivity range

Winston Cones

- Often scintillator edge area is bigger than PMT window area
- Winston Cone = Optimal shape for gathering light into a smaller area
  - Paraboloid of revolution



Example of decisions to be made setting up counters:
Efficiency (fraction of tracks through counter that actually get counted)
and time resolution vs HV and discriminator threshold voltage



Particle interactions in matter

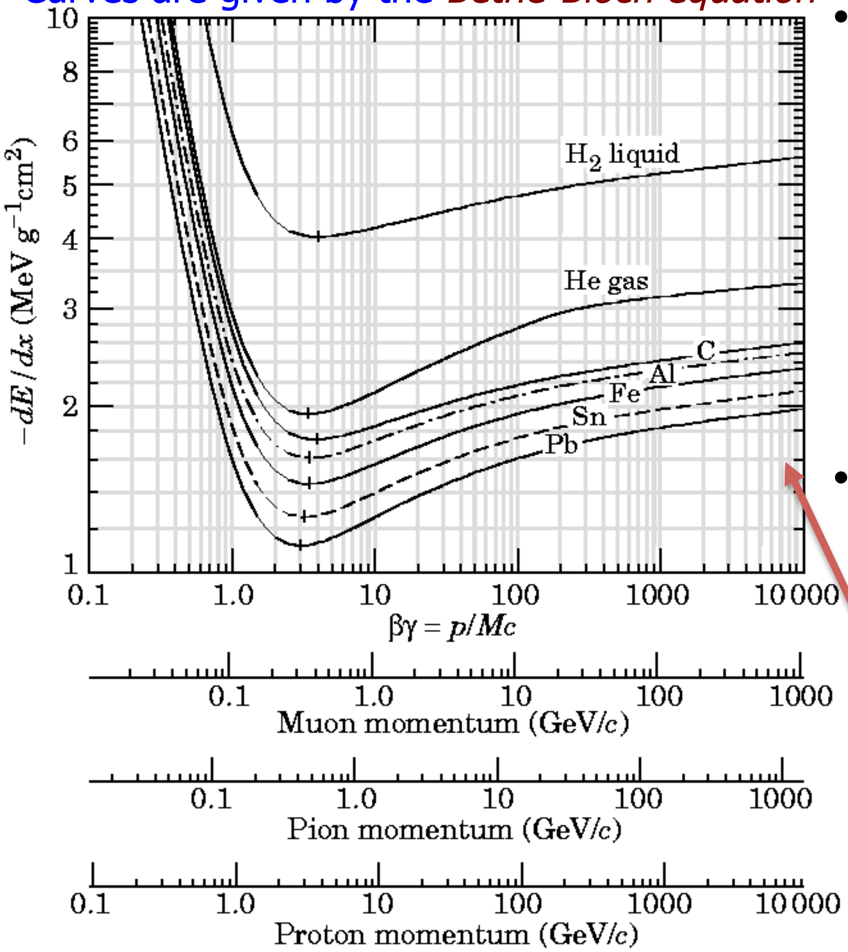
- Electromagnetic interactions
  - Ionization
  - Fluorescence
  - Photoelectric effect
  - Rayleigh and Raman scattering
  - Compton effect
  - Bremsstrahlung
  - Pair production

- Weak interactions
  - Radioactive decay
  - Neutrino interactions

- Strong interactions
  - Elastic scattering
  - Inelastic scattering
  - Fragmentation
  - Multiparticle production

Electromagnetic interactions of particles in matter

Curves are given by the *Bethe-Bloch equation**



- Ionization
  - Charged particle leaves ionization trail via inelastic Coulomb interactions with atomic electrons
  - Basis for most particle detectors (scintillators, gas detectors, solid state, bubble and cloud chambers, nuclear emulsion, etc)
- Ionization energy loss (dE/dx) or *stopping power*
  - Minimum-ionizing particles (γ =E/m >> 1)

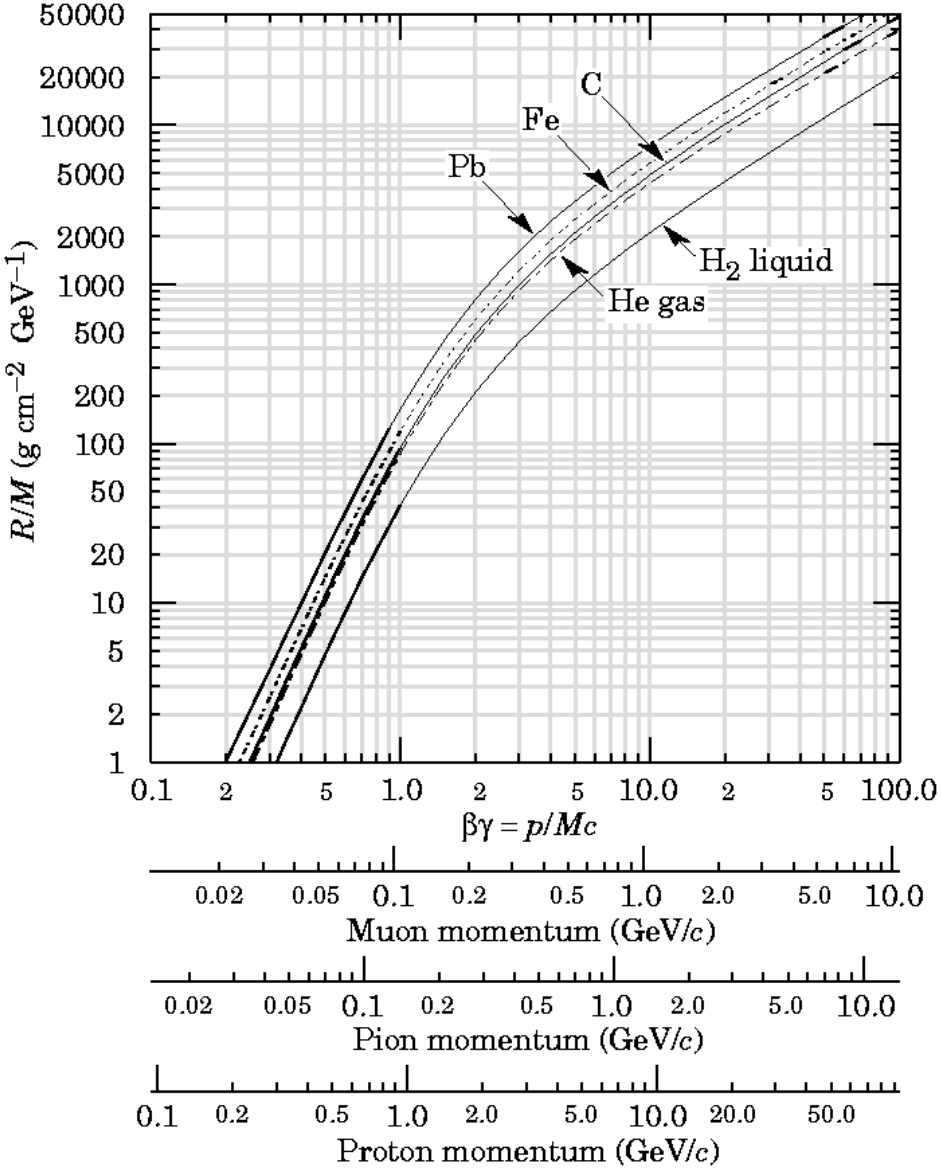
Rule of thumb:
dE/dx~ 2 MeV/(g/cm^2)
for "minimum-ionizing" particles
(actually: relativistic plateau)

*

$$\boxed{-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]}$$

See http://pdg.lbl.gov/ for a wide variety of reviews and data tables

Electromagnetic interactions of particles in matter



- Range: depth (in g/cm^2) that a particle penetrates
  - Integrate dE/dx to get range (neglecting nuclear interactions)
  - Straggling: random fluctuations in range - few % for mass > electron

Deflection processes

- Multiple scattering = Coulomb scattering off nuclei

$\theta_{plane} = (1/\sqrt{2})\theta_{space} = Z(13.6\ \mathrm{MeV}/\beta cp)\ \sqrt{x/X_0}\ \{1+0.038\ \ln(x/X_0)\}$

x/X_0 = thickness of material in radiation lengths (described later...)

Z=charge of particle, p=momentum, MeV/c

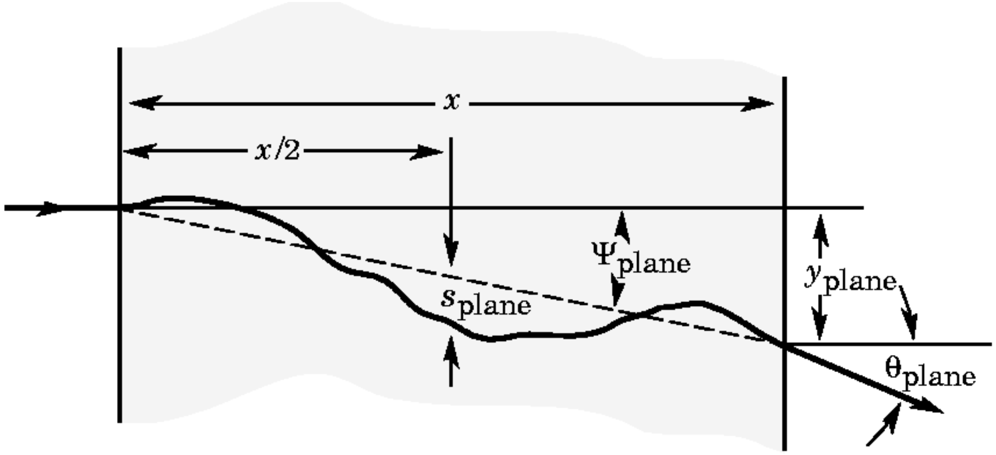
- Magnetic deflection:

Radius of curvature is

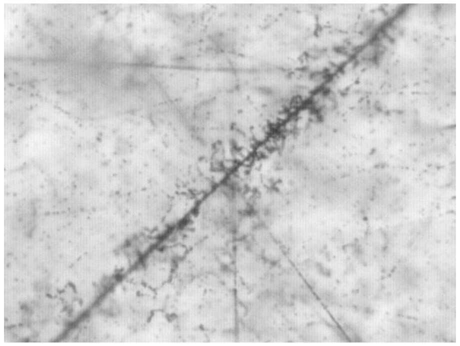
$$R(cm) = p(MeV)\frac{0.333}{Z \cdot B(tesla)}$$

Note that R is proportional to p/Z, which is called the *rigidity*

(rigidity units = MV, GV, etc).



- Delta Rays
  - Energetic knock-on electrons from ionization events
  - Tracks in detectors are mostly due to δ-rays
  - Can fake incoming particle tracks

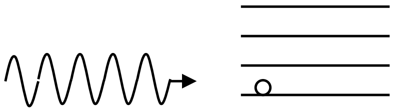


Track image from nuclear emulsion plate exposed to cosmic rays by balloon flight in Antarctica (Wilkes, 1990) showing heavy ion track with delta rays (lighter tracks are minimum-ionizing protons)

Overview of photon-electron processes

- Initial state for all processes:

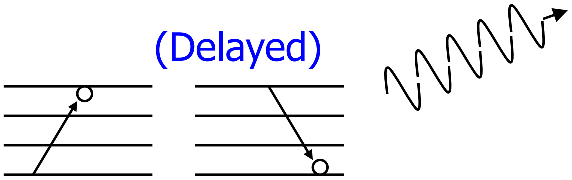
photon + atomic electron



- Final states:

Fluorescence:

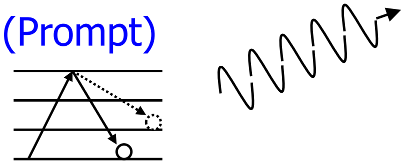
(Delayed)



excitation relaxation

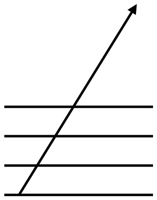
(Prompt)

Rayleigh (elastic) or Raman (inelastic) scattering:

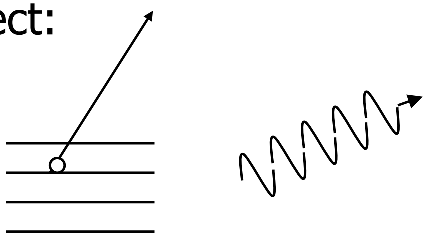


(electron does not escape)

Photoelectric effect:



Compton effect:



(free electrons produced)

What happens to gamma rays in matter

… depends on absorber material and its geometry

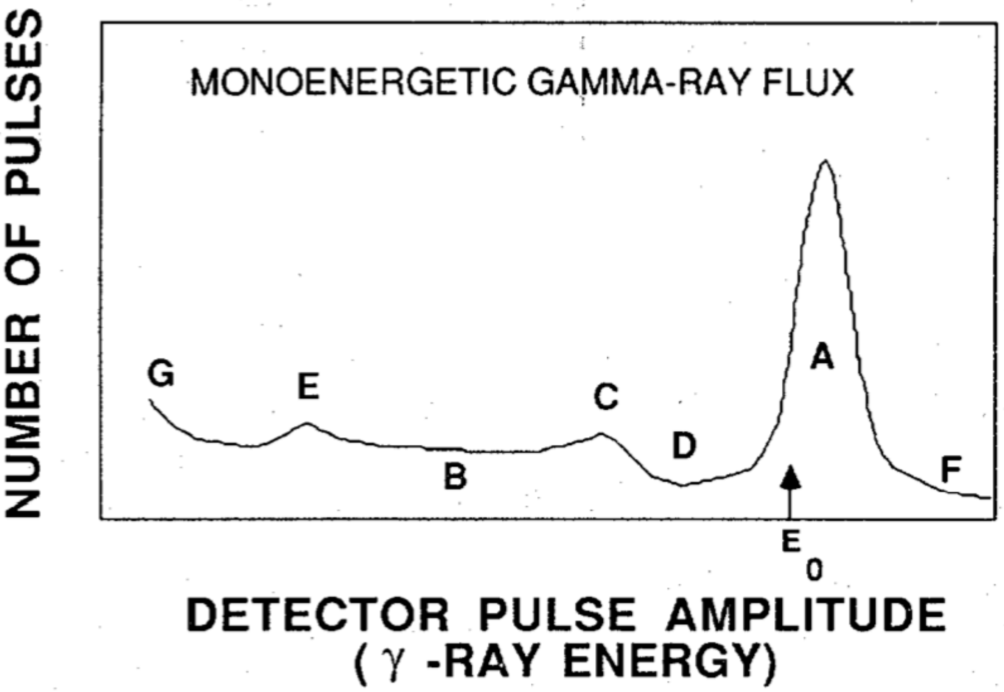
- Photoelectric absorption - atom absorbs gamma, e is ejected
  - – Dominant for low E gammas (<< 1 MeV), or high Z absorber
  - – Products can be
    - Electron with all the gamma's energy
    - In high-Z material: K shell electron ejected (10s of keV: L and M shells are usually too low-E to notice) – followed by atom's relaxation and another photon (fluorescence x-rays)
      - – Auger electron: atom relaxes by emitting an electron instead of a fluorescence photon (much lower probability)
- Compton electron – gamma scatters *inelastically*
  - – Process dominates in mid-range (~MeV) gamma energies
    - Atomic electron is kicked out with low kinetic energy – Compton electron
- Pair production – gamma disappears, becomes $e^+ e^-$ pair
  - – High energy gammas (>> 1 MeV) – in high-Z material
- Coherent scattering
  - – elastic scattering, gamma just changes direction: Rayleigh scattering

Detectors for gamma rays

- Sodium Iodide NaI(Tl) is widely used for gamma ray spectroscopy
  - About 25eV/photon at the PMT = about four times more photons than we get from a plastic scintillator
  - But: Hydroscopic, must remain sealed! Easily ruined...
  - Light decay time is slow, about 230 ns
    - Not very good for fast timing applications
  - Has also some very long lived phosphorescence states
    - Mean decay time of 0.15 s
    - Amounts to about 9% of light yield
    - Can present problems in high counting rate applications
- Other Alkali Halide Scintillators
  - CsI(Tl) and CsI(Na) are often used in space applications because gamma-ray absorption coefficient per unit size is larger than NaI(Tl)

What you see in the pulse height spectrum from a monoenergetic source

From: H. Smith and M. Lucas,
Gamma ray detectors



A. Full-energy photopeak
B. Compton continuum
C. Compton edge
D. Compton "valley"
E. Backscatter peak

F. Excess-energy region
Background gammas

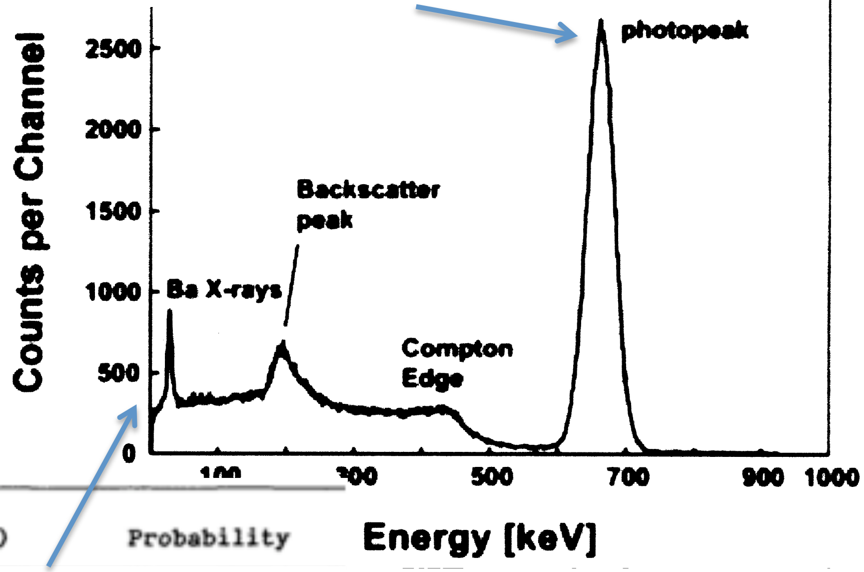
G. Low-energy rise
Noise in detector

Example of photon interactions

- The light output of a scintillator such as NaI from gamma-rays emitted from a low energy source (less than a few MeV) will in general be a spectrum resulting from energy deposited by
  - Photoelectrons
  - Compton electrons
  - K-capture x-rays

Typical pulse height spectrum of radiation emitted by a ^{137}Cs source detected in NaI(Tl)

Nuclide	Energy (keV)	Emission Probability
55-Cs-137	661.660(3)	0.851(2)



Nuclide	Trans	Energy (keV)	Probability
55-Cs-137	BaKα	31.82-32.19	0.0566(16)
55-Cs-137	BaKβ	36.36-37.45	0.0134(5)
55-Cs-137	BaKx	31.82-37.45	0.0700(20)

Understanding the observed pulse spectrum

- Energy spectrum of tracks detected in NaI from Cs-137
  - Betas are stopped by wrappings and not detected – only gammas
    - **But** gammas are not detected directly – only when they create electrons!
  - Features in the spectrum
    - Sharp lines ~30 keV from de-excitation of daughter Ba nucleus via energy transfer from nucleus to inner-shell (K) atomic electrons
    - "Photopeak" at 662 keV = full energy of gamma ray going to knocked out electron
    - Compton effect: nearly flat spectrum from zero up to "Compton Edge"=(622 keV - max energy loss for gamma = 181 keV for 180deg scatter) = 481keV
    - Backscatter peak = gammas that Compton-scattered **outside** the counter and tend to have E ~181 keV (=180 deg scatter)

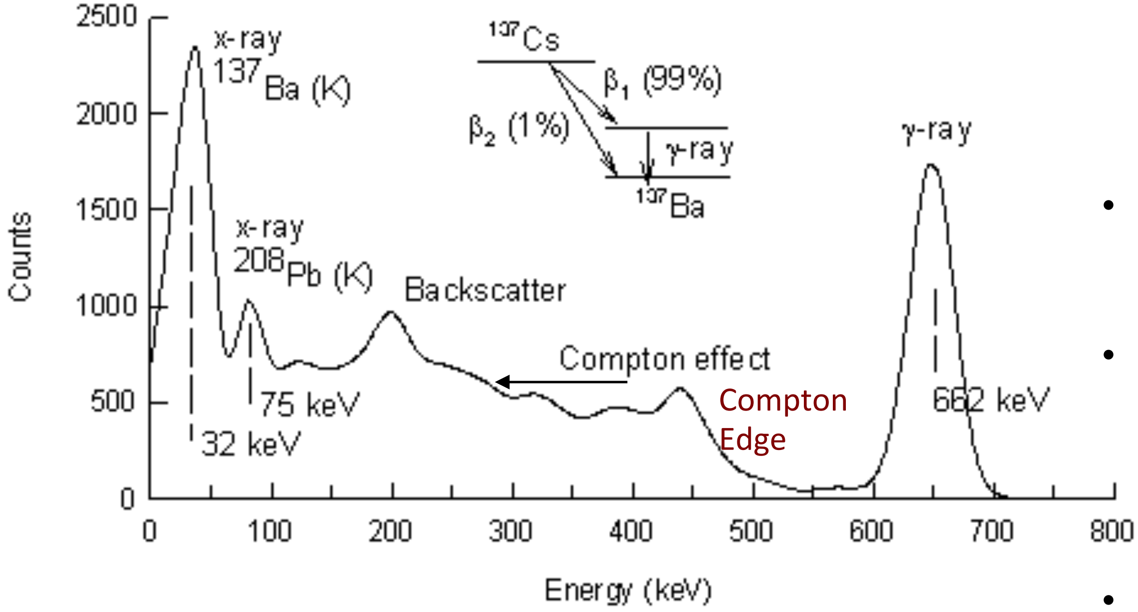
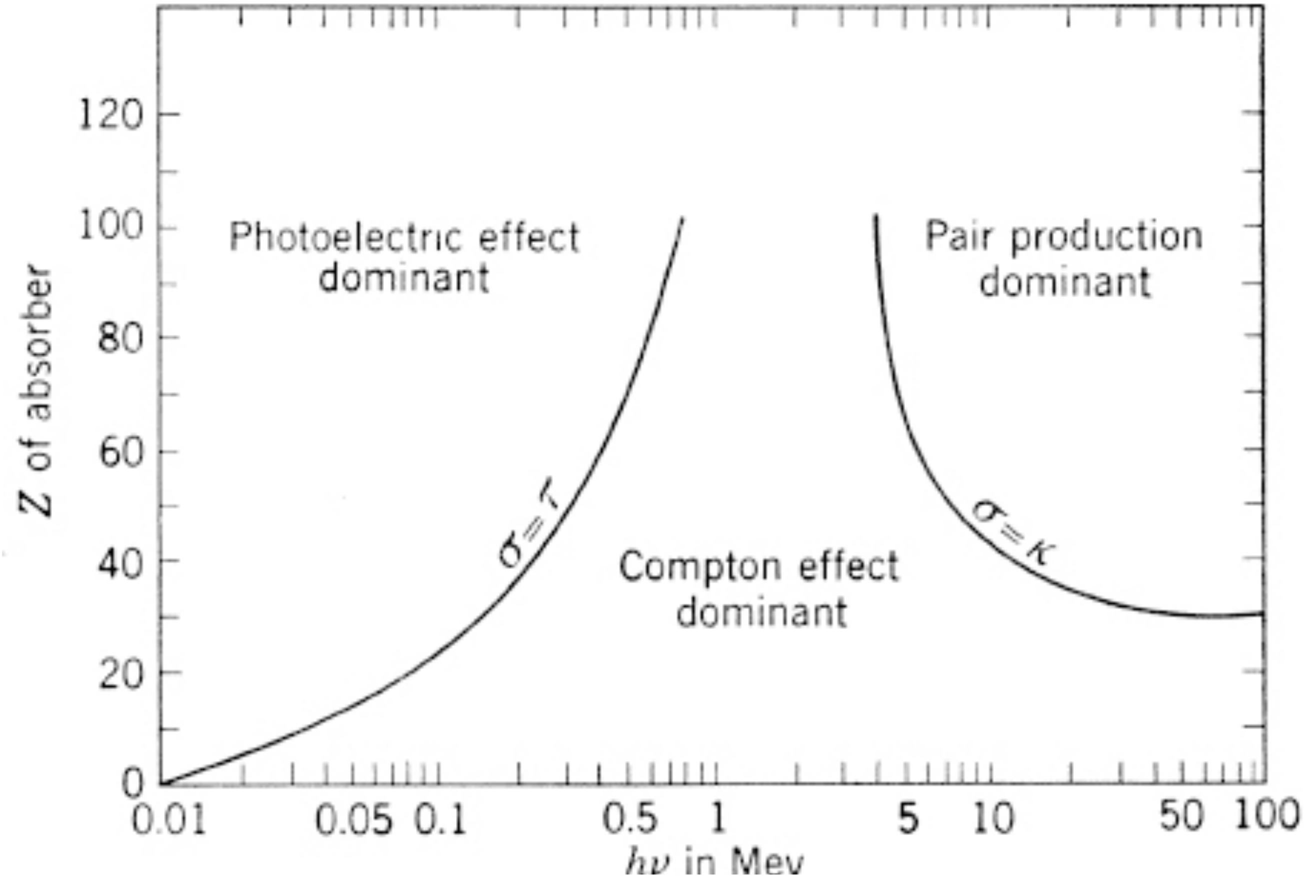


Figure 10.4 - Sample emission spectrum from ^{137}Cs.

From phys.fsu.edu

Energy and Z ranges for main processes



Tau ~ $Z^4 / E^{3.5}$

Kappa ~ Z^2

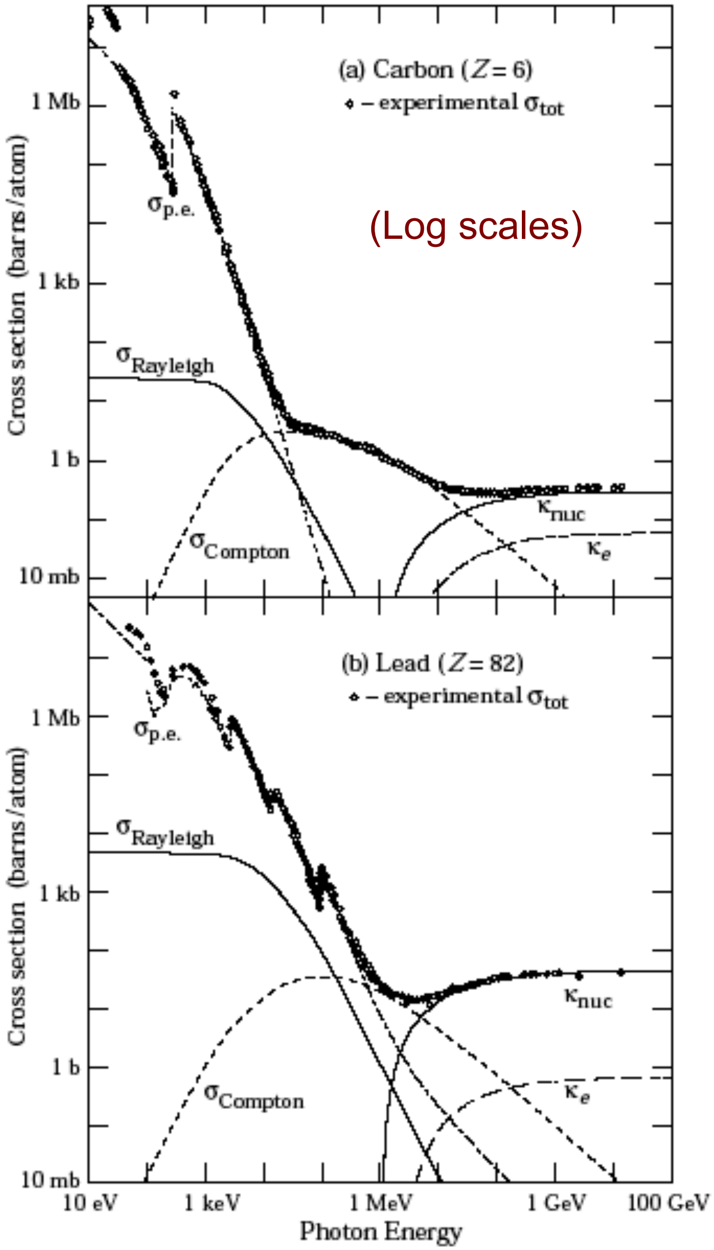
Photon interactions in low and high Z

- For heavy nuclei, bremsstrahlung and pair production dominate earlier than for light nuclei

- low energies (< 100 keV): Photoelectric effect

- medium energies (~1 MeV): Compton scattering

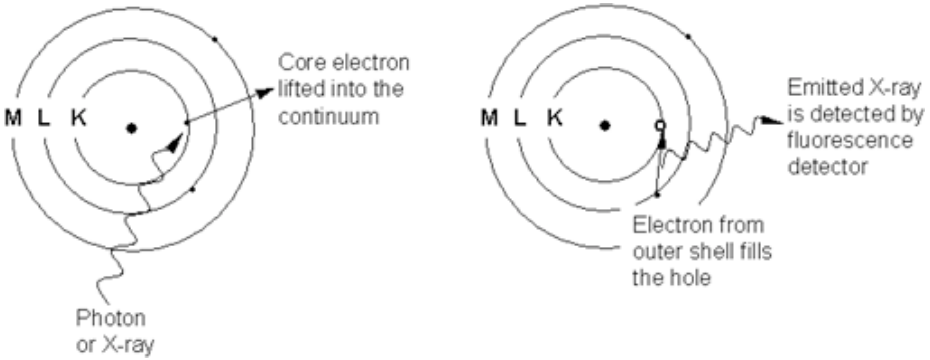
- high energies (> 10 MeV): e^+e^- pair production



(Log scales)

Photoelectric absorption

- Dominant interaction mechanism for gamma rays < few MeV
- Gamma interacts with atom, and a *photoelectron* is ejected from one of the atom's *inner* (K, L) electron shells
  - Ejected photoelectron energy $E_e = E_{gamma} - E_b$, where E_b = binding energy of electron in its atomic state before interaction
  - Atom captures a free electron and/or rearranges its electrons shells
    - Typically one or more x-rays are emitted in this process
- The photoelectron carries essentially the entire energy of the gamma ray
  - Measurement of photoelectron's energy provides a good estimate of the original gamma ray's energy
  - If gammas come from a radioactive source, we may see a sharp "photopeak" in light output of scintillator detectors
    - Provides an estimate of Q = nuclear energy released in gamma decay



Compton scattering

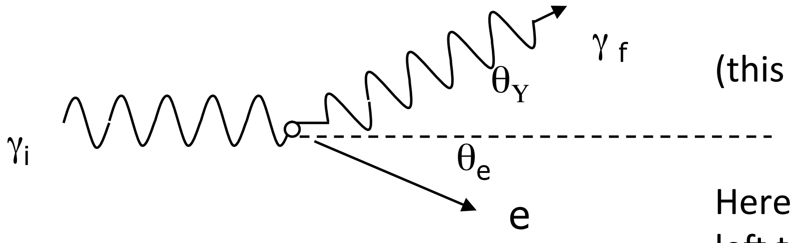
= Elastic collision of a gamma ray with an electron in absorbing material

- The incoming gamma is scattered through an angle θ with respect to its original direction
- A fraction of the photon's energy is transferred to the electron
  - recoils with energy ranging from 0 to a large fraction of the initial gamma ray energy
- From conservation of energy and momentum we obtain
  $h\nu = h\nu' + h^2\nu^2 (1 - \cos\theta)/m_0c^2]$ and

  $$\Delta\nu = \nu' - \nu = - \frac{2h\nu^2}{m_0c^2}\sin^2\frac{\theta}{2}$$

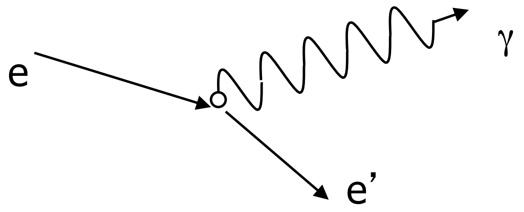
  where $h\nu$ ($h\nu'$) = energy of the incident (scattered) gamma ray and m_0c^2 is the rest-mass energy of the electron
- This gives the maximum energy that can be transferred to the scattered electron - the scattered gamma ray never has 0 energy
  - Therefore the observed energy in, say, a Na-I scintillating detector will have a distribution with a cutoff – the Compton edge

Compton effect: inelastic photon-electron scattering

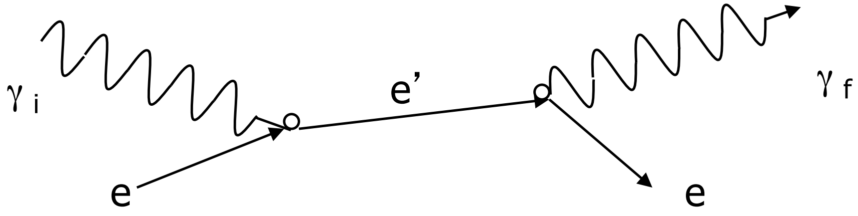


(this is just a sketch diagram of the process)

Here is a Feynman space-time diagram. Time goes left to right, space up and down. Any photon-e interaction must be composed of vertices like this:



Not just a sketch: Feynman’s Quantum Electrodynamics (QED, 1948) associates parts of these diagrams with a mathematical factors in the cross section calculation for any EM process.



But if all 3 particles above are free particles, it is impossible to conserve energy-momentum.

Actual Compton process must go via a “virtual electron” (temporary violation of conservation of p+E, cancelled at 2nd vertex)

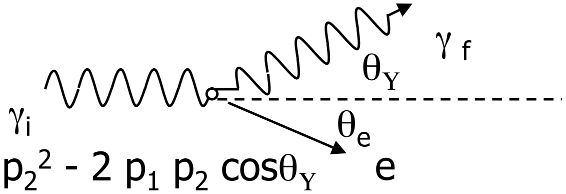
QED’s “Feynman rules” associate a factor $\alpha = e^2/(4\pi\varepsilon_0\hbar c)$ (=1/137, dimensionless) with each vertex in the diagram, so the total cross section for Compton scattering should be on the order of α^2

Compton kinematics

- Compton' s semi-classical result (1923):
  - Used Planck' s quantum hypothesis ($E=h\nu$) + classical mechanics ($p=E/c$ for radiation, conservation of energy and momentum)

    $p_1 = E_1/c = h\nu_1/c = h/\lambda_1$, $p_2 = h/\lambda_2$

    $E_1 >> $ binding energy, so e is effectively free



  - Conservation of $\underline{p}$: $\underline{p}_e = \underline{p}_1 - \underline{p}_2$,   so $p_e^2 = p_1^2 + p_2^2 - 2\, p_1\, p_2 \cos\theta_Y$
  - Conservation of E : $p_1c + mc^2 = p_2c + (mc^2 + p_e^2c^2)^{1/2}$ (m=electron mass)

    $((p_1 - p_2)c + mc^2)^2 = (mc^2 + p_e^2c^2)$

    $p_e^2 = p_1^2 + p_2^2 - 2\, p_1\, p_2 + 2mc^2(p_1 - p_2)/c$
  - Equate RHS of these equations:

  $p_1^2 + p_2^2 - 2\, p_1\, p_2 \cos\theta_Y = p_1^2 + p_2^2 - 2\, p_1\, p_2 + 2mc^2(p_1 - p_2)/c$

  $p_1\, p_2\, (1 - \cos\theta_Y) = mc^2(p_1 - p_2)/c$

  multiply by $hc/(p_1\, p_2\, mc^2)$: $(1 - \cos\theta_Y)hc/mc^2 = h/p_2 - h/p_1 = \lambda_2 - \lambda_1$

  hc/mc^2 has dimensions of length: $= \lambda_C$, the *Compton wavelength of the electron*

    $\lambda_C = 0.02$ A (angstrom $A=10^{-10}$ m, typical atomic diameter)

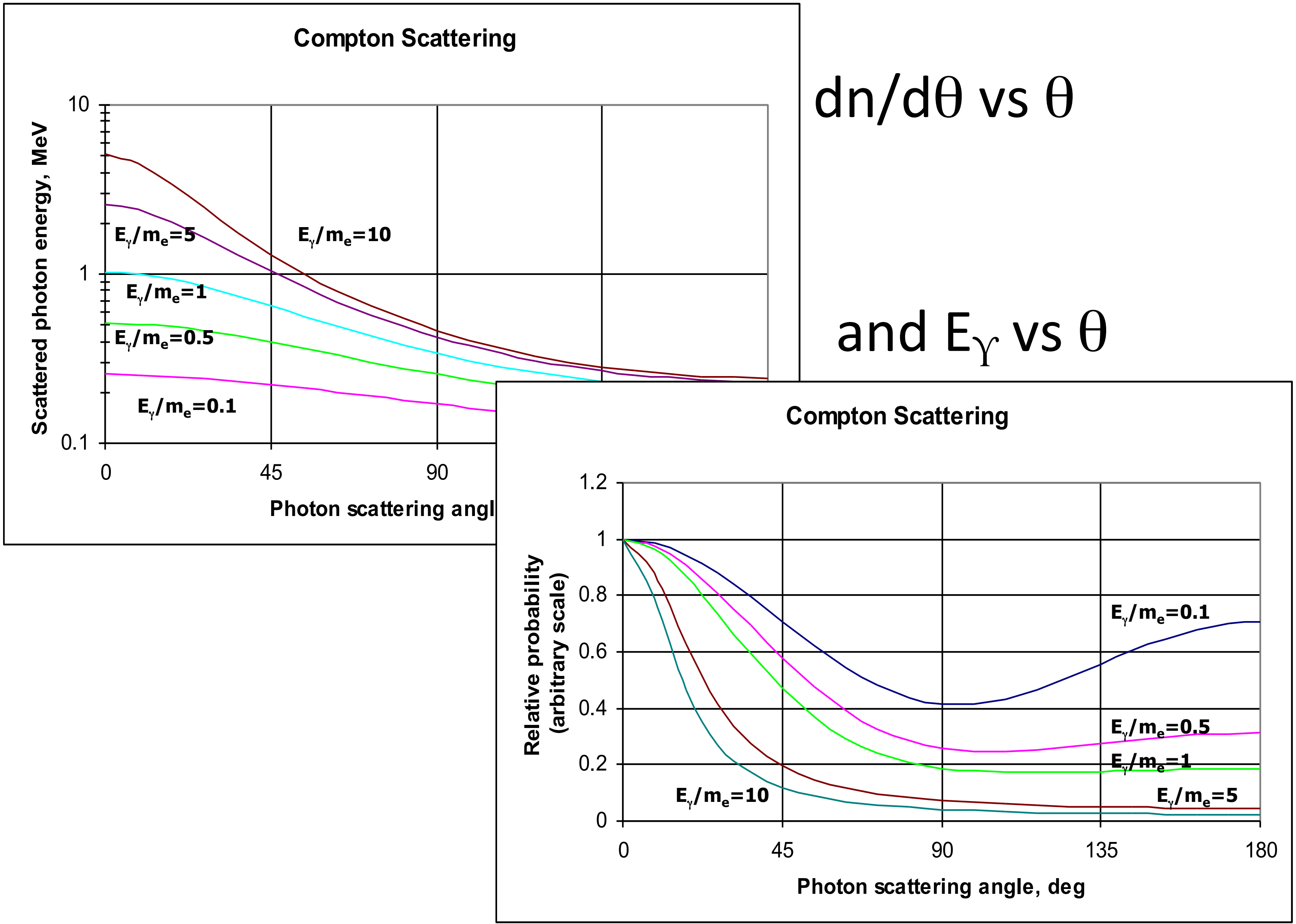
- Result: change in wavelength (energy loss) of Compton scattered photon is given by $\lambda_2 - \lambda_1 = (1 - \cos\theta_Y)\lambda_C$

  Using $E=hc/\lambda$, we can recast this as $hc(1/E_2 - 1/E_1) = (1 - \cos\theta_Y)\, hc/mc^2$

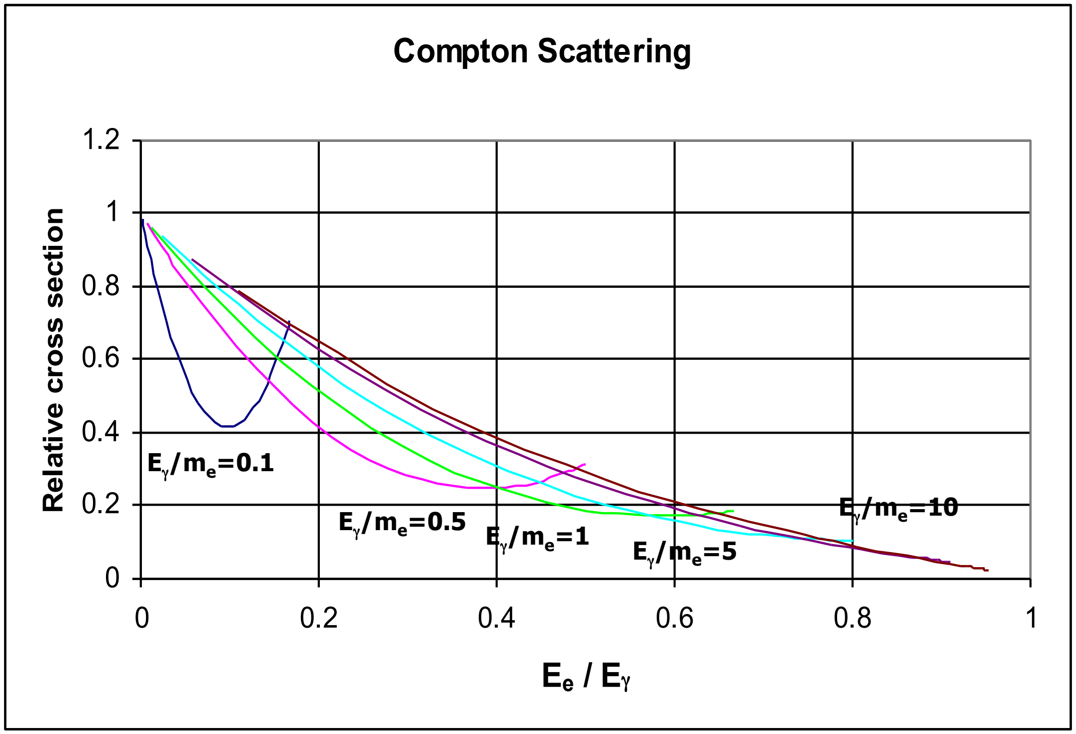
    $(1/E_2 - 1/E_1) = (1 - \cos\theta_Y)/mc^2$

dn/dθ vs θ

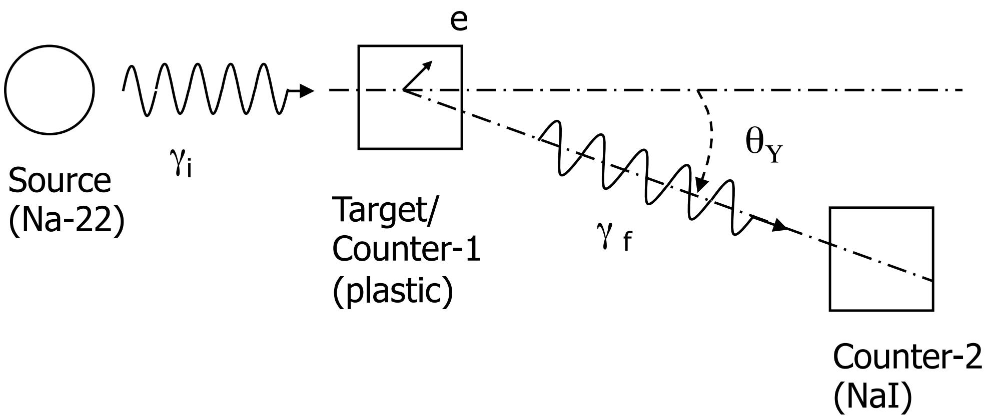
and E_γ vs θ



Compton electron energy distribution



Relative probability of Compton scattering vs energy (in units of m_e)



Compton scattering detector setup:
Trigger: C1 .and. C2
Data: C2 pulse height spectrum, and total count vs angle

Note:
if C1 is too thick, it will stop θ_Y
if C2 is too small it will not absorb θ_Y

Electromagnetic cascade processes

- Bremsstrahlung

  ("braking radiation") = emission of photon by charged particle when accelerated by electric field of a nucleus (or atomic electron)

- Radiation length X_0

  = distance (g/cm^2) for 37% (1/e) energy loss due to bremsstrahlung

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$

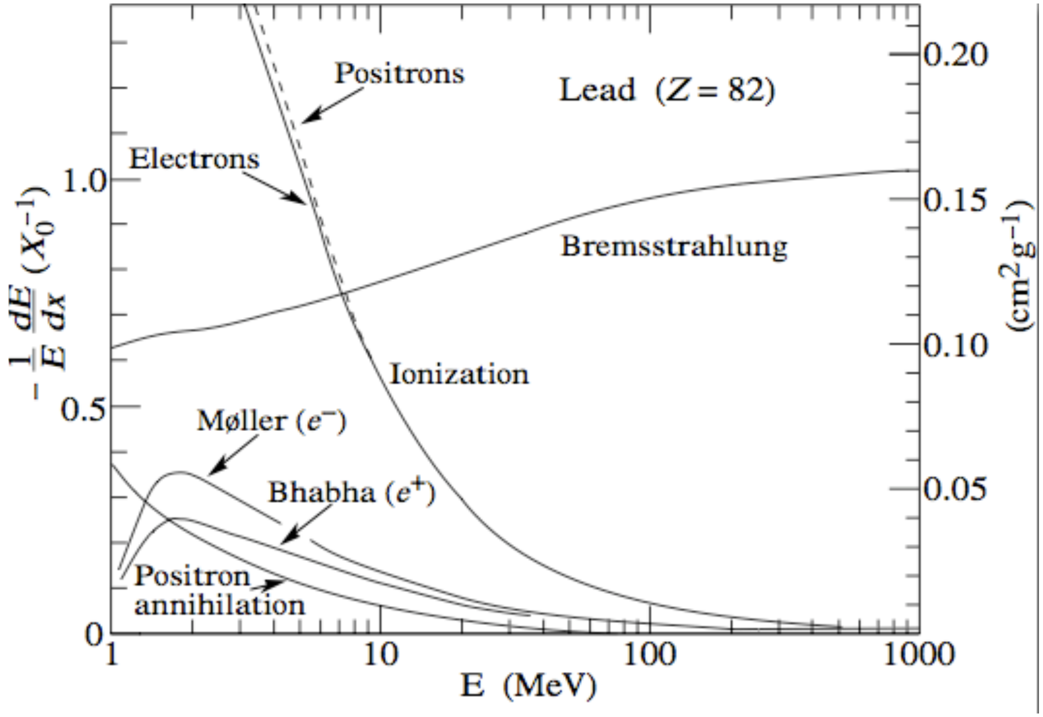
eg, X_0 =

44 g/cm^2 for scintillator,

13.8 g/cm^2 for Fe,

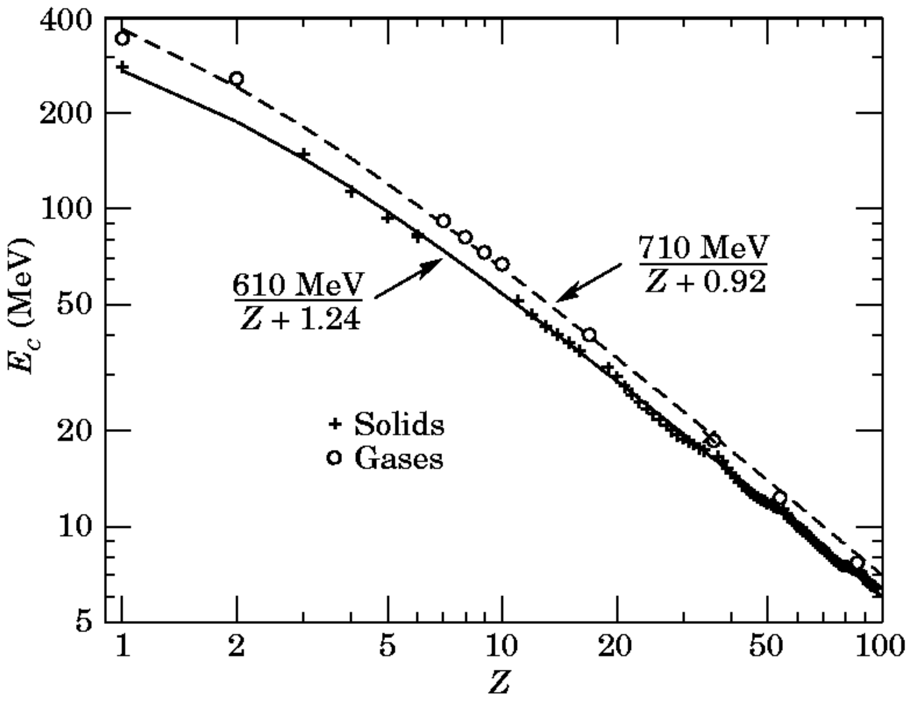
6.4 g/cm^2 for Pb

High-energy electrons and photons create "cascades" (or "showers") in dense materials, due to interplay between two processes: bremsstrahlung and pair production



Critical energy for materials

- Critical energy = energy at which dE/dx due to ionization is same as dE/dx due to bremsstrahlung
  - Below E_c, energy loss is predominantly due to ionization, above E_c, bremsstrahlung



Pair production

Dominant energy loss mode for very high energy electrons;

For energies below 10 MeV it is negligible

- Possible for photon energies greater than 2X mass of the electron (1.02 MeV)
  - γ-ray becomes an electron-positron pair in the E field of a nucleus
    - Particles' kinetic energy = initial photon E minus the rest-mass required to create the e^+e^- pair

Observed energy spectrum is complicated:

- The electrons lose energy by ionization or brem;
- The positron annihilates with an electron (after coming to rest) -> two γ-rays.

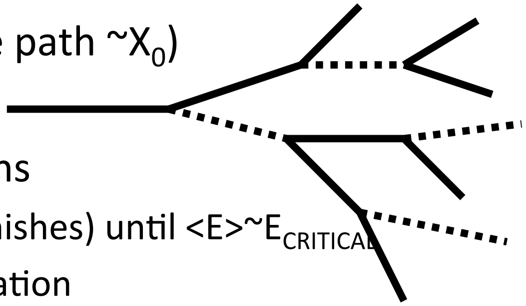
One or both gamma rays may escape the detector

Result is three peaks in the energy spectrum:

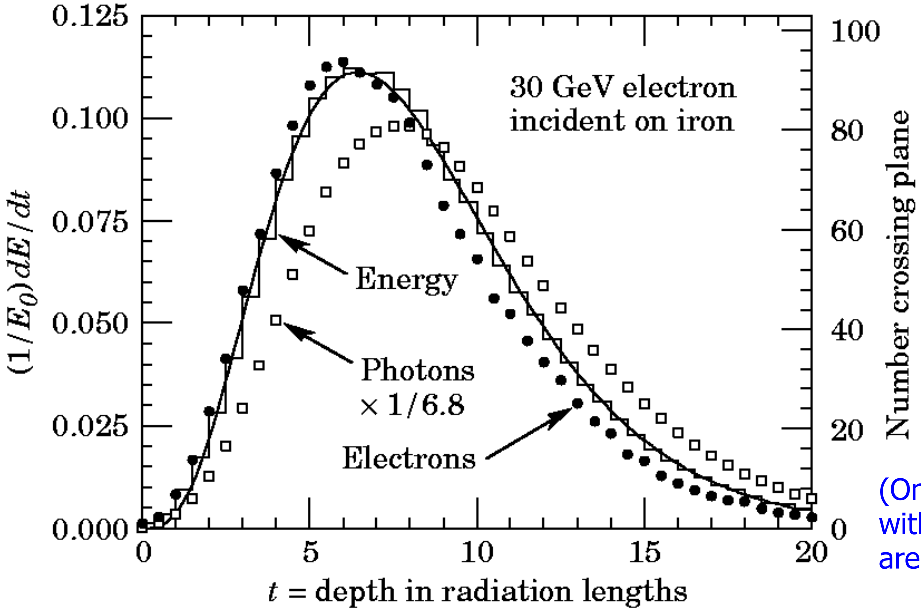
- total-energy peak (E),
- one-escape peak ($E-m_ec^2$) and a
- two-escape peak ($E-2m_ec^2$)

For high energy photons or electrons, pair production and subsequent Bremsstrahlung radiation create more γ-rays, which in turn create more e^+e^- pairs etc. leading to a shower of electrons

Electromagnetic cascade development



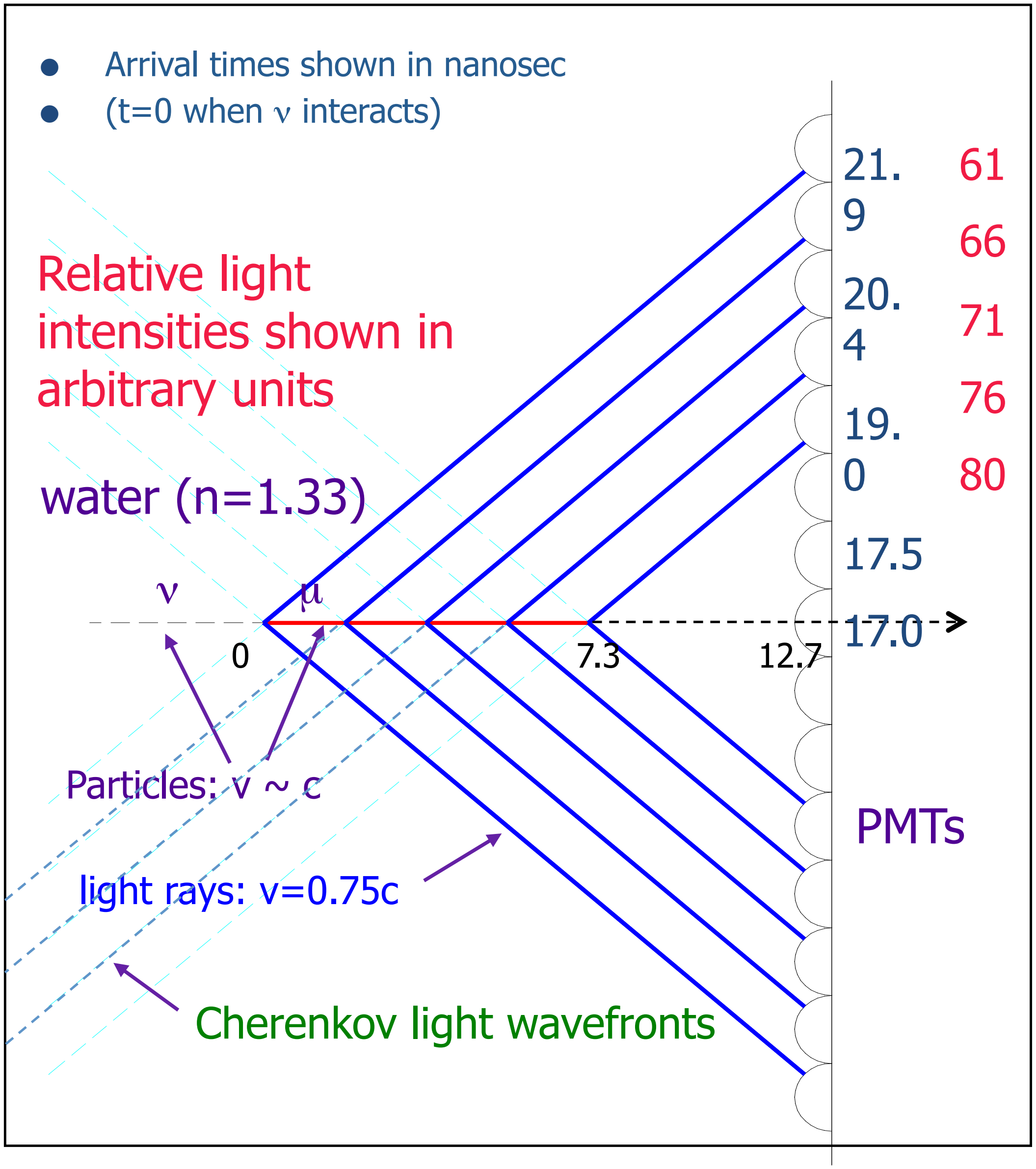
- Electron entering dense matter soon brems (mean free path ~X_0)
- Brem photon soon pair produces (mfp ~ $(7/9)X_0$)
  - etc, etc: result is a *cascade* of electrons and photons
  - Number of particles builds up (and <E> per particle diminishes) until <E>~$E_{CRITICAL}$
    - Then brem losses become less important than ionization



(Only particles with E>1.5 MeV are counted)

- Notice brem/PP cascade process does not *dissipate* energy, just swaps it from e's to photons and back again
- Main effect: divide energy up among more and more particles
- Energy is lost to medium (heating) only via ionization, after e's drop below E_c

Cherenkov radiation



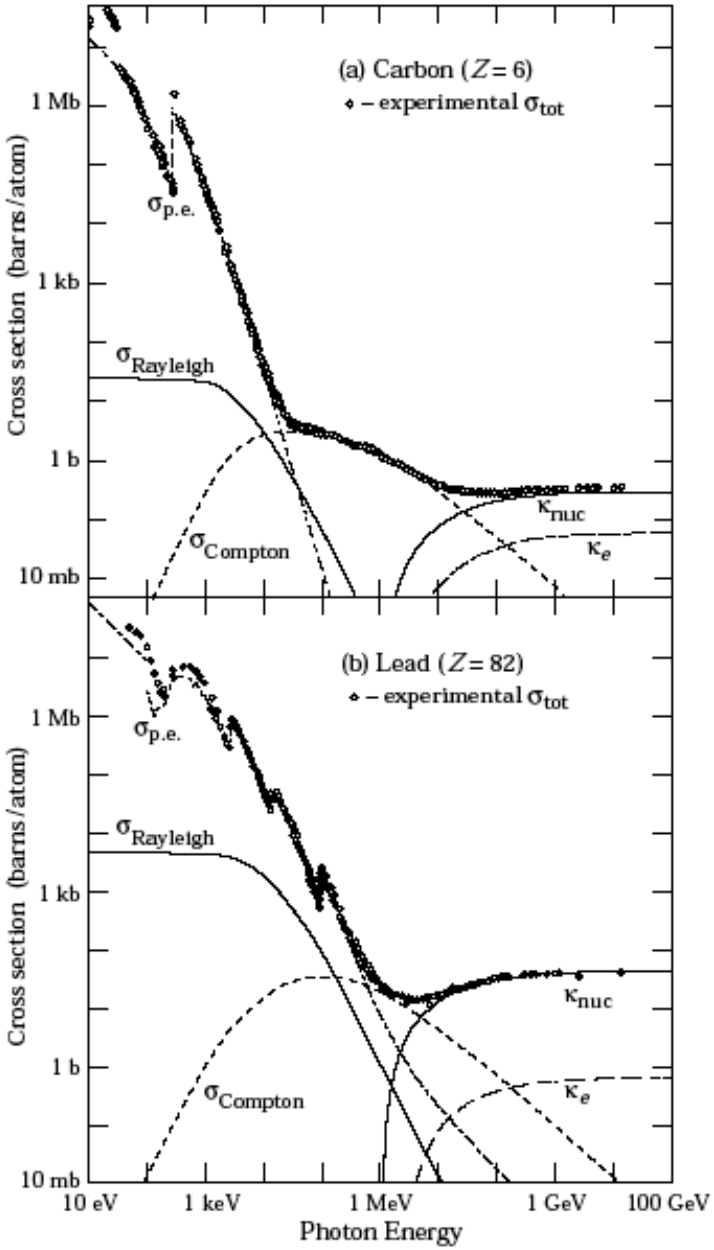
- Charged particle may travel faster than the speed of light in a material medium

  ($v_{E\text{-}M}$=c/n).
- Particle's field produces electromagnetic analog of a sonic boom

  Applications:
  - Ring-imaging Water Cherenkov Detectors (Super-Kamiokande)
    - Reconstruct track
  - Threshold detectors
    - Select particles faster or slower than v
    - If momentum is known, identify mass

(shown earlier)
Photon interactions overview

- For heavy nuclei, brem/pp dominate earlier than for light

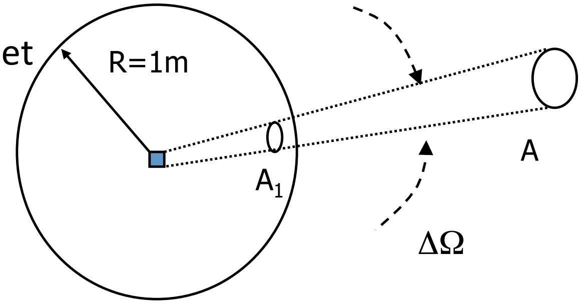


- low energies (< 100 keV): Photoelectric effect
- medium energies (~1 MeV): Compton scattering
- high energies (> 10 MeV): e^+e^- pair production

Cross sections

- First: Ω solid angle acceptance of detector:

  Project detector area as viewed from source onto a 1m radius sphere:



- Total cross section σ = N_{events} / (Δt N_{tgt} I_{beam})

  I_{beam} = N_{beam} /ΔtΔS for beam area ΔS larger than target

  N_{tgt} = number of target nuclei in beam area

  (= number of electrons in beam for Compton scattering)

  =($N_{avogodro}$ M_{tgt} /A_{tgt})Z_{tgt} (M_{tgt}=moles)

  σ has dimensions of area, unit : barn = 10^{-28} m^2

- Can have various partial cross sections:
  - vs energy = $d\sigma/dE$
  - vs angle = $d\sigma/d\theta$
  - vs several things at once: $d^3\sigma$ / dE dθ dΩ

    = cross section at energy E (per unit E) and angle θ (per unit θ), per unit solid angle dΩ centered on θ
  - area under $d\sigma$/d(whatever) curve = σ