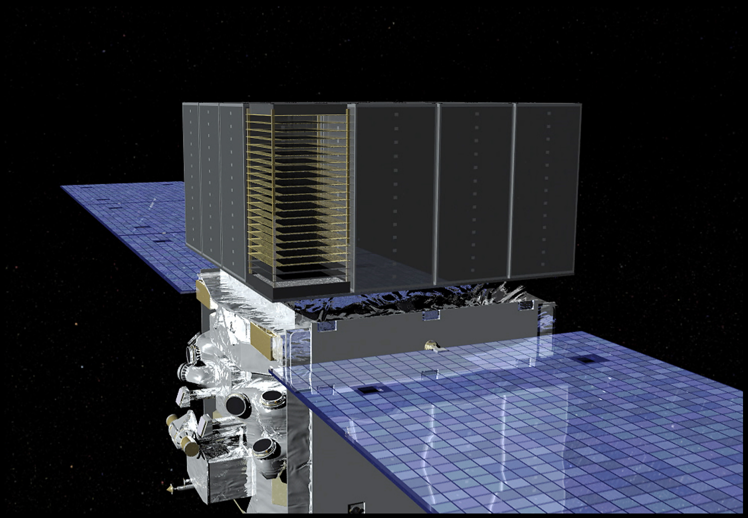
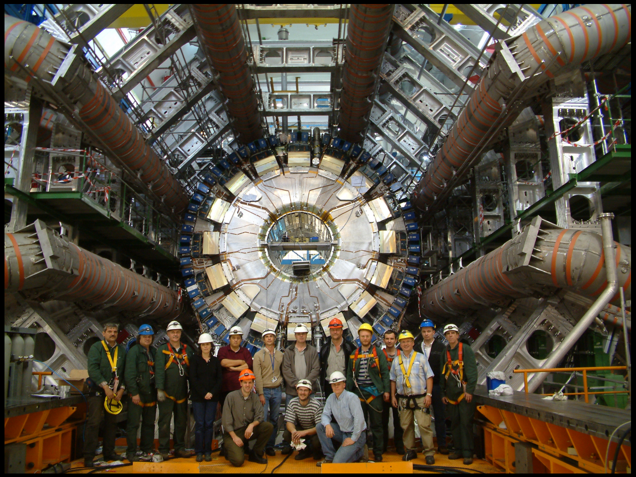
The physics of particle detectors





Justin Vandenbroucke (University of Wisconsin)
Fermi Summer School, Lewes, Delaware
May 31, 2016

Outline

- Charged particles in matter
  - Ionization
  - Bremsstrahlung
  - Cherenkov
- Photons in matter
  - Photoelectric absorption
  - Compton scattering
  - Pair production
- Particle showers
  - Electromagnetic showers
  - Hadronic interactions and showers
- Signals in detectors
  - Scintillation
  - Trackers
  - Photomultiplier tubes

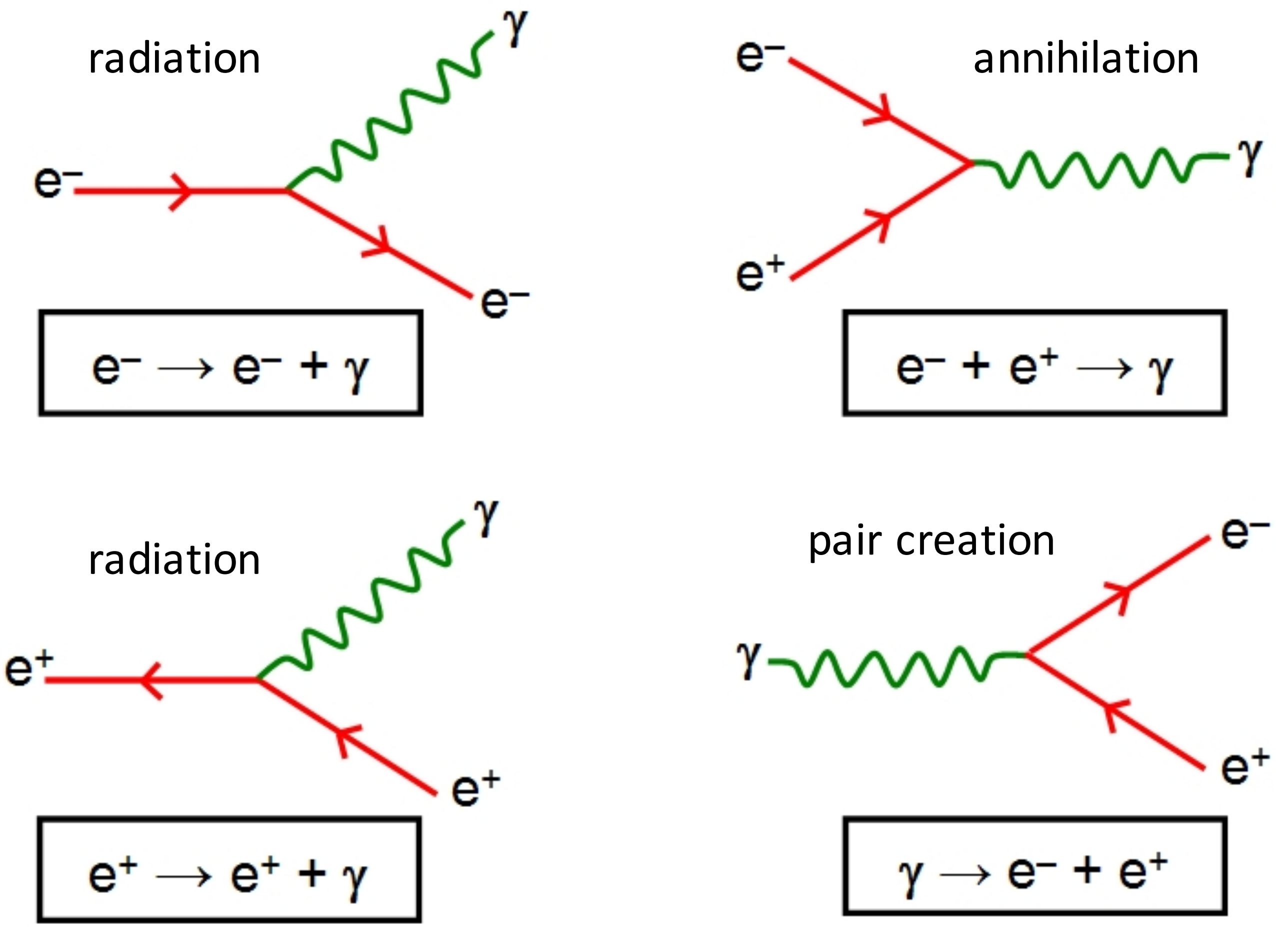
Why learn the physics of detectors?

- Understand the design and operation of your experiment
- Understand the data from your experiment and use it as well as you can
- Understand the way other experiments were designed and be able to critique them and their results
- Learn which systematic uncertainties are important and how to quantify them
- Design new experiments
- Same physical processes occur in detectors as in astrophysical sources that produce the particles

The Particle Data Book: a valuable resource

- Free from the Particle Data Group: request online
- Available as huge phone book, tiny summary pocket book, 50 MB PDF, or web site
- http://pdg.lbl.gov/
- Updated every two years
- Tables with summaries of particle properties: masses, livetimes, decay modes, branching ratios, …
- Short (dense) chapters reviewing Higgs searches, cosmic rays, interactions of particles in matter, neutrino oscillations, probability and statistics, cosmology, dark matter, …
- A very useful reference

Feynman diagrams: the QED vertex



radiation

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

annihilation

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

radiation

$e^+ \rightarrow e^+ + \gamma$

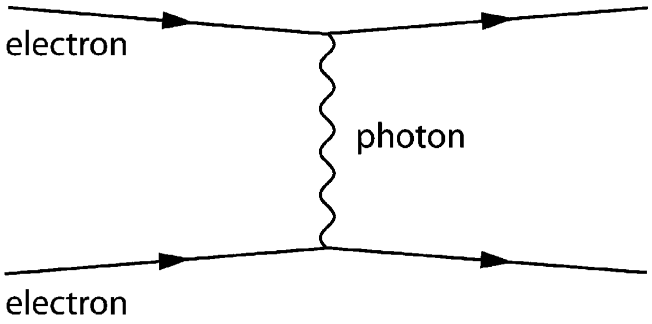
pair creation

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

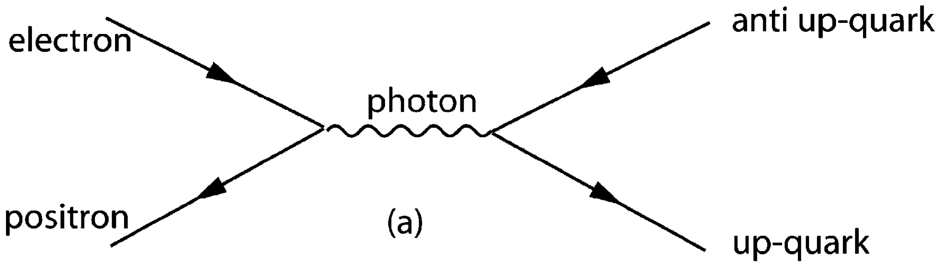
- It is the nonzero electric charge of the fermion that matters (can be lepton or quark)
- For full interactions, multiple vertices can be combined and momentum must be conserved

Interactions

electron-electron scattering:

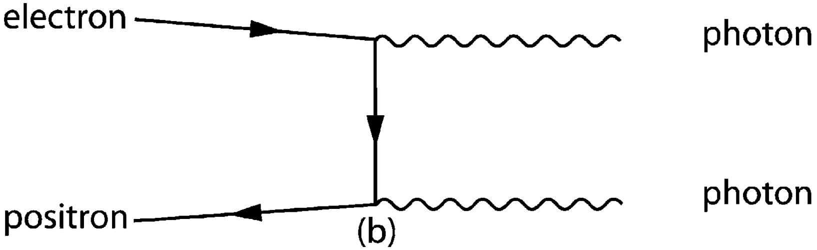


electron-positron annihilation followed by pair production:



(a)

electron-positron annihilation to two photons:

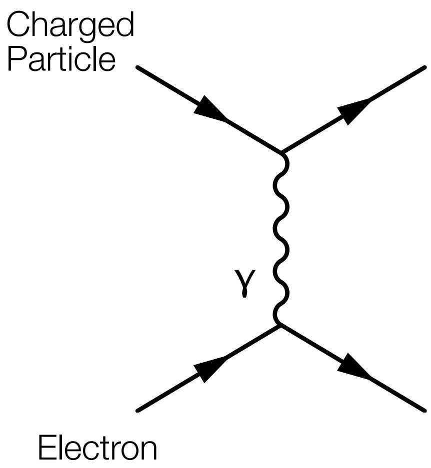


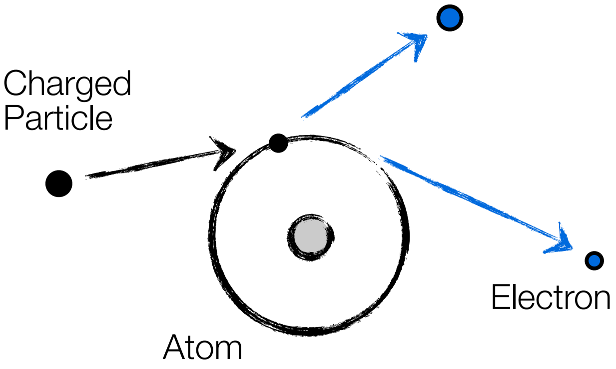
(b)

Also: Compton scattering, inverse Compton scattering

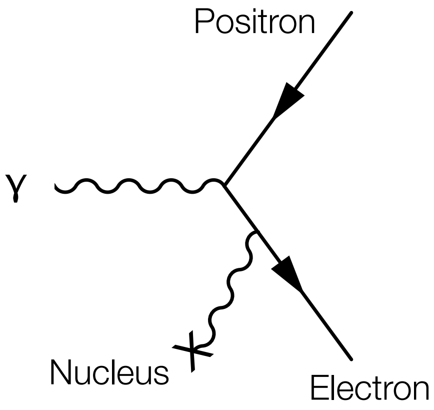
Electromagnetic interactions of electrons and photons in matter

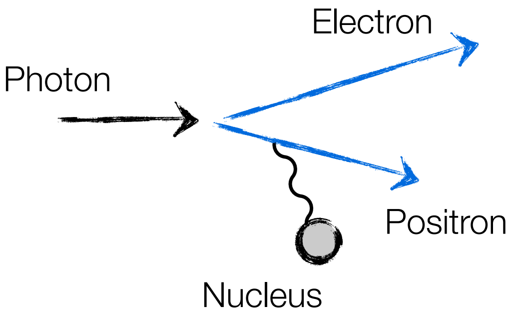
Ionization:



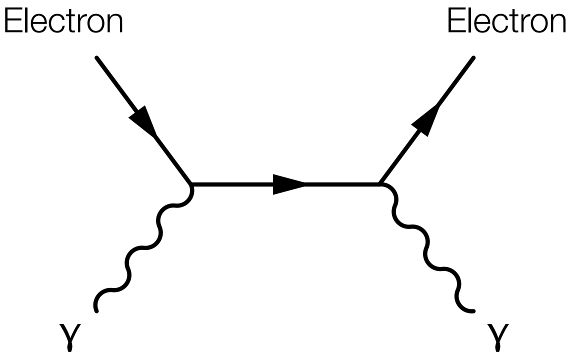


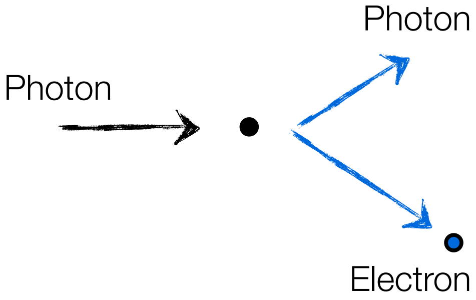
Pair production:





Compton scattering:

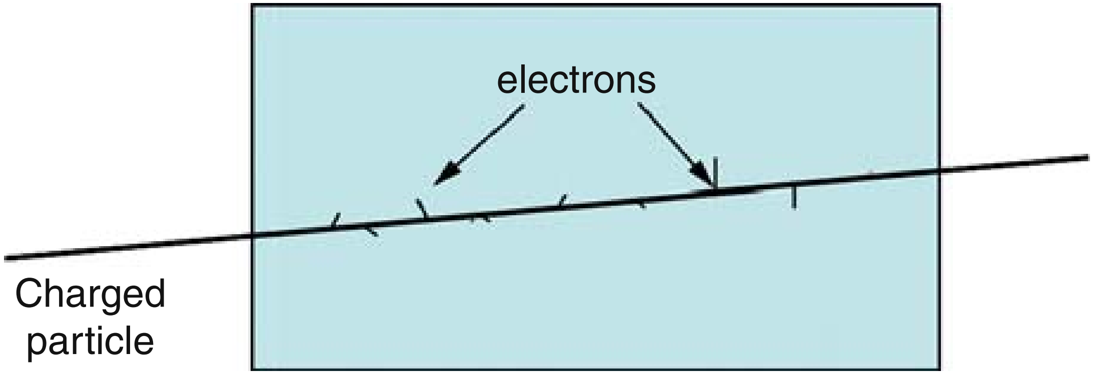




+ bremsstrahlung

Charged particles in matter

Energy loss by ionization



- **Ionizing radiation** = high energy particles energetic enough to ionize atoms in matter
- The energy transferred to the ionized electrons is *lost* by the incident particle
- Technically, “ionization” loss includes loss due to merely exciting rather than ionizing atoms
- Energy of the energized (either excited or free) electrons is distributed as E^{-2}
- Process is stochastic, with large fluctuations
- Intuition from classical mechanics and Coulomb interactions

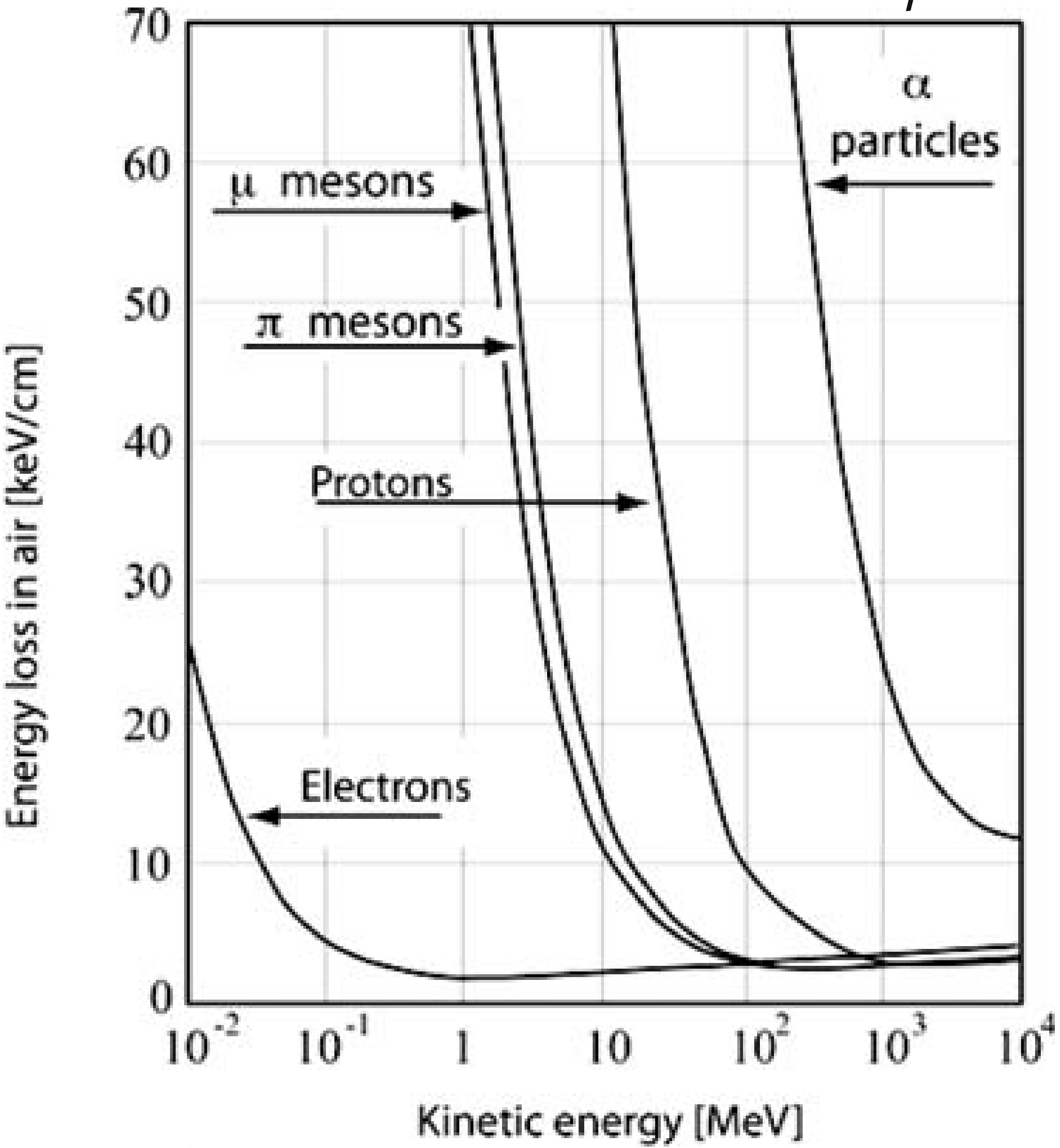
Conceptual expectations for ionization loss

- Dependence on density (ρ) of medium?
- Dependence on speed (β) of particle?
- Dependence on charge (Z) of incident particle?
- Dependence on nuclear charge (Z_{nucl}) of matter?

Ionization loss

$$\frac{dE}{dx} \approx \rho\,(2\,\mathrm{MeV cm^2/g})\frac{Z^2}{\beta^2}$$

- Slower particles ionize more
- At intermediate energies, heavier particles ionize more (because they travel more slowly)
- Higher-charge particles ionize more
- Once β increases to be close to 1, minimum is reached: "**minimum ionizing particle**" (MIP)
- Protons are MIPs from ~0.1 to ~100 GeV
- MIP energy loss depends only on particle charge and material density (not on particle mass)
- For fixed KE below MIP: higher mass means lower speed so greater dE/dx



Full expression for ionization loss: Bethe-Bloch equation

$$\frac{dE}{dx} = \rho \frac{Z_{\mathrm{nucl}}}{A_{\mathrm{r}}}(0.307\,\mathrm{MeVcm}^2/\mathrm{g})\frac{Z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2}\right) - \beta^2 - \frac{\delta(\beta)}{2}\right]$$

dE/dx = energy loss of particle per unit length

Z = charge of the particle divided by the proton charge

c = velocity of light

$\beta\gamma$ = relativistic parameters as defined in Sect. 1.3

ρ = density of the material

Z_{nucl} = dimensionless charge of the nuclei

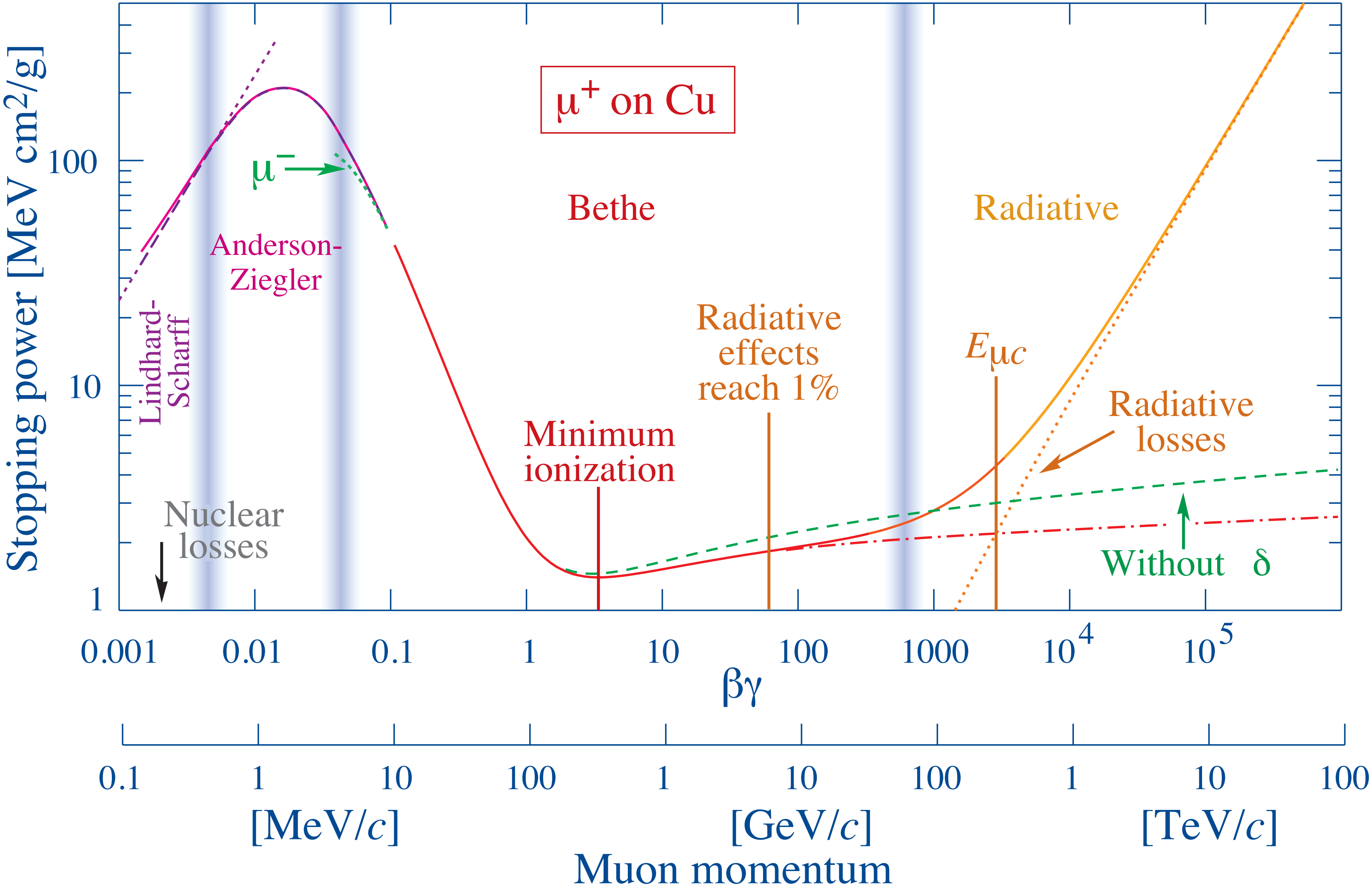
A_{r} = relative atomic weight

I = mean excitation energy in eV. Parameter usually determined experimentally. It is typically around (10 eV times Z_{nucl})

$T_{\max}$ = maximum energy transfer to the electron. For all incoming particles except the electron itself this is to a good approximation given by $\approx 2\ m_e c^2 \beta^2\gamma^2$. For electrons $T_{\max}$ is the energy of the incoming electron.

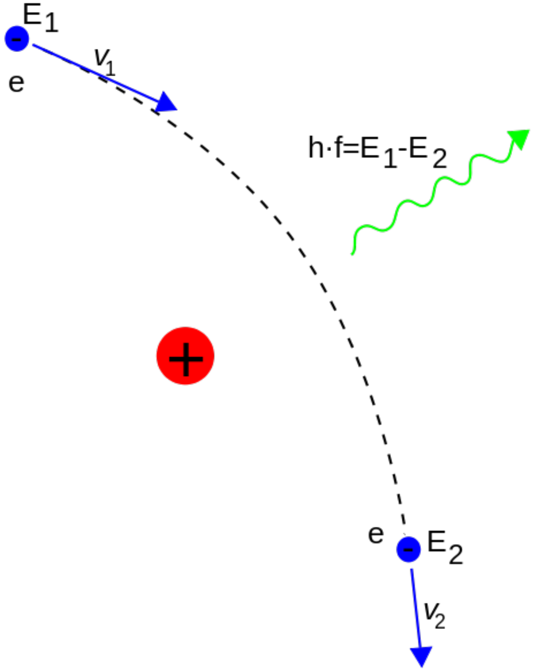
$\delta\beta$ = density-dependent term that attenuates the logarithmic rise of the cross section at very high energy. See (Ref. [6] in Chap. 1) for a discussion of this term.

Example: energy loss by muons in copper



Bremsstrahlung and radiation length

- **Bremsstrahlung** is radiation due to hard Coulomb interactions of a particle with atomic nuclei ("braking radiation")
- More important for light ($e^\pm$) than heavy particles
- Radiation is forward beamed
- dE/dx is proportional to energy: $\frac{dE}{dx} = -\frac{E}{X_0}$

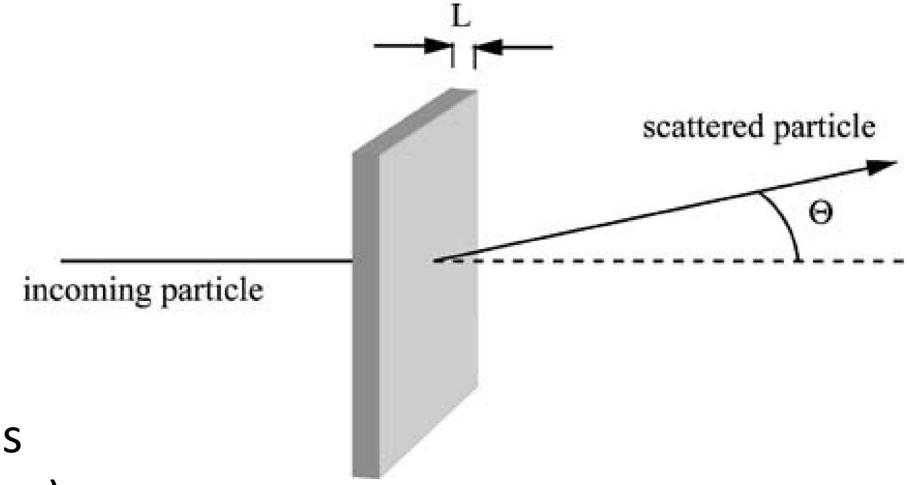


$$\frac{1}{X_0} \approx 4\alpha\, r_0^2 \frac{\rho N_A}{A_r} Z_{\mathrm{nucl}}(1+Z_{\mathrm{nucl}}) \ln\left(\frac{183}{\sqrt[3]{Z_{\mathrm{nucl}}}}\right)$$

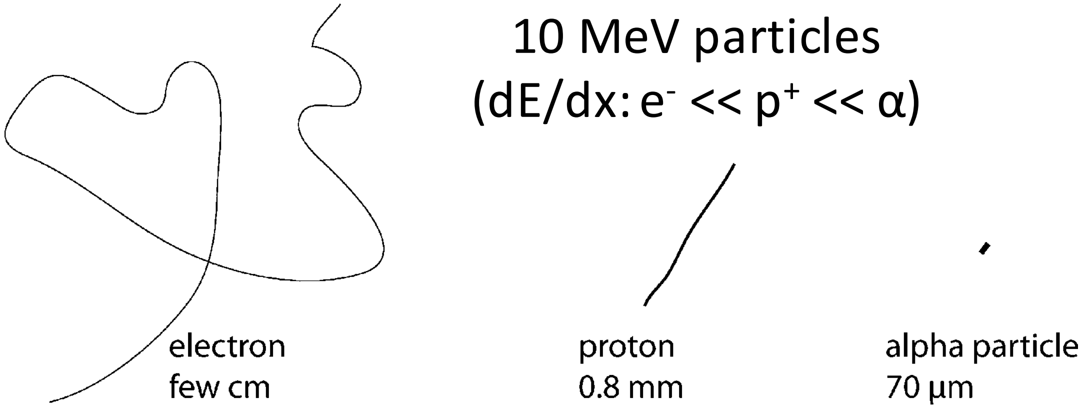
$X_0 =$ radiation length of the material
$N_A =$ Avogadro's number
$\alpha =$ fine structure constant ($\alpha \approx 1/137$)
$r_0 =$ classical electron radius ($2.82\ 10^{-15}$ m)

- The proportionality constant in bremsstrahlung dE/dx is by definition the **radiation length**, a property of the material
- Over one radiation length, the particle energy is reduced (on average) by one e-folding
- In water, radiation length = 36 cm

(Multiple) scattering

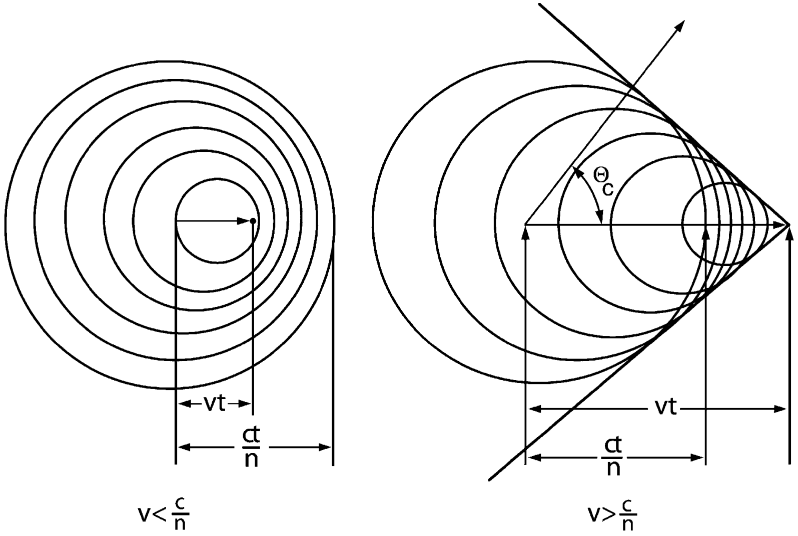


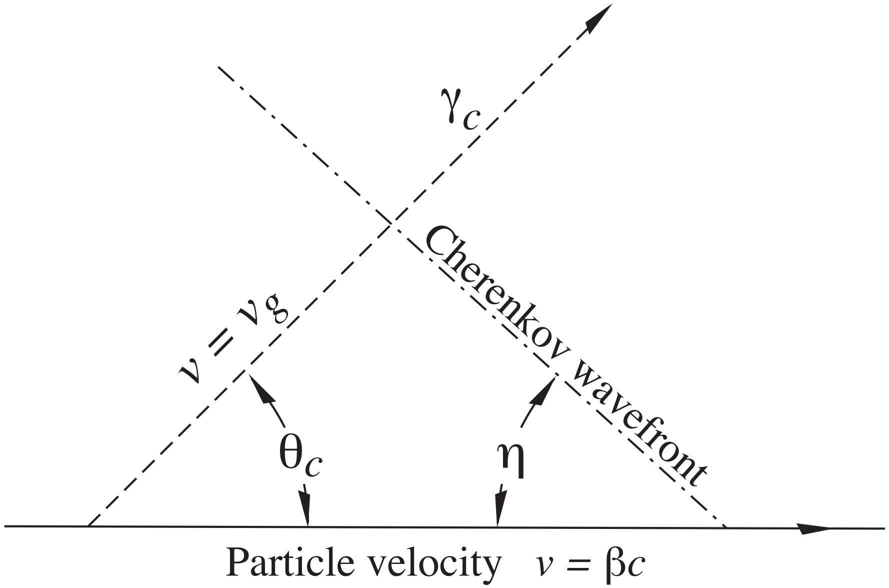
10 MeV particles
(dE/dx: $e^- \ll p^+ \ll \alpha$)



- In addition to losing energy, charged particles change direction due to Coulomb scattering
- More important for lighter particles ($e^\pm$)
- Probability of scattering is proportional to traversed length
- Traversing large amount of material, light particles can scatter multiple times
- Lower energy particles scatter more
- As particle loses energy, scattering angle increases
- At low energy, direction can be randomized
- Competition between direction randomization and energy loss

Cherenkov radiation





- Due to polarization of medium, produced when a relativistic charged particle travels through a medium faster than the speed of light in the medium (c/n)
- Typically a negligible contribution to particle energy loss
- Very useful for detecting particles and measuring their direction, energy, or mass/identity
- Radiation emitted along a narrow cone of opening angle θ_C (can vary with wavelength):

$$\cos(\theta_c) = \frac{(c/n)t}{v\,t} = \frac{c}{nv}$$

- Radiation intensity scales with particle Z^2
- Spectrum of Cherenkov light increases with frequency:

$$\frac{d^2E}{d\hbar\omega.dx} = \hbar\omega\,\frac{Z^2\alpha}{\hbar c}\left[1 - \frac{c^2}{n^2v^2}\right]$$

~200 photons/cm in water

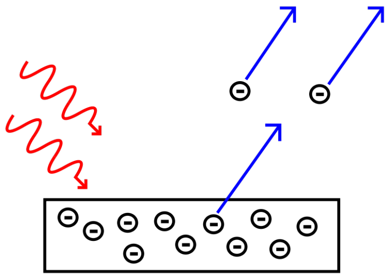
Stochastic nature of energy loss

- *dE/dx* describes the *mean* energy loss
- Most energy loss phenomena are actually discrete and stochastic, not smooth and continuous
- Stochastic nature of ionization loss is important for thin absorbers
- For thick absorbers, ionization loss is fairly smooth
- Stochastic nature of other interactions (bremsstrahlung, pair production, photonuclear interactions) typically important even for thick absorbers

Interactions of X-rays and gamma rays: photoelectric, Compton, pair production

- While ionization loss by charged particles is roughly continuous, photon processes are typically catastrophic: zero energy loss until one sudden event removes much or all of the photon energy

Photoelectric effect

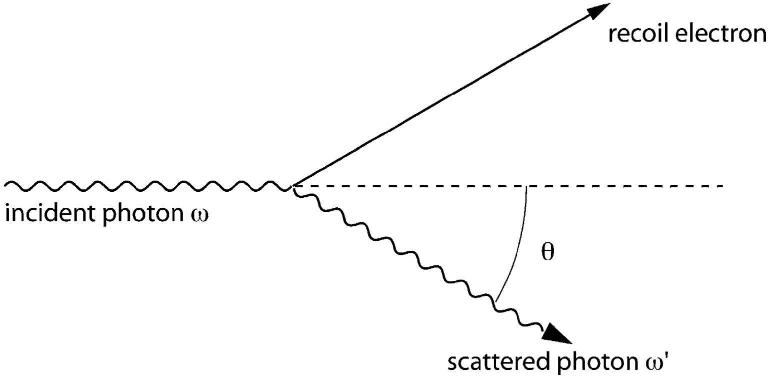


- Complete absorption of incident photon by atomic electron
- Electron is either excited or ejected
- Energy lost by photon equals kinetic energy transferred to electron minus binding energy
- Cross section
  - Decreases strongly with photon energy
  - Increases strongly with atomic charge Z

$$\sigma \approx \mathrm{Const}\frac{Z^n}{E_\gamma^{3.5}}$$

- n varies with energy between 4 and 5
- In addition to this overall smooth behavior, there are jumps at atomic shell energies
- Useful for photon detection (photomultipliers)

Compton scattering



- Elastic scattering of photon and electron
- Typically a high energy photon transfers energy to a low energy electron
- "Inverse" Compton scattering: high energy electron transfers energy to a low energy photon
- Can be useful for photon detection
- Can also be a nuisance: changes photon direction
- Cross section given by Klein-Nishina formula:

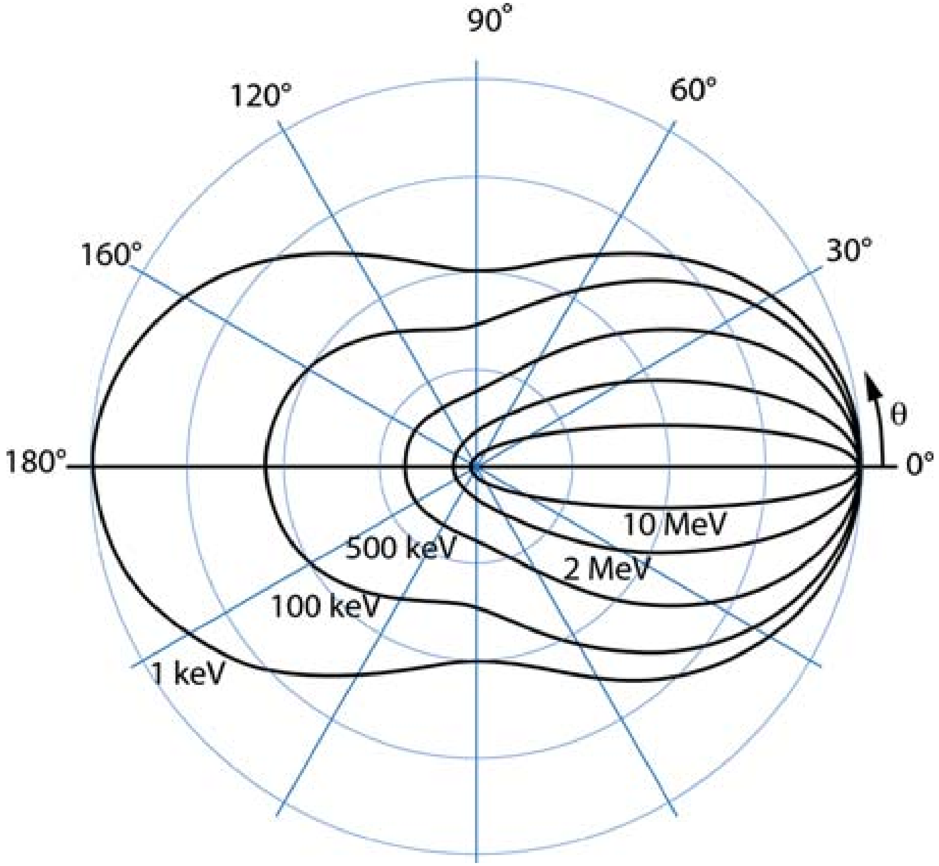
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{\hbar\omega'}{\hbar\omega}\right)^2\left(\frac{\hbar\omega}{\hbar\omega'} + \frac{\hbar\omega'}{\hbar\omega} - \sin^2\theta\right)$$

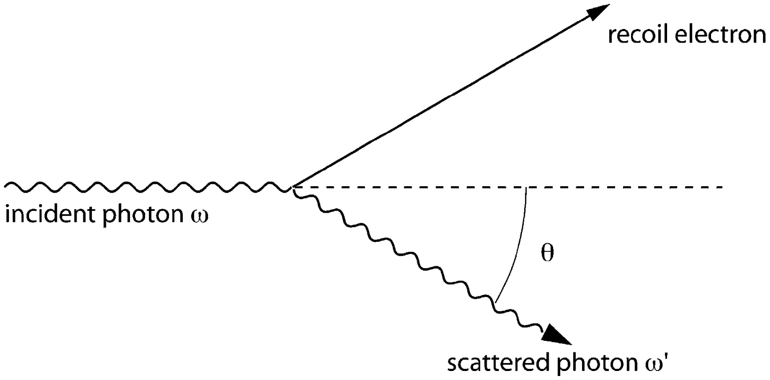
$$\sigma = \frac{8\pi}{3} r_0^2 \qquad \hbar\omega << m_e c^2$$

$$\sigma = r_0^2\,\pi\,\frac{m_e c^2}{\hbar\omega}\left[\ln\left(\frac{2\hbar\omega}{m_e c^2}\right) + \frac{1}{2}\right] \qquad \hbar\omega >> m_e c^2$$

- Low-energy limit is energy independent
  - Scattering off single electrons: Thomson scattering
  - Coherent scattering off bound electrons in atom: Rayleigh scattering

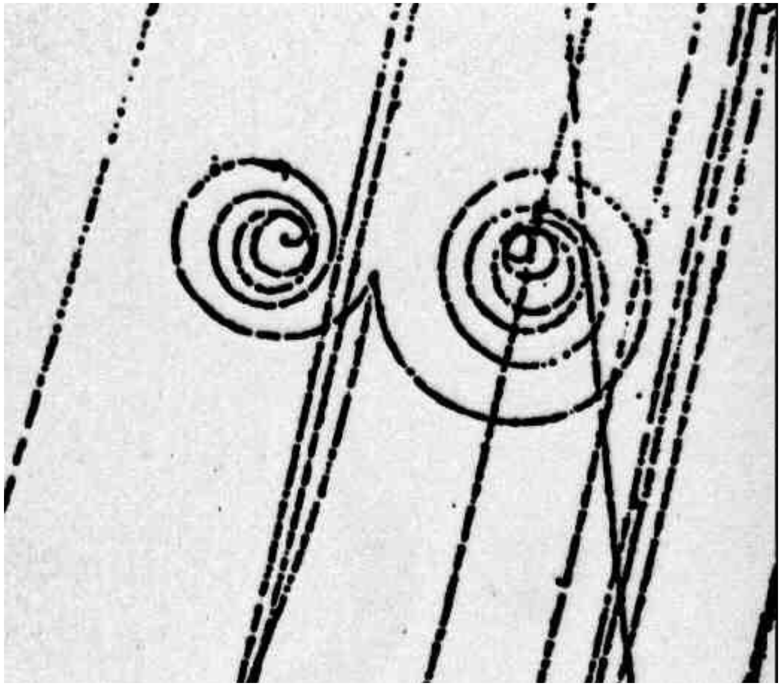
Angular distribution of Compton scattering

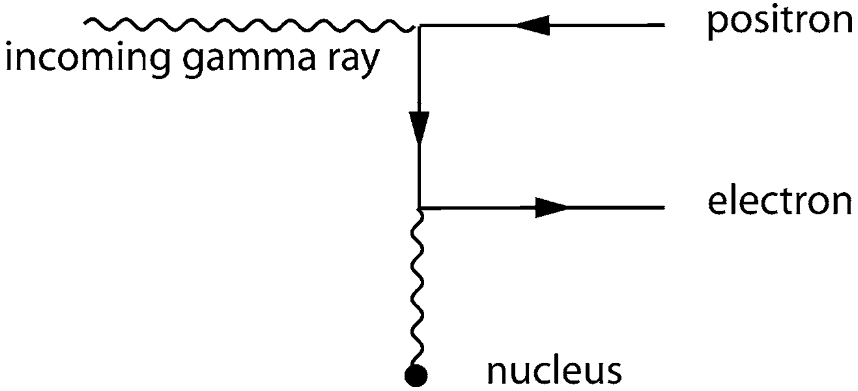




- At high energies, outgoing photon direction similar to incoming photon direction
- At low energies, direction is randomized more

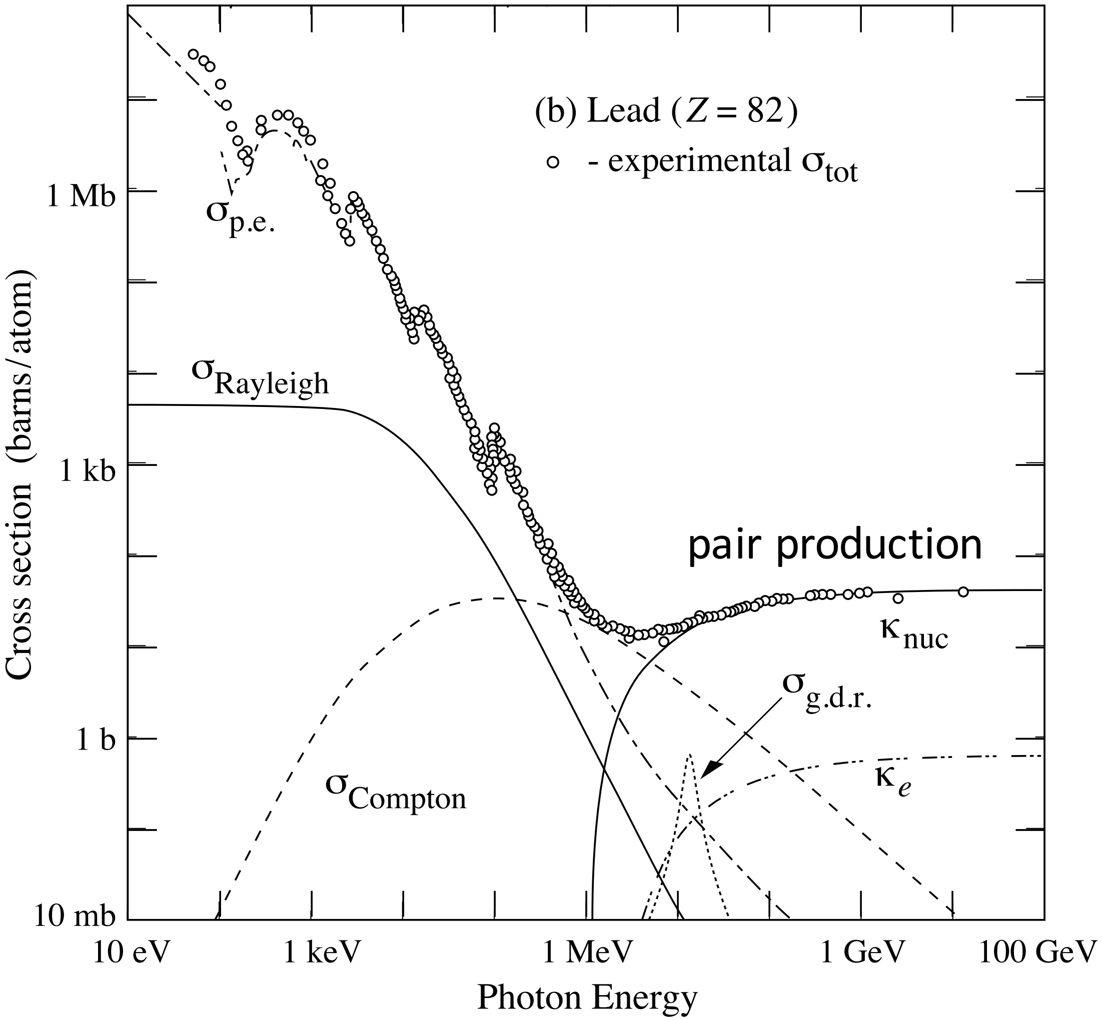
Pair production





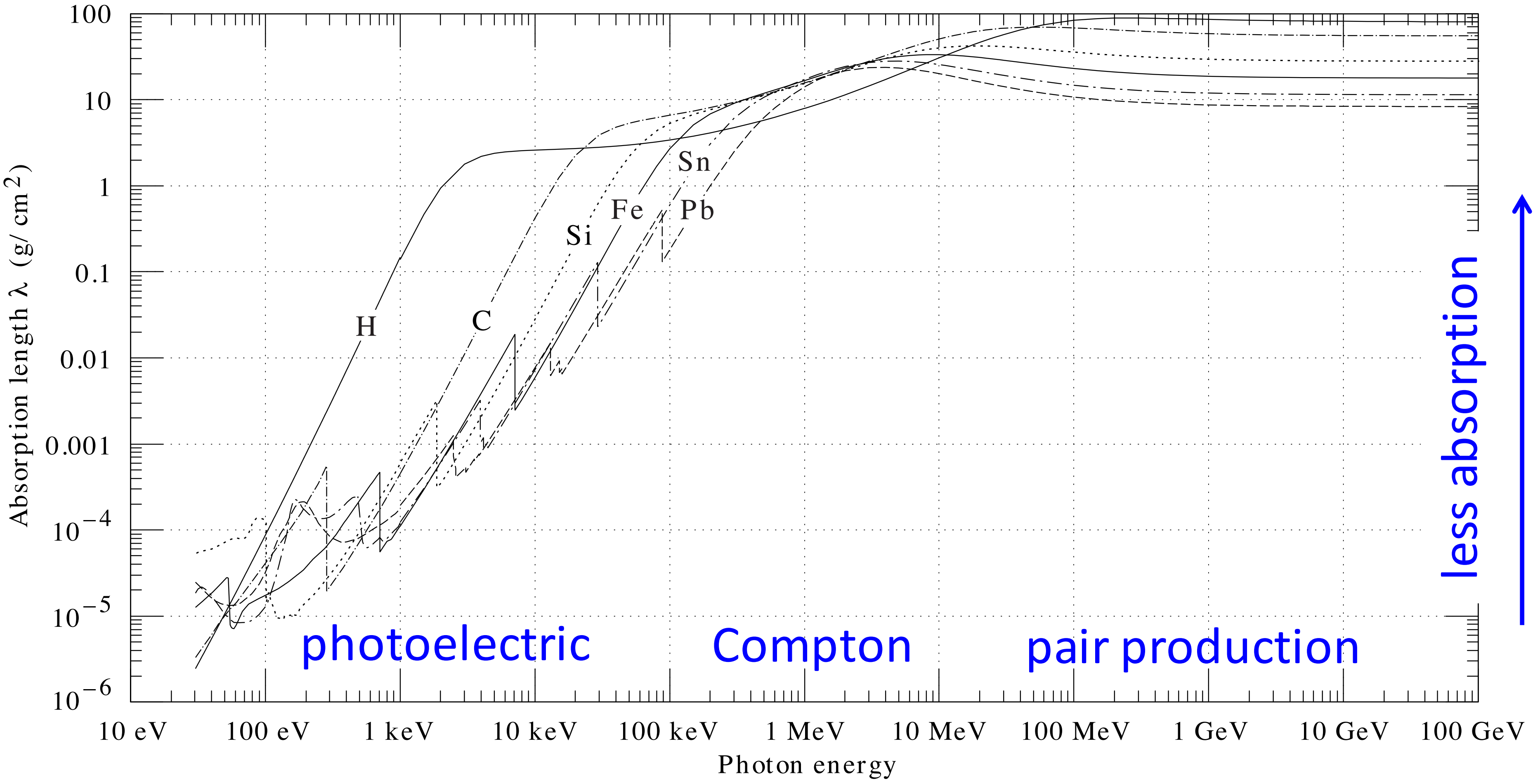
- Photon is converted to an electron-positron pair
- Cross section rises quickly from threshold to a constant value at high energy
- At high energy, mean free path for pair production is X_0*9/7
- Opening angle between electron and positron decreases with photon energy
- Electron and positron produced preferentially in the polarization plane of the gamma ray

Summary of photon interactions in matter



- A single photon interacts with a probability proportional to absorber thickness (for thin absorbers)
- A beam of photons is attenuated exponentially with distance

Absorption of a photon beam by matter



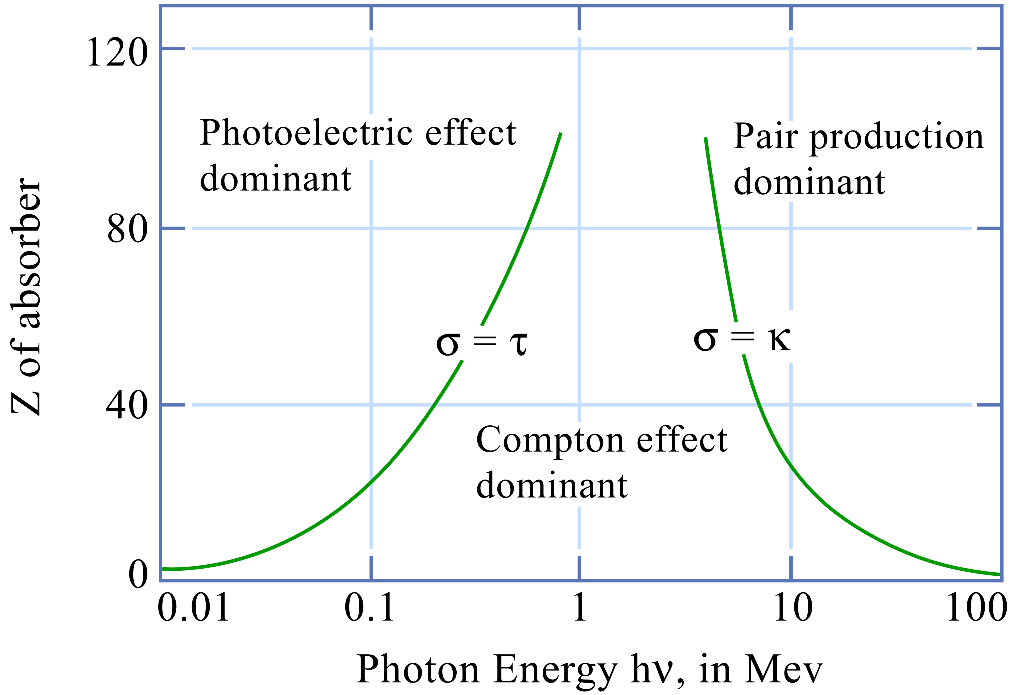
- Number (not energy) of photons in a beam is attenuated exponentially
- Absorption length inversely proportional to cross section

Dependence of photon interaction (mass attenuation coefficient) on material composition

- **Photoelectric effect** (photons see atomic shells)
  - Increases strongly with Z
  - Absorption edges (especially at K shell)
- **Compton scattering** (photons see individual electrons)
  - Scales with electron density (number of electrons per gram)
    - High in hydrogen due to lack of neutrons
    - Only varies by 20% in other elements
- **Pair production** (photons see nucleus)
  - Increases strongly with Z (approximately as Z^2)
  - High energy limit (>> $m_e c^2$):

$$\sigma = \frac{7}{9} 4\alpha r_0^2 Z_{nucl} \left(Z_{nucl} + 1\right) \ln\left(\frac{183}{3\sqrt{Z_{nucl}}}\right)$$

Photoelectric, Compton, and pair production probabilities



- Interaction probability μ (has units cm^{-1})
- τ: photoelectric probability
- σ: Compton probability
- κ: pair production probability
- Total interaction probability $\mu = \tau + \sigma + \kappa$

Particle showers

Radiative loss by electrons (or positrons)

- For high energy electrons, radiative energy loss dominates ionization energy loss
- Radiative energy loss by an electron passing through a medium is proportional to the energy of the electron:

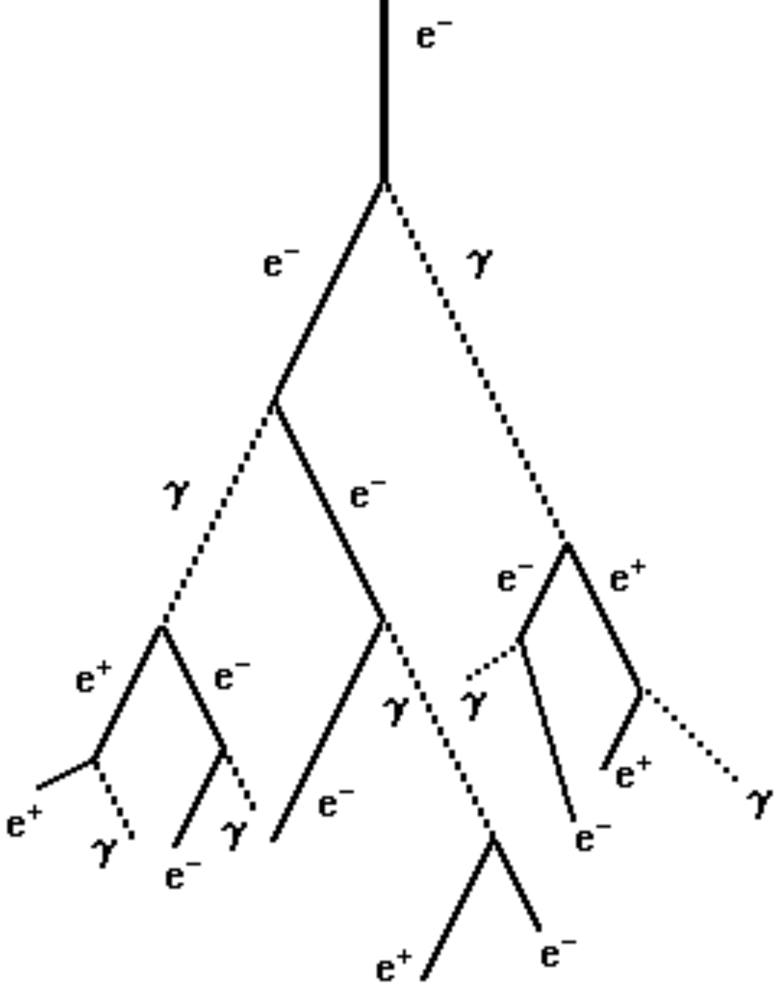
$$\frac{dE}{dx} = -\frac{E}{X_0}$$

- This means the energy of electrons passing through a medium decreases exponentially:

$$E = E_0 e^{-x/X_0}$$

- X_0 is the characteristic energy loss scale for electrons, the **radiation length** (depends on material roughly as $Z^{-1} (1+Z)^{-1}$)
  - Air: 37 g/cm^2
  - Lead: 6 g/cm^2
- The **critical energy** (~ 600/Z MeV) is the energy at which radiative energy loss equals ionization energy loss
- **Conversion length** = typical length for *photon* to travel before pair producing, ~(9/7) X_0

Electromagnetic shower: simple model



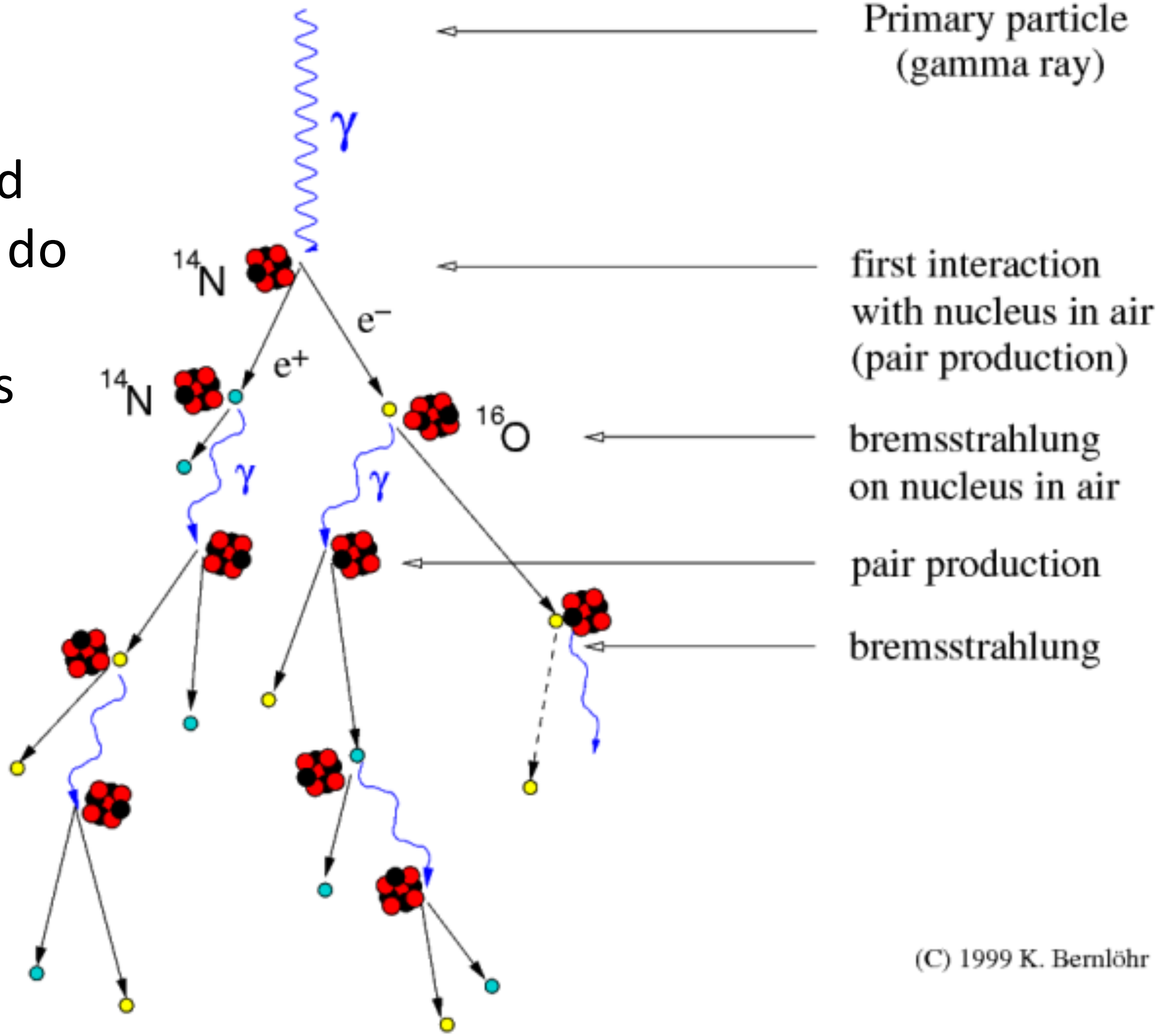
- Initiated by gamma, electron, or positron
- Alternation between
  - Pair production (must occur near a nucleus to conserve momentum)
  - Bremsstrahlung radiation (radiative energy loss caused by deceleration of $e^{\pm}$ in Coulomb field of nucleus: dominates ionization loss at high energy)
- Can occur in any medium with nuclei: crystal, ice, atmosphere, …

Electromagnetic shower development

- For a primary particle of energy E_0, after t radiation lengths (generations), the energy of each $e^\pm$ or gamma will be approximately $E_0/2^t$
- Continues until $E = E_{crit}$
- So shower maximum is at t_{max}, when $E_{crit} = E_0/2^{tmax}$
- Depth of shower max increases logarithmically with primary energy: $t_{max} = ln(E_0/E_{crit}) / ln2$
- Total track length of charged particles (number of radiation lengths) $\propto E_0/E_{crit}$

Development of gamma–ray air showers

- In purely electromagnetic showers (simplified model), the nuclei do not actively participate (only as catalysts for electromagnetic interactions)



Primary particle (gamma ray)

first interaction with nucleus in air (pair production)

bremsstrahlung on nucleus in air

pair production

bremsstrahlung

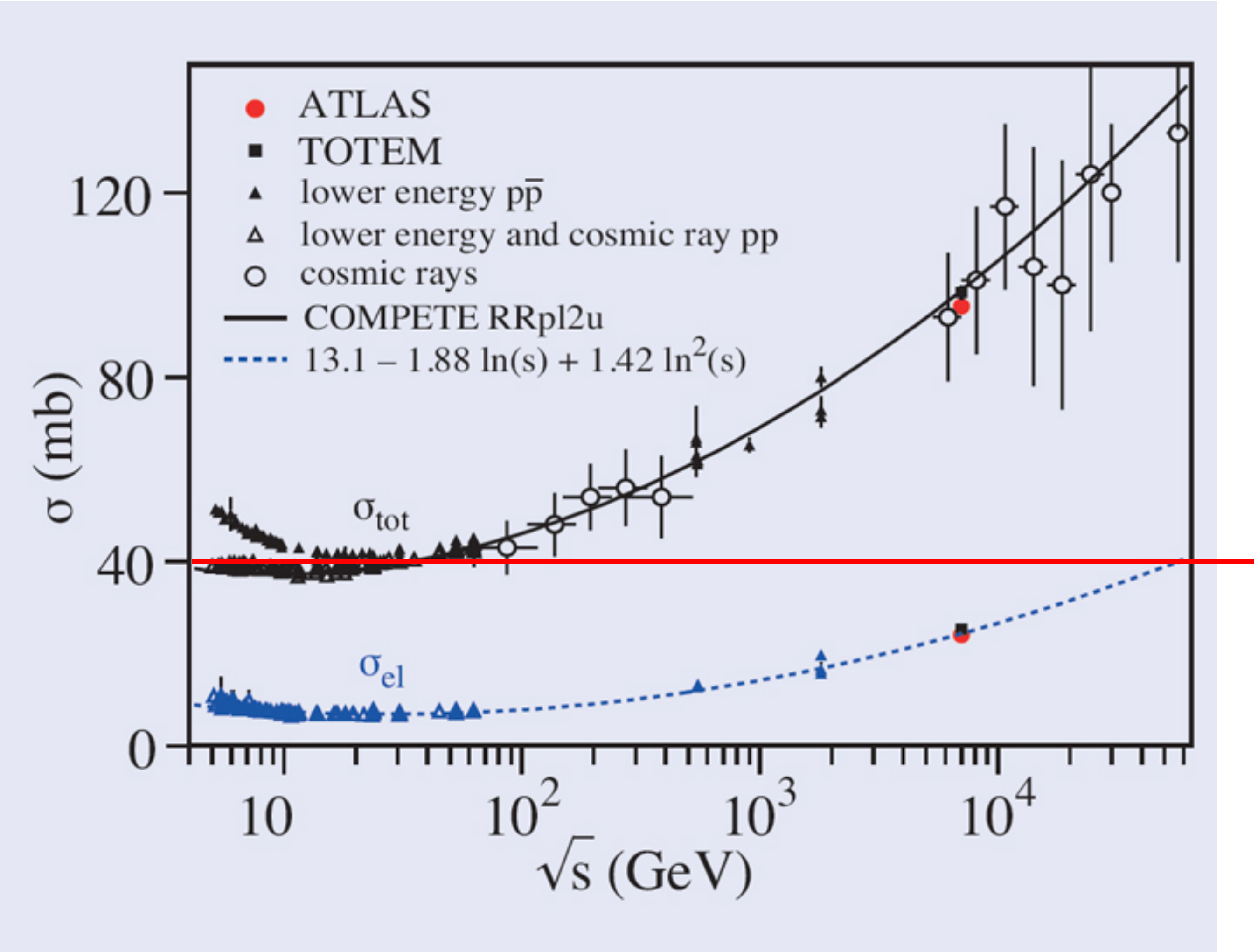
(C) 1999 K. Bernlöhr

Strong interactions

- So far we have focused on electromagnetic interactions: ionization loss, bremsstrahlung, photoelectric, pair production
- High energy hadrons (protons, neutrons, pions, …) can undergo strong interactions in matter
- Inelastic: produces quarks which hadronize to mesons or baryons
- Non-hadrons (electrons, muons, neutrinos, …) do not undergo strong interactions
- Because strong force has a very short range, strong cross section at high energy (above 1 GeV) is comparable to geometric cross section of nucleus
- 1 barn = 10^{-24} cm^2
- Proton radius ~1 fm, area ~40 millibarn
- Nucleus of atomic number A has cross section given approximately by

$$\sigma \approx 4 \times 10^{-26} (A)^{2/3} \, \mathrm{cm}^2$$

Strong interaction cross section grows slowly with energy



Simple estimate surprisingly accurate

Hadronic (strong) interaction length

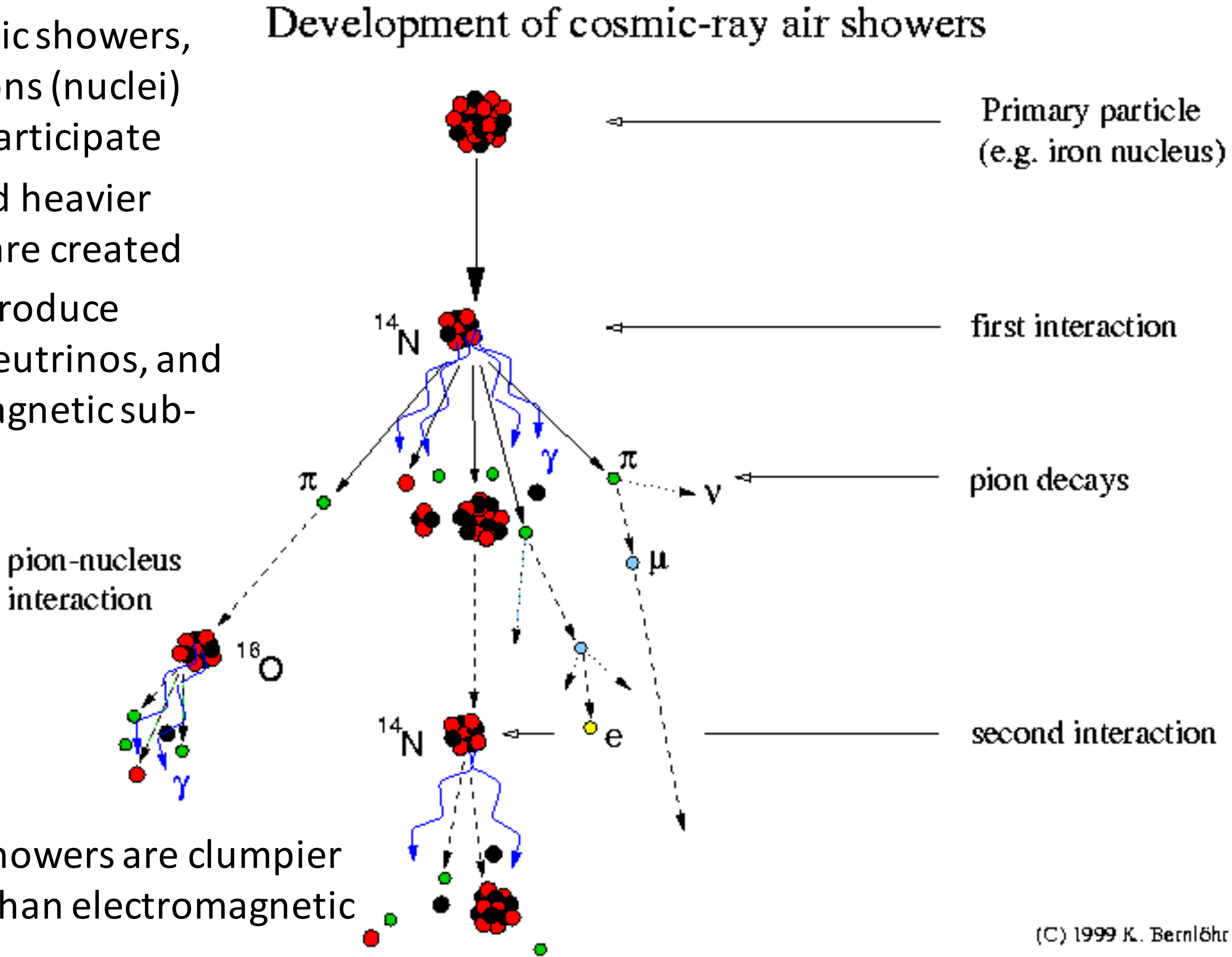
- Mean free path between hadronic interactions, for protons in matter
- Number density of nuclei in matter: $N = \rho N_A / A$
- N_A = Avogadro's number

$$\lambda = \frac{1}{N\sigma} \approx \frac{A^{1/3}}{\rho} \frac{1}{N_A \, 4 \times 10^{-26}} \approx \frac{A^{1/3}}{\rho} 35 \, \mathrm{g/cm^2}$$

- For typical solids, between 10 and 100 cm
- Typically larger than radiation length X_0 by factor of a few

Hadronic showers

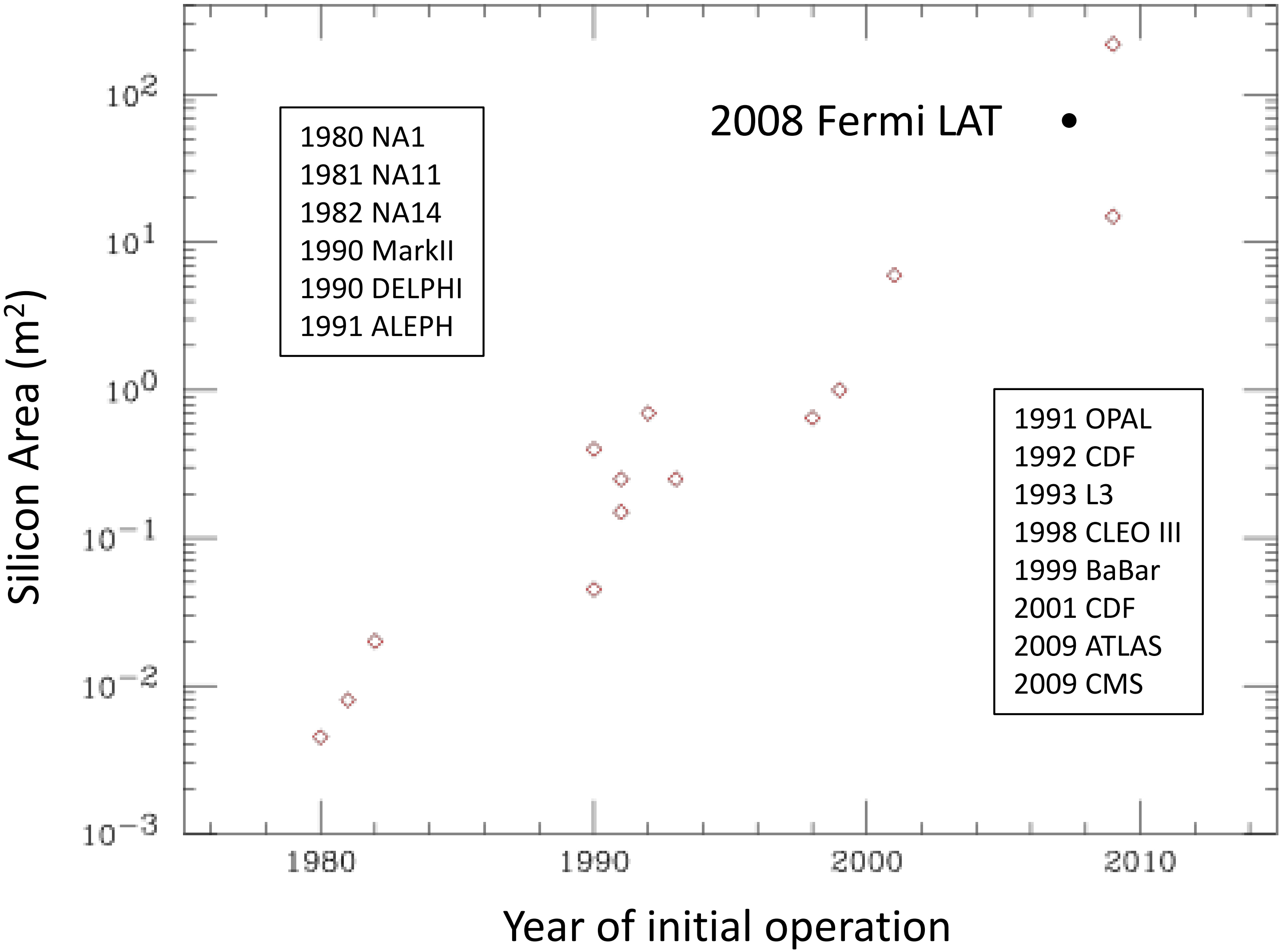
- In hadronic showers, the hadrons (nuclei) actively participate
- Pions (and heavier mesons) are created
- Mesons produce muons, neutrinos, and electromagnetic sub-showers



Hadronic showers are clumpier and longer than electromagnetic

Signals in detectors

Silicon trackers in high energy physics: a version of Moore’s law



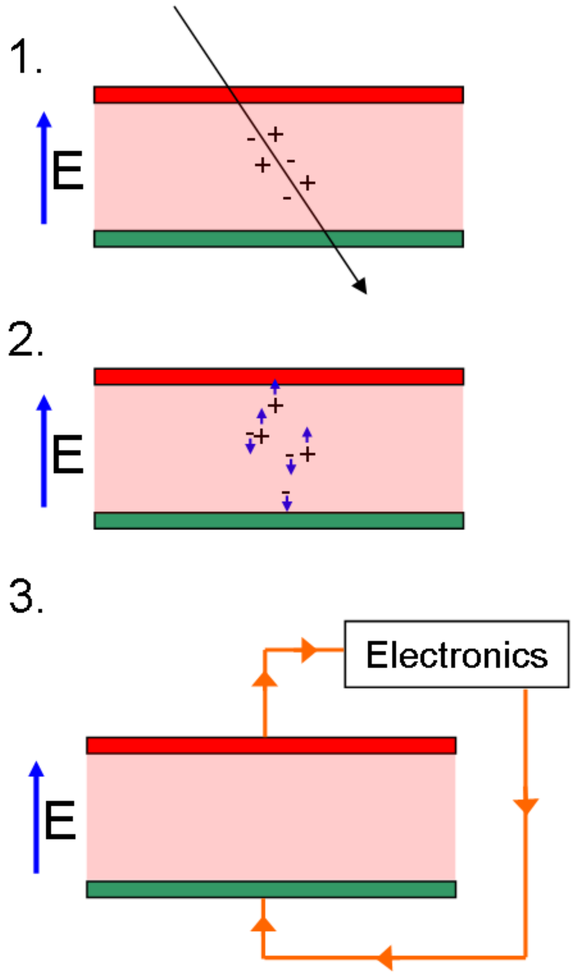
1980 NA1
1981 NA11
1982 NA14
1990 MarkII
1990 DELPHI
1991 ALEPH

2008 Fermi LAT ●

1991 OPAL
1992 CDF
1993 L3
1998 CLEO III
1999 BaBar
2001 CDF
2009 ATLAS
2009 CMS

PN junctions as particle detectors

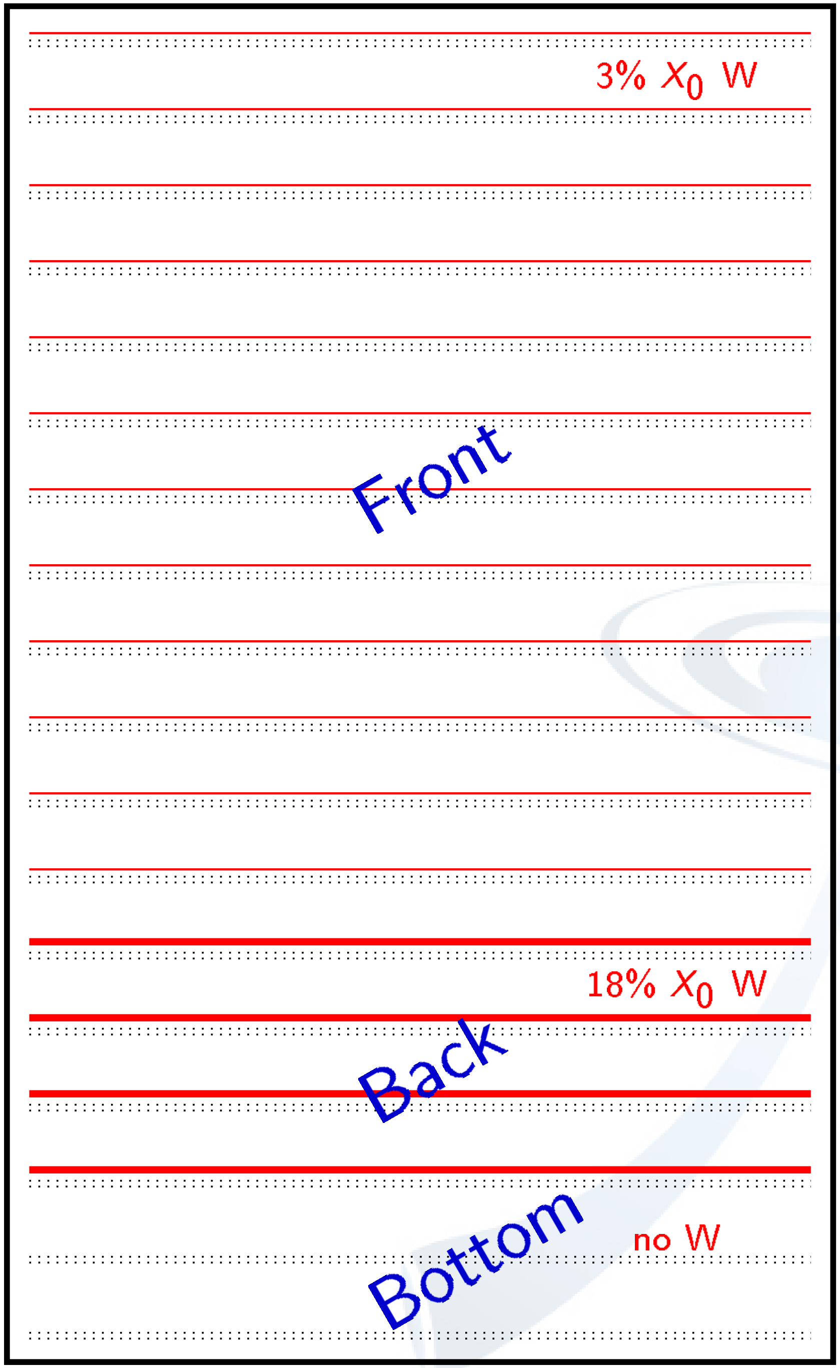
- If ionizing radiation interacts in depletion zone, current can flow to electrodes (analogous to gaseous detectors)
- Reverse bias is used to increase size of depletion zone (as large as several mm)
- Microstrip detectors
  - Long thin strips provide good resolution in one direction
  - Two crossed planes provide xy resolution
- Pixel detectors
  - Compact in both dimensions for xy resolution in a single detector
- Very good spatial resolution (better than wire chambers) but more expensive and subject to radiation damage
- Often cooled to reduce noise
- Much denser than gaseous detectors
- ~10^4 ion pairs per ionizing particle event: low noise electronics necessary



Microstrip detectors

- Each strip provides precise resolution in 2 of 3 dimensions
- Produced with many strips per sensor
- Example: single sensor with 512 strips with 130 µm pitch
- Width chosen based on resolution required (balanced against number of readout channels)
- Thickness comparable to depletion width
- Length as long as is feasible for manufacturing high purity silicon (~10 cm)

The Fermi LAT tracker



- Tracker is 1.5 radiation lengths total on axis (63% conversion efficiency)
- 73 m^2 of active silicon
- 11.5k sensors (silicon strip detectors)
- 0.9 M readout channels
- 18 xy silicon planes alternating with passive tungsten converter layers
- Front: 12 planes with 95 μm (0.03 X_0) converter
- Back: 4 planes with 720 μm (0.18 X_0) converter
- 400 μm silicon thickness
- 228 μm strip pitch
- 160 W power consumption (of 650 W total), compared to 1100 watt toaster

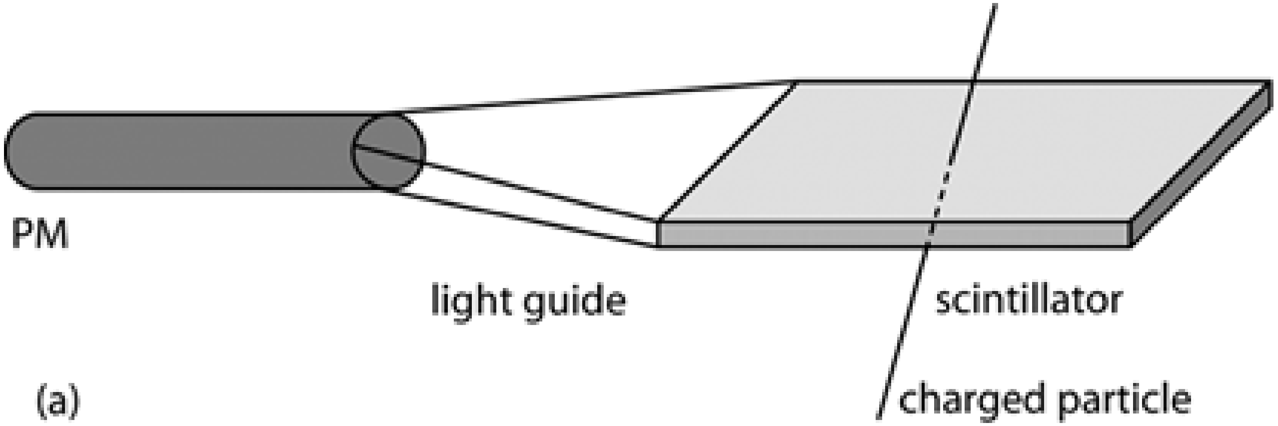
Scintillation light

- While collection of ionization is difficult in solids and liquids, scintillation light can be used instead as a proxy for charge collection
- Isotropic emission
- Depending on material, ~100x more photons than Cherenkov light
- Emitted at one or more spectral lines, not continuum
- Time scale of pulse is directly related to decay time of excited atom: short decay times are desirable
- Sometimes emitted in UV and one or more wavelength shifters (fluorescent material) are necessary to match material transparency and/or photo-detector sensitive band
- Wavelength shifters also have decay time, which is preferably short
- Depending on material, amount of light is roughly linear with deposited energy in ionization
- Large index of refraction (~1.5) promotes total internal reflection
- Scintillators useful for: calorimetry, spectroscopy, tracking, veto

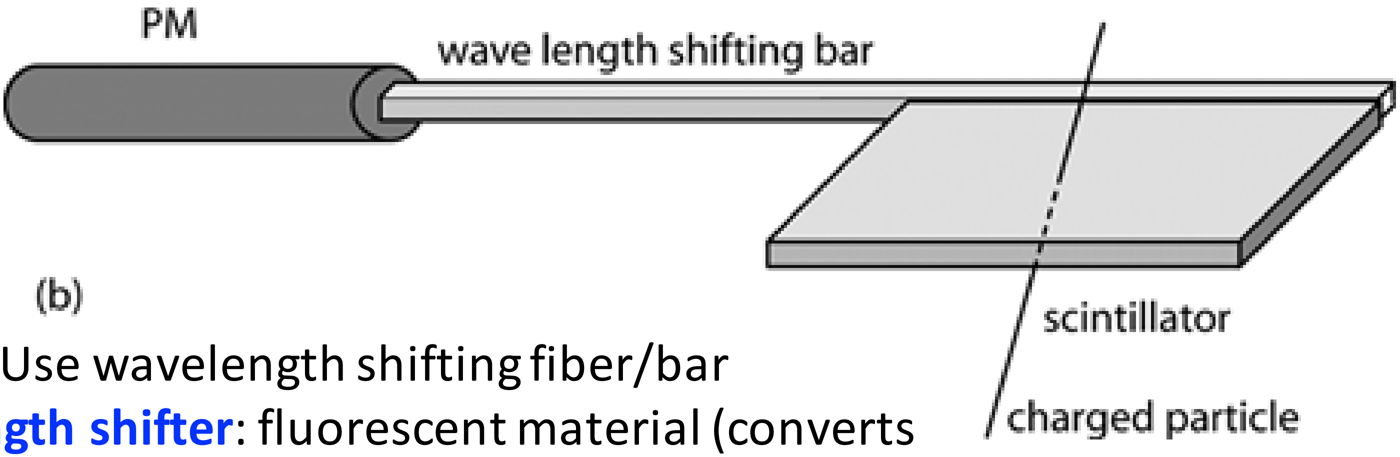
Types of scintillators

- Recall radiation length scales with $(Z)^{-1}(Z+1)^{-1}$
- **Organic solid (including plastic)**
  - Small Z (long radiation length)
  - Less expensive
  - Useful for charged particle tracking, calorimetry, veto
- **Inorganic solid**
  - Large Z (short radiation length)
  - More expensive
  - Useful for X-ray and gamma ray detection and calorimetry
- **Liquid**
  - Fluor (e.g. organic scintillator) dissolved in solvent/oil (useful for large neutrino detectors)
  - Argon, xenon (useful for collecting light and charge: TPCs)
- **Nitrogen (air)**

Readout of (plastic) scintillators



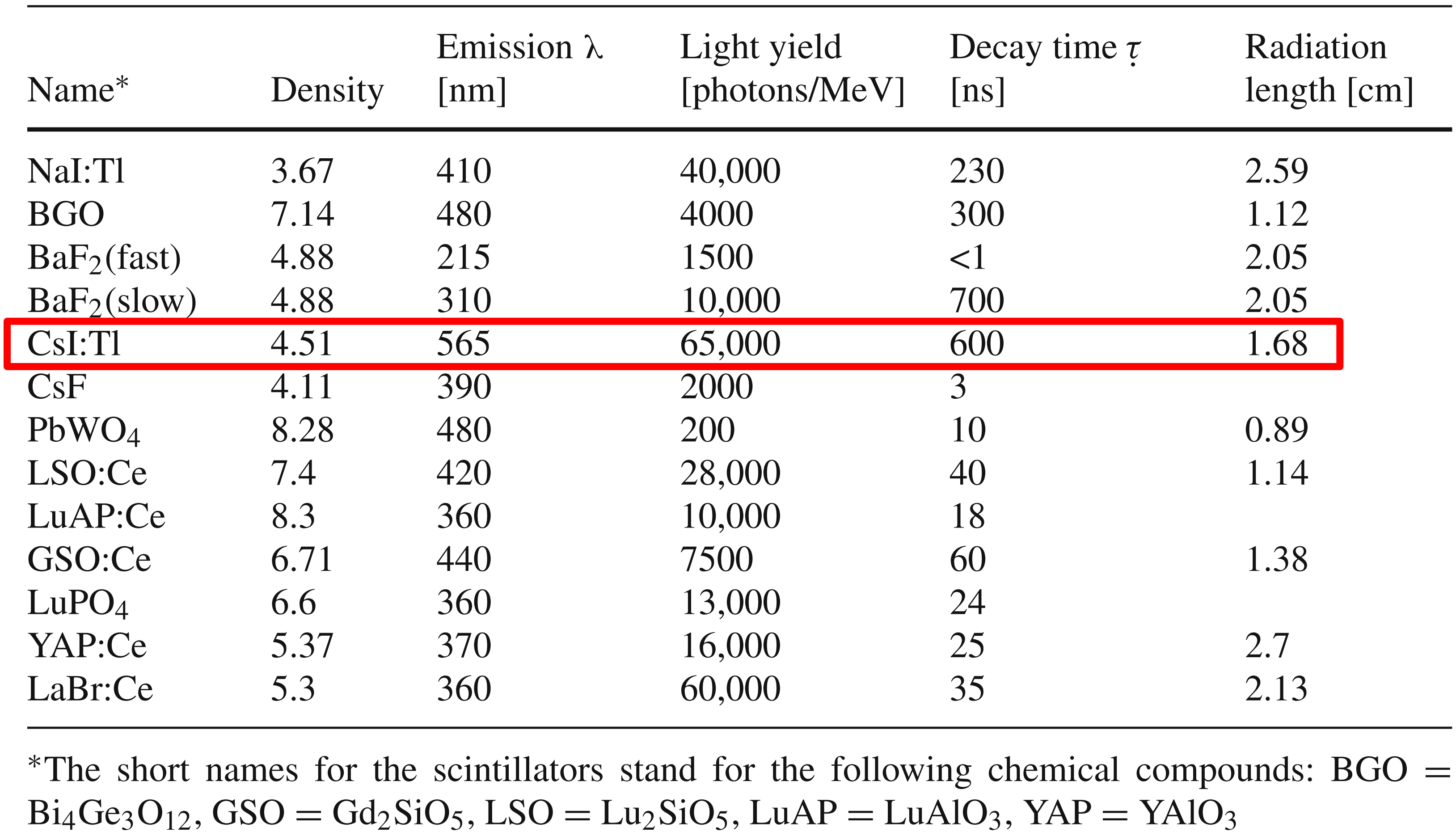
Rely on total internal reflection and use light guide to carry scintillation light to photomultiplier



Use wavelength shifting fiber/bar

Wavelength shifter: fluorescent material (converts short wavelength light to long wavelength)

Inorganic scintillators



Name*	Density	Emission λ [nm]	Light yield [photons/MeV]	Decay time τ [ns]	Radiation length [cm]
NaI:Tl	3.67	410	40,000	230	2.59
BGO	7.14	480	4000	300	1.12
BaF_2(fast)	4.88	215	1500	<1	2.05
BaF_2(slow)	4.88	310	10,000	700	2.05
CsI:Tl	4.51	565	65,000	600	1.68
CsF	4.11	390	2000	3	
$PbWO_4$	8.28	480	200	10	0.89
LSO:Ce	7.4	420	28,000	40	1.14
LuAP:Ce	8.3	360	10,000	18	
GSO:Ce	6.71	440	7500	60	1.38
$LuPO_4$	6.6	360	13,000	24	
YAP:Ce	5.37	370	16,000	25	2.7
LaBr:Ce	5.3	360	60,000	35	2.13

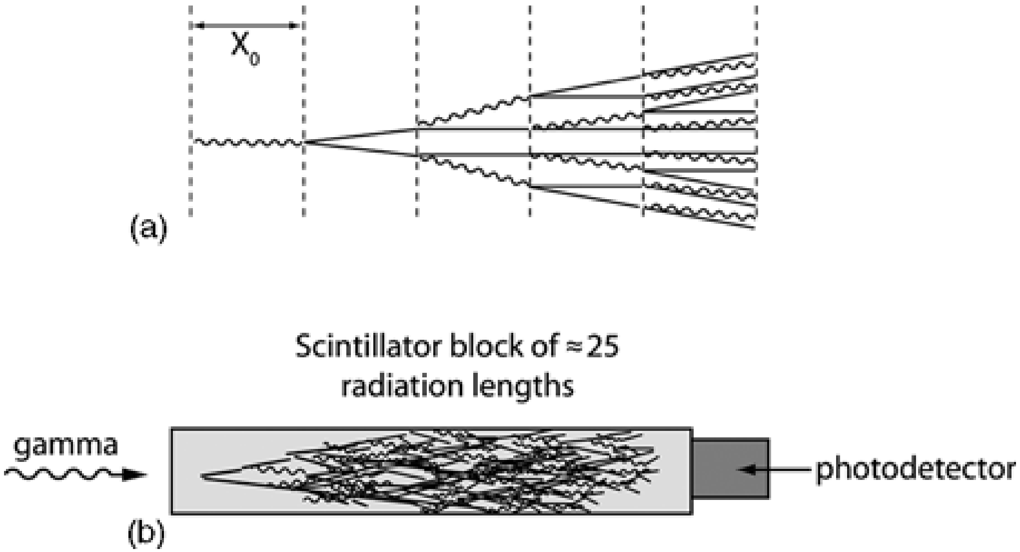
*The short names for the scintillators stand for the following chemical compounds: BGO = $Bi_4Ge_3O_{12}$, GSO = Gd_2SiO_5, LSO = Lu_2SiO_5, LuAP = $LuAlO_3$, YAP = $YAlO_3$

- DAMA: NaI:Tl
- Fermi Large Area Telescope calorimeter: CsI:Tl
- Fermi Gamma-ray Bust monitor: NaI:Tl (0.003 to 1 MeV) and BGO (0.15 to 30 MeV)
- CMS electromagnetic calorimeter: PWO

Calorimeters for particle detection

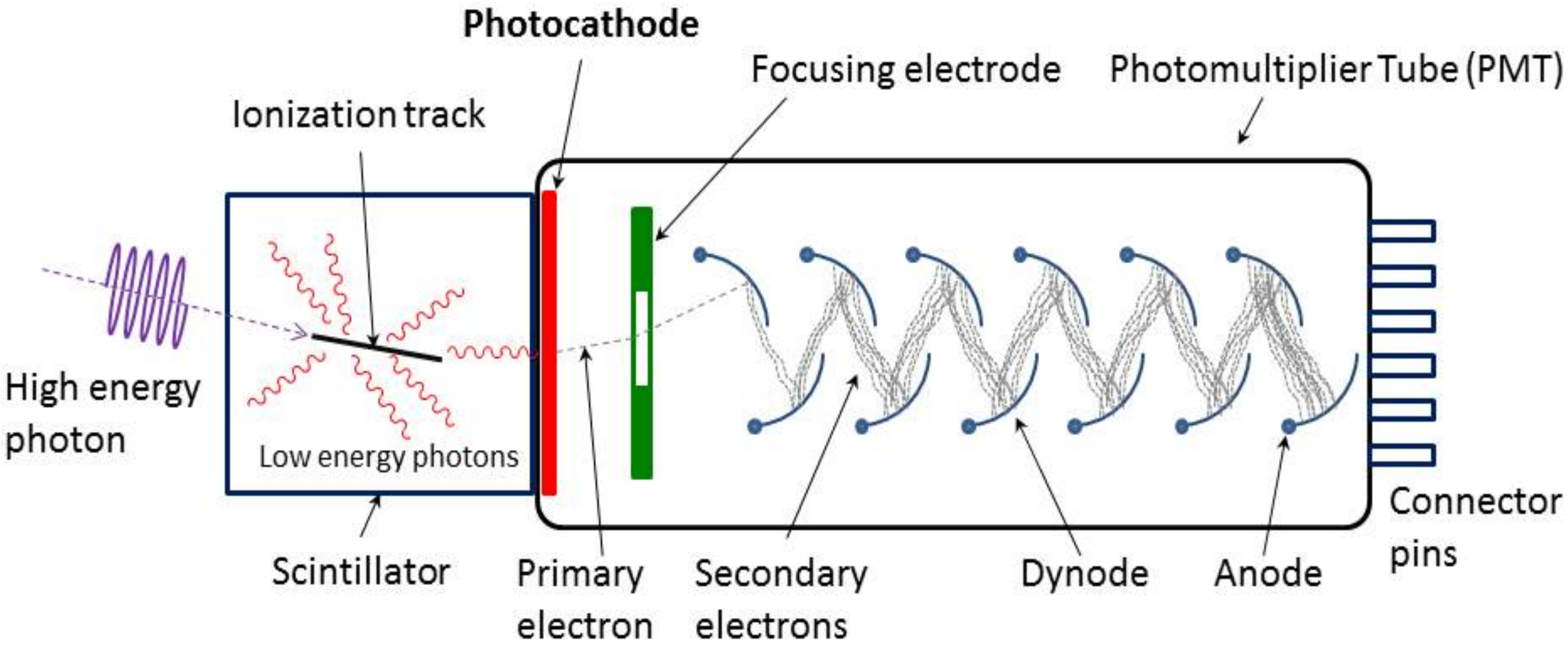
- **Calorimetry**: measuring energy of incident particle by containing entire shower and measuring its energy deposition
- **Homogeneous** calorimeters
  - Can be segmented into blocks read out separately (**hodoscopic**), but fully active
  - Segmentation provides position resolution for tracking incident particle trajectory
  - Fine segmentation can measure 3D development of shower (e.g. in Fermi LAT)
- **Sampling** calorimeters
  - For very large volumes (e.g. for hadronic calorimeters), too expensive to be entirely active
  - Instead, alternate active with passive (e.g. lead or steel) layers
  - Instead of containing entire energy deposition, shower profile is sampled and X_{max} can be determined

Electromagnetic calorimeters



- Typically small enough that they can be fully active rather than sampling
- Purpose is to identify and measure the energy (and trajectory) of gammas, electrons, and positrons
- Needs to be many radiation lengths long to contain full shower
- To fit in small volume, inorganic crystals (high density, short radiation length) can be used
- At accelerators: long, narrow crystals pointing toward interaction point
- Narrower than shower width: center of gravity determines incident position

Photomultiplier tube



- Each electron incident on a dynode produces *d* secondary electrons
- *d* typically 3-10
- For *n* dynode stages, gain = d^n, typically 10^6 or greater to detect single photons
- “Electron optics” of dynode chain optimized for
  - Good gain (favors more dynodes) and collection efficiency
  - Good transit time and transit time variation (favors fewer dynodes)

Wide variety of PMT shapes and sizes

Useful references

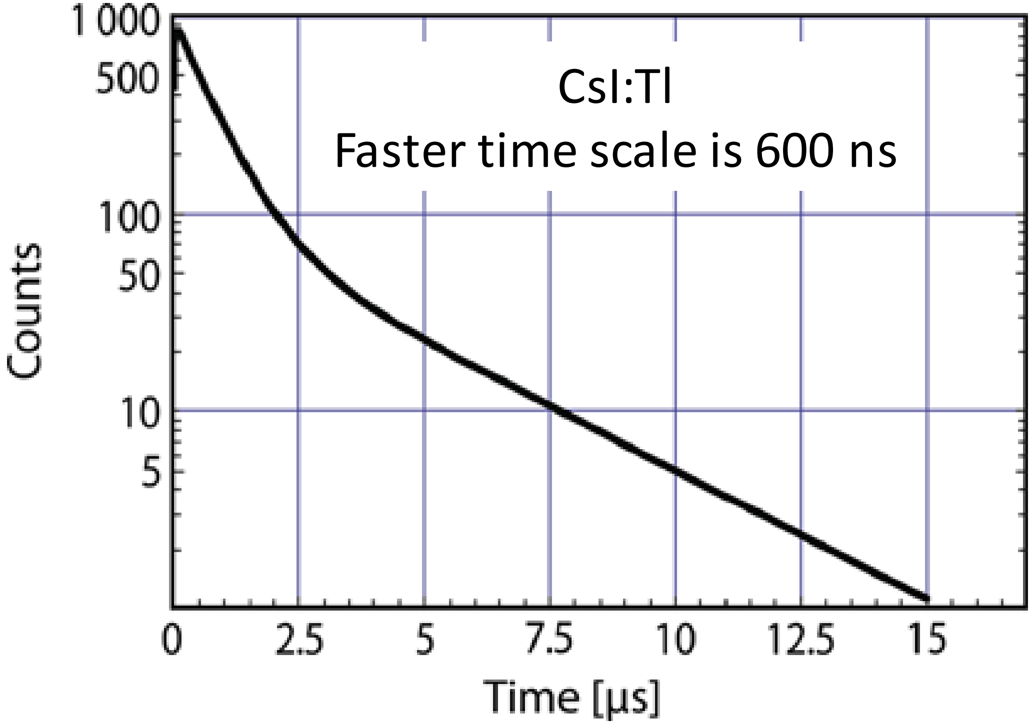
- The Particle Data Book from the Particle Data Group
- Tavernier, Experimental Techniques in Nuclear and Particle Physics
- Leo, Techniques for Nuclear and Particle Physics Experiments
- Knoll, Radiation Detection and Measurement
- Perkins, Particle Astrophysics
- Green, The Physics of Particle Detectors
- Grupen & Schwartz, Particle Detectors
- Ahmed, Physics & Engineering of Radiation Detection
- Slides from a course I teach at UW–Madison, Experimental Methods in Nuclear, Particle, and Astro Physics) https://www.physics.wisc.edu/~justin/teaching/physics736

Conclusions

- Key processes for charged particles: ionization, bremsstrahlung, hadronic interactions, Cherenkov radiation
- Key processes for photons: photoelectric absorption, Compton scattering, pair production
- Key technologies: silicon trackers, scintillating calorimeters, photomultipliers
- Understanding the physical processes underlying particle detectors helps you understand their data
- The same physical processes explain the birth of a particle in an astrophysical source as well as its death in a particle detector

Additional slides

Inorganic scintillators



- Typically ionic crystal doped with luminescent atoms
- Ionizing radiation produces electron-hole pairs
- Instead of collecting the electrons, they are captured by luminescence centers, producing scintillation
- Crystal impurities and defects can trap electrons before they reach luminescence centers: pure crystals desirable
- Can have more than one decay time scale
  - Two different lines (two lines from one dopant or two different dopants)
  - Defects that retain charges for long time
- Example: CsI:Tl (cesium iodide doped with thallium)

Energy resolution of calorimeters

Homogeneous calorimeters

$$\frac{\sigma\{E\}}{E} = \sqrt{\frac{a^2}{E[\mathrm{GeV}]} + b^2}$$

- Energy-dependent contribution (*a*) from statistical fluctuations in number of scintillation photons detected (energy dependent because proportional to E)
- Energy-independent contribution (*b*) from non-uniformities in detector
- Typically *a* between 2% and 3%, *b* between 0.5% and 1%
- Example: CMS a= 3%, b = 0.5%

Sampling calorimeters

- Resolution worse and set by
- Hadronic shower physics
- X_{max} fluctuations

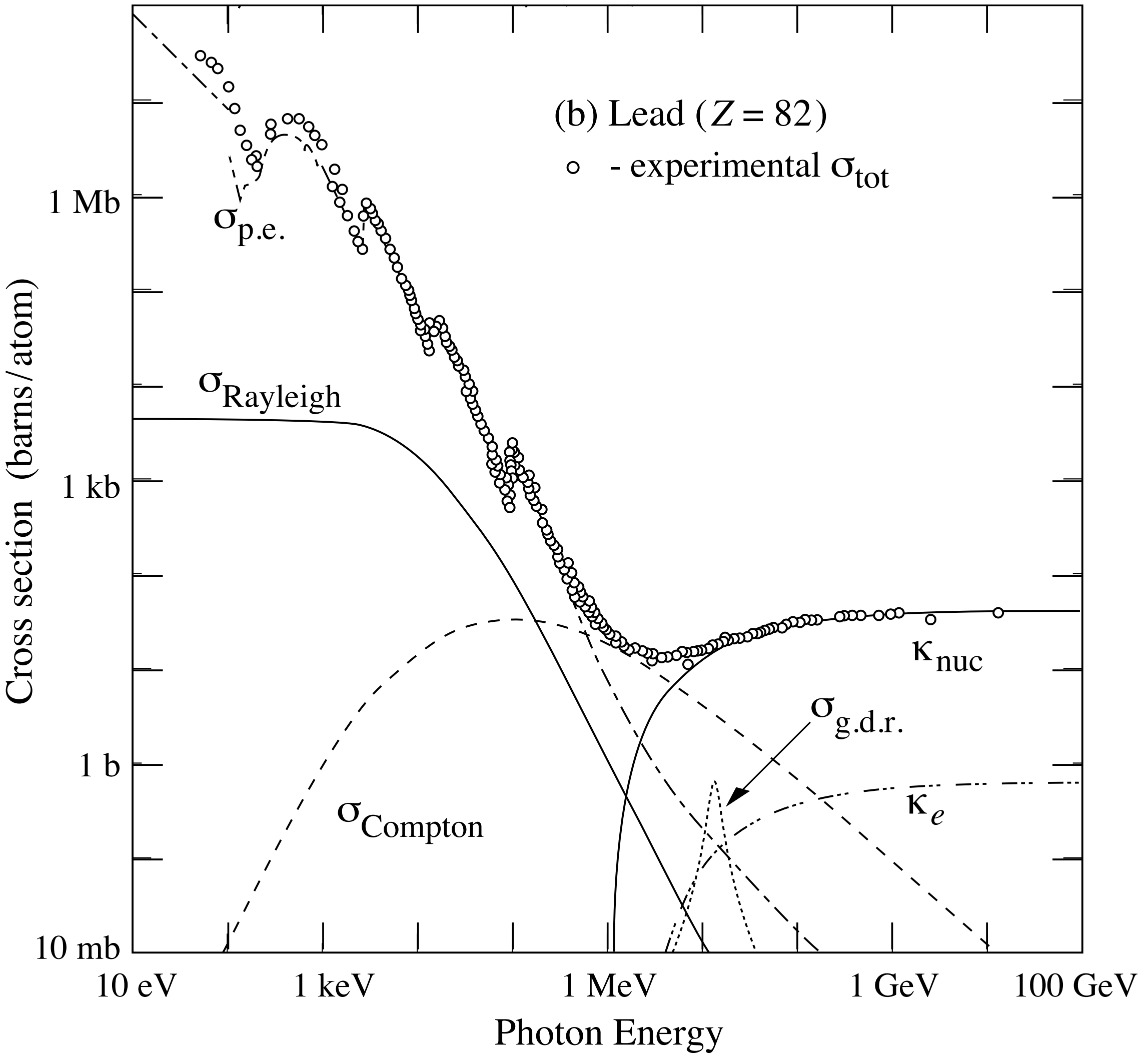
Other useful topics I'm skipping

- Detector technologies: gaseous particle detectors (ion chambers, proportional counters, Geiger counters, spark chambers, wire chambers, drift chambers, time projection chambers), transition radiation, Cherenkov radiation
- Signal mechanisms: fluorescence, phosphorescence
- Scintillator calorimeters for MeV gamma rays
- Other photon detectors: PIN diodes, MAPMTs, APDs, SiPMs

Vocabulary of light production

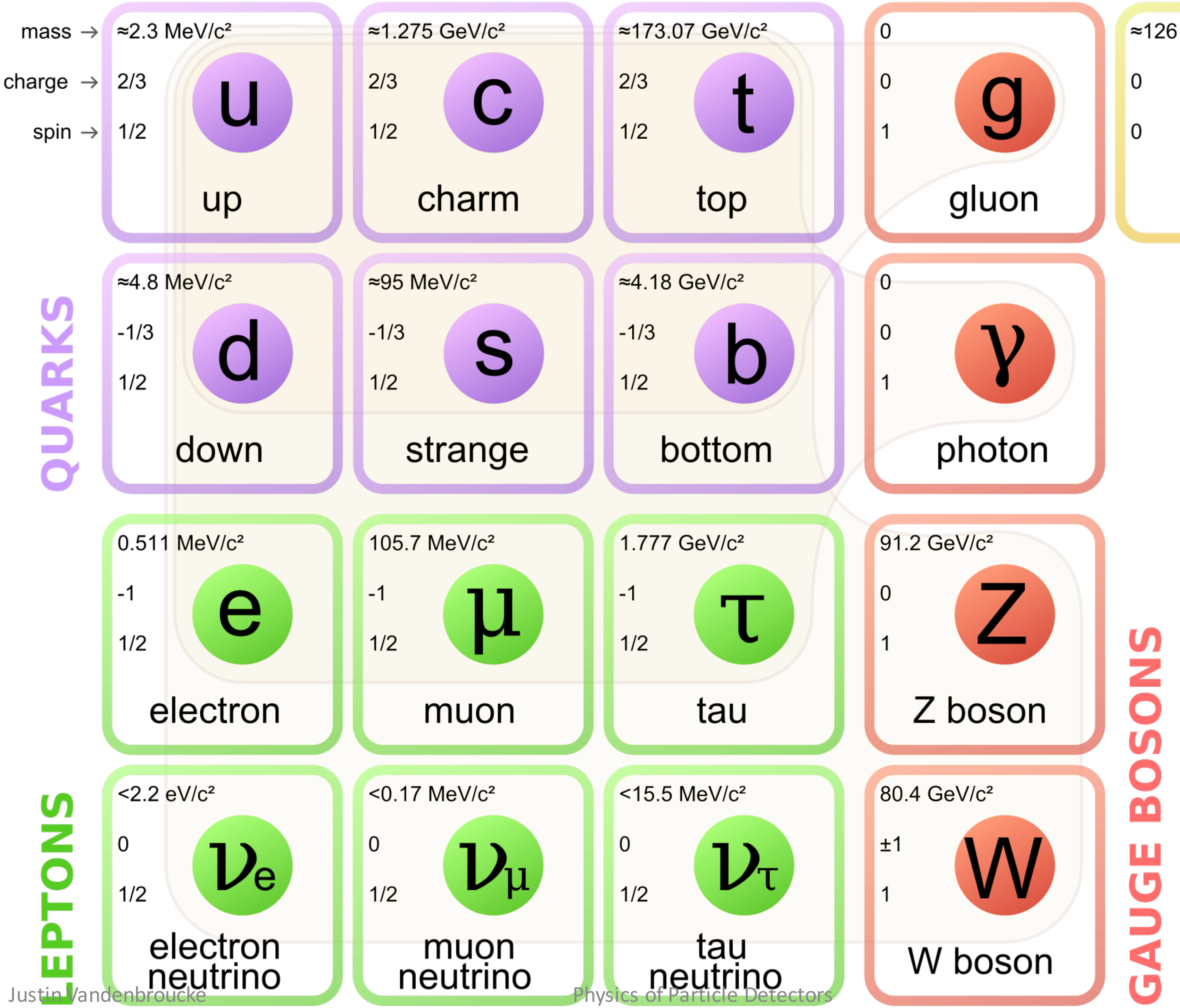
- **Scintillation (= radioluminescence)**
  - Production of a light flash by incident ionizing radiation
  - Deposited energy from energetic particle ~ 1/E
  - Low-energy depositions excite rather than ionize atoms
  - De-excitation releases photons
  - Present in many materials, efficient in some
- **Fluorescence (= photoluminescence)**
  - Incident energy is light that is absorbed, rather than ionizing radiation
  - Name for fluorescent material: fluor or wavelength shifter
- **Phosphorescence**
  - Incident energy can be light or ionizing radiation, but long decay time scale (>1 ms)

Photoelectric absorption edges



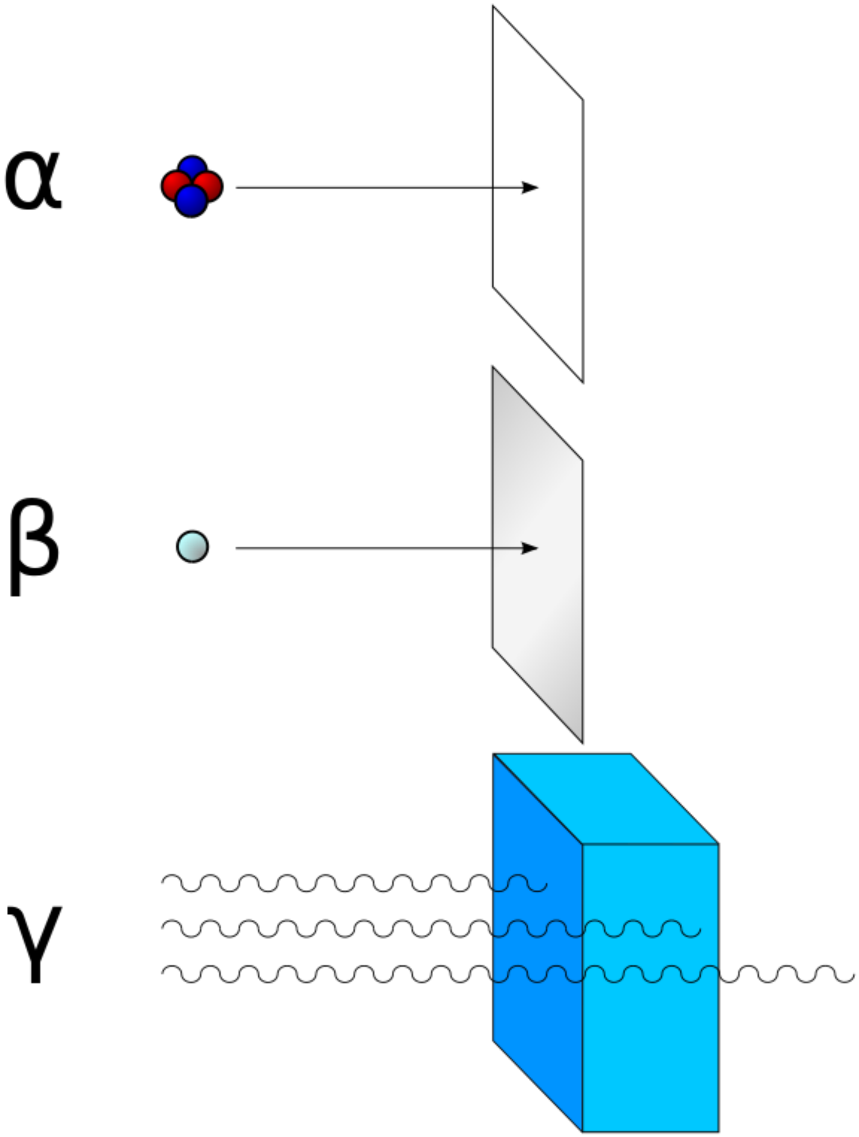
- Electron binding energies in lead (keV): 88.0, 15.9, 15.2, 13.0, 3.9, 3.6, 3.1, 2.6, 2.5

Standard Model review



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

Three types of nuclear radiation

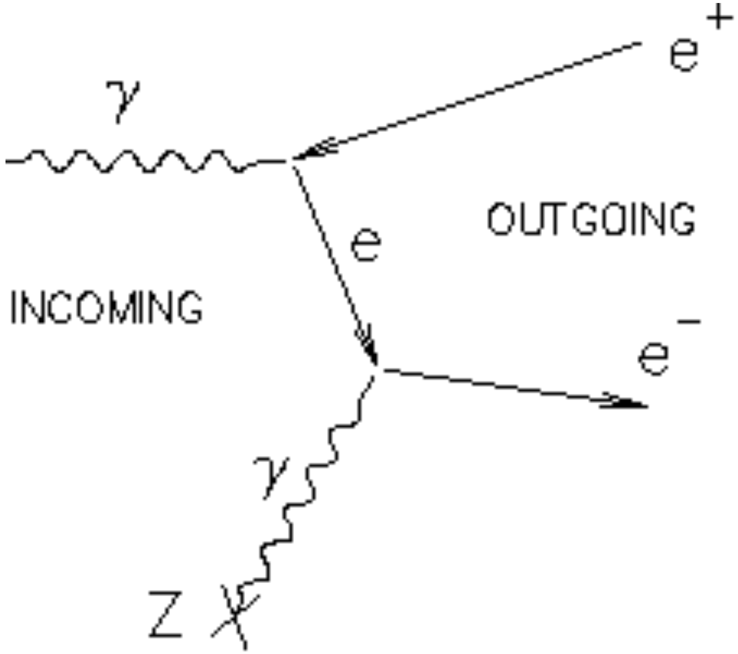


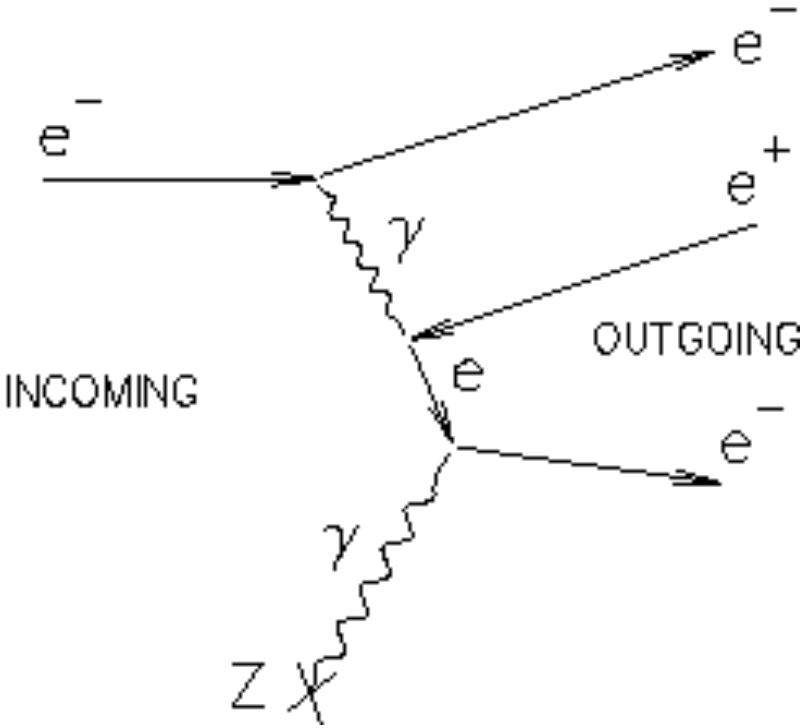
Stopped by single sheet of paper

Stopped by a few mm of aluminum

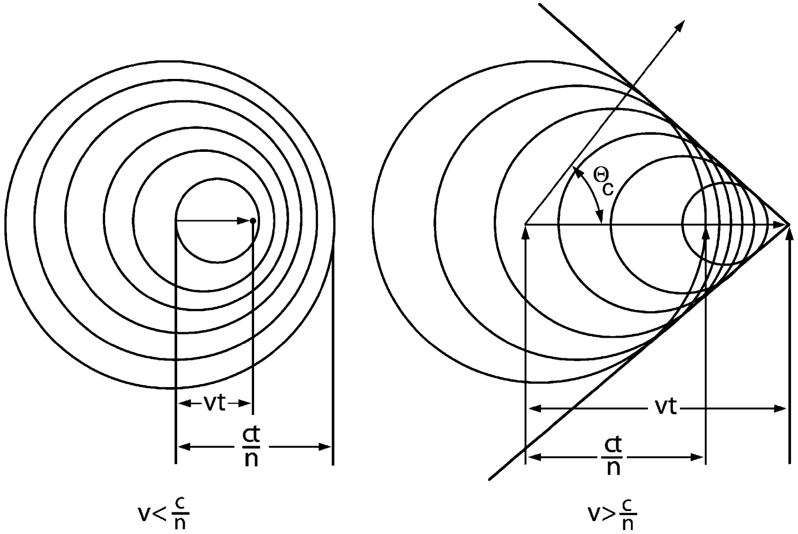
Stopped by several cm of lead

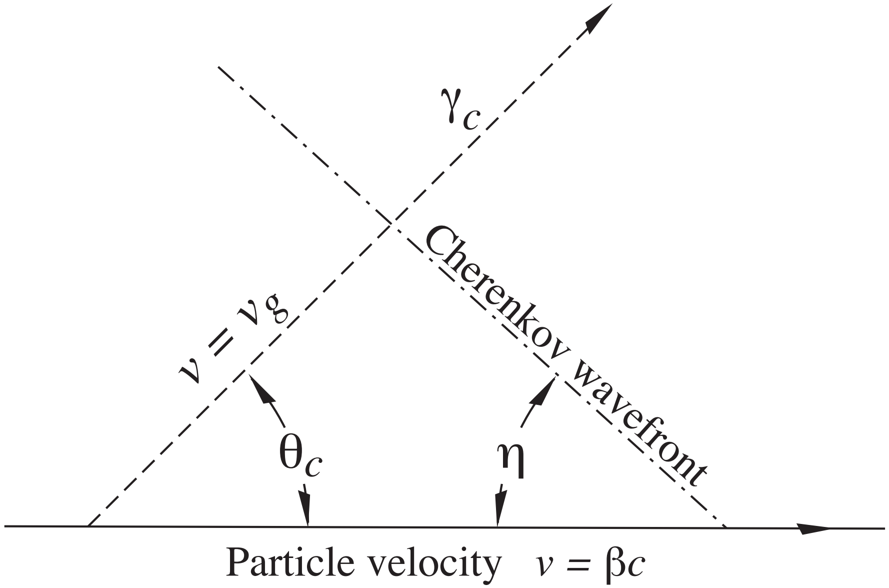
Pair production





Cherenkov radiation





- Due to polarization of medium, produced when a relativistic charged particle travels through a medium faster than the speed of light in the medium (c/n)
- Typically a negligible contribution to particle energy loss
- Very useful for detecting particles and measuring their direction, energy, or mass/identity
- Radiation emitted along a narrow cone of opening angle θ_C (can vary with wavelength):

$$\cos(\theta_c) = \frac{(c/n)t}{\nu\, t} = \frac{c}{n\nu}$$

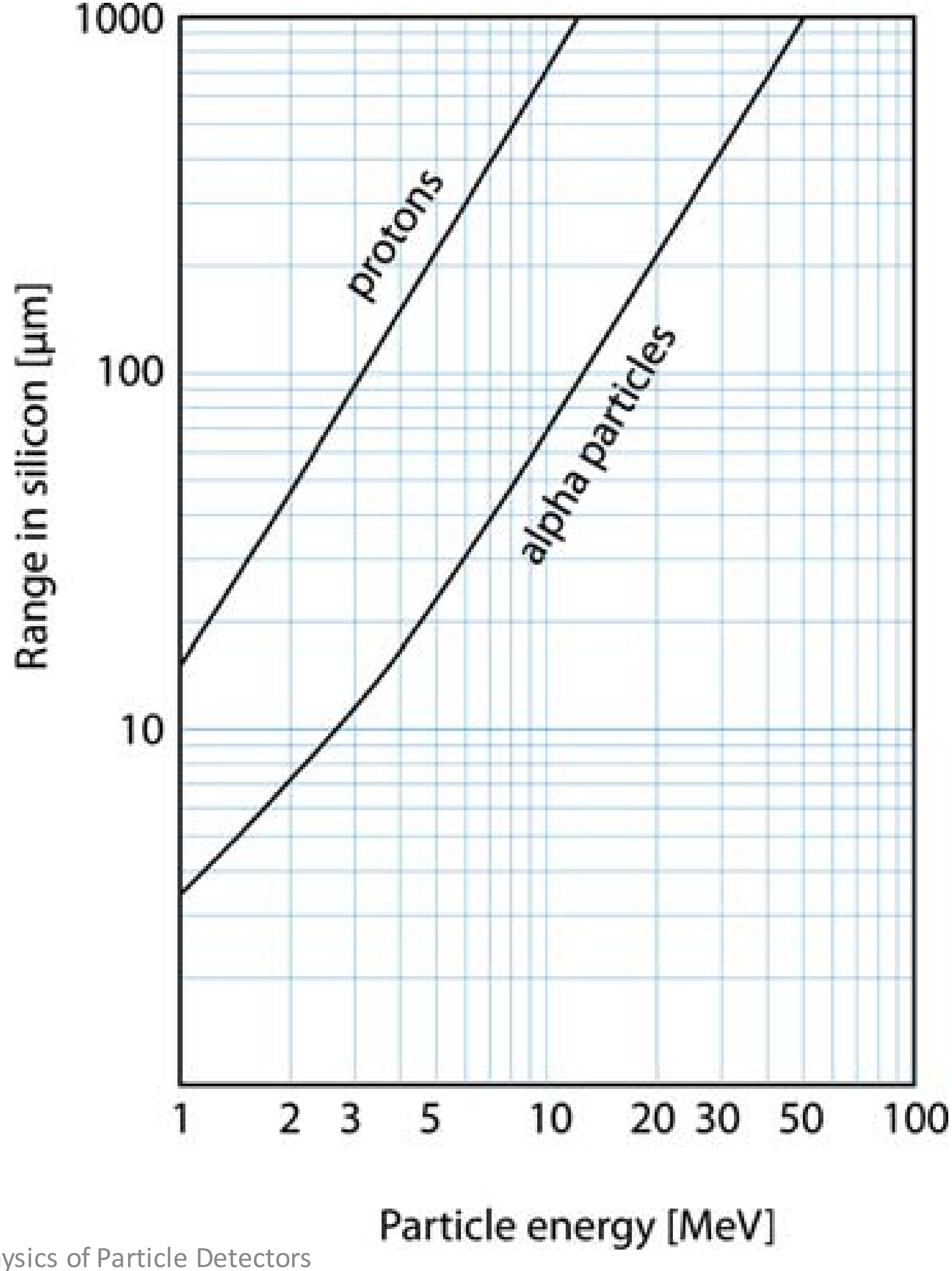
- Radiation intensity scales with particle Z^2
- Spectrum of Cherenkov light increases with frequency (Frank-Tamm formula):

$$\frac{d^2E}{d\hbar\omega.dx} = \hbar\omega\,\frac{Z^2\alpha}{\hbar c}\left[1-\frac{c^2}{n^2\nu^2}\right]\nu > \frac{c}{n}$$

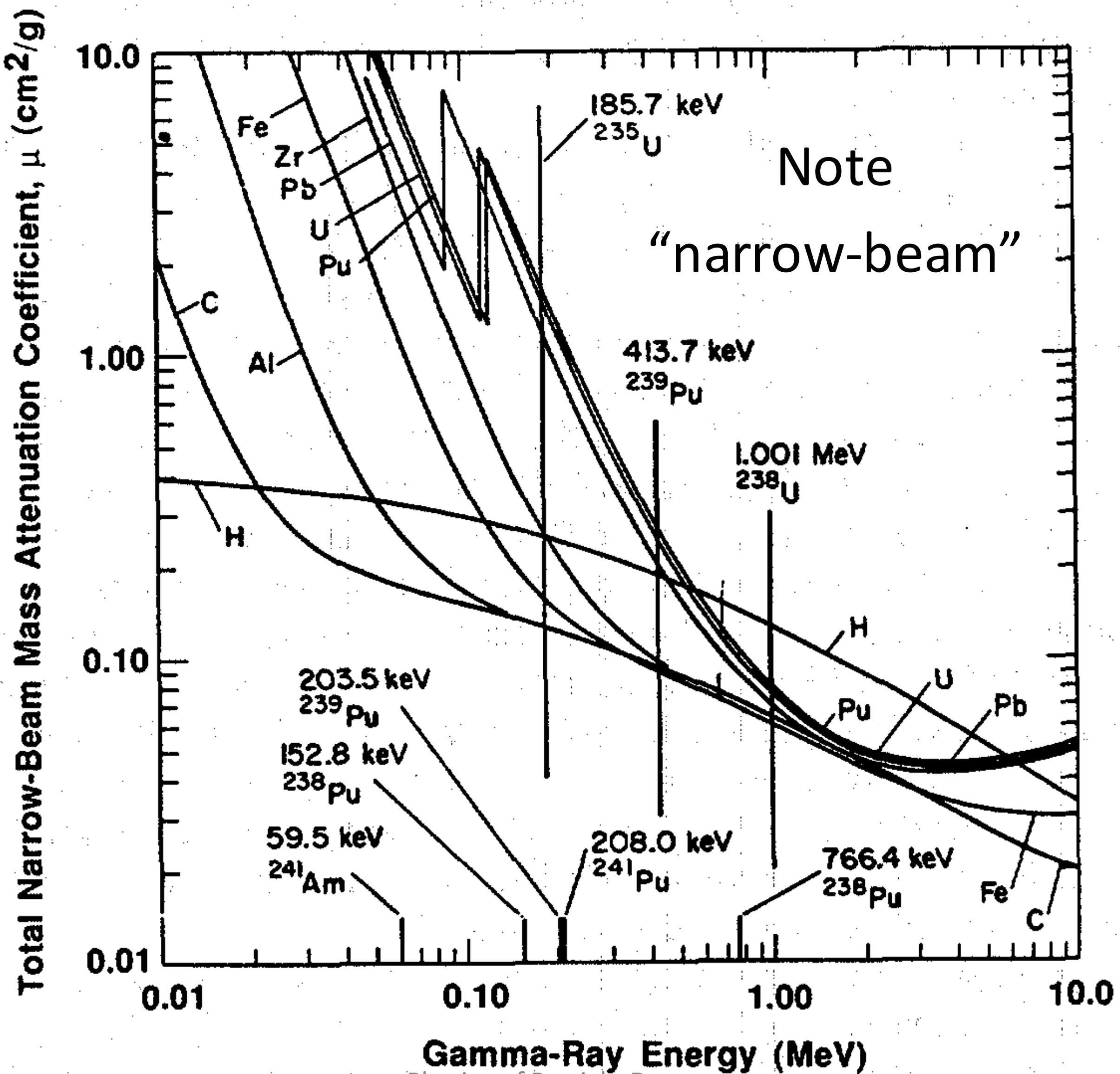
~200 photons/cm in water

Particle range

- Greater energy loss results in a shorter range
- Given dE/dx and E, can integrate to determine range
- Note this is the range considering ionization loss only
- Other interactions and particle lifetime must also be considered



Attenuation coefficient (inverse of attenuation length)

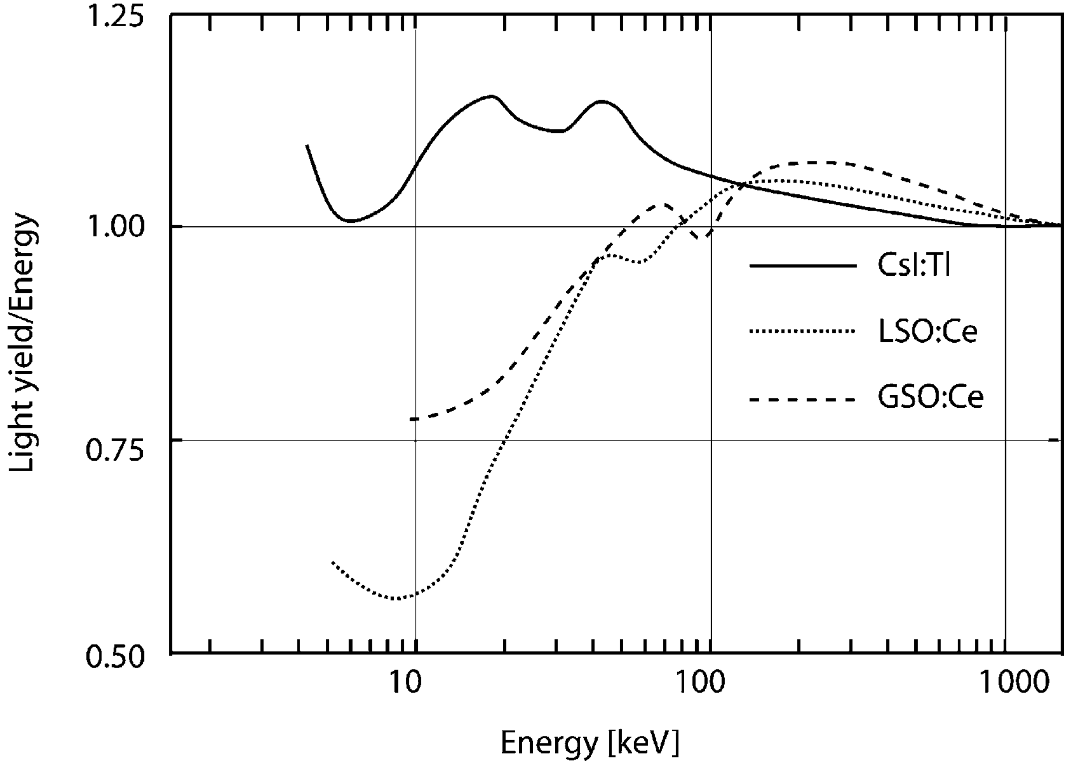


Note
“narrow-beam”

Example: calculation of shower max altitude for 10 TeV gamma ray

- Critical energy in air: E_{crit} = 100 MeV
- Radiation length in air: 36 g/cm^2
- x = total column depth along shower, measured from space toward ground
- X = total column depth of atmosphere (1030 g/cm^2)
- H = scale height of atmosphere, 6.5 km
- h = height above sea level
- Atmosphere column depth model: $x = X \exp(-h/H)$
- Shower max occurs at $x = \ln(E_0/E_{crit}) / \ln 2$ = 16.6 radiation lengths = 615 g/cm^2
- Plugging in to atmosphere model, altitude of shower max is 3.4 km

Linearity of scintillator light yield



- Can be calibrated
- However, nonlinearity especially a challenge for nuclear gamma ray energy measurement
- A ~1 MeV gamma can pair produce, or photo-absorb, or Compton and then photo-absorb
- If response is nonlinear, detected scintillation light depends on interaction history of incident gamma even for a constant incident gamma energy

Hadronic calorimeters

- Purpose is to measure energy (and trajectory) of hadrons (protons, neutrons, pions, kaons, …)
- First hadronic interaction typically produces many pions, which produce electromagnetic sub-showers and outgoing hadrons can also interact again to continue hadronic shower
- Radiation length scales as $Z^{-1} (Z+1)^{-1}$:

$$\frac{1}{X_0} \approx 4\alpha\, r_0^2 \frac{\rho N_\mathrm{A}}{A_\mathrm{r}} Z_\mathrm{nucl}(1 + Z_\mathrm{nucl}) \ln\left(\frac{183}{\sqrt[3]{Z_\mathrm{nucl}}}\right)$$

- Hadronic interaction length scales as $A^{1/3} \sim Z^{1/3}$:

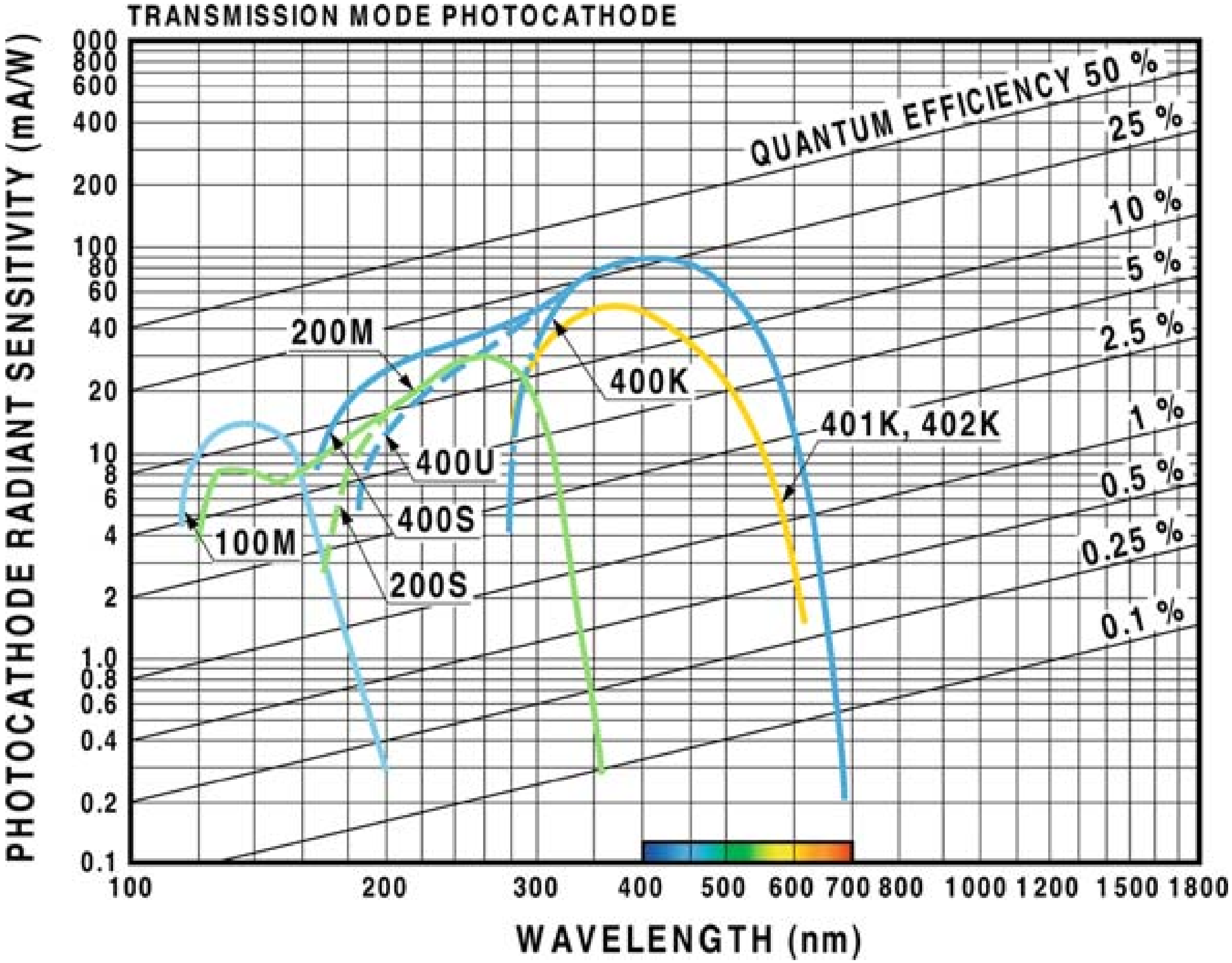
$$\lambda = \frac{1}{N\sigma} \approx \frac{A^{1/3}}{\rho} \frac{1}{N_A\, 4 \times 10^{-26}} \approx \frac{A^{1/3}}{\rho}\, 35\,\mathrm{g/cm^2}$$

- At high Z, $\lambda >> X_0$:

Element	Z	X_0 (cm)	λ (cm)
Iron	26	1.76	16.8
Copper	29	1.43	15
Tungsten	74	0.35	9.6

- Therefore hadronic calorimeters typically sampling, not homogeneous

Quantum efficiency

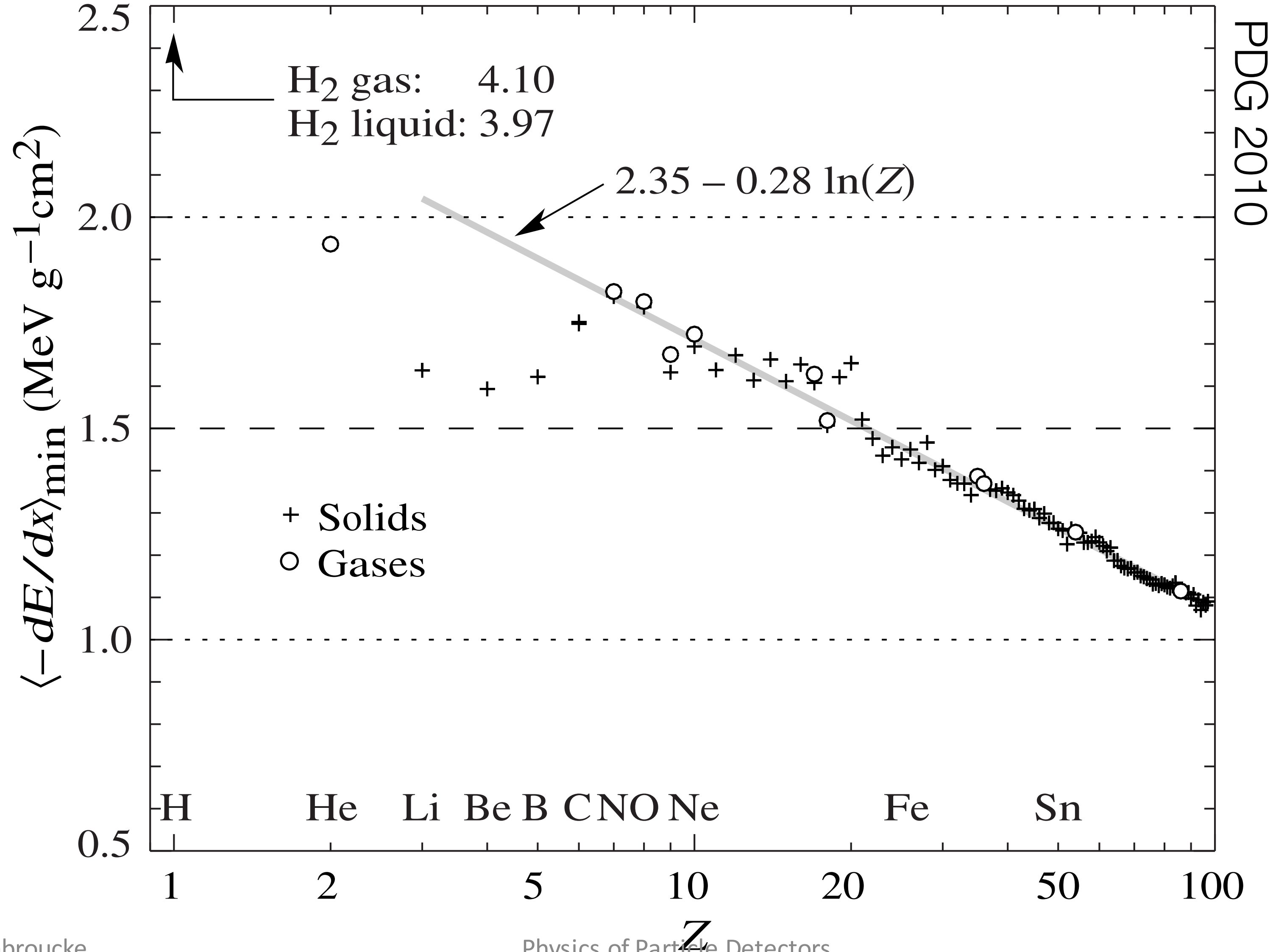


- **Quantum efficiency** = Fraction of photon absorption events that result in photo-electron emission by metal surface
- Function of wavelength for each material
- Choice of photocathode material determines QE as function of wavelength
- Typically peaks ~25%
- High quantum efficiency devices now available up to ~35-40% (more expensive)

Photomultiplier glass materials

- Glass often has trace radioactivity (potassium)
- For low-background experiments, special low-activity PMTs or silicon photodetectors can be used
- PMT window typically cuts off in UV
- Difficult/expensive to achieve good UV response
- Borosilicate glass passband: near IR to 300 nm
- Example challenge: xenon (for double beta decay and dark matter experiments) scintillation light is 175 nm

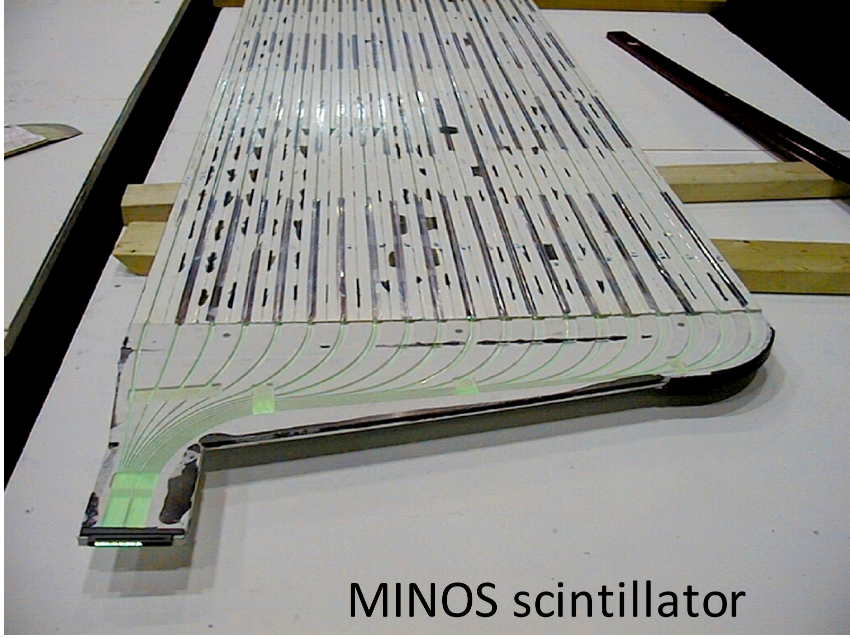
Minimum ionization loss is ~2 MeV/cm times the material density



Organic scintillators

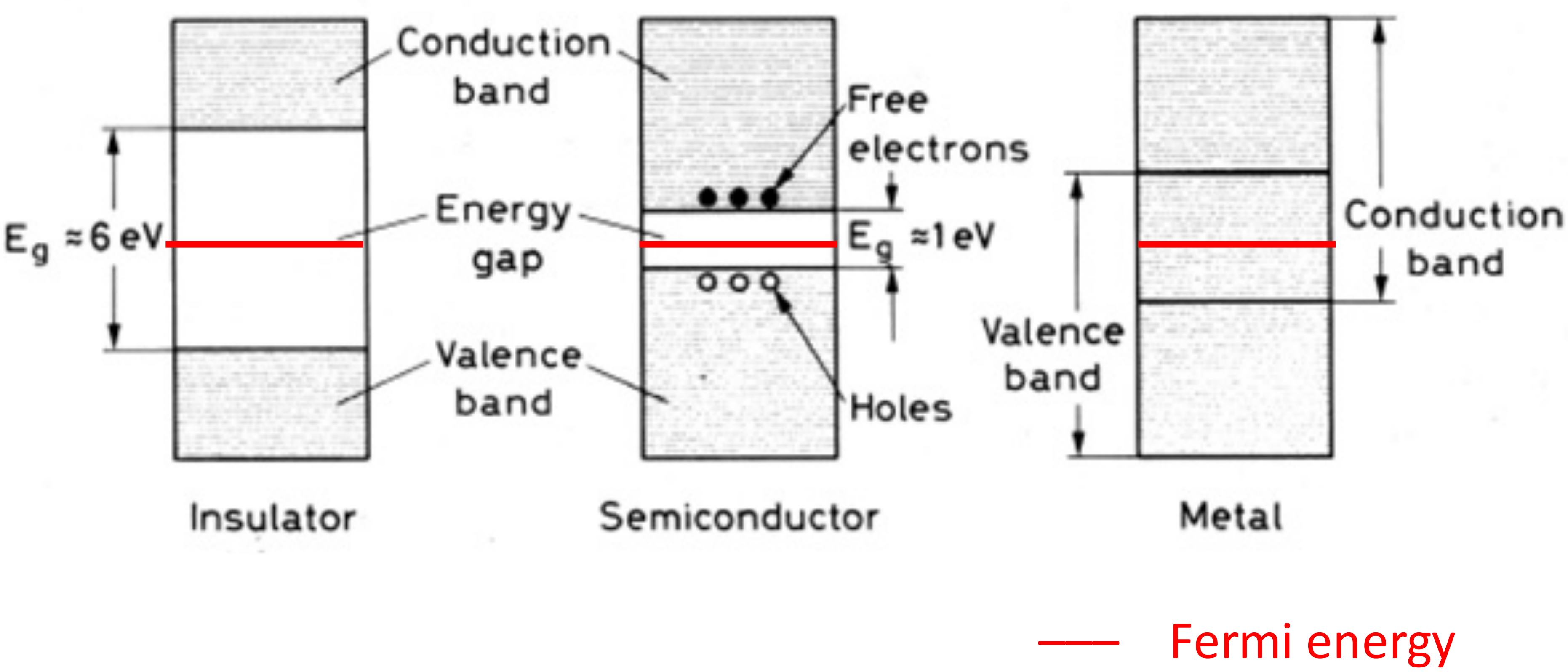
- **Organic crystals**
  - Expensive, not often used
- **Organic liquids**
  - Organic scintillator dissolved in solvent
  - Inexpensive per volume (useful for neutrino detectors)
- **Plastic**
  - Polystyrene (commonly used)
  - Polyvinyltoluene
  - Can be made in arbitrary shapes and sizes
  - Scintillate in UV, but short (few mm) absorption length
  - One or two fluors mixed in material to shift wavelength (shifting is sometimes two-step process)

Example plastic scintillator


MINOS scintillator

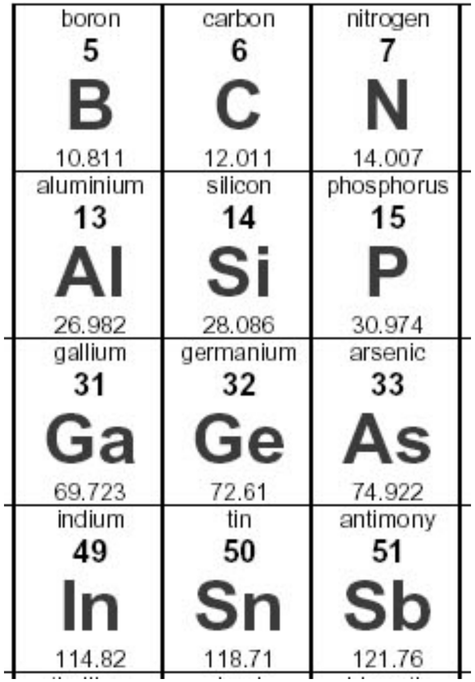
- Extruded polystyrene
- Two Fluors
  - 1% PPO: $C_{15}H_{11}NO$ = 2,5-diphenyloxazole
  - 0.03% POPOP = 1,4-di(-5phenyl-2-oxazolyl)-benzene(0.03%), used in liquids also
- Flours mixed into liquid at 200 °C
- Can be extruded up to 10 m long
- Channels (on surface) or hole (through volume) can be included for wavelength shifting fibers for readout
- Fabrication facility at Fermilab produced large volumes for
- Used for Double Chooz, Mu2e, MINOS, maybe IceCube

Conductors, insulators, and semiconductors

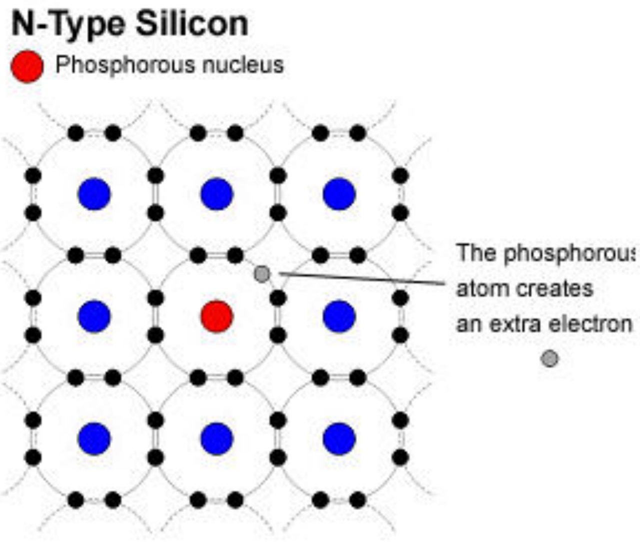


- Metal: no band gap, good conduction
- Insulator: large band gap, no electrons populate conduction band
- Semiconductor: small band gap, thermal tail of electrons populate conduction band

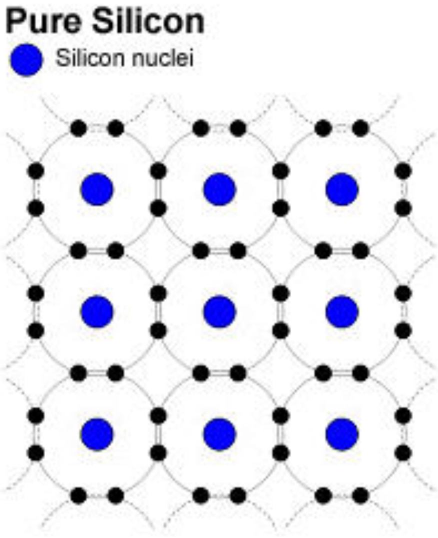
Doping

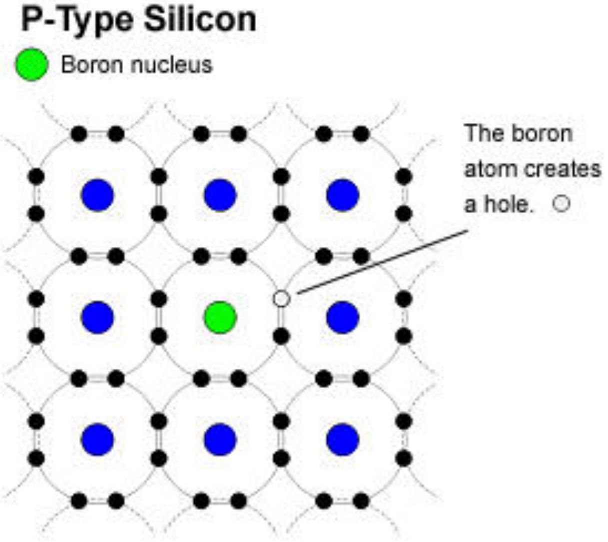


boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007
aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974
gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922
indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76



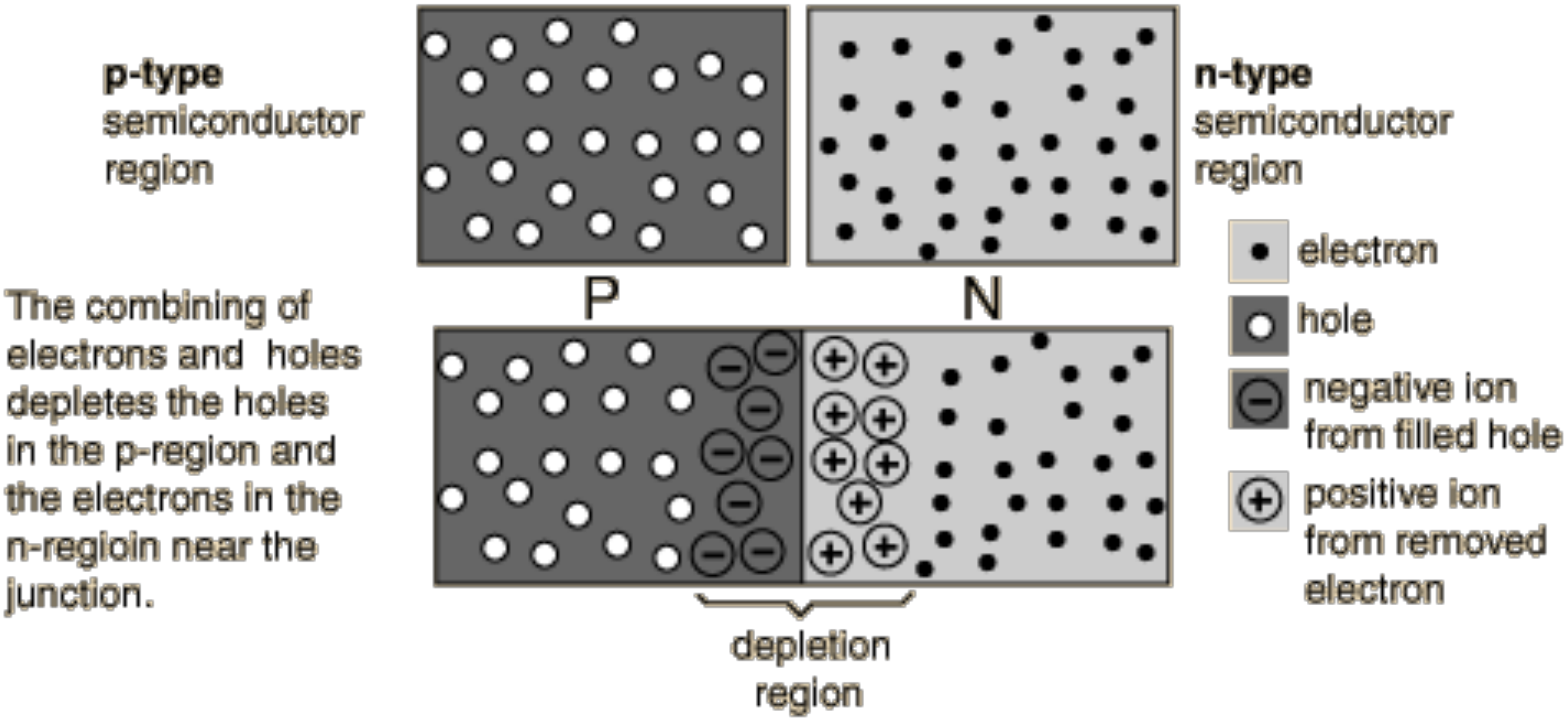
The phosphorous atom creates an extra electron





The boron atom creates a hole. ○

PN junction



- One crystal with p-type and n-type regions and interface between them
- Near interface, electrons and holes diffuse toward one another, swapping positions
- This halts when significant charge difference accumulates
- A voltage is naturally established (~0.6-0.7 V)
- **Depletion region** near interface now has no mobile charge carriers