Interactions of Particles with Matter – Part 1

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UNIVERSITY OF BIRMINGHAM

UK Adv Instr 2024

Two Lectures

Lecture 1: Mechanics of Particle Interactions with Matter

- Define “particle” interactions with “matter”
- Ionizing Radiation
- Non-Ionizing Radiation

Lecture 2: Detecting Particle Interactions with Matter

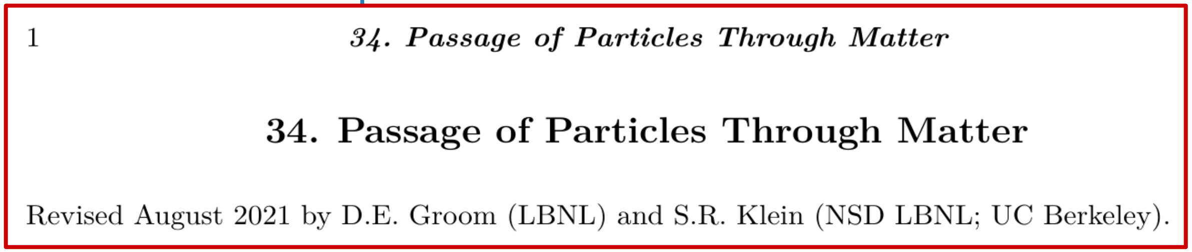
- Efficiencies and energy resolutions for individual sensors
- Brief overview of silicon sensor technologies
- Gaseous detectors for tracking
- Signal formation in a single diode

Further Reading

This is a survey lecture to summarize many mechanisms.

The following are references for a more in-depth understanding.

Particle Data Group's Review



1 *34. Passage of Particles Through Matter*

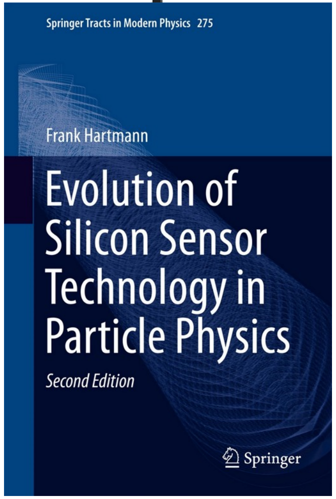
34. Passage of Particles Through Matter

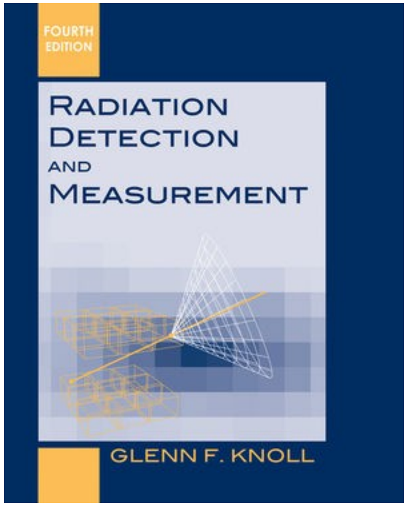
Revised August 2021 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

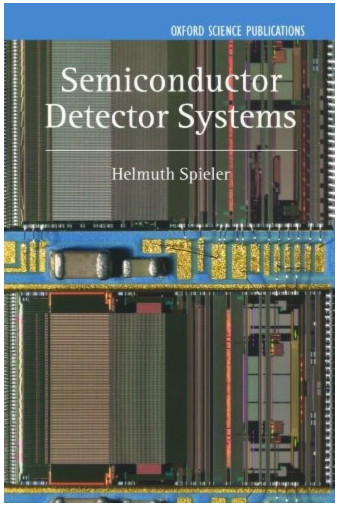
Applications of silicon strip and pixel-based particle tracking detectors

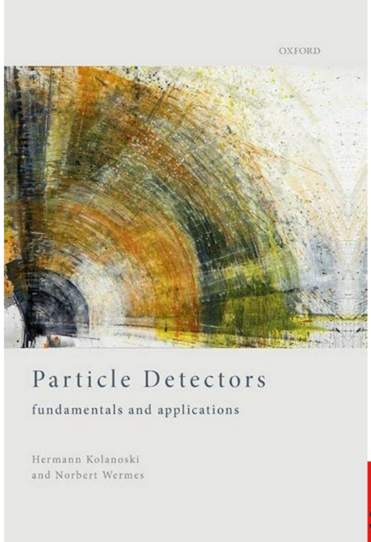
Philip Allport

Nature Reviews Physics **1**, 567–576 (2019) | Cite this article









Material based on Phil Allport's.

Properties of a Particle

How does it interact?

- Type (fermion, boson)
- Neutral, charged.
- Electroweak force, strong force.

Example Types of Particles

How about other particles (muons, pions, taus)?

- **Ions**
  - protons, alpha particles, fission fragments
  - Straight tracks
- **Electrons (β particles)**
  - Negative and positive
  - Scattered tracks
- **Neutrons**
  - Interact only with nucleons
- **Photons**
  - gamma-rays and X-rays
  - Interact with atoms/electrons

Charged Particles

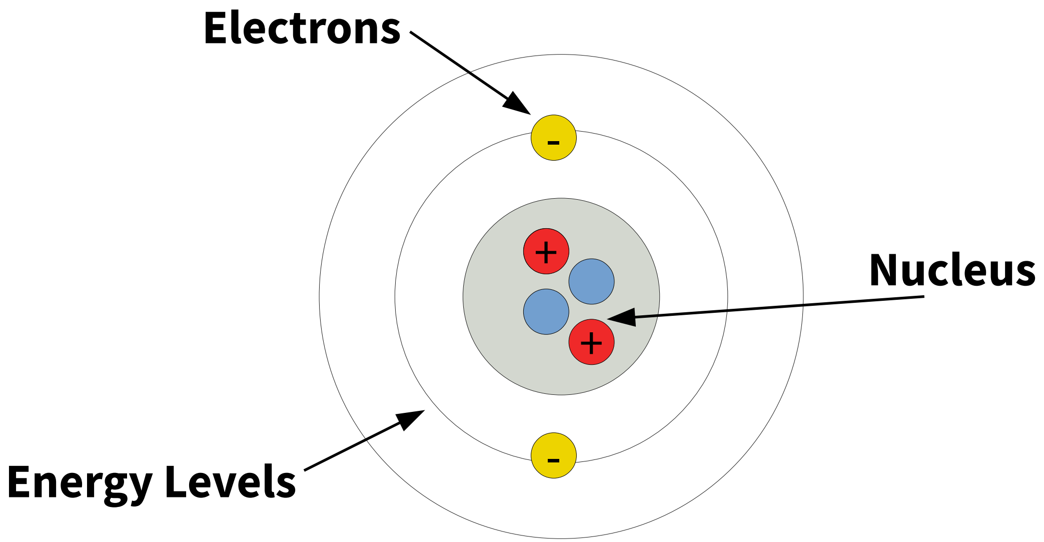
- Ionize atoms along the way
- Can be followed via a “track”

Neutral Particles

- Identified via secondary tracks

What is Matter?

Bohr's Model of the Atom:
A very simplified view, but practical.



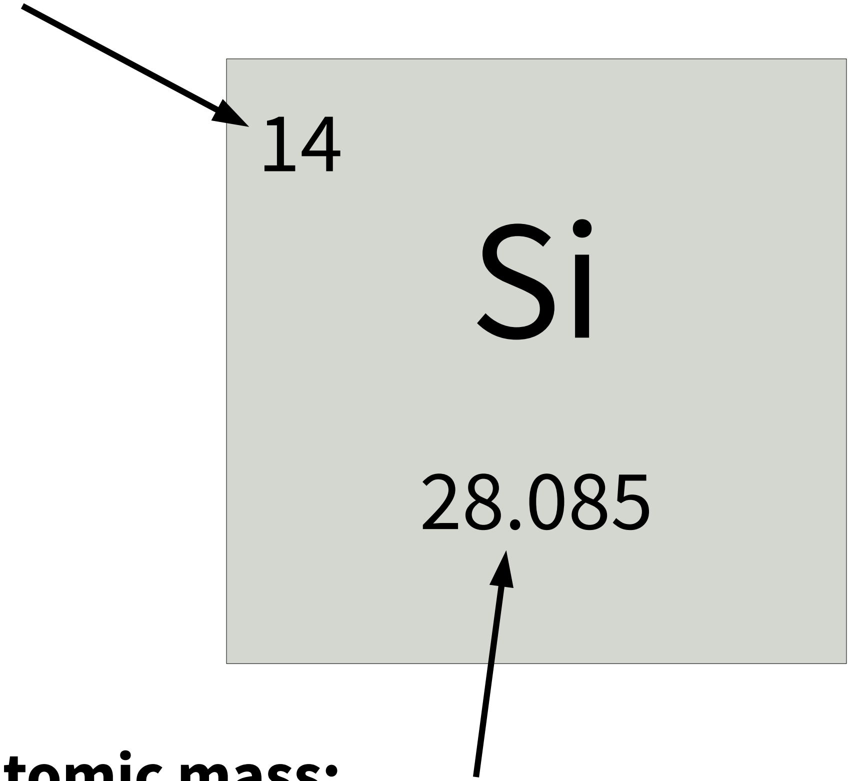
Matter: a collection of atoms bound together.

"solid state physics" for more information

Properties of Matter: Hadrons and Electrons

Atomic number:

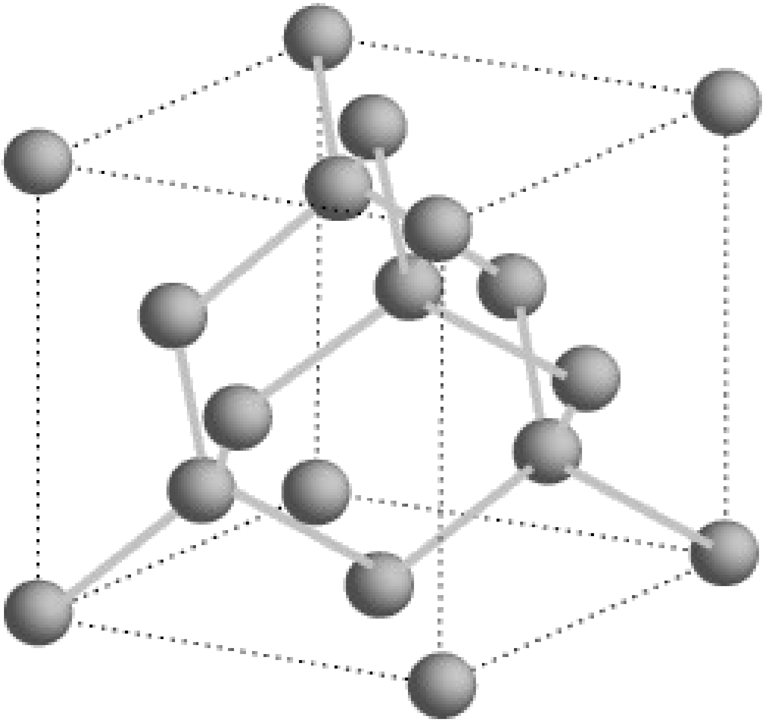
- How many protons.
- Roughly how many electrons. → ionizing interactions



Atomic mass:

- Roughly how many hadrons. → non-ionizing interactions

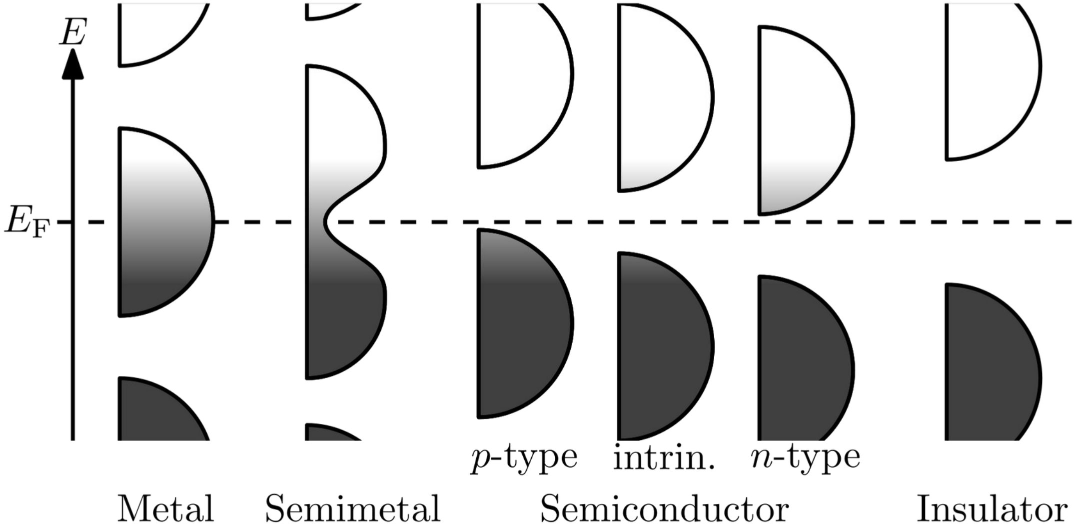
Properties of Matter: Structure



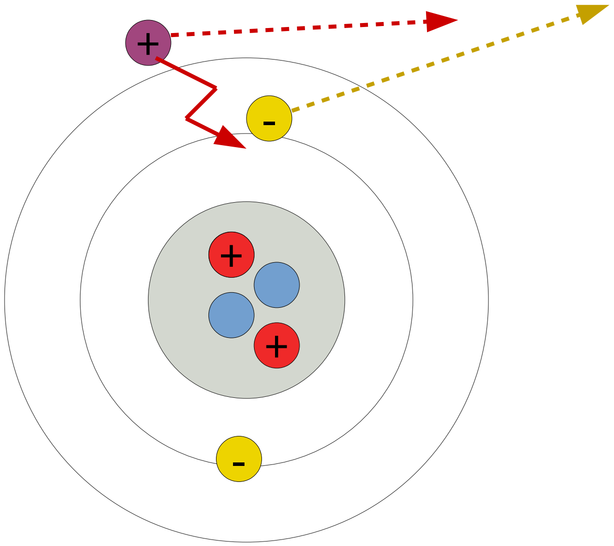
+

$$i\hbar\frac{d\Psi}{dt} = H\Psi$$

=



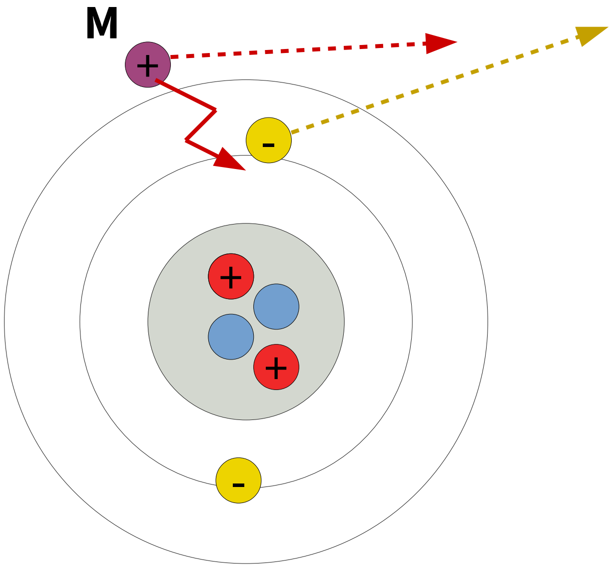
Example Interaction With Matter (Ionizing)



Ionizing interaction:

charged particle comes along and deposits energy to eject an electron from its orbital (or band)

Two Body Elastic Collision



Maximum energy transfer

$$4\frac{Mm_e}{(M+m_e)}E$$

For massive particles

$$\approx 4\frac{m_e}{M}E$$

ex: $m_\alpha \approx 7000\ m_e$

Scattering is stochastic (random) process, but roughly

- Massive particles go through material largely unaffected
- Light particles will scatter a lot

The Bethe-Bloch Formula

Stopping power / Linear Energy Transfer

How much energy does an incoming particle lose per distance

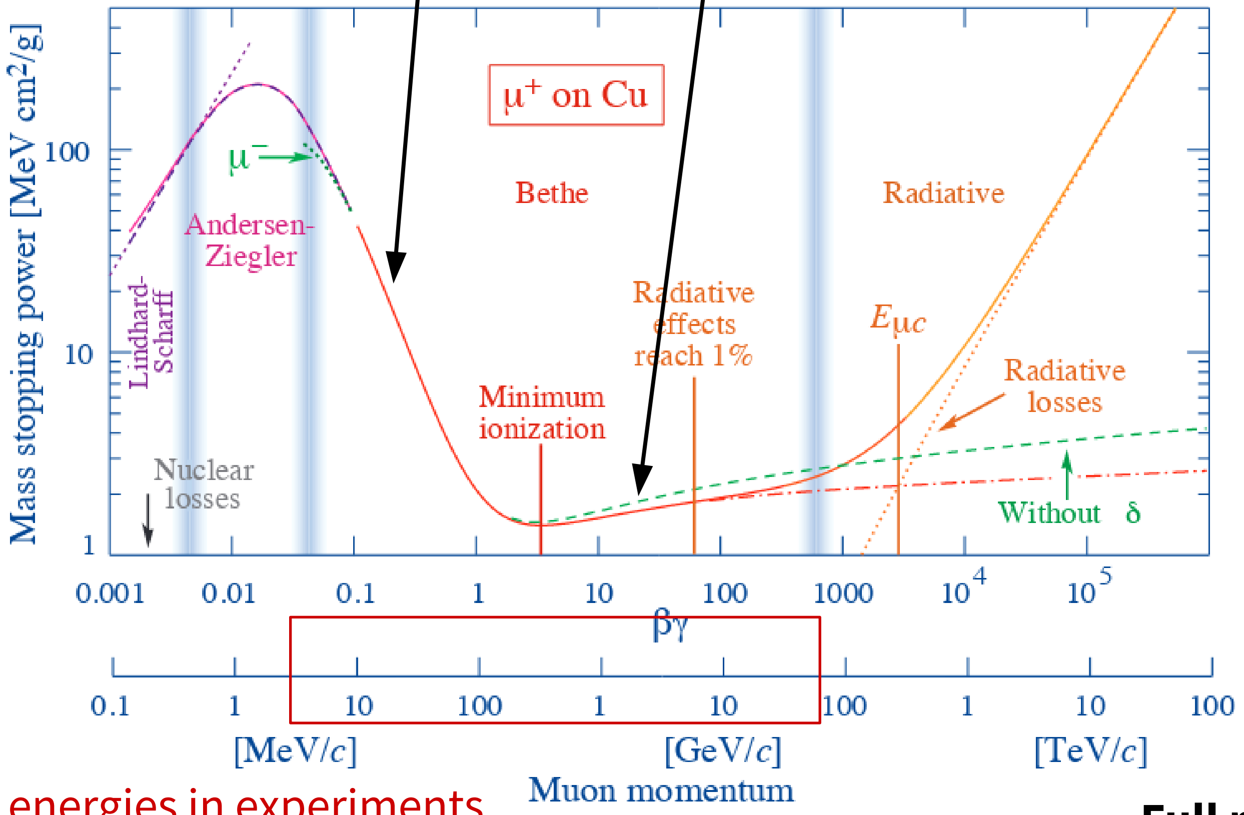
$$-\frac{dE}{dx} \cong \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} N Z \left[\ln \frac{2m_e v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

- e, m_e: charge and mass of electrons
- z,v: atomic number and velocity of incoming particle
- Z,N: atomic number and number density of material
- I: effective ionizing potential of the material atoms
  - Usually measured from data. (examples: hydrogen = 20 eV, other elements = 10 x Z eV).

The Bethe-Bloch Formula Plotted

$$-\frac{dE}{dx} \cong \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \left[\ln\frac{2m_e v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

Independent of material density



Typical energies in experiments

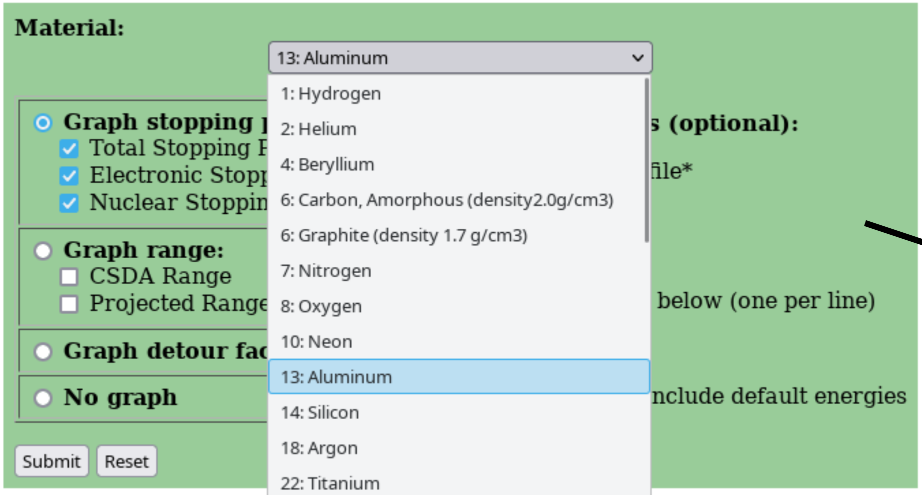
Full relativistic formula
at https://pdg.lbl.gov/

Protons in Different Materials

Tables for protons impacting on different materials.

- Proton accelerators are common irradiation facilities
- Lots of protons out of in the LHC collisions.

pstar
stopping-power and range tables for protons



Material: 13: Aluminum

● **Graph stopping p**
☑ Total Stopping P
☑ Electronic Stopp
☑ Nuclear Stoppin

○ **Graph range:**
☐ CSDA Range
☐ Projected Range

○ **Graph detour fac**

○ **No graph**

s (optional):
file*
below (one per line)
nclude default energies

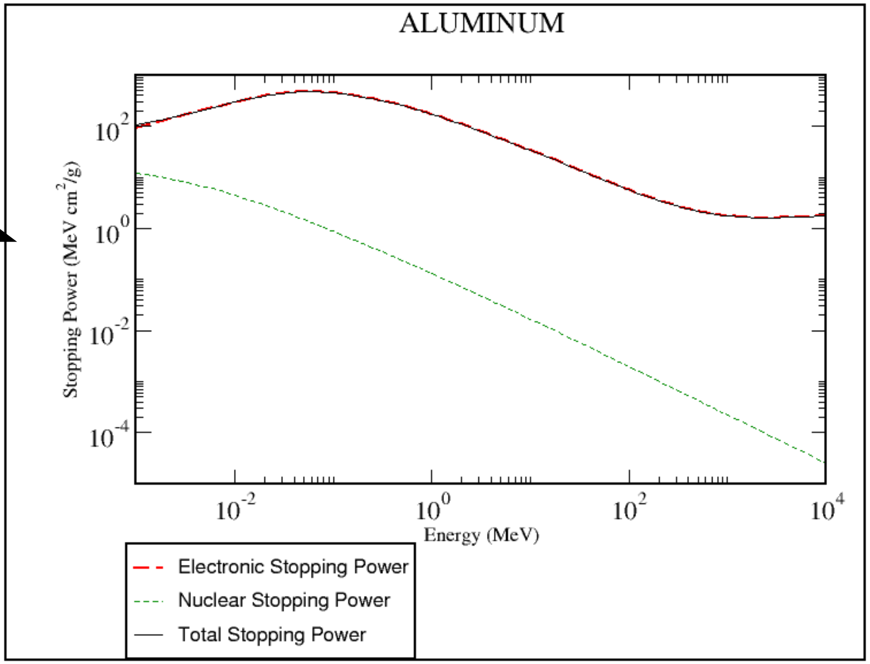
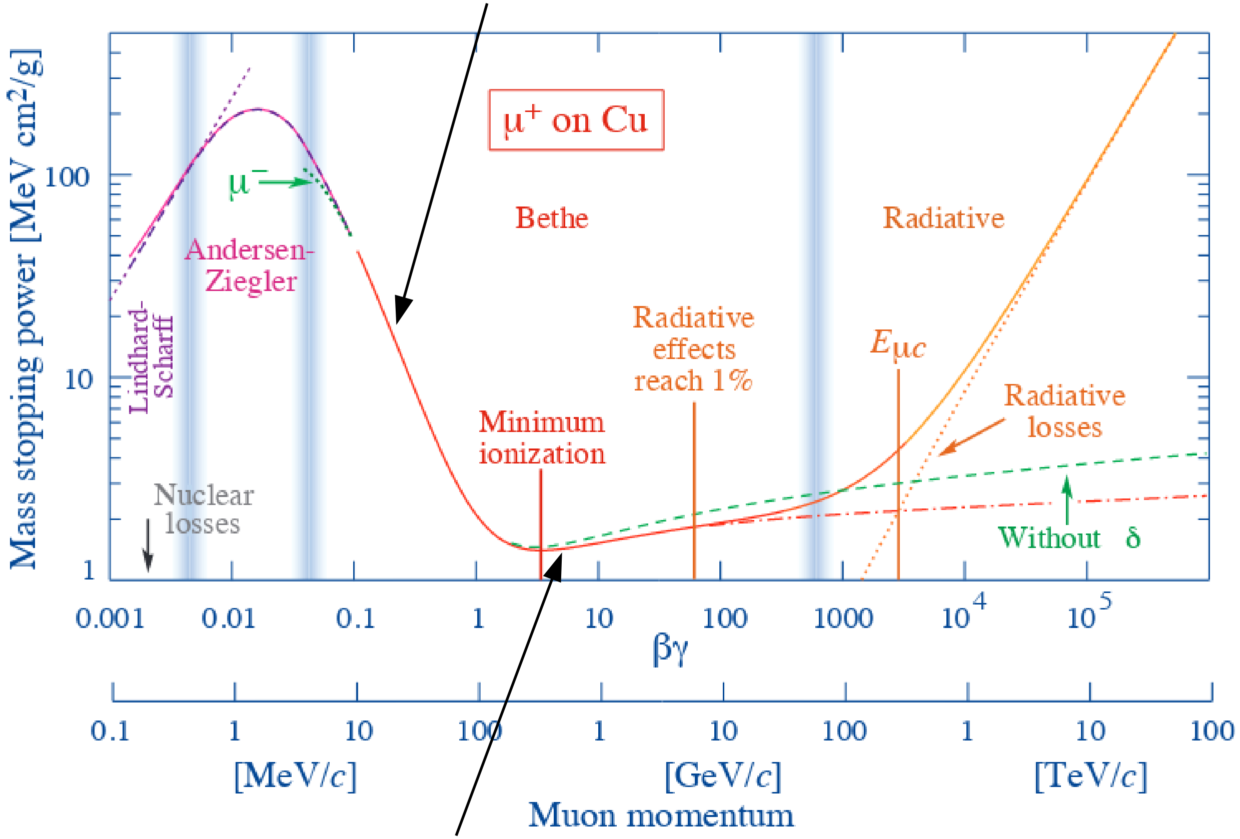


Table of values also available.

https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

The Bethe-Bloch Formula: Two Regimes

Source of Bragg Peak: “Slow” particles deposit energy fast and slow down even further.



Minimum Ionizing Particles (MIPs): “Fast” particles lose constant and small amount of energy.

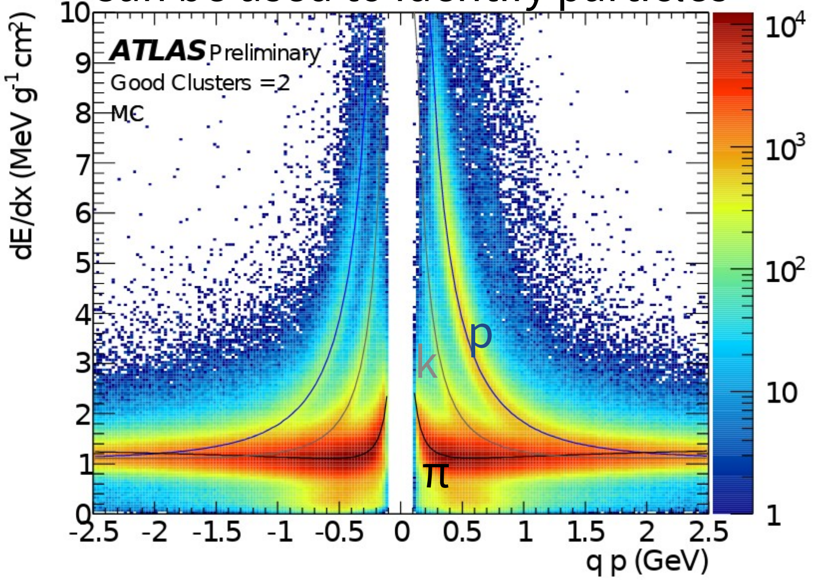
The Bethe-Bloch Formula: Non-Relativistic

For non-relativistic particles: terms in [] can be neglected.

(higher order corrections)

$$\boxed{-\frac{dE}{dx} \cong \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ} \left[\cancelto{\approx 1}{\ln\frac{2m_e v^2}{I}} - \cancelto{\approx 0}{\ln\left(1-\frac{v^2}{c^2}\right)} - \cancelto{\approx 0}{\frac{v^2}{c^2}}\right]$$

Can be used to identify particles



Incoming Particle

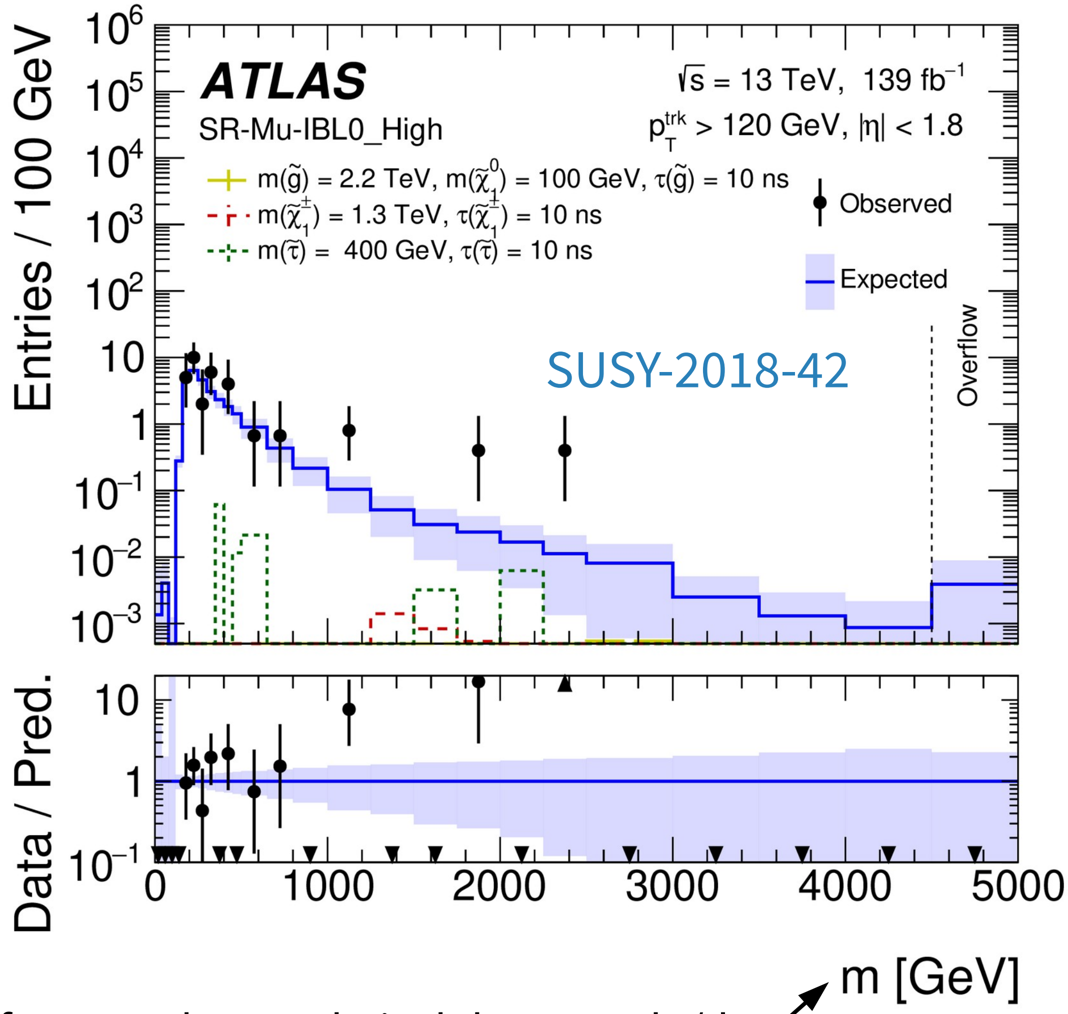
- dE/dx ∝ z^2/v^2 ∝ M_Z^2/E

Material:

- dE/dx ∝ NZ (electrons per unit volume)

Particle ID w/ dE/dx and BSM Physics

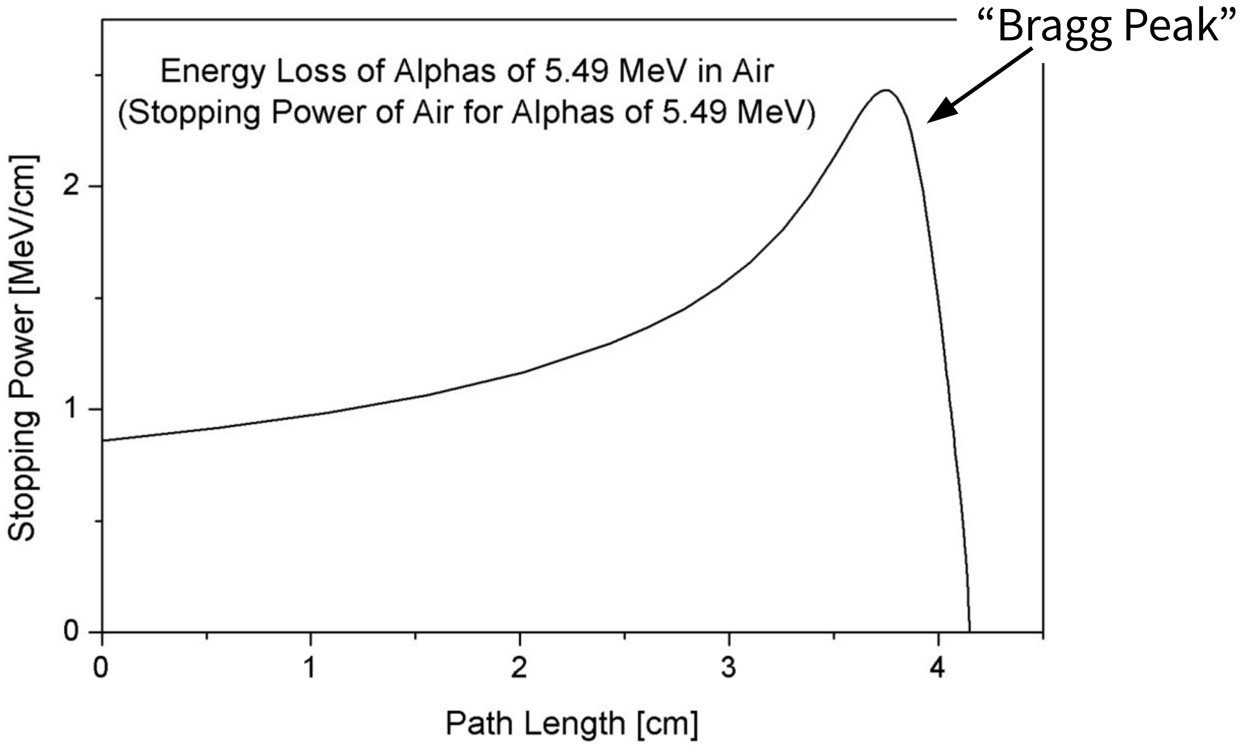
ATLAS search for *slow*, *massive*, *long-lived* new particles.



Reconstructed from track p_T and pixel detector dE/dx

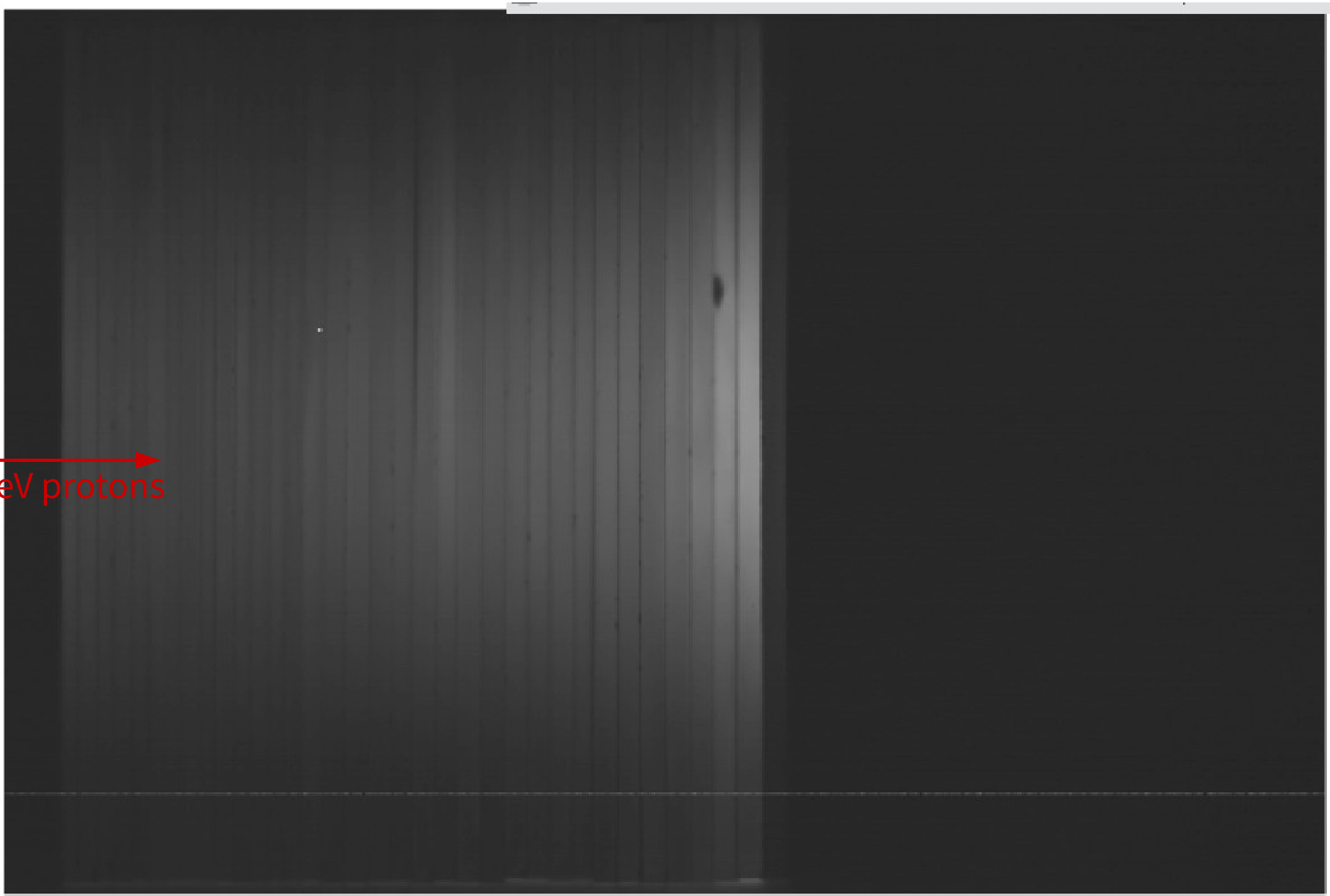
Bragg Peak

- **Most energy is deposited at end of trajectory**
  - Result of integrating Bethe-Block
- **Bethe-Block underestimates stopping power**
  - Ions pick up electrons from material → become less charged



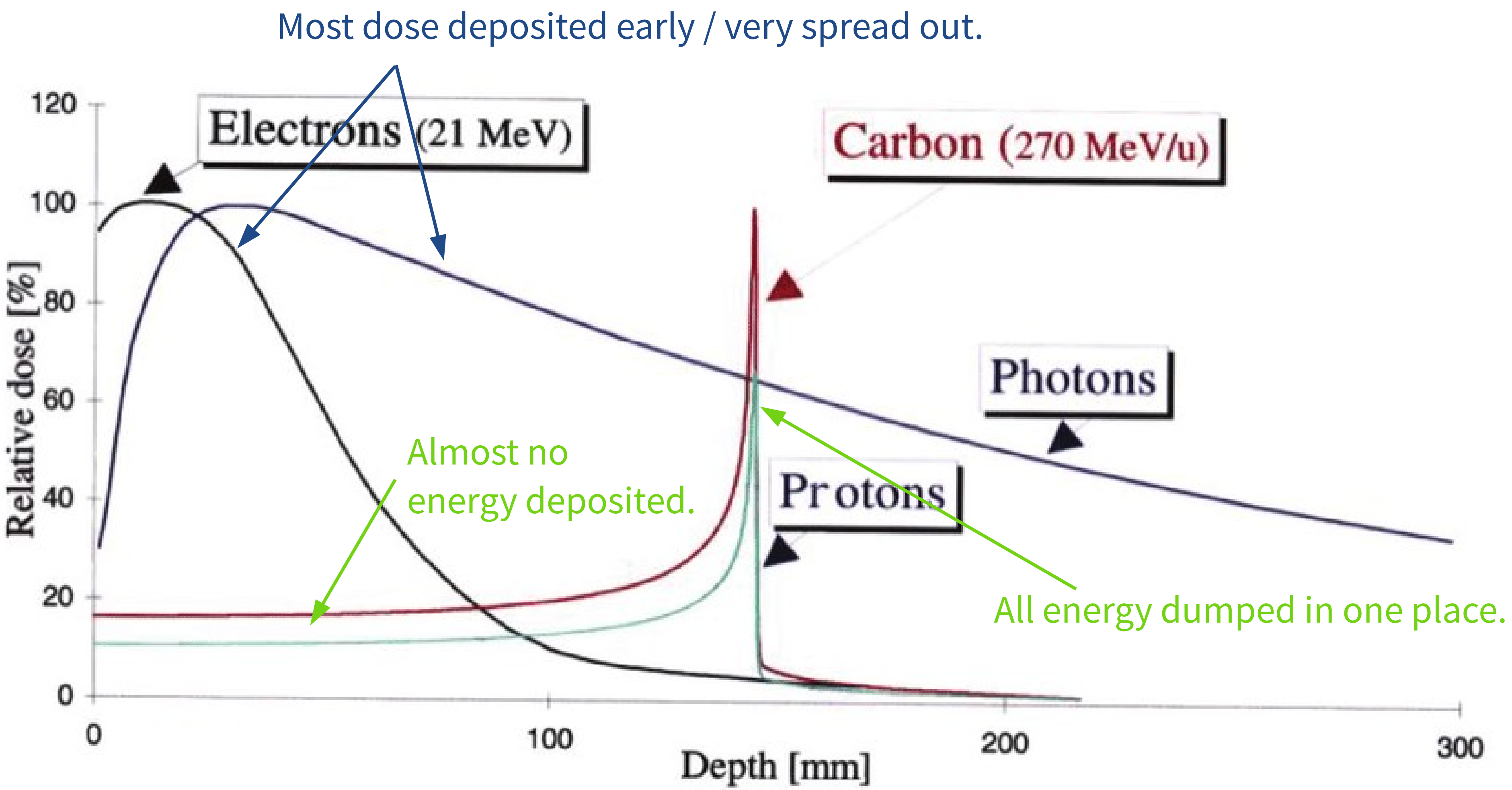
Bragg Peak in Action

Credit: A scintillator-based range telescope for particle therapy



106.17 MeV protons

Total Dose vs Depth

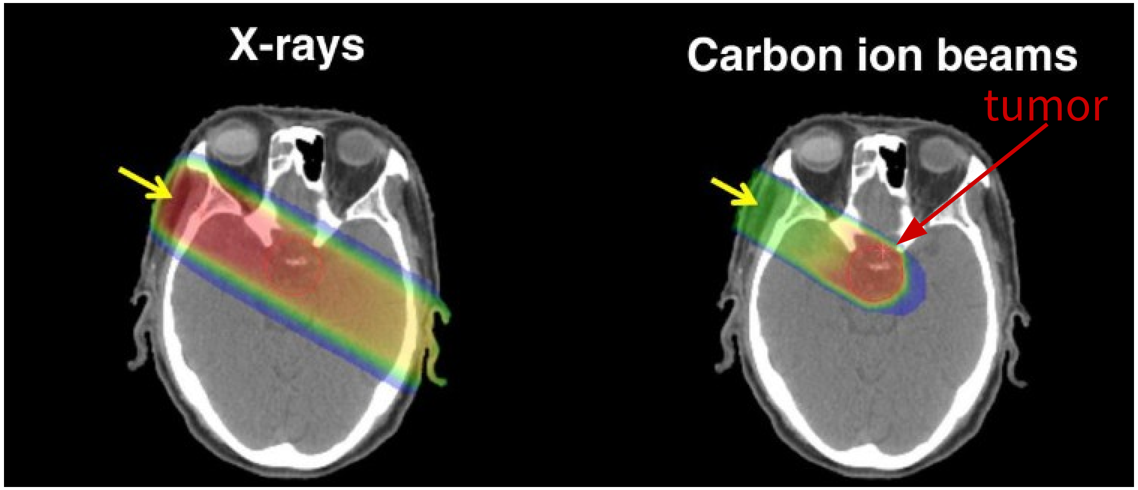


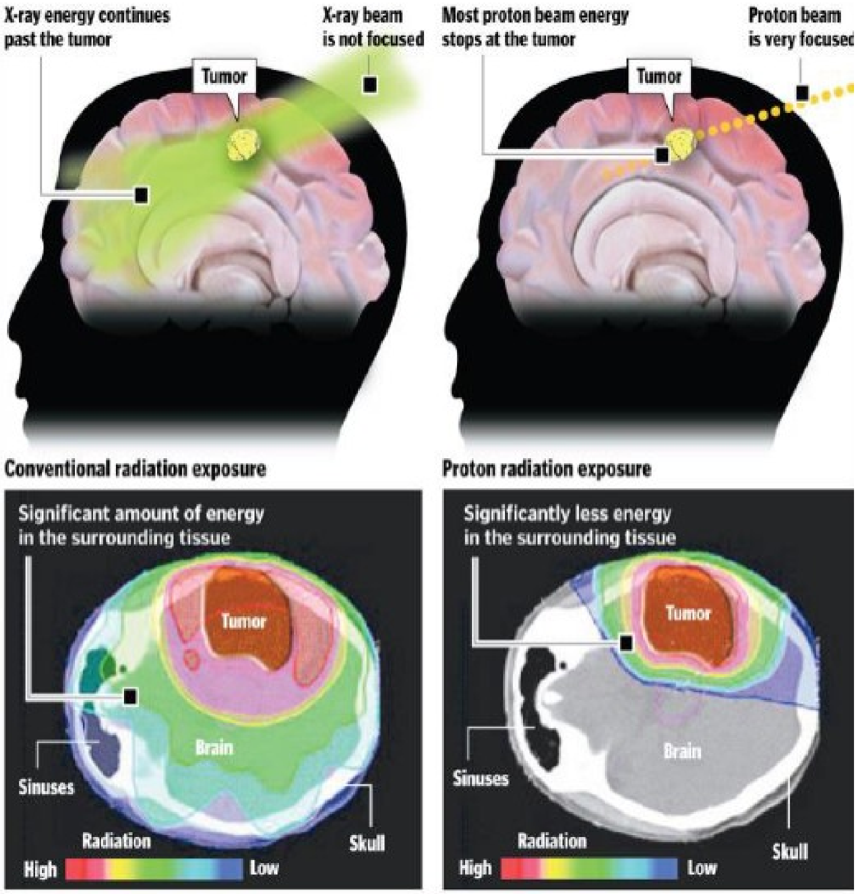
Credit: Advanced Radiation Treatment Planning of Prostate Cancer

Radiation Therapy for Cancer

Set the ion energy to place Bragg Peak at tumor.

Minimizes irradiating healthy tissue on the way.





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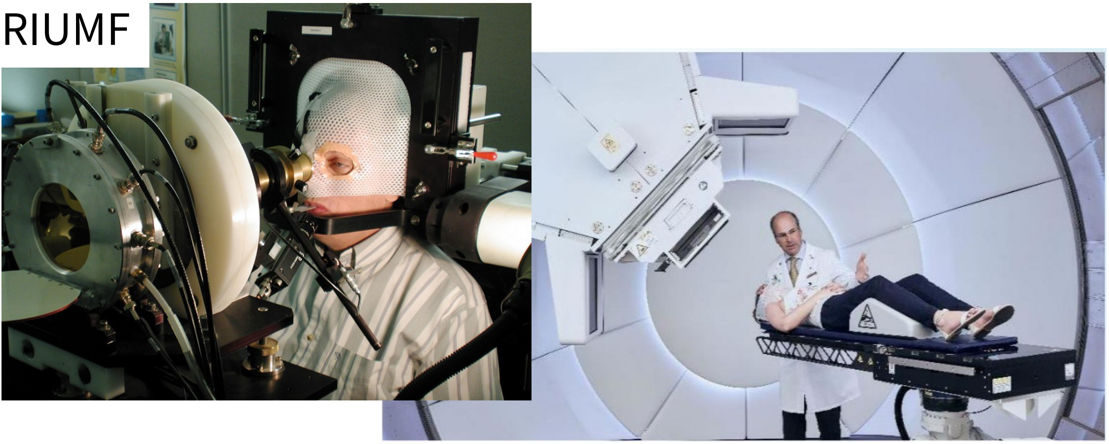
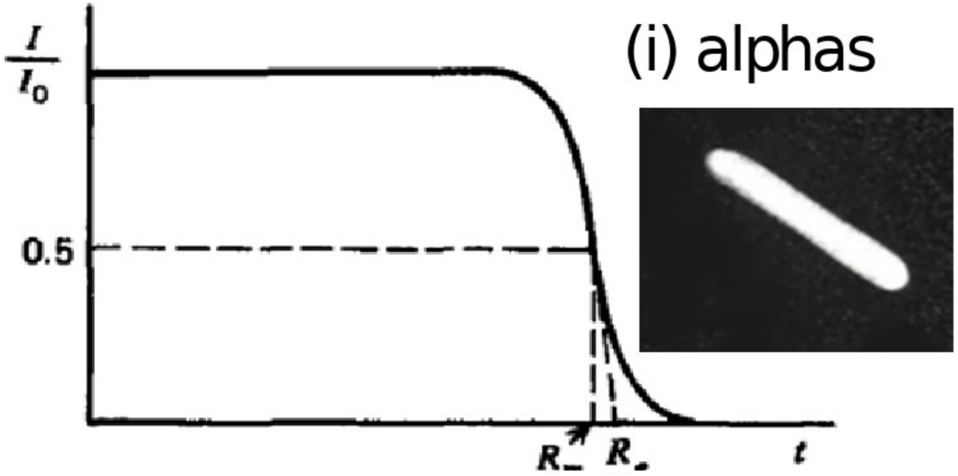
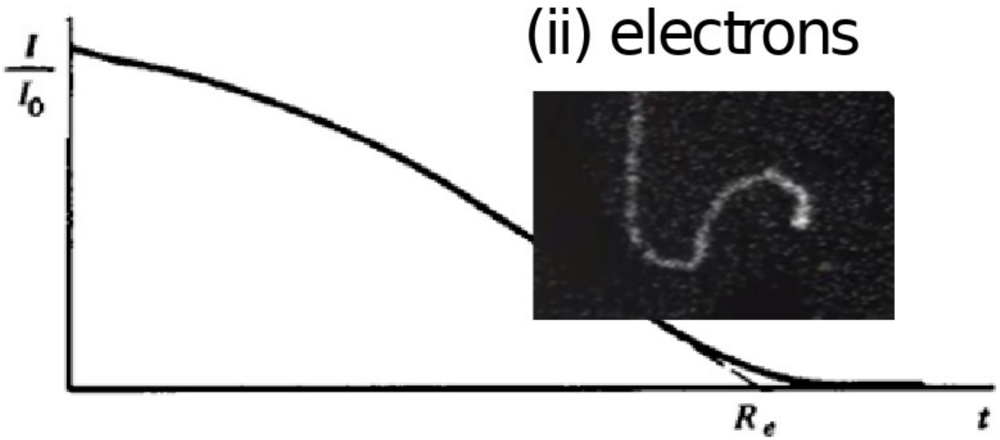


Electrons

Electrons do follow Bethe-Block, but are very light!

- Even electrons from radioactive decays can be relativistic, but…
- A large fraction of its energy can be deposited in a single interaction.
- Trajectory will include large scattering → even shorter depth.


(i) alphas


(ii) electrons

Credit: http://microcosm.web.cern.ch/en/cloud-chamber-video#overlay-context=en/cloud-chamber

Neutrons

Neutrons are uncharged → no interactions w/ electrons of atoms.

Interacts mainly with nucleus via strong force.

Also **protons** and WIMP Dark Matter.

Examples at *moderate energies*:

- **Scattering (elastic/inelastic): recoiling nucleus to ionize electrons**
  - Need large energy transfer (ie: light nucleus).
  - No measurement of neutron properties (random scattering).
  - Cross-section inversely proportional to velocity.
- **Radioactive Capture: (low energy) neutron captured by nucleus**
  - Gamma-ray is emitted, hard to detect.
- **Nuclear reactions (n,p), (n, α), (n, fission): detect charged results of decay**
  - Indirect relation to neutron energy.

Photons

Photoelectric Absorption

low energy, high Z

Compton Scattering

always

Pair Production

only at high energy

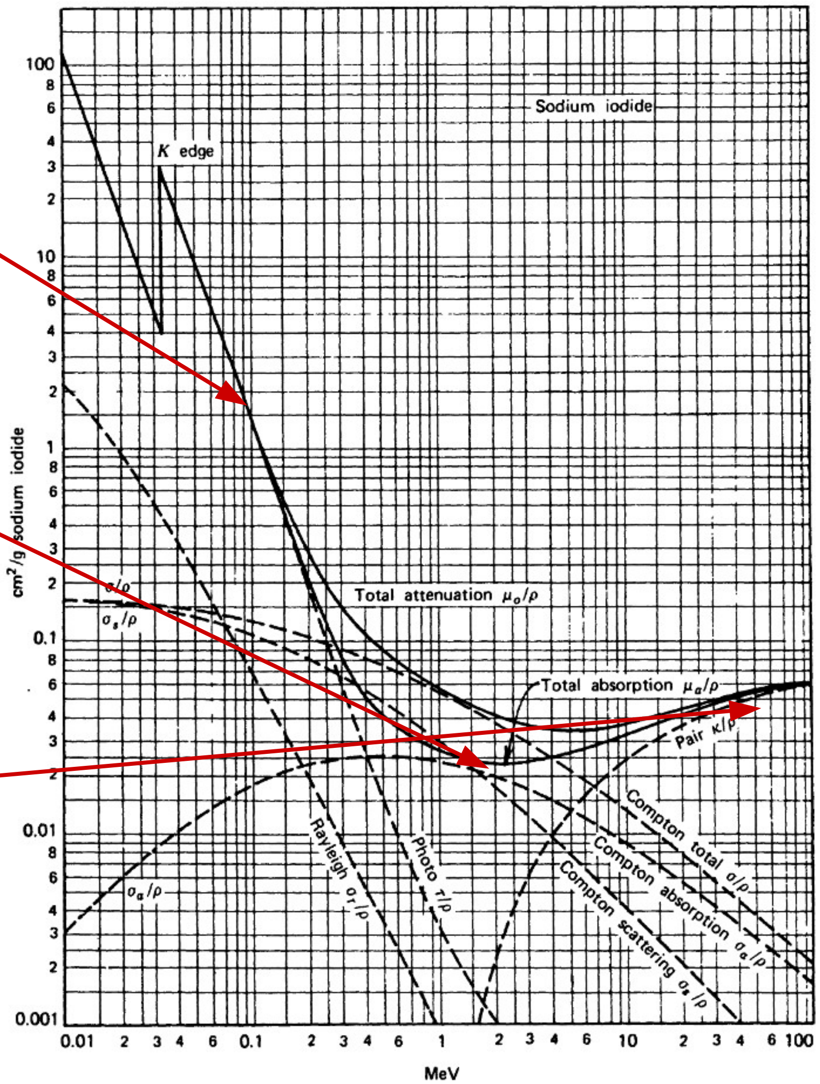


Figure 2.18 Energy dependence of the various gamma–ray interaction processes in sodium iodide. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

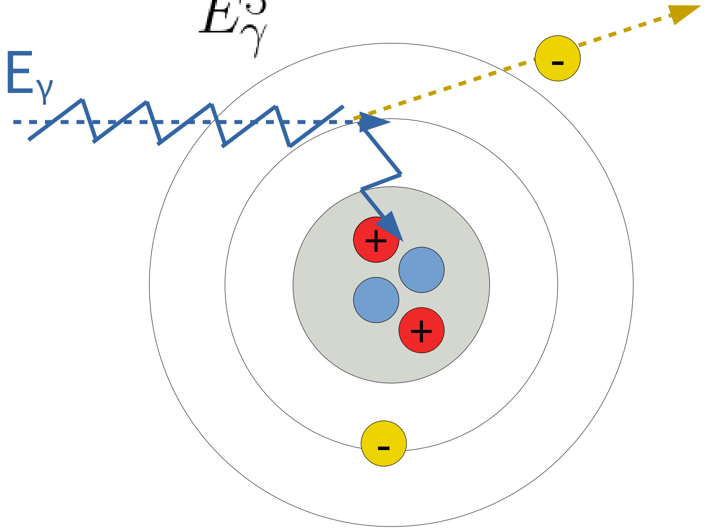
Photoelectric Absorption

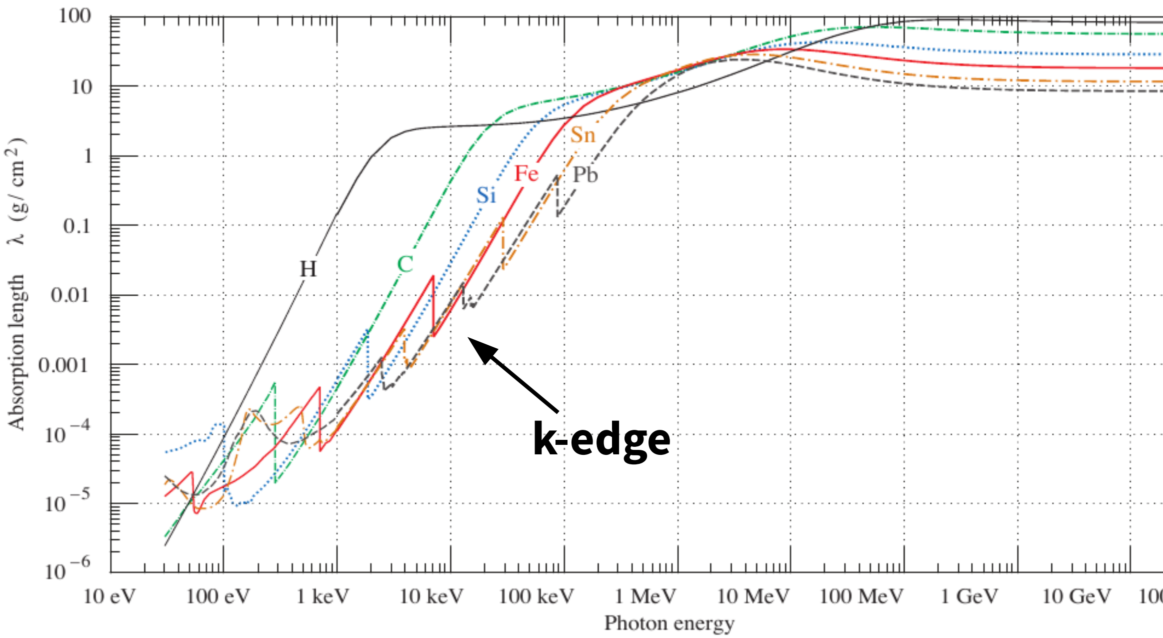
- **Entire energy of photon is absorbed to emit an electron**

$E_e = E_\gamma - E_{BE}$, E_{BE} is binding energy

- **Require nucleus to absorb for momentum conservation**
  - Mainly occurs with inner-shell electrons (K-electrons)
  - Outer electrons involved when K-*e* E_{BE} too high

$$\sigma \propto \frac{Z^4}{E_\gamma^3}$$

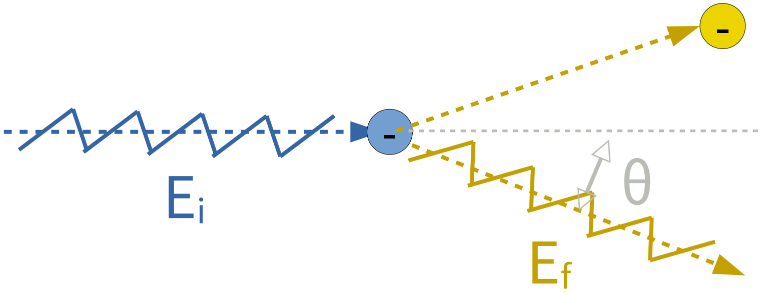




k-edge

Compton Scattering

Photons scattering off electrons



$$\frac{1}{E_f} - \frac{1}{E_i} = \frac{1}{m_e c^2}(1 - \cos\theta)$$

Cross-section depends on

- Inversely proportional to energy (Klein-Nishina formula)
- Proportional to number of electrons (Z)

Linear attenuation coefficient: $\mu = n\sigma$

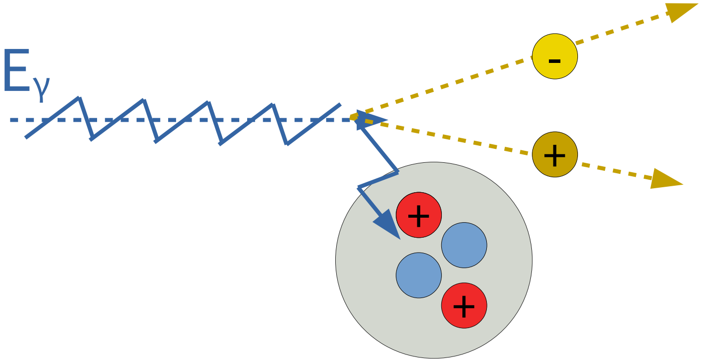
- Number density of atoms: $n = \rho N_A / A$
- Cross-section: $\sigma \propto Z$

$$\frac{\mu}{\rho} \propto \frac{Z}{A}$$

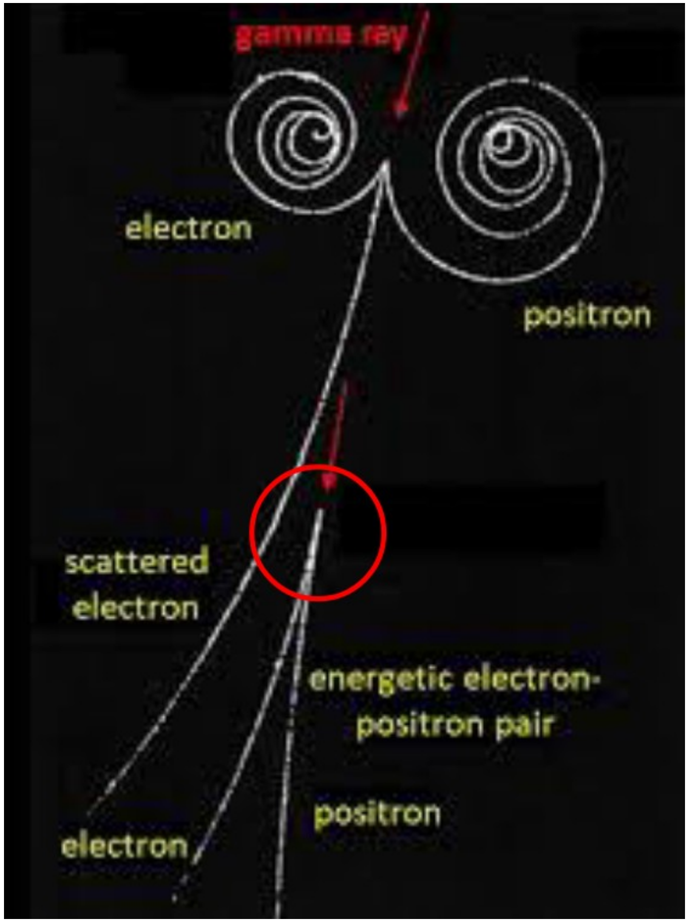
Pair Production

Photon converts into e^+/e^- pair

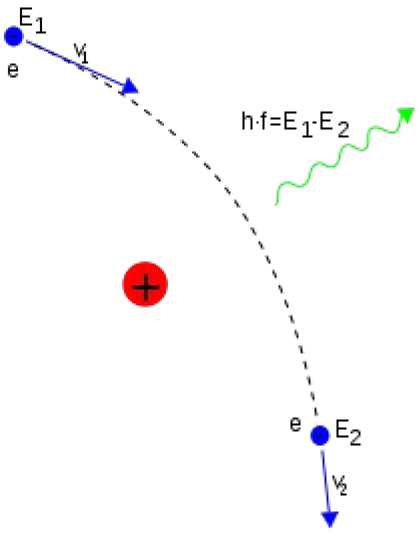
Needs to “scatter” of a nearby nucleus to conserve momentum



- **Requires $E_\gamma > 1.022$ MeV**
  - Produce two electrons (2x m_e)
- **Cross-section depends on**
  - Proportional to E_γ, significant above 5 MeV
  - Proportional to Z^2



Relativistic Phenomena

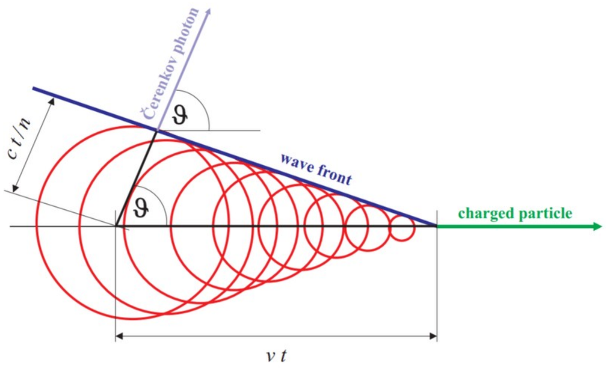


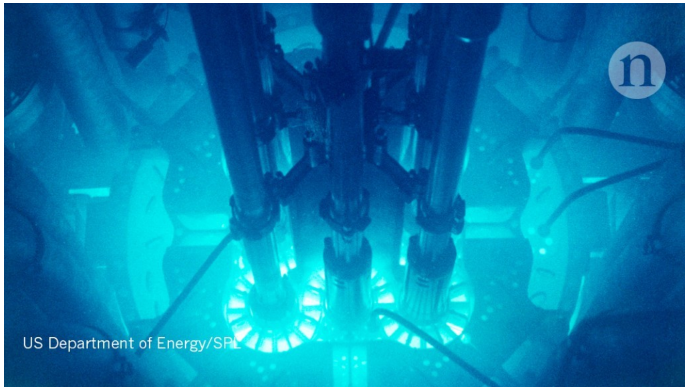
Bremsstrahlung (“parking radiation”)

- Accelerating charged particle radiate photons
- Charged nucleus = source of acceleration
- Combined with pair production = EM cascades

Chernekov Radiation

- Speed of light in material is less than speed of light in vacuum
- Highly relativistic particle can travel faster than light in *that medium*
- Result is a “light shockwave” in the visible spectrum

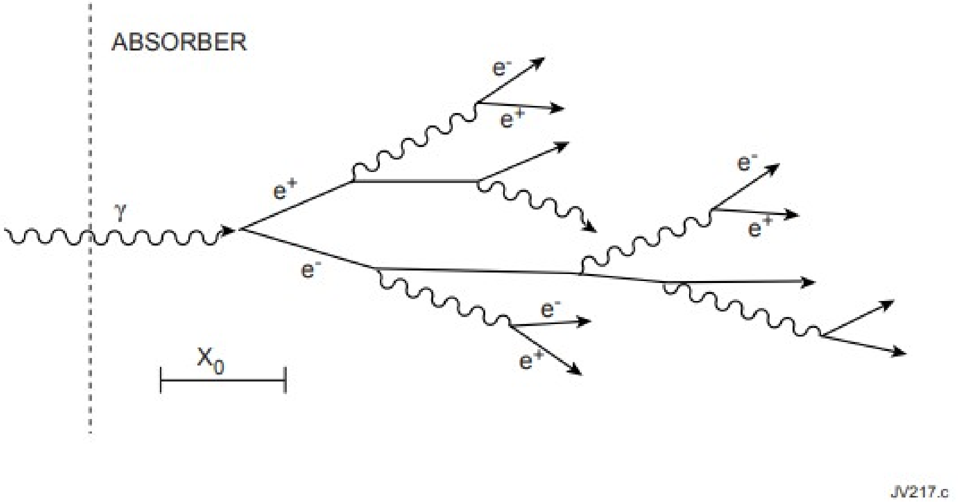



US Department of Energy/SRL

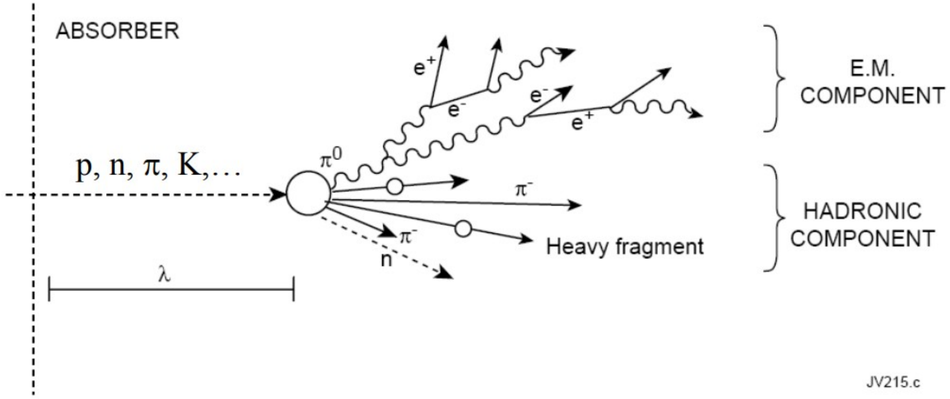
High Energy Interactions: Absorbing

Multiple interactions until critical (low) energy is reached.

EM Shower



Hadronic Shower



- **Exploited by calorimeters to measure particle's energy**
  - Made from high Z materials that encourage the above processes

Electromagnetic Shower

- Material is characterized by “radiation length”, X_0: $E = E_0\, e^{x/X0}$
- Each step causes energy to split by two.
- After N splits, energy is split into 2^N particles.
- Continues until reaching critical energy (E_C).
  - Ionization losses exceed Bremsstrahlung

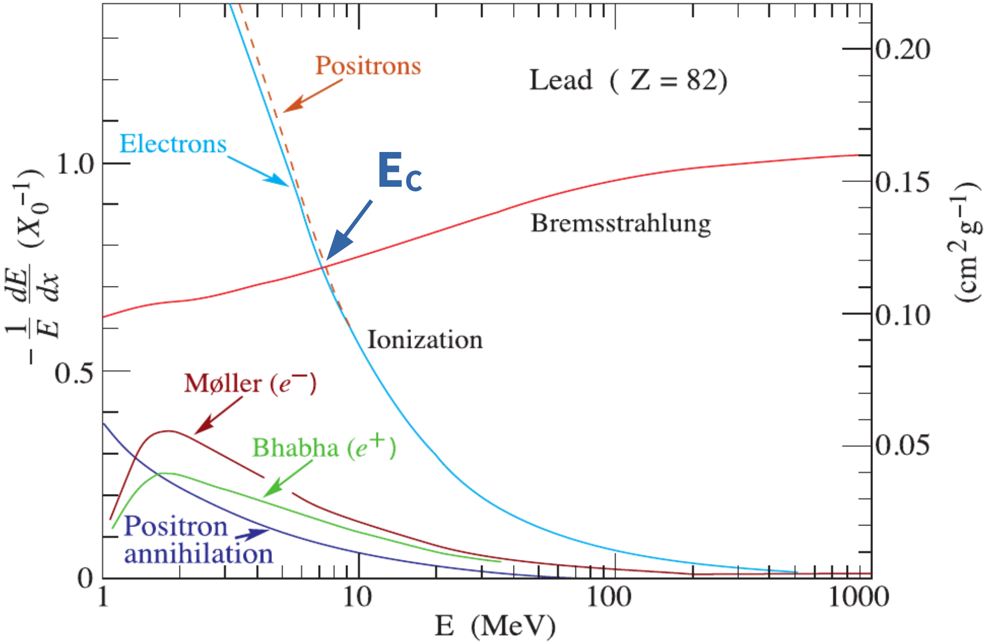
Shower depth

$$t_{\mathrm{MAX}} \approx X_0^{\ln\frac{E_I}{E_C}} / \ln 2$$

Shower width

$$R_M = \frac{21\ \mathrm{MeV}}{E_C} X_0[\mathrm{g/cm^2}]$$

“Moliere Radius”

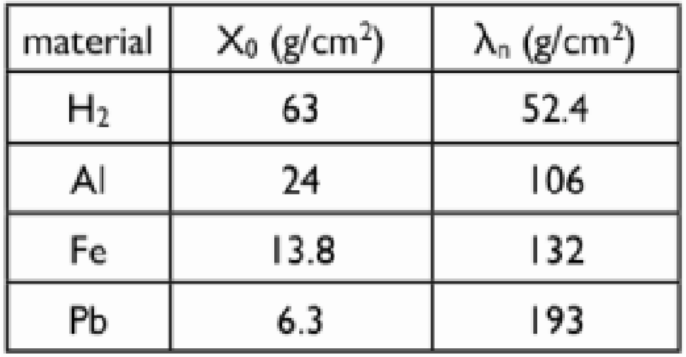


Hadronic Showers

- **Material is characterized by "nuclear interaction length"**

$$\lambda_I = A/(N_A\sigma_{inel})\ 35 \times A^{1/3}\ [g/cm^2]$$

  - Cross-section scales as $\sigma_{inel} = A^{2/3}$
- **Multiplicity of secondaries ln(E)**
  - 1/3 of secondaries as pions

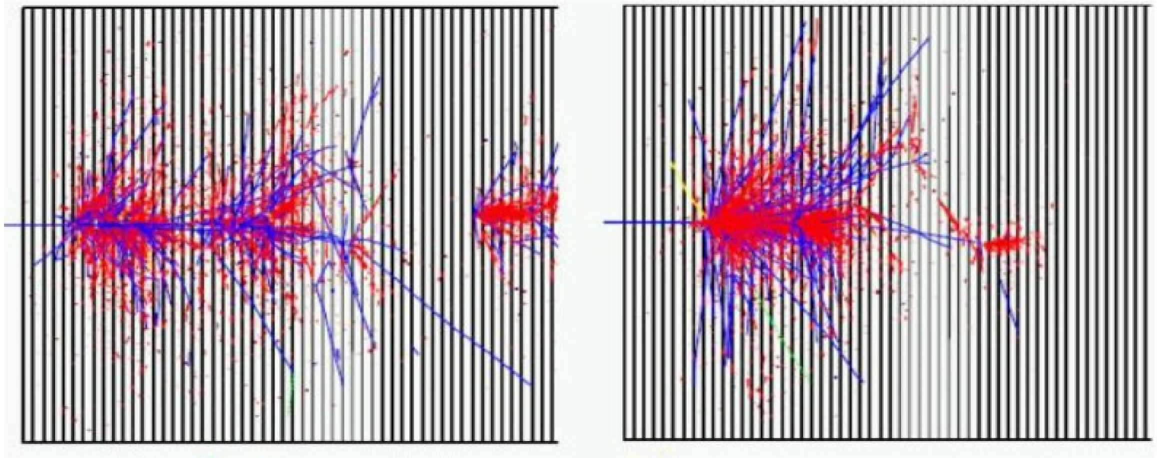


material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

$t_{max} = \lambda_I\ (0.2 \times \ln(E[GeV]) + 0.7)$

$t_{95\%}$ (cm) = 9.4 x ln(E[GeV]) +39 **[Fe]**

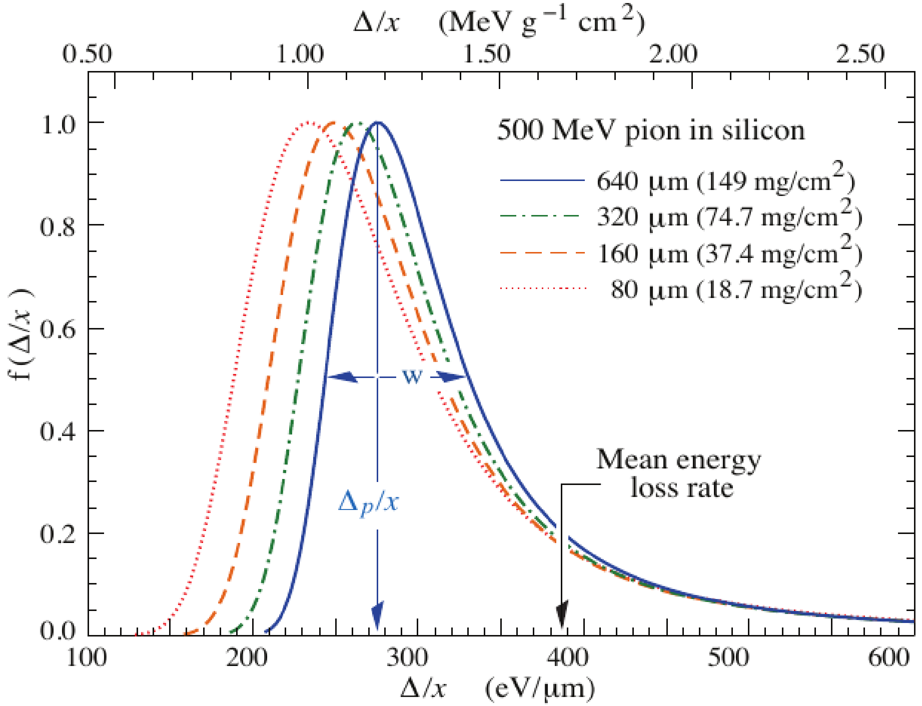
Simulations of hadron showers



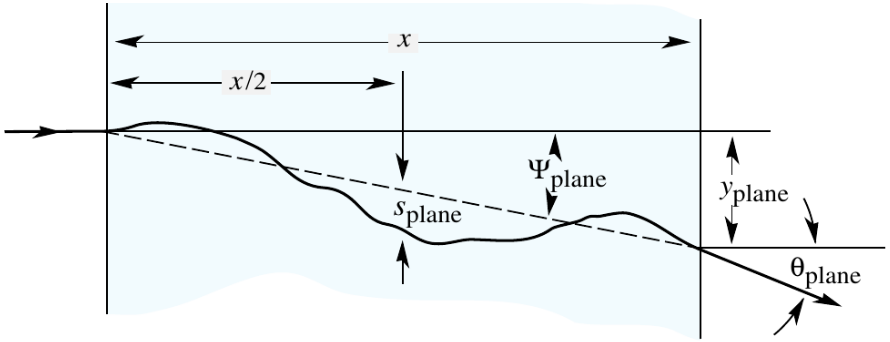
Red - e.m. component Blue – charged hadrons

High Energy Interactions: Passing Through

Multiple interactions without loosing large fraction of energy.



- **Example in 300 µm silicon**
  - Typical peak energy loss is ~80 keV
  - 3.6 eV to make an *eh*-pair (bandgap)
  - ~22500*e* for each traversing particle
- **ΔE fluctuations are Landau distr.**
- **Particle will also scatter at each interaction**



$$\theta_{rms} \approx \frac{13.6\ \text{MeV}}{\beta c p} Z \sqrt{\frac{x}{X_0}}$$

Radiation Damage

Attend **Laura Gonella**'s lecture!
May 17, 2024

What happens to the material due to these interactions?

- **Total Ionizing Damage (TID)**
  - Escaped electrons trapped inside structur
  - Affects both sensors and electronics!
- **Single Event Errors (SEE)**
  - High ionizing events inside electronics can cause bit flips
- **Displacement damage**
  - Damage to the material lattice can change performance
- **Nuclear interactions**
  - Changes to nucleus can cause materials to become radioactive

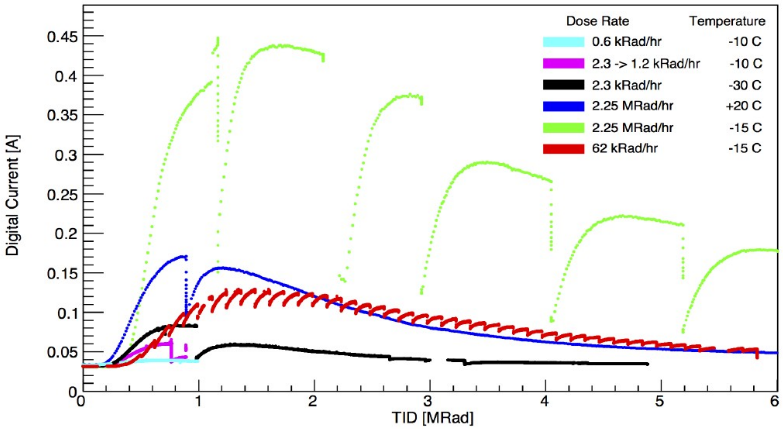


Figure 6.13: Digital current vs. TID for ABC130 chips during X-rays irradiations at different dose rates and temperatures.

Two Stars and a Wish

Feedback is very welcome!

Two Stars: What are two new things you learned or were explained well?

Wish: What is something you would want to learn about or should be explained better?

https://forms.gle/goeZhjDETr4dK8hd7