Video of the lecturer

Interactions of particles with matter (I)

Mitesh Patel (Imperial College London)

(with thanks to Mark Pesarasi and Michael McCann)

Contents

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- Lecture 1 – interaction of particles with matter
  - Reminder : the fundamental constituents of matter
  - The principles of particle detection
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  - Ionization (Bethe-Bloch formula)
  - Radiative losses – Bremsstrahlung, radiation length
  - Cherenkov radiation
  - Transition radiation
  - Energy loss of e- , e+ and photons – photoelectric effect, compton scattering, pair production

- Lecture 2 – Physics of shower development
  - Electromagnetic showers
  - Hadronic showers

- Lecture 3 - Particle identification

Introduction

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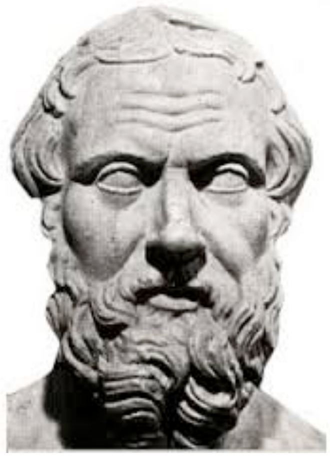
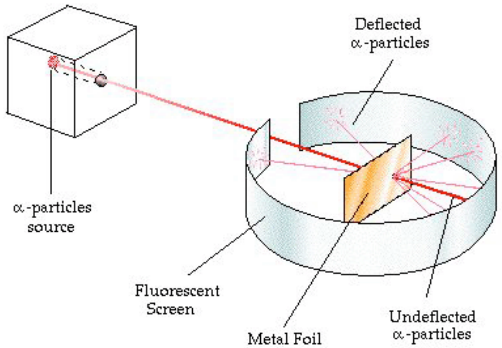
- The Large Hadron Collider experiments are the next step in our exploration of matter and the forces that act on it



- 5th century B.C., Democritus suggested all matter was made of infinitesimally small particles called atoms
- Through 18th and 20th centuries developed an understanding of sub-atomic structure e.g. Rutherford :



Exchange forces

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- Interactions between particles proceed through the exchange of a force-carrier
  - Carry discrete amounts of energy from one particle to another
  - Energy transfer due to this exchange like the passing of a basketball between two players

- The force carriers are called “bosons”
  - integer intrinsic angular momentum (spin)
- cf. quarks and leptons which are “fermions”
  - half integer spin

The fundamental forces (I)

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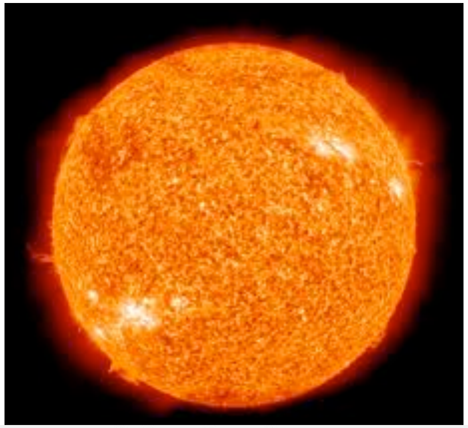
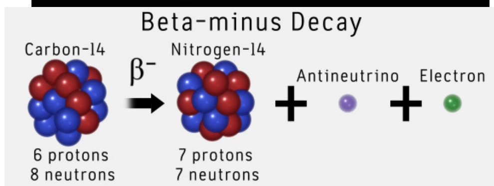
- Electromagnetism
  - Force between particles with electric charge
  - Attractive or repulsive
  - Long range
  - Holds atoms together
  - Force-carrier: the photon (basketball)

- Weak force
  - Responsible for radioactive decay and nuclear reactions in centre of stars
  - Force carriers : the W and Z bosons





The fundamental forces (II)

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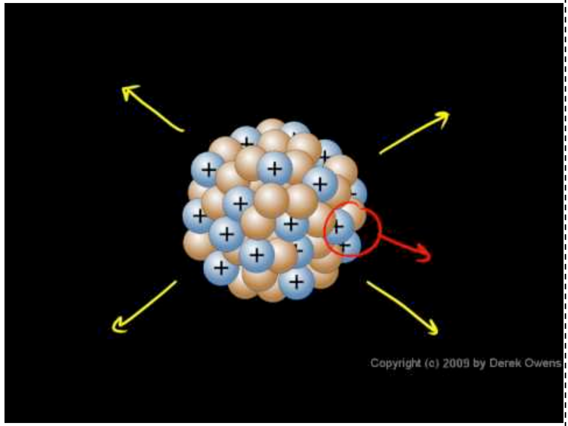
- Strong Force
  - Nucleus of an atom contains lots of protons that repel each other
  - Strong force binds them
  - Force-carrier : gluon



- Gravity
  - Attractive force, Long range
  - Holds planets, solar systems and galaxies together
  - Too weak to have any impact on particle physics experiments
  - Hypothetical force-carrier : graviton

The interactions of fundamental particles

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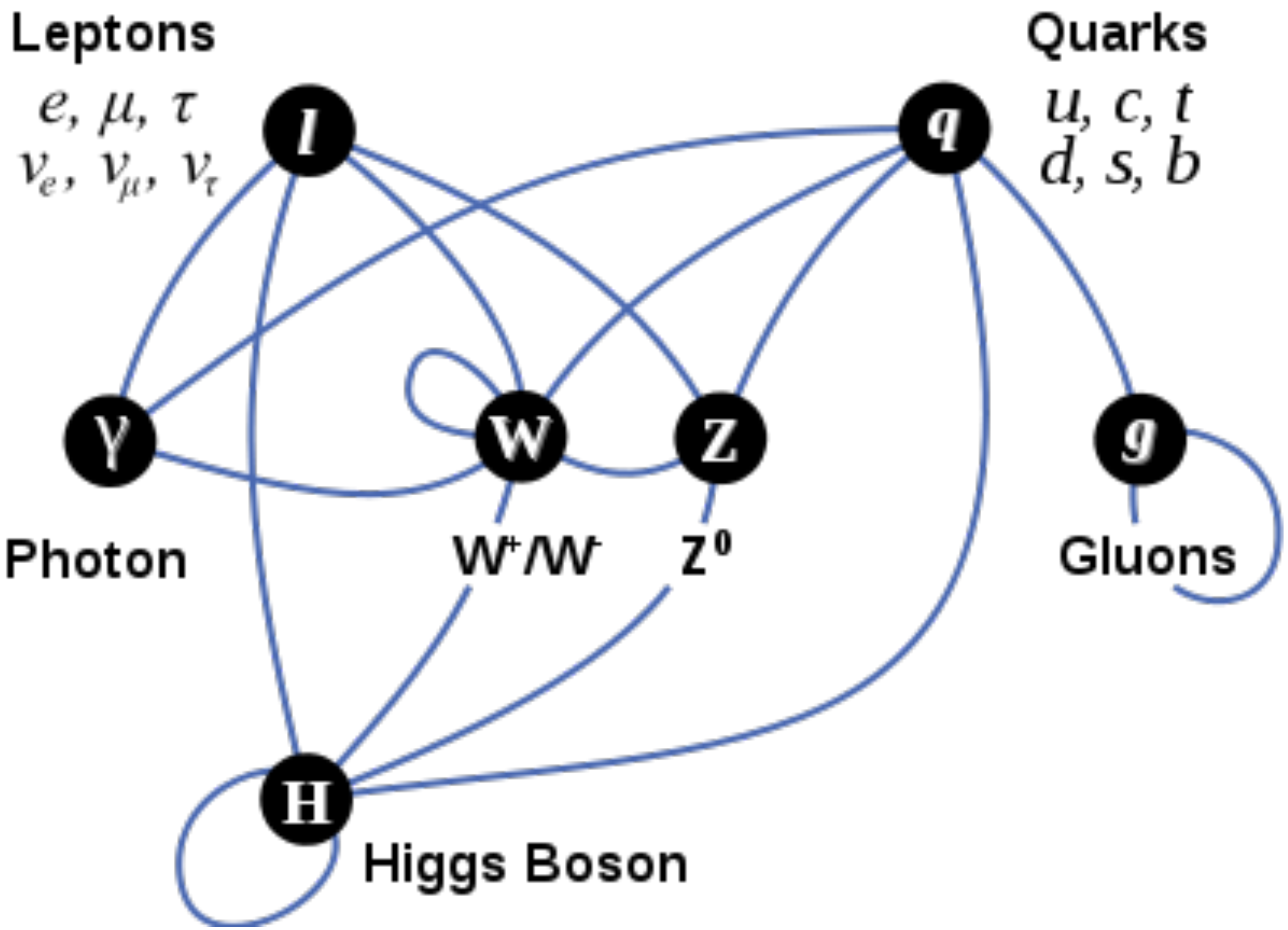

The principles of particle detection

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- To advance our understanding we need to be able to do experiments

- To detect a particle:
  - it must interact sufficiently with the material of the detector
  - It must transfer energy in some recognisable fashion, i.e. detection of particles happens via their energy loss in the material traversed

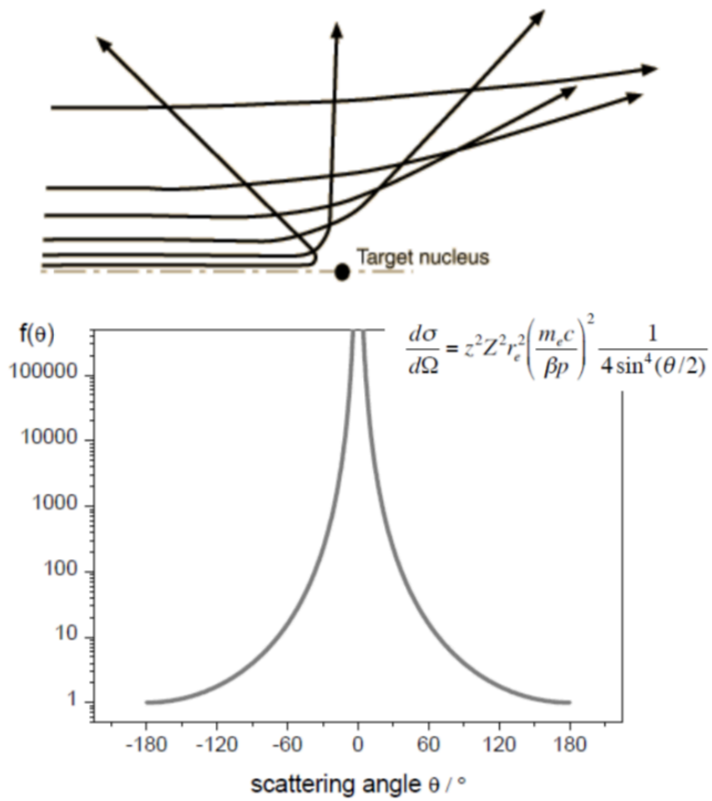
- Energy loss processes
  - charged particles ➡ ionisation, bremsstrahlung, Cherenkov
  - Hadrons ➡ nuclear interactions
  - Photons ➡ photoelectric, Compton, pair production
  - neutrinos ➡ weak interactions

Energy loss of heavy particles ($M \gg m_e$)
Multiple scattering

Video of the lecturer

while inelastic interactions with nuclei are normally only significant for $e^{+/-}$, elastic nuclear collisions are an important effect for all charged particles

- elastic Coulomb scattering produces a change in the particle direction without significantly affecting energy loss
- a single scatter is described well by the Rutherford scatter formula, where a small angle scatter is much more probably than a large one
- in a material of thickness *x*, a combination of small scatters result in a significant net deviation – multiple Coulomb scattering



Energy loss of heavy particles (M>> m_e)
Multiple scattering

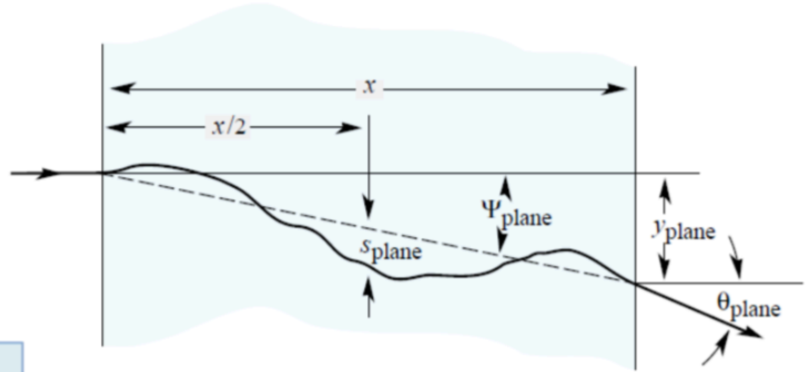
Video of the lecturer

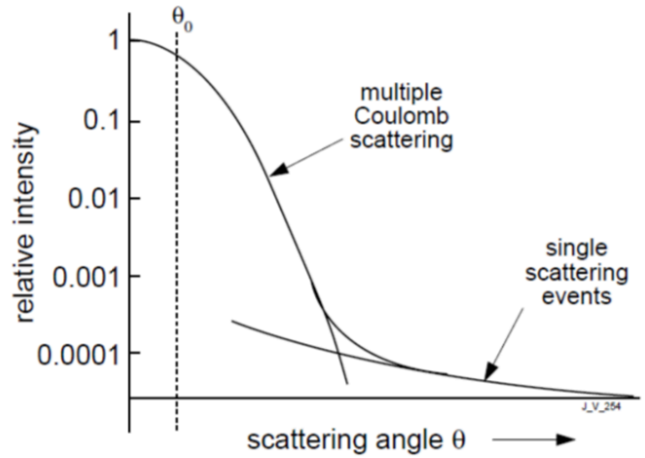
sum of all small angle scatters is described well by a Gaussian distribution, for the central 98% of the angular distribution

the spread of the distribution is defined by the scattering angle θ_0

$$\theta_0 = \theta_{plane}^{RMS}$$

$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\left[1 + 0.038\ln\left(x/X_0\right)\right]$$





Energy loss of heavy particles (M>> m_e)
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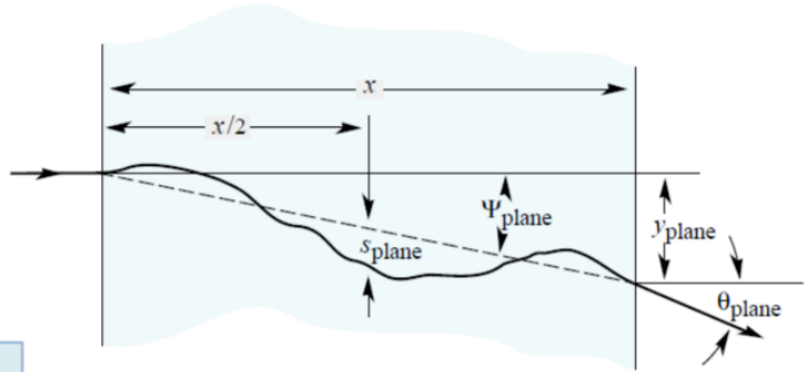
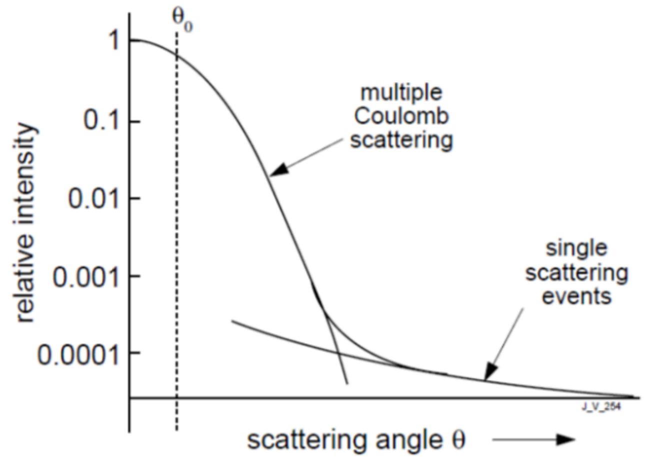
$$\theta_0 = \theta_{plane}^{RMS} = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

inversely proportional to momentum of incident particle

proportional to charge of incident particle

dependent on thickness in radiation lengths





Quiz

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Go to **www.menti.com** and use the code **19 21 45 6**

Mentimeter

The force carrying particles are called?

Bosons	Leptons	Hadrons	Fermions	Quarks
0	0	0	0	0

Press **ENTER** to show correct

Quiz

Video of the lecturer

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Mentimeter

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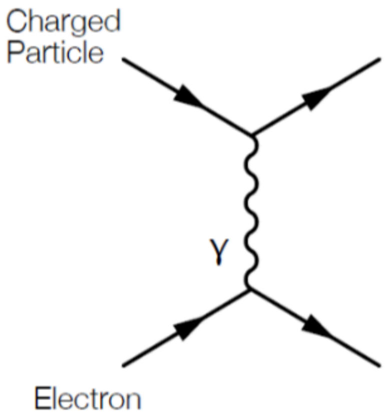
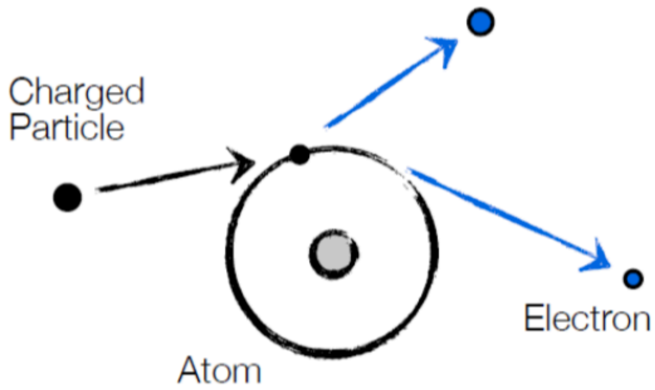
Ionization (Bethe-Bloch formula)

Video of the lecturer

- Main way moderately relativistic charged particles (other than electrons) lose energy in matter is through Coulomb interaction with the atomic electrons, i.e. ionisation





- Derive classical behaviour, then look at rel. effects

Ionization (Bethe-Bloch formula)

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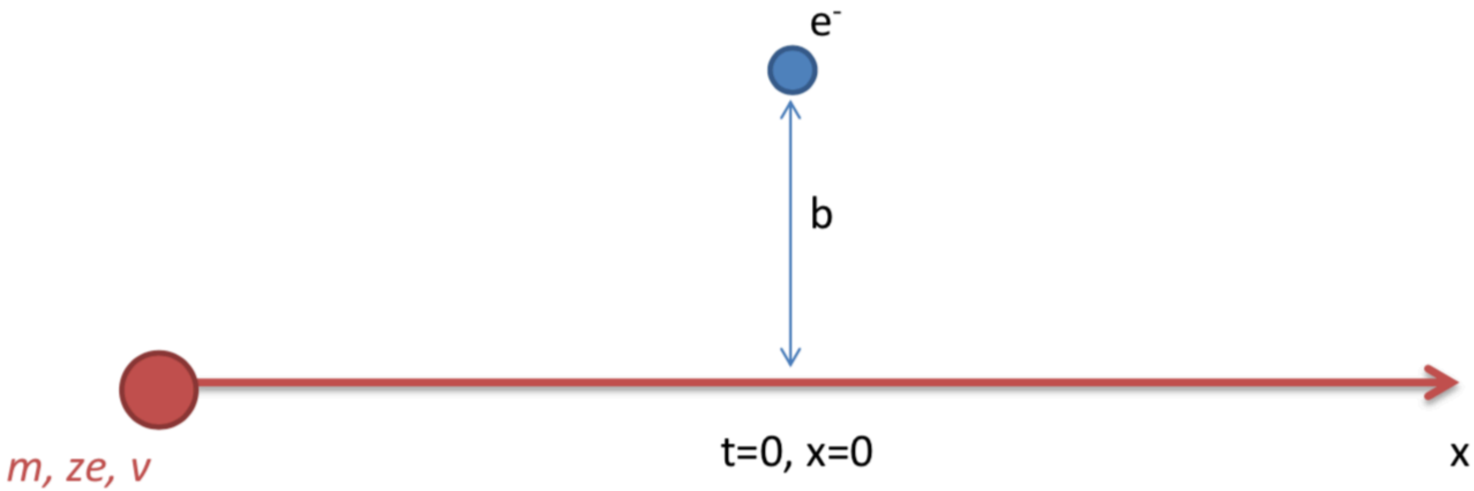
consider a heavy particle, with mass *m*, charge *ze*, velocity *v*, passing through material

an atomic electron sits at distance of closest approach *b* from trajectory

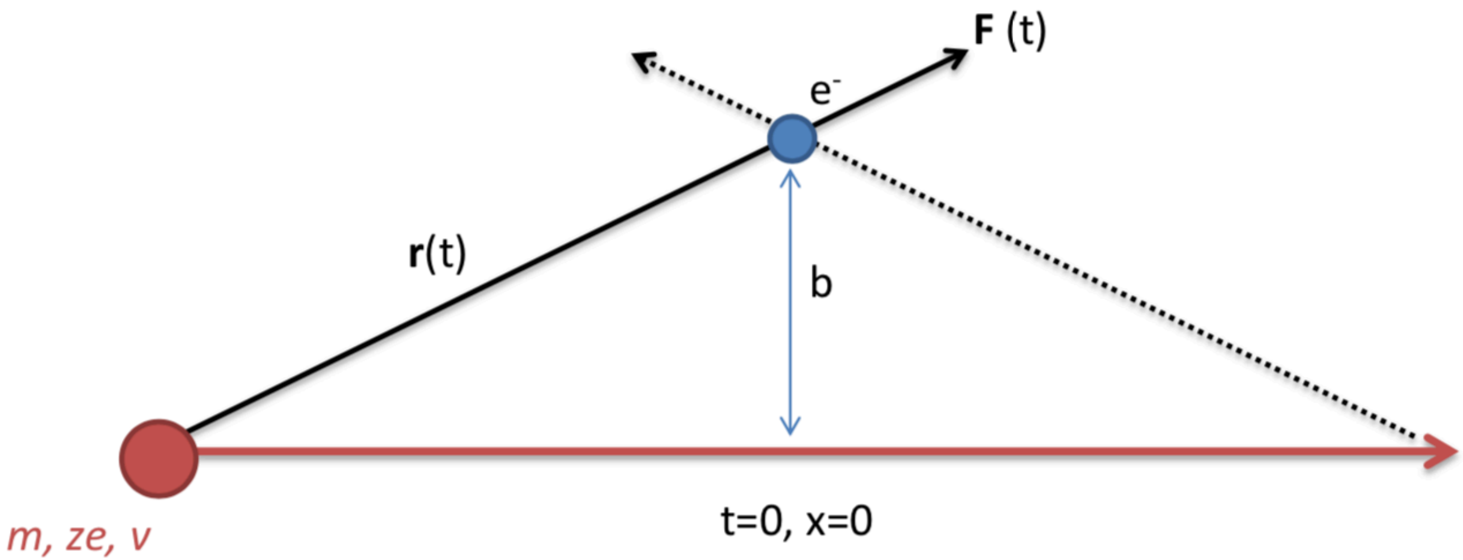
we assume m >> m_e
(electrons treated differently)



Ionization (Bethe-Bloch formula)

Video of the lecturer

force on electron given by: $\mathbf{F}(t) = -\dfrac{ze^2}{4\pi\varepsilon_0 \,|\, \mathbf{r}(t) \,|^2}\mathbf{r}(t) = F_y\hat{\mathbf{y}} + F_x\hat{\mathbf{x}}$



Ionization (Bethe-Bloch formula)

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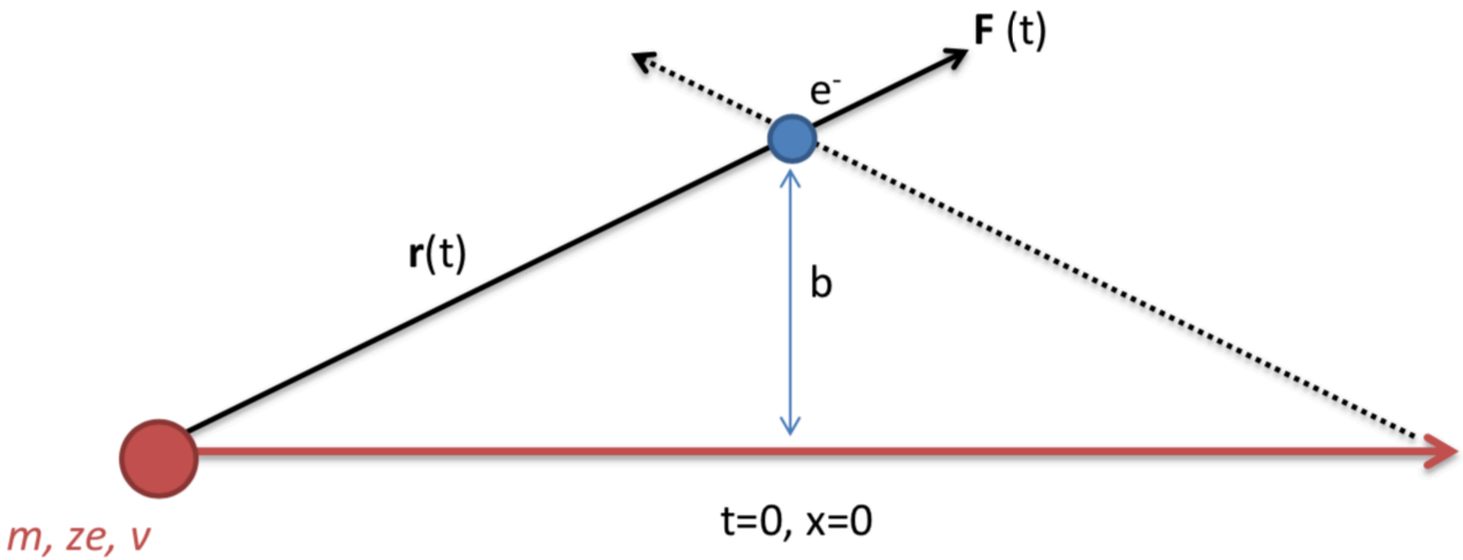
symmetry dictates that:

$$F_y(-t) = F_y(t)$$
$$F_x(-t) = -F_x(t)$$

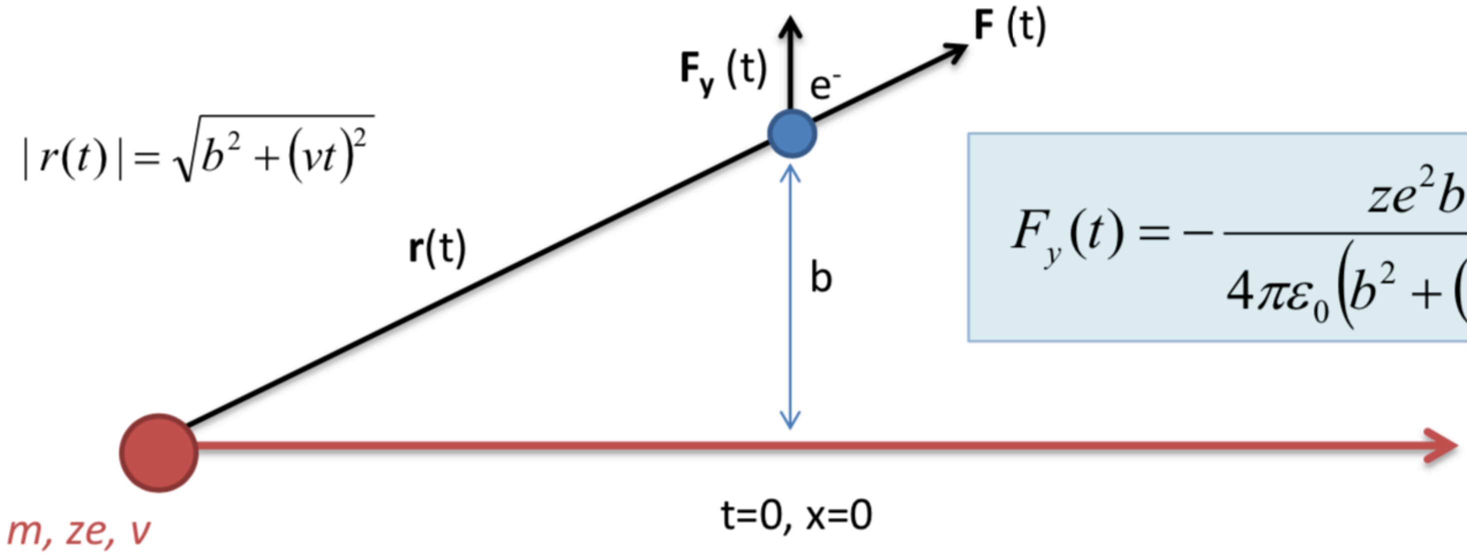


Ionization (Bethe-Bloch formula)

Video of the lecturer

hence: $$F_y(t) = -\frac{ze^2}{4\pi\varepsilon_0 \,|\mathbf{r}(t)|^2} \times \frac{b}{|\mathbf{r}(t)|}\,\hat{\mathbf{y}}$$

$$|r(t)| = \sqrt{b^2 + (vt)^2}$$



$$F_y(t) = -\frac{ze^2 b}{4\pi\varepsilon_0 \left(b^2 + (vt)^2\right)^{3/2}}$$

Ionization (Bethe-Bloch formula)

Video of the lecturer

integrate over all time to calculate the final velocity imparted to the electron:

$$dV_y = \frac{F_y(t)}{m_e} dt$$

$$V_y = -\int_{-\infty}^{\infty} \frac{ze^2 b}{4\pi m_e \varepsilon_0 \left(b^2 + (vt)^2\right)^{3/2}} dt$$

$$V_y = -\frac{ze^2}{4\pi m_e \varepsilon_0} \frac{2}{bv}$$

therefore the kinetic energy imparted is:

$$-\Delta E = \frac{1}{2} m_e V_y^2 = \frac{z^2 e^4}{8\pi^2 m_e \varepsilon_0^2} \frac{1}{b^2 v^2}$$

energy loss for just one scatter!

Ionization (Bethe-Bloch formula)

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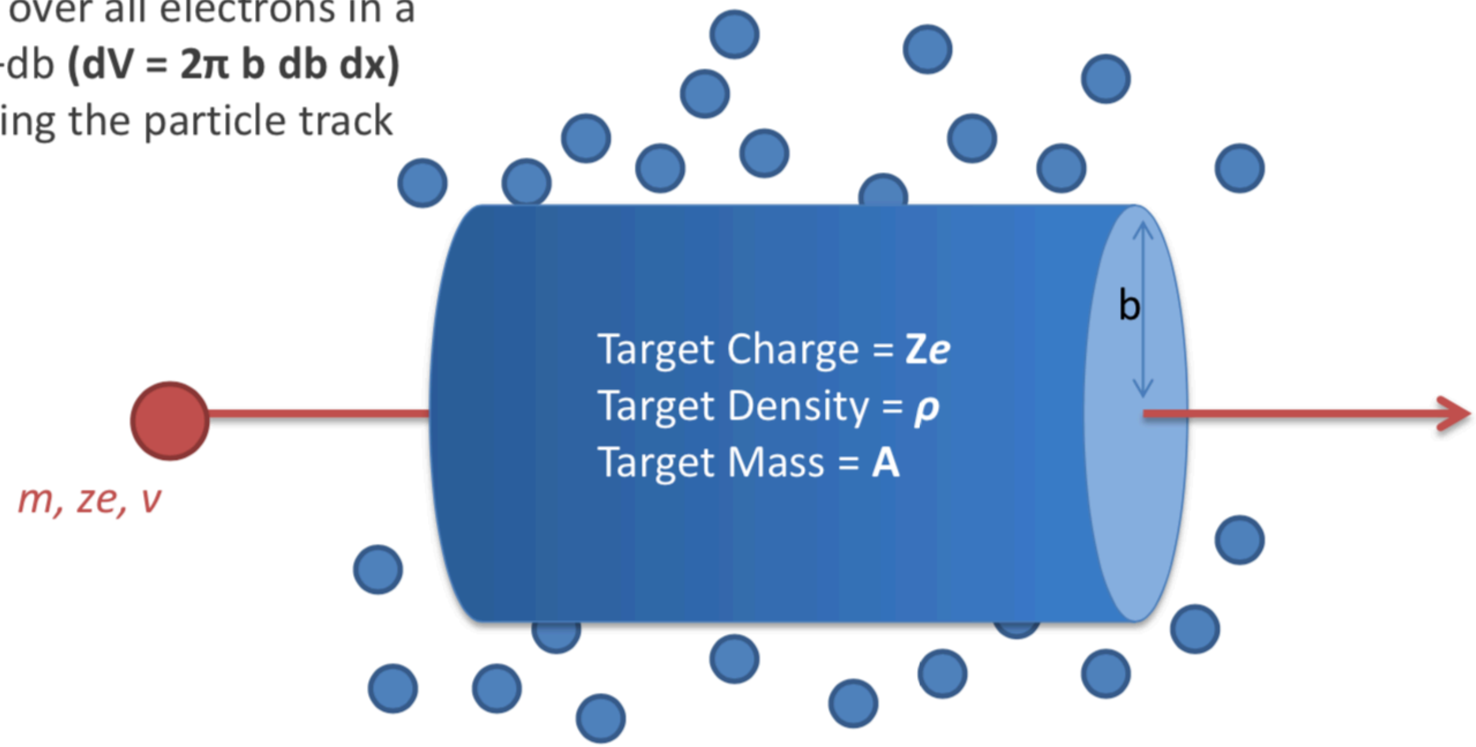
integrate over all electrons in a region b+db **(dV = 2π b db dx)** surrounding the particle track



electron density given as:
(electrons/cm³)

$$N_e = \frac{N_A \rho Z}{A}$$

Ionization (Bethe-Bloch formula)

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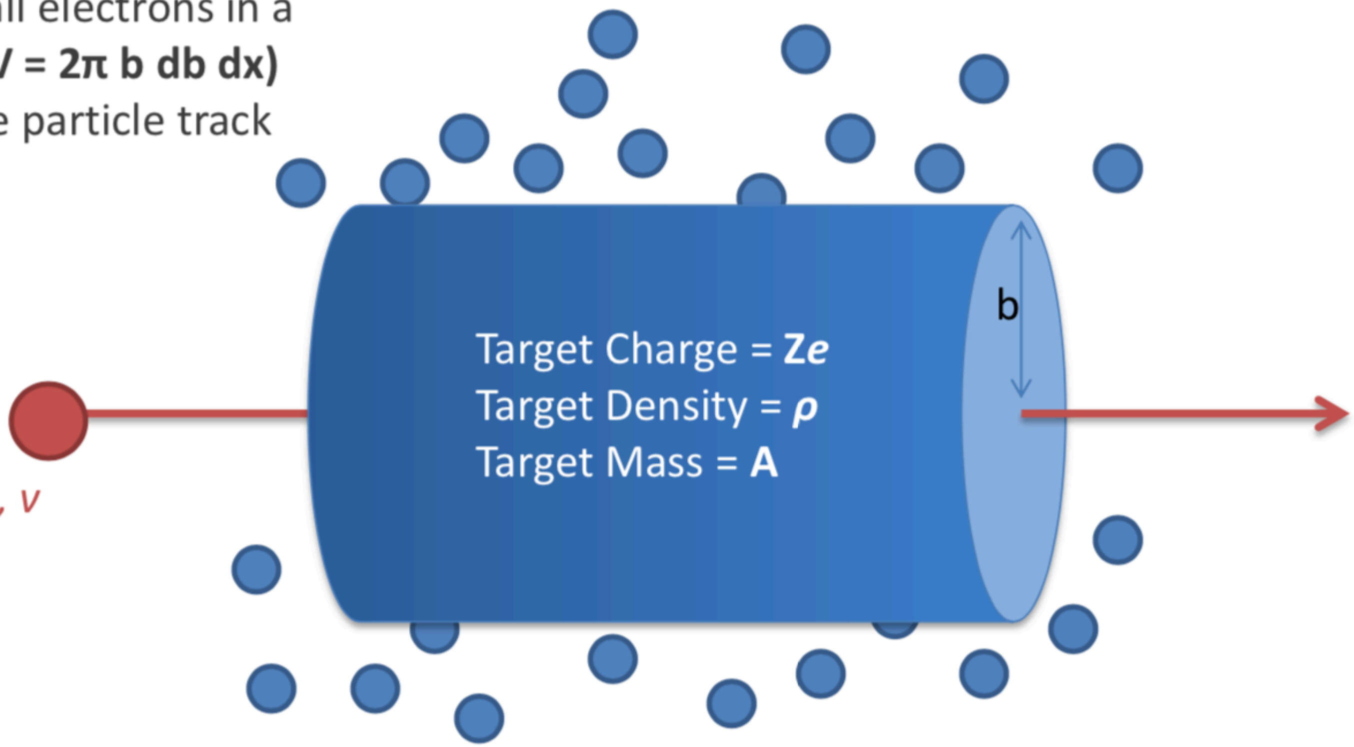
integrate over all electrons in a region b+db **(dV = 2π b db dx)** surrounding the particle track



hence:

$$-dE = 2\pi N_e \, \Delta E \, b \, db \, dx = \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2} \frac{1}{bv^2} \frac{N_A \rho Z}{A} db \, dx$$

Ionization (Bethe-Bloch formula)

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typical to express energy loss per unit distance (dx), normalised by density (a.k.a. mass stopping power) with units MeV g^{-1} cm^2

$$-\frac{1}{\rho}\frac{dE}{dx} = \int_{b\min}^{b\max} \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2}\frac{1}{bv^2}\frac{N_A Z}{A}\,db$$

$$= \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2}\frac{1}{v^2}\frac{N_A Z}{A}\int_{b\min}^{b\max}\frac{1}{b}\,db$$

$$= \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2}\frac{1}{v^2}\frac{N_A Z}{A}\ln\frac{b_{\max}}{b_{\min}}$$

note that impact parameter must be bounded to avoid divergences

Ionization (Bethe-Bloch formula)

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but remember that ΔE is proportional to b^{-2}

$$-\Delta E = \frac{1}{2} m_e V_y^2 = \frac{z^2 e^4}{8\pi^2 m_e \varepsilon_0^2} \frac{1}{b^2 v^2}$$

so we can re-express in terms of minimum and maximum energy transfers:

$$\ln \frac{b_{\max}}{b_{\min}} = \ln \left(\frac{E_{\max}}{E_{\min}} \right)^{1/2}$$

$$= \frac{1}{2} \ln \frac{E_{\max}}{E_{\min}}$$

$$E_{\min} = I$$

this is the ionisation energy

$$E_{\max} = m_e v^2$$

max energy imparted in a head on collision when $m_e \ll m$

Ionization (Bethe-Bloch formula)

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bringing it together:

$$-\frac{1}{\rho}\frac{dE}{dx} = \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2}\frac{1}{v^2}\frac{N_A Z}{A}\left[\frac{1}{2}\ln\frac{m_e v^2}{I}\right]$$

$\beta = v/c$

$$= \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}\right)\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}\right)\frac{4\pi z^2 m_e c^2}{\beta^2}\frac{N_A Z}{A}\left[\frac{1}{2}\ln\frac{m_e \beta^2 c^2}{I}\right]$$

classical radius of electron

$$= \left(4\pi N_A r_e^{\,2} m_e c^2\right) z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{m_e \beta^2 c^2}{I}\right]$$

$$= K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{m_e \beta^2 c^2}{I}\right]$$

Ionization (Bethe-Bloch formula)

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bringing it together:

$$-\frac{1}{\rho}\frac{dE}{dx} = \frac{z^2 e^4}{4\pi m_e \varepsilon_0^2}\frac{1}{v^2}\frac{N_A Z}{A}\left[\frac{1}{2}\ln\frac{m_e\beta^2c^2}{I}\right]$$

$$= \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}\right)\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}\right)\frac{4\pi z^2 m_e c^2}{\beta^2}\frac{N_A Z}{A}\left[\frac{1}{2}\ln\frac{m_e\beta^2c^2}{I}\right]$$

$$= \left(4\pi N_A r_e^2 m_e c^2\right) z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{m_e\beta^2c^2}{I}\right]$$

$$= K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{m_e\beta^2c^2}{I}\right]$$

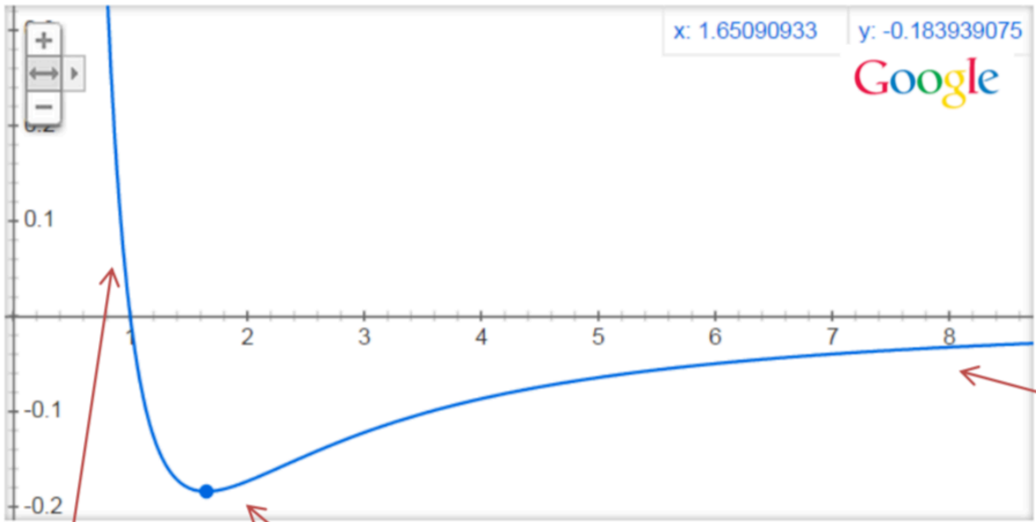
squared dependence on charge of **incident** particle

Ionization (Bethe-Bloch formula)

Video of the lecturer

$$-\frac{1}{\rho}\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{m_e\beta^2c^2}{I}\right]$$

Graph for (-ln(x))/x^2



energy loss reaches plateau at high β

energy loss **falls as $1/\beta^2$**

energy loss reaches **minimum** when $\ln\beta \approx 1/\beta^2$

Ionization (Bethe-Bloch formula)

Video of the lecturer

Bethe-Bloch formula:

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

with units MeV g^{-1} cm^2, where:

$$\gamma = \left[1-\beta^2\right]^{-1/2}$$

$X = \rho x$, where ρ is the density of the absorber material
N_A = Avagadro's number (6.022×10^{23} mol^{-1})
m_e = electron mass (0.511 MeV)
r_e = classical electron radius (2.82×10^{-13} cm)
$K = 4\pi N_A r_e^2 m_e c^2$ (0.307 MeV g^{-1} cm^2)
z = charge of incident particle in units of e
Z, A = atomic number and weight of absorber material
W_{max} = maximum kinetic energy which can be imparted to a free electron in a single collision

Ionization (Bethe-Bloch formula)

Video of the lecturer

Bethe-Bloch formula:

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

more rigorous treatment of the maximum and minimum energy transfer for relativistic particles

additional constants and dampening terms

classical treatment is a very good approximation for heavy nuclei, breaking down for lighter or relativistic particles

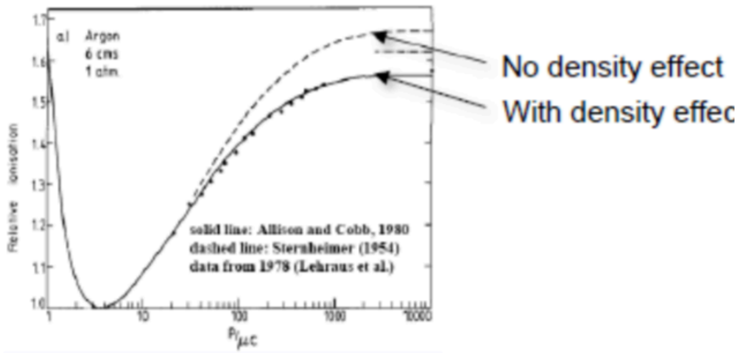
Ionization (Bethe-Bloch formula)

Video of the lecturer

- density effect

  at higher energies, E-field of the ionising particle polarises the absorber as it passes through, effectively shielding distant electrons from the full E-field

  => less energy loss, proportional to absorber density



- maximum energy transfer

  now takes into account mass (*m*) and energy of incident particle relative to ionised electron

$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / m + \left(m_e / m\right)^2}$$

- mean ionisation potential

  determined empirically for different absorbers

$$I \approx I_0 Z^{0.9} \quad \text{with } I_0 = 16\text{eV}$$

e.g. $I \approx 172$eV for silicon

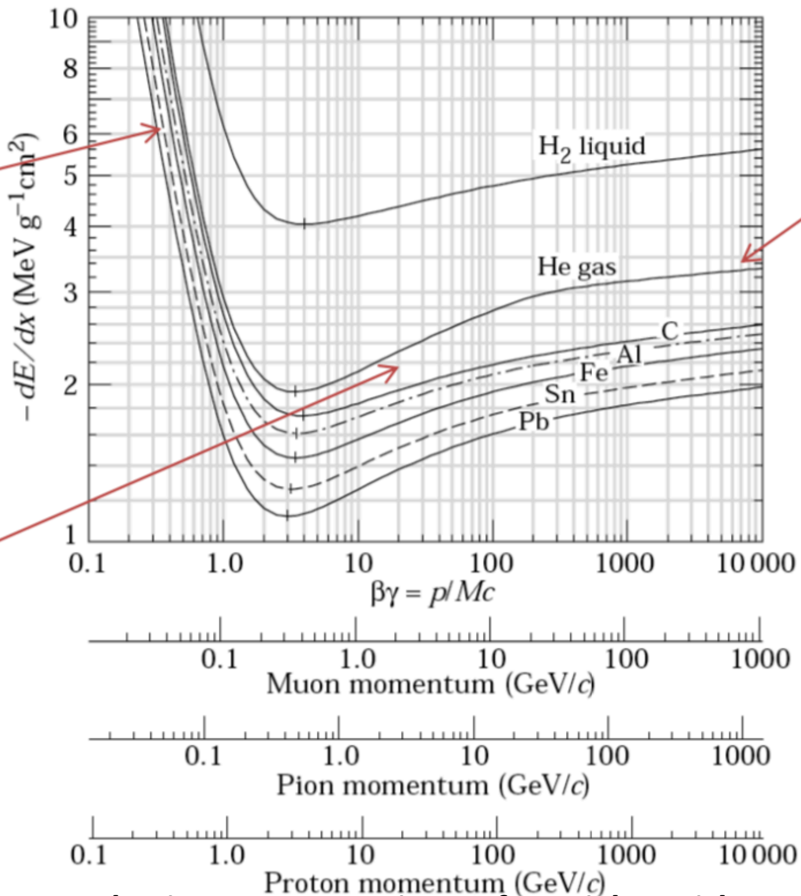
Ionization (Bethe-Bloch formula)

Video of the lecturer

understanding Bethe-Bloch

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

β^{-2} dependence (slower particles interact with electrons for longer time)



"Fermi plateau" – saturation due to density effect at high β

"relativistic rise" – extension of transversal E-field

$$E_y \rightarrow \gamma E_y$$

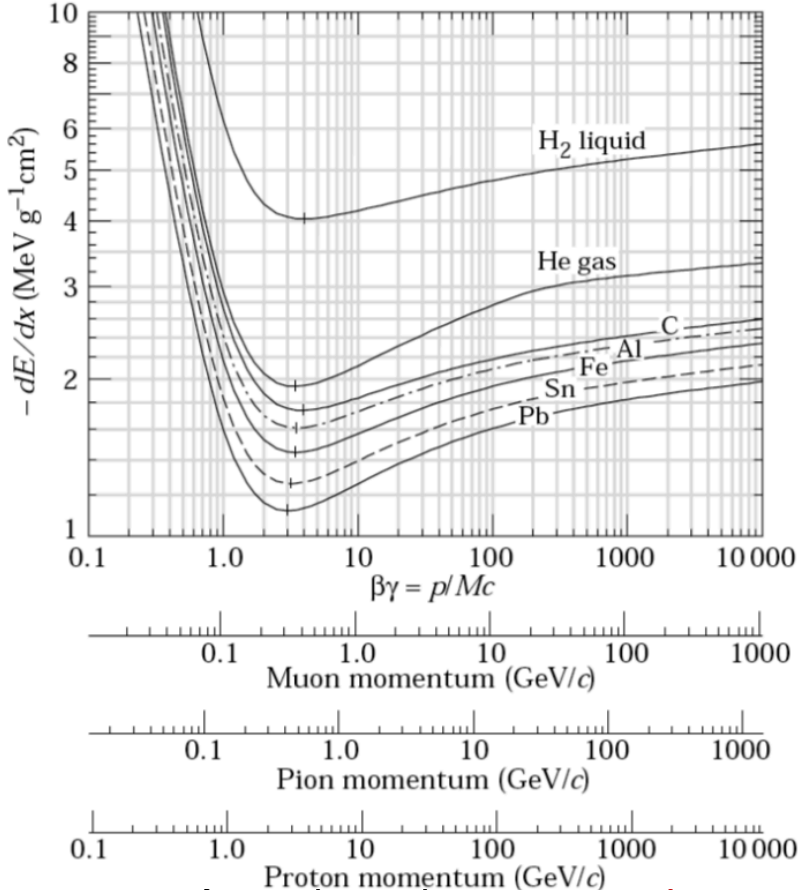
Ionization (Bethe-Bloch formula)

Video of the lecturer

understanding Bethe-Bloch

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

- dE/dX only **depends on β** – independent of incident particle mass (βγ<500)



Ionization (Bethe-Bloch formula)

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understanding Bethe-Bloch

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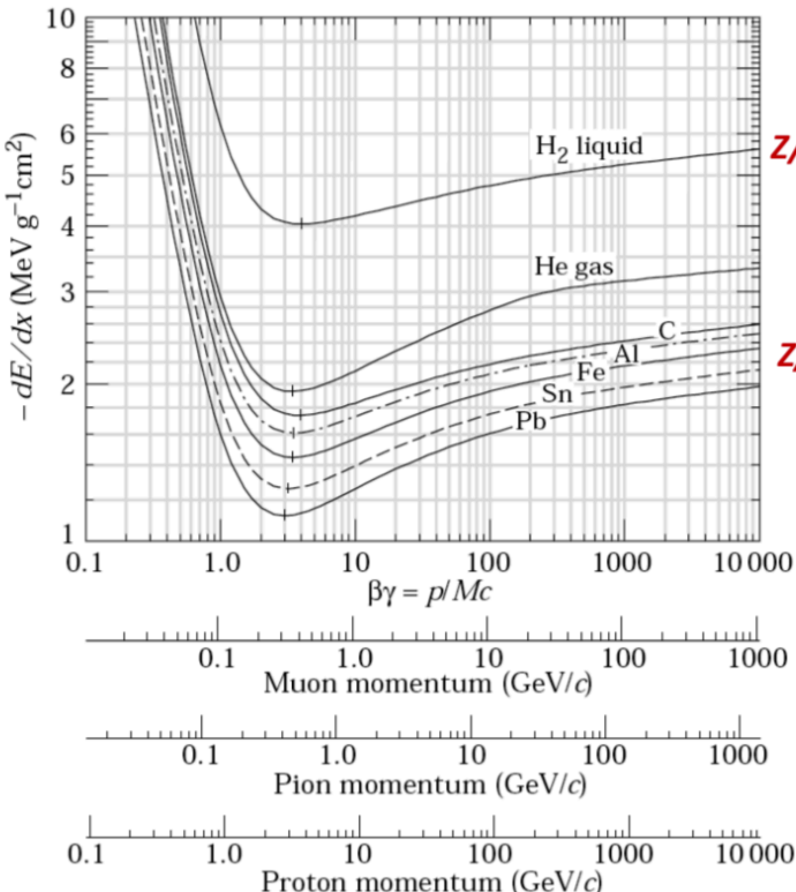
- dE/dX only **depends on β** – independent of incident particle mass (βγ<500)
- dE/dX **proportional to *Z/A* of absorber**, i.e. electron density



***Z/A* = 1**

***Z/A* ≈ 0.5**

Ionization (Bethe-Bloch formula)

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understanding Bethe-Bloch

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

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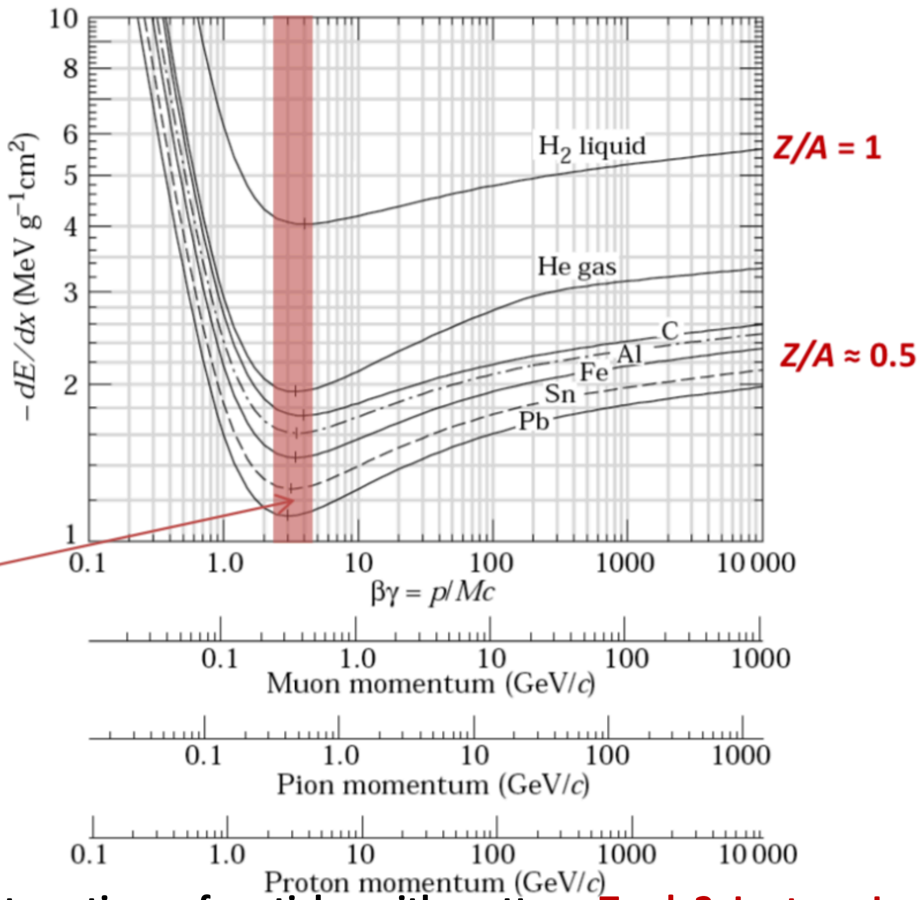
- dE/dX **proportional to *Z/A* of absorber**, i.e. electron density
- **minimum ionisation occurs at βγ ≈ 3-4** – referred to as Minimum Ionising Particles **(MIPs)**



Ionization (Bethe-Bloch formula)

Video of the lecturer

understanding Bethe-Bloch

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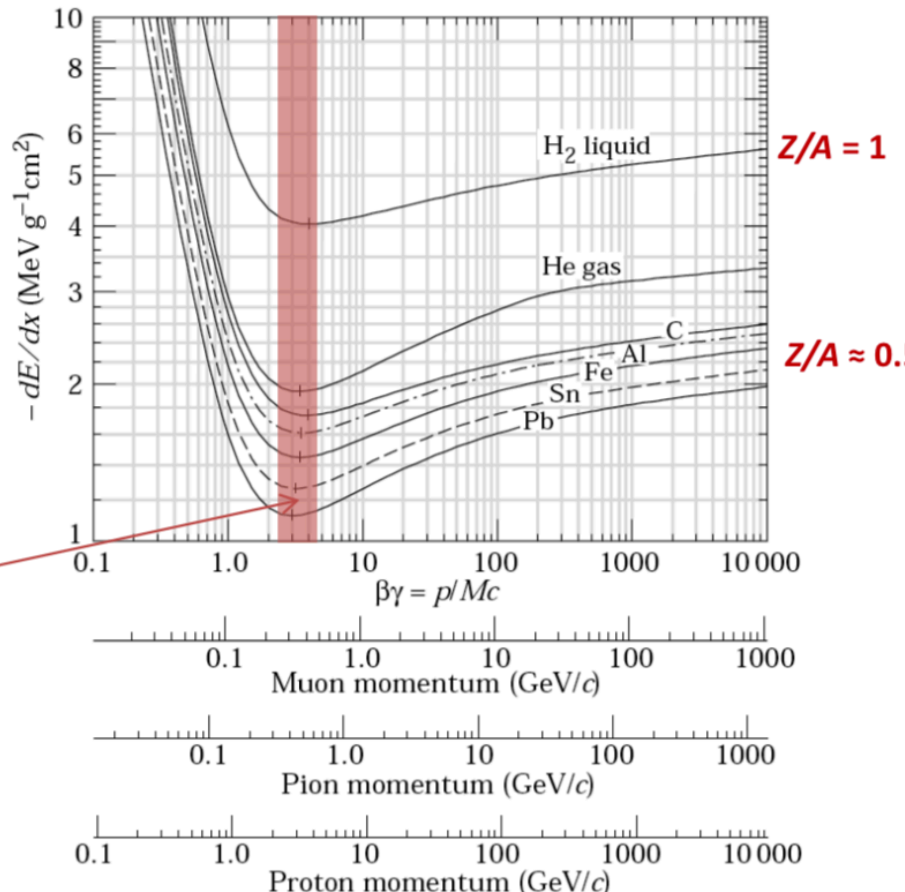

Ionization (Bethe-Bloch formula)

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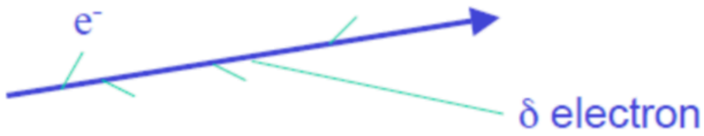
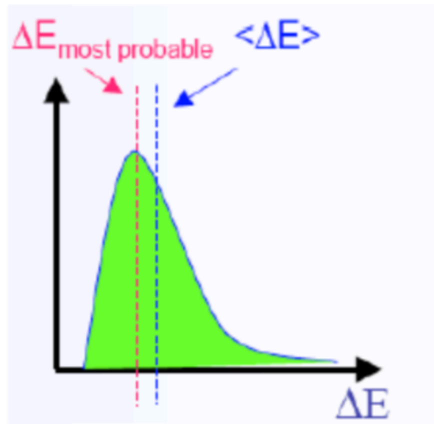
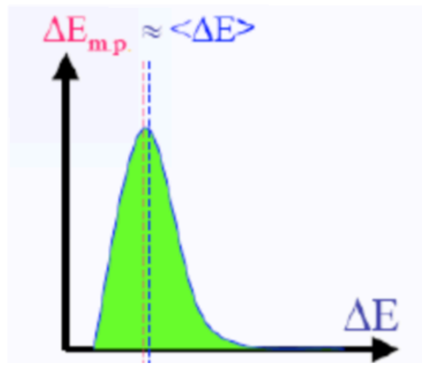
- for thin layers or low density materials
  - few interactions, low energy transfers more probable
  - some high energy collisions knock out electrons (*so called δ-electrons*)





⇒ **energy loss distribution skewed with large fluctuations towards higher losses**

- for thick layers or high density materials
  - many collisions, averaged out



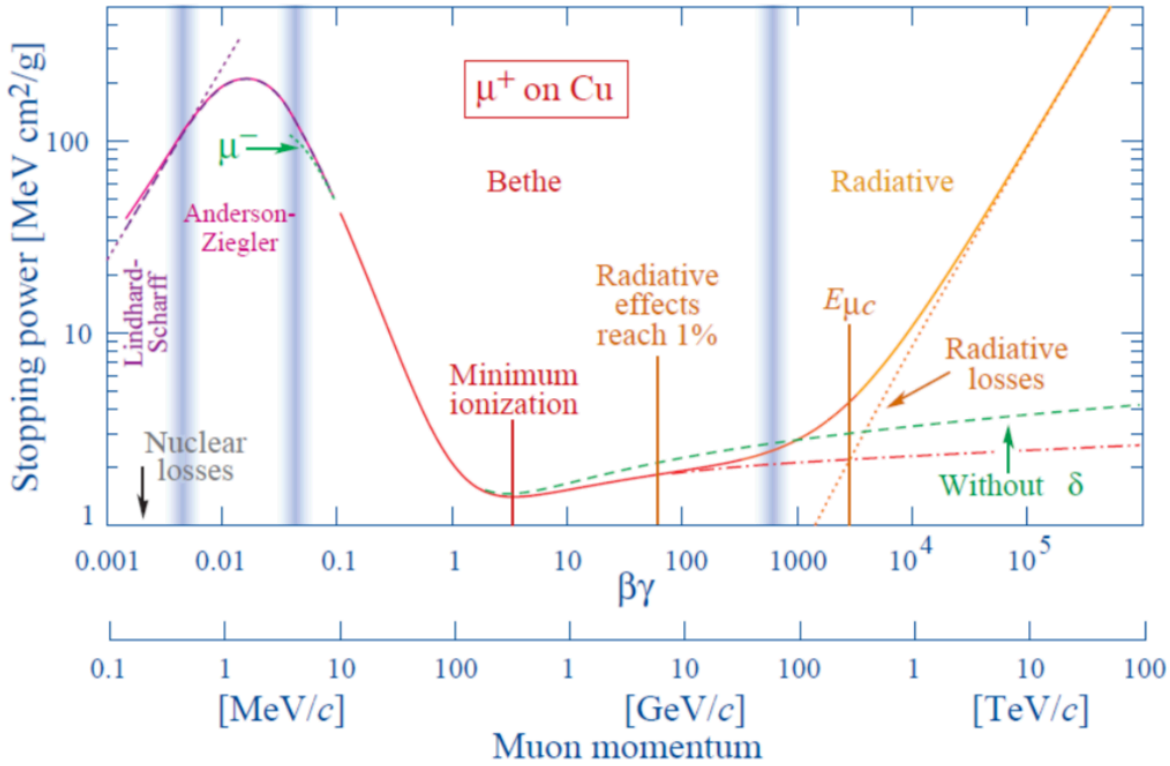
⇒ **central limit theorem, gaussian distribution**

Ionization (Bethe-Bloch formula)

Video of the lecturer

valid only for the range 0.1 < βγ < 1000

- at $v > 0.9999995c$, **radiative effects** start to dominate (*covered next*)



Ionization (Bethe-Bloch formula)

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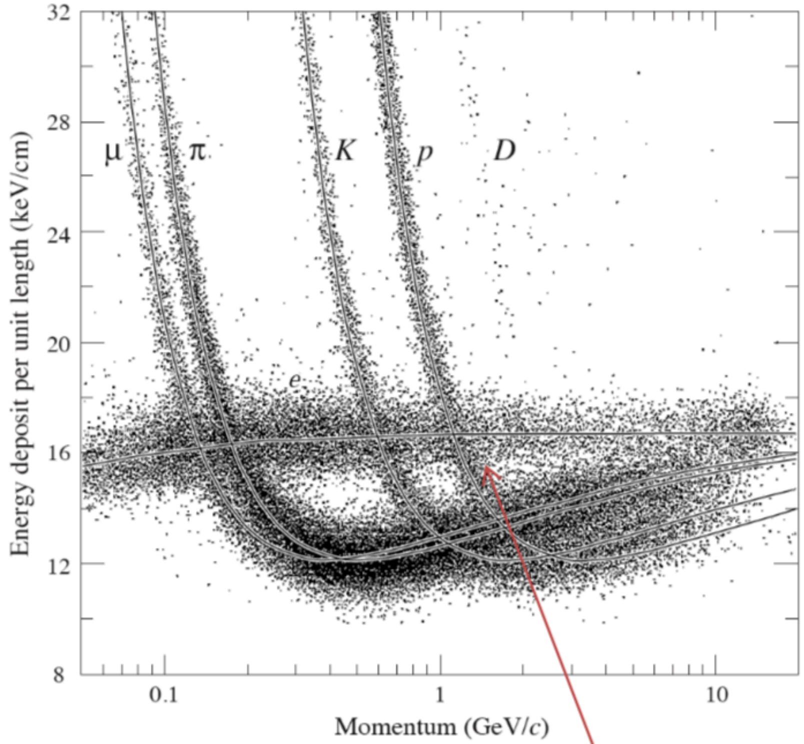
particle identification

- dE/dX is identical for particles with a given z, and only depends on β
- but for a given particle energy, Bethe-Bloch can be used to distinguish different particle species (mass)

$$\beta\gamma = \frac{p}{Mc}$$

- combining dE/dX with momentum measurement can identify particle species
  - most effective in βγ <3.5 region



statistical fluctuations about mean contribute to mis-identifications

Quiz

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The bethe-bloch formula for ionisation gives dE / dx proportional to

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0	0	0	0	0
The mass of the incident particle	Z of the absorber	Z/A oft he absorber	A of the absorber	Beta oft he incident particle

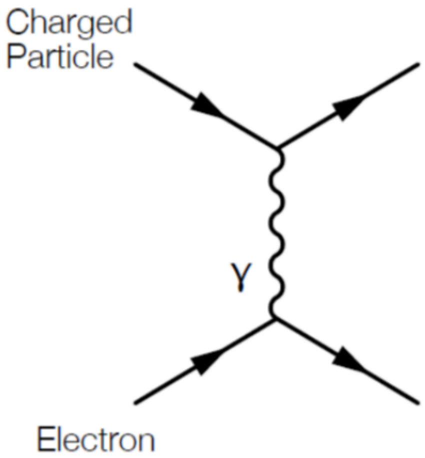
Press **ENTER** to show correct

Radiative losses – Bremsstrahlung

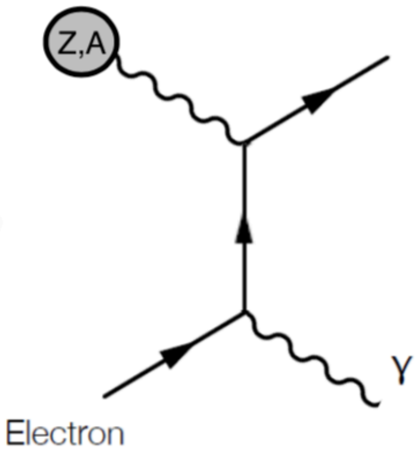
Video of the lecturer

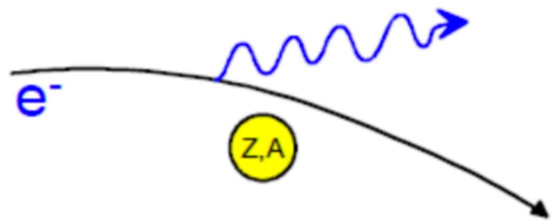
what are radiative losses?

- radiative energy losses are due to emission of EM radiation during scattering with the absorber atomic nuclei – **Bremsstrahlung**
- much more significant for electrons/positrons than any other particle



ionising





Bremsstrahlung

Radiative losses – Bremsstrahlung

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why is it significant at high incident particle energies/low masses?

- deriving rate of energy loss by Bremsstrahlung is not simple, approximate relation is given by

$$-\left.\frac{dE}{dx}\right|_{rad} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}}$$

where α = 1/137.036

- **proportional to energy *E* of incident particle** – can be seen as higher energy electrons imparting more energy to the emitted photon

- **proportional to (1/*m*)²** – radiative energy losses for muons is 40,000 times less than for electrons at the same energy! Muon brem only significant at >500GeV

Radiative losses – radiation length

Video of the lecturer

consider electron Bremsstrahlung

$$-\left.\frac{dE}{dx}\right|_{rad} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}}$$

this can be rewritten in the form:

$$-\left.\frac{dE}{dx}\right|_{rad} = \frac{E}{X_0}$$

where

$$\frac{1}{X_0} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \ln\frac{183}{Z^{1/3}}$$

defines the **radiation length** X_0, with units g cm^{-2}, divide by density to get X_0 in cm

therefore:

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

radiation length is the mean distance over which a high-energy electron loses all but 1/e of its energy by Bremsstrahlung (~63%)

Cherenkov Radiation

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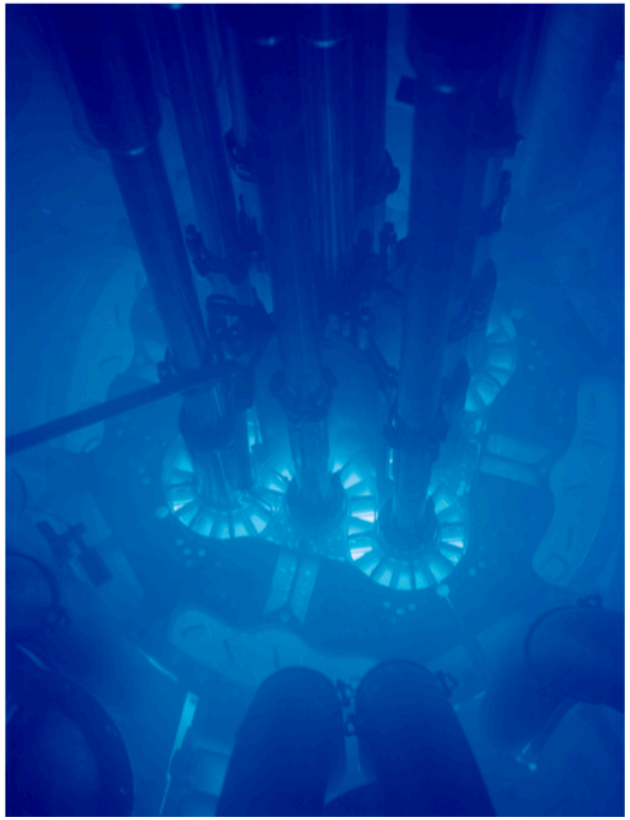
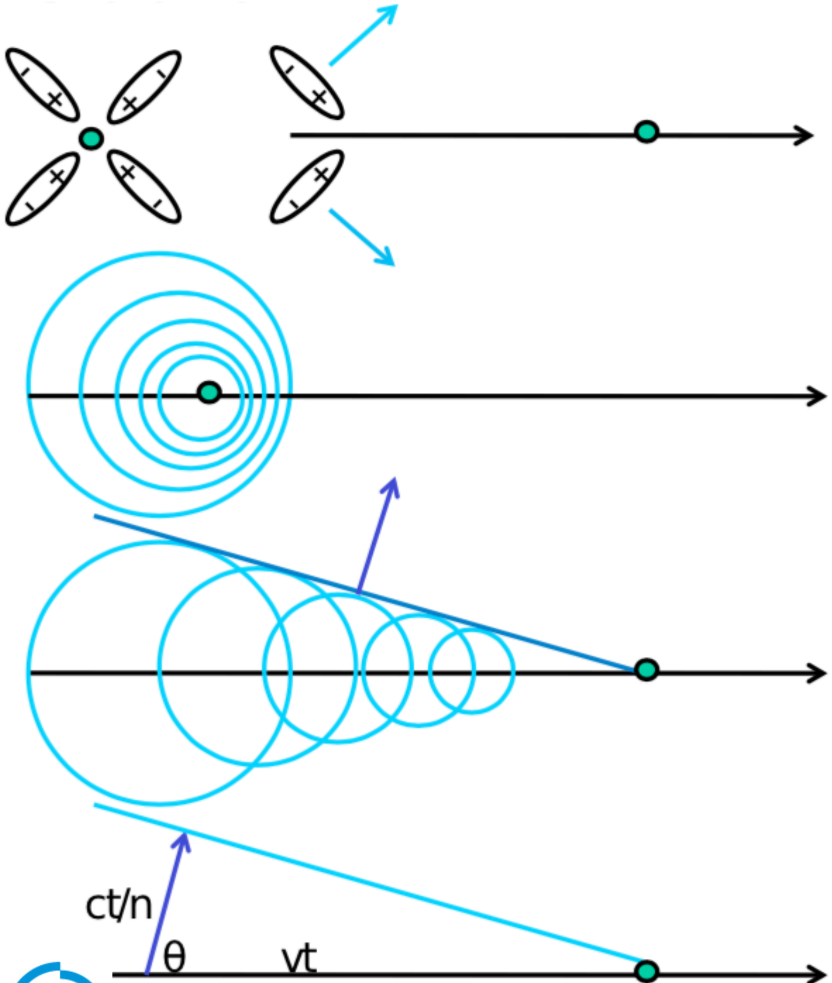
- Light emitted by medium excited by charged particle
- Particle moving faster than light in medium
- Responsible for the “eerie” radioactive glow
- Depends on velocity of particle



Cherenkov Radiation

Video of the lecturer



Charged particle polarises medium

With $\beta < 1/n$ no coherent emission

With $\beta > 1/n$ coherent wave front

$\cos(\theta) = ct/nvt = 1/n\beta$

Cherenkov Radiation

Video of the lecturer

- Coherent radiation emitted when charged particle exceeds the speed of light in a medium
- Photons emitted at an angle $\cos(\theta) = 1/ n\beta$
- Threshold for emission $\beta = 1/ n$
- Threshold Cherenkov detectors measure only presence of light
- Angle can be measured by Ring Imaging CHerenkov (RICH) detectors
- Or by Detector of Internally Reflection Cherenkov (DIRC)

Transition radiation

Video of the lecturer

- Radiation emitted when particle moves between medium with refractive indices n_1 and n_2
- Intensity ~ γ ; $\theta_{emission} = 1 / \gamma$
- Mostly x-rays and emission probability low
  - Need many layers
  - Need high $\gamma \sim 1000$
- For e– $p > 500$ MeV
- For pi+ $p > 150$ GeV

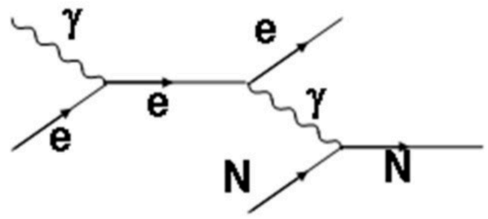
Energy loss of e- , e+ and photons

Video of the lecturer

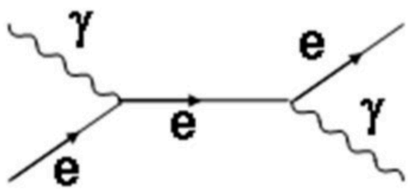
Energy loss of e- , e+ and photons

Video of the lecturer

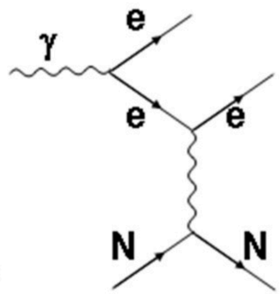
- Can separate photon interactions into low, medium and high energy regimes:

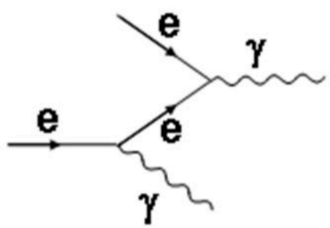


  - Low energy - Photo-electric effect
  - Medium energy - Thomson/Rayleigh scattering
    elastic (coherent) scattering against (free) e-
    - Compton scattering (mid-energy)
    inelastic (incoherent) scattering against e-



  - High energy - Pair production, annihilation





Photoelectric effect

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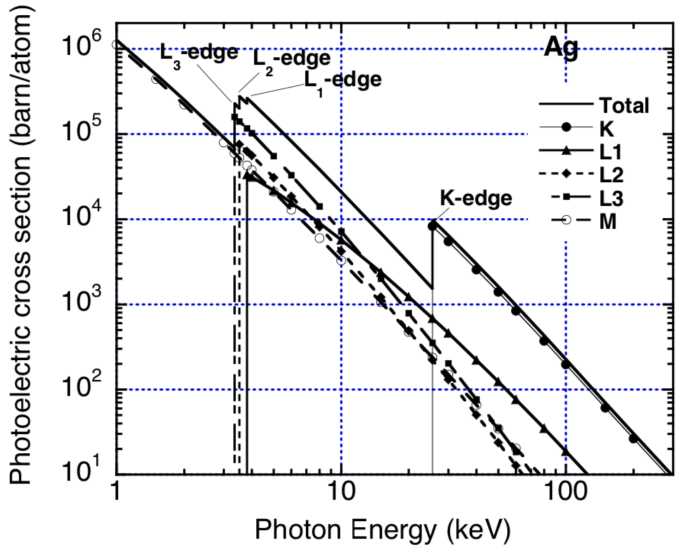
- Photon energy is completely absorbed, transferred to ejected atomic electron
- $E_{e-} = E_{\gamma} - E_B(nl)$, where E_B is the binding energy or work function
- Cross-section $\sim Z^5 / E_{\gamma}$



- Photomultipliers - extremely light-sensitive vacuum tubes with a photocathode inside - materials with low work function, so emit e- when illuminated

Compton effect

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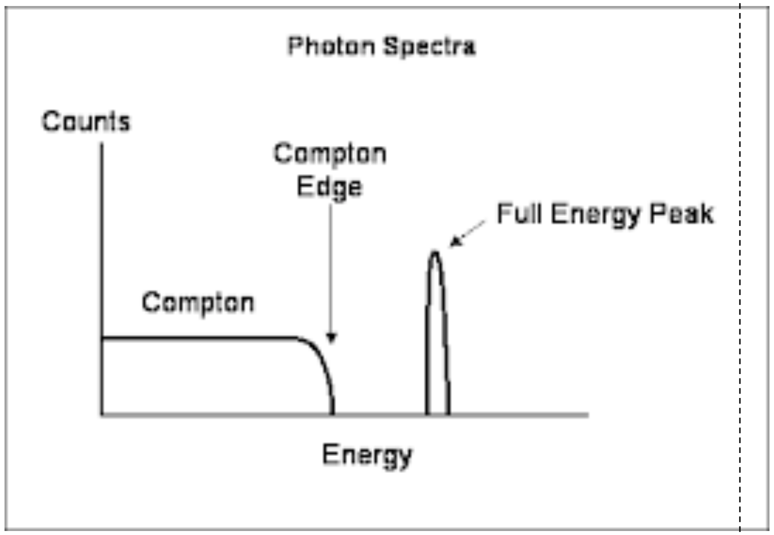
- Amount of energy exchanged varies with angle

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

- *E* is the energy of the incident photon; *E'* is the energy of the outgoing photon
- Maximum energy transferred when θ approaches 180°
- Impossible for the γ to transfer any more energy, hence there is a sharp cutoff at this energy, giving rise to the name *Compton edge*



Pair production

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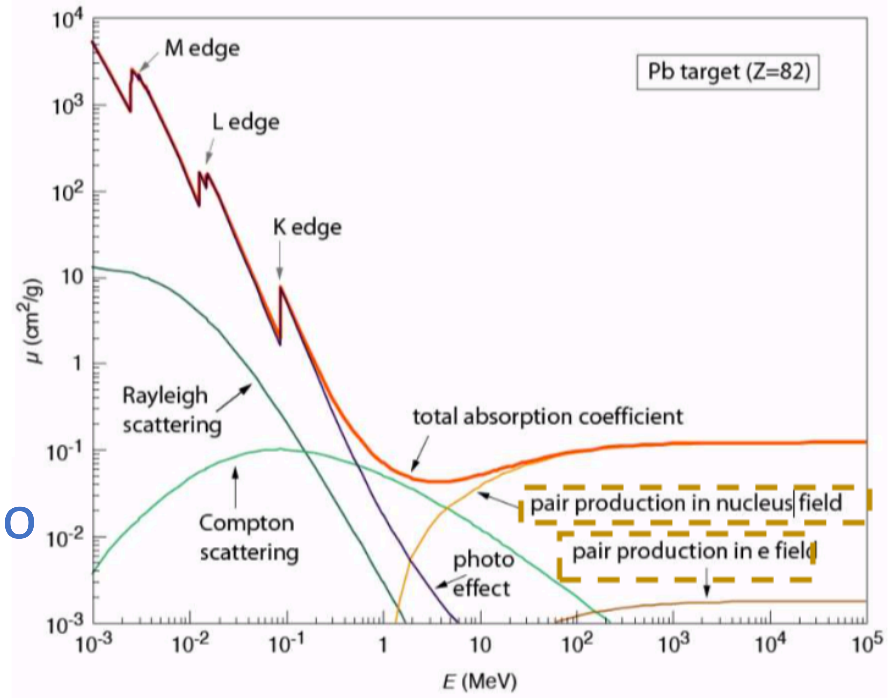
- Photon energy must be larger than $2 \times m_e c^2 \sim 1.022$ MeV

- Cross-section is quasi energy independent

$$\sigma_{PP} \sim 4\alpha r_e^2 Z^2 \left[\frac{7}{9} ln \frac{183}{Z^{1/3}} - \frac{1}{54}\right] \sim \frac{7}{9} \frac{A}{N_A \rho X_0}$$

- Mean free path can be related to radiation length X^0

$$\lambda_{int} = \frac{A}{N_A \rho \sigma_{PP}} = \frac{9}{7} X_0(\text{brems})$$



Quiz

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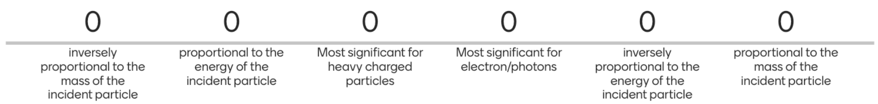
Mentimeter

Radiative or bremstrahlung energy losses are



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