Lecture # 1

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Introduction

- Particle physics → ultimate constituents of matter and the fundamental interactions
- Experiments have revealed whole families of short-lived particles
- Molecular hypothesis and the development of chemistry.
- Most scientist accepted → matter aggregates of atoms.

- Radioactivity and the analysis of low energy scattering → atoms have structure.
- Mass was concentrated in dense nucleus surrounded by cloud of electrons.
- The discovery of neutron - 1930
- Geiger tubes and cloud chambers → properties of cosmic ray particles.
- The modern discipline of particle physics → high energy nuclear physics + cosmic ray physics

Particles and Interactions

- Four interactions and their approximated strength at 10^{-18} cm are

$$Strong = 1$$

$$Electromagnetic = 10^{-2}$$

$$Weak = 10^{-5}$$

$$Gravitational = 10^{-39}$$

- Hundreds of new particles have been discovered
- Tried to group them into families with similar characteristics.
- Leptons do not obey strong interaction.
- Hadrons obey strong interactions.
- Hadrons are of two types:
- Baryons → ½ integral spin,
- Mesons → integral spin

- Protons
- Neutrons
- Prof. Salam's → weak neutral currents
- Bubble chamber
- Resonances
- Resonances can decay via strong interactions and thus have lifetime of 10^{-23} sec
- Antimatter
- Gauge bosons

Detectors

- Piece of equipment for discovering the presence of something, such as metal, smoke etc
- Particle detectors are extensions of our senses: make particle → visible to human senses
- How particles interact with matter ?
- The properties of the detectors used to measure these interactions
- Fundamental considerations involved in designing a particle physics experiment.

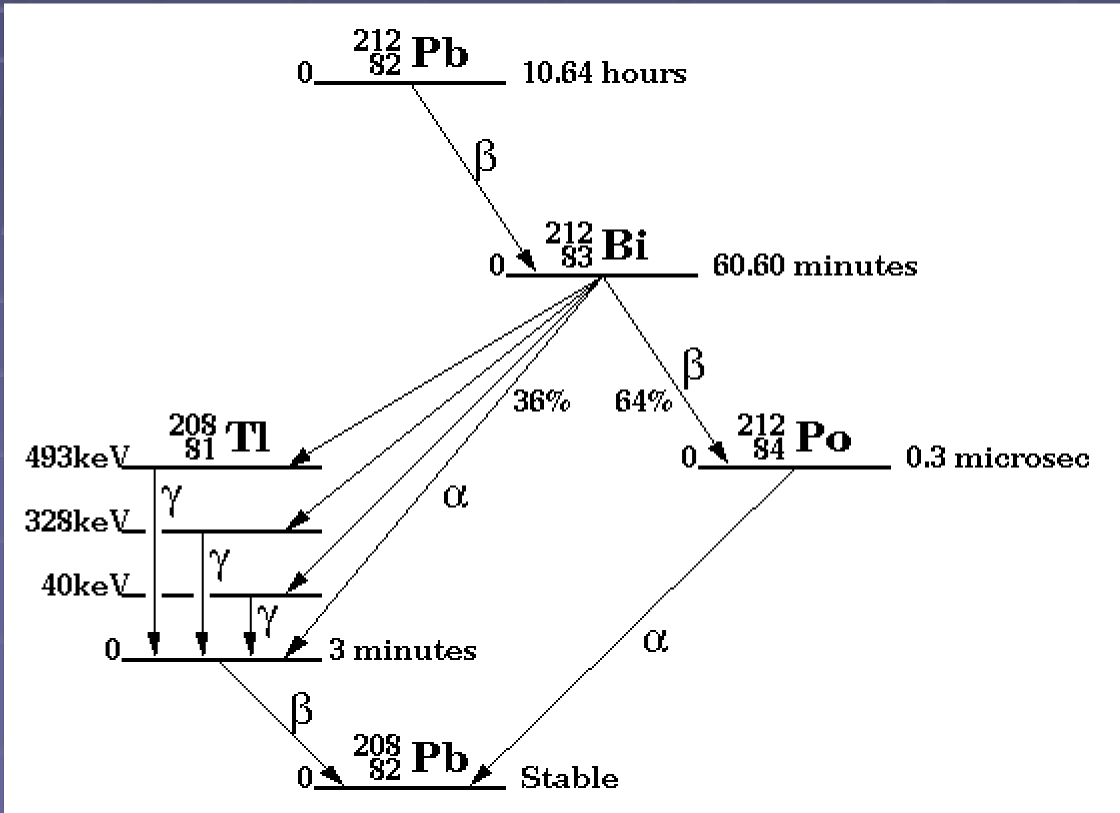
- Charge
- Mass
- Spin
- Magnetic moment
- Life time
- Branching ratios

- Tracking
- Momentum analysis
- Neutral particle detection
- Particle identification
- Triggering
- Data acquisition

Alpha decay

$$\left(Z,A\right)\rightarrow\left(Z-2,A-4\right)+\alpha$$

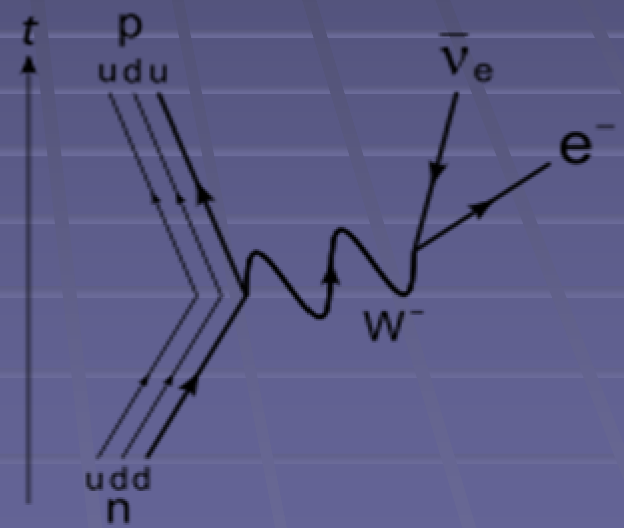
- Radioactive decay
- Particle trapped in a potential well by nucleus
- Fundamentally quantum tunneling process
- Transition between nucleus levels
- A 5 MeV α-particle travels at 10^7 m/s
- Short range, 3-4 cm in air



Beta decay

- Radioactive decay
- Fast electrons
- Weak interaction decay of neutron or proton
- Continuous energy spectrum, ranges from few keV to few tens of MeV

$$n \rightarrow p + e^{-} + \bar{\upsilon}$$



Electron capture

- β+ decay cannot occur in isolation
- Proton rich nuclei may also transform themselves via capture of an electron from one of the atomic orbitals
- Accompanied by electron capture process

$$energy + p + e^{-} \rightarrow n + \upsilon$$

- Leaves hole, another atomic electron fills
- Emission of characteristic x-ray or auger electrons

Auger Electrons

- An excitation → in the electron shell → transferred → atomic electron rather than to a characteristic x-ray
- This occurs after electron-capture
- Second ejected electron → Auger electron
- Monoenergetic energy spectrum
- Energy not more than few keV
- Susceptible to self-absorption

Gamma Emission

- Nucleus has discrete energy levels
- Transition between these levels by electromagnetic radiations
- Photon energy ranges keV-MeV
- Characterize high binding energy
- γ rays

Annihilation Radiation

- Annihilation of positrons
- ^{22}Na → irradiate absorbing material
- Positron will annihilate with the absorber electron to produce two photons
- Photons → opposite direction

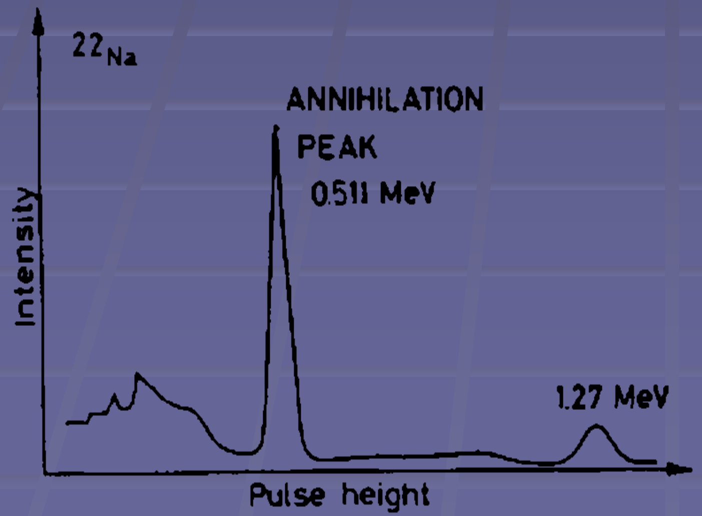


Fig. 1.4. Gamma-ray spectrum of a ^{22}Na source as observed with a NaI detector. Because of positron annihilation in the detector and the source itself, a peak at 511 keV is observed corresponding to the detection of one of the annihilation photons

Internal Conversion

- Nuclear excitation energy is directly transferred to an atomic electron rather than emitting a photon
- Electron K.E = excitation energy – atomic B.E
- Electrons monoenergetic
- Same energy as γ rays
- Few hundered keV to few MeV
- Mostly k-shell electrons ejected
- Nuclear source of monoenergetic electrons
- Used for calibration purpose

Scattering Cross section

- Gives a measure of probability for a reaction to occur
- Calculated in the form of basic interaction between the particles.

Differential cross-section

$$\frac{d\sigma}{d\Omega}(E,\Omega) = \frac{1}{F}\frac{dN_s}{d\Omega}$$

$$\sigma(E) = \int d\Omega \frac{d\sigma}{d\Omega}$$

Total cross-section

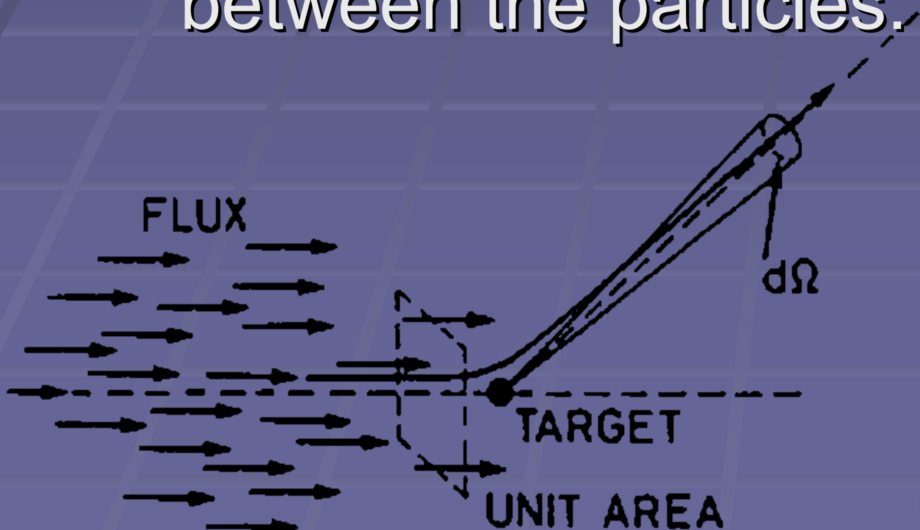


Fig. 2.1. Definition of the scattering cross section

Energy loss by atomic collisions

- Two principal features → passage of charged particle through matter

  1- a loss of energy by particle

  2- a deflection of the particle from its incident direction.

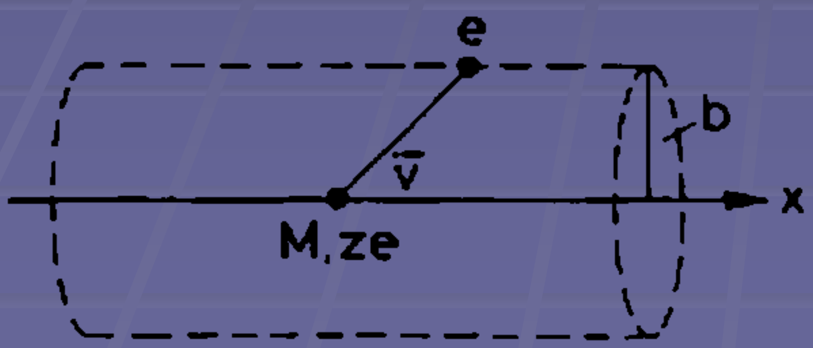
- These effects → results of two processes
- Inelastic collisions → atomic electrons
- Elastic scattering from nuclei
- Other process → Cherenkov radiation,
- → nuclear reaction
- → bremsstrahlung

- Inelastic collisions → almost solely responsible
- In these collisions ($\delta = 10^{-17} - 10^{-16}\ cm^2$), energy is transferred → particle to the atom causing an ionization or excitation
- The amount transferred in each collision is very small fraction of the particle K.E
- Large number of collisions per unit path length
- Substantial cumulative energy loss is observed.

- Soft collisions → excitation
- Hard collisions → ionization
- δ -rays or knock-on electrons
- Inelastic collisions → statistical in nature, their number per macroscopic path length large
- Elastic scattering from nuclei → not as often as atomic collisions
- Average energy loss per unit path length
- Stopping power or $\frac{dE}{dx}$

Bohr formula – Classical case

- Heavy particle with charge ze,M and v
- Calculations → impact parameter
- Electron is free and at initially at rest
- Inicident particle → undeviated
- Bohr formula good for heavy particles
- Breaks for light particles, because of quantum effects → not contain electronic coll. loss



$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4}{m_e \upsilon^2} N_e \ln\frac{\gamma^2 m \upsilon^3}{z e^2 \bar{\upsilon}}$$

The Bethe-Bloch Formula

- The energy transfer is parameterized in terms of momentum transfer rather than impact parameter.
- Momentum transfer is measureable quantity
- Impact parameter is not measureable

Shell correction

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2\upsilon^2 W_{\max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

Bethe-Bloch formula

Density correction

r_e : Classical electron radius

m_e Electron mass

N_a Avogadro's number

I Mean excitation potential

Z Atomic number of absorbing material

A Atomic weight of absorbing material

ρ Density of absorbing material

z Charge of incident particle

β v/c of incident particle

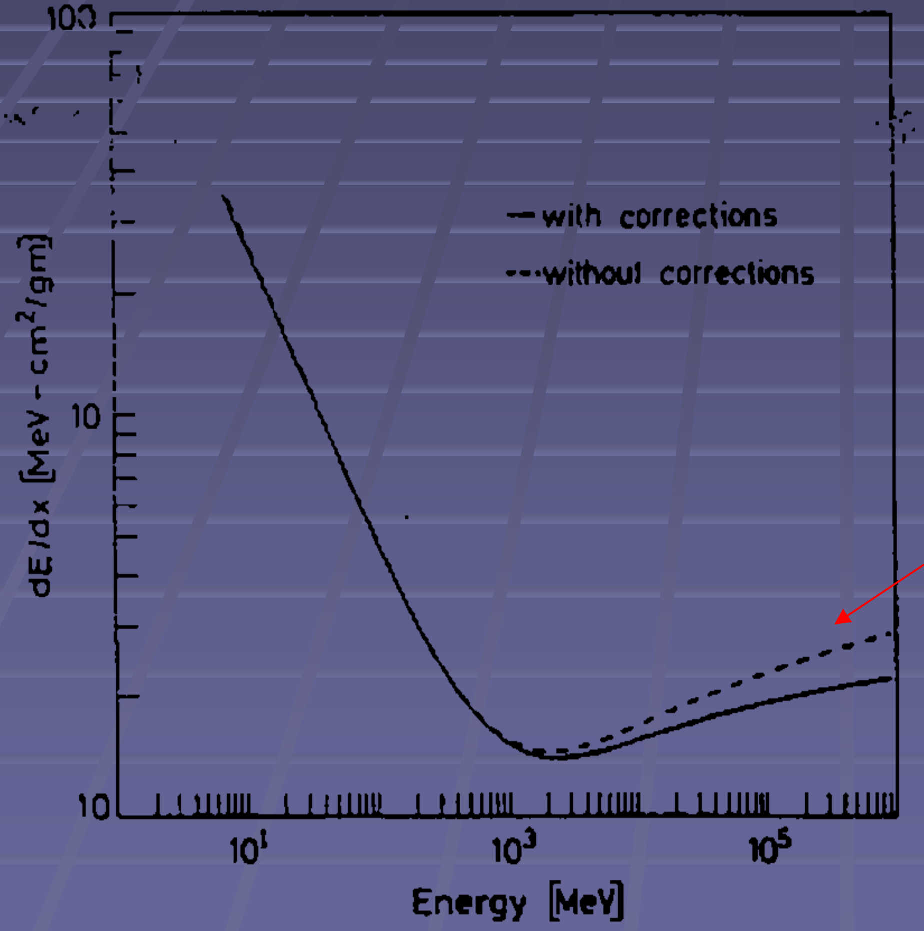
δ Density correction

C Shell correction

$W_{\max}$ Maximum energy transfer in one collision

- Density effect
- Electric field of particle → polarize atoms
- Electrons far from particle → shielded from full electric field intensity
- Collisions with these outer → contribute less total energy loss than predicted
- Energy increases → velocity increases radius → over which integration → increases
- Distant collisions → contribute more
- This effect → depends on density → density effect

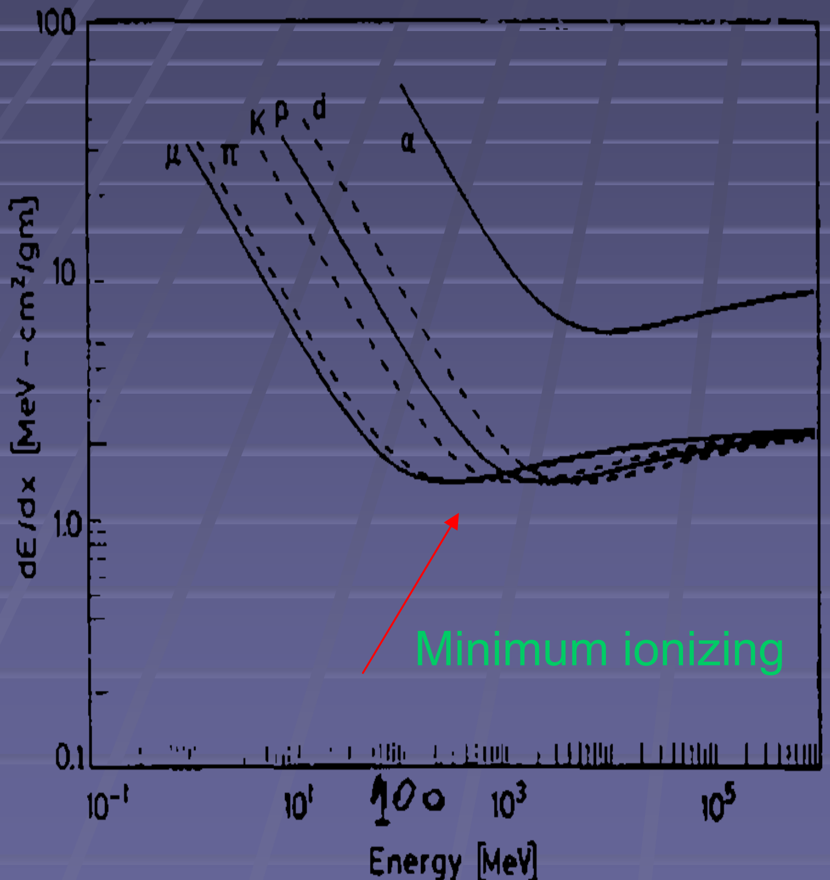
- Shell correction
- Shell correction accounts → velocity of particle comparable or smaller → orbital velocity of → electron
- At such energies assumption → electron stationary → not valid
- Bethe-Bloch formula breaks down
- The correction is generally small
- Other corrections also exist



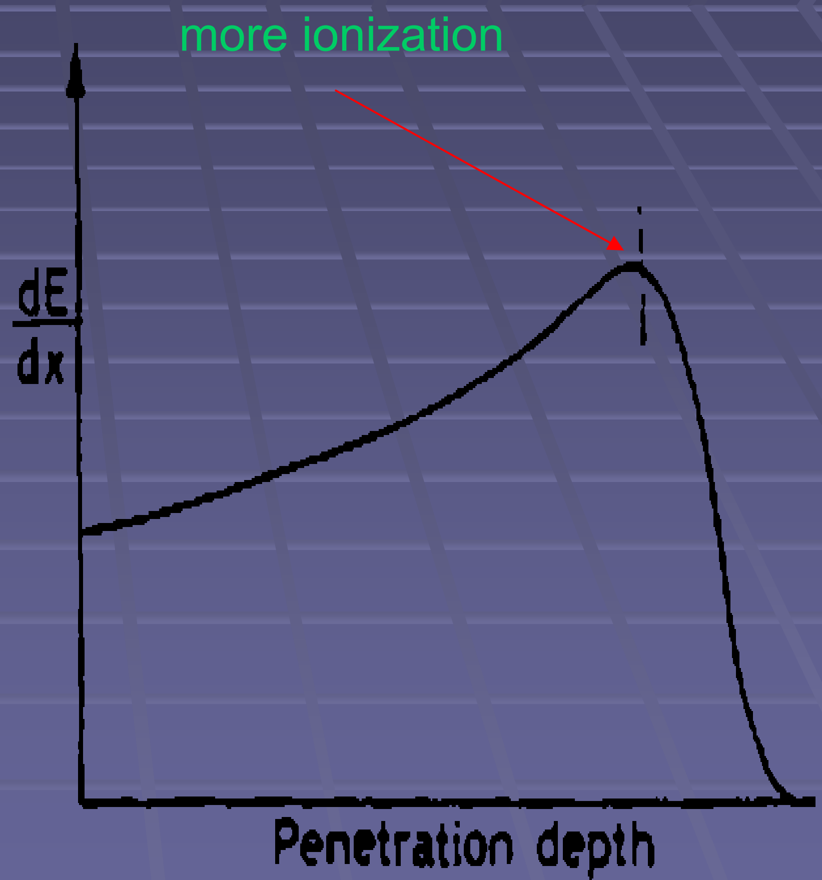
Comparison ob Bethe-Bloch formula, with and without density and shell correction function

Energy dependence of $\frac{dE}{dx}$

- At non-relativistic energies $\frac{dE}{dx}$ is dominated by → $\frac{1}{\beta^2}$
- Decreases with increase of velocity until 0.96c
- Minimum ionizing
- Below the minimum ionizing each particle exhibits its own curve
- This characteristic is used to identify the particle
- At low energy region the Bethe-bloch formula breaksdown
- Energy beyond 0.96c → $\frac{1}{\beta^2}$ almost constant
- $\frac{dE}{dx}$ rises → logarithmic dependence
- Relativistic rise → cancelled by density correction



The stopping power dE/dx as function of energy for different particles

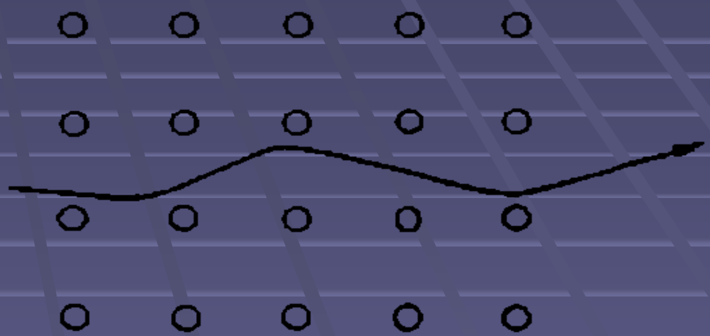


Bragg curve. Variation of dE/dx as function of penetration length. Particle is more ionizing towards the end of path

- At low velocity → comparable → velocity of orbital electron
- $\frac{dE}{dx}$ reaches a maximum → drops sharply again.
- No. of complicated effects → appear
- Tendency of the particle → pickup electrons for part of the time
- Lowers → effective charge → lowers $\frac{dE}{dx}$
- Heavy particle → energy deposition per unit path length → less at beginning → more at end
- Bragg curve

Channeling

- Materials → spatially symmetric atomic structures.
- Particle is incident at angles less than some critical angle with respect to a symmetry axis of the crystal.
- Critical angle
- Particle → a series of correlated small angle scatterings
- Slowly oscillating trajectory



Schematic diagram of scattering. Particle suffers a series of correlated scatterings

$$\Phi_c = \frac{\sqrt{zZa_0 Ad}}{1670\,\beta\sqrt{\gamma}}$$

Critical angle

Range

- How far penetrate → before lose all of their energy ? → Range
- Range depends → material, particle → their energy.
- How → calculate range
- Beam of desired energy → different thickness
- Ratio → transmitted to incident
- Range-number distance curve
- Range approached → ratio drops.
- The curve does not drop immediately to background level.

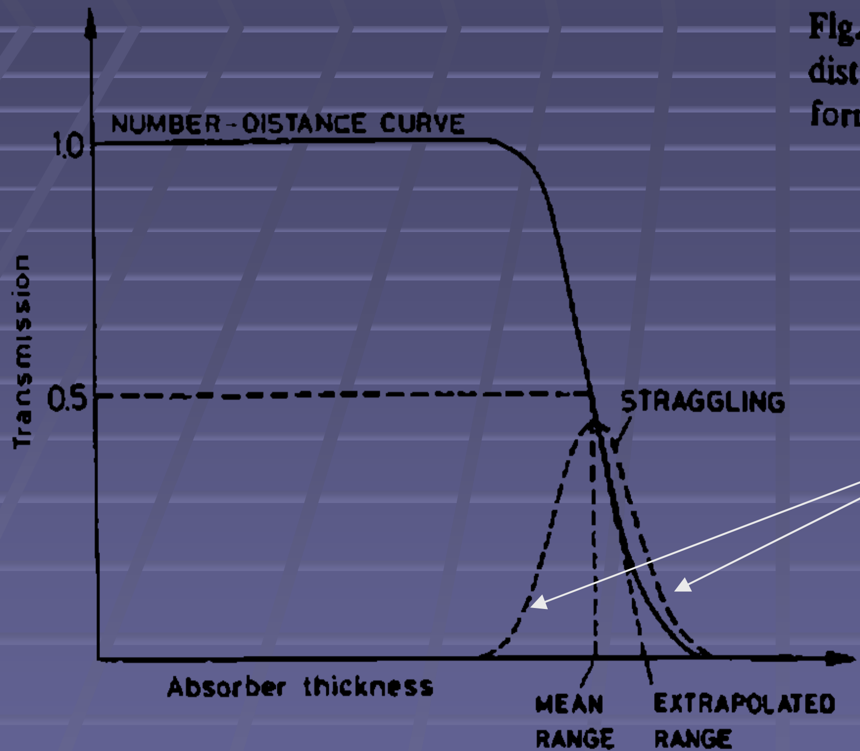


Fig. 2.7. Typical range number-distance curve. The distribution of ranges is approximately Gaussian in form

Statistical distribution of range

Approximate path length travelled

$$S(T_0) = \int_0^{T_0} \left(\frac{dE}{dx} \right)^{-1} dE$$

- The curve slopes down → certain spread of thickness
- Energy loss → not continuous, → statistical in nature.
- Two identical particles with same initial energy will not suffer the same number of collisions.
- A measurement → ensemble of identical particles, → statistical distribution of ranges centered about some mean value.
- Mean range → roughly half particles absorbed

- This phenomenon → range straggling
- Exact range → all particles absorbed
- Tangent to the curve → at midpoint → extrapolating to zero level
- This value → extrapolated or practical range
- Mean range → $S(T_0) = \int_0^{T_0} \left(\frac{dE}{dx} \right)^{-1} dE$
- Multiple scattering → small → heavy particle
- Semi-empirical formula

$$R(T_0) = R(T_{min}) + \int_{T_{min}}^{T_0} \left(\frac{dE}{dx} \right)^{-1} dE$$

Energy loss of electrons and positrons

- Collision loss
- Bremsstrahlung

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{coll} + \left(\frac{dE}{dx}\right)_{rad}$$

- Electron-electron bremsstrahlung
- Critical energy
- Radiation length
- Range of electrons

Collision loss

- Basic mechanism of collision loss valid for electrons and positrons
- Bethe-Bloch formula → modification
- Two reasons →
- Assumption small mass → remains undeflected
  - → invalid
  - → indistinguishability
- Allowable energy transfer term $W_{\max} = T_e/2$ ← Kinetic energy of incident particle

$$-\frac{dE}{dx} = 2\Pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{\tau^2(\tau+2)}{2\left(I/m_e c^2\right)^2} + F(\tau) - \delta - 2\frac{C}{Z}\right]$$

Bremsstrahlung

- Small contribution → few MeV or less
- At 10's of MeV, radiation loss → comparable or greater than collision loss
- Dominant energy loss mechanism → for high energy electrons → electromagnetic radiation
- Synchrotron radiation → circular acceleration
- Bremsstrahlung → motion through matter
- Bremsstrahlung cross-section → inverse square of particle mass

$$dE/dt = \left(2e^2/3c^3\right)a^2$$

Time rate of energy loss

$$\frac{d\sigma}{dk} = 5\frac{e^2}{hc} z_1^4 z_2^2 \left(\frac{mc}{M\upsilon_1}\right)^2 \frac{r_e^2}{k} \ln\frac{M\upsilon_1^2\gamma^2}{k}$$

Electron-electron bremsstrahlung

- E-E bremsstrahlung → arises from field of atomic electrons
- Critical energy → $E = E_c$
- Above this enrgy → radiat. loss → dominate collision-ionization loss
- Radiation length → distance over which electron energy is reduced by 1/e due to radiation loss
- Range of electrons → different from cal.

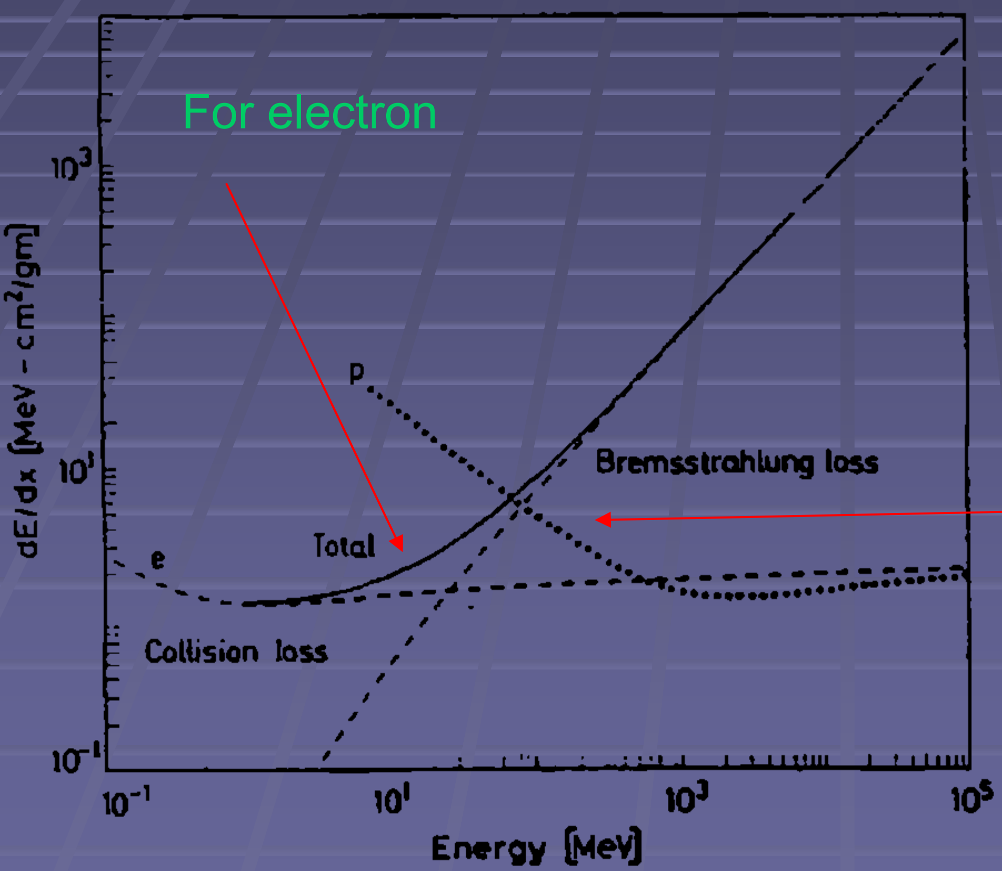
$$\left(\frac{dE}{dx}\right)_{rad} = \left(\frac{dE}{dx}\right)coll$$

Radiation length

$$L_{rad} = \frac{716\,Ag\,/\,cm^2}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)}$$

$$E_c = \frac{800MeV}{Z+1.2}$$

Critical enrgy



Radiation loss vs collision loss for electrons in copper.

Multiple Coulomb Scattering

- Charged particles → repeated elastic scattering from nuclei
- Small probability

Rutherford formula →

$$\frac{d\sigma}{d\Omega} = z_1^2 z_2^2 r_e^2 \frac{\left(m_e c / \beta p \right)^2}{4 \sin^4 \left(\theta / 2 \right)}$$

- $1 / \sin^4 \left(\theta / 2 \right)$ dependence → small angular deflections
- Small energy transfer → negligible
- Resultant → zigzag path
- Cumulative effect is net deflection

- Single scattering
- Thin absorber → small prob. of more than one coulomb scattering
- Rutherford formula → valid
- Plural scattering
- Average number of scattering < 20
- Neither → simple R.F nor statistical method valid

- Multiple scattering
- Average number of scattering > 20
- Small energy loss
- Statistical method → to obtain net angle deflection
- Small angle approximation → by Moliere
- Generally valid → upto 30 θ
- Backscattring of low energy electrons
- Susceptible to large angle deflections from nuclei

Multiple scattering of a charged particle. The scale and angle are greatly exaggerated

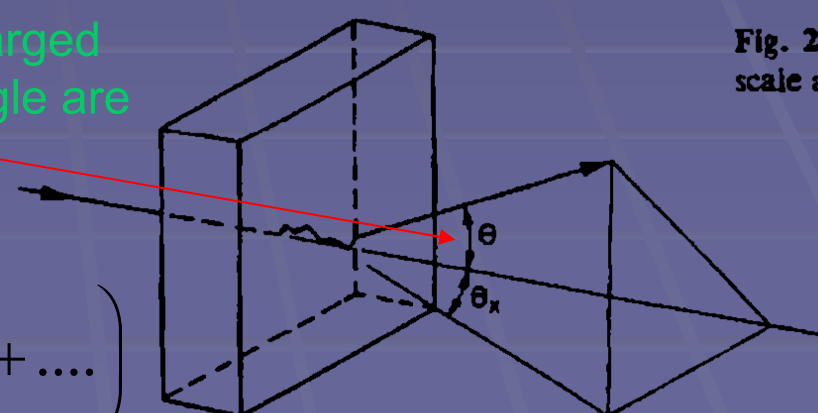


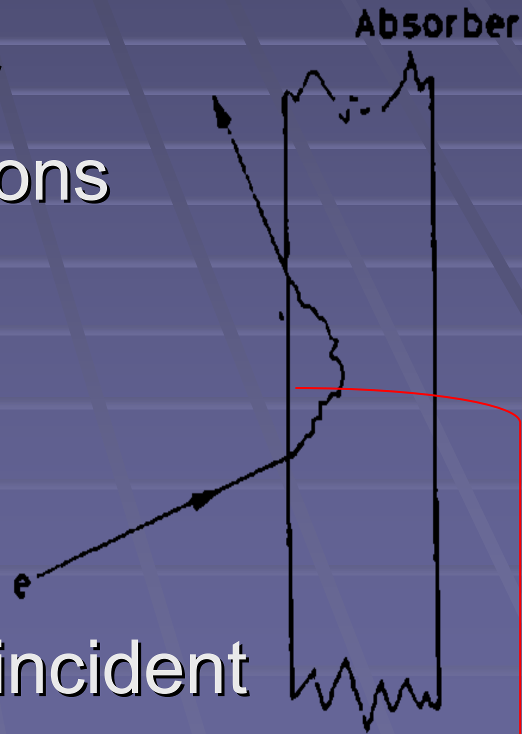
Fig. 2.
scale ar

Moliere polar angle distribution

$$P(\theta)d\Omega = \eta d\eta\left(2\exp\left(-\eta^2\right) + \frac{F_1(\eta)}{B} + \frac{F_2(\eta)}{B^2} + \ldots\right)$$

- Backscattering of low energy electrons
- Probability is so high, → multiply and turned around altogether
- Backscattering → out of absorber
- Effect strong → low energy electrons
- Depends on incident angle
- High-Z material NaI
- Non-collimated electrons,

  80 % reflected back
- Ratio backscattered → electrons incident electrons



Backscattering of electrons due to large angle multiple scattering

The interaction of neutrons

- No coulomb interaction with electron or nuclei
- Principal mean of interaction → strong force with nuclei
- These interactions are rare → short range
- Neutrons must come within → $\cong 10^{-13} cm$
- Normal matter → mainly empty
- Neutron → very penetrating particle

- Prinipal mechanism of energy loss
- Elastic scattering from nuclei → MeV range
- Inelastic scattering → nucleus is left in excited state → gamma emission
- Neutron must have → 1 MeV → for inelastic collision to occur
- Radioactive neutron capture
- Neutron capture cross-section → $\cong 1/\upsilon$
- Valid → at low energies

- Resonance peaks superimposed upon 1/v dependence
- Other nuclear interactions (n,p), (n,d), (n,α), eV-keV
- Fission
- High energy hadron shower

conclusions

- Role of detectors in HEP
- $-{dE}/{dx}$ → tried to understand basic expression of energy loss calculation
- Energy dependence of $-{dE}/{dx}$
- Channeling
- Range
- Energy loss of electrons and positrons
- Multiple coulomb scattering
- Interaction of neutrons

Thanks

The interactions of photons

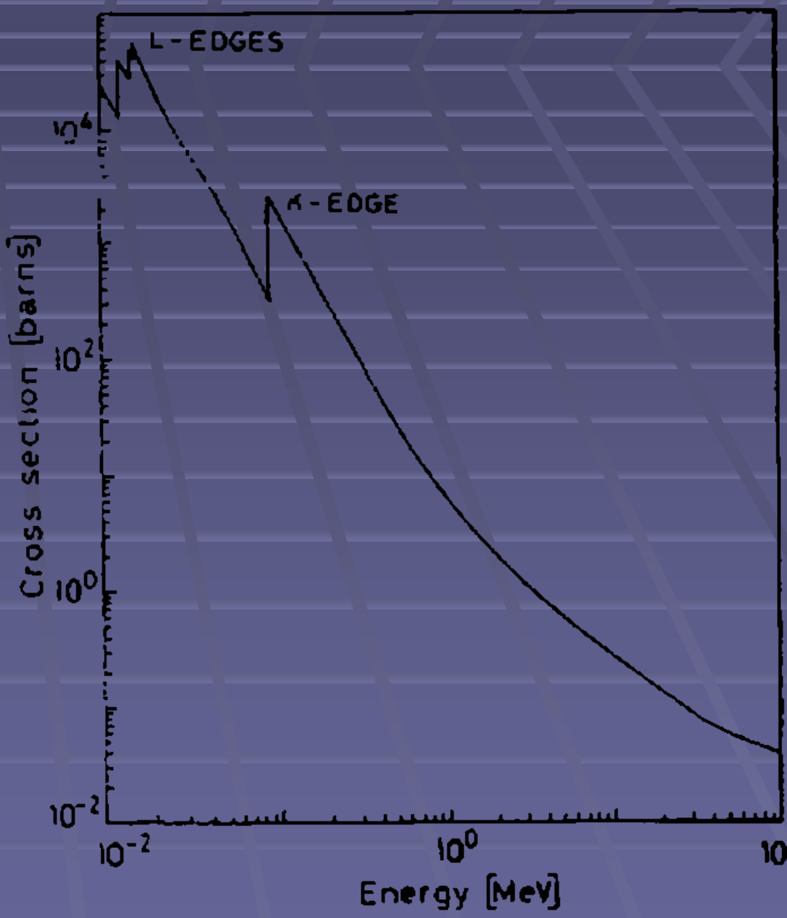
- Behavior of photons (x-rays, γ-rays) different from charged particles
- x-rays and γ-rays are many times more penetrating
- Much smaller cross-section relative to electron inelastic collisions
- P.E, C.S and P.P remove photons from beam
- Beam of photons is not degraded
- Photoelectric effect
- Compton scattering (including Thomson and Rayleigh scattering
- Pair production)

Photoelectric effect

- Absorption of photon by atomic electron
- Ejection of electron from atom
- Energy of outgoing electron

$$E = h\upsilon - B.E$$

- P.E always occur on bound electrons
- Nucleus absorb recoil momentum
- Cross-section increases as k-shell energy is approached
- L-absorption, M-absorption

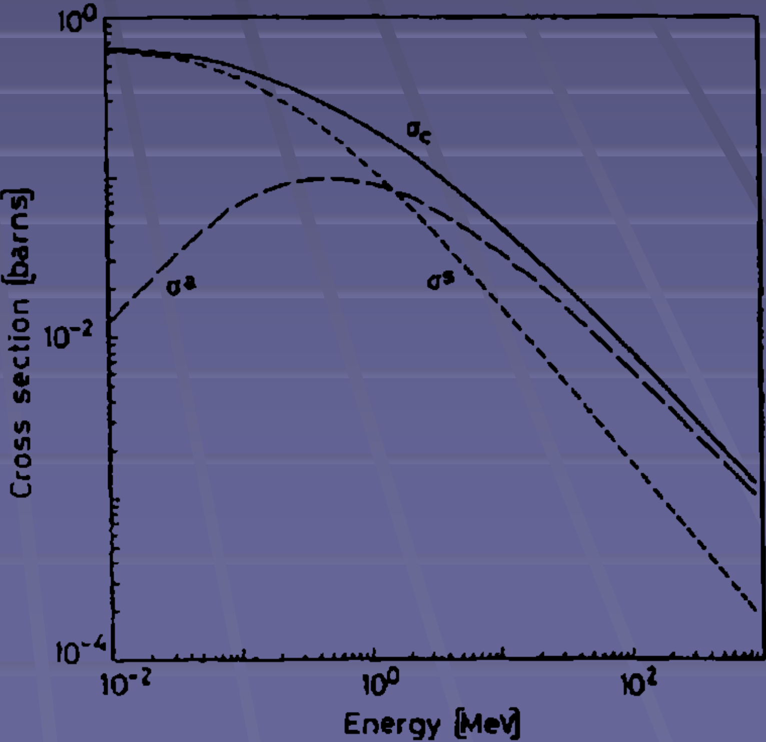


Photoelectric cross-section as a function of incident photon energy

Compton scattering

- Best understood process in photon interaction
- Scattering of photons on free electrons
- Compton scattered cross-section
- Average fraction of total energy contained in scattered photon
- Compton absorption cross-section
- Average energy transferred to recoil electron

- Thomson and Rayleigh scattering
- Coherent scattering



$$\sigma_c = \sigma^s + \sigma^a$$

$$h\upsilon^{-} = \frac{h\upsilon}{1 + \gamma\left(1 - \cos\theta\right)}$$

$$T = h\upsilon - h\upsilon^{-}$$

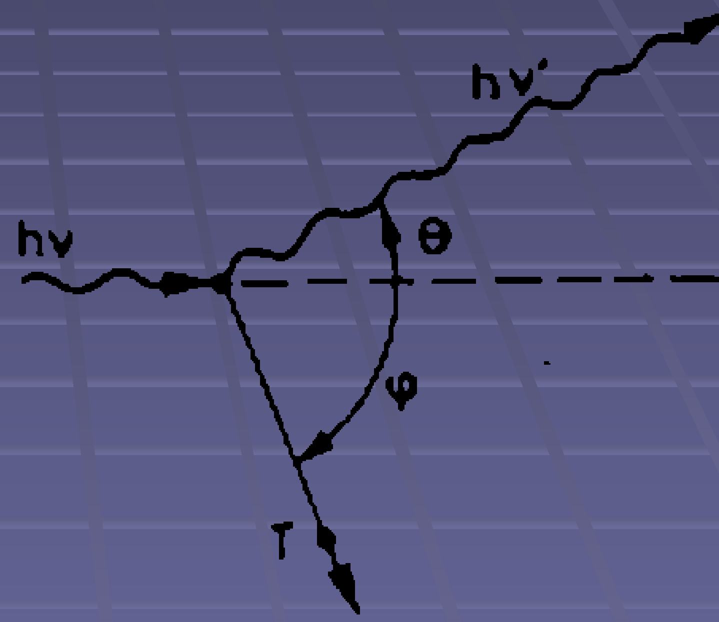


Fig. 2.22. Kinematics of Compton scattering

Pair production

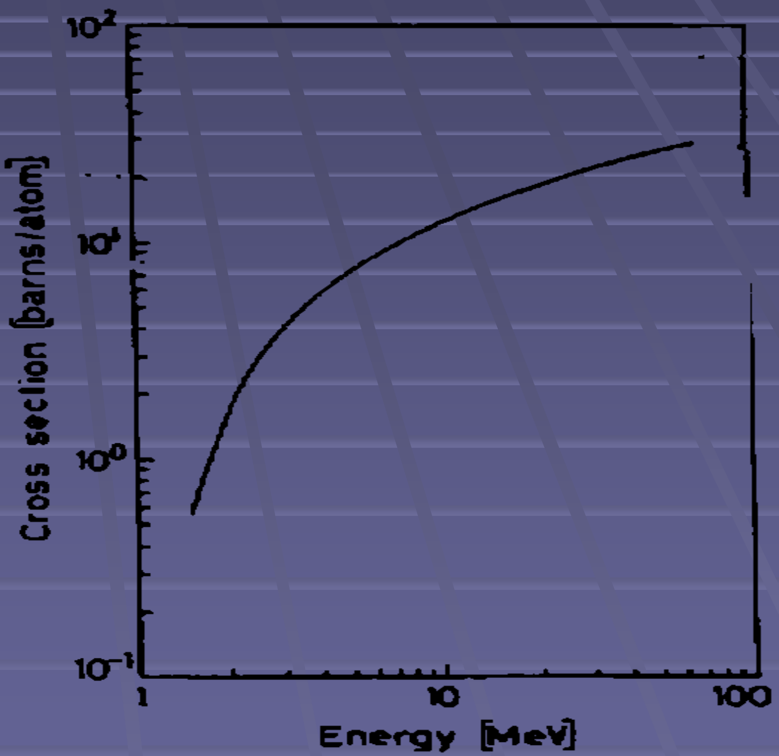


Fig. 2.25. Pair production cr
section in lead

Backup slides

Energy straggling: the energy loss distribution

- Thick absorber
- Very thick absorber
- Thin absorber