Nuclear Physics and Astrophysics

PHY-302

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Lecture 4 - Detectors

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Binding Energy

Nuclear mass M_N less than sum of nucleon masses

Shows nucleus is a bound (lower energy) state for this configuration of nucleons

Leads to concept of **binding energy** B of a nucleus

$$M_N(A,Z)c^2 = Zm_pc^2 + (A-Z)m_nc^2 - B$$

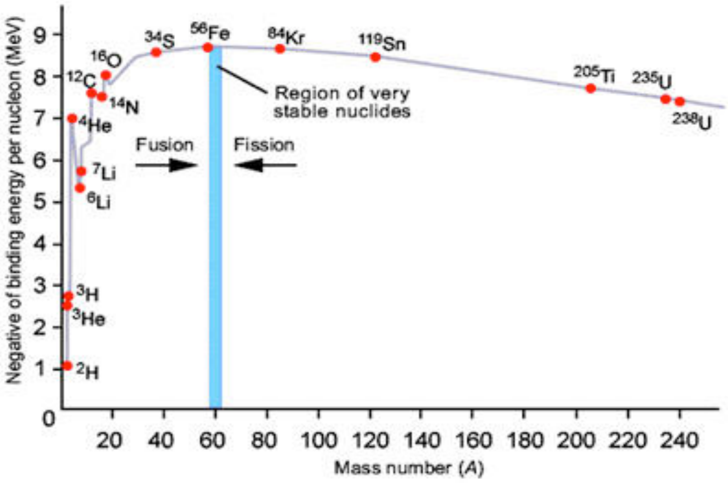
m_p = proton mass
m_n = neutron mass

Binding energy: Energy required to separate nucleus into component parts

Binding energy of average nucleon is ~ 8 MeV
significant compared to nucleon mass itself!

Binding Energy

Binding Energy Per Nucleon



The nuclear binding energy allows us to explain and investigate many nuclear properties e.g. fission, fusion and models of nuclear forces

We will attempt to understand this curve using the Semi-empirical mass formula (future lecture)

Detection of Nuclear Radiation

There are many different techniques for detecting nuclear radiation

All rely on interactions with detector apparatus to determine their properties

To simply show presence of radiation a simple counter / Geiger tube is sufficient

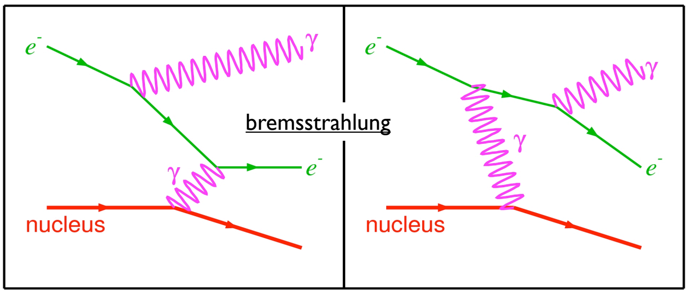
To measure the energy of particles a detector with response prop. to particle energy is needed

An important requirement would be to estimate backgrounds e.g. cosmic rays

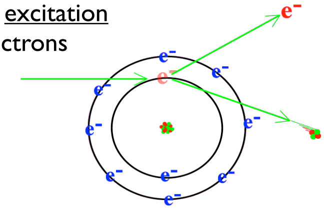
First we will look at how particles interact with matter

Particles can only be detected if the interact with detector material
- short range nuclear interactions (alpha particles & neutrons only)
- long range electromagnetic interactions : charged particles & photons only

- heavy particles: ionisation / excitation of atomic electrons
- electrons: bremsstrahlung
- photons: pair production
- photons: Compton scattering



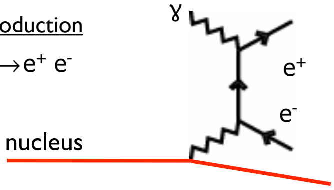
<u>ionisation</u> or <u>excitation</u>
of atomic electrons



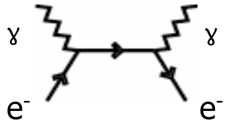
radiative energy losses occur at higher energies
only important for electrons / positrons
nucleus absorbs recoil - ensures-momentum conservation

<u>pair production</u>

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



γ interact via $e^+ e^-$ pair production if energy high enough
or <u>Compton scattering</u>:



Bethe-Bloch Formula

Relationship between range and energy can be understood from a QM calc. of collision processes - Bethe-Bloch Formula

energy loss of <u>heavy</u> ($M > m_e$) charged particle per unit distance in a material

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e c^2 \beta^2} \frac{N_A Z \rho}{A} \left[\ln\left(\frac{2 m_e c^2 \eta^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

Particle has multiple <u>electromagnetic</u> collisions with atomic electrons and nuclei of the medium

energy loss in single collision integrated over all distances

density of atomic e^-

Logarithmic corrections at large β for ionisation & screening of inner atomic electrons

<u>Properties of the particle</u>

β = velocity v/c
z = charge of incident particle

<u>Properties of the material</u>

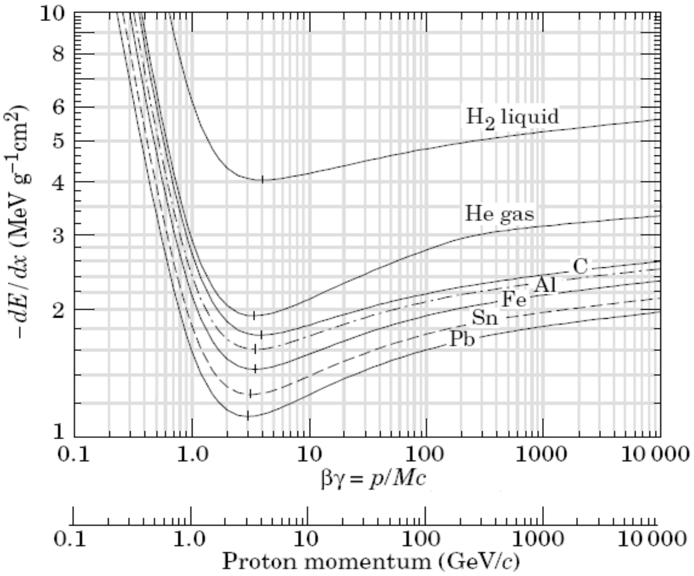
N_A = Avogadro's number
Z = atomic number of material
A = atomic mass of material
m_e = electron mass
I = mean ionization energy of material
ρ = material density

Notes:

- Dependent only on particle velocity & charge!
- Energy loss increases with Z
- Energy loss increases with density
- Complex fn of velocity with a point of minimum loss
- Above minimum energy loss increases slowly
- formula modified for electron case: bremsstrahlung!

Not Examined

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e c^2\beta^2}\frac{N_A Z\rho}{A}\left[\ln\left(\frac{2m_e c^2\eta^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$



Total energy loss of particle over distance R

$$E_{Tot} = \int_0^R \frac{\mathrm{d}E}{\mathrm{d}x}\mathrm{d}x$$

Typical range of particle with initial energy E_0

$$\mathrm{Range} = \int_{E_0}^0 \frac{1}{\mathrm{d}E/\mathrm{d}x}$$

When charged particles traverse matter, most interactions are Coulomb scattering by atomic electrons
Elastic collision of particle of mass M, and electron, energy loss is

$$\Delta T = T\frac{4m_e}{M}$$

T = initial kinetic energy

For 5 MeV α particle this is 2.7 KeV

Many collisions take place before a particle losses its energy

In glancing collisions the massive particle undergoes small deflections

Charged particles have an effective range in any given material

Suitable materials can ionised

many low energy electrons liberated - collect to form electronic pulse !

This is the basic principle of many detectors

Neutrons detected by nuclear absorption - leading to ionisation by the end product:

n + ^{3}He → ^{3}H + ^{1}H + 0.76 MeV

n + ^{6}Li → ^{4}He + ^{3}H + 4.79 MeV

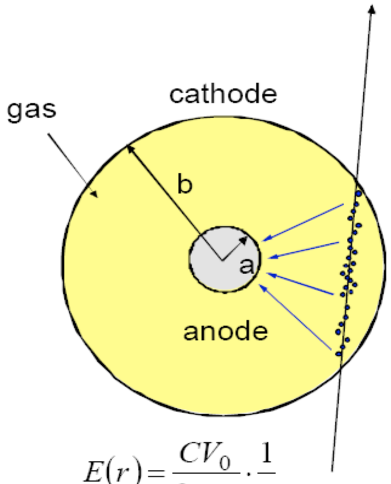
Gas Amplification

Incoming radiation ionises gas

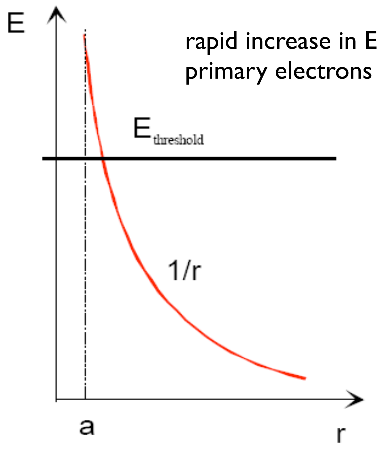
Ionisation produces only ~ 50 electron-ion pairs per cm of typical detector

Hard to detect 50 electrons!

Amplify by using ionised electrons to produce secondary ionisation:



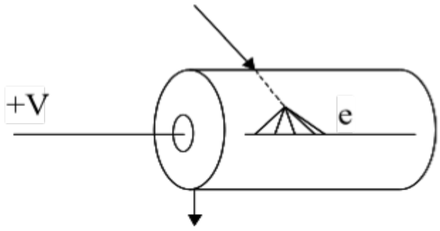
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

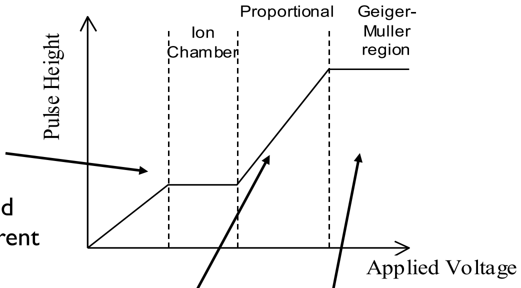


rapid increase in Electric field close to anode
primary electrons ionise gas close to wire

Gas Filled Detectors

Many detectors rely on radioactive materials ability to ionize
Most detectors use large E fields to capture and/or amplify charge produced
Simplest example is an Ionisation Chamber





Ionisation Chamber
- particle ionises gas
- low V means low amplification.
- Can detect several interactions integrated
- Output is a cont. current
- prop. to number of ionisations

Proportional Chamber
- can detect single ionisation events.
- Large amplifying voltage yields secondary ionisation
- Anode signal proportional to energy loss of particle

Geiger Muller Tube
Very high applied voltage
Output signal indep. of particle energy

Primary electrons accelerated by E field

Electrons cause further ionisation

⇒ avalanche of secondary e^-

Varying applied voltage changes mode of operation

Most chambers operate in proportional mode:

Number of secondary collisions is proportional to primary ions

Scintillation Detectors

- Scintillator counters operate by producing photons from radiation
- traversing particles excite atoms/molecules of the material which decay via photon emission
- Use Photo-multiplier tubes (PMT): convert light to electronic signal & amplify the no. electrons
- Photons hit photo-sensitive surface releasing electrons
- PMT contains a series of dynodes each at steps of about +100 V i.e. producing 100 eV e$^-$
- Anodes made of material requiring ~2-3 eV to emit an electron
- Thus amplification factors of 30-50 are possible, but more likely factor of 5
- Nevertheless a factor 5 for 10 anodes in a chain = gain of $5^{10} = 10^7$

initial photocathode
followed by dynodes
held at increasing
positive potentials
+100V, +200V, +300V...