Chapter 11: Nuclear and Particle Physics

The atomic nucleus can be represented as

$$\boxed{{}^{A}_{Z}X}$$

Example

$${}^{56}_{26}Fe$$

Element	: Iron-56
Proton no, Z	: 26
Nucleon no, A	: 56
Neutron	: 56-26 = 30
	A - Z = N

where **X** = symbol for the element
Z = atomic number (number of protons)
A = atomic mass number
= total number of protons and neutrons

11.1 Binding Energy and Mass Defect

Einstein Mass-Energy Relation

- From the theory of relativity, it leads to the idea that **mass is a form of energy**.
- Mass and energy can be related by the following relation:

$$\boxed{E = mc^2}$$

where E : amount of energy
m : rest mass (**must be in kg**)
c : speed of light in vacuum

Unit conversion of mass and energy

The electron-volt (eV)

- Is a unit of **energy**
- Is defined as the kinetic energy gained by an electron in being accelerated by a potential difference (voltage) of 1 volt.

$$\boxed{\begin{aligned} 1\,\text{eV} &= 1.60\times10^{-19}\ \text{J} \\ 1\,\text{MeV} &= 10^{6}\ eV = 1.60\times10^{-13}\ \text{J}\end{aligned}}$$

The atomic mass unit (u)

- Is a unit of **mass**
- Is defined as exactly $\frac{1}{12}$ the mass of a neutral carbon-12 atom.

$$\boxed{\begin{aligned} 1\,\text{u} &= \frac{\text{mass of } {}^{12}_{6}C}{12} \\ 1\,\text{u} &= 1.66\times10^{-27}\ \text{kg}\end{aligned}}$$

- 1 atomic mass unit (**u**) can be converted into unit of energy by using the mass-energy relation:

$$\boxed{\begin{aligned} E &= mc^2 \\ &= \left(1.66\times10^{-27}\right)\left(3.00\times10^{8}\right)^2 \\ &= 1.49\times10^{-10}\ \text{J} \end{aligned}}$$

In **joule**: $1\,\text{u} = 1.49\times10^{-10}$ J

In **eV/c^2** or **MeV/c^2**:

$$\boxed{E = \frac{1.49\times10^{-10}}{1.60\times10^{-19}} = 935.1\times10^{-6}\ \text{eV/c}^2 = 935.1\,\text{MeV/c}^2}$$

L.O 11.1.1 Define and use mass defect

Mass defect is defined as the **difference** between the sum of the masses of individual nucleons that form an atomic nucleus and the mass of the nucleus.

$$\boxed{\Delta m = \left(Zm_p + Nm_n\right) - M_A}$$

where m_p : mass of proton
m_n : mass of neutron
M_A : mass of nucleus
Z : number of proton
N : number of neutron

The **mass of a nucleus (M_A)** is always **less than the total mass of its constituent nucleons ($Zm_p + Nm_n$)**:

$$M_A < \left(Zm_p + Nm_n\right)$$

- The reduction in mass arises because the act of c**ombining the nucleons to form the nucleus** causes some of their **mass to be released as energy**.
- Any attempt to **separate the nucleons** would involve them being **given** this **same amount of energy**. The energy is called the **binding energy** of the nucleus.

L.O 11.1.2 Define and use binding energy

Energy required to separate a nucleus into its individual protons and neutrons. **OR** Energy released when nucleus is formed from its individual nucleons.

The binding energy of the nucleus is equal to the energy equivalent of the mass defect. Hence

$$\boxed{E_B = \Delta mc^2}$$

where E_B : amount of energy
Δm : rest mass
c : speed of light in vacuum

There are **2 methods** to determine the value of Binding Energy, E_B:

E_B in unit **joule**	E_B in unit **MeV**
Δm in unit **kg**	Δm in unit **u**
$c = 3\times10^8\ \text{m s}^{-1}$	$c^2 = \dfrac{931.5\,\text{MeV}}{\text{u}}$

L.O 11.1.3 Determine binding energy per nucleon

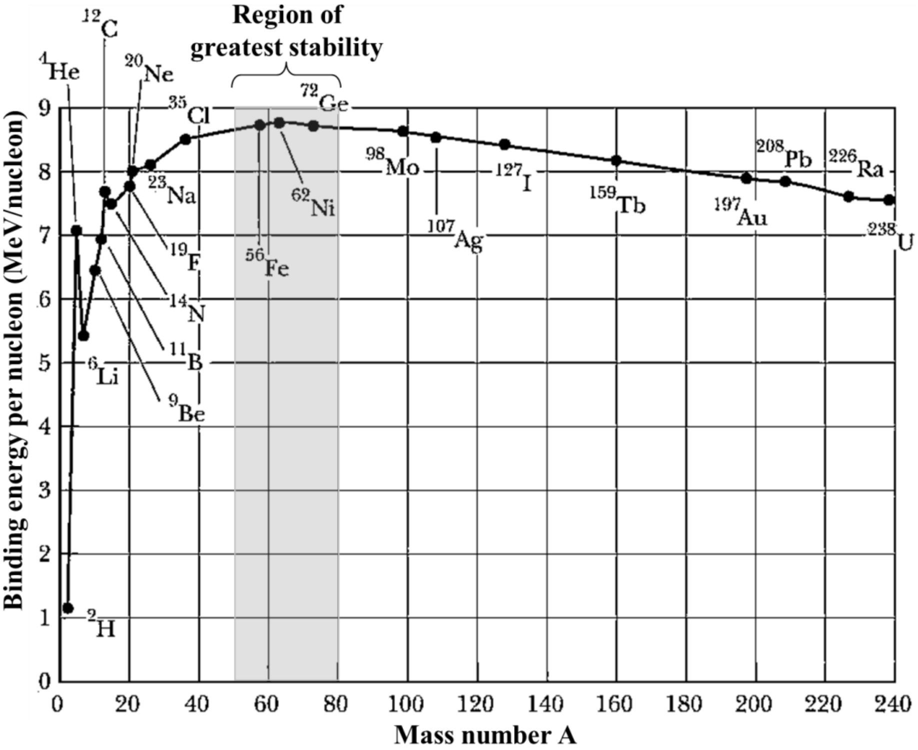
Binding energy per nucleon is defined as mean (average) binding energy of a nucleus.
It is **a measure of the nucleus stability** where

$$\text{Binding energy per nucleon} = \frac{\text{Binding energy, } E_B}{\text{Nucleon number, } A}$$

$$\boxed{\text{Binding energy per nucleon} = \frac{\Delta mc^2}{A}}$$

L.O 11.1.3 Sketch and describe graph of binding energy per nucleon against nucleon number

Graph of binding energy per nucleon against nucleon number



- For light nuclei the value of E_B/A rises rapidly from 1 MeV/nucleon to 8 MeV/nucleon with increasing mass number A.
- For the nuclei with **A between 50 and 80**, the value of E_B/A ranges between 8.0 and 8.9 MeV/nucleon. The nuclei in this range are **very stable**.
- The nuclide $^{62}_{28}Ni$ has the largest binding energy per nucleon (8.7945 MeV/nucleon).
- For nuclei with A > 62, the values of E_B/A decreases slowly, indicating that the nucleons are on average, less tightly bound.
- For heavy nuclei with **A between 200 to 240**, the binding energy is between 7.5 and 8.0 MeV/nucleon. These nuclei are **unstable** and radioactive.

Example

Question	Solution
Calculate the binding energy of an aluminum nucleus $\left({}^{27}_{13}Al\right)$ in MeV. (Given mass of neutron, m_n = 1.00867 u ; mass of proton, m_p = 1.00782 u ; speed of light in vacuum, $c = 3\times10^8$ m s^{-1} and atomic mass of aluminum, M_A = 26.98154 u)	
Calculate the binding energy per nucleon of a boron nucleus $\left({}^{10}_{5}B\right)$ in J/nucleon. Given atomic mass of boron, M_A = 10.01294 u.	

Exercise

Question
Calculate the binding energy in joule of a deuterium nucleus. The mass of a deuterium nucleus is 3.34428×10^{-27} kg. **Answer: 2.78×10^{-13} J**
Calculate the average binding energy per nucleon of the nitrogen-14 nucleus $\left({}^{14}_{7}N\right)$. Given atomic mass of nitrogen-14 atom = 14.003074 u **Answer: 7.47 MeV/nucleon**

11.2 Radioactivity

L.O 11.2.1 Explain α, β^+, β^- and γ decays

Radioactivity / Radioactive decay is **disintegration of unstable nucleus to a more stable daughter nuclide** with the emission of alpha, beta particles and gamma ray.

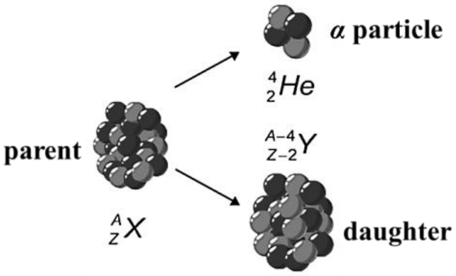
Radioactive decay is a **spontaneous** and **random** process.

- Random means the time of decay of each atom **cannot be predicted**.
- Spontaneous means it happens by itself without external stimuli (**unplanned**). The decay is unaffected by normal physical or chemical processes, such as heat, pressure and chemical reactions.

3 kinds of rays are produced by naturally occurring radioactivity: **alpha particle (α), beta particle (β) and gamma rays (γ).**

Alpha Decay (α)

- An α-particle is a $_2^4He$ nucleus consists of **two protons** and **two neutrons.**
- It is positively charged particle and its value is +2e with mass of 4.001502 u.
- Alpha particle has **least penetrating ability**, can be blocked by a sheet of paper.
- **Its motion can be deflected by both magnetic field & electric field.**
- When a nucleus undergoes alpha decay it loses 4 nucleons (2 protons and 2 neutrons).



- The reaction can be represented by **general equation** below:

$$_Z^AX \rightarrow {}_{Z-2}^{A-4}Y + {}_2^4He + Q$$

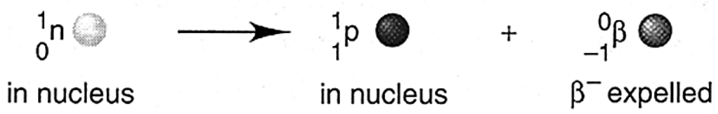
Parent **Daughter** **α-particle** **Energy released**

Beta Decay (β)

- Beta particle has same **mass as an electron or 0.000549 u.**.
- Beta particle can be electrically positive **(β$^+$ or positron)** or negative **(β$^-$ or negatron)**
  - Symbol for **positron:** $_{+1}^{0}\beta, \beta^+$ or $_{+1}^{0}e$
  - Symbol for **negatron:** $_{-1}^{0}\beta, \beta^-$ or $_{-1}^{0}e$
- Beta particle has **moderate penetrating ability** and blocks by a few millimeters aluminum.
- **Its motion can be deflected by both magnetic field & electric field.**
- **2 type of beta decay: β$^-$ decay and β$^+$ decay**

β^- decay

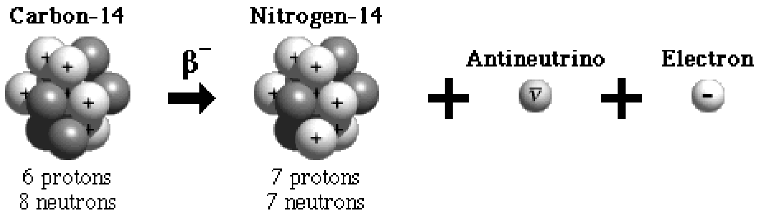
- β^- decay occurs when an unstable nucleus has **too many neutrons** compared with the number of protons.
- Through the β^- decay, **a neutron is converted into a proton** and creates a more stable daughter nucleus.



- **General form for β^- decay is**

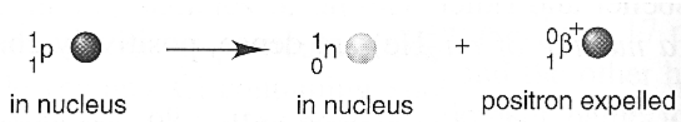
${}^{A}_{Z}X$	$\rightarrow$	${}^{A}_{Z+1}Y$	$+$	${}^{0}_{-1}\beta$	$+$	$\bar{v}$	$+$	Q
Parent		**Daughter**		**β-particle**		**Anti-neutrino**		**Energy released**

- Another elementary particle called **antineutrino ($\bar{v}$)** emitted in this decay**.**
- Existence of antineutrino is a must in order to obey the law of conservation of energy & angular momentum (to account the missing energy in negatron decay).
- **Example:**



β^+ decay

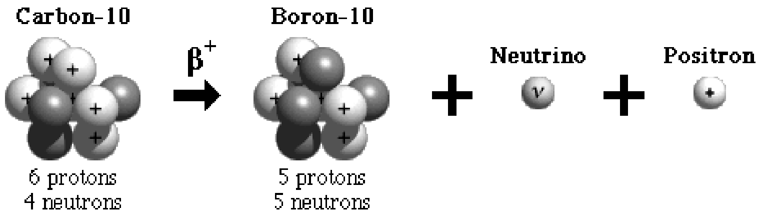
- β^+ decay occurs when an unstable nucleus has **too many protons** compared with the number of neutrons.
- Through the β^+ decay, **a proton is converted into a neutron** and creates a more stable daughter nucleus.



- **General form for β^+ decay is**

${}^{A}_{Z}X$	$\rightarrow$	${}^{A}_{Z-1}Y$	$+$	${}^{0}_{+1}\beta$	$+$	v	$+$	Q
Parent		**Daughter**		**β-particle**		**Neutrino**		**Energy released**

- Another elementary particle called **neutrino (v)** emitted in this decay**.**
- Existence of neutrino is a must in order to obey the law of conservation of energy & angular momentum (to account the missing energy in positron decay).
- **Example:**



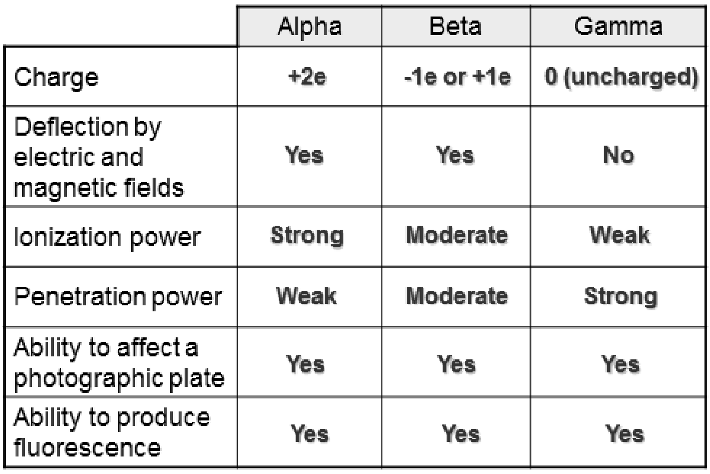
Gamma Decay (γ)

- Gamma ray is a **high energy photon**.
- It is uncharged (**neutral**) and zero mass (emission of gamma ray **does not change the parent nucleus into a different nuclide**).
- Gamma ray has the **most penetrating ability** → a few centimeters in lead.
- It **cannot be deflected by any magnetic field**.
- Gamma rays are **emitted when an excited nucleus jumps to lower energy level**.
- Very often, a nucleus is left in an excited energy state after it has undergone alpha or beta decay. This nucleus can then undergo 2nd decay to **lower energy level by emitting a high energy photon called gamma (γ) ray**.
- The decay can be written as:

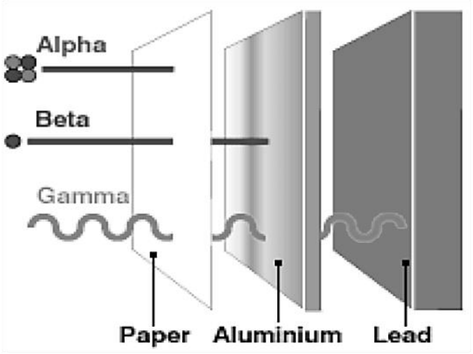
$${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

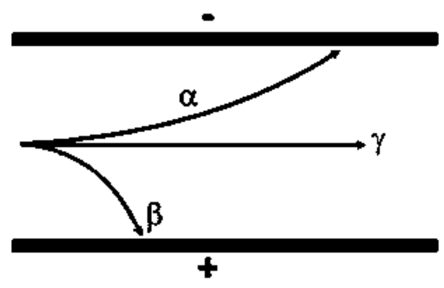
Excited energy state **Lower energy state** **γ-ray**

Comparison of the properties between alpha particle, beta particle and gamma ray.

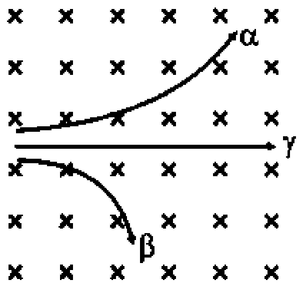


	Alpha	Beta	Gamma
Charge	+2e	-1e or +1e	0 (uncharged)
Deflection by electric and magnetic fields	Yes	Yes	No
Ionization power	Strong	Moderate	Weak
Penetration power	Weak	Moderate	Strong
Ability to affect a photographic plate	Yes	Yes	Yes
Ability to produce fluorescence	Yes	Yes	Yes



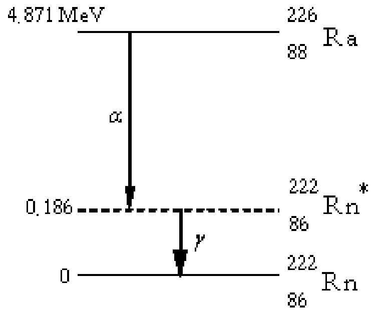


Deflection in electric field



Deflection in magnetic field

Example

Question	Solution
 Write an equation to represent the decay. What is the wavelength of the 0.186 MeV γ-ray photon emitted by radium $^{226}_{88}Ra$?	

L.O 11.2.2 State decay law and use $\frac{dN}{dt} = -\lambda N$

Law of radioactive decay states that "for a radioactive source, the rate of decay (**dN/dt**) is **proportional** to the number of radioactive nuclei present (or not yet decayed), **N**."
Mathematically,

$$\boxed{\frac{dN}{dt} = -\lambda N}$$

Negative sign means the number of nuclei present **decreases** with time

Decay constant

L.O 11.2.3 Define and determine activity, *A* and decay constant, *λ*

From $\frac{dN}{dt} = -\lambda N$, we get

$$\boxed{\lambda = -\frac{dN/dt}{N}}$$

- Decay constant, λ is the **ratio** of rate of decay to the number of radioactive atoms in sample.
- **SI unit** for decay constant, λ: **s^{-1}**
- The decay constant is a **characteristic** of the radioactive nuclide. It has **different values for different nuclides**. The larger the decay constant, the greater is the rate of decay.

Activity, *A* of a radioactive sample is defined as the **number of decays** (or disintegrations) **per second** that occur.

$$\boxed{A = \frac{dN}{dt}}$$

- **SI unit** for activity, A: **Becquerel (Bq) → 1 Bq = 1 decay per second**
- **Another SI unit usually used: Curie (Ci) → 1 Ci = 3.7 × 10^{10} Bq**

L.O 11.2.4 Use $N = N_0 e^{-\lambda t}$ or $A = A_0 e^{-\lambda t}$

From the basic law of radioactive decay:

$$\frac{dN}{dt} = -\lambda N$$

Rearranging the equation:

$$\frac{dN}{N} = -\lambda d\mathrm{t}$$

Suppose that at time t = 0 s, the number of undecayed nuclei in the radioactive sample is N_o
At time t = t, let the number of undecayed nuclei left is N
Integrate the above equation:

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{0}^{t} dt$$

$$\left[\ln N\right]_{N_0}^{N} = -\lambda \left[t\right]_0^t$$

$$\ln \frac{N}{N_0} = -\lambda t$$

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$\boxed{N = N_0 e^{-\lambda t}}$$

This equation is called **exponential law of radioactive decay**. It states that the **disintegration or radioactive decays** of a radioactive substance **reduces exponentially with time**.

From the law of radioactive decay, $\frac{dN}{dt} = -\lambda N$ and definition of activity, $A = \frac{dN}{dt}$

$$A = -\lambda N \qquad \text{and} \qquad N = N_0 e^{-\lambda t}$$

$$A = -\lambda\left(N_0 e^{-\lambda t}\right)$$

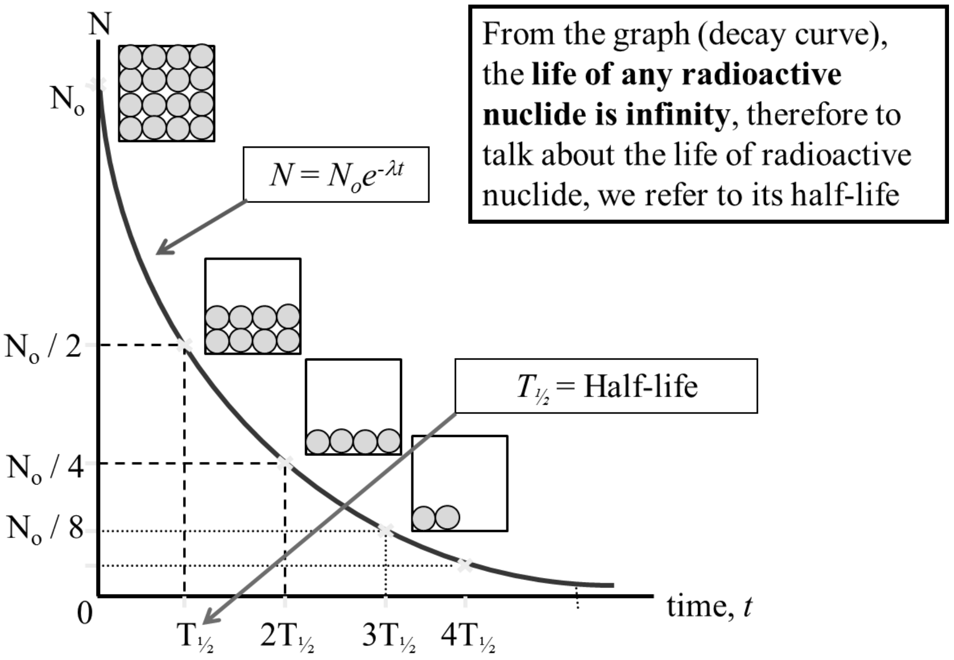
$$A = -(\lambda N)_0 e^{-\lambda t} \qquad \text{and} \qquad A_0 = -\lambda N_0$$

$$\boxed{A = A_0 e^{-\lambda t}}$$

Activity at time *t* **Activity at time *t* = 0**

L.O 11.2.5 Define and use half life

Graph of *N* (number of remaining nucleus) versus *t* (decay time)



From the graph (decay curve), the **life of any radioactive nuclide is infinity**, therefore to talk about the life of radioactive nuclide, we refer to its half-life

The decay rate of a nuclide is commonly expressed in terms of its half-life rather than the decay constant.

Half-life $T_{½}$ is defined as **time required for the number of radioactive nuclei to decrease to half of the original number of nuclei.**

From $N = N_0 e^{-\lambda t}$, when $t = T_{½}$ and $N = \frac{N_0}{2}$:

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{½}}$$

$$\frac{1}{2} = e^{-\lambda T_{½}}$$

$$e^{\lambda T_{½}} = 2$$

$$\lambda T_{½} = \ln 2$$

$$\boxed{T_{½} = \frac{\ln 2}{\lambda}}$$

- The half-life of any given radioactive nuclide is **constant**; it does not depend on the number of nuclei present.
- The **units** of the half-life are second (s), minute (min), hour (hr), day and year (yr).

Example

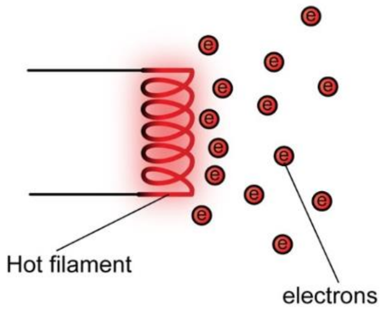
Question	Solution
The half life of the radioactive nucleus Radium, $^{226}_{88}Ra$ is 1.6×10^{3} year. a) What is the decay constant of this nucleus ? b) If a sample contains 3.0×10^{16} $^{226}_{88}Ra$ nuclei at t = 0 s, determine its activity at this time. c) What is the activity after sample is 2.0×10^{3} year old ?	
Initially, a radioactive sample contains of 1.0×10^{6} nuclei. The half-life of the sample is $T_{1/2}$. Calculate the number of nuclei present after $0.5T_{1/2}$.	
80% of a radioactive substance decays in 4 days. Determine a) the decay constant b) its half life	
A radioactive sample contains 3.5 μg of pure C, which has a half life of 20.4 min. a) Determine the number of nuclei in the sample at t = 0 s. b) What is the activity in Becquerel of the sample initially and after 8.0 h ? c) Calculate the number of radioactive nuclei remaining after 8.0 h ?	

Exercise

Question
A radioactive source contains 1.0×10^{-6} g of Pu-239. If the source emits 2300 alpha particles per second, calculate a. the decay constant b. the half-life (Given Avogadro constant, $N_A=6.02\times10^{23}$ mol^{-1}) **Answer: 9.13×10^{-13} s^{-1}; 7.59×10^{11} s**
Thorium-234 has a half-life of 24 days. The initial activity of this isotope is 10 μCi. Calculate a. the activity of the isotope after 72 days b. the time taken for the activity to fall to 2.5 μCi **Answer: 1.25 μCi; 48 days**
A uranium-238 isotope which has a half-life of 4.47 x 10^{9} years decays by emitting alpha particle into thorium-234 nucleus $\left({}^{234}_{90}Th\right)$. Calculate a. the decay constant b. the mass of uranium-238 required to decay with activity of 6.00 μCi c. the number of alpha particles per second for the decay of 30.0 g uranium-238 **Answer: 1.55×10^{-10} years^{-1}; 17.86 g; 3.73×10^{-10} particles/second**
The half-life of Radon ${}^{219}_{86}Rn$ is 4.0 s. a. What do the numbers 86 and 219 represent in the symbol ${}^{219}_{86}Rn$? b. Calculate the decay constant of ${}^{219}_{86}Rn$. c. Given that 219 g of Radon contains 6.02×10^{23} atoms, calculate the rate of disintegration of 1.00 g of ${}^{219}_{86}Rn$. **Answer: 0.173 s^{-1}, 4.76×10^{21} Bq**
Radioactive can be used for radioactive dating, i.e. a method to determine the age of an artifact based on decay rate and half-life of carbon-14. The half-life of carbon-14 is known to be 5600 years. If a 10 gram of carbon sample from a live tree gives the decay rate of 500 per hour and a 10 gram sample from an artifact gives decay rate of 100 per hour, calculate the age of the artifact. **Answer: 1.30×10^{4} years**

11.3 Introduction to Particle Physics

L.O 11.3.1 State thermionic emission



Mobile electrons in metals, also called valence electrons, are responsible for electric current conduction. If we increase the temperature of the metal, electrons start to move faster and some may have enough energy to escape (evaporate) from the metal. The higher the temperature, the higher will be the current of escaping electrons. This temperature induced electron flow is called **thermionic emission**. In other word, **thermionic emission** is a process of emission of charge particle (known as thermion) such as electrons from the surface of a heated metal.

L.O 11.3.2 Explain the acceleration of particle by electric and magnetic field

A particle accelerator is a machine that uses electromagnetic field to accelerate elementary charge particles, such as electrons or protons, to very high energies. Beams of high-energy particles are useful for fundamental and applied research in the sciences. Particle accelerators use **electric fields** to speed up and increase the energy of a beam of particles, which are steered and focused by **magnetic fields**.

Electrons accelerate when placed in an **electric field** (E). An electron placed between a negatively charged cathode and positively charged anode will feel a force $F = qE$. A particle with mass m to which a force is applied will have an acceleration $a = F/m$, therefore a particle in an electric field will experience an acceleration $a = qE/m$.

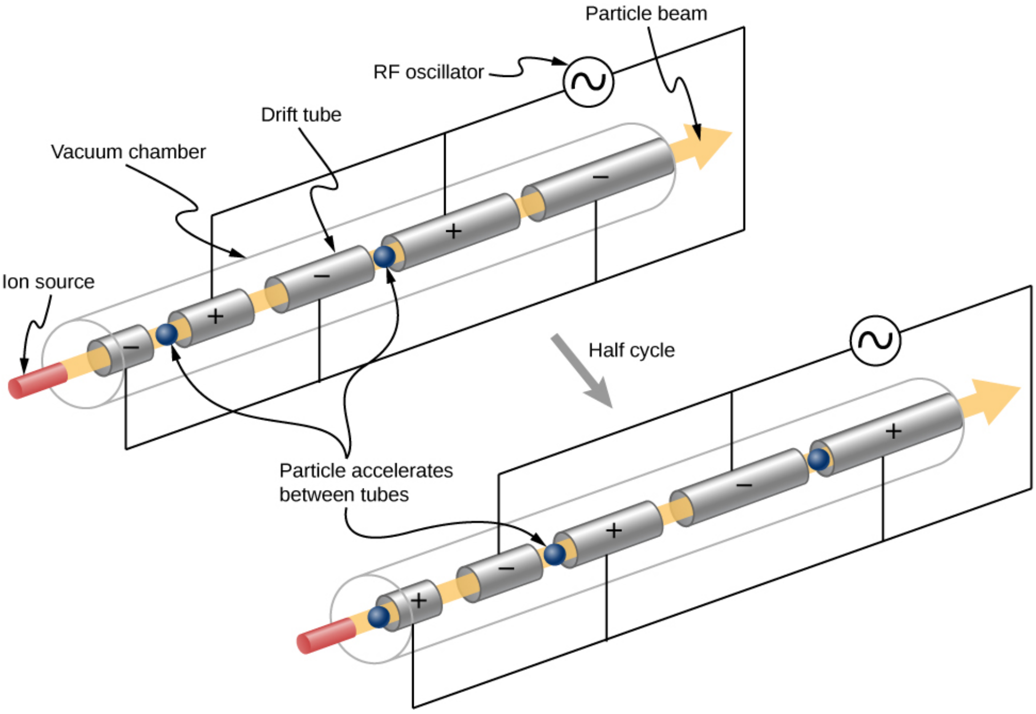
When a charged particle (such as a proton or electron) travels through a **magnetic field** (B) at a speed v, it has a momentum $p = mv$ and it feels a force $F = qvB$. Unlike the force created by an electric field, the force created by a magnetic field is perpendicular to the direction of travel therefore the particle changes its direction (but not its speed).

L.O 11.3.3 State the role of electric and magnetic field in particle accelerator (LINAC and Cyclotron) and detector (general principles of ionisation and deflection only)

There are two basic types of particle accelerators: linear accelerators (LINAC) and cyclotron.

Particle accelerator: LINAC

Charged particles produced at the beginning of the LINAC are accelerated by a continuous line of charged hollow tubes. The voltage between a given pair of tubes is set to draw the charged particle in, and once the particle arrives, the voltage between the next pair of tubes is set to push the charged particle out. In other words, voltages are applied in such a way that the tubes deliver a series of carefully synchronized electric kicks. Modern LINAC employs radio frequency (RF) cavities that set up oscillating electromagnetic fields, which propel the particle forward like a surfer on an ocean wave.



Particle accelerator: Cyclotron

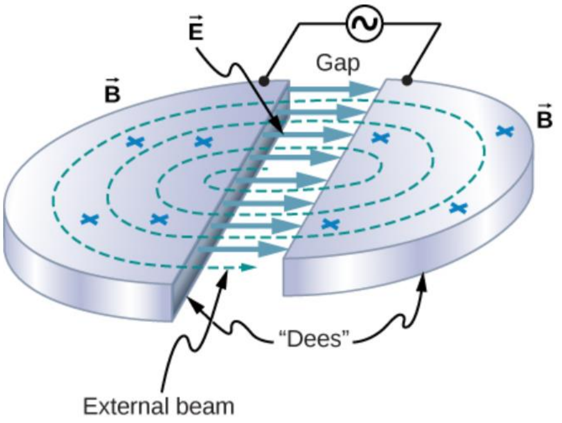
A cyclotron uses alternating electric fields and fixed magnets to accelerate particles in a circular spiral path. A particle at the center of the cyclotron is first accelerated by an electric field in a gap between two D-shaped magnets (Dees). As the particle crosses over the D-shaped magnet, the particle is bent into a circular path by a Lorentz force (the force which is exerted by a magnetic field on a moving electric charge). Since this provide centripetal force:

$$F_B = F_C$$

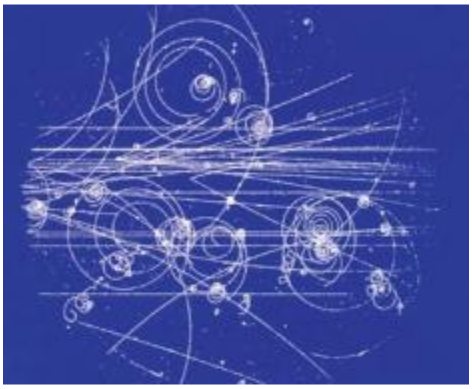
$$qBv = \frac{mv^2}{r}$$

$$v = \frac{qBr}{m}$$

This shows that the velocity is proportional to the radius, so as the particles get faster they spiral outwards.



Particle Detector - Cloud chamber/ Bubble chamber: Deflection

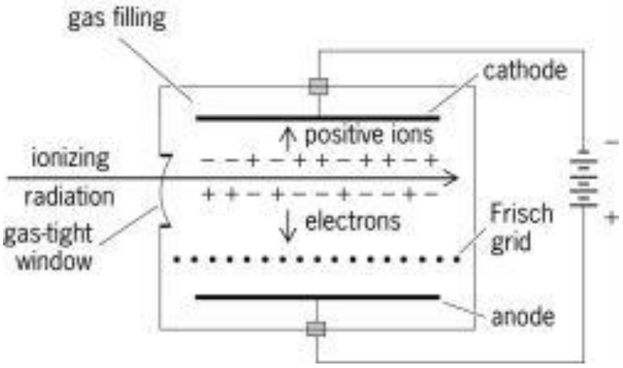


If we've created particles in a collision in an accelerator, we want to be able to look at them. And that's where particle detectors come in. The aim of a **particle detector** is to quantify the momenta and discover the identity of the particles that pass through it after being produced in a collision or a decay. The principle of a particle detector is simple. It will never "see" a particle directly, but shows where it has travelled, what signature tracks it leaves behind and the effect it has on the detector when it is stopped as it flies out of the collision.

Cloud and bubble chambers are usually operated with a constant magnetic field perpendicular to the path of the particles. This way we can observe the particles as they spin through a spiral pattern. This happens because the magnetic force acting on the charged particles causes a centripetal pattern. By simply measuring the radius of their path we can figure out quantities such as charge to mass ratio.

Both cloud and bubble chambers suffer from the drawback that they cannot detect neutral particles, since only ions (and ionizing photons) can cause any change in the chambers. Instead, we have to look for the interactions of other particles with neutral particles. For example, if we see a charged particle interact with something we can't "see" we can guess it was a neutral particle.

Particle Detector – Ionisation Chamber: Ionisation



An ionisation chamber is defined as a device used for detection or measurement of ionizing radiation. It consists basically of a sealed chamber containing a gas and two electrodes between which a voltage is maintained by an external circuit. When ionizing radiation, e.g., a photon, enters the chamber (through a foil-covered window), it ionizes one or more gas molecules. The ions are attracted to the oppositely charged electrodes; their presence causes a momentary drop in the voltage, which is recorded by the external circuit. The observed voltage drop helps identify the radiation because it depends on the degree of ionization, which in turn depends on the charge, mass, and speed of the photon.

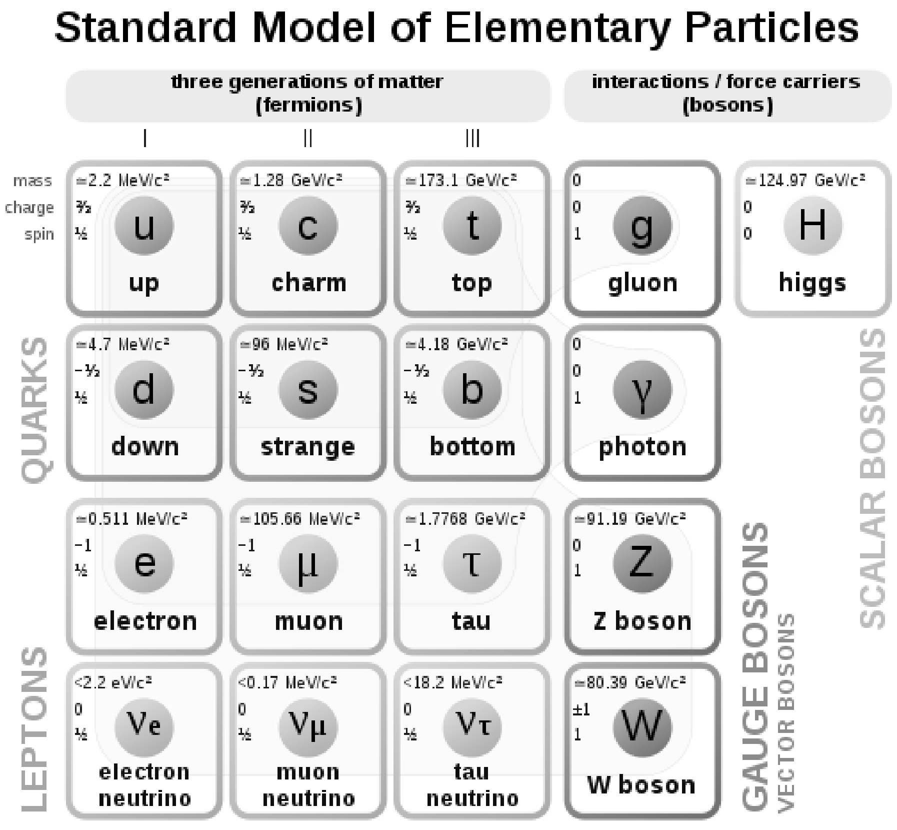
L.O 11.3.4 State the need of high energies required to investigate the structure of nucleon

The scattering of high energy electrons by nucleons (protons and neutrons) can reveal the internal structure of these particles. It was thought that nucleons were fundamental particles but the results of the electron scattering experiments suggest the existence of point like particles within the proton. As the diffraction of particles depends on their wavelength, so the more energetic the particle the shorter the wavelength ($E = hc/\lambda$) and the finer the detail that can be observed. So very high energies are needed to probe the very internal structure of a proton or neutron.

Apart from the fact that high energies correspond to short wavelengths, another reason is many unstable elementary particles have large masses and, due to conservation of energy, can only be produced by decay from highly energetic systems ($E = mc^2$). The heaviest elementary particle detected so far, the 'top' quark has approximately 175 GeV, nearly 200 times the mass-energy of a proton. At this point it should be mentioned that the total energy in accelerator beams required to create such massive particles in sufficient intensities is quite substantial.

L.O 11.3.5 Indicate the standard quark-lepton model particles (baryons, meson, leptons and hadrons)

The standard model of particle physics attempts to explain everything in the universe in terms of fundamental particles. A fundamental particle is one which cannot be broken down into anything else. These fundamental particles are the building blocks of matter, and the things which hold matter together. The standard model is represented by the following diagram:



The particles in the standard model can be put into two groups: fermions and bosons. Fermions are the building blocks of matter. Fermions can be put into two categories: quarks and leptons. Quarks make up called **hadrons** and are held together by strong nuclear force. Hadrons can be split into 2 types:

i) **Baryons** which contain three quarks or three antiquarks such as proton and neutron

ii) **Mesons** which contain a quark and an antiquark such as pion and kaon

Leptons are fundamental particles which have no internal structure. They are not made up of smaller particles and do not feel strong nuclear forces. Electron and neutrinos are leptons. **Bosons** are force-carriers. They carry the electromagnetic, strong, and weak forces between fermions.

Fundamental forces			
Force	Relative strength	Range/ m	Gauge - boson
Strong	1	10^{-15}	Gluon
Electromagnetic	1/137	Infinite	Photon
Weak	10^{-6}	10^{-18}	W^+, W^-, Z bosons
Gravitation	10^{-39}	Infinite	Graviton (predicted)

L.O 11.3.6 Explain the corresponding antiparticle for every particle

In particle physics, every type of particle has an associated antiparticle with the same mass but with opposite physical charges (such as electric charge).

Type of Particle	**Name**	**Antiparticle**	**Relation to Forces**	**Unique Properties**
Quark	Up	Antiup	Experiences strong, electromagnetic, weak, & gravity	Color charge, cannot be isolated
	Down	Antidown		
	Strange	Antistrange		
	Charmed	Anticharmed		
	Top	Antitop		
	Bottom	Antibottom		
Lepton	Electron	Positron	Experiences electromagnetic, weak, & gravity	Lepton number
	Muon	Antimuon		
	Tauon	Antitauon		
	Electron neutrino	Positron neutrino	Experiences weak, & gravity	Lepton number, no electric charge
	Muon neutrino	Antimuon neutrino		
	Tauon neutrino	Antitauon neutrino		
Guage boson (exchange particle)	Gluon	Gluon	Mediates strong	Massless, no electric charge
	Photon	Photon	Mediates electromagnetic	
	W^- boson	W^- boson	Mediates weak	Can change quark flavor
	Z boson	Z boson	Mediates weak	No electric charge
Higgs boson	Higgs boson	Higgs boson	Accounts for mass	No electric charge, recently discovered