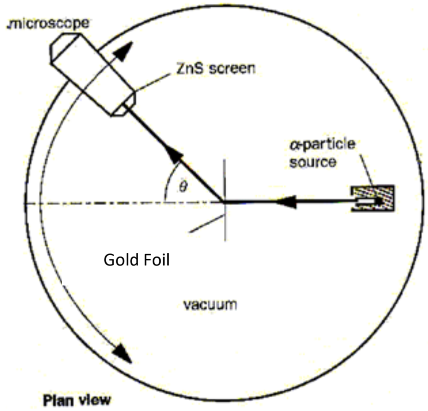
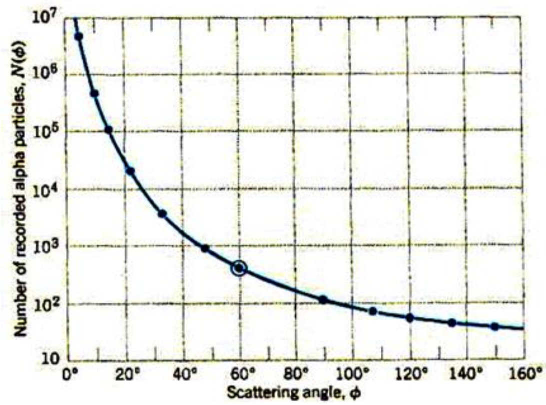
Nuclear Physics

Rutherford Alpha (He^{2+}) Scattering Experiment



Key features of the Setup:

- An Alpha source
- Thin Metal Foil → Gold foil
- Fluorescence detector → ZnS Screen
- Vacuum Chamber
  - Prevent collision with air



Results:

- Most He^{2+} have little or no deviation
  - Volume of the atom is made up mainly of empty spaces
- A small fraction of He^{2+} were deflected by more than 90° and a very small proportion were deflected by 180°
  - Nucleus consists of a positive charge concentrated in a very small space

Nuclide – a particular species of a nucleus that is specified by its proton and neutron number
Nuclide notation:

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

Where *X* is the symbol of the element, *Z* is the proton number, *A* is the nucleon number (sum of the number of protons and neutrons)
Subatomic Particles

Sub-atomic particle	Rest mass	Charge
Proton (${}^{1}_{1}H$ or ${}^{1}_{1}p$)	1.6726 x 10^{-27} kg	+1.6 x 10^{-19} C
Neutron (${}^{1}_{0}n$)	Approximately mass of proton 1.6749 x 10^{-27} kg	0
Electron (${}^{0}_{-1}e$)	9.11 x 10^{-31} kg (≈ 1/1800 x mass of protons)	-1.6 x 10^{-19} C

Isotopes – are nuclides having the same atomic number (same element) but different mass number
Atomic mass unit (u) – a unit of mass. 1u is defined as 1/12 the mass of a carbon-12 atom,

$$1u = 1.661 \times 10^{-27} \text{ kg}$$

Electronvolt (eV) – is a non-SI unit for energy equal to the energy gained by an electron when it is accelerated through a potential difference of one volt. (1eV = 1.60 x 10^{-19} J)

Mass Defect

- Mass of an atom is less than the sum of masses of their separate constituents – protons, neutrons and electrons
- The difference between the mass of a nucleus and the mass of its constituent particles taken separately is known as *mass defect*
  - Mass defect = Mass of protons and neutrons – Nuclear mass
  - $Z M_p + (A - Z)M_n - M$
    - where Z: proton number; A: mass number; M_p: mass of a proton; M_n mass of a neutron; M: mass of the nucleus

Nuclear Binding Energy

- Binding energy is the work that would have to be done *(energy absorbed) to separate* a nucleus into its constituent protons and neutrons. OR
- Binding energy is the *energy released* if a *nucleus is formed* from its constituent separate protons and neutrons

Mass-Energy Equivalence

- Einstein proposed that mass and energy are equivalent, that is, it is possible to interchange mass and energy, $E = mc^2$.
- Binding energy is the energy equivalent of the mass defect of the nucleus,

$$E = \Delta mc^2, \ \Delta m \text{ is the mass defect}$$

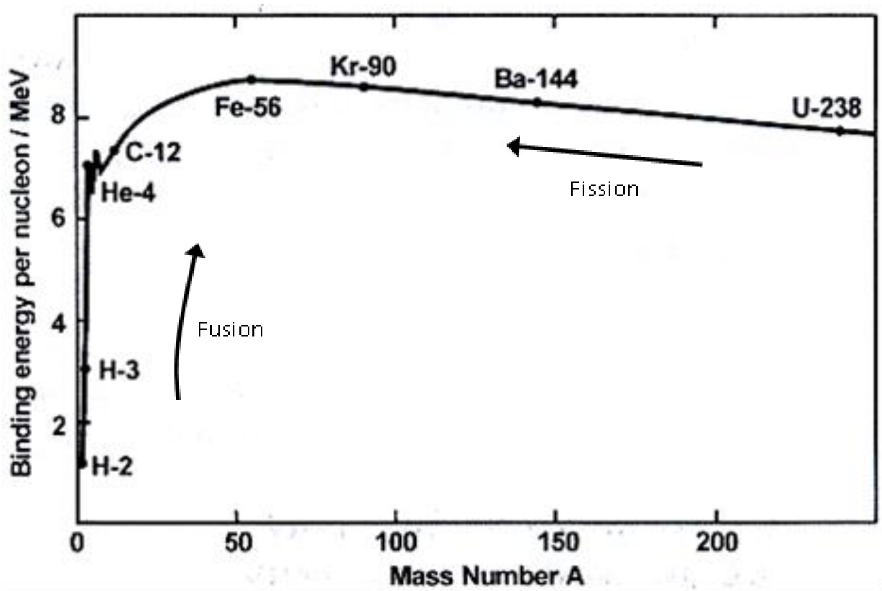
Nuclear Processes

- A nuclear reaction (or process) can be represented as,
  - ${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N$
- In a nuclear process, the following are conserved
  - Nucleon number
  - Proton number
  - Mass-Energy
  - Momentum
- Note: Nuclear reaction/process outlined is only one of the many possible reactions. It is unlike chemical reactions that are definite without other product. In a nuclear reactions, many different products are possible even if the initial products are the same
- Calculate energy released in a nuclear process,
  - E = (total mass of product – total mass of reactant)c^2

Binding Energy per Nucleon

- $\text{Binding Energy per nucleon} = \dfrac{\text{Binding Energy of a nucleus}}{\text{Number of nucleons}}$
- It is the average energy per nucleon needed to separate nucleus into separate nucleons
- It is a measure of nucleus stability. Greater binding energy per nucleon means a more stable, more tightly bound nucleus

Binding Energy per Nucleon Curve



<u>Features of the curve</u>

- The curve is experimentally obtained. There is only one such curve.
- Fe-56 has the highest binding energy per nucleon at ~8.8 to 9 MeV
    - There exist a maximum due to two competing factors
        - When nucleon number is low, binding energy is low
        - When nucleon number is high, it means high number of protons and neutron in a tight confined nucleus
- Heavy nucleus can get stability from nuclear fission (splitting) to form lighter nuclei with higher binding energy per nucleons
- Lighter nucleus can get stability from nuclear fusion (combining) to form heavier nuclei with higher binding energy per nucleons
    - In both nuclear fission and fusion, there will be a release of energy equal to the difference in the binding energy of the products and reactants

Nuclear Fission

- Heavy nucleus splits into lighter nuclei of approximately *equal mass*
- Along with emissions of neutrons
- Total mass of daughter nuclei is lesser than the original nucleus (decrease in total mass), with the release of energy (in the form of KE of the daughter nuclei and/or electromagnetic energy – gamma-ray photon(s))

<u>Mechanism of Fission</u>

1. Neutron Capture.
    - A slow moving neutron is captured by the heavy nucleus
        - “Slow” as fission is NOT using a high energy neutron to smash up the heavy nucleus

2. Instability
    - The addition of the neutron in the nucleus causes the nucleus to be unstable
3. Fission
    - Due to the instability, the heavy nucleus is split into two or more lighter nuclei
    - Release of more fast moving neutrons
4. Fission Chain Reaction
    - Neutrons generated can cause further initiation of fission reactions when they are captured by more heavy nucleus, and so on

Nuclear Fusion

- Two or more nuclei of low mass number collide and combine to form heavier nucleus
- Often with emission of another lighter particle
- Decrease in total mass and release of energy
- Initial input of energy is required. Nuclei are positively charged. Hence energy is required to overcome the electric potential energy due to the repulsive force between the two charges, so that the nuclei can come close together to react

Radioactivity (radioactive decay) – is the spontaneous and random disintegration (or decay) of an unstable nucleus into a more stable one with the emission of either an alpha-particle, or a beta-particle, and/or usually accompanied by the emission of a gamma ray photon.

- **Spontaneous**: Decay cannot be controlled and unaffected by external physical conditions (unlike a fission that requires neutron capture)
- **Random**: Impossible to predict exactly which nucleus or when a particular nucleus will decay
- Alpha Decay → Alpha-particle emitted
- Beta Decay → Beta-particle emitted
- In both Alpha and Beta Decays, gamma ray photons may or may not be emitted
- If daughter nucleus is still unstable, further different decay can happen. This is known as *decay chain*

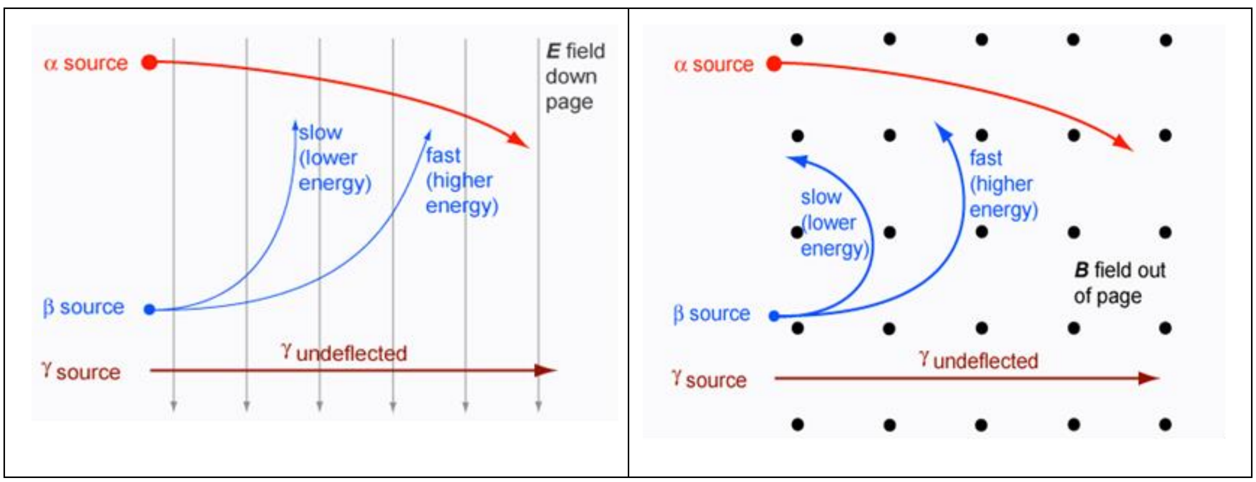
Types of Radiations

Radiation	Nature	Charge	Mass	Speed	Energy
Alpha particle (α)	Helium-4 nucleus (2p + 2n), ${}^{4}_{2}He$	+2e	~ 4 m_{proton}	0.1c	3 - 7 MeV
Beta particle (β)	High speed electron , ${}^{0}_{-1}e$	-e	~ (1/1800) m_{proton}	Wide range: 0 - 0.9c	0 - 1 Mev
Gamma ray photon (γ)	Electromagnetic radiation of very short wavelength	No charge	massless	c	0.1-10 MeV

Penetrating Ability vs Ionising Ability

Radiation	Penetrating ability: Stopped by	Ionising ability	Effect of magnetic and electric fields
Alpha particle (α) He^{2+}	- 2-4 cm of air - A thin sheet of paper - A thin sheet of mica - Human skin	A great deal	Deflect in same direction as positive charge
Beta particle (β) e^{-}	- 6 cm - 3 m of air - Few mm of light metals such as aluminium (> 5 mm thick aluminium)	Some	Strong deflection in opposite direction to α particle
Gamma ray photon (γ)	- 400-500 m of air - Several cm of dense metals such as lead (a 2.5 cm thick lead absorbs about half the incident Y-ray photons) - Several metres of lighter materials such as concrete	Very little	No effect

α, β and γ in Fields



α-Decay

- α-particles are helium-4 nuclei (${}^{4}_{2}He$)
- $${}^{A}_{Z}X \rightarrow {}^{(A-4)}_{(Z-2)}Y + {}^{4}_{2}He + Q$$
- Most energy Q is carried away by the α-particle
  - Prove by conservation of momentum and take ratio of respective kinetic energy

β-Decay

- β-particle is a high speed electrons emitted from the nucleus. (NOT an orbital electron)
- β-particle is produced when a neutron decays into a proton, ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + Q$
- ${}^{A}_{Z}X \rightarrow {}^{A}_{(Z+1)}Y + {}^{0}_{-1}e + Q$
- β-particles detected have a very wide and continuous range of energies, unlike in α-particle decay where the α-particles have a very narrow range of energies
    - Suggested that another particle is emitted together with the β-particles. This particle is the neutrino (or antineutrino)
        - Prove by conservation of momentum → if only two particles *Y* and β, velocity of β is definite, with a narrow range due to usual fluctuations
        - Neutrino and Antineutrino are hard to detect or considered in the conservation of proton or mass numbers as they are not proton/electrons/neutrons and are charge-neutral

γ-Decay

- γ photon is emitted when an excited nucleus de-excite. (NOT due to electronic transitions by the orbital electrons)
- Since γ photon are electromagnetic energy, there is no change in charge, proton or nucleon numbers of the nucleus
- Wavelength (frequency) of the γ photon is characteristic to the type of nucleus

Radiation Detection

- Detected by a Geiger mÜller tube connected to a ratemeter/counter
    - When the radiation enters the tube, it ionises the atoms and moelcules in the tube, causing electrical pulse
    - This pulse is detected as a “count” of the radiation.
    - A “count” DOES NOT mean one ionizing radiation particle. “Count” is proportional to the large numbers of ionizing particles
    - Geiger mÜller tube cannot distinguish the species of radiation (α, β or γ)
- Count Rate
    - Number of count collected per second.
    - Rate at which emissions from a radioactive source are detected
    - Fluctuations in count rate indicates radioactivity is random
- Background Radiation
    - Even in the absence of a radioactive source count rate is detected
    - Such count rate is from the background radiation
        - Cosmic radiation
        - Natural radioactive materials in rocks
        - Emissions from medical, military and industrial instruments
    - To account for background radiation
        - Measure count rate without source ($C_{background}$)

- Subtract background count rate from total count rate measured in the presence of the source, $C_{actual} = C_{recorded} - C_{background}$

Activity, *A* – of a radioactive source is the number of nuclei disintegrating per unit time

- SI unit: Becquerel (Bq) or s^{-1}
- $A = -\frac{dN}{dt}$

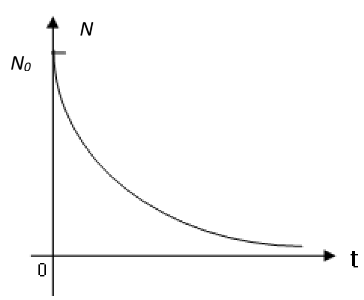
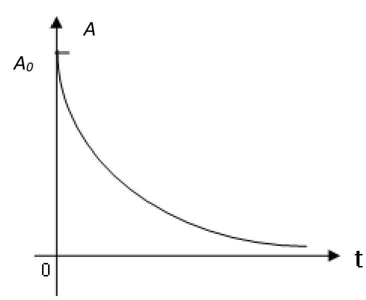
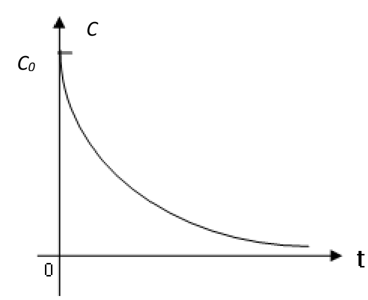
Radioactive Decay Law – Rate of disintegration (or activity) of a radioactive sample at any instant in time is directly proportional to the number of undecayed, radioactive nuclei present at that time

- $-\frac{dN}{dt} \propto N$, where N is the number of undecayed nuclei, Hence
- $-\frac{dN}{dt} = \lambda N$, $A = \lambda N$

Decay Constant, *λ* – is the probability of decay per unit time of a nucleus. Unit: s^{-1}

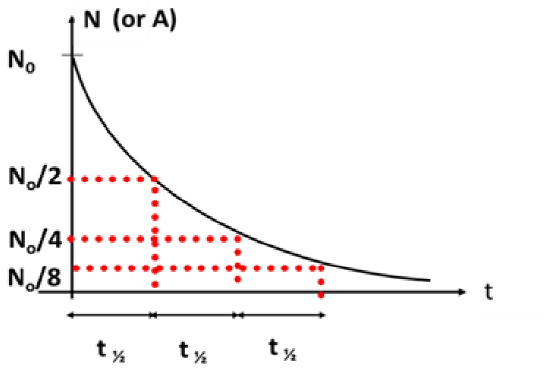
Exponential Nature of Decay

- Solving $-\frac{dN}{dt} = \lambda N$, yield $N = N_0 e^{-\lambda t}$
  - $N = N_0 e^{-\lambda t}$ is known as the radioactive decay equation, relating the number of radioactive nuclei remaining after time to N_0

		
$N = N_0 e^{-\lambda t}$	$A = A_0 e^{-\lambda t}$, since $A = \lambda N$	$C = C_0 e^{-\lambda t}$, since $C \propto A$

Half-life

- Time taken for half the nuclei in a sample of nuclide to decay, based on the average time taken in a sample with a large number of radioactive nuclei. OR
- Time taken for the activity of a sample of the nuclide to decrease to half its initial value, based on the average time taken in a sample with a large number of nuclei

	At t = 0, $N = N_0$ Then after $t_{1/2}$ (half-life), $N = N_0/2$ Therefore, $\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}}$ $ln\left(\frac{1}{2}\right) = -\lambda t_{1/2}$ $t_{1/2} = \frac{ln\ 2}{\lambda}$

- $\frac{x}{x_0} = e^{-\lambda t} = e^{-\left(\frac{ln 2}{t_{1/2}}\right)t} = e^{-ln 2\left(\frac{t}{t_{1/2}}\right)} = e^{\left(ln\frac{1}{2}\right)\left(\frac{t}{t_{1/2}}\right)} = \left(\frac{1}{2}\right)^{\left(\frac{t}{t_{1/2}}\right)}$
    - Therefore $x = x_0\left(\frac{1}{2}\right)^n$
        - Where n is the number of half-lives elapsed and x can be N, A or C

Biological Effects of Radiation

- Direct damage to DNA, ionizing DNA molecules by breaking it into fragment
- Produce free radicals in body, causing undesirable reactions and damage
- Replication of cell affected, risk of cancer
- Application of Radiation
    - Irradiate food to kill bacteria
    - Pest removal
- Exposure to radiation itself is not as dangerous as ingesting the sources of radiation