Nuclear Physics

- A nuclide is defined as a particular species of nucleus that is specified by its proton number and neutron number.
- Isotopes of an element have the **same** number of protons and electrons, but they have **different** number of neutrons.
- The unified atomic mass unit is equivalent to **one-twelfth** of the mass of a carbon-12 atom.
- Mass defect is the amount by which the mass of an atomic nucleus is **less** than the sum of masses of its constituent particles[1].
- Binding energy of a nucleus is the amount to energy that is required to **break** a nucleus into its constituent nucleons (i.e. protons and neutrons).
- Binding energy per nucleon is defined as the binding energy of a nucleus divided by the number of nucleons in the nucleus[2].
- Radioactive decay occurs when an unstable nucleus emits an alpha or beta particle or gamma ray. In the process, the nucleus is transformed into a different and more stable nuclide. This decay is spontaneous[3] and random[4].
- Count rate is a measure of the rate of radiation received by a radioactivity detector, assuming that every ionizing radiation (α, β or γ) triggers one count on the ratemeter.
- Background radiation is the radiation detected by a radiation counter when no radioactive source is nearby.
- (/) Activity A of a radioactive isotope is defined as the number of nuclear disintegrations per unit time.
- (/) The decay constant λ, of a sample of radioactive nuclide is the probability that a nucleus will decay per unit time.
- The half-life of a radioactive isotope is the **average** time taken for its activity to be halved.

$$1kWh = 3.6 \times 10^6 J$$
$$1eV = 1.60 \times 10^{-19} J$$
$$1u = 1.66 \times 10^{-27} kg$$
$$E = mc^2$$

Mass defect= sum of masses of nucleons – mass of nucleus

Binding energy per nucleon = $\frac{binding\ energy}{number\ of\ nucleons}$

$$A = -\frac{dN}{dt}$$
$$A = \lambda N$$
$$x = x_o e^{-\lambda t}, x = N, m, A\ or\ C$$
$$t_{\frac{1}{2}} = \frac{ln2}{\lambda}$$

N- number of **un**decayed nuclei, m- mass of radioactive sample, A- activity, C- count rate

N.B. Nuclear reaction equations and calculations are based on one nucleus, hence small values will be obtained.

Rutherford experiment involving scattering of alpha particles by thin films of heavy metals:

[1] mass is lost because energy is released when individual nucleus come together to form the nucleus

[2] better indicator rather than binding energy, because larger binding energy of nucleus does not mean greater stability, as larger number of protons in nucleus cause stronger electric repulsion

[3] rate of decay is not affected by external conditions like temperature and pressure

[4] while it is impossible to predict when and which nucleus will decay, it is possible to predict the fraction of nuclei that will decay per unit time for a large number of nuclei

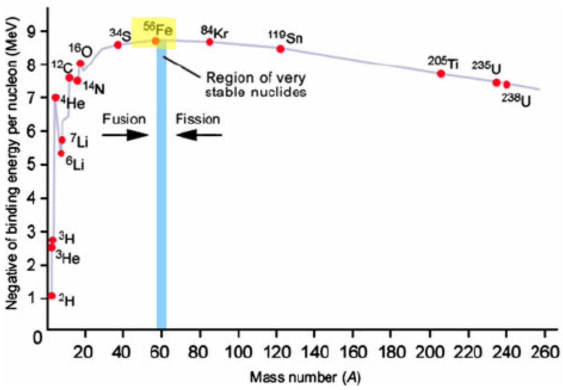
Observation	Deduction
Majority of $\alpha\, particles$ passed straight through the foil **undeflected or with little deflection**.	Nucleus is **very small** in size compared to the atom Atom comprises mainly **empty space**
A **very small fraction** of the particles was **scattered backward**	Majority of **mass of atom is concentrated in a very small positively charged region**

Nuclide equations

$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{A}_{Z}X$

- Conservation of charge: proton number
- Conservation of mass: nucleon number
- Conservation of mass-energy: BE $= (\Delta m)c^2$
- Best to use α, β, γ symbols as much as possible
- Better to write radioactive decay equation rather than to account for radioactive decay one species by one species.

Nuclear Fusion	Nuclear Fission
Light nuclei fuse into heavier nucleus	Heavy nuclei split into 2 lighter nuclei N.B. Can have chain reaction for fission
Goal: Increase binding energy per nucleon of particles involved to increase stability	
To suggest which nuclear reaction is more likely to occur 1. Overall loss in energy (lose more energy → become more stable 2. Compare binding energy per nucleon of products of the nuclear reactions	
Calculations	
Positive: release of energy Negative: supply of energy	
$E(\Delta m)c^2$ Δm is not mass defect. Its $mass\ of\ reactants - product.$ Mass of neutron should be included in calculation. No BE but have mass.	By conservation of energy: BE of reactant + energy released = BE of products Free neutron or proton has no binding energy and shouldn't include in calculation Smallest particle to have binding energy is deuterium $^{2}_{0}H$ (1p and 1n).



Be careful whether question gives you BE or BE per nucleon as vertical axis

Particle	α	β	γ[5]
Example	${}^{238}_{92}U \rightarrow {}^{234}_{90}90 + {}^{4}_{2}He$	${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$	-
Nature	Helium nucleus	High speed electron	EM radiation
Notation	${}^{4}_{2}He$	${}^{0}_{-1}e$	${}^{0}_{0}\gamma$
Charge	+2e	-e	No charge
Mass	4u	1/1800 u	0
Range	0.1c	0.9c	c
Ionizing power	**strongest** (~10^5 ions per cm)	~10^3 ions per cm	weak
Penetrating power	stopped by few cm or air/ paper	~5mm aluminum	**most penetrating** (several cm of lead)
Efield and Bfield	deflected	deflected (smaller r)	undeflected
Emission of particle causes	Proton no $\downarrow \times 2$ Neutron no $\downarrow \times 2$	Proton no $\uparrow \times 1$ Neutron no $\downarrow \times 1$	-

N.B. Nuclide can decay through different pathways to achieve more stable nucleus (decay chain). Other particles: ${}_{+1}\beta$, anti-neutrino $\bar{v}_e$ and neutrino v_e.

Discovery of neutrino from Beta (Minus) Decay i.e. neutron decay into proton, electron (beta-particle) and anti-neutrino

Expectation:

Given nucleus at rest decays into 2 daughter nuclei (one of it is beta particle), from COE, momenta and KE of daughter particles should be completely constrained to be fixed value. By POCLM, the electron emission should also be collinear in the opposite direction to recoil of nucleus.

Reality:

- Continuous spread of energies for emitted electrons suggests violation of COE.
- Electrons emitted in all directions suggest violation of POCLM.

Hence, neutrino was proposed to accompany the outgoing electron and carried off missing energy that was required to satisfy energy conservation and momentum conservation.

Explain why although the lead container provides adequate shielding for the particle emissions, some X-ray emissions can be detected outside the lead container.

- Beta particles are high speed/ high energy electrons. When they approach the high atomic mass lead atoms with charged nuclei, strong electric forces cause sudden deceleration/ acceleration (changes in direction of the beta particles), resulting in emission of Bremsstrahlung (braking radiation) of photon energy in the x-ray range.

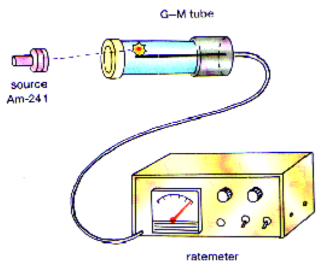
- When the high speed electrons approach the high atomic mass lead atoms, they knock out inner shell electrons of the lead atoms (electrons bound most closely to the nucleus).

[5] Radioactive photon = gamma ray, BUT photon may not = gamma ray

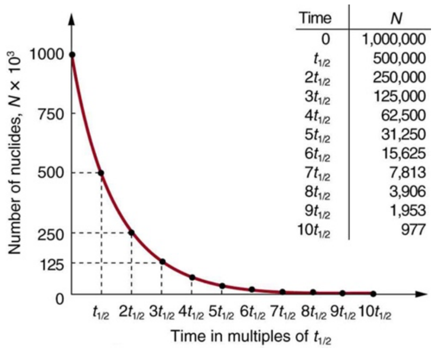
The subsequent de-excitation of electrons from higher energy levels to the vacant inner shell energy levels results in the emission of X-ray photons.

- Hence, low atomic mass materials e.g. plastic, wood, water is used for shielding to reduce unintended X-ray emission.

To measure count rate: Geiger-Muller (GM) Tube



Illustrated together with the concept of half-lives:



Activity is in all directions, count rate (captured by GM Tube) will only be able to capture radiations emitted in some directions.
Hence, if question requires you to use count rate value as activity, the following assumptions are made: ① Activity is uniform in all directions and ② count rate = activity

Effects of ionising radiation on living tissue and cells

Direct	Indirect
Radiation interact with DNA → break/ affect bonds in DNA → mutation leading to cancer/ affect ability of cell to reproduce and survive	Radiation → create highly reactive free radicals when radiation interacts with and breaks bond in water molecule → initiate harmful chemical reaction within cell → impair cell function and damage cells indirectly

Safety Precaution for Planning

- Handling:
  - Reduce time of contact with radioactive materials to minimum.
  - Sources should be manipulated remotely with tongs or in glove box
  - Ingestion of radioactive material should be avoided
  - Protective laboratory clothing should be worn
  - Workers in restricted areas must wear flim badges or thermoluminescent dosimeters to monitor the accumulated dosage that they are exposed to over a certain interval of time.
  - Radioactive sources should be kept in rooms with proper shielding
  - Radioactive materials be labelled to inform worker handling the material
  - Routing radiation survey monitoring to determine radiation levels in workspace

- Storage: Keep all radioactive materials in lead containers when not in use, because most alpha and beta particles emit gamma radiation.
- Disposal: Radioactive waste should be encased in concrete, sealed in steel tanks then buried underground

Applications
- Tracers: identify rate of uptake of minerals by plants, find pipe leaks (use radioisotope with shorter half-life to avoid permanent soil contamination)
- Manufacturing: monitor thickness/ faults in material as extent to which absorption of radiation takes place in matter depends on thickness and density of material
- Radiotherapy: treat tumour

Choosing the appropriate radioactive source for the task
- Longer half life → decay activity relatively constant → if used as fuel, power available more constant
- Alpha emission is easier to capture to generate power as it is the least penetrative
- Gamma radiation is highly penetrating → slight change in thickness would not cause any change in amount of gamma radiation detected → would not affect output from detector → ineffective to monitor thickness of manufactured products
- Shorter half-life → high activity so small amount of sample needed + decay quickly so less risk to patient and others

Pointers
- Radioactive Decay: Given that a stationary nucleus of mass number A undergoes radioactive decay and emits an alpha particle. If total energy released is E, what is the KE of the alpha particle.

Stationary nucleus $\xrightarrow{\text{decay}}$ $\underbrace{{}^{4}_{2}He + \underline{n}}_{\text{Total KE released, } E}$

mass no = A

What is KE of alpha particle?

$KE = \frac{1}{2}mv^2 = \frac{1}{2}(mv)(v)$

By POCLM,

$0 = m_n v_n + m_\alpha v_\alpha$

$m_n v_n = \boxed{-} m_\alpha v_\alpha$

due to direction ∴ mv constant

$\frac{v_n}{v_\alpha} = -\frac{m_\alpha}{m_n}$

$\frac{KE_n}{KE_\alpha} = \frac{\frac{1}{2}(mv)(v_n)}{\frac{1}{2}(mv)(v_\alpha)}$

$= \frac{v_n}{v_\alpha}$

$= -\frac{m_\alpha}{m_n}$

Sign not impt concerned w magnitude

$KE_\alpha = KE_n\left(\frac{m_n}{m_\alpha}\right)$

$KE_\alpha + KE_n = KE_n\left(\frac{m_n}{m_\alpha}\right) + KE_n$

$E = \left(1 + \frac{m_n}{m_\alpha}\right)KE_n$

$$KE_n = \frac{m_\alpha}{m_\alpha + m_n}E$$

$$KE_\alpha = \frac{m_n}{m_\alpha + m_n}E$$

$$= \frac{A-4}{A}E$$

- **Accounting for background radiation and reduced distance between detector and radiation source**

When a detector is pointed towards a radioactive sample that is 80.0cm away and has a half life of 20 minutes, it gives an average count rate of $78s^{-1}$. In the absence of the source, the average count rate is $10s^{-1}$.
What is the average count rate expected 40 minutes later, with the detector still pointed towards the sample but now located 40.0cm away. Regard the sample as a point source of radiation.

A) $78s^{-1}$
B) $68s^{-1}$
C) $27s^{-1}$
D) $17s^{-1}$

Solution:
Actual count rate at 80cm, t=0min
= Count rate – Background radiation
= 78 – 10 = $68s^{-1}$
Actual count rate at 80cm, 40min

$$C = C_o e^{-\lambda t}$$

$$C = 68e^{-\frac{ln2}{20}(40)} = 17s^{-1}$$

Actual count rate at 40cm, 40min

$$I \propto \frac{1}{r^2} \rightarrow \frac{1}{\left(\frac{1}{2}\right)^2} = 4$$

Recorded count rate at 40cm, 40cm

$$C = 4 \times 17 + 10 = 78s^{-1}$$

- Efield concepts can be tied with nuclear concepts.
  - Given an alpha particle is passing close to a nucleus, such that it is deflected by an acute angle, how can we increase the angle of deflection by manipulating KE and distance of alpha particle from nucleus
    Answer: We can decrease KE of alpha particle (given constant distance and electric force, decreasing KE decreases velocity and increases angle of deflection) and decrease its distance from nucleus (increase electric force and increase angle of deflection)
  - Given a gold foil scattering experiment, a proton and a alpha particle have the same KE approach a gold nucleus head on. Find the ratio of $\frac{distance\ of\ cloests\ approach\ between\ proton\ and\ gold\ nucleus}{distance\ of\ closest\ appraoach\ between\ alpha\ aprticle\ and\ gold\ nucleus}$.
    Answer: (Consider KE being converted to electric potential energy) Since KE of both particles is the same, $\frac{Qq_p}{4\pi\varepsilon_o r_p}$=$\frac{Qq_n}{4\pi\varepsilon_o r_n}$. Simplifying, $\frac{r_p}{r_n} = \frac{q_p}{q_n} = \frac{1}{2}$.

- Suggest why it may be difficult/ impossible to take a photograph of the deflection (if any) of alpha, beta particles and gamma radiation being emitted from a single source in a magnetic field.
  - No source can produce alpha, beta particles and gamma radiation simultaneously
  - Gamma rays are weakly ionizing and may not produce tracks
  - Beta particles have weak ionizing power compared to alpha particles and their tracks are thin and meandering, not the solid tracks illustrated
  - Mass to charge ratio for alpha particles is appx 4000 times that of beta particles. Either alpha particles have an almost straight track which would overlap with the tracks of gamma rays, if any or beta particles would have a small radius such that only a dot is seen