

U1 AOS 2 Summary - Nuclear Physics

Nuclear Stability:

Forces within a nucleus:

- **Electrostatic force:** Long distance repulsive force that acts between protons.
- **Strong nuclear force:** Short distance attractive force that acts between nucleons (protons and neutrons).
- **Weak nuclear force:** Neither attractive nor repulsive force that acts within nucleons. Allows the conversion between protons and neutrons during beta decay.

Factors affecting nuclear stability include:

- The mass number ('size of nucleus')
- The number of protons
- The number of neutrons

If the mass number is too high, the nucleus has too many protons or too many neutrons, then it can experience a nuclear decay depending on the reason of its instability.

Isotope: A variation of the same element containing the same number of protons, but a different number of neutrons.

Radioisotope: A radioactive isotope.

Line of stability

- Neutrons are present in nuclei to shield from the protons' electrostatic repulsion (ie. the repulsion between protons is balanced by the strong nuclear force between nucleons).
- For small nuclei, the ratio of stability is 1 proton : 1 neutron. However, this ratio increases for larger nuclei, becoming roughly ~ 1 protons : 1.5 neutron ratio.

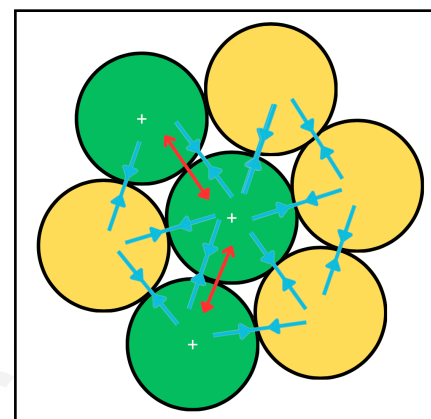
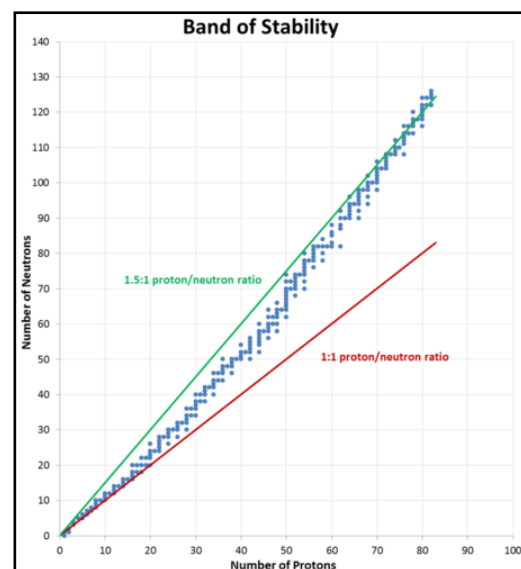


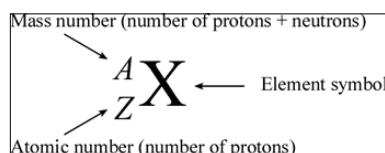
Diagram of a nucleus illustrating the strong nuclear forces (blue) and the electrostatic forces (red). Notice how the strong nuclear forces are acting between all nucleons.



Plot of the number of neutrons against number of protons for all known isotopes (blue) alongside mathematical plots of 1.5:1 ratio (green) and 1:1 ratio (red)

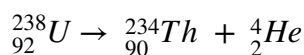
Nuclear Physics Foundational Skills:

Atomic symbol:



Nuclear equations

Example (uranium decay):



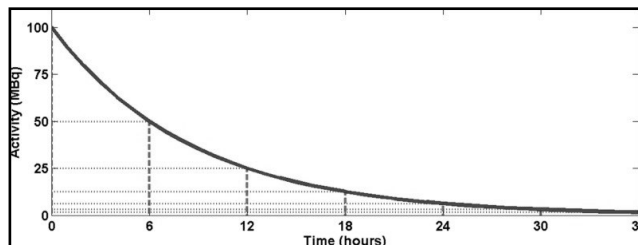
Atomic numbers and mass numbers must add up on both sides, respectively.

Radioactive Decay:

Activity (measured in becquerels, Bq)

- Rate of radioactive decay. Measures how 'quickly' a sample of isotopes is decaying.
 Note: 1 Bq = 1 disintegration per second.

- The occurrence of a radioactive decay is random. However, the larger the mass of your radioactive sample, the higher this probability and thus the faster the rate of decay.
 - The rate of radioactive decay (activity) is proportional to the mass of your radioactive sample. $A \propto m$*



Decay curve illustrating the 'slowing down' of activity (rate of decay) as time passes. This occurs due to the decrease in available radioisotope as time passes.

Half-Life ($t_{1/2}$)

Half life is the time it takes for half a sample of radioisotope to decay.

To calculate the number of undecayed nuclei:

$$N = N_0 \left(\frac{1}{2} \right)^n$$

N = Final number of undecayed nuclei
 N_0 = Initial number of undecayed nuclei
 n = number of half-lives elapsed (total time/half-life)

This formula also works for mass and activity of the sample, i.e.

$$m = m_0 \left(\frac{1}{2} \right)^n \text{ and } A = A_0 \left(\frac{1}{2} \right)^n$$

Types of Radiation

	When emission occurs	Charge	Mass	Speed	Ionising power	Penetrating power
Alpha particle	Unstable nuclei with too high mass number, or when n:p ratio needs to be adjusted.	(+2)	Heavy	Slowest	Highest	Lowest
Beta plus particle	Unstable nuclei with too many protons	(+1)	Light	Fast	Medium	Medium
Beta minus particle	Unstable nuclei with too many neutrons	(-1)	Light	Fast	Medium	Medium
Gamma ray	Unstable excited nuclei (have excess energy)	0	(No mass)	Fastest	Lowest	Highest

Penetrating power: measures how easily a particle or ray can penetrate a material of certain density. Relates to the mass of a particle (ie. heavier particles, such as alpha particles, have the least penetrating power).

Types of Decay and Equations:

Alpha (α) Decay

- The emission of a large alpha particle reduces the size of the nucleus, increasing its stability.

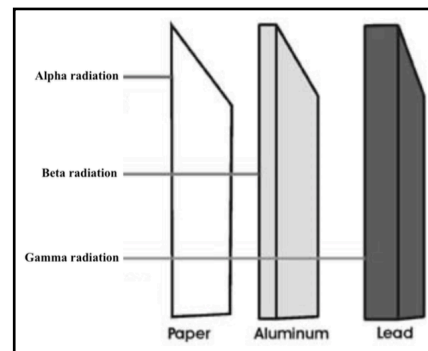
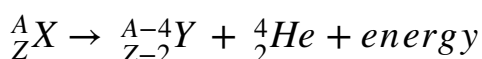
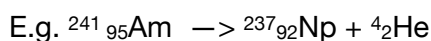
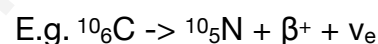
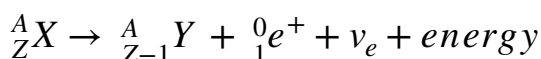


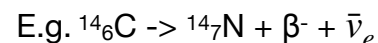
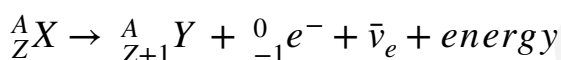
Illustration of penetrating power of the three radiations. Gamma radiation can penetrate both paper and aluminium due to its high penetrating power.

Beta (β^+ and β^-) Decay

- Beta plus (β^+) decay involves a proton converting into a neutron, resulting in the emission of a beta plus particle (ie. **positron**) and a neutrino.



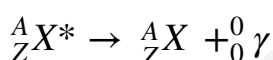
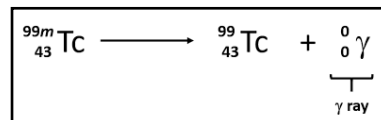
- Beta minus (β^-) decay involves a neutron converting into a proton, resulting in the emission of a beta minus particle (ie. **electron**) and an antineutrino.



Gamma (γ) Decay

γ = gamma rays - very short wavelength and very high frequency electromagnetic waves. In essence, energy in form of EM radiation.

Eg.



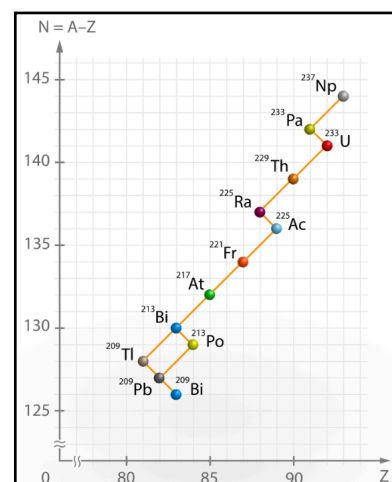
Decay series

A decay series is a series of radioactive decays of different radioactive decay products as sequential series of transformations.

NOTE: Just because a nucleus undergoes a decay does not mean that the daughter nucleus is completely stable. Usually, multiple decays have to occur before stability is reached.

Effect of Radiation on Humans:

- Alpha, beta and gamma radiation are **ionising**, meaning that have the ability to dislodge electrons out of atoms in human cells, causing mutations and potentially leading to the formation of cancers.



An example of a decay series showing the possible transitions between isotopes due to various decays.

Radiation	Ionising power	Capacity for Cell Damage	Effects of Low Dose	Effects of High Dose
Alpha	High	Little - if the radiation source is external since they cannot penetrate human skin (too large/charged) Significant - if the radiation source is internal	Low	Moderate (unless swallowed/enter via wound)
Beta	Medium	Medium - may cause burns	Moderate - Burns	Great - Burns - Tumours
Gamma	Low	Significant - extremely energetic and can pass into cells to cause damage -> tumour/cancer	Low Dose - <1Sv = nausea, reduced WCC - 2Sv = rash, hair loss High Dose - 4Sv = 50% chance of death in 2 months, leukemia + tumour - 8Sv = certain death within 1-2 weeks	

Absorbed dose (SI unit: J kg⁻¹ or Gray, Gy)

- Measures the amount of energy absorbed by a quantity of tissue.

$$\text{Absorbed Dose} = \frac{\text{Energy Absorbed by Tissue}}{\text{Mass of Tissue}}$$

Equivalent dose (SI unit: Sievert, Sv)

- Takes into account the type of radiation, as some types are more harmful than others, using quality factors (QF)

$$\text{Equivalent Dose} = \text{Absorbed Dose} \times \text{Quality Factor}$$

Radiation	QF
Alpha-particles	20
B-particles	10
Gamma rays	1
X-rays	1
Neutrons (From nuclear fusion/fission)	1

Effective dose (SI unit: Sievert, Sv)

- Takes into account the sensitivity of the body part to radiation, as some organs absorb radiation more, using Weighting (W).

$$\text{Effective Dose} = \Sigma(\text{Equivalent Dose} \times \text{Weighting})$$

Summary:

$$\text{Effective Dose} = \Sigma \left(\underbrace{\frac{\text{Energy Absorbed by Tissue}}{\text{Mass of Tissue}}}_{\text{Absorbed dose}} \times \text{Quality Factor} \times \text{Weighting} \right)$$

|-----|
 Equivalent Dose

Radioisotopes in Medical Industry:

Radioisotopes can be used in the medical industry for 2 purposes:

- Imaging
- Radiation therapy

They are mainly used to diagnose and treat cancers.

Imaging

- Radioisotopes emit low-dose gamma rays and can be attached to sugar->absorbed by rapidly dividing cancer cells->radiation detector identifies body locations emitting radiation (ie. cancer cells).

Properties of radioisotopes

- Short half-life->preferred to expel radioactive substance from body
- Sufficient energy to be detected without causing damage to patient
- Emit gamma rays only, not beta/alpha radiation (beta/alpha will be trapped in patients tissue and not detected)
- Eg. ^{18}F , $^{15}\text{O}_2$, ^{64}Cu (PET scans), $^{99\text{m}}\text{Tc}$, ^{18}F (SPECT).

Radiation therapy

External Beam Therapy Cobalt-60/Gamma Knife

- Low dose radiation has the ability to damage cells->over long periods can lead to mutations and development of cancer.
- High-dose radiation has the ability to kill cells->can be used to target cancer cells and be fired directly into the cancer.

E.g. ^{60}Co

Chemotherapy

Radioisotopes can also be delivered to cancer sites->emitted radiation will kill the cancerous cells.

Properties of radioisotopes

- Short half-life
- Emit alpha or beta radiation -> need to destroy surrounding tissue
- Little gamma rays emitted -> don't want to damage surrounding healthy cells
- E.g. ^{131}I for thyroid cancer

Nuclear Energy:

Mass-energy equivalence:

Energy is equivalent to mass and is related by the equation:

$$E = mc^2$$

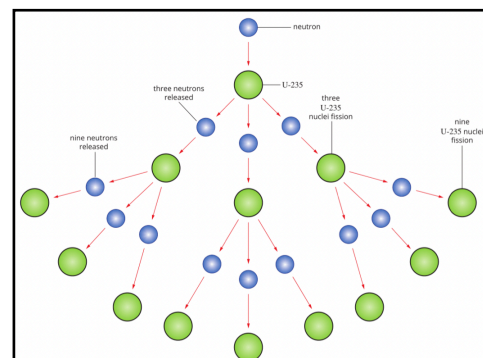
Nuclear fission:

- A nucleus is fissile if it is capable of undergoing fission after absorbing a neutron.
- Nuclear fission involves the **absorption of a neutron** by a nucleus, leading to its increased instability and subsequent decay. This results in the emission of more neutrons, alongside the release of energy resulting from a *mass defect*.
- To sustain a nuclear fission chain reaction, **critical mass** is required

E.g. Uranium fission: $^{235}_{92}\text{U} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3\ ^1_0\text{n}$.

Factors that influence criticality:

- **Mass:** the more material there is, the more likely that neutrons can encounter another nucleus to sustain a chain reaction.
- **Shape:** the flatter the shape, the less likely neutrons are going to hit other nuclei.



A diagram of a nuclear fission chain reaction

Moderation

- Chain reactions can be controlled using graphite/cadmium rods to absorb neutrons as necessary.
- A decrease in neutron concentration leads to a decrease in probability of fission reaction occurrence->slows down chain reaction.

Nuclear fusion:

- Unlike fission, which involves the splitting of a larger nucleus into smaller nuclei, nuclear fusion involves the *combination* of smaller nuclei into a larger nucleus.
- However, the mass of the larger nucleus is still smaller than the combined mass of the parent nuclei. This mass defect results in the release of energy.

E.g. Fusion of hydrogen: $2_1\text{H} + 2_1\text{H} \rightarrow 4_2\text{He}$

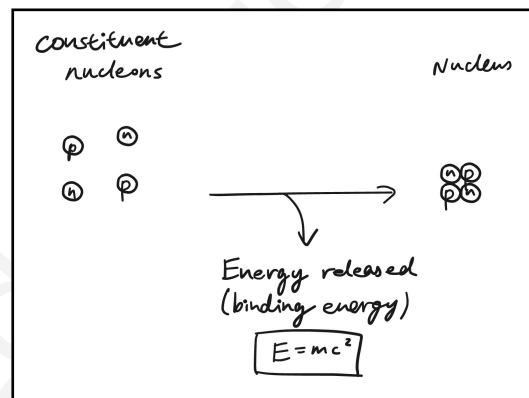


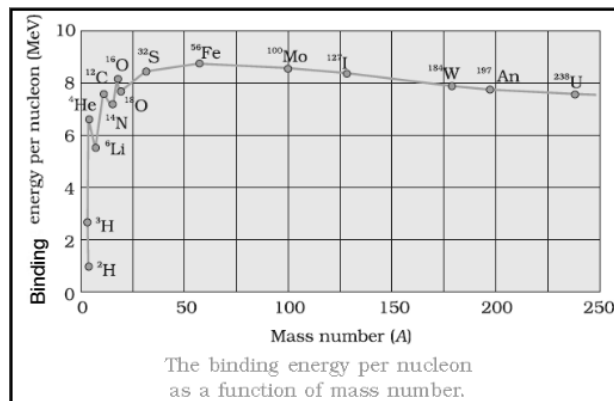
Diagram illustrating the nuclear fusion of individual nucleons to form a nucleus, resulting in energy release. Every nucleus in the universe has formed this way, which is why the total mass of a nucleus is always less than the combined mass of its individual nucleons due to a mass defect resulting from the fusion.

Binding energy:

- The energy released when constituent nucleons come together to form the nucleus OR the energy required to split a nucleus into its constituent nucleons
- Mass defect Δm :** The mass difference between constituent nucleons and the nucleus formed. Relationship between mass defect and binding energy: $E = \Delta mc^2$

Binding energy curve

- The binding energy curve plots binding energy per nucleon against mass number. This is because as mass number increases -> binding energy (TOTAL) also increases.
- The greater the binding energy per nucleon - the more energy is released during bond formation -> the **more stable the nucleus** as it reaches a lower energy level.
- As an isotope with low BE per nucleon transitions into an isotope with high BE per nucleon -> it becomes more stable by releasing energy.



Viability of Nuclear Energy in Australia

- Nuclear fission can be utilised to generate electricity
- Advantages:** abundant uranium deposits, energy efficient
- Disadvantages:** radioactive + toxic waste products, risk of accidents, extremely long half-lives, costly to set up