27 Nuclear Power

27.1 Energy and Mass

The mass of an object increases when it gains energy.

$$E = mc^2$$

This relation is demonstrated in **annihilation** and **pair production**.

Energy Changes in Reactions

Reactions on a nuclear or sub-nuclear scale involve significant changes of mass.

$$\text{Energy released } Q = \Delta mc^2$$

In any change where energy is released, the total mass after than change is always less than the total mass before the change, because **mass is converted to energy** which is released.

27.2 Binding Energy

- The **binding energy** of the nucleus is the **work done that must be done to separate** a nucleus into its constituent neutrons and protons.
- The **mass defect** Δm of a nucleus is defined as the difference between the mass of the separated nucleons and the mass of the nucleus.

$$\begin{aligned} \Delta m &= Zm_p + (A - Z)m_n - M_{\text{nuc}} \\ \text{Binding energy} &= \Delta mc^2 \end{aligned}$$

α Particle Tunnelling

If two protons and two neutrons inside a sufficiently large nucleus bing together as a cluster, because the binding energy of an α particle is very large, the α particle therefore gains enough energy to give it a small probability of quantum tunnelling from the nucleus.

Nuclear Stability

The **binding energy per nucleon** of a nucleus is the average work done per nucleon to remove all the nucleons from a nucleus.

The binding energy per nucleon is a **measure of stability** of a nucleus.

- Comparing the binding energies per nucleon of two different nuclides, the nuclide with more binding energy per nucleon is more stable.

- The binding energies per nucleon has a **maximum value** between $A = 50$ and $A = 60$.

  Nuclear fission occurs when a large unstable nucleus splits into two fragments, the binding energy per nucleon increases in the process.

  Nuclear fusion fuse small nuclei together to form a large nucleus. The produce nucleus has more binding energy per nucleon.

27.3 Fission and Fusion

Induced Fission

Fission of a nucleus occurs when a nucleus splits into two approximately equal fragments.

Induced fission occurs when $^{235}_{92}\mathrm{U}$ is bombarded with neutrons.

Each fission event releases energy and two or three neutrons.

- **Fission neutrons** released in a fission event, are capable of causing a further fission event as a result of a collision with another $^{235}_{92}U$ nucleus.
- A **chain reaction** is where fission neutrons produced further fission events which release fission neutrons and so on.

Energy is released in a fission event, because the fragments **repel each other**, they therefore **gain kinetic energy**.

The energy released is equal to the change in binding energy.

Nuclear Fusion

Nuclear takes place when two nuclei combine to form a bigger nucleus - the binding energy per nucleon of the produce is greater than of the initial nuclei.

Nuclear fusion can only take place if the two nuclei **collide at high speed**, this is necessary to **overcome the electrostatic repulsion** between the two nuclei. So they become close enough to interact through the strong nuclear force.

Solar energy is produced as a result of fusion reactions inside the sun.

27.4 The Thermal Nuclear Reactor

- The **reactor core** is a steel container with **fuel rods** spaced evenly inside.

  The reactor core also contains **control rods** and a **coolant**, such as pressurised water.

- The control rods are connected to a **heat exchanger** through steel pipes.

- A **pump** force coolant through the reactor core and the heat exchanger, where it is used to raise steam to drive the turbines that turn the electricity generators in the power station.
- The **fuel rods** contains enriched uranium with about 2-3% U-235.
- The **control rods** absorb neutrons, the depth of the control rods is automatically adjusted to keep the number of neutrons in the core constant - so exactly one fission neutron per fission event on average goes on to produce further fission.

  This keeps the rate of release of fission energy constant.
- Fission neutrons need to be slowed down significantly to cause further fission of U-235.

  Fuel rods are surrounded by a **moderator** so the neutrons are **slowed down by repeated collisions** with the moderator atoms.
- In a **thermal nuclear reactor**, the fission neutrons are slowed down to kinetic energy comparable to the kinetic energies of the moderator molecules.

For a chain reaction to occur, the mass of the fissile material must be greater than a minimum mass referred to as the **critical mass**.

- Some neutrons escape from the fissile material without causing fission.
- If the mass is less than the critical mass, too many fission neutrons escape because the surface area to mass ration of the material is too high.

Safety Features

- **Thick steel vessel** of the reactor core, to withstand high pressure and temperature in the core.

  Also absorbs β radiation, some of γ radiation, and neutrons from the core.
- **Tick concrete walls** of the building the core is in, which absorbs neutrons and γ radiation that escaped the reactor vessel.
- **Emergency shut-down system** to insert the control rods fully into the core to stop fission completely.
- Sealed fuel rods are **inserted and removed remotely** into/from the core.

Spent fuel rods are much more dangerous, before use U-235 and U-238 emit only α radiation, which is absorbed by the fuel cans.

After use emit β and γ radiation due to the many neutron-rich fission products.

Radioactive Waste

Radioactive waste is categorised as high, intermediate, or low-level waste **according to its activity**.

- **High-level radioactive waste**, e.g spent fuel rods are **removed by remote control** and **stored underwater** in cooling ponds for years, where they will continue to release heat due to radioactive decay.
- **Intermedia-level waste** are **encased in concrete** and stored in specifically constructed buildings with walls of reinforced concrete.
- **Low-level waste** e.g. protective clothing is sealed in metal drums in buried in large trenches.