OCR B Physics A Level

Module 6.2: Fundamental Particles

Notes

6.1.1 Probing Deep into Matter

Rutherford's Atomic Model

Rutherford's **alpha scattering experiment** disproved the **Plum Pudding Model**:
- A stream of alpha particles were fired at a thin layer of gold foil
- The angles at which the particles were scattered were recorded
- Some passed straight through (proving that most of the atom is empty space) but some were deflected by large angles (proving the existence of a very small, positive nucleus)

This led to the **nuclear** model of the atom:
- A small, massive nucleus, containing protons and neutrons
- Electrons arranged in discrete shells in orbit around the nucleus

The closest approach of a scattered particle to a nucleus can be calculated. This depends on the initial kinetic energy of the particle. All of the kinetic energy is converted into electrical potential energy, so the more kinetic energy a particle has, the more electric potential energy it can convert and the closer it can get to the nucleus.

$$\frac{1}{2}mv^2 = \frac{kQq}{r} \quad \text{or} \quad r = \frac{2kQq}{mv^2}$$

Matter and Antimatter

Hadrons	Leptons
• Feel the **strong interaction** (or the Strong Force) • NOT **fundamental particles** (they are made up of quarks) • Eg. protons, neutrons	• Interact via the **weak interaction** and gravity • No (or almost no) mass • **Fundamental particles** • Eg. electrons, neutrinos

Antiparticles have the same mass as their matter counterparts, but the opposite charge.

Particle	Antiparticle
Proton, p	Antiproton, $\overline{p}$
Neutron, n	Antineutron, $\overline{n}$
Electron, *e-*	Positron, *e+*
Neutrino, v	Antineutrino, $\overline{v}$

Pair Production

Matter can be created from energy.

$$Erest = mc^2$$

When this occurs, equal amounts of matter and antimatter are created. This is called **pair production**. For every particle, its equivalent antiparticle is also created.

Annihilation

This is the reverse of pair production. A particle and antiparticle fuse together and produce energy in the form of a **gamma ray**. The energy of the gamma ray is equal to the sum of the energies of the particles.

Cloud chambers are used to observe pair production and annihilation. These contain vapour - when the gas molecules are ionised (by ionising radiation), the vapour condenses. This forms tracks that follow the movement of ionising radiation.

Fundamental Particles

Quarks are **fundamental particles**, meaning that they are not made up of smaller particles.

There are two types of quark that you need to know about: **up** and **down** (and their anti-quark counterparts: **anti-up** and **anti-down**).

Quark	Symbol	Charge
Up	u	+⅔
Down	d	-⅓
Anti-up	$\bar{u}$	-⅔
Anti-down	$\bar{d}$	+⅓

Particle	Quarks	Charge
Proton	uud	+ ⅔ + ⅔ - ⅓ = **+1**
Neutron	udd	+ ⅔ - ⅓ - ⅓ = **0**
Antiproton	$\bar{u}\,\bar{u}\,\bar{d}$	- ⅔ - ⅔ + ⅓ = **-1**
Antineutron	$\bar{u}\,\bar{d}\,\bar{d}$	- ⅔ + ⅓ + ⅓ = **0**

Particle Accelerators

Dental X-ray tubes are used in **particle accelerators**. Electrons are boiled off a hot piece of metal wire, and accelerated from a negative plate towards a positive plate. The electrons have electric potential energy qV and gain **kinetic** energy $\frac{1}{2}mv^2$.

$$qV = \frac{1}{2}mv^2$$

This can be used to work out the final speed of the electrons after acceleration:

$$v = \sqrt{\frac{2qV}{m}}$$

Linear particle accelerators involve charged plates lined up in a straight path. As particles move through the accelerator, the charges are reversed at time intervals to ensure that the particles keep accelerating. The **maximum speed of the particles is limited only by the length of the accelerator.**

Circular accelerators such as **cyclotrons** can reach higher speeds because they are continuous, so are not limited by length. However, **the velocity of particles cannot exceed the speed of light.**

Einstein's Equations

$$Etotal = Erest + Ekinetic$$
$$Erest = mc^2$$
$$Etotal/Erest = \gamma$$

Electron Arrangement

Electrons are arranged around the atom in **discrete energy levels**. They can move up/down energy levels by emitting or absorbing **photons**.

Line spectra provide evidence of this. White light is a continuous spectrum. When light passes through a cool gas, the light emerging has certain wavelengths missing from it. This is because the low energy electrons in the cool gas have absorbed photons of the correct wavelength (for the discrete energy jumps), so have removed them from the light.

Absorption spectra occur when light passes through cold gases. **Emission spectra** are formed when hot gases cool, emitting photons as electrons drop down to lower energy levels.

Fluorescent tubes use this principle. Mercury atoms inside the tubes cool and release UV photons, causing them to fluoresce.

The **wave** model of the atom explains this behaviour; it models electron shells as standing waves. The wavelength of the electron (using **de Broglie's wavelength equation**) must form a whole number of waves around the shell/orbital. This is related to the energy of the electrons.

6.2.2 Ionising Radiation and Risk

Types of Radiation

Atoms can be **unstable** due to:

- Having too many neutrons
- Having too much mass (too many nucleons)
- Having too few neutrons
- Having too much energy

Unstable atoms are radioactive; they release radiation to become more stable.

Radiation	
Alpha, α	• 2 protons, 2 neutrons • Mass: 4 • Charge: +2 • Highly **ionising** • Weakly **penetrating** • Slow • Absorbed by paper or a few cm of air • Occurs when nuclei have **too much mass**
Beta Minus, β-	• Electron • Mass: 0 • Charge: -1 • Weakly **ionising** • Fast • Absorbed by a few mm of metal (aluminium) • Occurs when nuclei have **too many neutrons**
Beta Plus, β+	• Positron • Mass: 0 • Charge: +1 • Annihilated by electrons, so has negligible range (stopped almost immediately) • Occurs when nuclei have **too many protons** (or too few neutrons)
Gamma, γ	• **EM radiation** (gamma waves) • Mass: 0 • Charge: 0 • Very weakly ionising • Very fast - the speed of light • Absorbed by lead or several feet of concrete • Intensity decreases with distance according to the **inverse square law** • Occurs when nuclei have **too much energy**

Risk

Risk is described in terms of **consequence** and **likelihood**.

For example: *stubbing your toe is very likely, but has low consequences, whereas a nuclear accident is very unlikely but has very devastating consequences.*

Doses of Radiation

Absorbed dose is the amount of radiation absorbed per kg of body tissue.

$$absorbed\ dose = \frac{energy\ deposited\ /\ J}{mass\ /\ kg}$$

Effective dose is a measure of the tissue damage caused by the radiation.

$$effective\ dose = absorbed\ dose \times quality\ factor$$

The **quality factor** is a measurement of how damaging radiation is.

Binding Energy

The mass of a nucleus is less than the sum of the protons and neutrons which make it up. This discrepancy is known as the **mass defect** and occurs because some mass is converted into energy, called the **binding energy** which holds the nucleus together.

The binding energy can be worked out using **Einstein's equation:**

1. Work out the mass defect, in kg (you may have to convert from **u**).
2. Use $E = mc^2$ to work out the corresponding energy.

Binding energy between atoms cannot be compared, as they all have different numbers of nucleons. Work out the **binding energy per nucleon** in order to compare.

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

The most stable nucleus (iron) has the highest binding energy per nucleon.

(Remember that binding energy is negative. Highest here means most negative).

Nuclear Energy

Nuclear fission involves breaking apart nuclei to release energy.

- Energy is released because the new smaller nuclei have a lower total mass, so some mass is converted into energy.
- Fission can be **spontaneous** or **induced by the absorption of neutrons**.

The **critical mass** is the amount of fuel needed to create a perfect chain reaction. This is when one fission event produces a neutron that induces another fission event. **Sub-critical** masses of fuel will cause the reaction to fizzle out, whereas **super-critical** masses of fuel may cause a **nuclear explosion**.

Control rods absorb neutrons in order to slow down and control the rate of reaction.

Nuclear **fusion** involves joining two smaller nuclei to form one larger one. It also releases energy.

- Energy is released because the new nucleus has a much higher binding energy per nucleon.
- Very **high temperatures** are required to overcome the **electrostatic force** between the nuclei, meaning that fusion is not currently a viable source of energy (it usually requires more energy than it produces).
- Fusion occurs in stars like the sun.