## Chapter 11 Particle Physics

### 11.1 Atoms, nuclei and radiation

Candidates should be able to:

1 infer from the results of the α-particle scattering experiment the existence and small size of the nucleus

2 describe a simple model for the nuclear atom to include protons, neutrons and orbital electrons

3 distinguish between nucleon number and proton number

4 understand that isotopes are forms of the same element with different numbers of neutrons in their nuclei

5 understand and use the notation $^{A}_{Z}X$ for the representation of nuclides

6 understand that nucleon number and charge are conserved in nuclear processes

7 describe the composition, mass and charge of α-, β- and γ-radiations (both $\beta^-$ (electrons) and $\beta^+$ (positrons) are included)

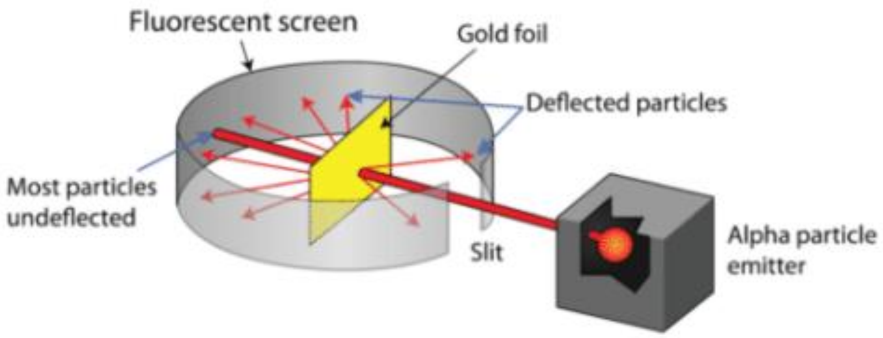
8 understand that an antiparticle has the same mass but opposite charge to the corresponding particle, and that a positron is the antiparticle of an electron

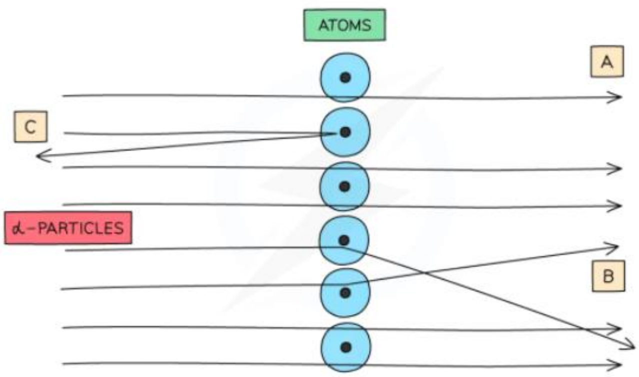
9 state that (electron) antineutrinos are produced during $\beta^-$ decay and (electron) neutrinos are produced during $\beta^+$ decay

10 understand that α-particles have discrete energies but that β-particles have a continuous range of energies because (anti)neutrinos are emitted in β-decay

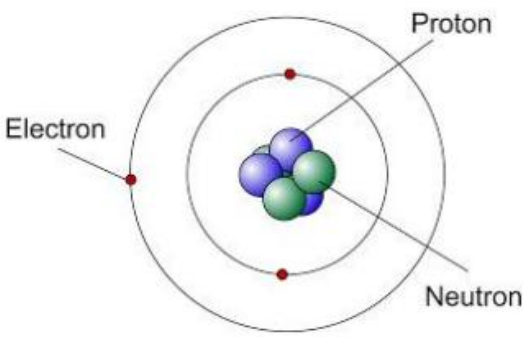
11 represent α- and β-decay by a radioactive decay equation of the form $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha$

12 use the unified atomic mass unit (u) as a unit of mass

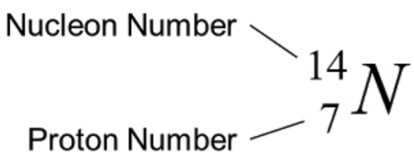


- **α-particle scattering** provided the proof of the structure of the atom.
- When α-particles are fired at thin gold foil, most of them go straight through but a small number bounce straight back.
- From this experiment Ernest Rutherford inferred that
  1) **a atom is mainly empty space** since most of the α-particles went straight through.
  2) **a positive nucleus is at the center** since some α-particles deflected through small angles of $<10^0$
  3) **the nucleus is extremely small, and this is where the mass and charge of the atom is concentrated** since only a small number of α-particles deflected straight back at angles $>90^0$




- Atoms of all elements are made up of three types of particles: **protons, neutrons, and electrons**.
- The proton number is the number of protons in an atom.

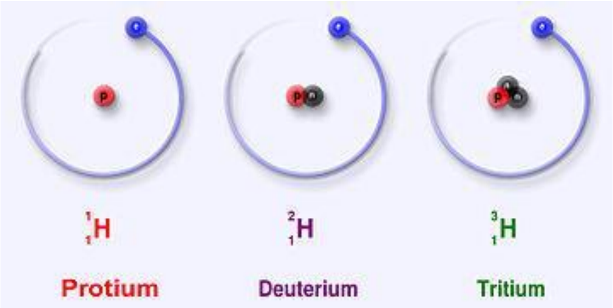



- Almost all the mass of an atom is concentrated in the nucleus.
- The nucleus consists of protons and neutrons.
- Their total number is called the nucleon number.

- Nuclear processes such as fission and fusion can be represented using nuclear equations.
- For e.g., the nuclear fission equation

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{90}_{38}Sr + ^{144}_{54}Xe + 2\,^{1}_{0}n$$

- From the equation above, you can see that the **nucleon number** and **charge** on the right and left side of the equation are always **conserved**.
- **Isotopes** are atoms of certain elements which have the same proton numbers but different nucleon numbers obviously because the number of neutrons is different.
- Isotopes have the same chemical properties but different physical quantities (eg. molecular mass, density, etc.).
- So think of protons as a type of atomic DNA.
- E.g., of isotopes
- Protium, Deuterium, Tritium are isotopes of the hydrogen element.




- Uranium-232, Uranium-233, Uranium-234, Uranium-235, Uranium-236, Uranium-237, Uranium-238 and Uranium-239 are isotopes of the uranium element.
- Since isotopes have an imbalance of neutrons and protons, they are unstable.
- To maintain stability, they emit radiation.
- Below are the three types of radiation and their properties

| | α | β | γ |
|---|---|---|---|
| **Charge** | Positive | Negative | No charge |
| **Ionization** | Strongest ionization | Less than α | Less than β |
| **Penetration** | Least | More than α | Most penetrating |
| **Protection** | A thick sheet of paper | A few millimetres of Perspex or aluminium | Several centimetres of lead |
| **Deflection in electric field** | Can be deflected | Can be deflected | Not deflected |
| **Deflection in magnetic field** | Can be deflected | Can be deflected | Not deflected |

- Also, all matter particles have **antimatter** counterparts.
- Antimatter are particles that are identical to their matter counterpart but with **opposite charge**.

| MATTER | CHARGE | ANTIMATTER | CHARGE |
|---|---|---|---|
| ELECTRON $e^-$ | −1 | POSITRON $e^+$ | +1 |
| PROTON p | +1 | ANTI-PROTON $\bar{p}$ | −1 |
| NEUTRON n | 0 | ANTI-NEUTRON $\bar{n}$ | 0 |

- Alpha (α) particles are high energy particles made up of 2 protons and 2 neutrons

$$^{4}_{2}\alpha \quad \text{OR} \quad ^{4}_{2}He$$

- Beta ($\beta^-$) particles are high energy electrons emitted from the nucleus (emitted by nuclei that have too many neutrons).
- Beta ($\beta^+$) particles are high energy positrons (antimatter of electrons) also emitted from the nucleus (emitted by nuclei that have too many protons).

| $^{0}_{-1}\beta$ | $^{0}_{+1}\beta$ |
|---|---|
| BETA MINUS | BETA PLUS |

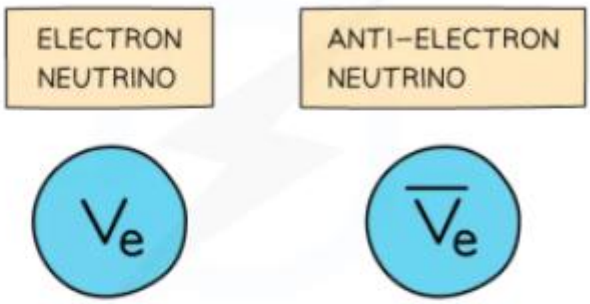
- Gamma (ϒ) rays are high energy electromagnetic waves.

$$^{0}_{0}\gamma$$

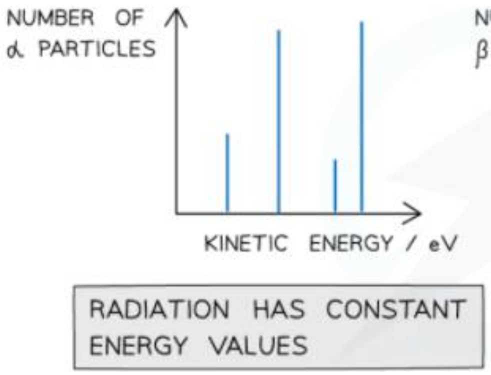
- If these particles hit other atoms, they can knock out electrons, ionizing the atom.

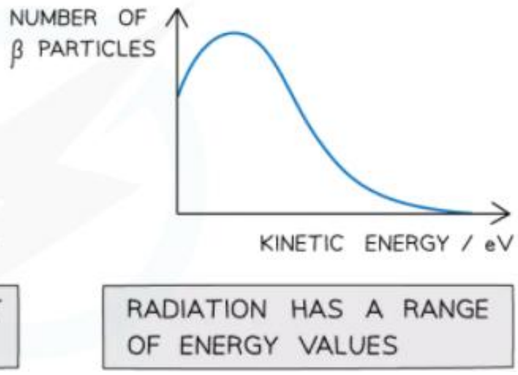
| Particle | Composition | Mass / u | Charge / e | Speed / c |
|---|---|---|---|---|
| Alpha ($\alpha$) | 2 protons + 2 neutrons | 4 | +2 | 0.05 |
| Beta minus ($\beta^-$) | Electron ($e^-$) | 0.0005 | −1 | > 0.99 |
| Beta plus ($\beta^+$) | Positron ($e^+$) | 0.0005 | +1 | > 0.99 |
| Gamma ($\gamma$) | Electromagnetic wave | 0 | 0 | 1 |

- An electron neutrino is a type of subatomic particle with no charge and negligible mass which is also emitted from the nucleus.
- Anti-neutrino is the antiparticle of a neutrino.
- Electron anti-neutrinos are produced during Beta ($\beta^-$) decays and electron neutrinos are produced during Beta ($\beta^+$) decays




- When the number of alpha (α) particles is plotted against kinetic energy,
- there are spikes that appear on the graph while beta particles shows a curve (see below).
- This shows that α particles have discrete energies while β have continuous energies.
- The energy released in beta decay is shared between the β particles and neutrinos.
- This indicates the presence of neutrinos.




- Below are steps to represent α and β using a radioactive decay equation

*Alpha decay*

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

1) During an alpha decay, a radioactive atom X decay and emits an alpha particle ($^{4}_{2}He$).
2) Atom X losses 2 neutron and 2 proton and become atom Y.
   e.g.

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

*Beta decay*

$$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e$$

1) A beta particle is an electron emitted from a nucleus.
2) The beta particles are very small and move with very high speed.
3) During a beta decay, a radioactive atom X decay and emits a beta particle ($_{-1}^{0}e$).
4) One of the neutron is disintegrated to become proton and electron. The electron is emitted out from the nucleus whereas the proton stay in the nucleus
5) Hence, the proton number goes up by 1 while the nucleon number remains unchanged.
   e.g.

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}_{-1}^{0}e$$

The unified atomic mass unit (u) is roughly equal to the mass of one proton or neutron:

$$1u = 1.66 \times 10^{-27}\ kg$$

- The mass of an atom in amu is approximately equivalent to the nucleon number.
- E.g., the amu for Carbon-12 is 12u

## 11.2 Fundamental particles

Candidates should be able to:

1 understand that a quark is a fundamental particle and that there are six flavours (types) of quark: up, down, strange, charm, top and bottom

2 recall and use the charge of each flavour of quark and understand that its respective antiquark has the opposite charge (no knowledge of any other properties of quarks is required)

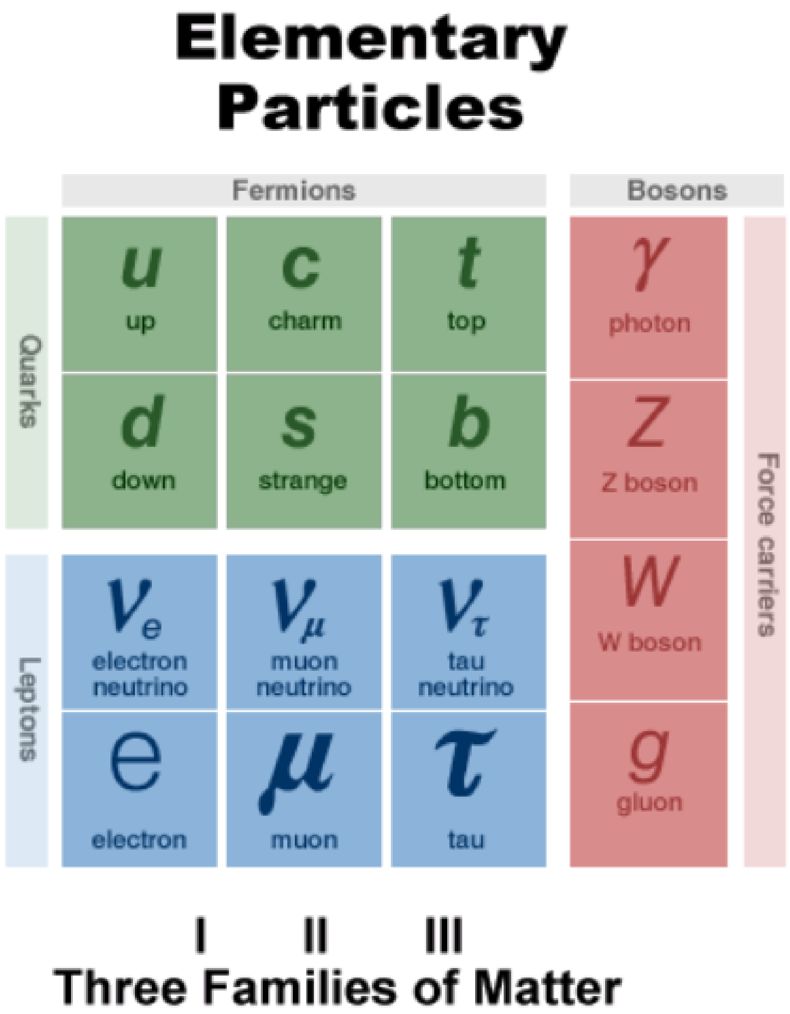
3 recall that protons and neutrons are not fundamental particles and describe protons and neutrons in terms of their quark composition

4 understand that a hadron may be either a baryon (consisting of three quarks) or a meson (consisting of one quark and one antiquark)

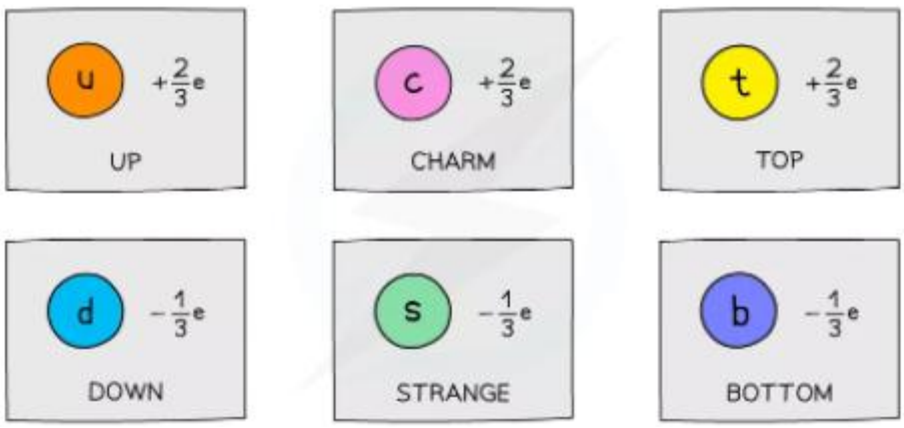
5 describe the changes to quark composition that take place during $\beta^-$ and $\beta^+$ decay

6 recall that electrons and neutrinos are fundamental particles called leptons

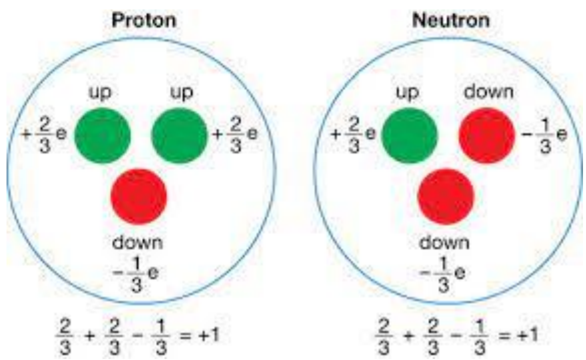
- Fundamental particles are particles that cannot be broken down into even smaller parts.



- An example of a fundamental particle are electrons.
- Quarks are **fundamental particles** that make up other subatomic particles such as protons and neutrons.
- Quarks are never alone.
- They are always in pairs or groups of three.
- There are six types of quarks (see diagram above).
- Protons and neutrons are a group of particles called hadrons.
- Hadrons are made up of quarks.
- There are two types of hadrons:
  1) Baryon (made up of three quarks)
  2) Mesons (made up of a quark and an anti-quark)
- The charge of a baryon (proton, anti-proton, neutron or anti-neutron) is determined by the sum of the charges of its quarks
- Each type of quark has a relative charge:

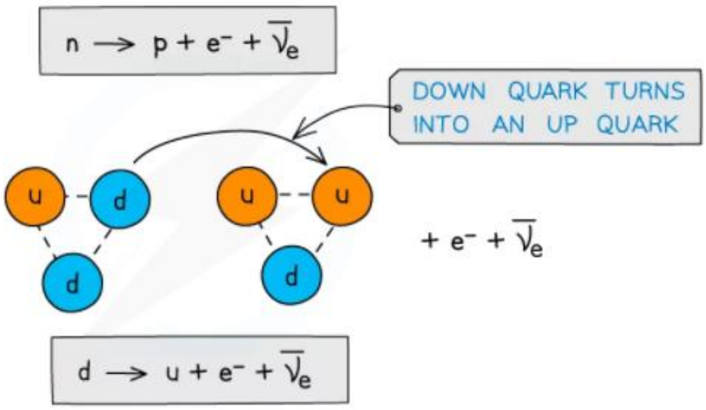



- E.g., a neutron has 0 charge hence it is made up of 1 up and 2 down quarks.




- The anti-particle of a quark is the anti-quark.


- Leptons are another group of fundamental particles.
- There also six leptons altogether (see diagram above).
- Neutrinos are the most commonly available leptons.
- The three types of neutrinos are electron, muon and tau.
- The muon and tau particle are very similar to the electron with a slight higher mass.
- Electrons, muon and tau have a charge of -1e and a mass of 0.0005u.
- A $\beta^-$ decay is when a neutron turns into a proton emitting an electron and anti-electron neutrino.
- In fundamental particle terms, this happens because a down quark turns into an up quark.




- A $\beta^+$ decay is when a proton turns into a neutron emitting a positron and an electron neutrino.
- In fundamental particle terms, this happens because an up quark turns into a down quark.