

Particle physics

A-Level Physics 9702 · Topic 11 revision notes · AS

Inside the atom and beyond: the nuclear model, nuclide notation, alpha, beta and gamma radiation, decay equations, quarks, hadrons and leptons.

20 definitions to learn word for word, 12 equations in their own column, 8 diagrams and graphs. Read it, cover it, test yourself.

1. 11.1a Alpha-particle scattering and the nuclear atom
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5. 11.2b Leptons and beta decay at quark level

■ Definitions (mark-scheme wording) ■ Equations ■ Exam traps

11.1a Alpha-particle scattering and the nuclear atom

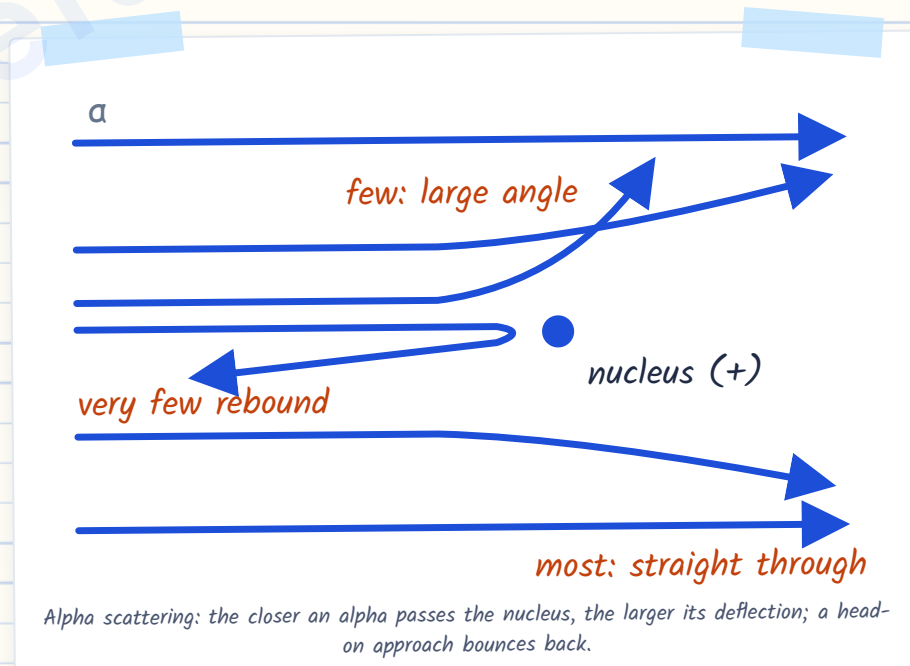
Definitions

Nucleus: the tiny, dense, positively charged centre of the atom containing almost all of its mass.

Nucleon: a proton or a neutron (a particle in the nucleus).

Key points

- ✓ Alpha particles fired at thin **gold foil** in a vacuum; detector moved round to count at each angle.
- ✓ **Most pass straight through:** the atom is mostly empty space.
- ✓ **A few deflect through large angles:** charge is concentrated in a small positive region that repels them.
- ✓ **Very few rebound** ($> 90^\circ$): the nucleus is very small but contains most of the mass.
- ✓ Nucleus diameter $\sim 10^{-15}$ m to 10^{-14} m; atom diameter $\sim 10^{-10}$ m.
- ✓ Electrons occupy the space around the nucleus; atom is neutral overall.



Watch out!

- ! The **few large deflections** show the nucleus is small and dense; the **many undeflected** show empty space. Do not swap the conclusions.
- ! Deflection is by electrostatic repulsion, not collision with electrons.

11.16 Nuclides, isotopes and nuclear equations

Definitions

Proton number (Z): the number of protons in the nucleus.

Nucleon number (A): the total number of protons and neutrons in the nucleus.

Nuclide: a nucleus with a particular number of protons and a particular number of neutrons.

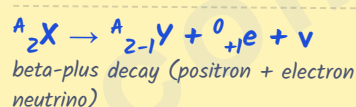
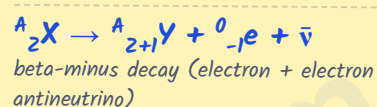
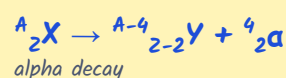
Isotopes: nuclei of the same element with the same number of protons but different numbers of neutrons.

Unified atomic mass unit (u): one twelfth of the mass of an atom of carbon-12; $1\text{ u} = 1.66 \times 10^{-27}\text{ kg}$.

Key points

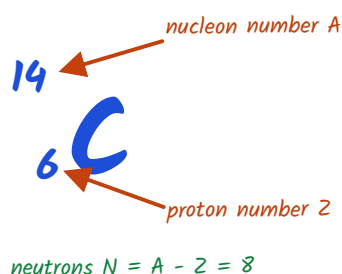
- ✓ Notation ${}^A_Z\text{X}$: nucleon number on top, proton number below; neutrons $N = A - Z$.
- ✓ Isotopes have the same **chemistry** (same electrons) but different nuclear stability.
- ✓ In every nuclear equation, **nucleon number and charge (proton number) are conserved**.
- ✓ Alpha decay: A falls by 4, Z falls by 2.
- ✓ Beta-minus decay: A unchanged, Z rises by 1 (a neutron becomes a proton).
- ✓ Beta-plus decay: A unchanged, Z falls by 1 (a proton becomes a neutron). Gamma: A and Z unchanged.

Equations

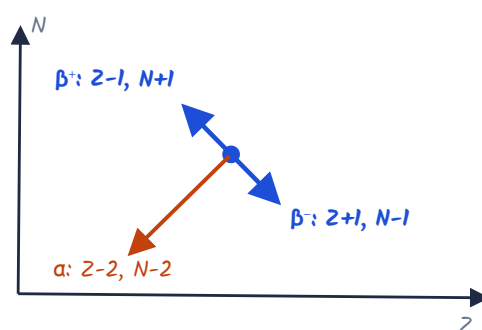


$$N = A - Z$$

number of neutrons



Nuclide notation for carbon-14: 6 protons, 14 nucleons, so 8 neutrons.



Decay on an N-Z chart: alpha moves 2 down and 2 left; beta-minus moves one neutron to a proton (down 1, right 1); beta-plus the reverse.

Watch out!

- ! Beta-minus **raises** Z by one; the electron is written ${}^0_{-1}\text{e}$ so the charges balance.
- ! Isotopes differ in **neutron** number, not proton number.

11.1c Alpha, beta and gamma radiation

Definitions

Alpha particle: a helium-4 nucleus: two protons and two neutrons, charge $+2e$.

Beta-minus particle: a fast-moving electron emitted from the nucleus, charge $-e$.

Beta-plus particle: a positron (the antiparticle of the electron) emitted from the nucleus, charge $+e$.

Gamma radiation: high-energy electromagnetic radiation (photons) emitted from the nucleus; no charge, no mass.

Antiparticle: a particle with the same mass as its partner but opposite charge (and other opposite quantum numbers).

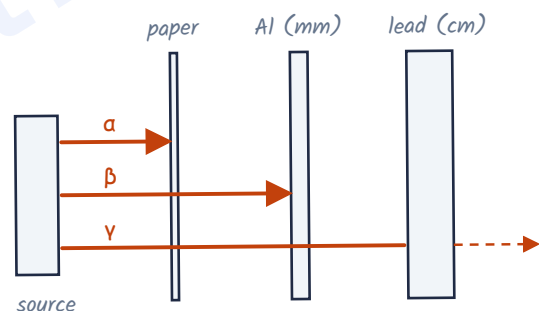
Equations

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

electronvolt used for particle energies
J

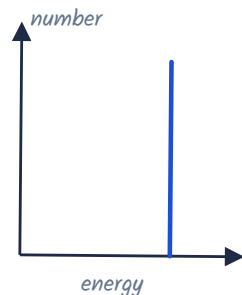
Key points

- ✓ Ionising power: α strongly, β moderately, γ weakly. Penetration is the reverse order.
- ✓ Stopped by: α a sheet of paper or a few cm of air; β a few mm of aluminium; γ reduced by several cm of lead.
- ✓ Speeds: α about $0.05c$; β up to about $0.99c$; γ travels at c .
- ✓ In a field, α and β are deflected in opposite directions; γ is undeflected.
- ✓ Alpha particles from one nuclide have **discrete** energies (a few MeV).
- ✓ Beta particles have a **continuous range** of energies because the (anti)neutrino carries away a variable share.

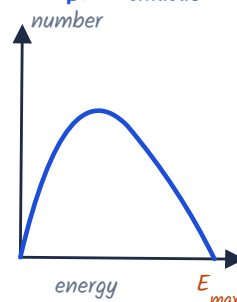


Penetration: paper stops alpha, a few mm of aluminium stops beta, several cm of lead only reduces gamma.

α : discrete



β : continuous



Energy spectra: alpha particles have a single discrete energy; beta particles have a continuous range up to a maximum.

Watch out!

- ! A continuous beta spectrum is the evidence for the **(anti)neutrino**; energy is shared between two particles.
- ! Gamma emission does not change A or Z; it follows another decay that leaves the nucleus excited.

11.2a Quarks and hadrons

Definitions

Fundamental particle: a particle that is not made of other particles (e.g. quarks, leptons).

Quark: a fundamental particle that combines with others to form hadrons; six flavours: up, down, strange, charm, top, bottom.

Hadron: a particle made of quarks (baryons and mesons).

Baryon: a hadron made of three quarks (e.g. proton, neutron).

Meson: a hadron made of a quark and an antiquark.

Equations

$$Q_u = +\frac{2}{3}e, Q_d = -\frac{1}{3}e$$

charges of up and down quarks
C

$$Q_p = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1e$$

proton (uud)
C

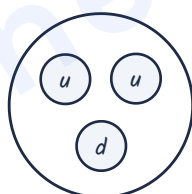
$$Q_n = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

neutron (udd)
C

Key points

- ✓ Up, charm, top: charge $+\frac{2}{3}e$. Down, strange, bottom: charge $-\frac{1}{3}e$.
- ✓ Each quark has an **antiquark** with the opposite charge (e.g. anti-up: $-\frac{2}{3}e$).
- ✓ Proton = **uud** (charge $+e$); neutron = **udd** (charge 0).
- ✓ Antibaryons are three antiquarks, e.g. antiproton = anti-u anti-u anti-d (charge $-e$).
- ✓ Mesons: quark + antiquark, e.g. $\pi^+ = u + \text{anti-d}$ (charge $+e$).
- ✓ Hadron charges are always **whole numbers** of e ; quarks are never found alone.
- ✓ Protons and neutrons are **not fundamental**.

charge $+1e$

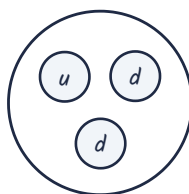


proton = uud

$$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$$

Quark content: uud gives $+1e$ (proton); udd gives 0 (neutron). Three quarks each, so both are baryons.

charge 0



neutron = udd

$$\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

quarks

u up	c charm	t top	$+\frac{2}{3}e$
d down	s strange	b bottom	$-\frac{1}{3}e$

antiquarks: opposite charge

The six quark flavours and their charges; antiquarks have the opposite charge.

Watch out!

- ! A meson is a quark and an **antiquark**, not two quarks.
- ! Down quark charge is $-\frac{1}{3}e$, not $-\frac{2}{3}e$; check that uud sums to exactly $+1$.

11.2b Leptons and beta decay at quark level

Definitions

Lepton: a fundamental particle that is not made of quarks, e.g. the electron and the (electron) neutrino.

Neutrino: a lepton with no charge and almost zero mass, emitted in beta decay.

Weak interaction: the fundamental interaction responsible for beta decay (changing one quark flavour into another).

Key points

- ✓ Leptons (electron, neutrino) and quarks are **fundamental**.
- ✓ Beta-minus: a **down quark becomes an up quark**, so udd (neutron) becomes uud (proton).
- ✓ Beta-plus: an **up quark becomes a down quark**, so uud (proton) becomes udd (neutron).
- ✓ Beta-minus emits an electron and an **electron antineutrino**; beta-plus emits a positron and an **electron neutrino**.
- ✓ Charge is conserved at quark level: $-\frac{1}{3} = +\frac{2}{3} + (-1) + 0$.
- ✓ Beta decay is caused by the **weak interaction**.

Equations

$$d \rightarrow u + e^- + \bar{\nu}$$

beta-minus at quark level

$$u \rightarrow d + e^+ + \nu$$

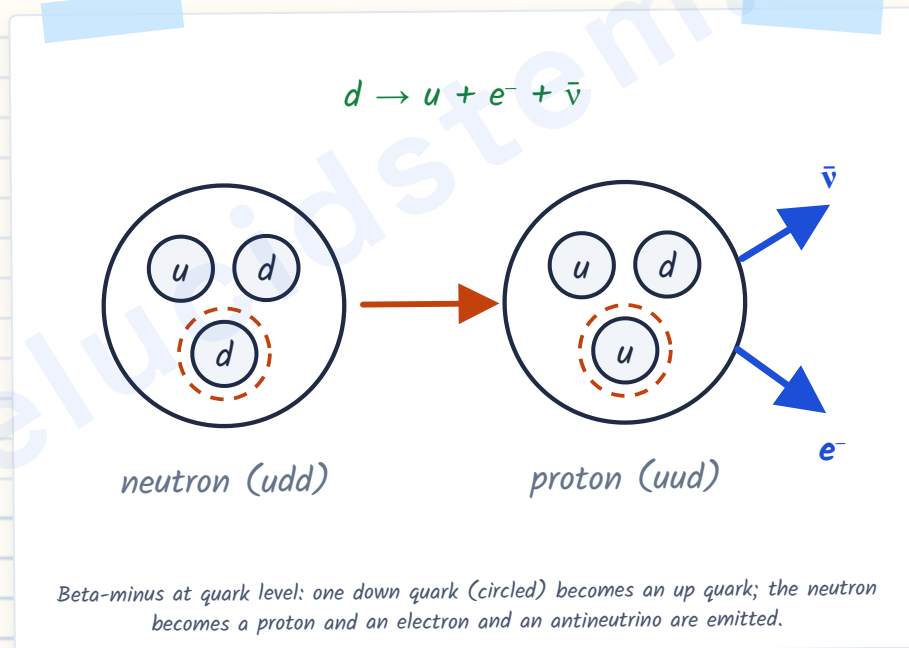
beta-plus at quark level

$$n \rightarrow p + e^- + \bar{\nu}$$

beta-minus at nucleon level

$$p \rightarrow n + e^+ + \nu$$

beta-plus at nucleon level



Watch out!

- ! Match the neutrino to the decay: beta-minus with the **antineutrino**, beta-plus with the **neutrino**.
- ! Electrons are leptons: they are **not** made of quarks and not found in the nucleus before the decay.