Unit 21 · Nuclear Chemistry and Applications of Radioactivity

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Applied Chemistry (Units 18–21 together): 8 of 75 marks; 3 MCQs and 1 short question, no long one
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** MCQ: rays passed between charged plates (+ above, − below): α bends to the **− plate**, β to the **+ plate** (more), γ goes **straight**
- **MCQ (1 mark)**
  - C-14 for dating; α least penetrating; reactors run on fission; α is ${}^{4}_{2}\mathrm{He}$; fusion; per kg fusion most energy
  - SI unit becquerel; U-235 fuel; an artificial radioisotope; not given out naturally (a positron)
  - after α then 2β from U-238: same element, A − 4; I-131 after 24 days: 1/8; Co-60's γ rays
- **Short (5 marks, in parts)**
  - radioactivity and its units; nuclear vs chemical reaction; natural vs artificial, each with an example and use
  - fission vs fusion; why fusion isn't used yet; controlled vs uncontrolled; Pu-239 fission sketch; C-12 + C-12; C-14 formation
  - nuclear power, for and against; weapons; uses of Co-60, I-131, Na-24, F-18; harmful effects; radiocarbon dating; α, β, γ compared

Key terms

Radioactivity: spontaneous breakdown of an unstable nucleus, giving out α, β or γ radiation (Becquerel, 1896).

Transmutation: one element changed into another (the **nucleus** changes).

Isotopes: same Z, different A; **radioisotope**: a radioactive one.

Natural radioactivity: spontaneous, in nuclei found in nature (U-238, Th-232, Ra-226, Po-210, K-40, C-14).

Artificial (induced) radioactivity: made in a stable nucleus by bombarding it (n, α, p) (Joliot-Curies, 1934).

Fission: heavy nucleus splits into two lighter ones + 2–3 neutrons + about 200 MeV; **chain reaction**.

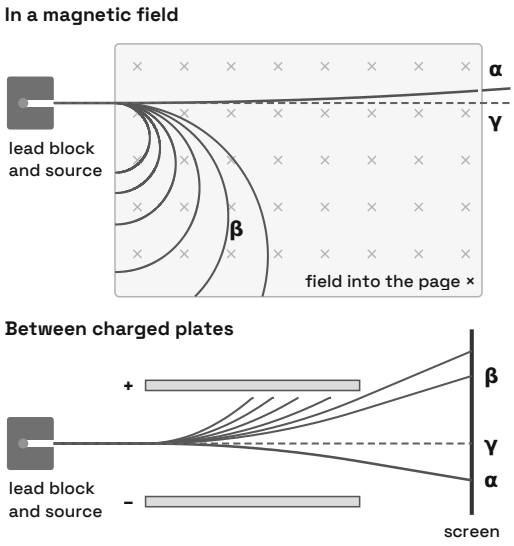
Fusion: light nuclei join at tens of millions of degrees; not a chain reaction.

Half-life: time for half the nuclei to decay.

α, β and γ

	α	β	γ
nature	He nucleus (2p + 2n)	fast electron from the nucleus	electromagnetic (photons)
symbol	${}^{4}_{2}\mathrm{He}$	${}^{0}_{-1}\mathrm{e}$	γ
charge, mass	+2, 4 u	−1, 1/1840 of H	0, 0
ionizing	greatest	about 1/100 of α	least, about 1/10,000
penetrating	least: paper, few cm air	few mm aluminium	greatest: thick lead, concrete
speed	about 1/20 c (5–7%)	up to 99% of c	c

- in a field: α and β bend **opposite** ways (α to −, β to +), β much more; γ straight on



α, β and γ in a magnetic field and between charged plates.

Unit of activity	
becquerel (Bq), SI	1 disintegration per second
curie (Ci)	3.7×10^{10} dps (1 g Ra-226)
rutherford (Rd)	10^6 dps

Nuclear equations

- **mass numbers (top) and atomic numbers (bottom) both balance**
- α: A − 4, Z − 2; β^-: A same, Z + 1 (n → p); β^+ ${}^{0}_{+1}e$: Z − 1 (p → n); γ: no change
- U-238, one α then two β^-: ${}^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}Th \xrightarrow{\beta} {}^{234}_{91}Pa \xrightarrow{\beta} {}^{234}_{92}U$: same element, A 4 less
- ${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$ (natural; chain of 14 decays to Pb-206, half-life 4.47 billion years: dates rocks)
- ${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$ (half-life 5,730 years)

Artificial

- ${}^{27}_{13}Al + {}^{1}_{0}n \longrightarrow {}^{24}_{11}Na + {}^{4}_{2}He$; ${}^{24}_{11}Na \longrightarrow {}^{24}_{12}Mg + {}^{0}_{-1}e$ (15.0 h)
- ${}^{27}_{13}Al + {}^{4}_{2}He \longrightarrow {}^{30}_{15}P + {}^{1}_{0}n$; ${}^{30}_{15}P \longrightarrow {}^{30}_{14}Si + {}^{0}_{+1}e$ (2.5 min; Joliot-Curies)
- ${}^{131}_{53}I \longrightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$ (8.0 days; from Te-130 + n)
- N-14 + n → C-14 (+ p); P-31 + n → **P-32**; Co-59 + n → **Co-60**; I-127 + n → **I-128** (25 min)
- N-14 + α → O-17 + p (Rutherford, 1919): transmutation, but O-17 is **stable**

Natural radioactivity	Artificial radioactivity
spontaneous, in nature	started by bombarding a stable nucleus
U-238, Ra-226, C-14	Na-24, P-30, Co-60, I-131
Becquerel, 1896	Joliot-Curies, 1934
dating (C-14, U–Pb), groundwater (tritium)	medicine, industry, Pu-239 fuel

Nuclear reaction	Chemical reaction
the **nucleus** changes: new element	only outer electrons; elements stay
huge energy (MeV per nucleus)	small (eV per bond)
rate not changed by temperature, catalyst	changed by them
isotopes behave differently	isotopes react alike

Fission and fusion

- ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n$ + about **200 MeV**
- also ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{95}_{38}Sr + {}^{139}_{54}Xe + 2{}^{1}_{0}n$ (100+ pairs)
- ${}^{239}_{94}Pu + {}^{1}_{0}n \longrightarrow {}^{140}_{54}Xe + {}^{97}_{40}Zr + 3{}^{1}_{0}n$
- **controlled**: each fission causes one more (control rods of B or Cd absorb neutrons; moderator water or graphite): reactor; **uncontrolled**: more than one each: bomb
- ${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$ + **17.6 MeV** (D–T, fusion reactors)
- D + D → ${}^{3}_{2}He + {}^{1}_{0}n$ or ${}^{3}_{1}H + {}^{1}_{1}H$; ${}^{3}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + 2{}^{1}_{0}n$
- ${}^{12}_{6}C + {}^{12}_{6}C \longrightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$
- C-14 in the air: ${}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{14}_{6}C + {}^{1}_{1}H$

	Fission	Fusion
what	heavy nucleus splits	light nuclei join
start	slow neutron	tens of millions of degrees
chain reaction	yes (neutrons)	no (heat keeps it going)
energy	**more per reaction** (200 MeV)	**more per kg** (about 4×: 3.4×10^{14} against 8.2×10^{13} J/kg)
waste	long-lived radioactive	little; fuel in sea water
use	power stations, Mo-99, submarines, atom bombs	Sun, hydrogen bombs; reactors not yet

- fusion not yet used: fuel must be held at 100+ million °C (plasma, magnets) and give out more energy than it takes

- nuclear power: about a tenth of the world's electricity (8.9%, 2025); U-235, Pu-239 bred from U-238
  - for: little CO_2; tiny fuel; steady day and night; fewer deaths than coal, oil, gas
  - against: accidents; waste for thousands of years; costly, slow; weapons
- weapons: **fission** (U-235, Pu-239; Hiroshima, Nagasaki); **fusion** (hydrogen bomb, started by a fission bomb)

Uses

Radioisotope	Use
Co-60 (γ 1.17, 1.33 MeV)	radiotherapy (teletherapy); sterilizing syringes, gloves; radiography
I-131 (8.0 days)	thyroid: overactive, cancer (β kills cells, γ counted)
Na-24 (15 h)	leaks in buried pipes; blood circulation
F-18 (110 min)	PET scans (positrons)
Tc-99m (6.0 h, 140 keV γ)	imaging: gamma camera, SPECT
Ir-192 (74 days)	brachytherapy; weld radiography
Cs-137 (30 years)	blood irradiators
Pu-238 (87.7 years)	RTGs: Voyager, Curiosity, Perseverance
Am-241	ionization smoke detectors (α)
Kr-85, Sr-90	thickness gauges (β)
Fe-59; S-35, P-32	iron metabolism; labeling proteins, DNA (Hershey–Chase)

- sterilized items do **not** become radioactive; CT uses **X-rays**, not a radioisotope

Radiocarbon dating

- C-14 made in the air, $^{14}CO_2$ → plants → animals; alive, the same share as air; dead, it decays
- $t = \frac{t_{1/2}}{\log 2} \log \frac{N_0}{N} = \frac{2.303}{\lambda} \log \frac{N_0}{N}$, **t½ = 5,730 years** (exams; data tables 5,700 ± 30)
- 25% left = two half-lives = **11,460 years**; 70.0% left: $5730/0.3010 \times \log(1/0.700) \approx 2{,}950$ years
- I-131: 24 days = 3 half-lives: **1/8** left
- once-living things up to about 50,000 years; rocks by U–Pb, K–Ar

Harmful effects

- **ionizing**: breaks bonds, makes ions, free radicals: damages cells and **DNA** (mutations)
- cancer (leukemia, thyroid); burns and **radiation sickness** (nausea, hair loss, bleeding; death above a few Sv); infertility, birth defects; weaker immunity (bone marrow); contaminated food chains (Cs-137, Chernobyl)
- dose in **sieverts**: background about 2.4 mSv a year; chest X-ray 0.1 mSv; protect by **time, distance, shielding**

COMMON MISTAKES

✗ Al-27 + n → Na-23
✓ **Na-24** + α (A: 28 = 28; Z: 13 = 13).

✗ Al-27 + n → P-30
✓ Al-27 + α → P-30 + n.

✗ N-14 + α → O-17 + p is artificial radioactivity
✓ transmutation; O-17 is stable.

✗ P-31 + n → S-32; I-127 + n → I-131
✓ **P-32**, **I-128** (neutron capture keeps the element).

✗ U-238 α decay is fission
✓ it only throws out a helium nucleus.

✗ D + D → He-4
✓ He-3 + n, or T + p.

✗ fusion gives more energy per reaction
✓ fission per reaction; fusion **per kg**.

✗ α at 1/10 the speed of light
✓ about **1/20**.

✗ Pu-239 → Xe-140 + Sr-94
✓ Z adds to 92; **Zr-97**.