Unit 6 · Atomic Structure

STUDY NOTES

Key terms

Cathode rays: fast electrons from the cathode of a discharge tube (very low pressure, high voltage).

Canal rays: positive rays through holes in the cathode; atoms of the gas with electrons knocked off.

Nucleons: protons + neutrons.

Atomic number Z: protons in the nucleus (= electrons in a neutral atom); decides the element.

Mass number A: protons + neutrons; always whole.

1 u (amu): 1/12 of the mass of one carbon-12 atom = 1.6605×10^{-27} kg.

Relative atomic mass: average mass of an element's atoms ÷ (1/12 of a carbon-12 atom); no unit.

Isotopes: same Z, different A (different neutrons).

Isobars: same A, different Z; different elements.

Isotones: same N, different Z, different A.

Stationary orbit (shell, energy level): allowed orbit where an electron doesn't radiate.

Formulas

$N = A - Z$	N neutrons, A mass number, Z atomic number **Use:** counting particles; ion: only electrons change
$mvr = \frac{nh}{2\pi}$	m, v, r electron's mass, speed, orbit radius; $n = 1, 2, 3\ldots$; $h = 6.626 \times 10^{-34}$ J s **Use:** Bohr's allowed orbits
$\Delta E = E_2 - E_1 = h\nu$	ν frequency of the light **Use:** energy of a jump
$E_n = -\frac{13.6}{n^2}$ eV	1 eV = 1.602×10^{-19} J; negative = bound **Use:** hydrogen's levels
average = $\frac{m_1\%_1 + m_2\%_2}{100}$	m isotope's mass, % its share **Use:** average atomic mass; backward: let one be x %, the other $(100 - x)$ %

- each shell holds at most $\mathbf{2n^2}$
  - K 2
  - L 8
  - M 18
  - N 32
- lower shells fill first
- symbol: ${}^{A}_{Z}\mathrm{X}$, e.g. ${}^{23}_{11}\mathrm{Na}$: 11 p, 11 e, 12 n; Na^+: 11 p, 12 n, 10 e

6.1 Dalton's atomic theory (1803; book 1808)

Laws behind it:

- **Conservation of mass** (Lavoisier, 1789): products' total mass = reactants'
- **Constant proportions** (Proust, 1797): a compound has the same elements in the same proportion by mass (water: 8 g O per 1 g H)
- **Multiple proportions** (Dalton's own prediction): two elements, several compounds → masses of one with a fixed mass of the other in a simple ratio (12 g C with 16 g and 32 g O: 1 : 2)

Postulate	Modified
indivisible atoms, smallest unit of an element	made of e^-, p^+, n^0; still smallest particle in a **chemical** reaction
one element: alike in mass; different elements: different	**isotopes** (Cl-35, Cl-37); **isobars** (Ar-40, Ca-40); identity = number of protons
combine in simple whole-number ratios	many complex: $C_{12}H_{22}O_{11}$, starch
keep identity; not created or destroyed	true in chemical reactions; **nuclear** reactions: transmutation, a little mass → energy

- postulate 4 → conservation of mass; postulates 2, 3 → constant proportions

6.2 Subatomic particles

	Electron	Proton	Neutron
found by	Thomson, 1897	Goldstein (canal rays), 1886; named Rutherford, 1920	Chadwick, 1932
where	round nucleus	nucleus	nucleus
charge (C)	-1.602×10^{-19}	$+1.602 \times 10^{-19}$	0
mass (kg)	9.109×10^{-31}	1.6726×10^{-27}	1.6749×10^{-27}
mass (u)	0.000549	1.00728	1.00866
relative charge, mass	−1, 1/1836	+1, 1	0, 1

Properties of cathode rays

- straight lines from the cathode; sharp shadow
- bend toward the + plate, and in a magnetic field → **negative**
- glass, zinc sulphide glow where they strike
- heat thin foil; pass through very thin foil
- make **X-rays** at a metal target (Röntgen, 1895)
- same for any gas or cathode metal

How each was found

- **Thomson**: e/m (today 1.76×10^{11} C/kg) > 1000 × hydrogen ion's; same in every gas → part of **every** atom; plum pudding model (1904)
- **Millikan** (from 1909): oil drops → e, so the electron's mass
- **Canal rays**: e/m changes with the gas; largest for hydrogen
- **Rutherford** (1919): alpha into nitrogen → hydrogen nuclei out; named the proton
- **Chadwick**: alpha on beryllium → neutral radiation knocks protons out of paraffin wax → mass ≈ proton's
- helium: 2 protons but ≈ 4 × hydrogen's mass → needed neutrons

6.3 Rutherford's model (1909–1911)

Setup: radioactive source in lead box with a slit → alpha beam (He nucleus, charge +2) → thin gold foil (≈ 300 atoms thick) → zinc sulphide screen flashes, counted through a moving microscope; evacuated box.

Observation	Conclusion
most pass straight	most of the atom is **empty space**
a few: large angles	+ charge packed in a tiny region; repels
very few bounce back (platinum: 1 in 8,000)	that region, the **nucleus**, very small and heavy

Postulates

- small, dense, positive **nucleus** with all + charge, almost all mass
- nucleus 10^{-15}–10^{-14} m; atom ≈ 10^{-10} m
- electrons orbit like planets (**planetary model**); attraction holds them
- electrons = positive charge units → neutral; mostly empty

Limitations

- **stability**: circling charge accelerates, radiates, spirals in (hydrogen: 1.6×10^{-11} s); atoms last billions of years
- **line spectra**: spiral would give every color; hydrogen gives sharp colors
- no arrangement of electrons

6.4 Bohr's model (1913)

Postulates

1. only fixed circular orbits: stationary orbits, $n = 1, 2, 3\ldots$ (K, L, M, N)
2. in an orbit: **no energy given out**
3. each orbit fixed energy: $E_1 < E_2 < E_3 \ldots$
4. allowed only if $mvr = \dfrac{nh}{2\pi}$
5. energy only in **jumps**: $\Delta E = E_2 - E_1 = h\nu$; inward gives out, outward takes in exactly that

Hydrogen

- radius $\propto n^2$: 1 : 4 : 9 : 16; first orbit 0.053 nm
- $E_1 = -13.60$ eV
- $E_2 = -3.40$ eV
- $E_3 = -1.51$ eV
- $E_4 = -0.85$ eV
- 3 → 2: 1.89 eV = 3.03×10^{-19} J, red, 656 nm
- bigger jump → higher frequency

Merits:

- atoms stable
- hydrogen's line spectrum calculated
- hydrogen's size and 13.6 eV to remove the electron
- shells and $2n^2$

Limitations:

- one-electron atoms or ions only (H, He^+, Li^{2+})
- can't explain lines that are pairs or split in a magnetic field
- no fixed track (since 1926: electron cloud, **orbital**)

Rutherford	Bohr
orbits of any size	only fixed orbits, fixed energies
electron should radiate, fall in	no radiation in an orbit; energy only in jumps
can't explain stability, line spectra	explains stability, hydrogen's spectrum

6.5 Isotopes, isobars, isotones

	Z	N	A	same element?
Isotopes	same	different	different	yes
Isobars	different	different	same	no
Isotones	different	same	different	no

- isoto**p**es: **p**rotons; isoto**n**es: **n**eutrons; isob**a**rs: m**a**ss number
- **isotopes**
  - H-1 protium, H-2 deuterium (D), H-3 tritium (T)
  - C-12, 13, 14
  - Cl-35, 37
  - U-235, 238
- **isobars**: Ar-40, K-40, Ca-40; C-14, N-14
- **isotones**
  - C-14, N-15, O-16 (8 each)
  - Na-23, Mg-24 (12)
  - K-39, Ca-40 (20)

Properties of isotopes

- same chemistry: same electrons (D_2O still puts out fires)
- slightly different physical properties: density, boiling point, diffusion (D_2O boils at 101.4 °C, ≈ 11% denser)
- some stable, some radioactive (C-14, tritium, U-235)
- same place in the periodic table (*isos* + *topos*)

Uses

- C-14: dating, up to about 50,000 years
- Co-60: gamma rays kill cancer cells; sterilize equipment
- I-131: thyroid diseases
- U-235: nuclear fuel (0.7% of natural uranium)
- D_2O: slows neutrons in reactors

Average atomic mass

- Cl: 75.76% Cl-35 (34.969 u), 24.24% Cl-37 (36.966 u) → **35.45**; with mass numbers 35.48 (exams: 35.5)
- no atom has mass 35.45; average of a crowd

COMMON MISTAKES

✗ mass number = atomic mass
✓ A counts particles (whole); atomic mass is a measured average, rarely whole.

✗ ion's neutrons or protons change
✓ only electrons: Mg^{2+} 10 e, O^{2-} 10 e.

✗ isobars behave alike
✓ different elements, different electrons; isotopes behave alike.

✗ E from the difference in n
✓ subtract the two levels' energies.

✗ jumping outward gives out light
✓ outward takes in; inward gives out.

✗ alpha bounce shows empty space
✓ passing straight shows empty space; bounce shows the nucleus.

✗ electron circles a neat track
✓ shells are energy levels; electron cloud.