



Topic E.4

NUCLEAR FISSION

*Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference*

Topics Covered

Nuclear fission
Chain reactions & criticality
Reactor components
Energy calculations
Safety & environment

Exam Relevance

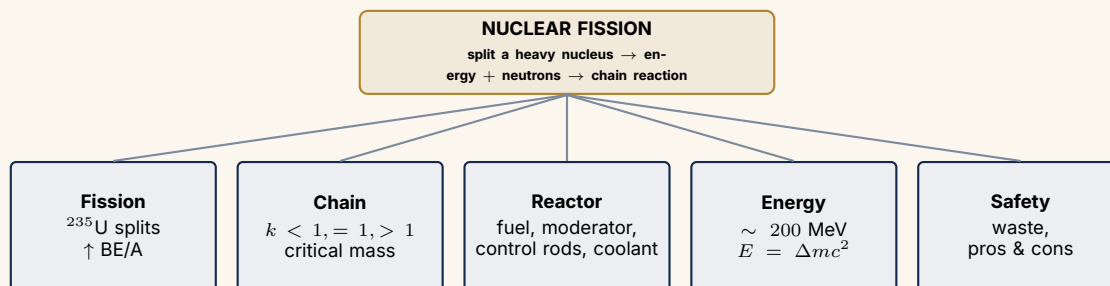
P1 & P2 (SL + HL)
200 MeV per fission
 k : sub/critical/super
 $E = \Delta mc^2$
Waste & thermal pollution

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The Big Picture — How E.4 Fits Together

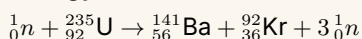


§1 — Nuclear Fission

E.4 SL & HL

Definition

Fission: A heavy nucleus absorbs a slow (thermal) neutron and splits into two lighter nuclei (fission fragments) plus 2–3 neutrons and energy.



Conservation Laws

In every nuclear reaction:

- Mass number A is conserved
- Proton number Z is conserved
- Energy-mass is conserved

TRICK Always check both A and Z when balancing fission equations. Set up simultaneous equations if two unknowns.

TRAP Do NOT confuse “fission” (heavy $\rightarrow$ light) with “fusion” (light $\rightarrow$ heavy). Both release energy but by moving toward higher BE/nucleon.

Binding Energy & Fission

Fission releases energy because products have **higher BE/nucleon** than U-235.

Energy released: $E = BE_{\text{products}} - BE_{\text{reactants}}$

U-235: $BE/A \approx 7.6 \text{ MeV}$

Fragments: $BE/A \approx 8.4 \text{ MeV}$

$\Rightarrow E \approx 200 \text{ MeV}$ per fission

NOTE Iron-56 has the highest BE/nucleon (8.79 MeV). Nuclei on either side can release energy by moving toward Fe-56.

FROM THE PHOTON QUESTION BANK

Conserve *both* A and Z when balancing; justify energy release as “products have higher BE/nucleon”, not just “mass lost”.

§2 — Chain Reactions

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Multiplication Factor k

$$: k = \frac{\text{neutrons in gen } (n+1)}{\text{neutrons in gen } n}$$

- $k < 1$: subcritical (reaction dies)
- $k = 1$: critical (steady reactor)
- $k > 1$: supercritical (bomb)

TRICK For k : count neutrons available for fission only. Subtract neutrons lost (absorbed by control rods) and those escaping through walls from total produced.

TRICK Two ways to steer the chain: the number k (keep $= 1$ for a reactor) is physically set by two parts — the *mod-*

erator slows neutrons (raises k), *control rods* absorb them (lower k).

Critical Mass (HL)

Critical mass = minimum mass for sustained chain reaction ($k \geq 1$).

Determined by competition:

- Fission $\propto$ volume $\propto r^3$
- Leakage $\propto$ surface area $\propto r^2$

Larger mass $\Rightarrow$ smaller leakage fraction.

TRAP Critical mass is NOT the mass at which fission starts. Fission occurs in a single atom. Critical mass is about *sustaining* the chain reaction.

§3 — Nuclear Reactor Components

E.4 SL & HL
Component Summary Table

Component	Function	Example materials
Fuel rods	Contain fissile material; site of fission	Enriched U-235 (~3–5%)
Moderator	Slows fast neutrons to thermal energies by elastic collisions	Water (H ₂ O), heavy water (D ₂ O), graphite
Control rods	Absorb neutrons to regulate reaction rate; fully inserted $\rightarrow$ shutdown	Boron, cadmium, hafnium
Heat exchanger	Transfers thermal energy from coolant to secondary water circuit	Pressurised water, CO ₂
Containment	Shields environment from radiation	Concrete, lead, steel

TRICK Moderator atoms should be **light** (similar mass to neutron $\Rightarrow$ maximum energy transfer per collision) and **poor neutron absorbers**.

TRAP Statement “the heat exchanger slows neutrons” is **WRONG**. The moderator slows neutrons. The heat exchanger only moves thermal energy to produce steam.

FROM THE PHOTON QUESTION BANK

Top-tested skill: *distinguish moderator (slows neutrons) from control rods (absorb neutrons)*. Also know the chain nuclear $\rightarrow$ thermal $\rightarrow$ kinetic $\rightarrow$ electrical.

PWR — Two Water Circuits

In a pressurised water reactor, water is **both moderator and coolant**, kept liquid by a **pressuriser**:

- **Primary circuit:** radioactive water, core $\rightarrow$ steam generator (heat exchanger).
 - **Secondary circuit:** clean water boiled to steam $\rightarrow$ turbine $\rightarrow$ condenser; never touches the core.
- Overall efficiency $\approx$ 30–40% (waste heat lost to environment).

§4 — Energy Calculations

E.4 SL & HL (Quantitative: HL)
Key Formulae

Mass defect: $\Delta m = Zm_p + (A - Z)m_n - m_{\text{nucleus}}$

Energy from mass defect: $E = \Delta m \cdot c^2$

Useful conversion: $1 \text{ u} \equiv 931.5 \text{ MeV}$

Power from mass loss: $P = \dot{m} c^2$

Energy from fission rate: $P = R \cdot E_{\text{fission}}$

atomic masses can be used directly.

TRICK When using atomic masses (not nuclear masses), the electron masses cancel in the subtraction for Δm , so

TRICK Two ways to see the **~200 MeV**: climb the BE/A curve (products more tightly bound) or mass defect $E = \Delta mc^2$ — same energy, counted two ways.

Energy Density Comparison

Fuel	Energy / MJ kg ⁻¹
Coal	≈ 30
Oil	≈ 45
Enriched U (3%)	≈ 5 × 10 ⁶
Pure U-235	≈ 8 × 10 ⁷

Nuclear ≈ 10⁵–10⁶ × fossil fuels.

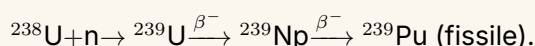
NOTE $E \approx 200 \text{ MeV}$ per U-235 fission = $3.2 \times 10^{-11} \text{ J}$.
Use this if exact masses not given.

FROM THE PHOTON QUESTION BANK

$\Delta m > 0 \Rightarrow$ energy released; $1 \text{ u} \equiv 931.5 \text{ MeV}$. Power:
 $P = R E_{\text{fission}}$ or $P = \dot{m} c^2$ — convert $\text{mg h}^{-1} \rightarrow \text{kg s}^{-1}$
first, then apply efficiency.

§6 — Fuel, Reprocessing & Weapons
E.4 SL & HL
Enrichment & Reprocessing

- Natural U is $< 1\%$ ²³⁵U $\Rightarrow$ **enriched** to ~3–5% for reactor fuel.
- Reprocessing**: recover unused U and bred Pu-239 from spent fuel; separate waste.

Breeding Pu-239 & Weapons


Reactor = **controlled** ($k = 1$); weapon = **uncontrolled** ($k \gg 1$). Enrichment/reprocessing $\Rightarrow$ proliferation risk.

TRAP Fast **breeder** reactor makes more fissile fuel (Pu-239 from U-238) than it burns — don't confuse "breeder" with "moderator".

§5 — Safety & Environment
E.4 SL & HL
Advantages

- Very high energy density
- Low CO₂ during operation
- Reliable baseload (weather-independent)
- Small land footprint

Disadvantages / Risks

- Long-lived radioactive waste (HLW)
- Meltdown / accident risk
- Thermal pollution (aquatic ecosystems)
- High construction cost
- Proliferation risk
- Uranium mining damage

TRAP "Nuclear power produces no pollution" is WRONG in IB exams. It produces radioactive waste and thermal pollution. Say: low *carbon* emissions, not pollution-free.

Five-Step Method for Fission Energy Calculations (HL)

- Write balanced equation and identify all species.
- Find $\Delta m = m_{\text{reactants}} - m_{\text{products}}$ (in u).
- Convert: $E = \Delta m \times 931.5 \text{ MeV}$ (or $\times c^2$ in SI).
- Convert to joules if needed: $\times 1.602 \times 10^{-13}$.
- Scale to power: $P = R \times E_{\text{fission}}$ or $P = \dot{m} c^2$.