IB DP PHYSICS · THEME E NUCLEAR AND QUANTUM PHYSICS · E.4 · ~5 MIN READ

E.4 Fission

Spontaneous and neutron-induced fission, the energy released, chain reactions and critical mass, the parts of a nuclear power station (fuel, moderator, control rods, coolant, heat exchanger, shielding), and nuclear waste.

Fission | Energy released | Chain reaction | Critical mass | Moderator & control rods | Heat exchanger | Shielding | Nuclear waste

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- In **fission** a heavy nucleus (uranium-235, plutonium-239) splits into two lighter nuclei and a few neutrons. It can be **spontaneous** or **induced** by absorbing a neutron.
- The products have a higher **binding energy per nucleon**, so the total mass falls and about **200 MeV** is released per fission, mostly as kinetic energy of the fragments.
- The released neutrons can cause further fissions: a **chain reaction**. Above the **critical mass** it is self-sustaining.
- A reactor controls the chain reaction with a **moderator** (slows neutrons), **control rods** (absorb neutrons) and removes the heat with a **coolant** and **heat exchanger**.
- **E.4 is the same at SL and HL.**

BY THE END YOU CAN

- Describe spontaneous and neutron-induced fission and write balanced fission equations.
- Explain the energy released using binding energy and mass defect.
- Explain chain reactions and critical mass.
- Describe the roles of fuel, moderator, control rods, coolant, heat exchanger and shielding.
- Discuss the advantages and problems of nuclear power, including waste.

Riyaz Sir

1 Fission

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$

a typical induced fission: A and Z both balance

- **Thermal neutrons:** U-235 captures slow ("thermal") neutrons far more readily than fast ones, which is why reactors need a moderator.
- **Energy released:** the fragments are near the peak of the binding-energy curve (E.3), so the products are more tightly bound. The mass defect Δm becomes energy Δmc^2.

WORKED EXAMPLE

In one fission the total mass falls by 0.186 u. Find the energy released.

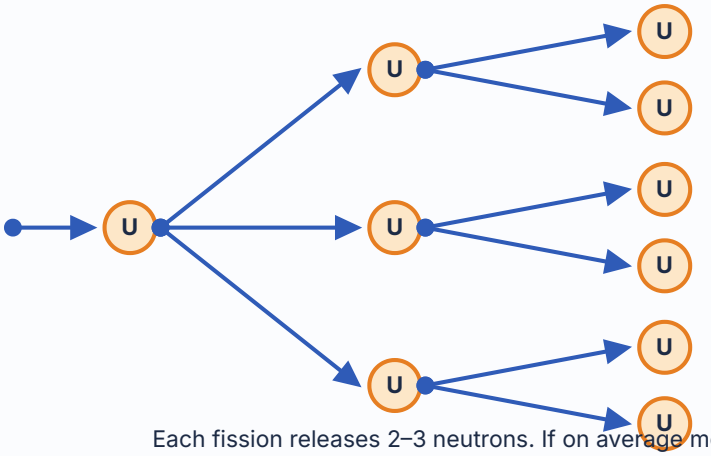
1. E = 0.186 × 931.5 MeV M1
2. **= 173 MeV (2.8×10^{-11} J)** A1

WORKED EXAMPLE

A 1000 MW (electrical) power station is 33 % efficient. Estimate the mass of U-235 it uses per day (200 MeV per fission).

1. thermal power = 3000 MW, so energy per day = $3.0 \times 10^{9} \times 86\,400 = 2.6 \times 10^{14}$ J M1
2. fissions = $2.6 \times 10^{14}/(200 \times 10^{6} \times 1.6 \times 10^{-19}) = 8.1 \times 10^{24}$ M1
3. **mass = $(8.1 \times 10^{24}/6.02 \times 10^{23}) \times 0.235$ kg ≈ 3.2 kg** A1

2 Chain reactions



critical mass:
enough fuel that
≥ 1 neutron per fission
goes on to cause another

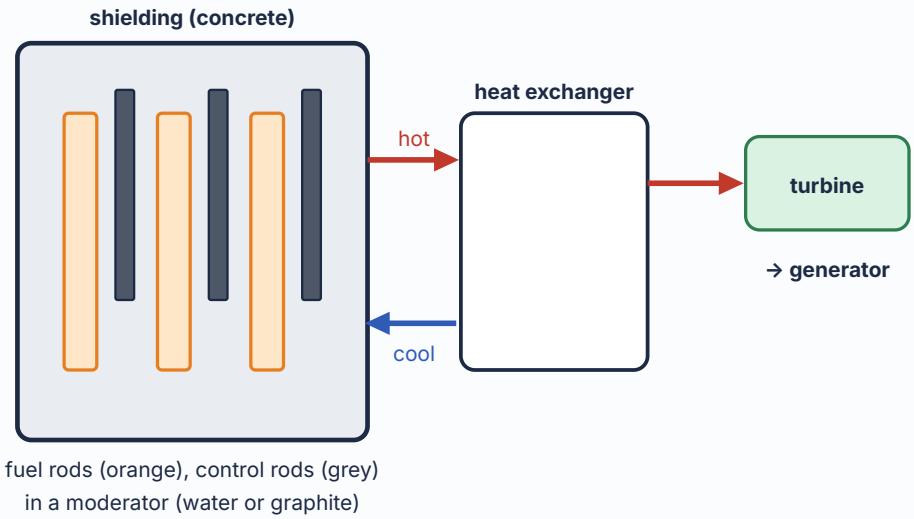
Each fission releases 2–3 neutrons. If on average more than one causes another fission, the chain reaction grows.

One neutron in, three out: without control the number of fissions multiplies every generation.

Critical mass — the smallest mass of fuel in which, on average, exactly one neutron from each fission causes another fission. Below it too many neutrons escape through the surface.

- **Subcritical:** the reaction dies out. **Critical:** steady (a reactor). **Supercritical:** it grows rapidly (a bomb, which reactors are designed never to reach).

3 The nuclear reactor



Energy flows from the fuel to the coolant, through the heat exchanger to make steam for the turbine.

Part	Job
fuel rods	enriched uranium (more U-235 than natural); fission happens here
moderator	water or graphite: slows fast neutrons by collisions so U-235 can capture them
control rods	boron or cadmium: absorb neutrons; pushed in to slow the reaction or shut down
coolant	water or gas: carries thermal energy away from the core
heat exchanger	transfers energy from the coolant to water, making steam for the turbine
shielding	thick steel and concrete: absorbs neutrons and γ radiation

COMMON MISTAKE

Saying the moderator absorbs neutrons. The moderator **slows them down**; the control rods **absorb** them.

EXAM TIP

Why is a light-atom moderator best? A neutron loses most energy colliding with a nucleus of similar mass (like snooker balls). Hydrogen (in water) and carbon (graphite) are light.

4 Nuclear power: pros and cons

- **For:** no CO_2 while operating; huge energy density (about 10^6 times that of fossil fuels, A.3); steady output independent of the weather.
- **Against:** radioactive waste with long half-lives must be stored safely for thousands of years; risk of accidents (Chernobyl, Fukushima); expensive to build and decommission; proliferation concerns.
- **Waste:** spent fuel contains highly radioactive fission products and plutonium. It is cooled under water, then vitrified (sealed in glass) and stored deep underground.

LINKING QUESTION

Steam from the heat exchanger drives a turbine and generator (D.4); the maximum efficiency of turning that heat into work is the Carnot limit (B.4).

IDEA FOR YOUR IA / EXPLORATION

Model the effect of a moderator with a simulation (or coin-flip neutrons in a grid) and investigate how the chance of capture changes the growth of a chain reaction.

Test yourself — cover the answers first

QUICK CHECK

1. What is induced fission?
2. Why is energy released in fission?
3. What is the job of the moderator?
4. What is the job of the control rods?
5. What is critical mass?

EXAM-STYLE

6. Balance: ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + x\,{}^{1}_{0}n$.
7. How many fissions per second produce 1.0 W if each releases 200 MeV?

Show answers

1. a heavy nucleus splitting after absorbing a neutron
2. the products have higher binding energy per nucleon, so mass is lost and becomes energy
3. to slow neutrons down
4. to absorb neutrons and control the rate
5. the mass for which, on average, one neutron per fission causes another fission
6. A: $236 = 144 + 89 + x$
   $x = 3$
7. $200\ \text{MeV} = 3.2 \times 10^{-11}\ \text{J}$
   $1.0/3.2 \times 10^{-11}$
   = **3.1×10^{10} fissions per second**

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