# Fission

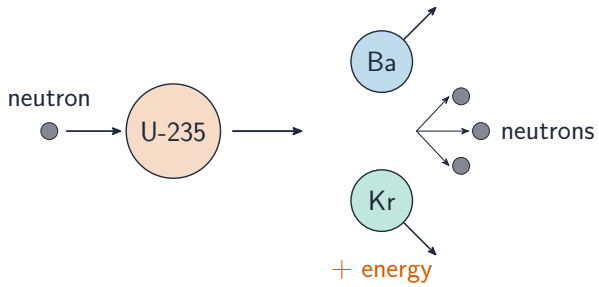
E.4 · SL and HL

# Why cool a shut-down reactor?

> Stopping the chain does not remove decay heat.

- Radioactive products already formed continue decaying.
- Neutron control and thermal-energy removal are different tasks.
- Follow the energy: fission $\rightarrow$ fuel heat $\rightarrow$ turbine $\rightarrow$ generator.

# Neutron-induced fission




- One possible U-235 channel produces barium, krypton and three neutrons.
- Fragment identities, neutron counts and immediate channel energies vary.

# Balancing a fission equation

- Nucleons: $1 + 235 = 141 + 92 + 3$.
- Protons: $0 + 92 = 56 + 36$.

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

**Spontaneous fission** needs no incoming neutron; not every neutron absorption causes fission.

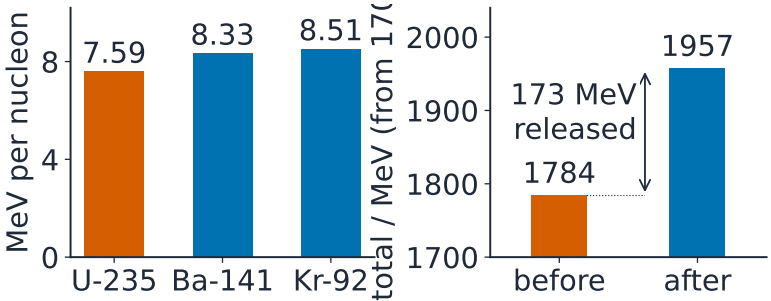
# Energy from the mass difference

1. **Known.** Atomic masses: U-235 235.043930 u; Ba-141 140.914411 u; Kr-92 91.926156 u; n 1.008665 u. Three neutrons leave; 1 u $c^2 = 931.5$ MeV.
2. **Initial.** $m_i = 235.043930 + 1.008665 = 236.052595$ u.
3. **Final.** $m_f = 140.914411 + 91.926156 + 3(1.008665) = 235.866562$ u.
4. **Energy.** $Q = (m_i - m_f)c^2 = 0.186033 \times 931.5 = 173.29$ MeV.

## Decision

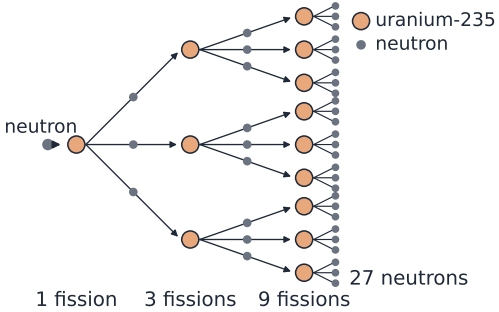
About $2.77 \times 10^{-11}$ J using 1 MeV $= 1.60 \times 10^{-13}$ J.

# Energy from binding energy




- Released energy equals the total binding-energy increase, not a per-nucleon difference alone.
- Displayed values are rounded; free neutrons have zero nuclear binding energy.

# Chain reactions




- The drawing assumes every shown neutron causes another fission.
- Real neutron escape and non-fission absorption reduce successful successors.

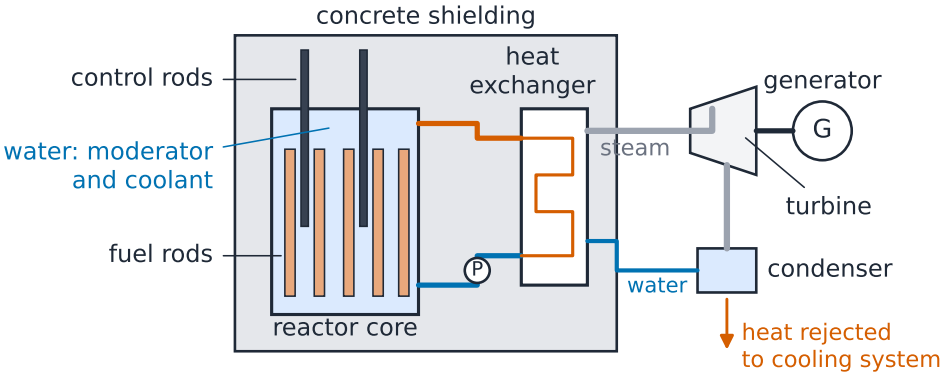
# Check: a steady reactor

**Your turn**

At steady expected fission power, how many successor fissions does each fission cause on average after neutron losses?

A. Zero
B. Exactly one
C. Exactly two
D. Three

# Inside a power station




Pressurised-water model: separate **coolant** loops; the condenser rejects heat.

# Moderator and control rods

## Moderator

Slows neutrons by collisions with suitable light nuclei.

Materials can include water and graphite.

## Control rods

Absorbs neutrons using suitable absorber material.

Insertion reduces the neutrons available to continue the chain.

# Shutdown, shielding and containment

## Neutron chain and heat

Absorbers suppress the self-sustaining chain.

Existing radioactive products still release heat.

## Radiation and material

Shielding attenuates transmitted radiation.

Containment and fuel barriers limit release of radioactive material.

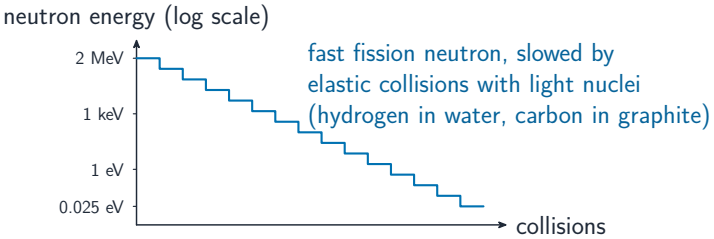
# How much fuel?

1. **Known.** 1000 MW electrical; $\eta = 0.33$; deposited heat 200 MeV $= 3.20 \times 10^{-11}$ J per fission; nucleus mass $235 \times 1.661 \times 10^{-27}$ kg; 86400 s/day.
2. **Thermal input.** $P_{\mathrm{th}} = P_{\mathrm{el}}/\eta = 10^{9}/0.33 \approx 3.03 \times 10^{9}$ W.
3. **Fission rate.** $\dot{N} = P_{\mathrm{th}}/E_f \approx 9.47 \times 10^{19}$ per second.
4. **Daily mass.** $m = \dot{N}\Delta t\, m_U \approx 3.19$ kg.

## Decision

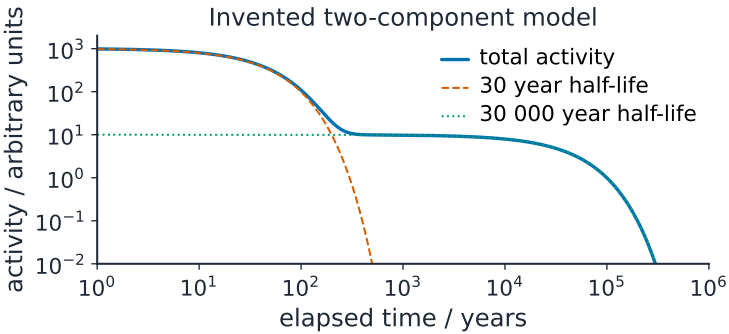
Assigned ideal model: uranium-235 fissioned, not total fuel loaded.

# The moderator slows neutrons




Slow neutrons are more likely to cause fission

# Fission products




- Invented 30 year and 30 000 year activity components, not a real inventory.
- A mixture can have changing dominant components and no single half-life.

# Managing the waste

> Waste routes depend on half-lives, activity, heat and material form.

- Storage manages cooling and shielding; reprocessing leaves radioactive residues.
- Geological disposal aims at long-term passive isolation; not all spent fuel is vitrified.

# Fission and climate change

## For

Low direct operational carbon emissions.

High fuel energy density; can supply sustained electricity.

## Against

Waste, heat management and accident risk.

Costs, construction time and security concerns.

# Exam tips

> One successor fission per fission on average gives a steady expected chain.

- Balance nucleon and proton numbers, and count the neutrons.
- Use either masses or binding energies, never a mix.
- The **moderator** slows neutrons; control rods absorb them.

# Check yourself

## Try these

For n + U-235 $\rightarrow$ Xe-140 + Sr-94 + x n, find x; check $92 = 54 + 38$.

Explain why moderating neutron energy and absorbing neutrons are different functions.

A station supplies 600 MW electrical at $\eta = 0.32$. Assign $3.20 \times 10^{-11}$ J deposited per fission, $3.16 \times 10^{7}$ s operation and nucleus mass $235 \times 1.661 \times 10^{-27}$ kg. Find U-235 mass fissioned.