

Nuclear Fission and Fusion

Where does nuclear energy come from, and how do fission and fusion differ?

●●● Intermediate

Nuclear Chemistry

Last reviewed 4 October 2026

Before you start: it helps to understand [Radioactive Decay and Half-Life](#) and [Isotopes and Average Atomic Mass](#).

What is it?

Nuclear reactions can release millions of times more energy than chemical reactions. They come in two kinds:

- **Fission:** a heavy nucleus, such as uranium-235, **splits** into two medium-sized nuclei, releasing neutrons and energy.
- **Fusion:** two light nuclei, such as isotopes of hydrogen, **join** to form a heavier nucleus, releasing energy.

The energy comes from **mass**. A nucleus has slightly **less** mass than the protons and neutrons that make it up. This missing mass, the **mass defect** (Δm), was converted into energy when the nucleus formed, according to Einstein's equation:

$$E = \Delta m c^2$$

where $c = 2.998 \times 10^8$ m/s is the speed of light. The same energy, the **binding energy**, would be needed to pull the nucleus apart again.

KEY IDEA

Nuclei with a higher **binding energy per nucleon** are more stable. Iron-56 is near the top of the curve. Splitting very heavy nuclei (fission) or joining very light ones (fusion) moves towards iron, so both **release** energy.

Why does it matter?

- **Electricity.** Nuclear power stations use controlled fission of uranium-235 and generate electricity without burning fuel or emitting carbon dioxide while they run.
- **The stars.** The Sun shines by fusing hydrogen into helium; most elements up to iron were made by fusion in stars.

- **Future energy and risks.** Fusion reactors are being developed as a cleaner energy source; fission produces long-lived radioactive waste, and both processes underlie nuclear weapons.

How does it work?

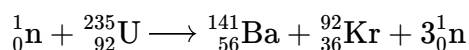
1. Mass defect and binding energy

1. Add up the masses of the separate protons and neutrons.
2. Subtract the measured mass of the nucleus: this is the mass defect, Δm .
3. Convert Δm to kilograms ($1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$) and use $E = \Delta m c^2$. The units give $\text{kg m}^2 \text{ s}^{-2} = \text{J}$.
4. Divide by the number of nucleons (protons + neutrons) to compare nuclei.

Nuclear energies are often given in **mega-electronvolts**: $1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$.

2. Fission and the chain reaction

When uranium-235 absorbs a slow neutron, it splits. One of many possible splits is:



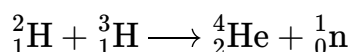
Each fission releases about **200 MeV** and **2 or 3 neutrons**. If at least one of these neutrons causes another fission, a **chain reaction** follows. The smallest mass of fuel that can keep the chain going is the **critical mass**.

A **nuclear reactor** controls the chain reaction:

- **Fuel rods:** uranium enriched in uranium-235.
- **Moderator** (water or graphite): slows the neutrons so they are captured by uranium-235 more easily.
- **Control rods** (boron or cadmium): absorb neutrons; lowering them slows the reaction.
- **Coolant:** carries the heat away to make steam, which drives turbines.

3. Fusion

Fusion needs temperatures of millions of degrees, so that the positively charged nuclei collide fast enough to overcome their repulsion. The most promising reaction for reactors fuses deuterium and tritium:



In the Sun, a series of steps has the overall effect $4{}_1^1\text{H} \longrightarrow {}_2^4\text{He} + 2{}_+1^0\text{e}$ (plus neutrinos and gamma rays).

	Fission	Fusion
Nuclei	heavy split	light join
Fuel	uranium-235, plutonium-239	hydrogen isotopes
Conditions	slow neutrons, critical mass	millions of degrees
Waste	radioactive fission products	mainly helium (little long-lived waste)
Status	power stations since the 1950s	experimental

∞ THINK OF IT LIKE THIS

Think of nucleons as people in groups, where the most comfortable group size is medium (iron). People in a huge, crowded group (uranium) are happier if it splits in two; people in tiny groups (hydrogen) are happier if they join up. Either change makes everyone more comfortable, and the “relief” is released as energy.

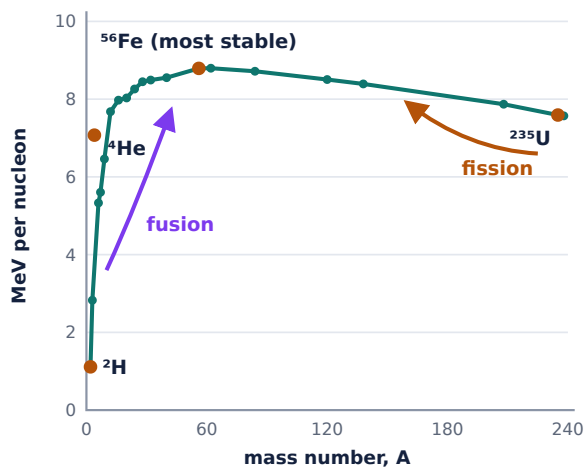
🔍 MORE PRECISELY

Chemical reactions also turn a tiny amount of mass into energy, but it is far too small to measure: about one part in 10^{10} of the mass, compared with about one part in 10^3 in fission. Binding energy uses $E = \Delta m c^2$ because the strong nuclear force holding nucleons together is far stronger than the electrical forces in chemical bonds. In a nuclear power station, the fuel contains only a few percent of uranium-235, which cannot explode like a bomb, but the reactor must still be cooled even after shutdown, because its fission products keep releasing decay heat.

Visualise it

Binding energy per nucleon

Higher on the curve = more tightly bound = more stable.

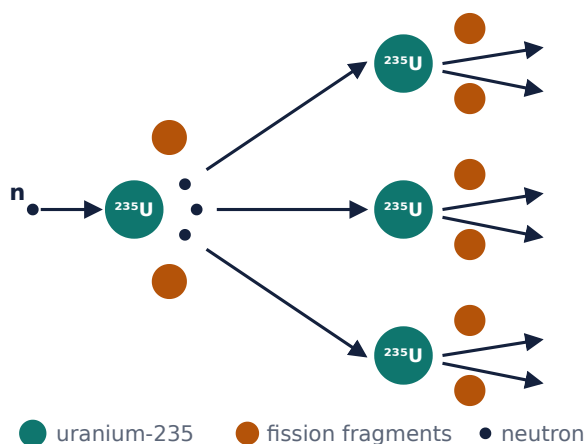


Moving towards iron, from either side, releases energy.

Iron-56 is near the peak: fusion of light nuclei and fission of heavy ones both move up the curve and release energy.

A fission chain reaction

Each fission releases 2–3 neutrons that can split more nuclei.



Control rods absorb neutrons to keep a reactor steady.

One neutron in, two or three out: each fission can trigger several more.

Worked example

WORKED EXAMPLE: Binding energy of carbon-12

Question: A carbon-12 nucleus (6 protons, 6 neutrons) has a mass of 11.996709 u. Find its binding energy and its binding energy per nucleon. (proton 1.007276 u; neutron 1.008665 u)

Step 1 Mass of the separate nucleons: $6(1.007276 \text{ u}) + 6(1.008665 \text{ u}) = 12.095646 \text{ u}$

Step 2 Mass defect: $\Delta m = 12.095646 \text{ u} - 11.996709 \text{ u} = 0.098937 \text{ u}$

Step 3 In kilograms:

$$\begin{aligned}\Delta m &= 0.098937 \text{ u} \\ &\times 1.66054 \times 10^{-27} \frac{\text{kg}}{\text{u}} \\ &= 1.6429 \times 10^{-28} \text{ kg}\end{aligned}$$

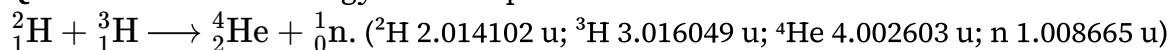
Step 4 Energy:

$$\begin{aligned}E &= (1.6429 \times 10^{-28} \text{ kg}) \\ &\times (2.998 \times 10^8 \text{ m/s})^2 \\ &= 1.477 \times 10^{-11} \text{ J}\end{aligned}$$

Step 5 In MeV: $\frac{1.477 \times 10^{-11} \text{ J}}{1.602 \times 10^{-13} \text{ J/MeV}} = 92.17 \text{ MeV}$; per nucleon: $\frac{92.17 \text{ MeV}}{12} = 7.68 \text{ MeV per nucleon}$

 WORKED EXAMPLE: Energy from deuterium–tritium fusion

Question: Find the energy released per mole of helium formed in



Step 1 Mass before: $2.014102 \text{ u} + 3.016049 \text{ u} = 5.030151 \text{ u}$

Step 2 Mass after: $4.002603 \text{ u} + 1.008665 \text{ u} = 5.011268 \text{ u}$

Step 3 $\Delta m = 0.018883 \text{ u}$ per reaction, so $0.018883 \text{ g per mole} = 1.8883 \times 10^{-5} \text{ kg/mol}$

Step 4 Energy:

$$\begin{aligned} E &= (1.8883 \times 10^{-5} \frac{\text{kg}}{\text{mol}}) \\ &\quad \times (2.998 \times 10^8 \text{ m/s})^2 \\ &= 1.697 \times 10^{12} \text{ J/mol} \end{aligned}$$

Step 5 That is **$1.697 \times 10^9 \text{ kJ/mol}$** , about two million times the 890 kJ/mol released by burning methane.

Common mistake

 **COMMON MISTAKE:** Thinking mass is lost and energy appears from nowhere

Mass and energy are two forms of the same thing. The products of a nuclear reaction have slightly less mass, and the missing mass appears as the kinetic energy of the products and as radiation. Total mass-energy is conserved.

 **COMMON MISTAKE:** Forgetting to convert u to kg

$E = \Delta m c^2$ gives joules only when Δm is in **kilograms** and c in **m/s**. Using Δm in u or g/mol without converting gives an answer that is wrong by a large factor.

 **COMMON MISTAKE:** Mixing up fission and fusion

Fission divides (heavy nuclei split); **fusion fuses** (light nuclei join). Both release energy, but only fission is used in today's power stations.

NOTATION NOTE

- u is the unified atomic mass unit, 1/12 of the mass of a carbon-12 atom (also written amu or Da).
- A neutron is written ${}_0^1\text{n}$; deuterium ${}_1^2\text{H}$ (also D) and tritium ${}_1^3\text{H}$ (also T).
- A shortcut: 1 u of mass defect corresponds to 931.5 MeV.

Remember this

REMEMBER THIS

- Mass defect = mass of separate nucleons – mass of nucleus; binding energy $E = \Delta m c^2$ (Δm in kg, c in m/s, E in J).
- Binding energy per nucleon peaks near iron-56; fission of heavy and fusion of light nuclei both release energy.
- Fission: U-235 + slow neutron → two fragments + 2–3 neutrons + about 200 MeV; chain reaction controlled by moderator and control rods.
- Fusion: light nuclei join at millions of degrees; powers the Sun.

References

1. Brown, T. L.; LeMay, H. E., Jr.; Bursten, B. E.; Murphy, C. J.; Woodward, P. M.; Stoltzfus, M. W. Chemistry: The Central Science, 15th ed.; Pearson, 2022.

Practise this topic with flashcards and a quiz at chemistryclarity.com/chemistry/fission-and-fusion/