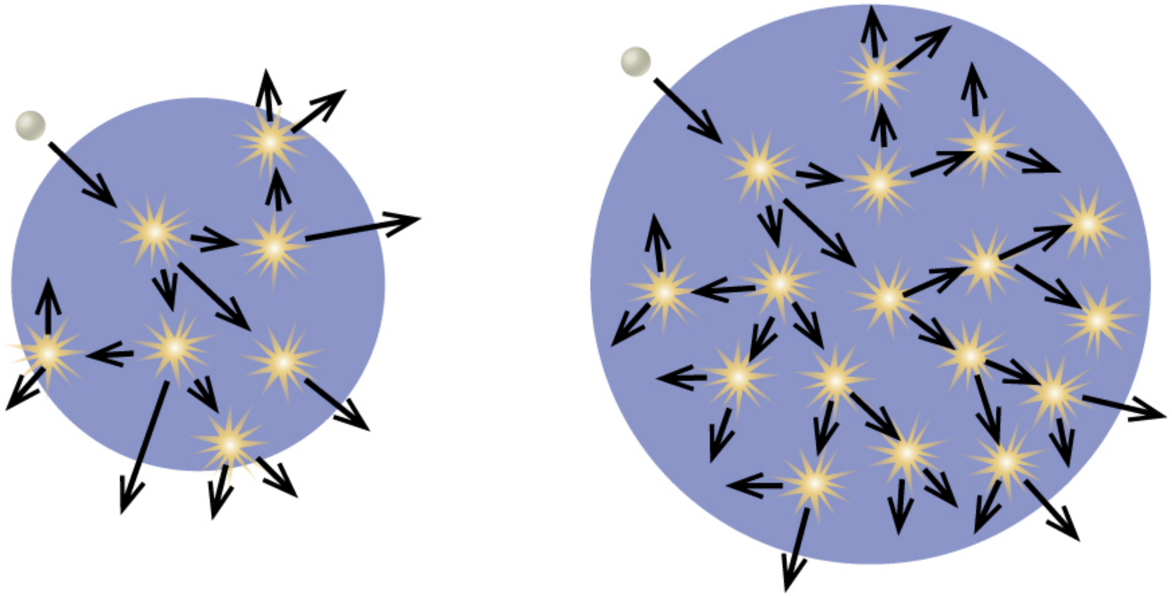
PHY20004 Nuclear Physics Class 5:

Nuclear fission

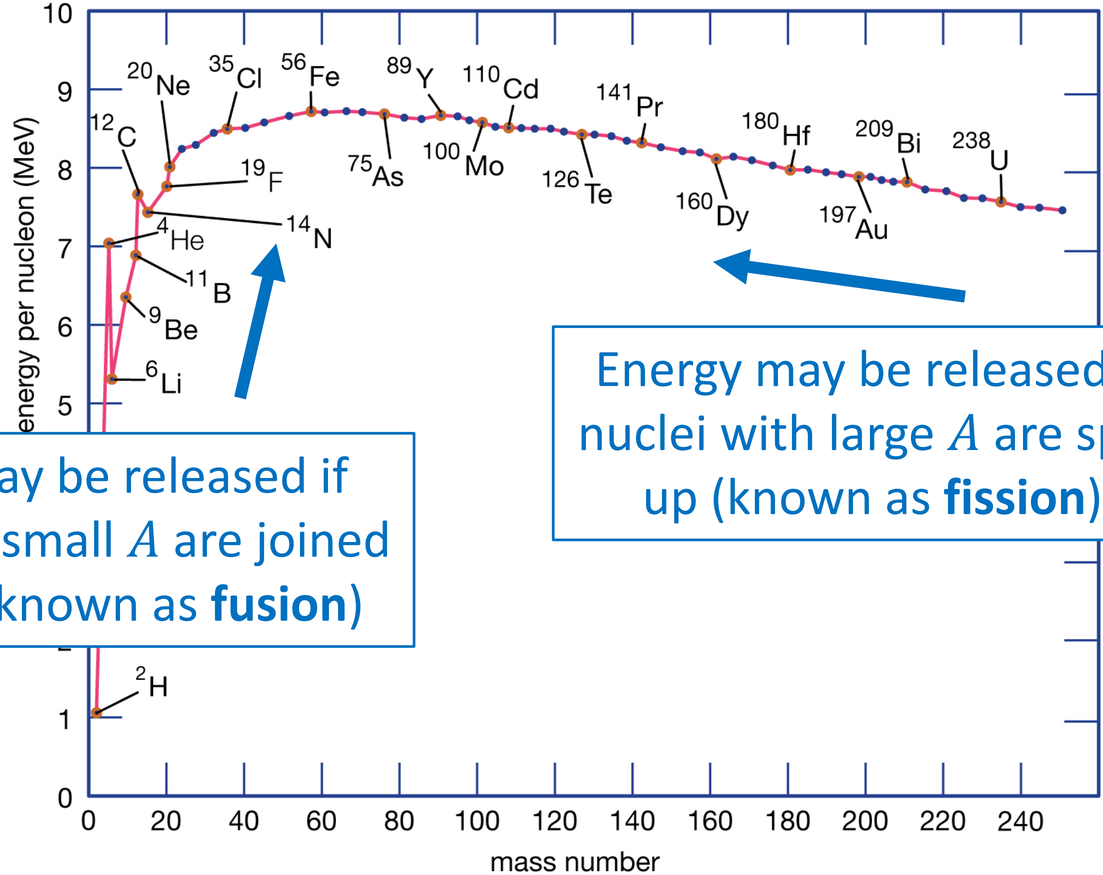
In this class we will describe how energy can be released through nuclear fission, and its practical application in fission reactors



Producing energy by fission

- Let's consider again the variation of the **binding energy per nucleon**, B/A, with the **number of nucleons**, A:

Increasing binding energy is equivalent to **releasing** energy

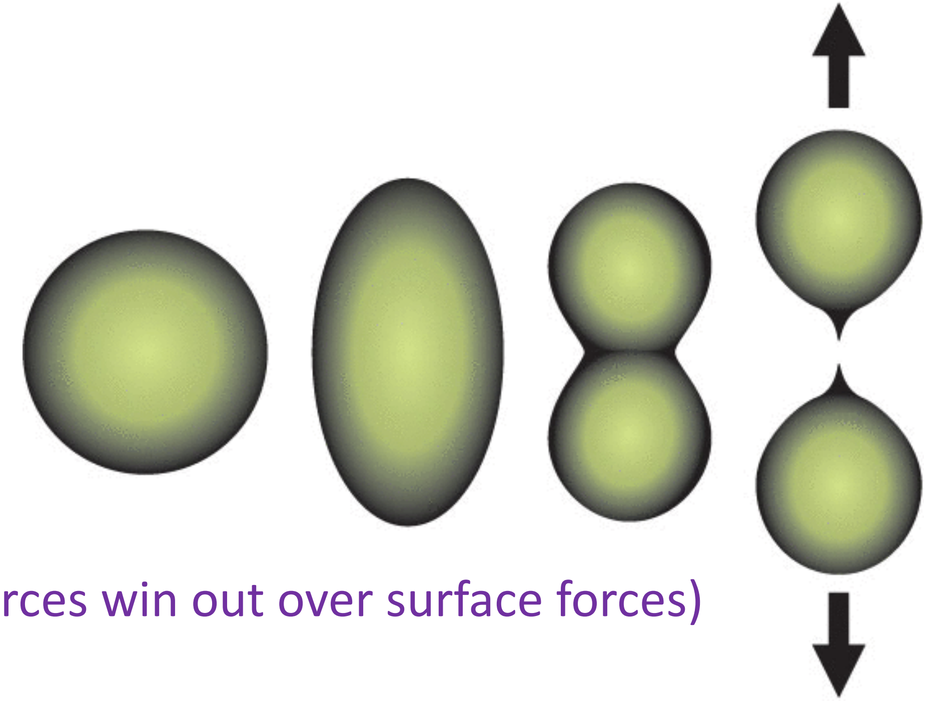


Energy may be released if nuclei with small A are joined together (known as **fusion**)

Energy may be released if nuclei with large A are split up (known as **fission**)

Producing energy by fission

- The break-up of a nucleus into two nuclei of approximately equal mass, releasing energy, is known as **nuclear fission**
- The process of fission, which involves the deformation of the nucleus, is well-described by the **liquid drop model**

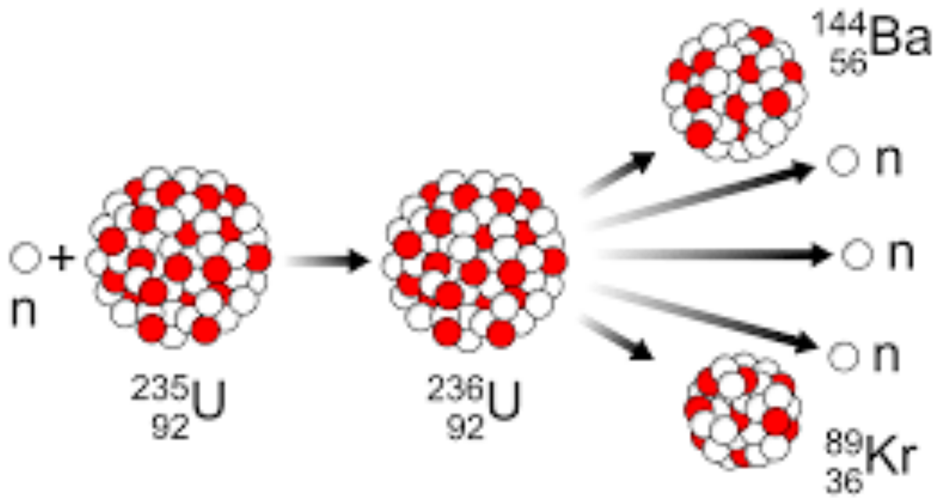


(Coulomb forces win out over surface forces)

Producing energy by fission

- The break-up of a nucleus into two nuclei of approximately equal mass, releasing energy, is known as **nuclear fission**
- Fission can happen **spontaneously**, but it can also be **induced** by bombarding nuclei with energetic particles, which trigger more unstable states

The fission of ^{235}U can be induced by **bombardment with neutrons**, creating an unstable ^{236}U nucleus which is highly prone to disintegration

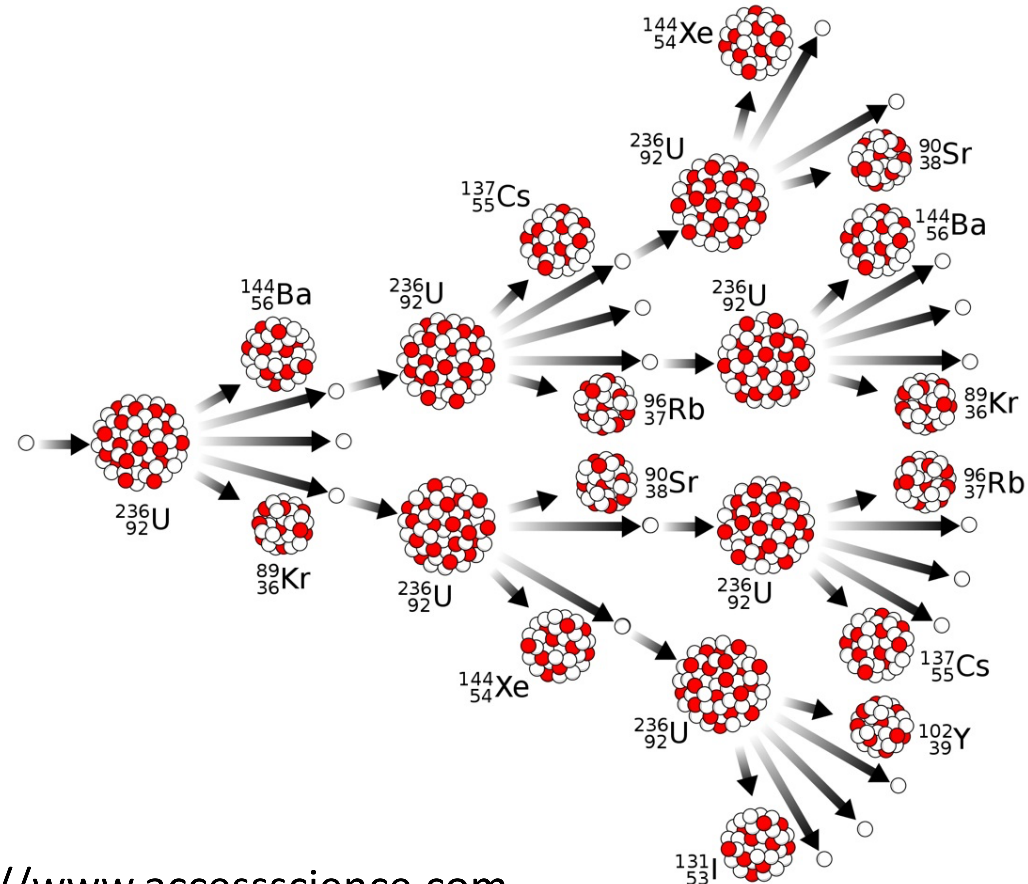


Credit: https://commons.wikimedia.org

Since this process also produces neutrons, we can create a **chain reaction**!

Producing energy by fission

- If fission produces further energetic particles, we can create a **self-sustaining chain reaction**, releasing energy!



(What could go wrong?!)

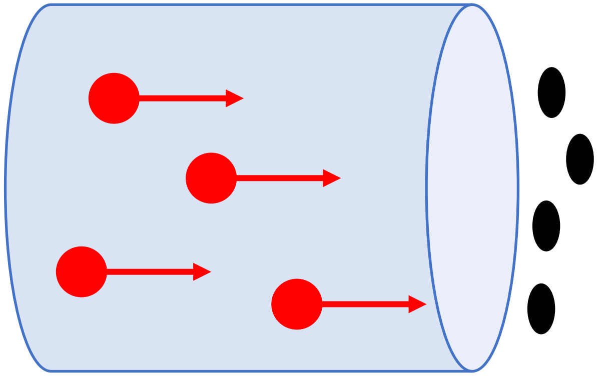
Credit: https://www.accessscience.com

Reaction cross-sections

- When particles are bombarding a target, the probability of a nuclear reaction occurring is given by its **cross-section** (symbol σ), defined as:

Number of reactions per second per nucleus	$=$	Cross-section (σ)	$\times$	Flux of incident particles (ϕ)
Units: s^{-1}		Units: m^{2}		Units: $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$

Beam of particles (number passing unit area per second $= \phi$)

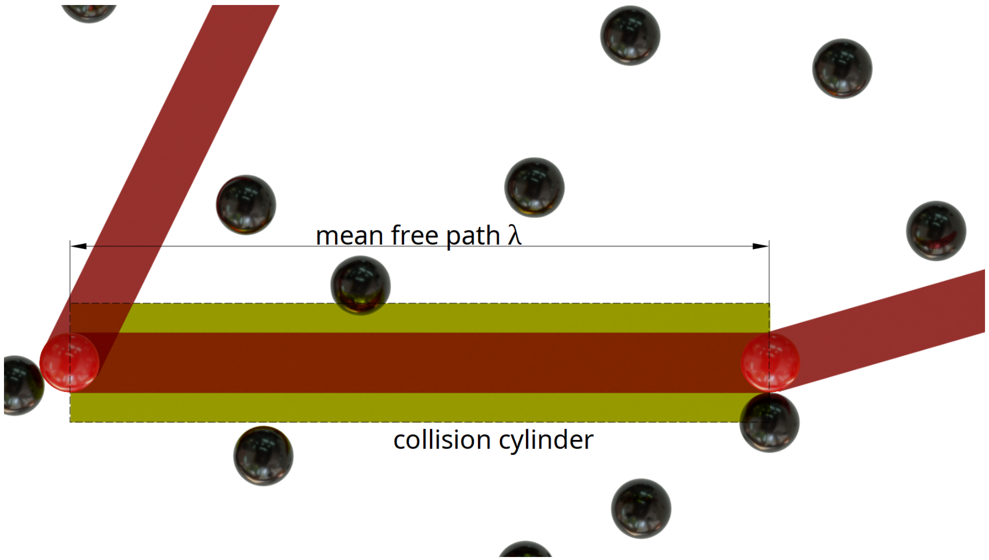


Geometrical interpretation: each target nucleus is associated with a little projected area $= \sigma$

- A common unit for cross-section is **barns** (b) – $1\ \mathrm{b} = 10^{-28}\ \mathrm{m}^2$

Mean free path

- The reaction cross-section also determines the **mean free path** of the bombarding particles (how far they travel, before initiating a reaction, symbol λ)

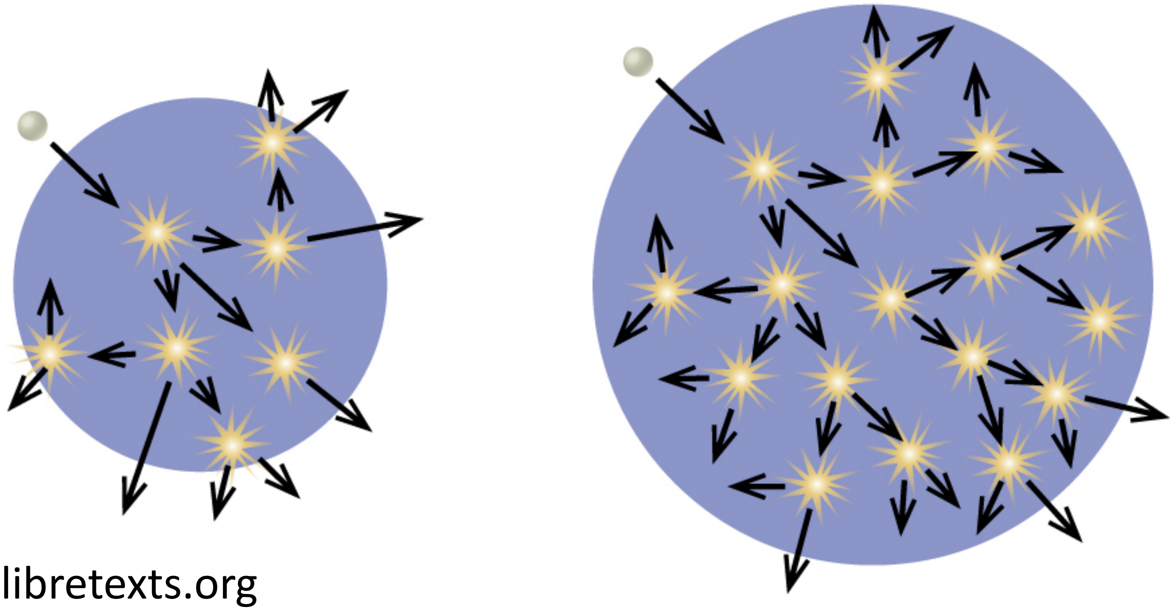


Credit: https://www.tec-science.com

- Let the number density of the target nuclei be n
- Consider a cylinder of cross-sectional area σ and length λ
- The number of reactions that happen in this cylinder is $n \times \lambda\sigma = 1$ for the mean free path
- Hence, $\lambda = 1/n\sigma$

How to build a nuclear reactor

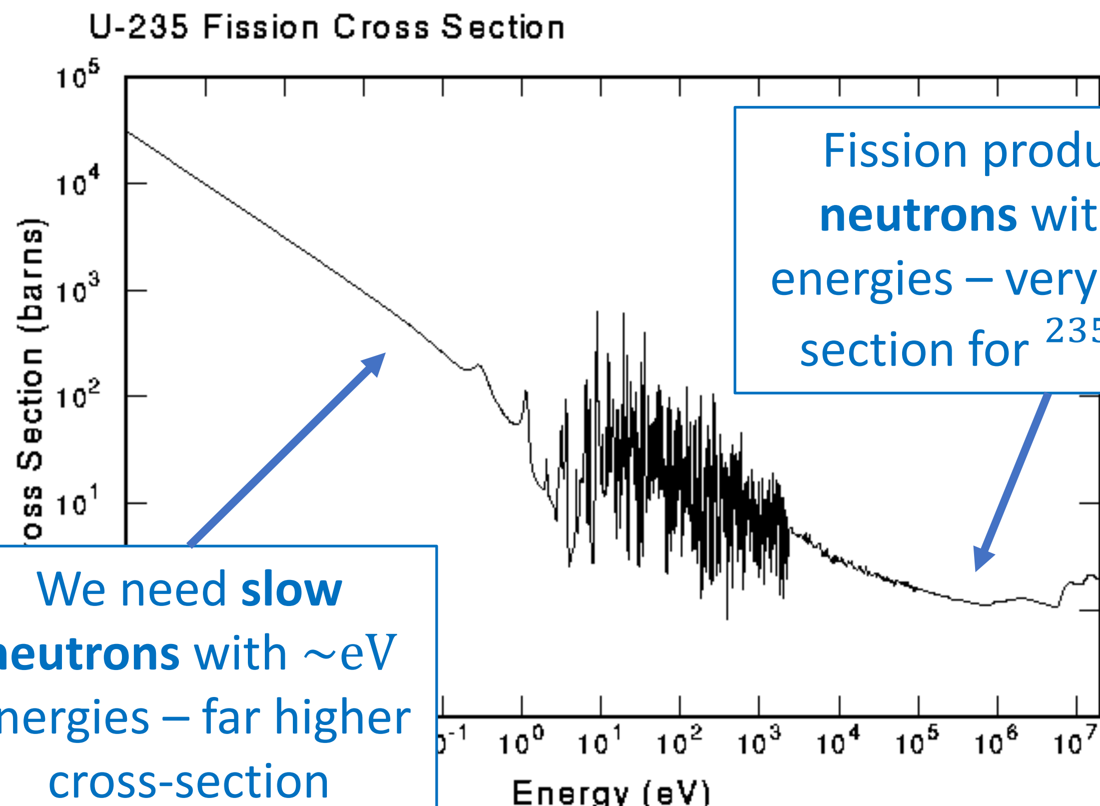
- *There are various design issues to consider when building a reactor to harness energy from nuclear fission*
- **Problem 1**: the fissile material must be *larger than the mean free path* of the bombarding neutrons, otherwise they'll pass through – this is known as the **critical mass** (≈ 50 kg for ^{235}U)



Credit: https://chem.libretexts.org

How to build a nuclear reactor

- **Problem 2**: fission produces neutrons with *far too high energies* to efficiently induce the next fission reaction



Fission produces **fast neutrons** with $\sim\mathrm{MeV}$ energies – very low cross-section for $^{235}\mathrm{U}$ fission

We need **slow neutrons** with $\sim\mathrm{eV}$ energies – far higher cross-section

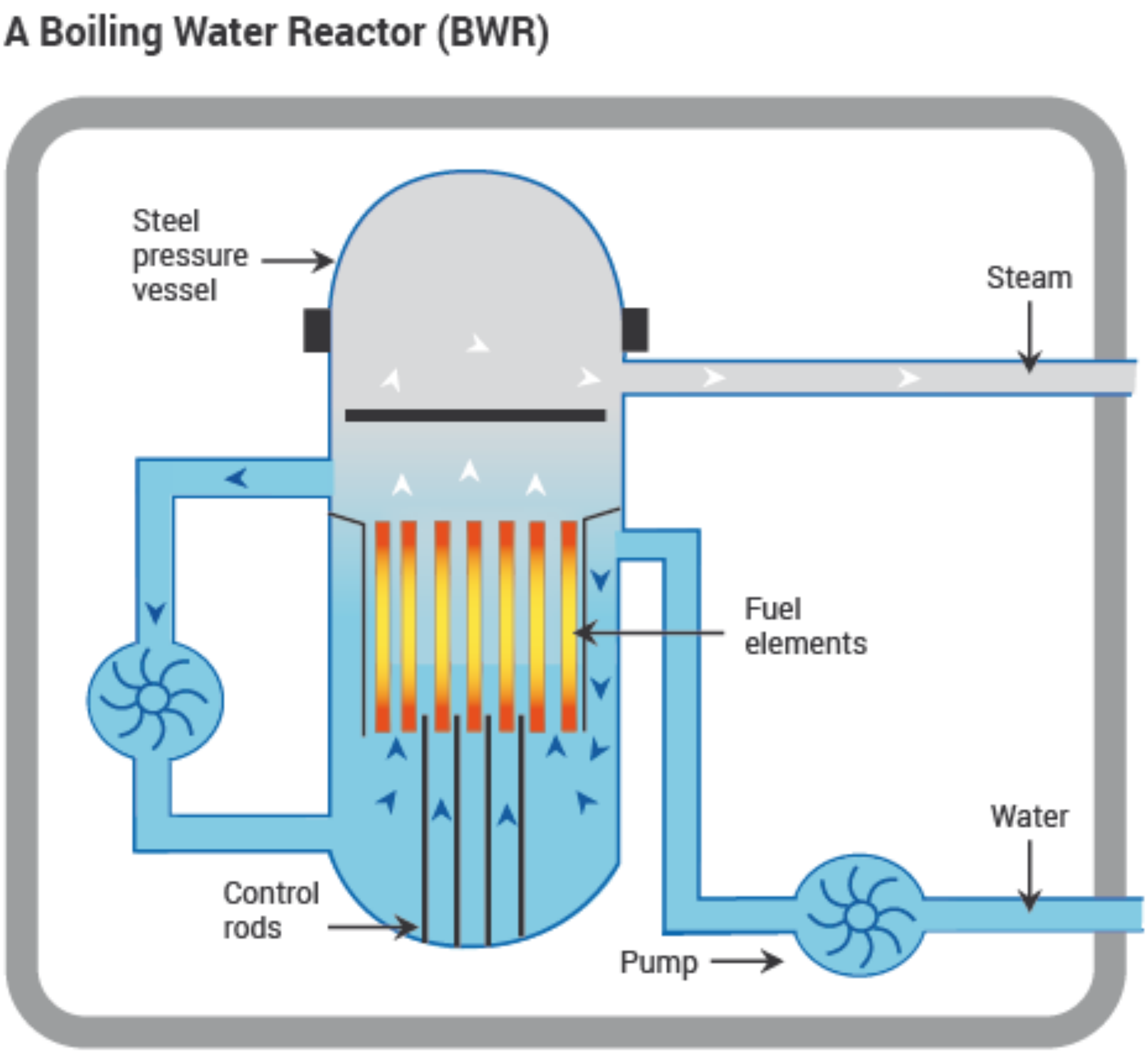
The neutrons can be slowed down through collisions with a moderator surrounding the fissile material, such as **water** or **carbon**

Credit: http://content.science20.com

How to build a nuclear reactor

- *A few more design points …*
- $^{235}\mathrm{U}$ is a highly fissile nuclide, but only comprises 0.7% of natural uranium, whereas $^{238}\mathrm{U}$ is 99.3%. Fission will proceed more efficiently if the $^{235}\mathrm{U}$ fraction is enriched
- Prudent to add control rods that strongly absorb neutrons (e.g. cadmium, boron) for controlling the neutron flux
- $^{238}\mathrm{U}$ in the fuel will absorb neutrons to produce $^{239}\mathrm{U}$, which β-decays into $^{239}\mathrm{Pu}$, another very useful nuclear fuel (reactors producing $^{239}\mathrm{Pu}$ are known as "breeder reactors")
- The released nuclear energy is used to heat steam to generate electricity … just like a fossil fuel power plant

How to build a nuclear reactor



Here's a standard design of a nuclear fission reactor: note that the water is being used as both a moderator and to transfer the nuclear energy

Credit: https://www.world-nuclear.org

Key take-aways

- The fission (splitting) of large nuclei **releases energy** by increasing the binding energy per nucleon
- Fission can happen spontaneously, but can also be **induced** by bombardment with energetic particles
- A **chain reaction** of self-sustained fission is possible because neutron-induced fission produces neutrons
- A minimum size (**critical mass**) is required to achieve a self-sustaining reaction (criticality)
- The probability of nuclear reactions occurring is described by the **reaction cross-section**