Nuclear Physics

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Reference

Concepts of Modern Physics (6th Ed) – Arthur Beiser

University Physics with Modern Physics (13th Ed) – Young, Freedman

Nuclear composition

Atomic nuclei of the same element have the same numbers of protons but can have different numbers of neutrons

Atomic mass unit	$1\ \text{u} = 1.66054 \times 10^{-27}\ \text{kg}$

Some Masses in Various Units

Particle	Mass (kg)	Mass (u)	Mass (MeV/c^2)
Proton	1.6726×10^{-27}	1.007276	938.28
Neutron	1.6750×10^{-27}	1.008665	939.57
Electron	9.1095×10^{-31}	5.486×10^{-4}	0.511
${}^{1}_{1}$H atom	1.6736×10^{-27}	1.007825	938.79

Nuclear radii

$$R = R_0 A^{1/3}$$

$$R_0 \approx 1.2 \times 10^{-15}\ \text{m} \approx 1.2\ \text{fm}$$

Find the density of the $^{12}_{6}C$ nucleus.

$$2.4 \times 10^{17}\ \text{kg/m}^3$$

Mass Defect

The mass of an atomic nucleus is less than the sum of the individual masses of the free constituent protons and neutrons (according to Einstein's equation $E=mc^2$) and this 'missing mass' is known as the mass defect, and represents the energy that was released when the nucleus was formed.

Binding energy

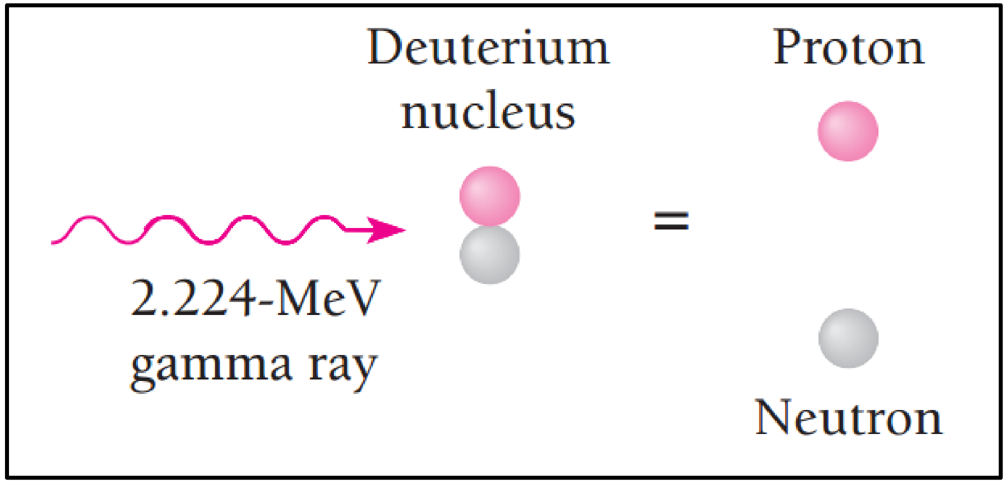
The missing energy that keeps a nucleus together

Mass of ${}^{1}_{1}H$ atom	1.007825 u
mass of neutron	1.008665 u

However, the measured mass of the ${}^{2}_{1}H$ atom is only 2.014102 u

$$\boxed{\Delta E = (0.002388\ \text{u})(931.49\ \text{MeV/u}) = 2.224\ \text{MeV}}$$

Binding energy



The binding energy E_b in MeV of the nucleus ${}^{A}_{Z}X$, which has $N = A - Z$ neutrons, is given by

$$E_b = [Zm({}^{1}_{1}\mathrm{H}) + Nm(n) - m({}^{A}_{Z}X)](931.49\ \mathrm{MeV/u})$$

Example

The binding energy of the neon isotope $^{20}_{10}\mathrm{Ne}$ is 160.647 MeV. Find its atomic mass.

$$\boxed{E_b = [Zm(^1_1\mathrm{H}) + Nm(n) - m(^A_Z X)](931.49\ \mathrm{MeV/u})}$$

Here $Z = 10$ and $N = 10$.

$$m(^A_Z X) = [Zm(^1_1\mathrm{H}) + Nm(n)] - \frac{E_b}{931.49\ \mathrm{MeV/u}}$$

$$m(^{20}_{10}\mathrm{Ne}) = [10(1.007825\ \mathrm{u}) + 10(1.008665)] - \frac{160.647\ \mathrm{MeV}}{931.49\ \mathrm{MeV/u}} = 19.992\ \mathrm{u}$$

Example

(a) Find the energy needed to remove a neutron from the nucleus of the calcium isotope $^{42}_{20}\text{Ca}$. (b) Find the energy needed to remove a proton from this nucleus. (c) Why are these energies different?

Solution

(a) Removing a neutron from $^{42}_{20}\text{Ca}$ leaves $^{41}_{20}\text{Ca}$. From the table of atomic masses in the Appendix the mass of $^{41}_{20}\text{Ca}$ plus the mass of a free neutron is

$$40.962278 \text{ u} + 1.008665 \text{ u} = 41.970943 \text{ u}$$

The difference between this mass and the mass of $^{42}_{20}\text{Ca}$ is 0.012321 u, so the binding energy of the missing neutron is`

$$(0.012321 \text{ u})(931.49 \text{ MeV/u}) = 11.48 \text{ MeV}$$

Example

(*a*) Find the energy needed to remove a neutron from the nucleus of the calcium isotope $^{42}_{20}\mathrm{Ca}$. (*b*) Find the energy needed to remove a proton from this nucleus. (*c*) Why are these energies different?

Solution

(b) Removing a proton from $^{42}_{20}\mathrm{Ca}$ leaves the potassium isotope $^{41}_{19}\mathrm{K}$. A similar calculation gives a binding energy of 10.27 MeV for the missing proton.

(c) The neutron was acted upon only by attractive nuclear forces whereas the proton was also acted upon by repulsive electric forces that decrease its binding energy.

Binding energy per nucleon

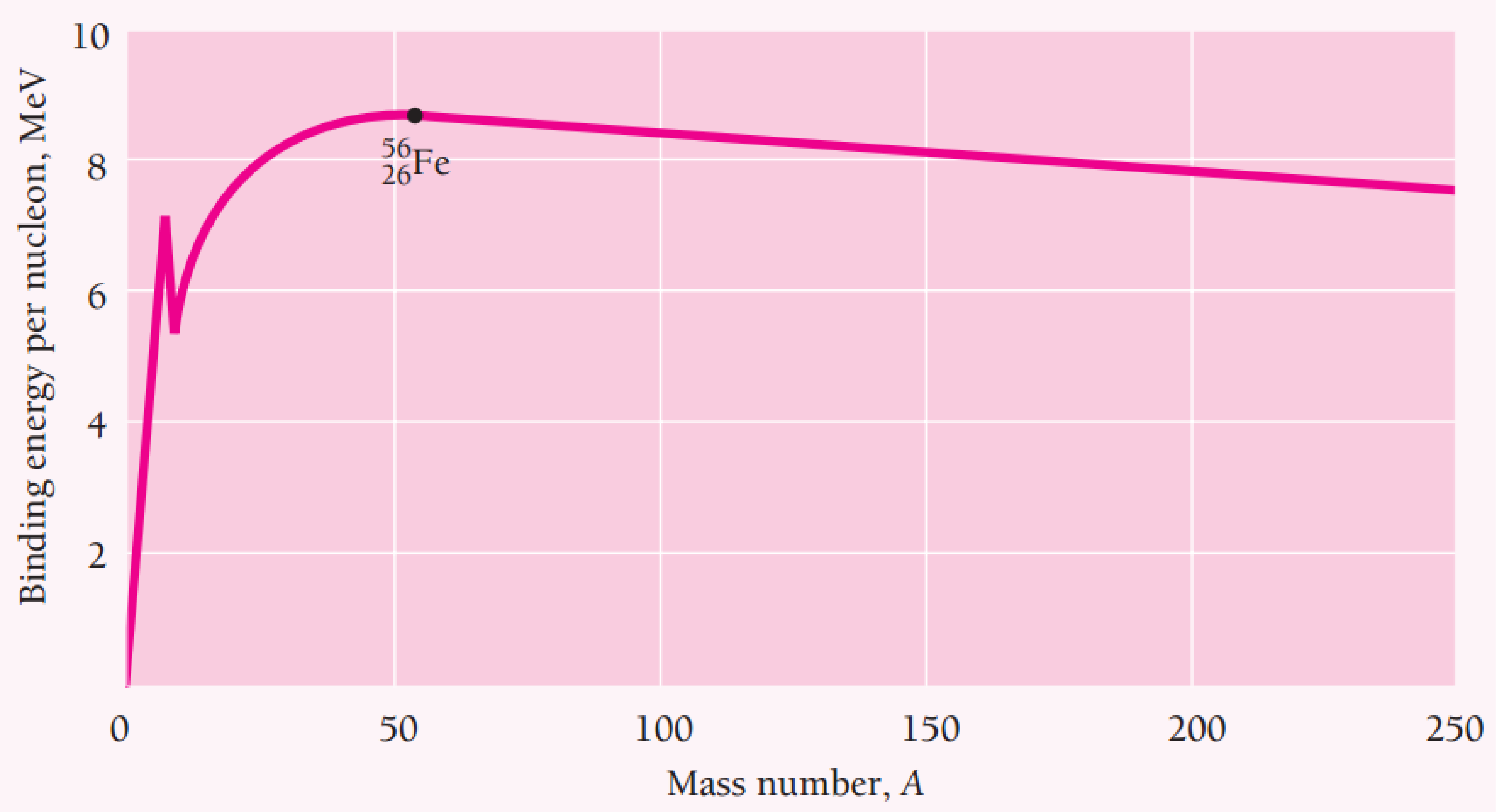
The binding energy per nucleon for a given nucleus is an average found by dividing its total binding energy by the number of nucleons it contains.

The binding energy per nucleon for ${}^{2}_{1}\mathrm{H}$ is (2.2 MeV)/2 =1.1 MeV/nucleon, and for ${}^{209}_{83}\mathrm{Bi}$ it is (1640 MeV)/209 =7.8 MeV/nucleon.

What is the binding energy per nucleon for ${}^{235}_{92}\mathrm{U}$?

The atomic mass of ${}^{235}_{92}\mathrm{U}$ is 234.043925 u.

Binding energy per nucleon



The strong interaction

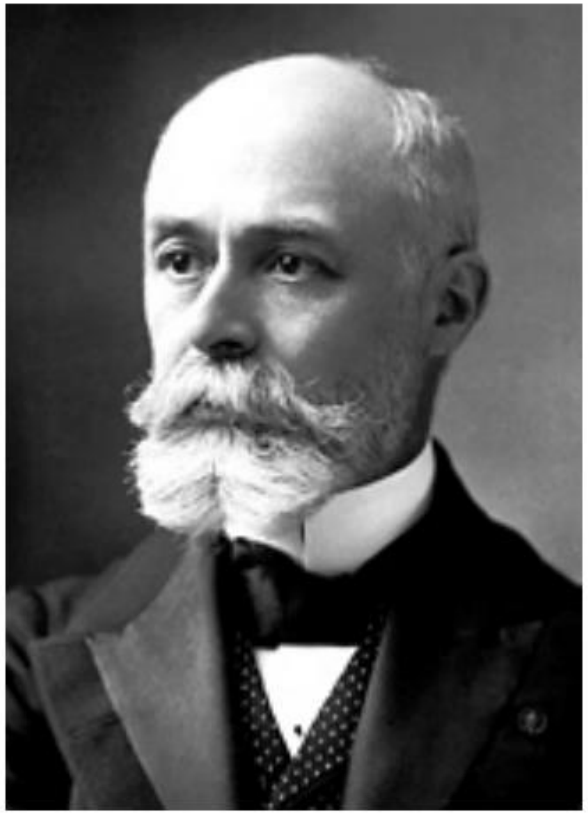
The short-range attractive forces between nucleons arise from the strong interaction.

The strong interaction is what holds nucleons together to form nuclei, and it is powerful enough to overcome the electric repulsion of the positively charged protons in nuclei provided neutrons are also present to help.

Toward the end of the 19th century, minerals were found that would darken a photographic plate even in the absence of light.

This phenomenon is now called radioactivity.

Marie and Pierre Curie isolated two new elements that were highly radioactive; they are now called polonium and radium.



Henri Becquerel

Pierre Curie

Marie Curie

The Nobel Prize in Physics 1903 for their work on radioactivity

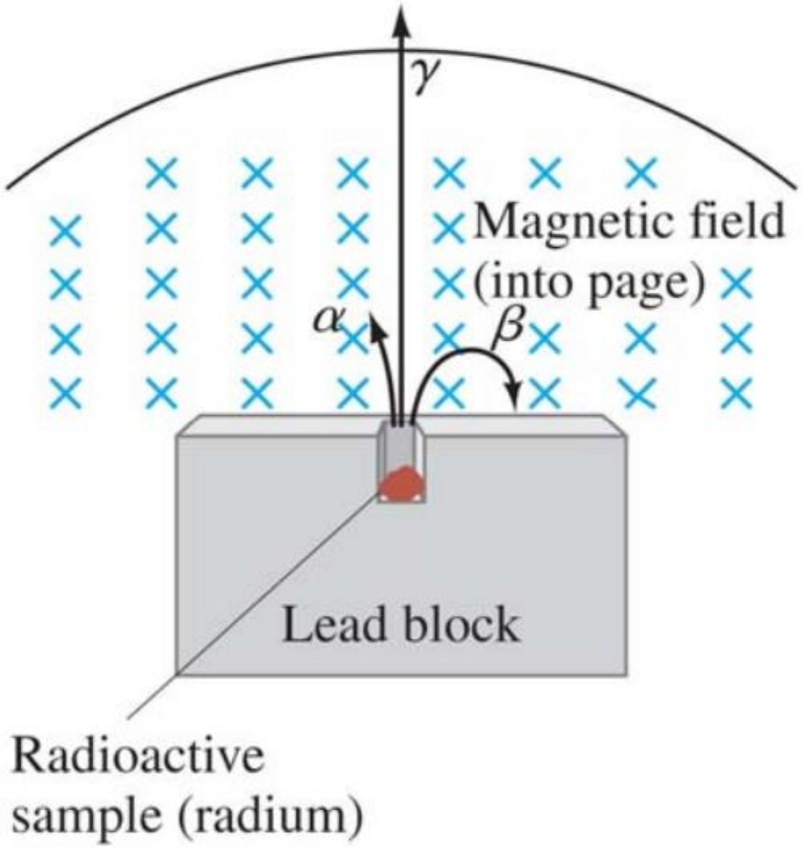
Radioactivity

The emission of elementary particles by some atoms when their unstable nuclei disintegrate

Radioactive Decay

Decay	Transformation	Example
Alpha decay	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	${}^{238}_{29}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
Beta decay	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-}$	${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$
Positron emission	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+}$	${}^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + e^{+}$
Electron capture	${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y$	${}^{64}_{29}Cu + e^{-} \rightarrow {}^{64}_{28}Ni$
Gamma decay	${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$	${}^{87}_{38}Sr^{*} \rightarrow {}^{87}_{38}Sr + \gamma$

Radioactivity



1. **Why do some nuclei decay ?**

2. **Why emit α's, and not protons, or neutrons ?**

Radioactivity

Activity law $$R = R_0 e^{-\lambda t}$$

Radioactive decay $$N = N_0 e^{-\lambda t}$$

Half-life $$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Nuclear Reaction

$$^{14}_{7}\mathrm{N} + ^{1}_{0}\mathrm{n} \rightarrow ^{14}_{6}\mathrm{C} + ^{1}_{1}\mathrm{H}$$

$$^{14}\mathrm{N(n,p)}^{14}\mathrm{C}$$

$$^{1}_{1}\mathrm{H} + ^{12}_{6}\mathrm{C} \rightarrow ^{13}_{7}\mathrm{N} + \gamma$$

$$^{4}_{2}\mathrm{He} + ^{13}_{6}\mathrm{C} \rightarrow ^{16}_{8}\mathrm{O} + ^{1}_{0}n$$

The conventional symbols for nuclear species, or **nuclides**, follow the pattern ${}^{A}_{Z}X$,

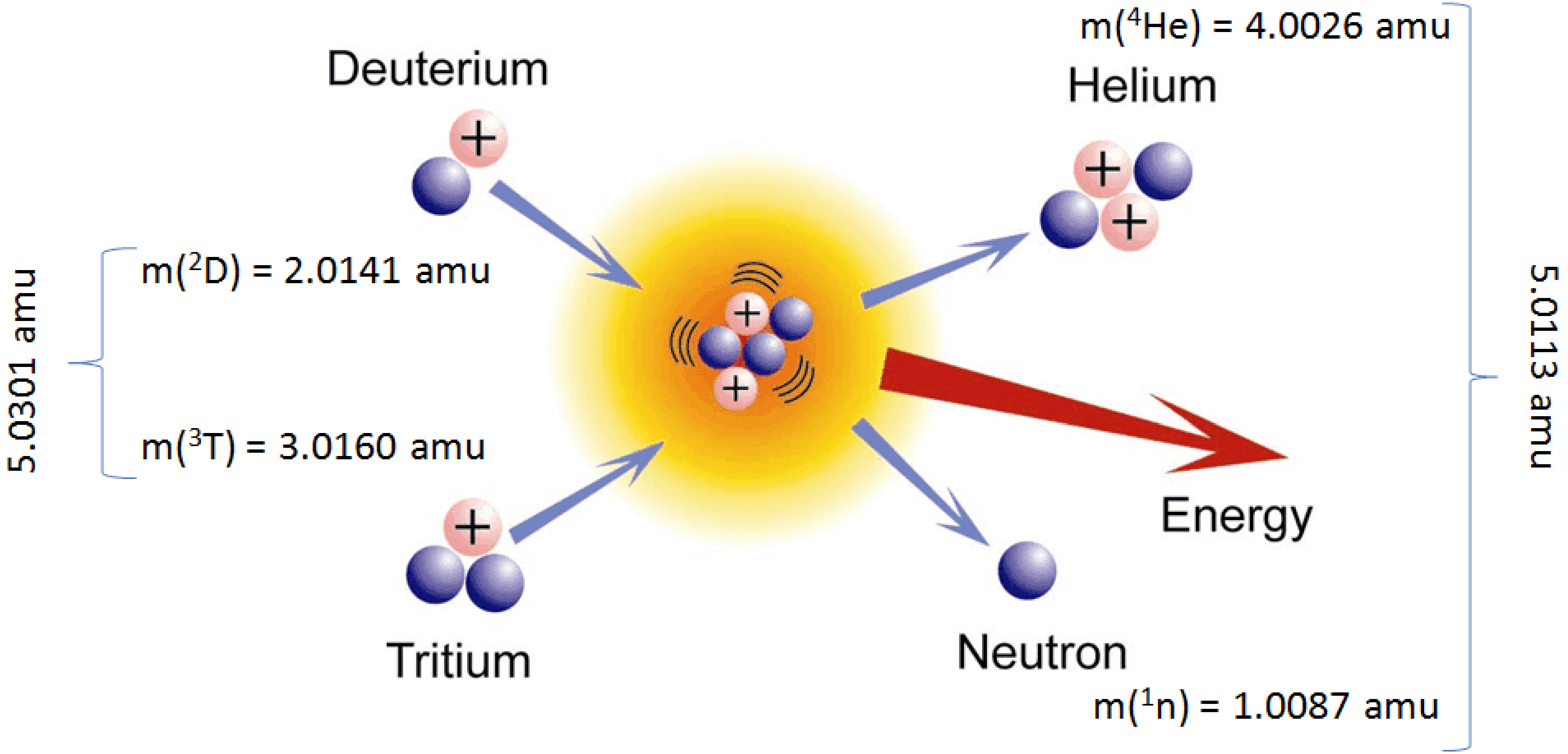
where X = chemical symbol of the element
Z = atomic number of the element
= number of protons in the nucleus
A = mass number of the nuclide
= number of nucleons in the nucleus
$N = A - Z$ neutrons

Alpha decay

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$$

Parent nucleus → Daughter nucleus + Alpha particle

Q-value – Energetics of Nuclear Reactions



Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Q-value – Energetics of Nuclear Reactions

The Q **value** of the nuclear reaction

$$A + B \rightarrow C + D$$

is defined as the difference between the rest energies of A and B and the rest energies of C and D:

$$Q = (m_A + m_B - m_C - m_D)c^2$$

If Q is a positive quantity, energy is given off by the reaction.

Q-value – Energetics of Nuclear Reactions

The **Q-value** of this reaction is the same as the **excess kinetic energy** of the final products:

$$\boldsymbol{Q = T_{\mathrm{final}} - T_{\mathrm{initial}}}$$

$$\boldsymbol{= (T_C + T_D) - (T_A + T_B)}$$

Q-value – Energetics of Nuclear Reactions

Write down the reaction $^{14}N(\alpha,p)^{17}O$.

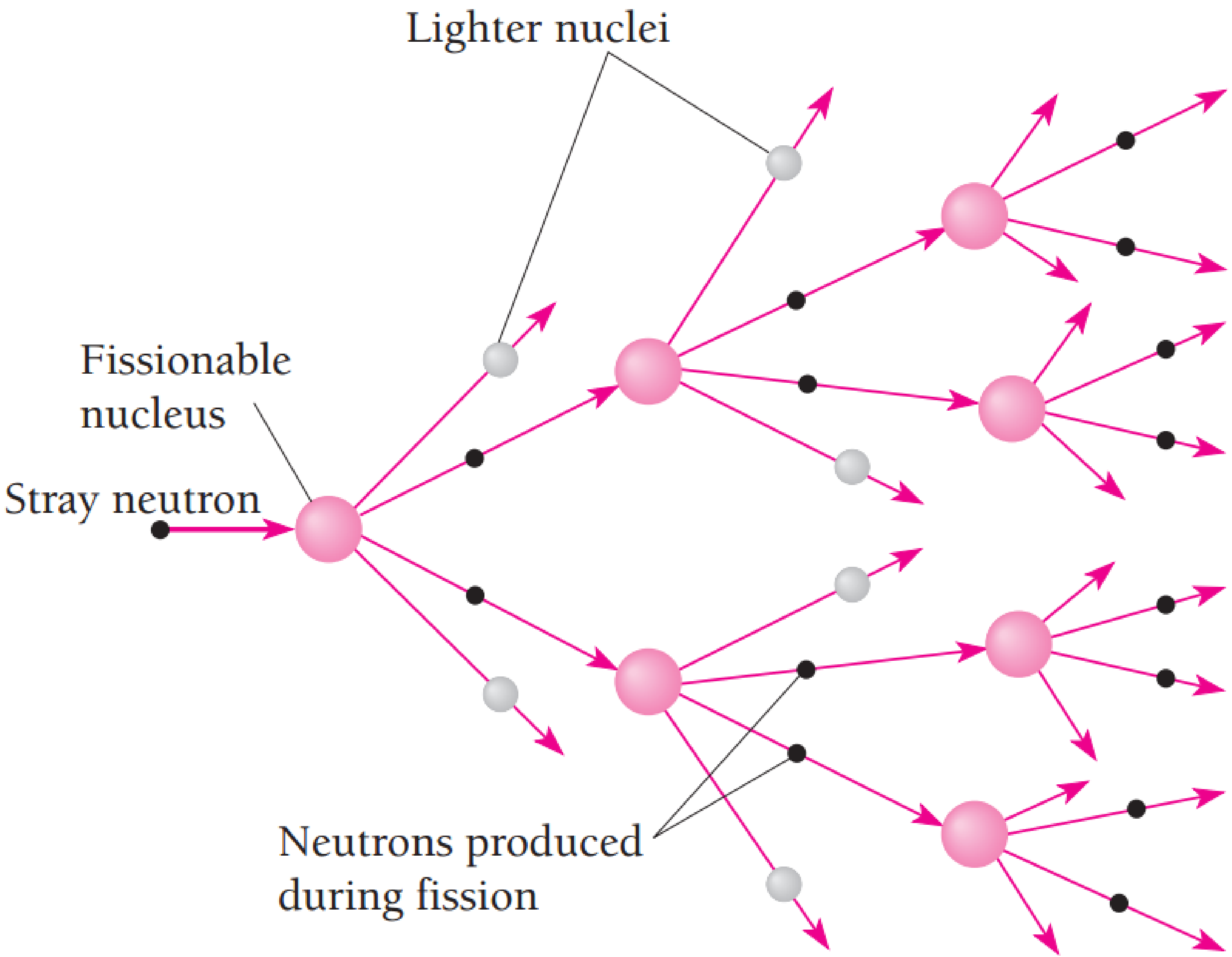
The masses of ^{14}N, ^{4}He, ^{1}H, and ^{17}O are respectively 14.00307 u, 4.00260 u, 1.00783 u, and 16.99913 u.

$$
\begin{aligned}
Q &= (14.00307\ \mathrm{u} + 4.00260\ \mathrm{u} - 1.00783\ \mathrm{u} - 16.99913\ \mathrm{u})\ (931.5\ \mathrm{MeV/u}) \\
&= -1.20\ \mathrm{MeV}
\end{aligned}
$$

Nuclear Reactions

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + {}^{1}_{0}n + {}^{1}_{0}n$$

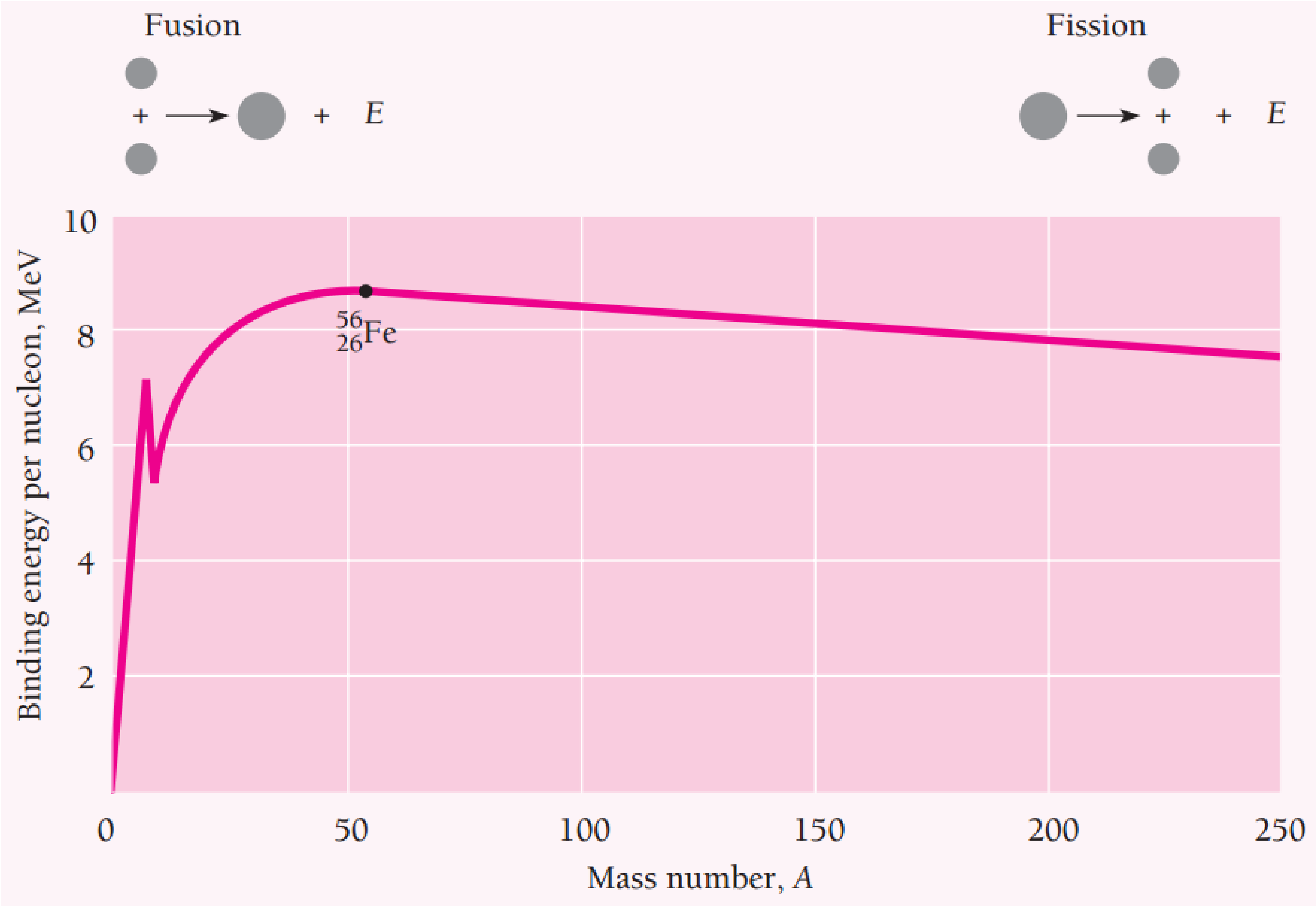
Nuclear Reactions



Nuclear Reactions

There are two main types of nuclear reactions: fusion and fission

In **fusion** reactions, two light nuclei are combined to form a heavier, more stable nucleus. In **fission** reactions, a heavy nucleus is split into two nuclei with smaller mass numbers. Both processes involve the exchange of huge amounts of energy: about a million times more energy than that associated with ordinary chemical reactions.


Fusion
+
+
E
Fission
+
+
E
10
8
6
4
2
Binding energy per nucleon, MeV
$^{56}_{26}Fe$
0
50
100
150
200
250
Mass number, A

Nuclear Fission

A nuclear reaction in which a heavy nucleus splits spontaneously or on impact with another particle, with the release of energy.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + {}^{1}_{0}n + {}^{1}_{0}n$$

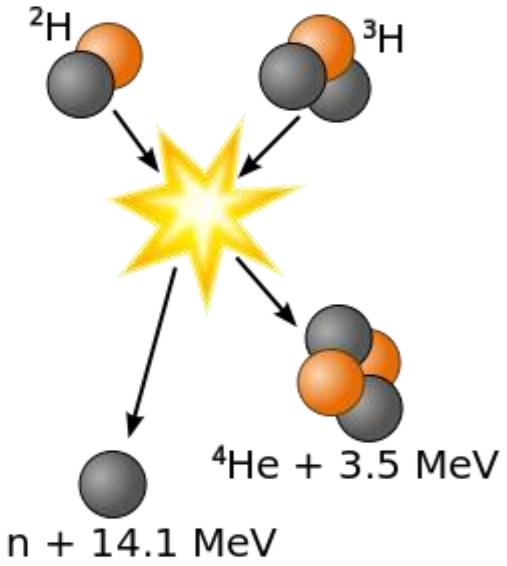
Nuclear Fusion

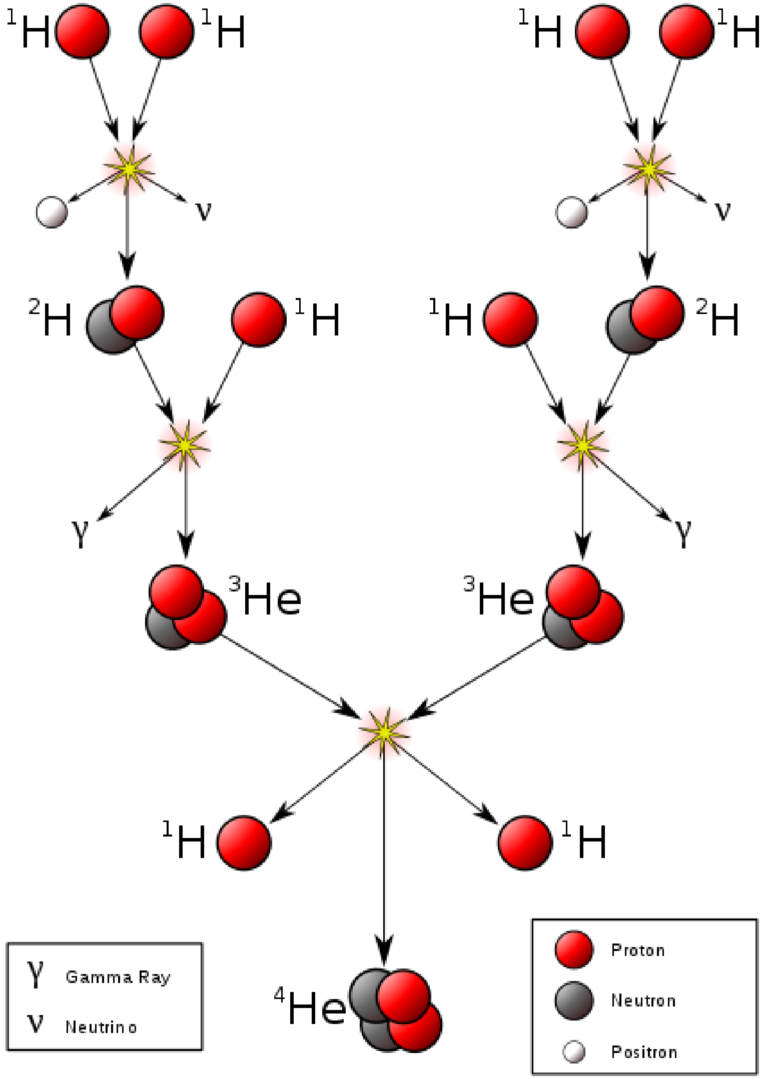
Nuclear fusion is an atomic reaction in which multiple atoms combine to create a single, more massive atom. The resulting atom has a slightly smaller mass than the sum of the masses of the original atoms. The difference in mass is released in the form of energy during the reaction

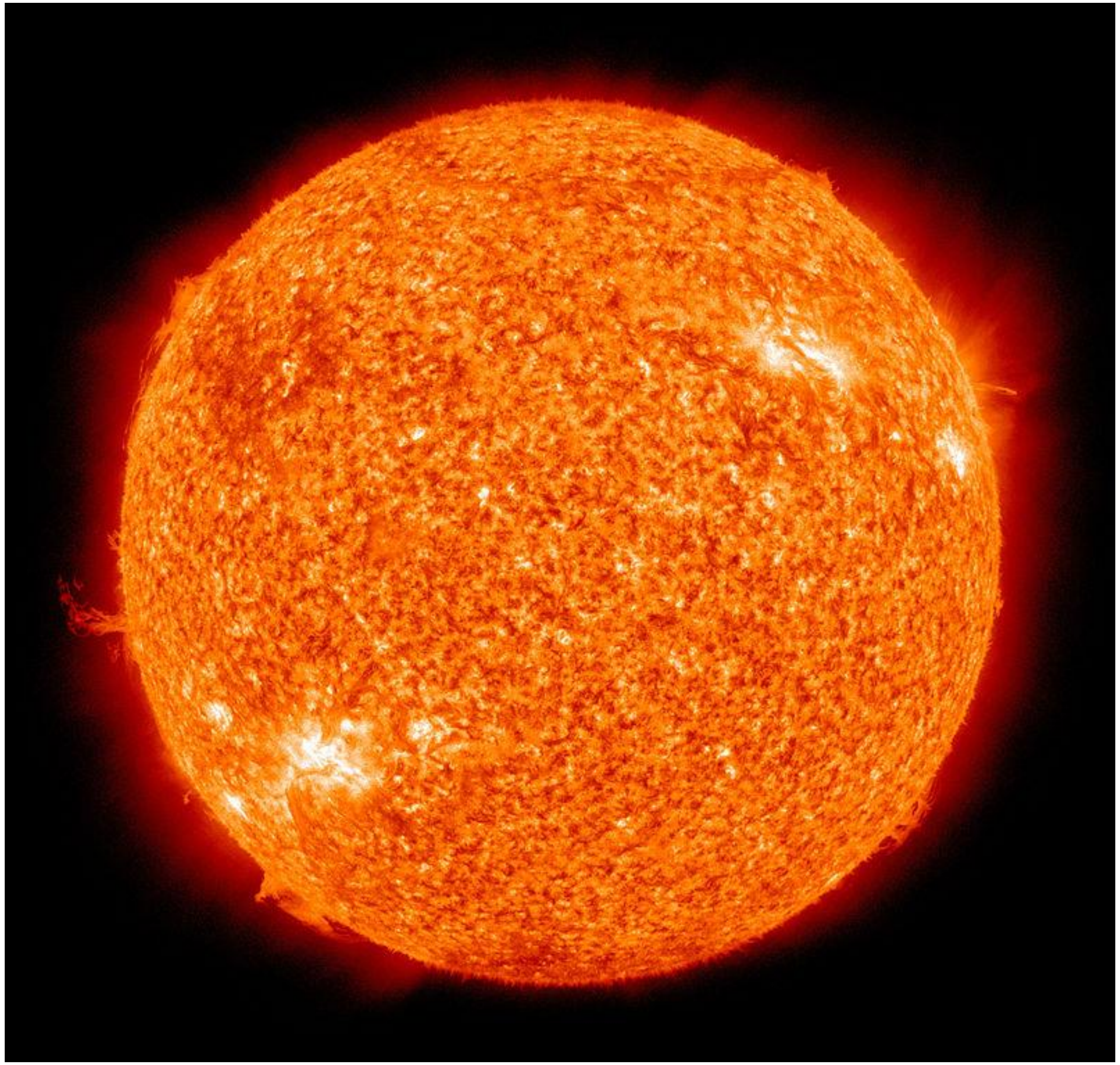
$$^{4}_{2}\text{He} + ^{12}_{6}\text{C} \rightarrow ^{16}_{8}\text{O}$$

$$^{12}_{6}\text{C} + ^{12}_{6}\text{C} \rightarrow ^{24}_{12}\text{Mg}$$

$$^{12}_{6}\text{C} + ^{12}_{6}\text{C} \rightarrow ^{20}_{10}\text{Ne} + ^{4}_{2}\text{He}$$



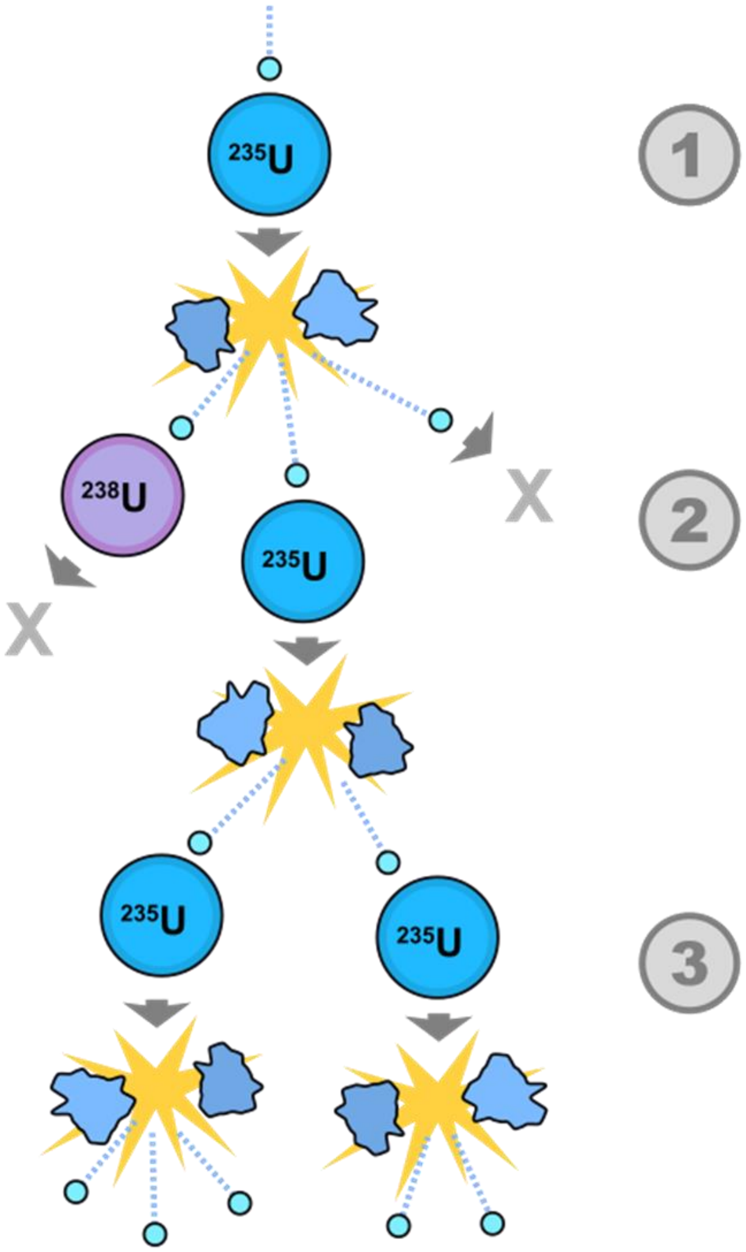




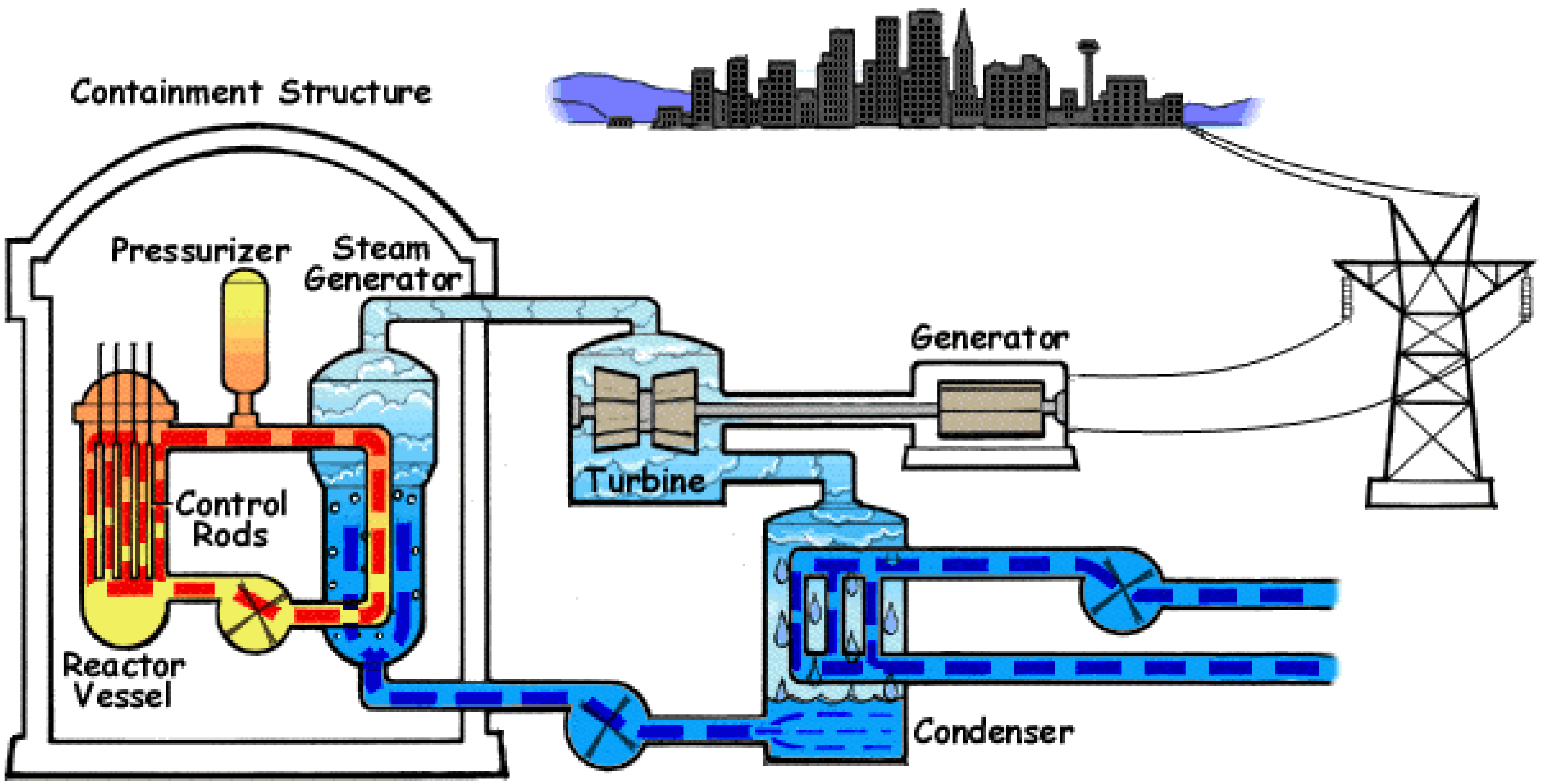
The proton-proton chain reaction dominates in stars the size of the Sun or smaller.

Hydrogen bomb:
man-made fusion device

Nuclear Reactor



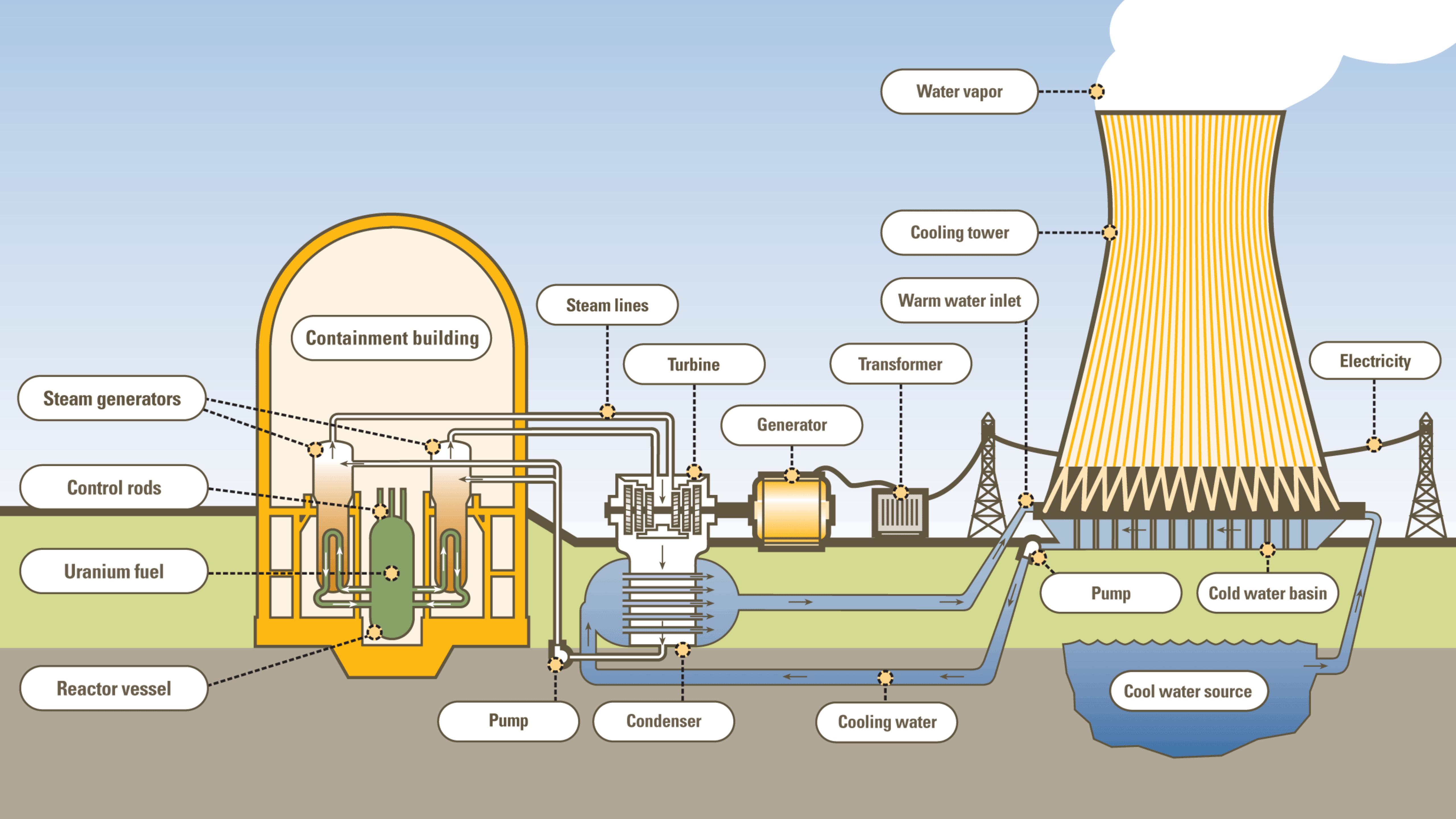
Nuclear Reactor



Nuclear Reactor

A nuclear reactor is a system that contains and controls sustained nuclear chain reactions. Reactors are used for generating electricity, moving submarines, producing medical isotopes for imaging and cancer treatment, and for conducting research.

Fuel, made up of heavy atoms that split when they absorb neutrons, is placed into the reactor vessel (basically a large tank) along with a small neutron source. The neutrons start a chain reaction where each atom that splits releases more neutrons that cause other atoms to split. Each time an atom splits, it releases large amounts of energy in the form of heat. The heat is carried out of the reactor by coolant, which is most commonly just plain water. The coolant heats up and goes off to a turbine to spin a generator.


Water vapor
Cooling tower
Containment building
Steam lines
Warm water inlet
Turbine
Transformer
Electricity
Steam generators
Generator
Control rods
Uranium fuel
Pump
Cold water basin
Reactor vessel
Cool water source
Pump
Condenser
Cooling water

Main components of a Nuclear Reactor

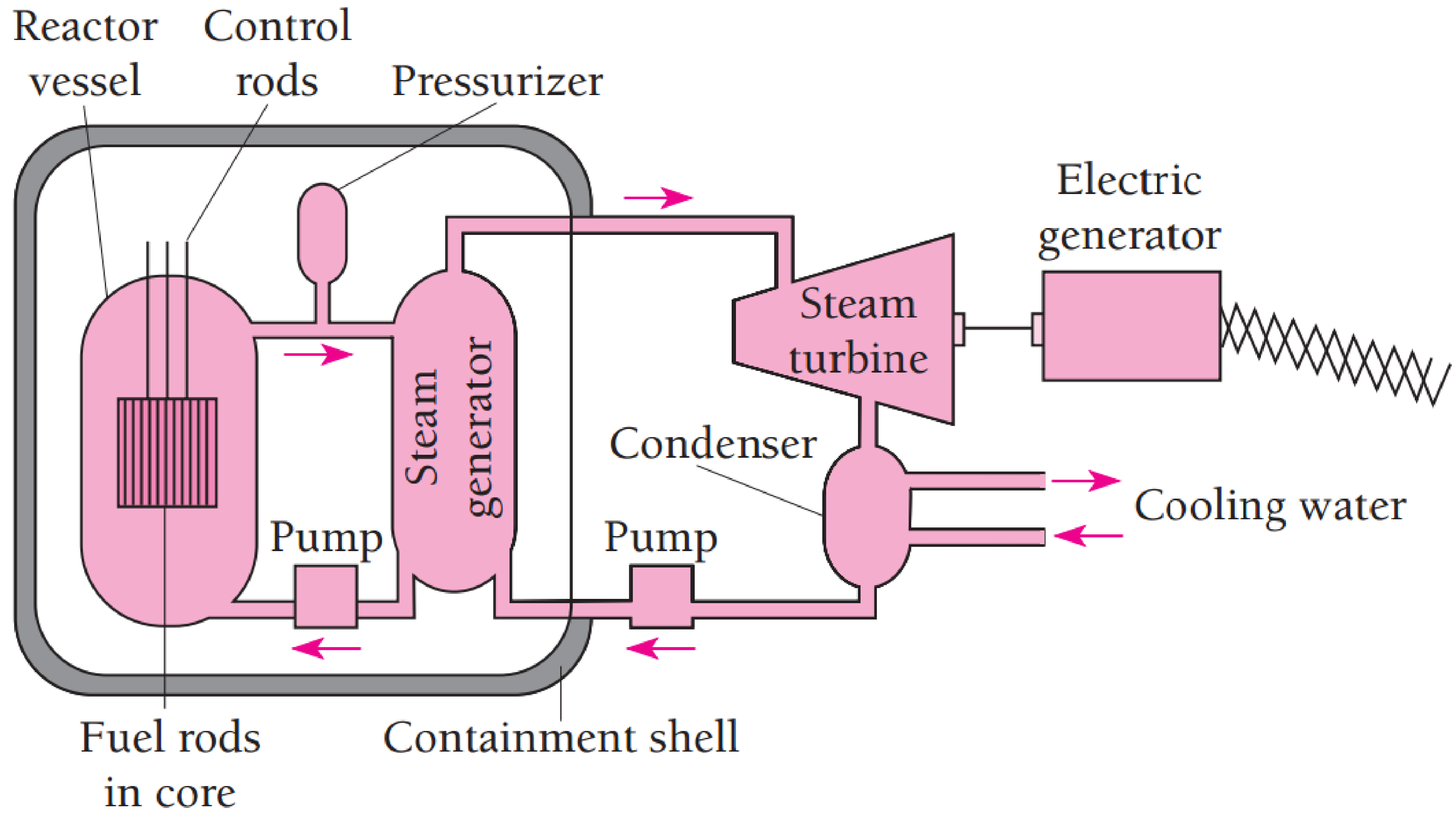
The core

The coolant

The turbine

The containment

Cooling towers



Main components of a Nuclear Reactor

The core of the reactor contains all of the nuclear fuel and generates all of the heat. It contains low-enriched uranium (<5% U-235), control systems, and structural materials. The core can contain hundreds of thousands of individual fuel pins.

The coolant is the material that passes through the core, transferring the heat from the fuel to a turbine. It could be water, heavy-water, liquid sodium, helium, or something else. In the US fleet of power reactors, water is the standard.

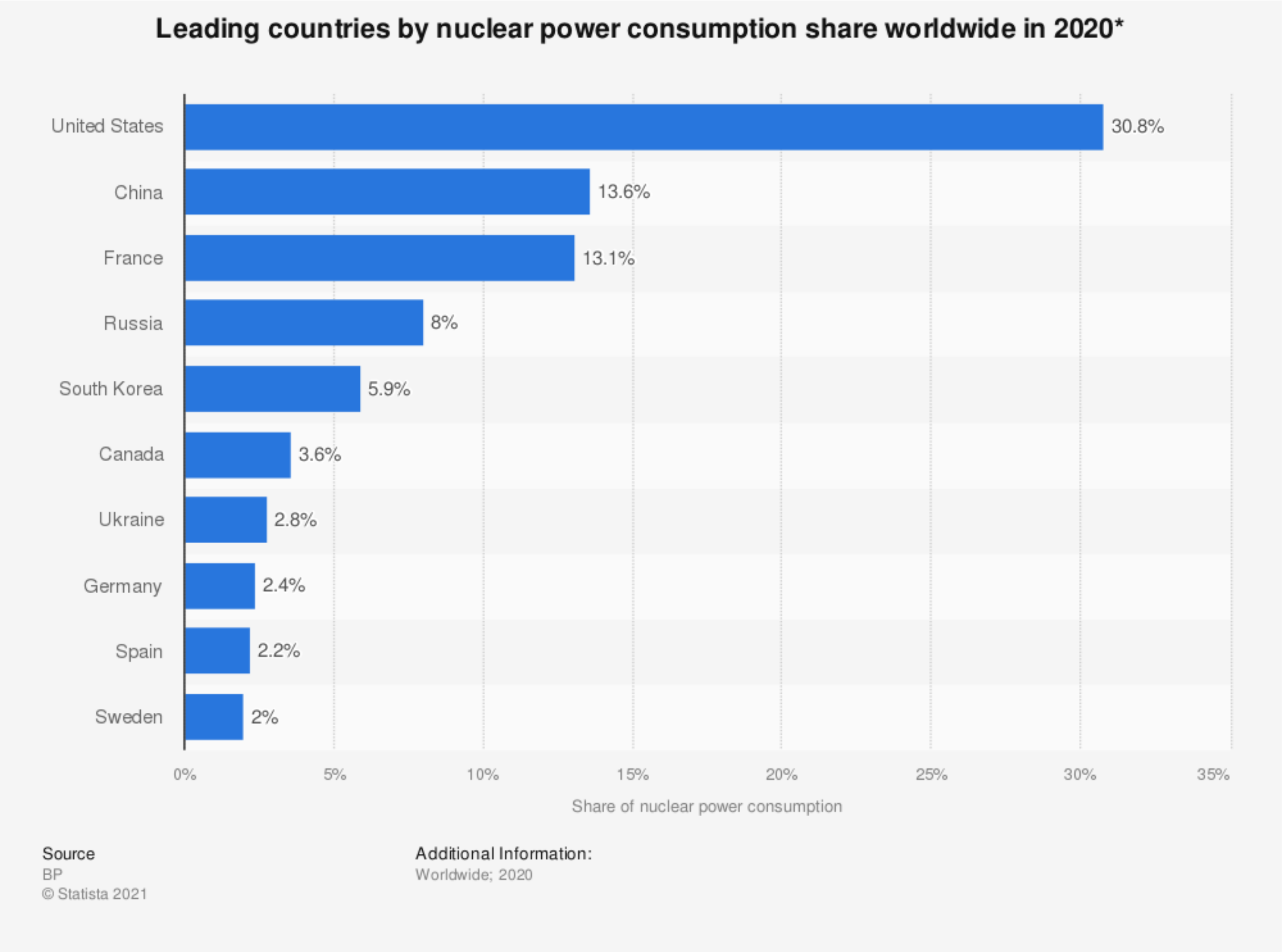
The turbine transfers the heat from the coolant to electricity, just like in a fossil-fuel plant.

Main components of a Nuclear Reactor

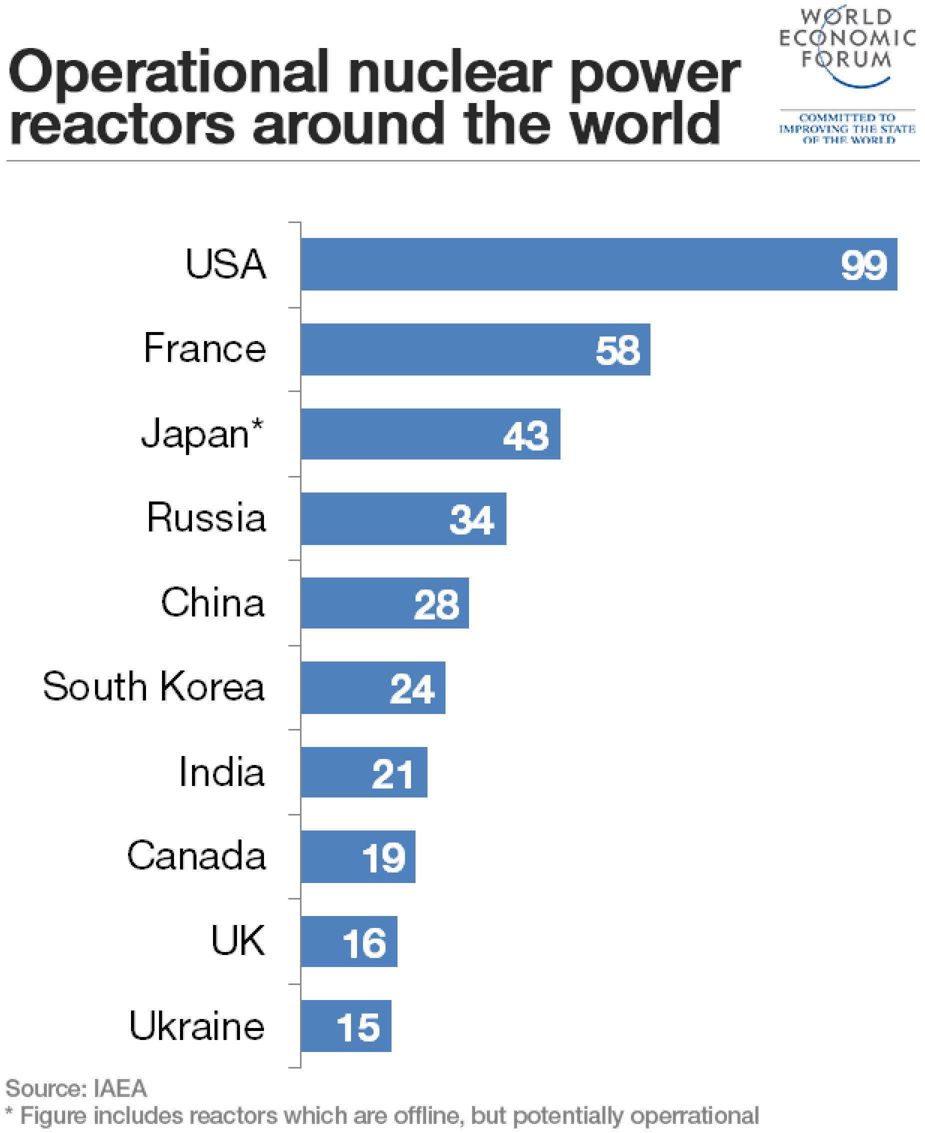
The containment is the structure that separates the reactor from the environment. These are usually dome-shaped, made of high-density, steel-reinforced concrete. Chernobyl did not have a containment to speak of.

Cooling towers are needed by some plants to dump the excess heat that cannot be converted to energy due to the laws of thermodynamics. These are the hyperbolic icons of nuclear energy. They emit only clean water vapor.

https://whatisnuclear.com/articles/nucreactor.html



Leading countries by nuclear power consumption share worldwide in 2020*
United States 30.8%
China 13.6%
France 13.1%
Russia 8%
South Korea 5.9%
Canada 3.6%
Ukraine 2.8%
Germany 2.4%
Spain 2.2%
Sweden 2%
0% 5% 10% 15% 20% 25% 30% 35%
Share of nuclear power consumption
Source
BP
© Statista 2021
Additional Information:
Worldwide; 2020



Operational nuclear power reactors around the world
WORLD ECONOMIC FORUM
COMMITTED TO IMPROVING THE STATE OF THE WORLD
USA 99
France 58
Japan* 43
Russia 34
China 28
South Korea 24
India 21
Canada 19
UK 16
Ukraine 15
Source: IAEA
* Figure includes reactors which are offline, but potentially operational

Fusion reaction

The energy source of the future?

Enormous as the energy produced by fission is, the fusion of light nuclei to form heavier ones can give out even more per kilogram of starting materials. It seems possible that nuclear fusion could become the ultimate source of energy on the earth: safe, relatively non-polluting, and with the oceans themselves supplying limitless fuel.

$$\boxed{{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + 4.0\ \mathrm{MeV}}$$

$$\boxed{{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}n + 3.3\ \mathrm{MeV}}$$

Fusion reaction

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$$ {}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n + 17.6\ \mathrm{MeV} $$

Fusion reaction

A successful fusion reactor has three basic conditions to meet:

1 The plasma temperature must be high so that an adequate number of the ions have the speeds needed to come close enough together to react despite their mutual repulsion. Taking into account that many ions have speeds well above the average and that tunneling through the potential barrier reduces the ion energy needed, the minimum temperature for igniting a D-T plasma is about 100 million K, which corresponds to an "ion temperature" of $kT \sim 10$ keV.

2 The plasma density n (in ions/m^3) must be high to ensure that collisions between nuclei are frequent.

3 The plasma of reacting nuclei must remain together for a sufficiently long time τ. How long depends on the product $n\tau$, the confinement quality parameter. In the case of a D-T plasma with $kT \sim 10$ keV, $n\tau$ must be greater than roughly 10^{20} s/m^3 for breakeven, more than that for ignition

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