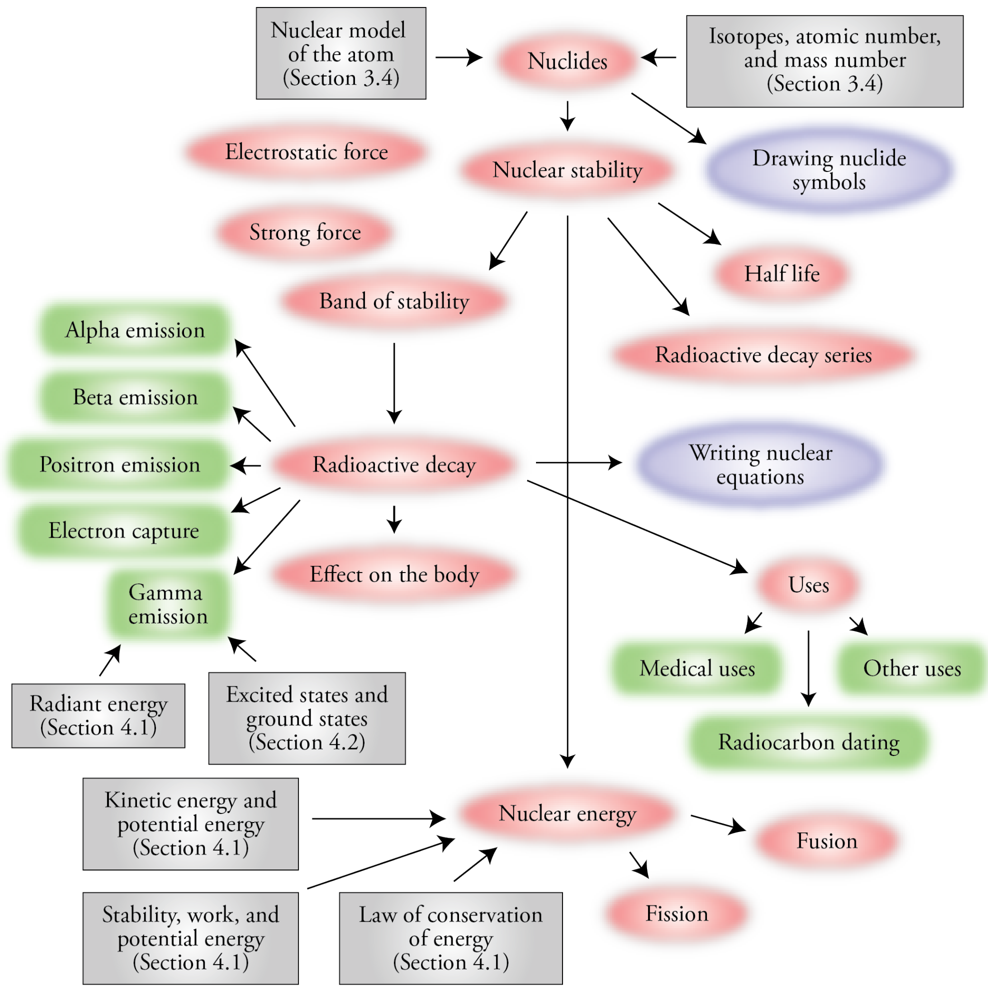
Chapter 16
Nuclear Chemistry

An Introduction to Chemistry

by Mark Bishop

Chapter Map



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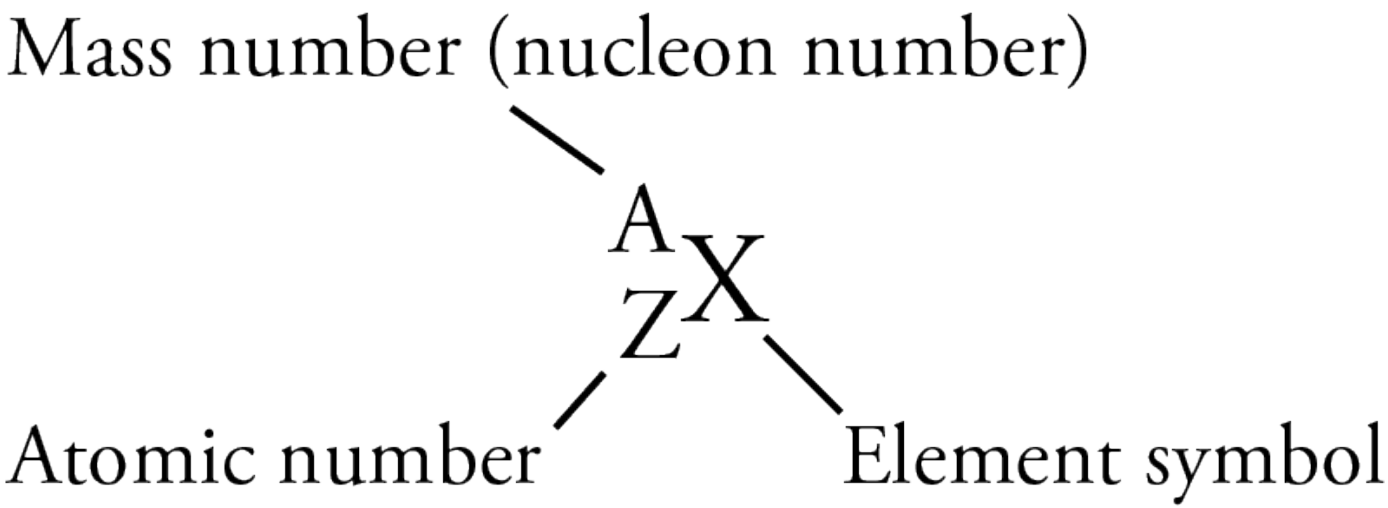
Nuclides

- ***Nuclide*** = a particular type of nucleus, characterized by a specific number of protons and neutrons and therefore a specific atomic number and nucleon number.
- ***Nucleon number*** or *mass number* = the number of ***nucleons*** (protons and neutrons) in the nucleus of a nuclide.

Nuclide Symbolism



Radioactive Iodine

- One of the products of the fission reaction of uranium atoms with 92 protons and 143 neutrons is iodine atoms with 53 protons and 78 neutrons.

${}^{235}_{92}\mathrm{U}$	${}^{235}\mathrm{U}$	U-235	uranium-235
${}^{131}_{53}\mathrm{I}$	${}^{131}\mathrm{I}$	I-131	iodine-131

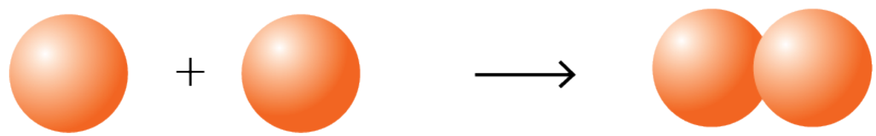
Two Forces in Nucleus

- ***Electromagnetic force*** = the force that causes opposite electrical charges to attract each other and like charges to repel each other.
- ***Strong force*** = the attractive force between nucleons (protons and neutrons).

Formation of a Helium Nucleus

- Helium-2 with just two protons nucleus is unstable.

$$p + p \longrightarrow {}^{2}_{2}He^{2+}$$

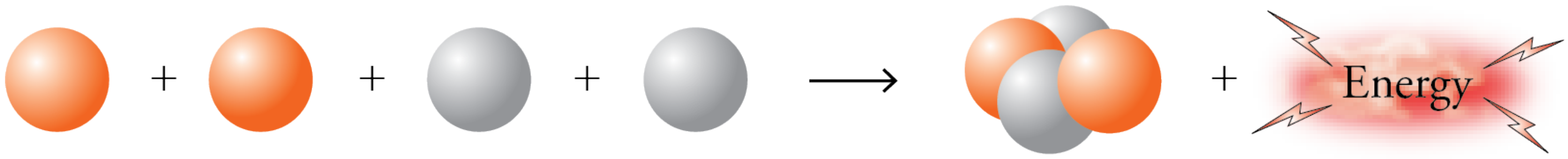


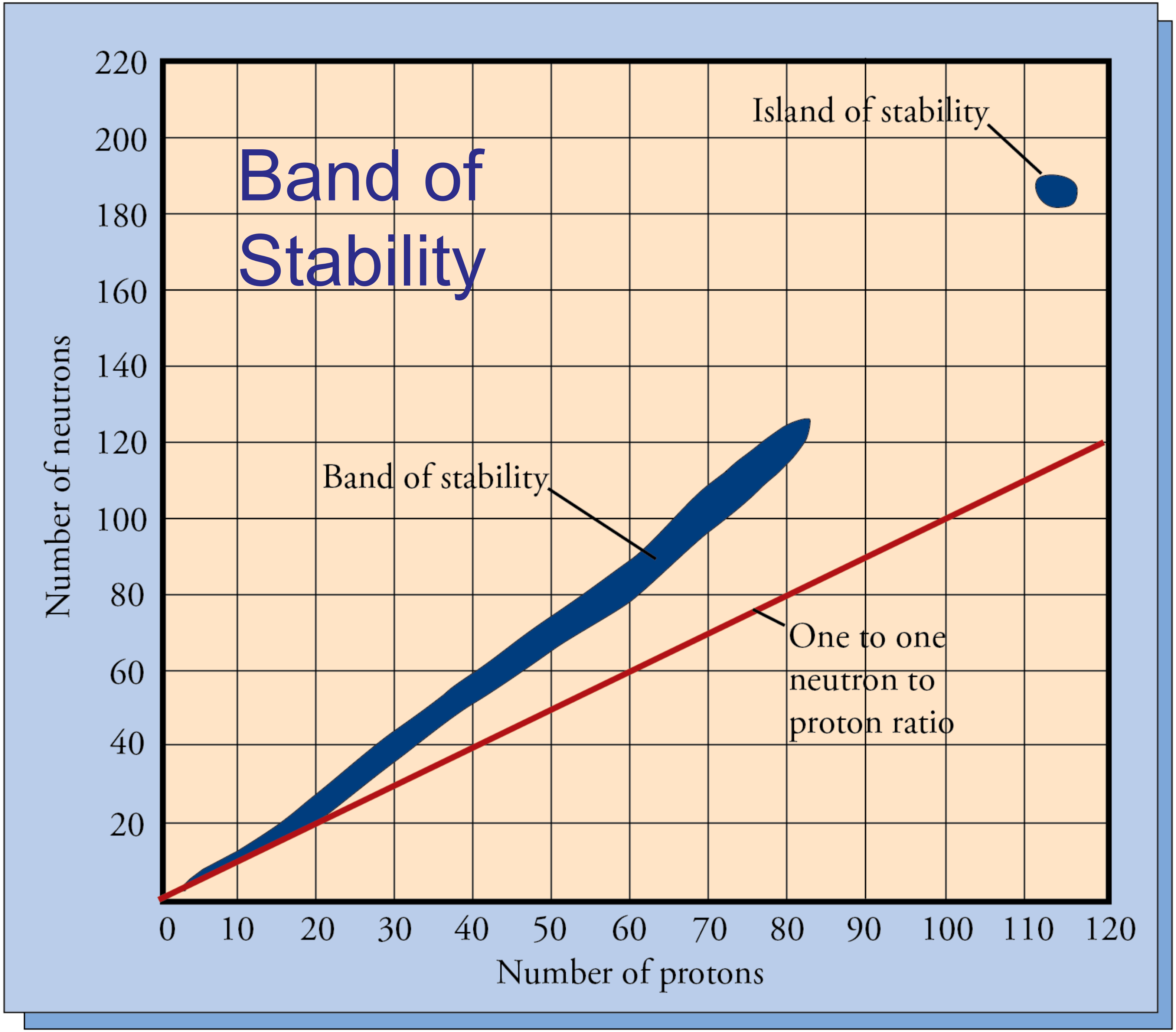
- The shorter the distance between the protons is, the stronger the electromagnetic repulsion between them.
- When they are close enough to form a helium nucleus, the strong force is not strong enough to overcome the electromagnetic repulsion, so the protons are pushed apart.

Nuclear Stability

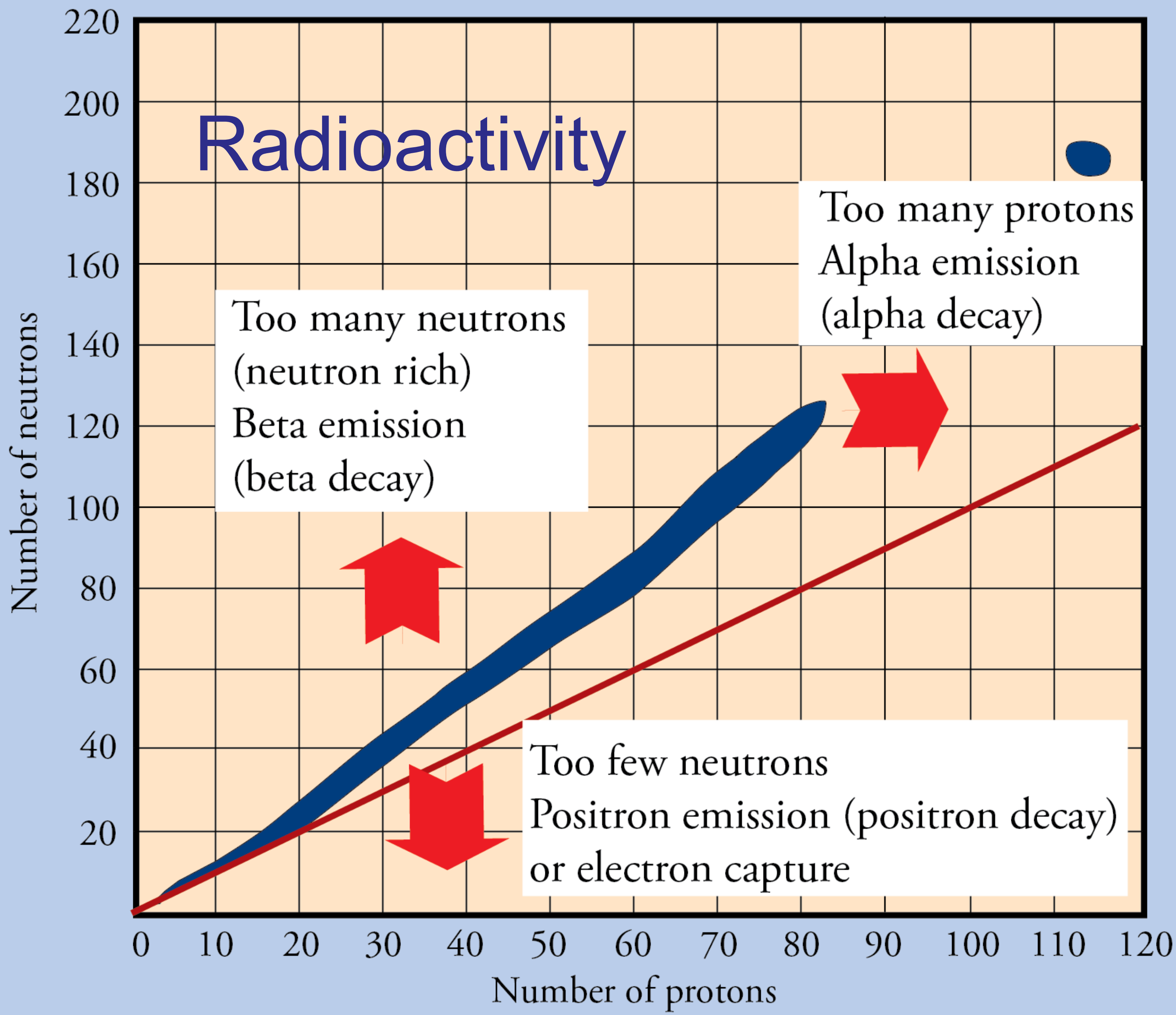
- Neutrons increase the attraction from the strong force without increasing electromagnetic repulsion between nucleons.
- Combining two neutrons with two protons increases the strong force enough to overcome the electromagnetic repulsion, making a stable helium nucleus.

$$p + p + n + n \longrightarrow {}^{4}_{2}He^{2+}$$



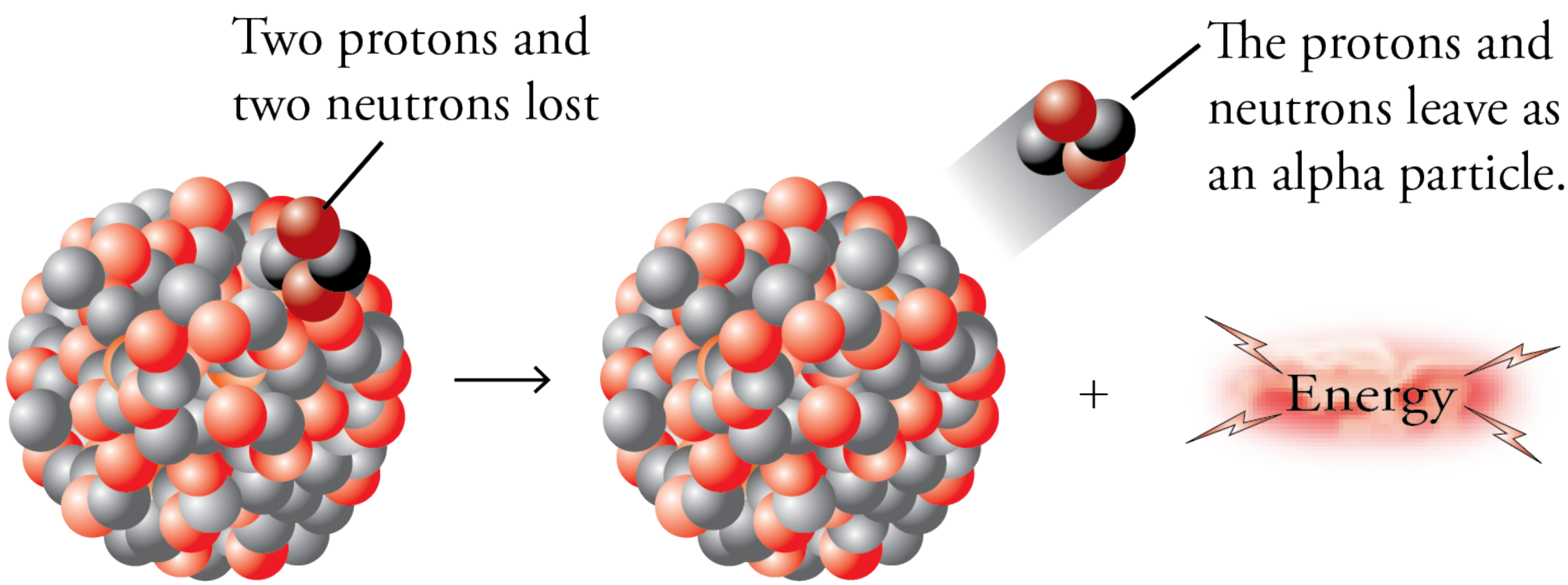

Band of Stability
Island of stability
Band of stability
One to one neutron to proton ratio
Number of neutrons
Number of protons
0
10
20
30
40
50
60
70
80
90
100
110
120
20
40
60
80
100
120
140
160
180
200
220

Radioactivity



Alpha Emission

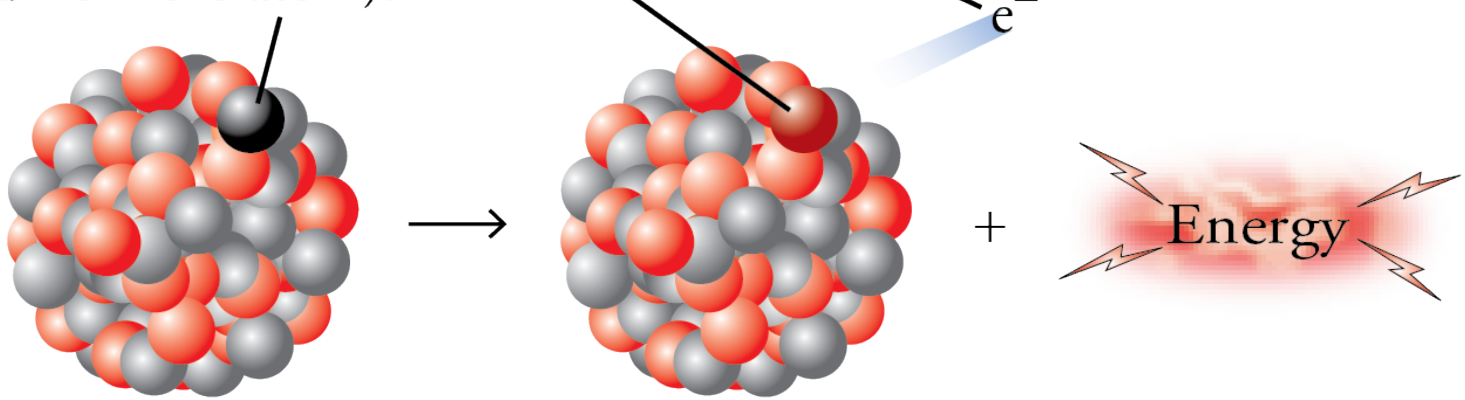
$$^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$$



Beta Emission

$$^{131}_{53}\text{I} \longrightarrow \, ^{131}_{54}\text{Xe} + \, ^{0}_{-1}\text{e}$$

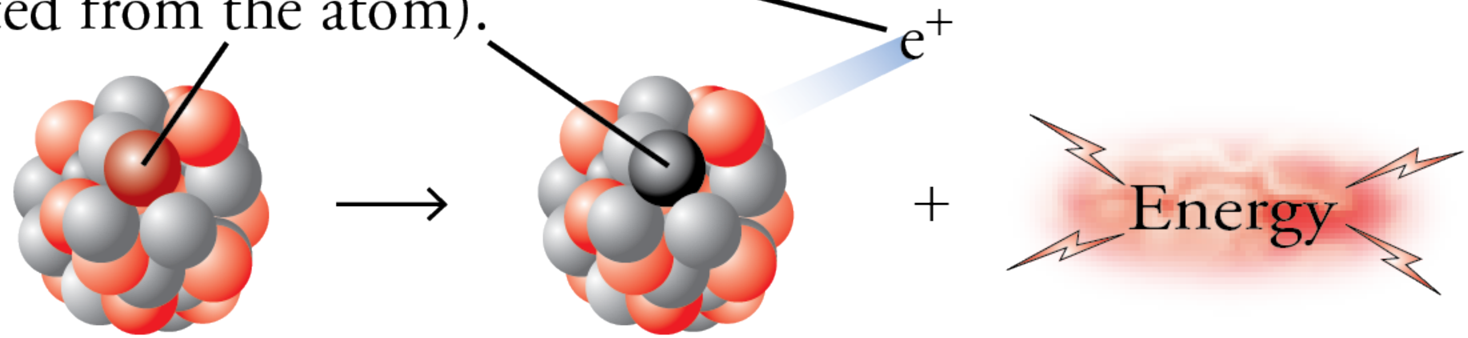
A neutron becomes a proton (which stays in the nucleus) and an electron (which is ejected from the atom).



Positron Emission

$$^{40}_{19}K \longrightarrow \ ^{40}_{18}Ar + \ ^{0}_{+1}e$$

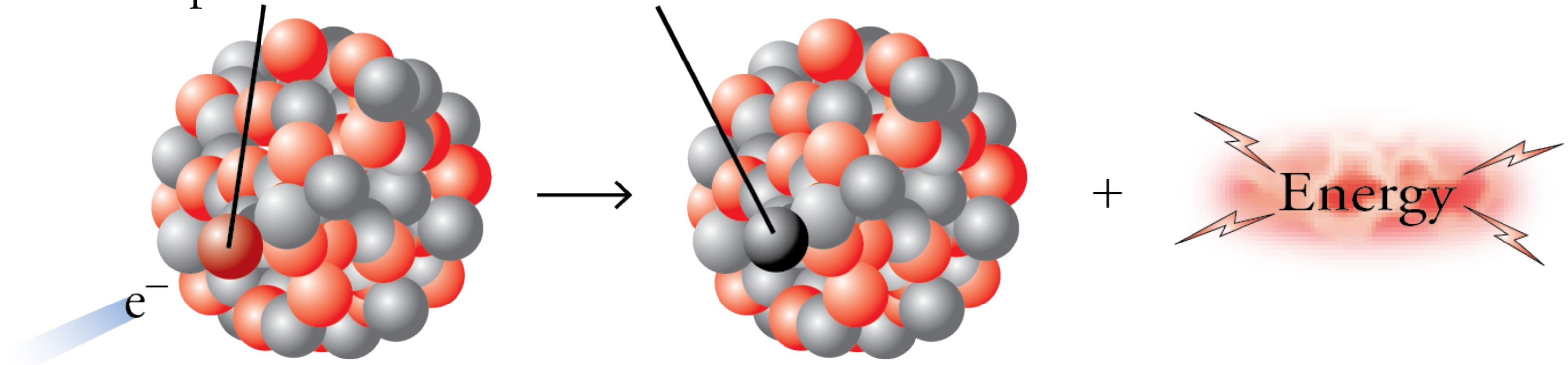
A proton becomes a neutron (which stays in the nucleus) and a positron (which is ejected from the atom).



Electron Capture

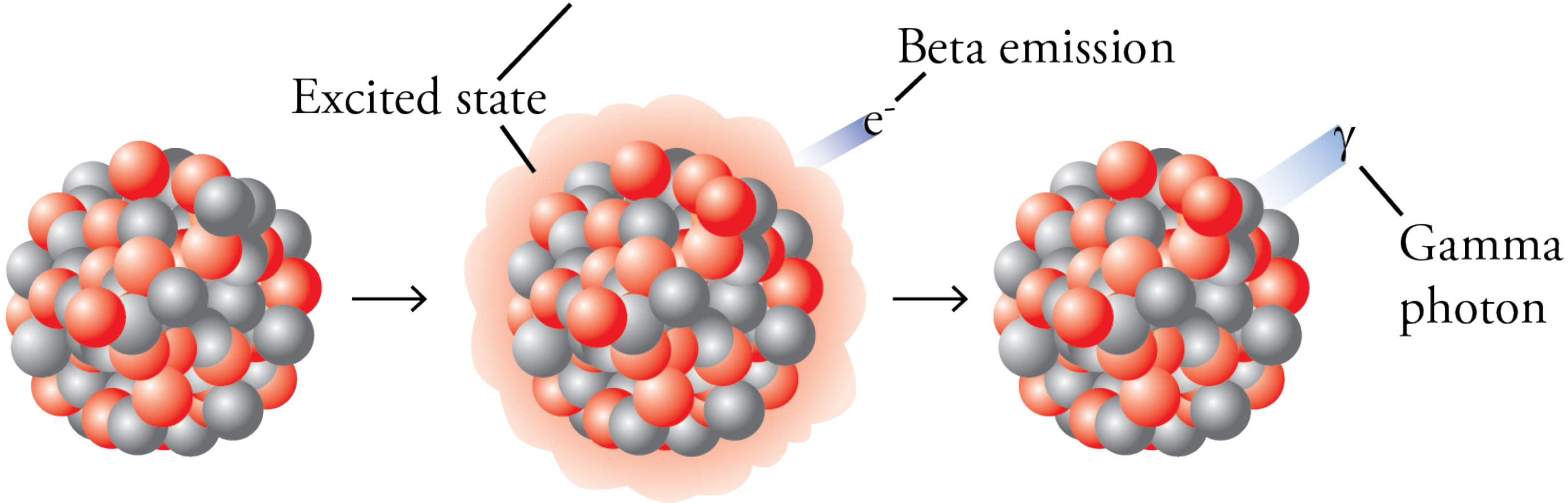
$${}^{0}_{-1}e + {}^{125}_{53}I \longrightarrow {}^{125}_{52}Te$$

An electron combines with a proton to form a neutron.



Gamma Emission

$$^{137}_{55}\mathrm{Cs} \longrightarrow {}^{137}_{56}\mathrm{Ba}^{*} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{137}_{56}\mathrm{Ba} + \gamma\text{-photon}$$



Nuclear Reactions

- Nuclear reactions involve changes in the nucleus, whereas chemical reactions involve the loss, gain, and sharing of electrons.
- Different isotopes of the same element may undergo very different nuclear reactions, even though an element's isotopes all share the same chemical characteristics.

Nuclear Reactions (2)

- Unlike chemical reactions, the rates of nuclear reactions are unaffected by temperature, pressure, and the presence of other atoms to which the radioactive atom may be bonded.
- Nuclear reactions, in general, give off much more energy than chemical reactions.

Nuclear Equations

Alpha emission

mass number	238		234	+	4	=	238
	$^{238}_{92}\text{U}$	$\longrightarrow$	$^{234}_{90}\text{Th}$	+	$^{4}_{2}\text{He}$		
atomic number	92		90	+	2	=	92

Beta emission

mass number	131		131	+	0	=	131
	$^{131}_{53}\text{I}$	$\longrightarrow$	$^{131}_{54}\text{Xe}$	+	$^{0}_{-1}\text{e}$		
atomic number	53		54	+	(−1)	=	53

Positron emission

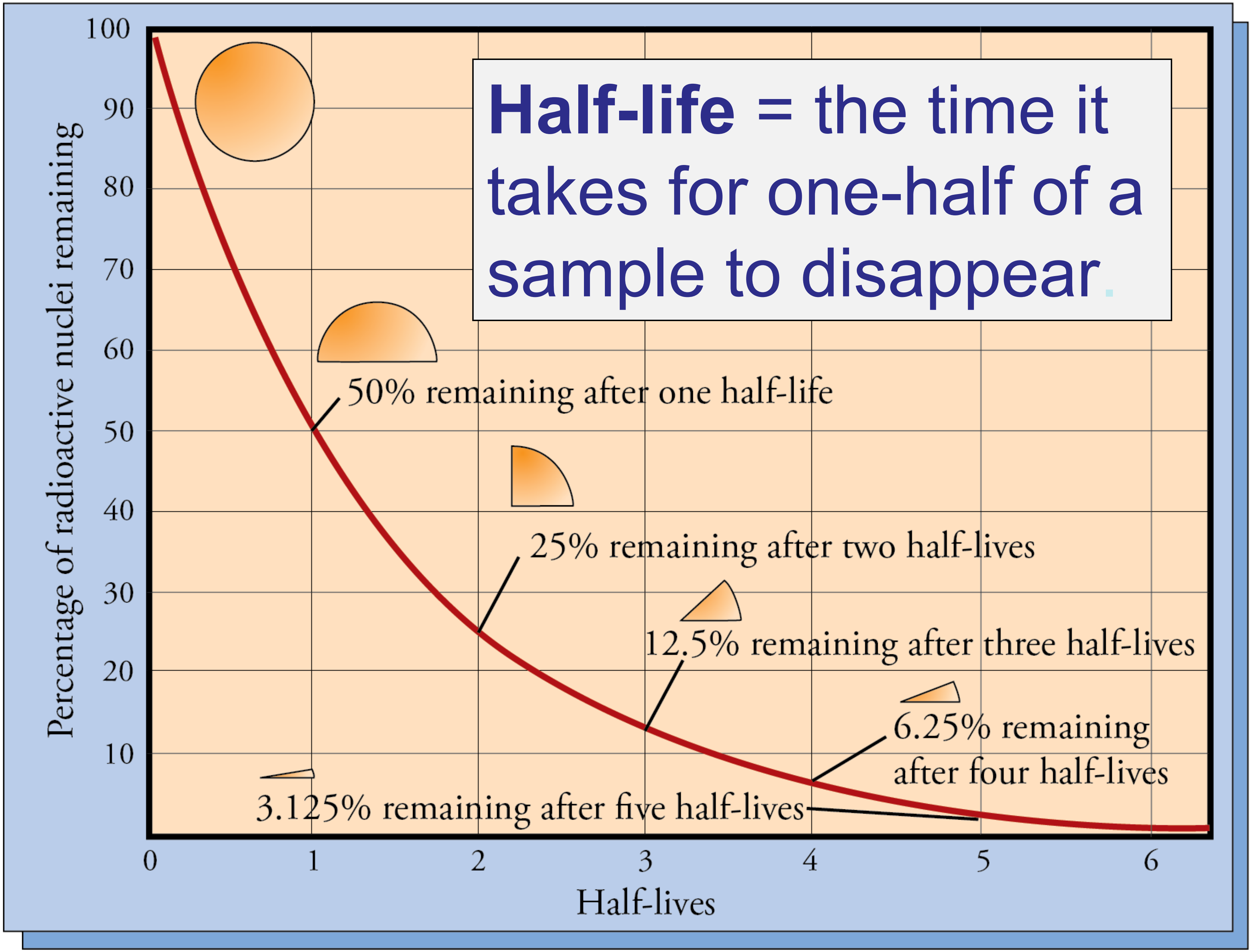
mass number	40		40	+	0	=	40
	$^{40}_{19}\text{K}$	$\longrightarrow$	$^{40}_{18}\text{Ar}$	+	$^{0}_{+1}\text{e}$		
atomic number	19		18	+	1	=	19

Electron capture

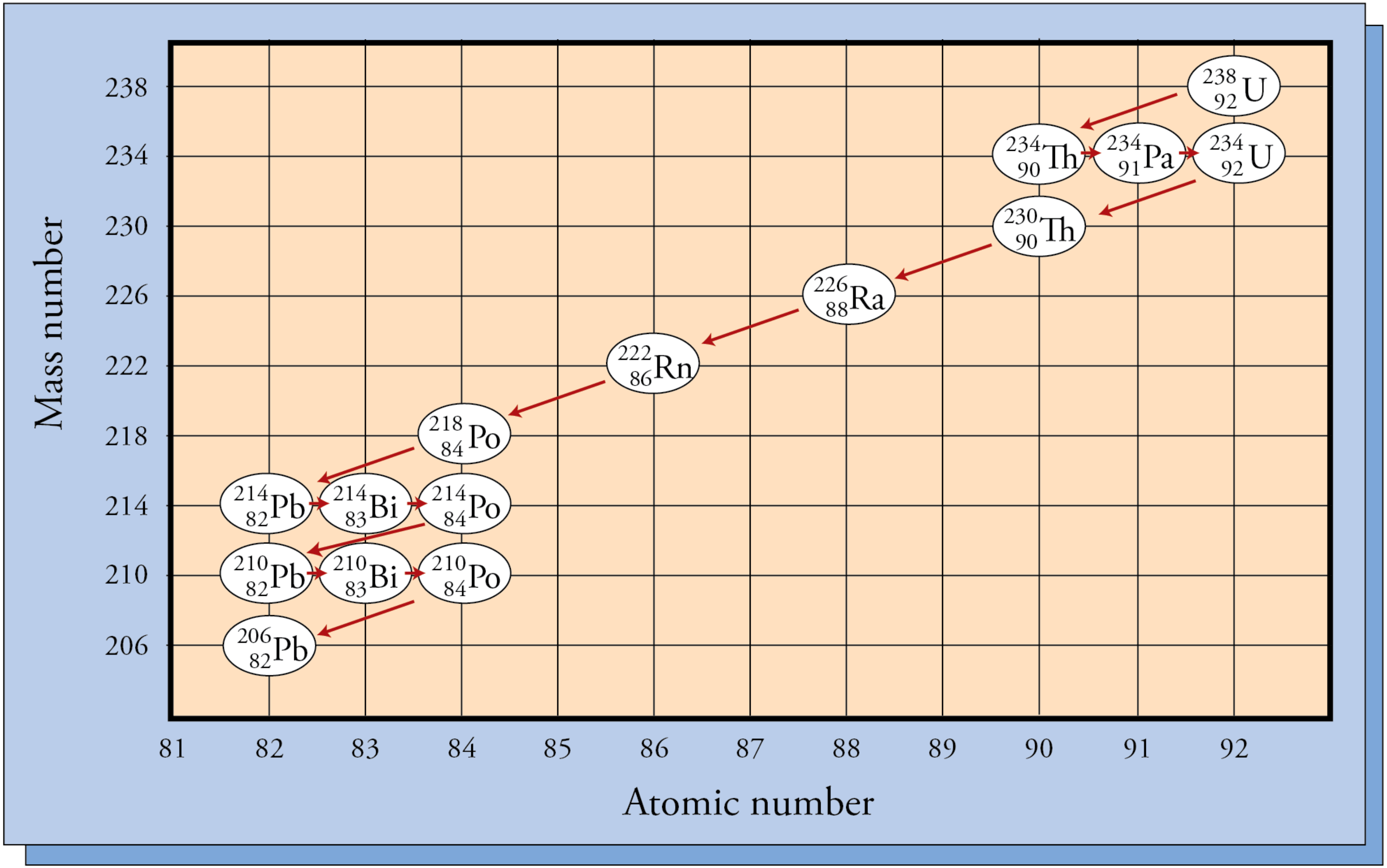
mass number	0	+	125	=	125		125
	$^{0}_{-1}\text{e}$	+	$^{125}_{53}\text{I}$			$\longrightarrow$	$^{125}_{52}\text{Te}$
atomic number	−1	+	53	=	52		52

General Nuclear Equations

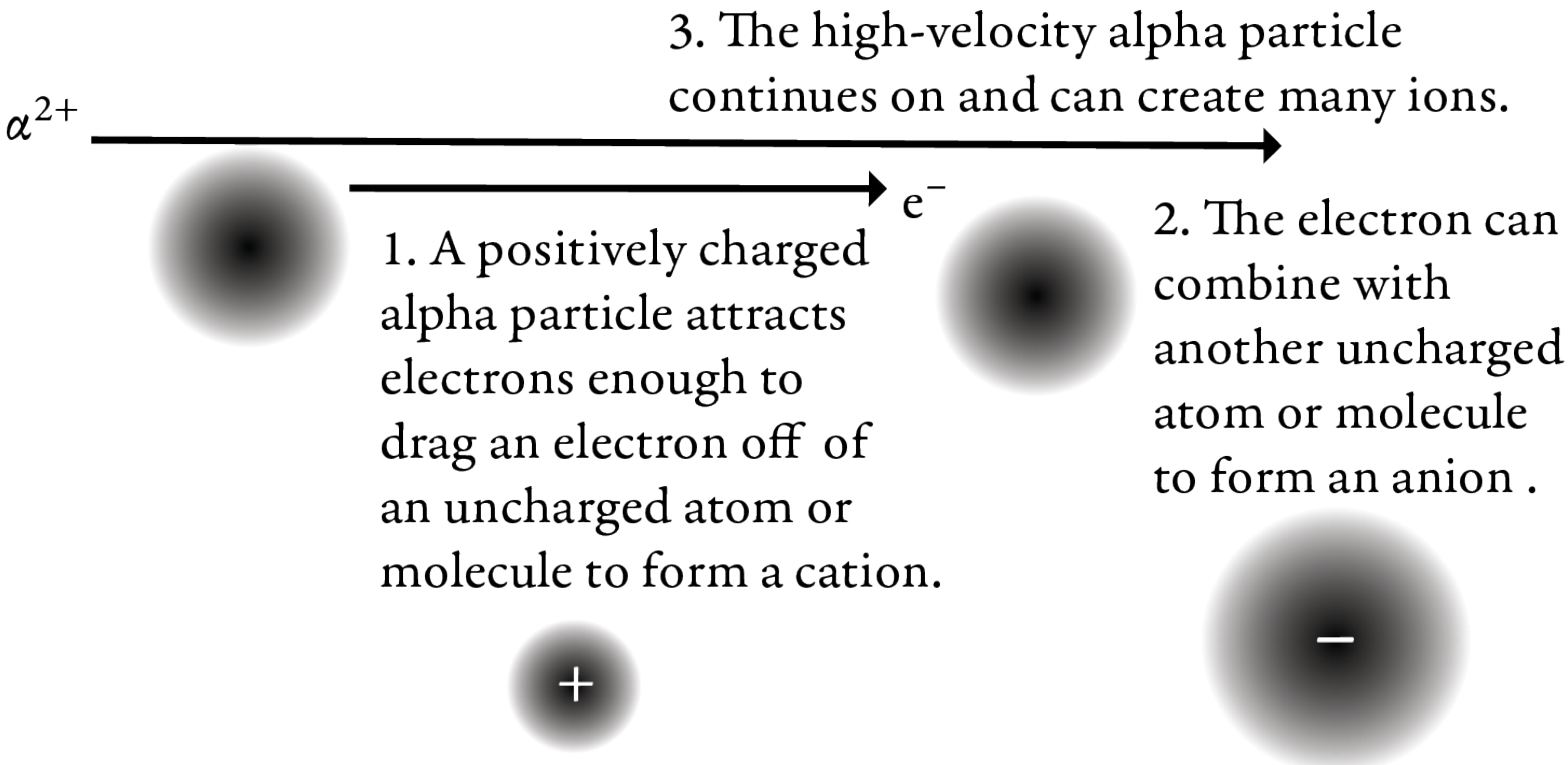
Alpha emission	$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
Beta emission	$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$
Positron emission	$^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$
Electron capture	${}^{0}_{-1}e + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y$


Half-life = the time it takes for one-half of a sample to disappear.
Percentage of radioactive nuclei remaining
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
Half-lives
50% remaining after one half-life
25% remaining after two half-lives
12.5% remaining after three half-lives
6.25% remaining after four half-lives
3.125% remaining after five half-lives

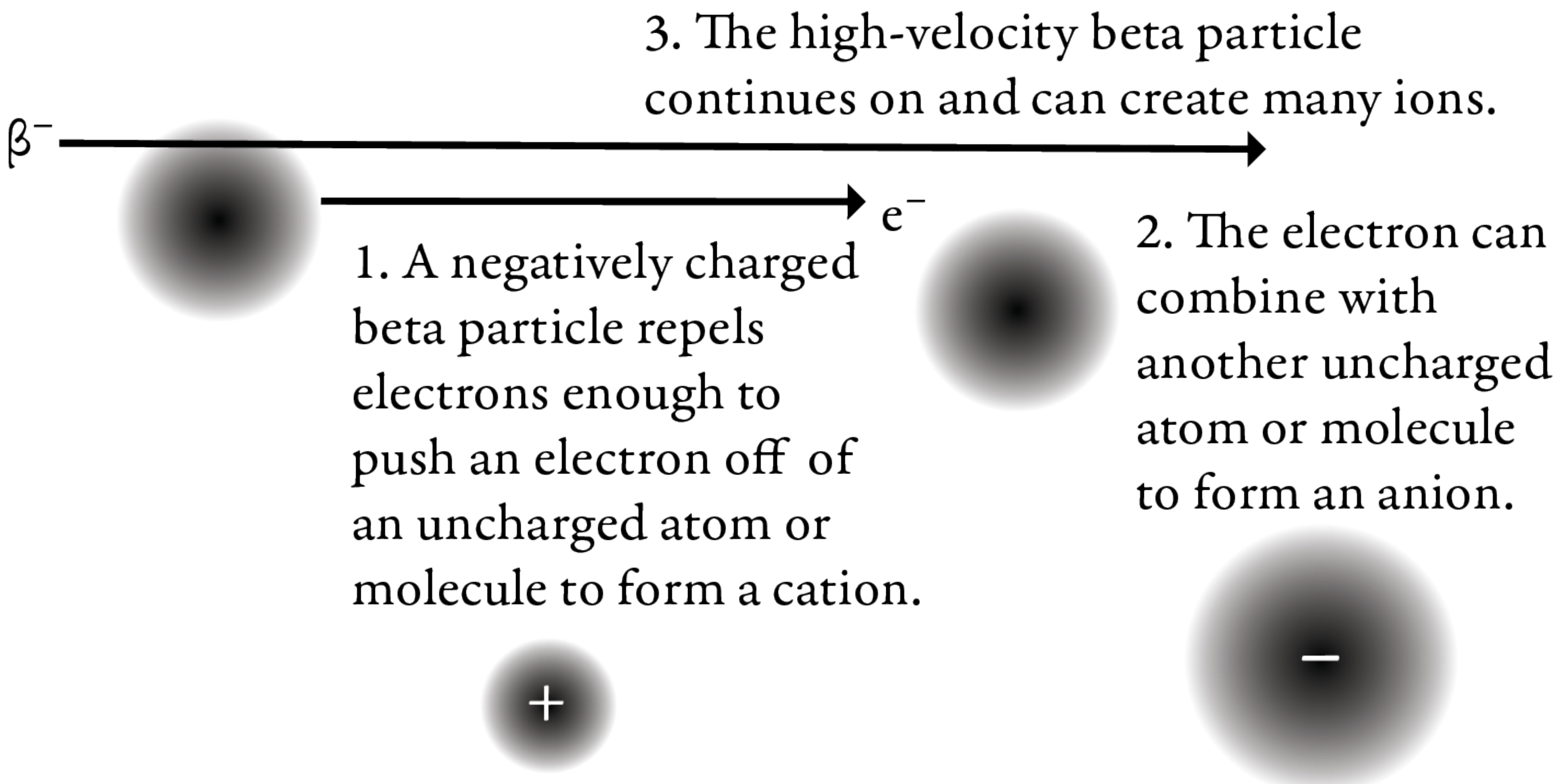
Radioactive Decay Series



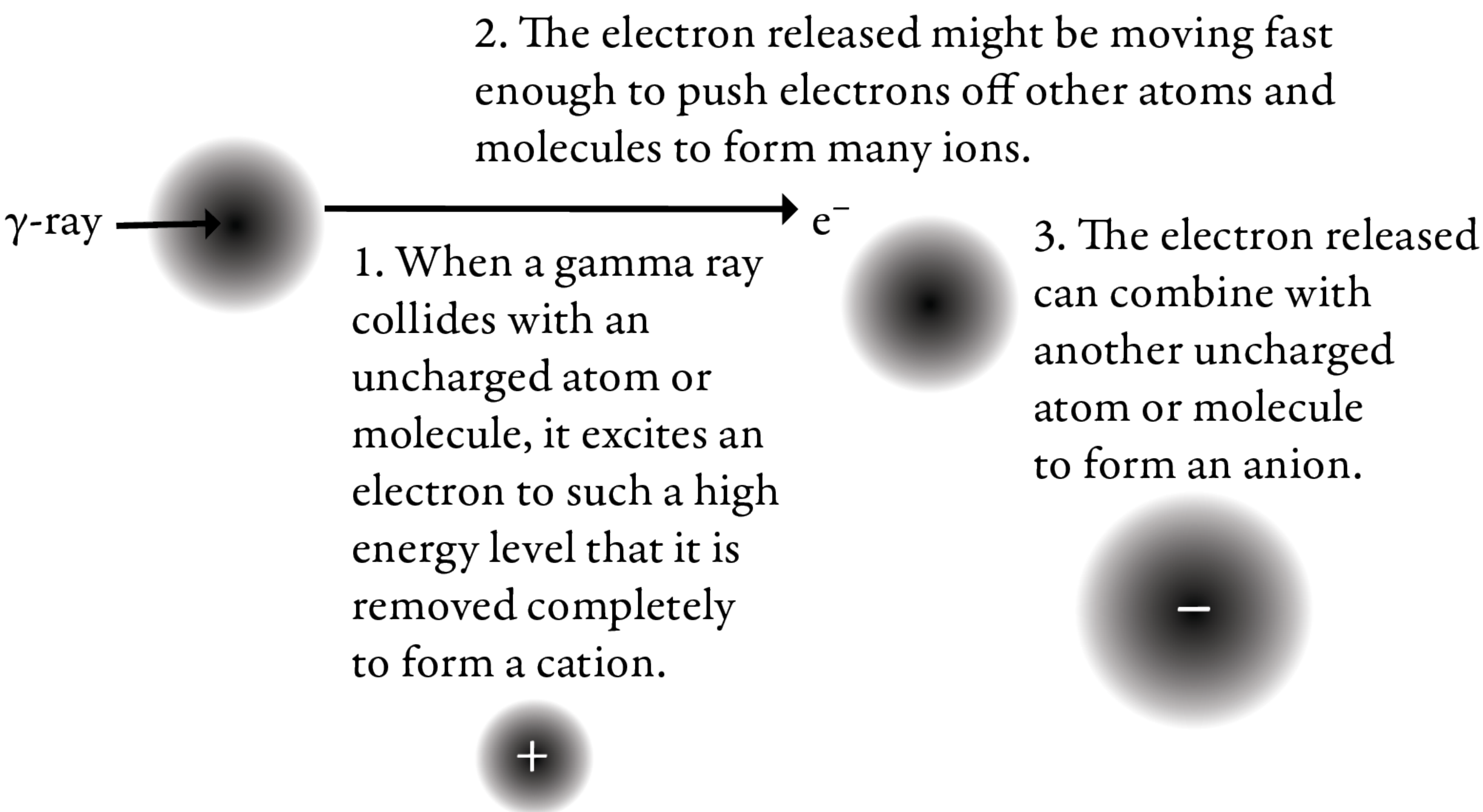
Ionization by Alpha Particles



Ionization by Beta Particles



Ionization by Gamma Rays



Radiation Effect on Body

- As the radioactive emissions ionize atoms and molecules, such as water molecules, they also form highly reactive free radicals, which are particles with unpaired electrons.

$$H_2O \rightarrow H_2O\bullet^{+} + e^{-}$$

$$H_2O\bullet^{+} + H_2O \rightarrow H_3O^{+} + \bullet OH$$

$$H_2O + e^{-} \rightarrow H\bullet + OH^{-}$$

- These reactive particles react with important substances in the body, leading to immediate damage and delayed problems, such as cancer.

Penetration by Radioactive Emissions

- There is an animation that will provide a review of radioactivity at the following web address.
- A portion of this animation describes the relative penetrating ability of alpha particles, beta particles, and gamma photons.

https://preparatorychemistry.com/radioactivity_Canvas.html

Uses for Radioactive Nuclides

- Cancer radiation treatment
- Computer imaging techniques
- Radiocarbon dating
- Smoke detectors
- Food irradiation
- Radioactive tracers

MRI Imaging

- Protons act like tiny magnets.
- When patients are put in the strong magnetic field, the proton magnets in their hydrogen atoms line up either with or against the field (called parallel and anti-parallel).

parallel + radio wave photons → anti-parallel

anti-parallel → parallel + emitted energy

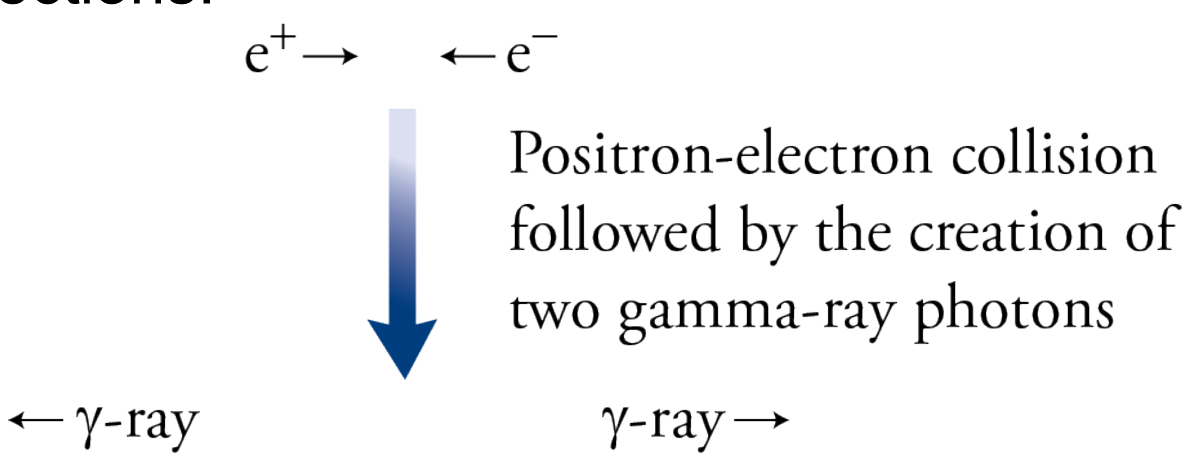
- Emitted energy is detected by scanners placed around the patient’s body.

MRI Imaging (2)

- Soft tissues contain a lot of water (with a lot of hydrogen atoms) and bones do not, so the MRI process is especially useful for creating images of the soft tissues of the body.
- Hydrogen atoms absorb and re-emit radio wave photons in different ways depending on their environment, so the computer analysis of the data yields images of the soft tissues.

PET Scan

- A solution containing a positron-emitting substance is introduced into the body. The positrons collide with electrons, and the two species annihilate each other, creating two gamma photons that move apart in opposite directions.



PET Scan (2)

- The gamma photons are detected and the data analyzed by a computer to yield images.
- Different nuclides are used to study different parts of the body.
  - Fluorine-18 for bones
  - Glucose with carbon-11 for the brain

Radiocarbon Dating

[If not for radiocarbon dating,] we would still be floundering in a sea of imprecisions sometimes bred of inspired guesswork but more often of imaginative speculations.

Desmond Clark, Anthropologist

- Dating to about 50,000 years
- Natural carbon is 98.89% carbon-12, 1.11% carbon-13, and 0.00000000010% carbon-14, which come from

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

Radiocarbon Dating (2)

- Carbon-14 is oxidized to CO_2, which is then converted into substances in plants, which are then eaten by animals.
- Carbon-14 is a beta emitter with a half-life of 5730 years (±40 years), so as soon as it becomes part of a plant or animal, it begins to disappear.

$$^{14}_{6}C \rightarrow\ ^{14}_{7}N +\ ^{0}_{-1}e$$

Radiocarbon Dating (3)

- When alive, intake of ^{14}C balances the decay, so ratio of ^{14}C to ^{12}C remains constant at about 1 in 1,000,000,000,000.
- When the plant or animal dies, it stops taking in fresh carbon, but the ^{14}C it contains continues to decay. Thus the ratio of ^{14}C to ^{12}C drops steadily.
- The $^{14}C/^{12}C$ ratio in the sample is used to calculate its age.

Radiocarbon Dating (4)

- Assuming that the $^{14}C/^{12}C$ ratio has been constant over time, if the $^{14}C/^{12}C$ ratio in a sample is one-half of the ratio found in the air today, the object would be about 5730 years old. A $^{14}C/^{12}C$ ratio of one-fourth of the ratio found in the air today would date it as 11,460 years old (2 half-lives), etc.
- It' s not that simple…the percentage of ^{14}C in the air varies due to factors such as volcanoes and natural variations in cosmic radiation.

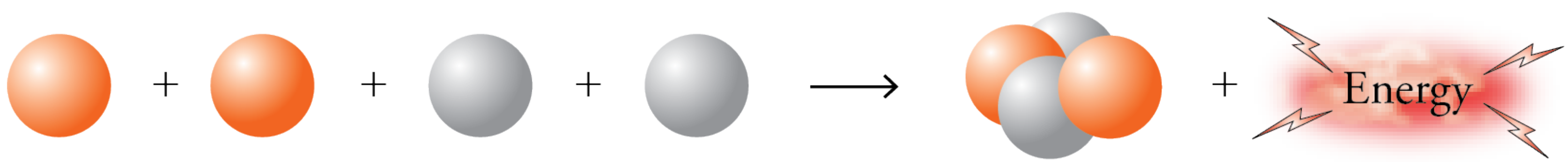
Radiocarbon Dating (5)

- Tree rings show that the $^{14}C/^{12}C$ ratio has varied by about ±5% over the last 1500 years.
- Very old trees, such as the bristlecone pines in California, yield calibration curves for radiocarbon dating to about 10,000 years.
- These calibration curves are now used to get more precise dates for objects.

Nuclear Stability and Binding Energy

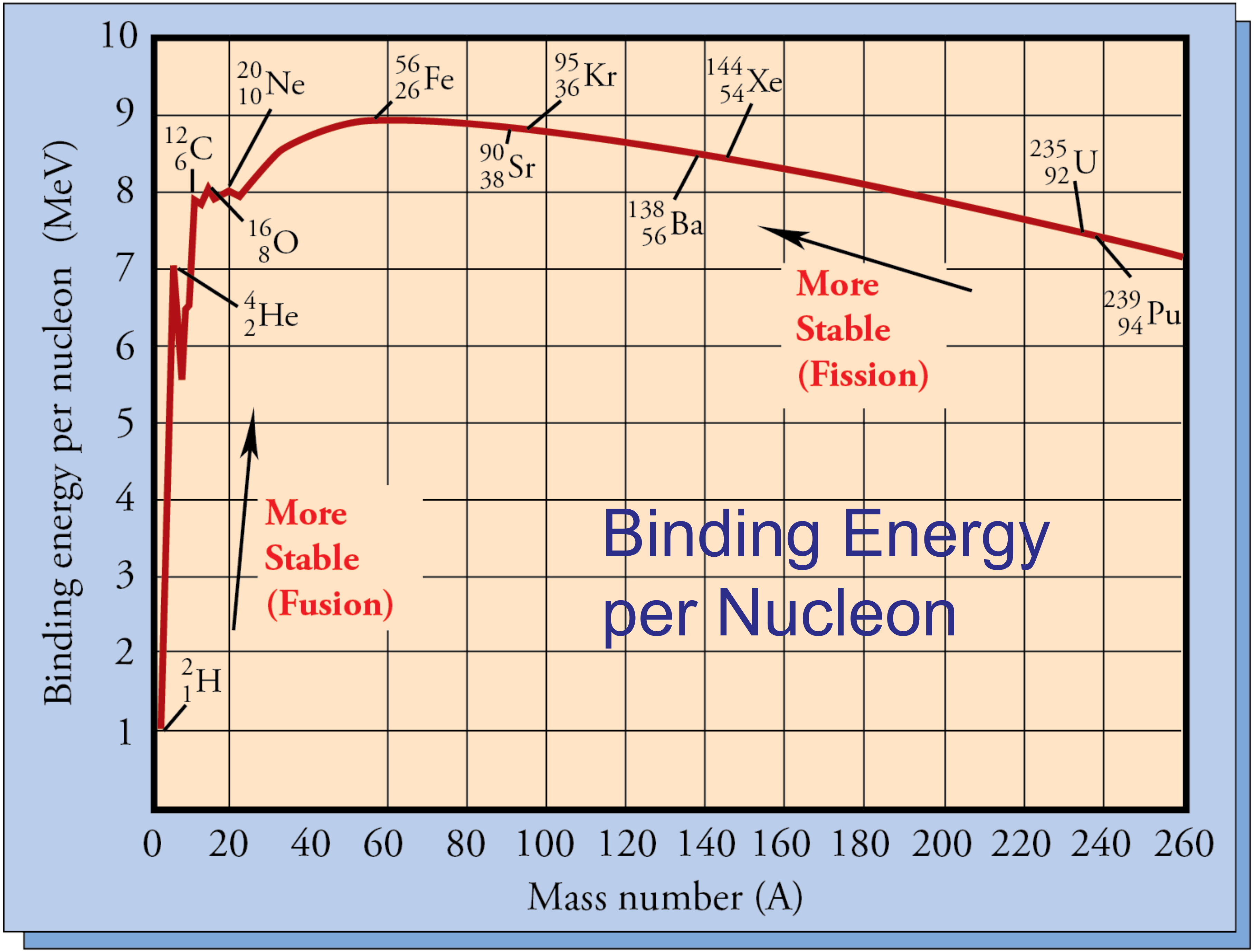
- ***Binding energy*** = the amount of energy released when a nucleus is formed.
- When two protons and two neutrons combine to form a helium nucleus, energy is released. This is the total binding energy for the helium nucleus.

$$p + p + n + n \longrightarrow {}^{4}_{2}He^{2+}$$



Nuclear Energy

- The **binding energy per nucleon**, which is the total binding energy divided by the number of nucleons (protons and neutrons), is a good indication of nuclear stability.
- For example, because a uranium-235 atom has many more nucleons than an iron-56 atom, it has a much larger total binding energy, but an iron-56 atom is significantly more stable than a uranium-235 atom. This is reflected in the higher binding energy per nucleon for iron-56.
- Binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56.
- Binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms.



Binding Energy per Nucleon
Binding energy per nucleon (MeV)
Mass number (A)
10
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
160
180
200
220
240
260
$^{2}_{1}H$
$^{4}_{2}He$
$^{12}_{6}C$
$^{16}_{8}O$
$^{20}_{10}Ne$
$^{56}_{26}Fe$
$^{90}_{38}Sr$
$^{95}_{36}Kr$
$^{138}_{56}Ba$
$^{144}_{54}Xe$
$^{235}_{92}U$
$^{239}_{94}Pu$
More Stable (Fusion)
More Stable (Fission)

Nuclear Energy

- Because binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56, fusing small atoms to form larger atoms (***nuclear fusion***) releases energy.
- Because binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms, splitting large atoms to form medium-sized atoms (***nuclear fission***) also releases energy.

Nuclear Fusion

$$^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$$

$$\text{Deuterium} + \text{Tritium} \longrightarrow \text{Helium} + \text{Neutron}$$

- Products are much more stable than reactants, so products have much lower PE, and a lot of energy is released.

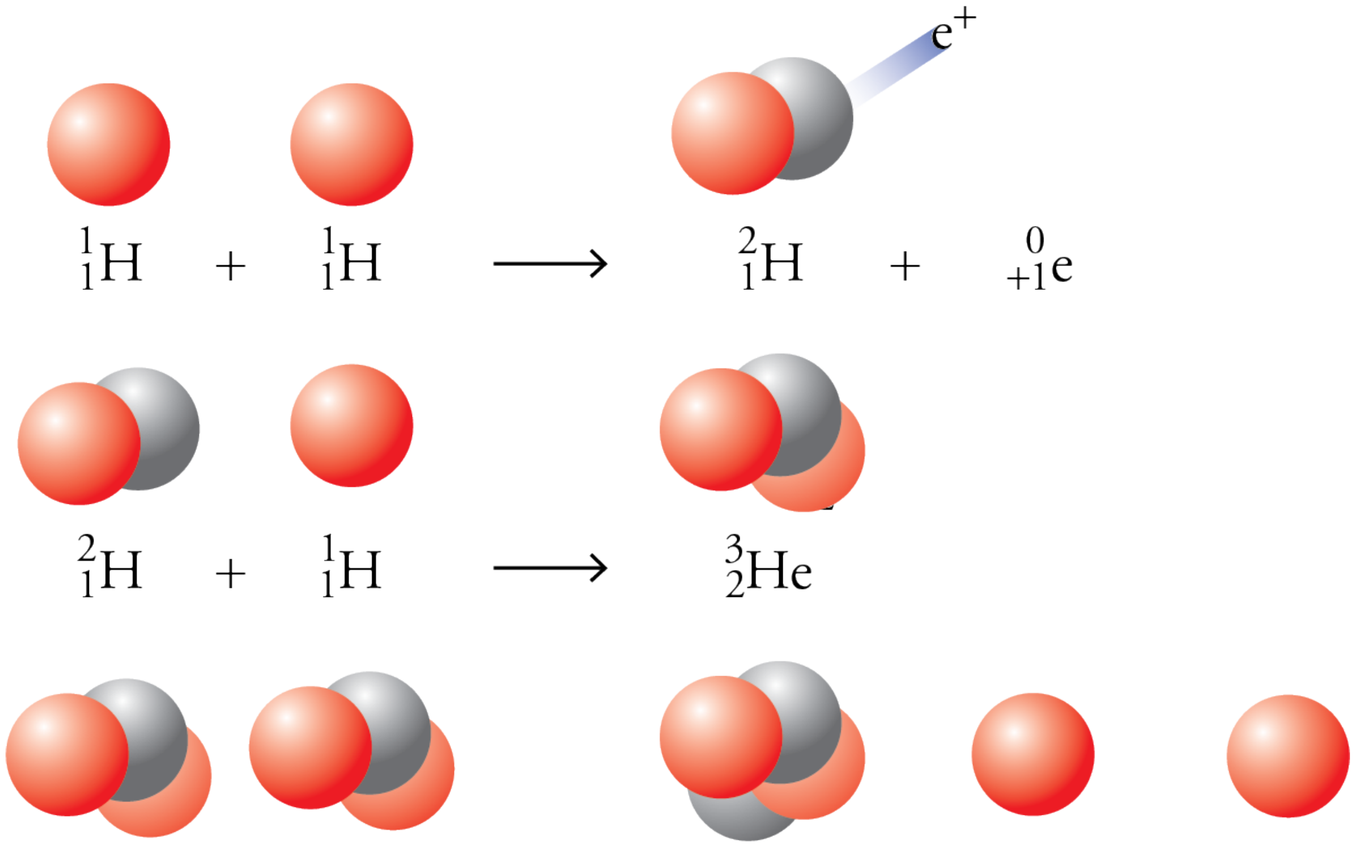
Nuclear Fusion

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

$$ \text{Deuterium} + \text{Tritium} \longrightarrow \text{Helium} + \text{Neutron} $$

- Requires a very high temperature (about 10^6 ºC) to initiate the fusion.
  - The electromagnetic repulsion between the positive nuclei is felt at a relatively long range.
  - The strong force attraction is only significant when the nuclei are very close.
  - Therefore, unless the nuclei are rushing together at a very high velocity (very high temperature), the +/+ repulsion slows the nuclei down, stops them, and accelerates them away from each other before they are close enough for the strong force to play a role.

Nuclear Fusion Powers the Sun

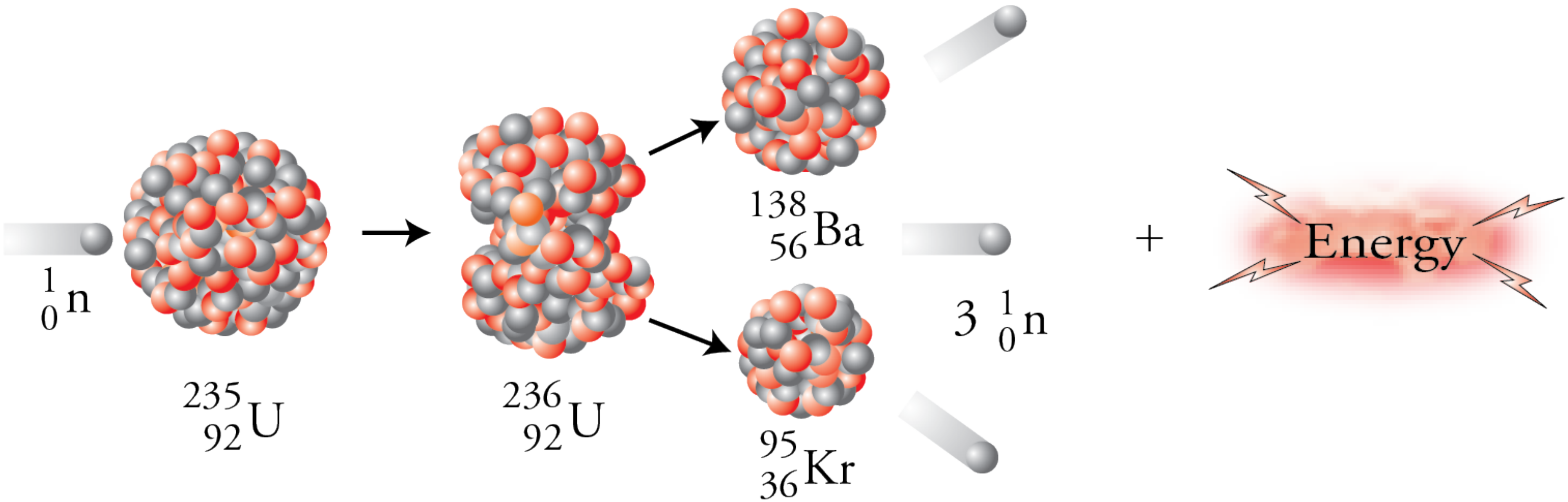


$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \longrightarrow ^{2}_{1}\mathrm{H} + ^{0}_{+1}\mathrm{e}$$

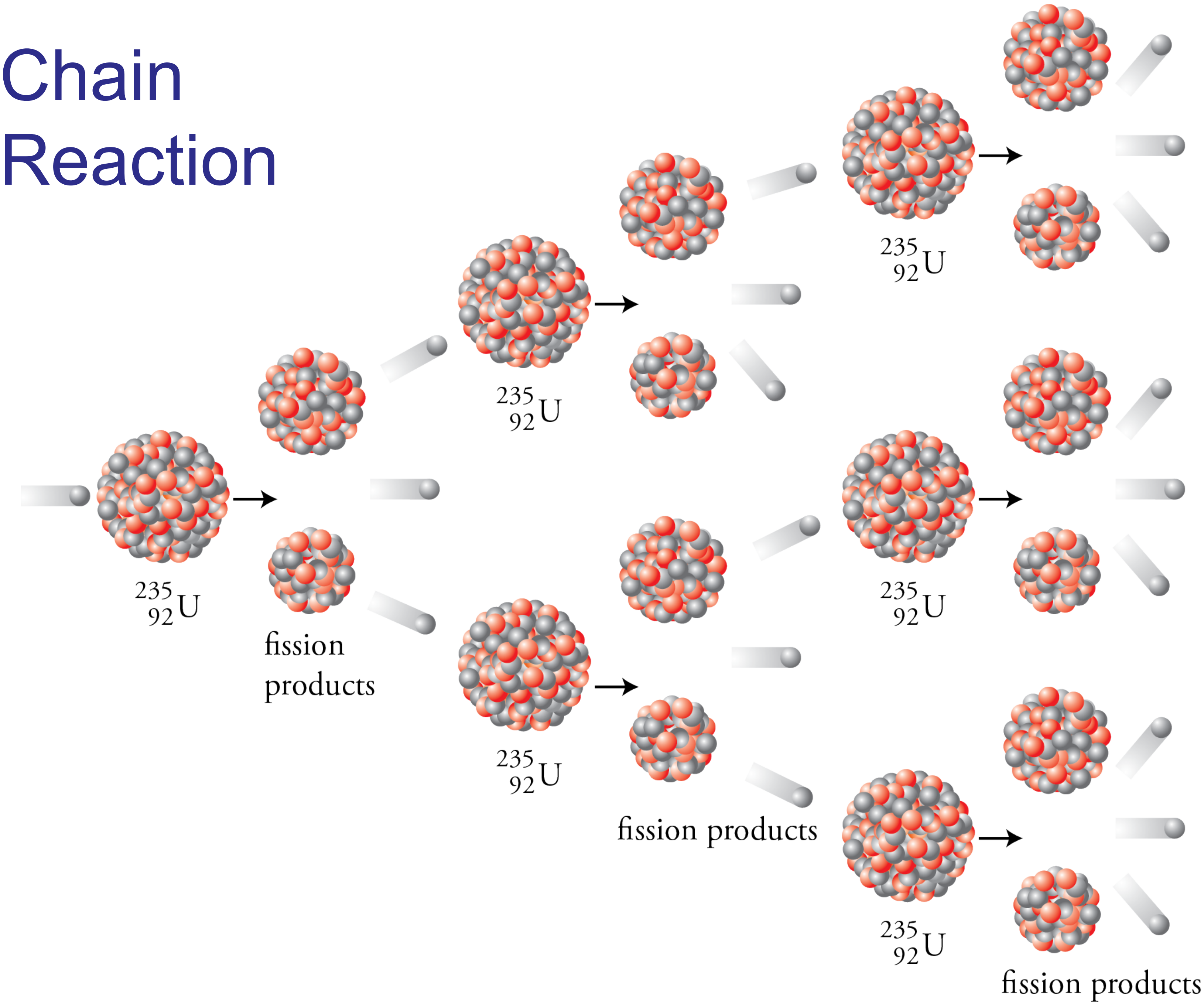
$$^{2}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He}$$

$$^{3}_{2}\mathrm{He} + ^{3}_{2}\mathrm{He} \longrightarrow ^{4}_{2}\mathrm{He} + ^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H}$$

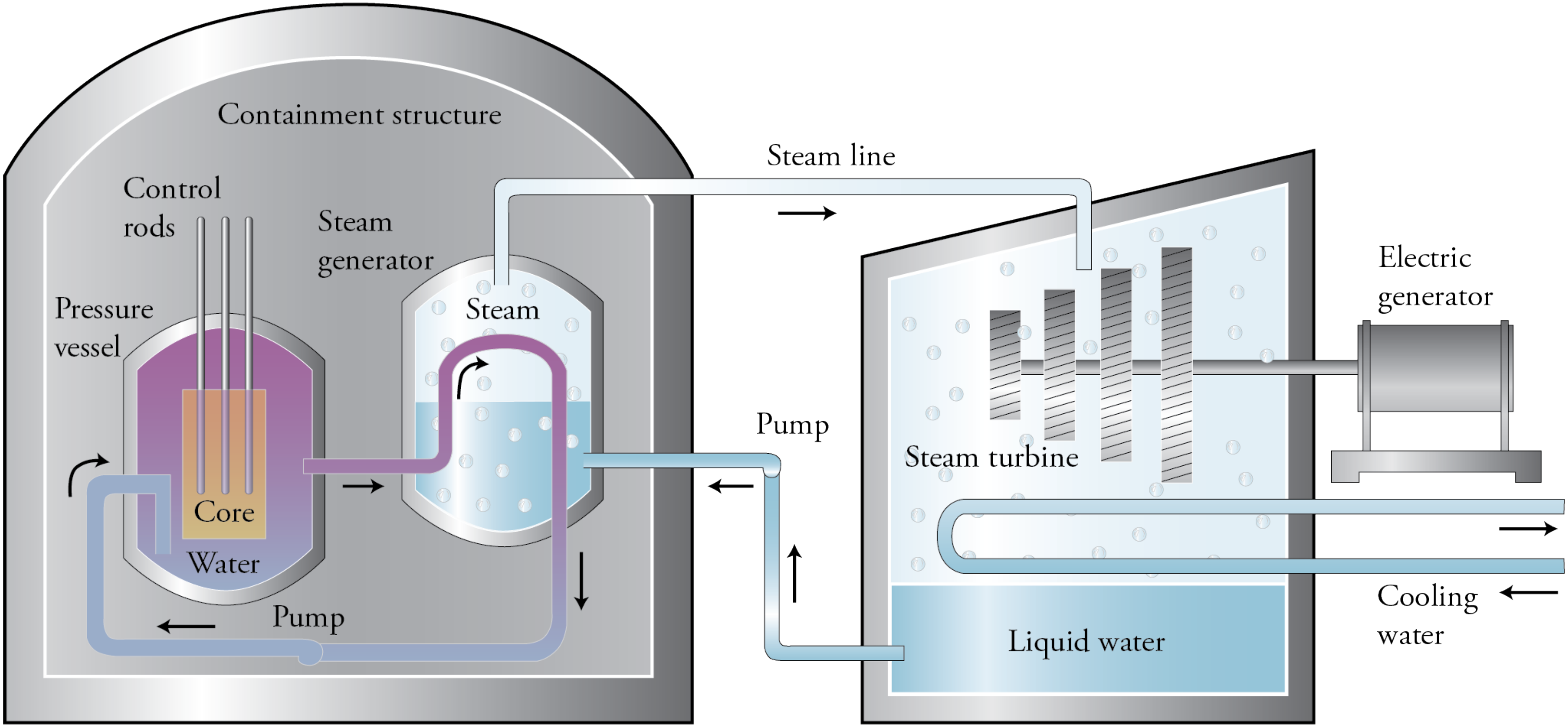
Nuclear Fission



Chain Reaction

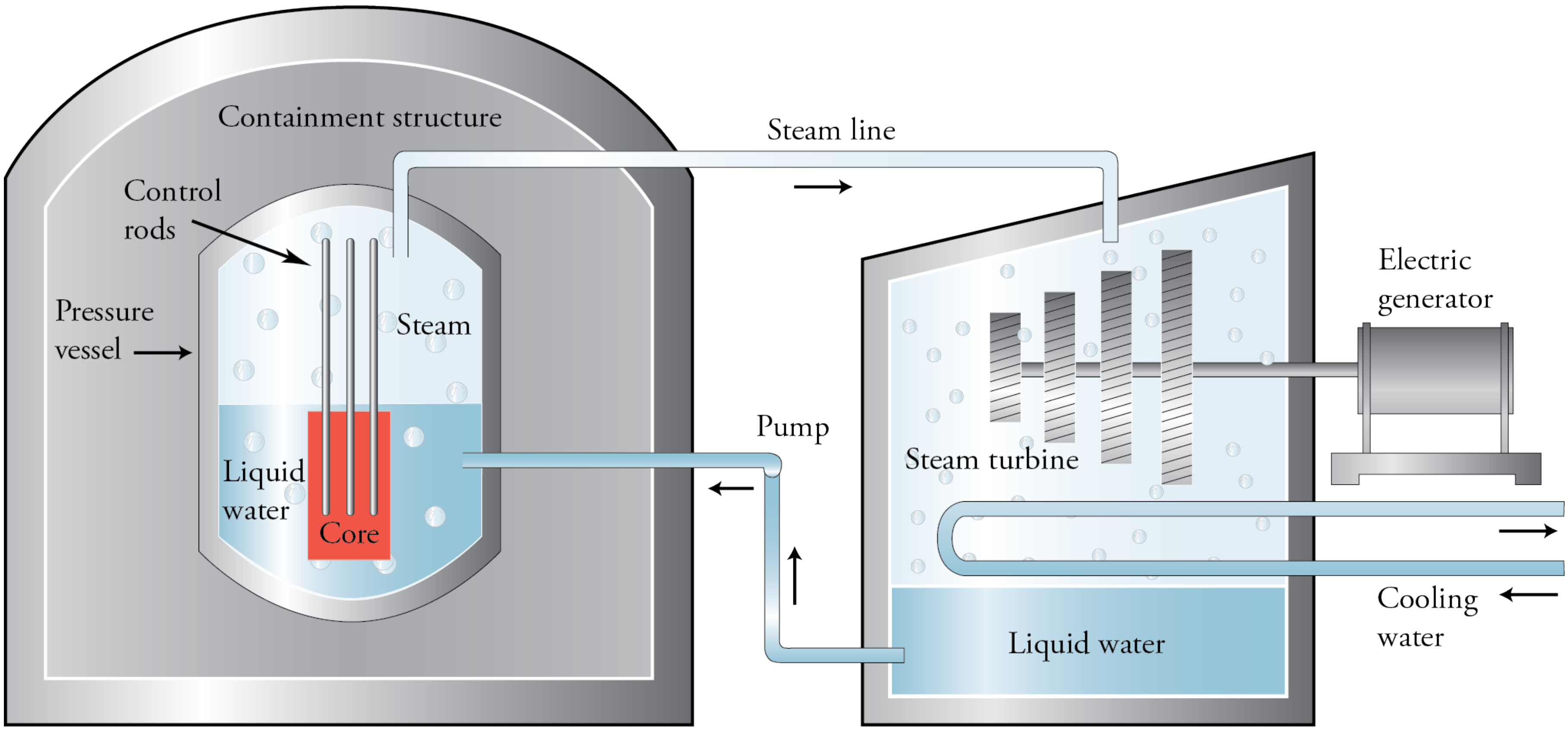


Nuclear Power Plant



Pressurized Water Reactor (PWR)

Nuclear Power Plant



Boiling Water Reactor (BWR)

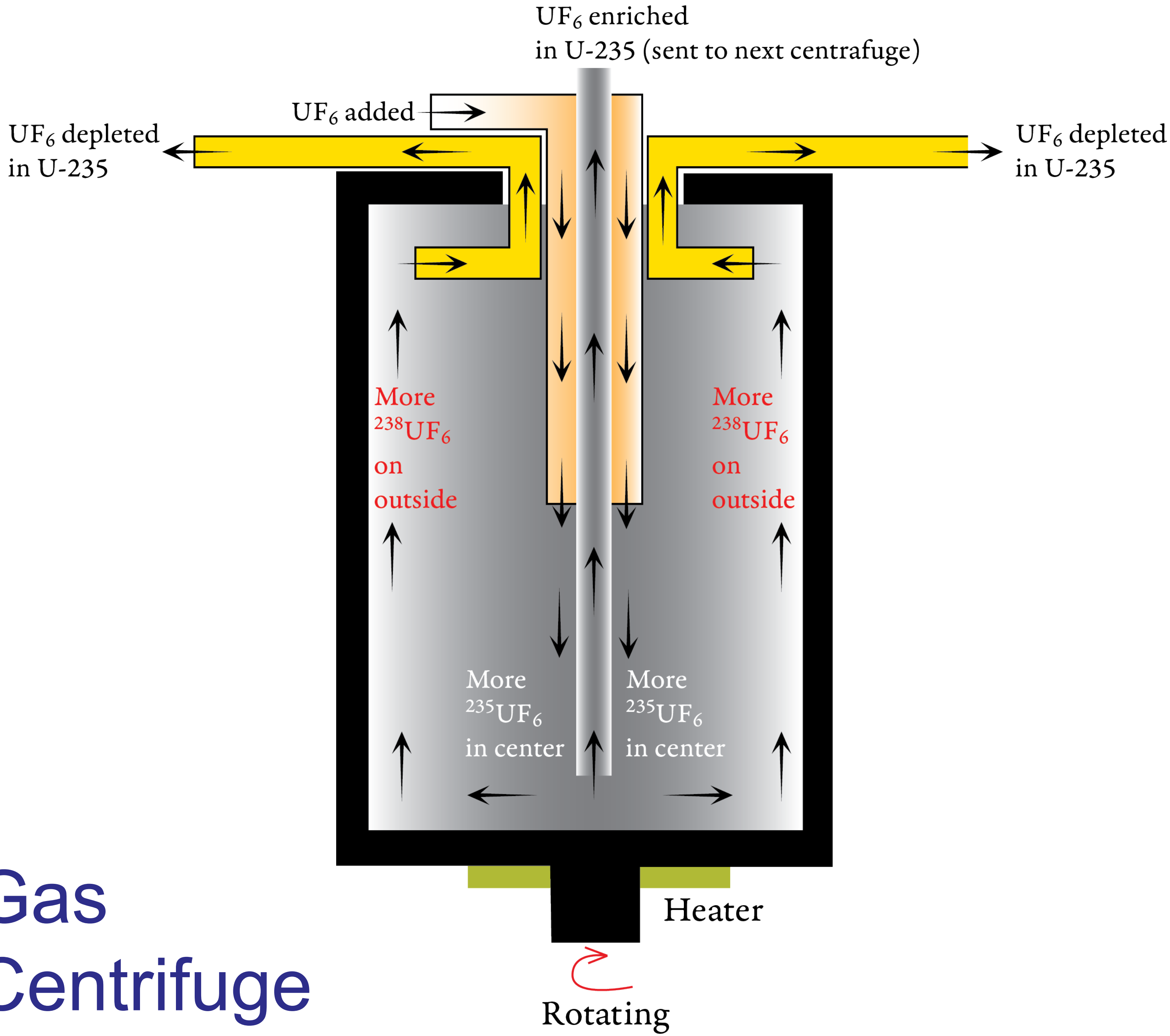
Nuclear Power Plant (2)

- To get a sustained chain reaction, the percentage of ^{235}U must be increased to about 3%, in part because the unfissionable ^{238}U absorbs too many neutrons.

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$



Gas Centrifuge

Nuclear Power Plant (3)

- Fuel rods
  - A typical 1000-megawatt power plant will have from 90,000 to 100,000 kg of enriched fuel packed in 100 to 200 zirconium rods about 4 meters long.
- Moderator slows neutrons
  - ^{235}U atoms are more likely to absorb slow neutrons.
  - Can be water

Nuclear Power Plant (4)

- Control Rods
  - Substances, such as cadmium or boron, absorb neutrons.
  - Control rate of chain reaction
  - Dropped at first sign of trouble to stop fission reaction