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

Mass number (nucleon number)

$$^{A}_{Z}X$$

Atomic number

Element symbol

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.

$^{235}_{92}U$ ^{235}U U-235 uranium-235

$^{131}_{53}I$ ^{131}I I-131 iodine-131

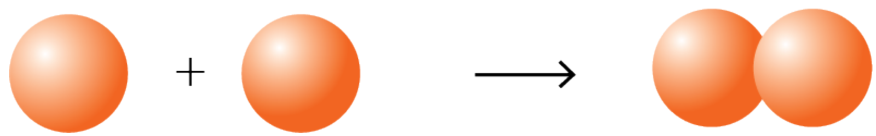
Two Forces in Nucleus

- ***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.

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

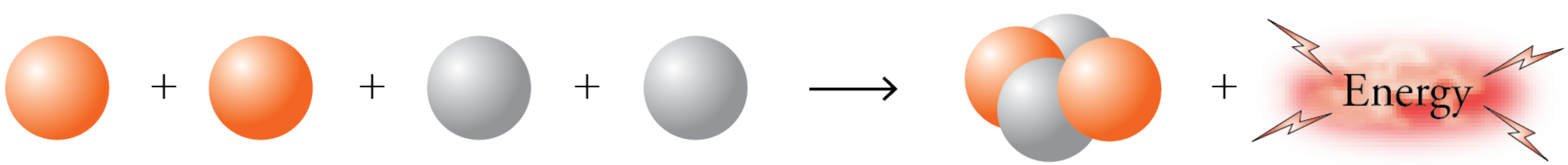


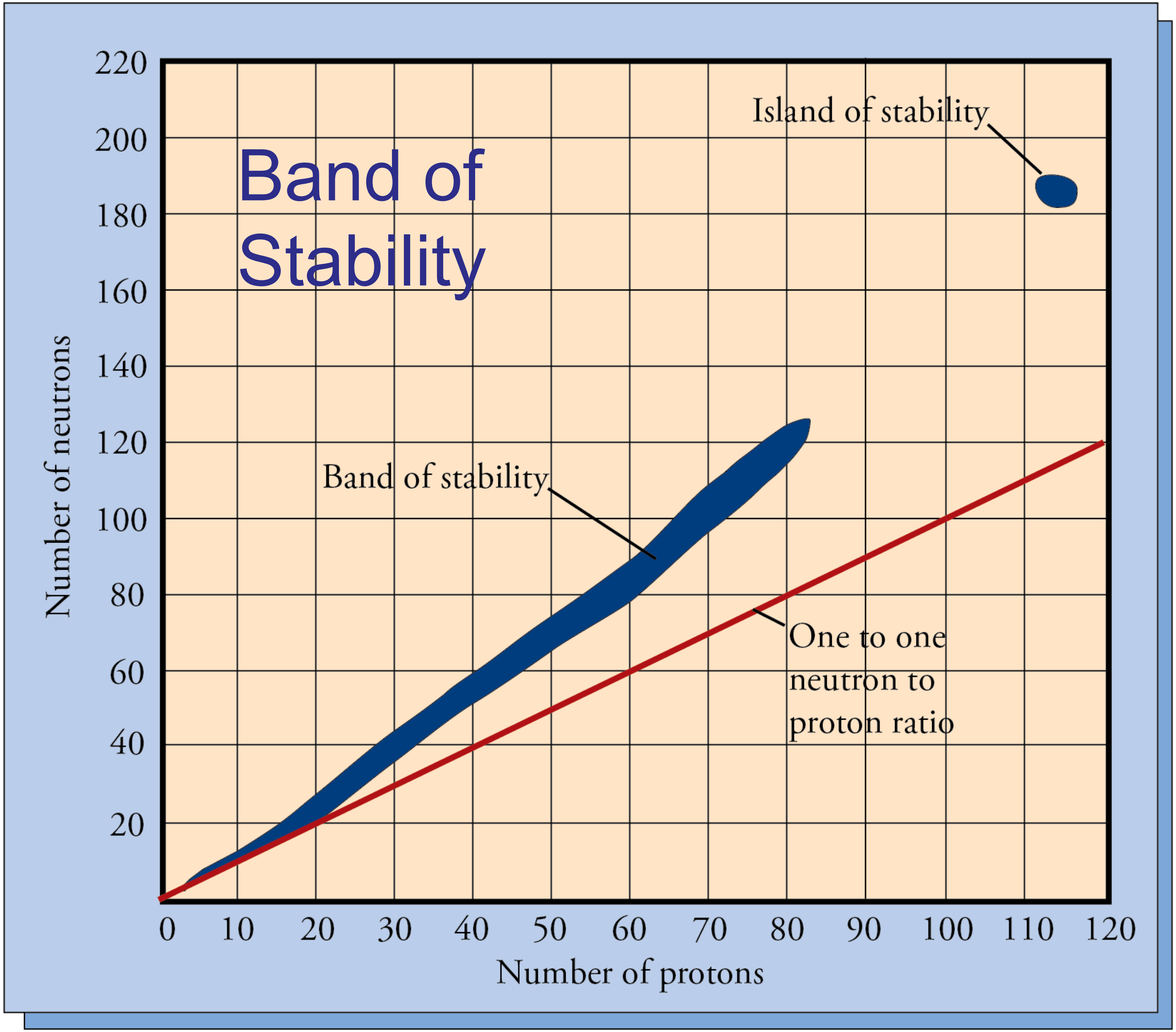
- The shorter the distance between the protons is, the stronger the electromagnetic repulsion between them.
- When they are close enough to form a helium nucleus, the strong force is not strong enough to overcome the electromagnetic repulsion, so the protons are pushed apart.

Nuclear Stability

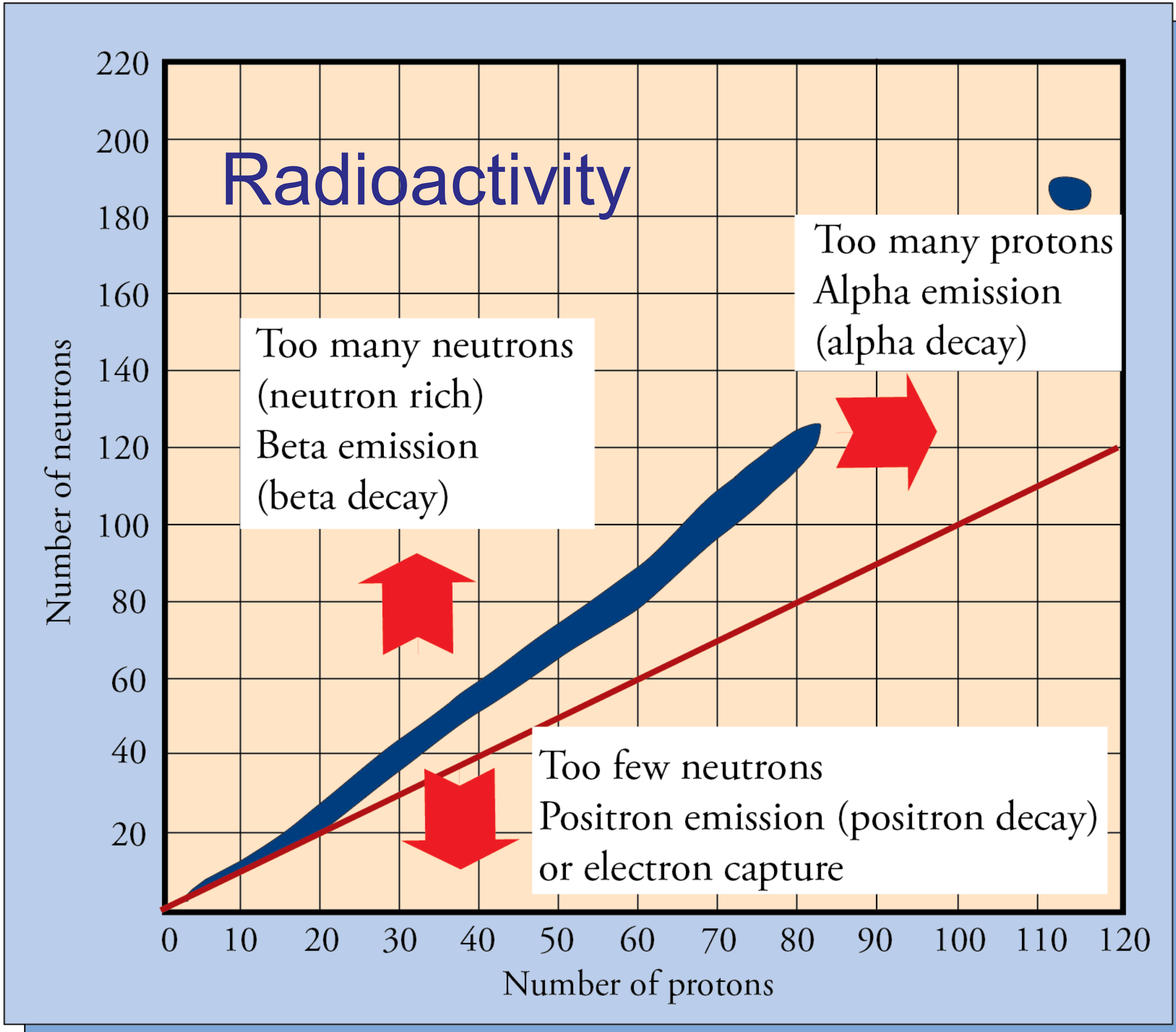
- Neutrons increase the attraction from the strong force without increasing electromagnetic repulsion between nucleons.
- Combining two neutrons with two protons increases the strong force enough to overcome the electromagnetic repulsion, making a stable helium nucleus.

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





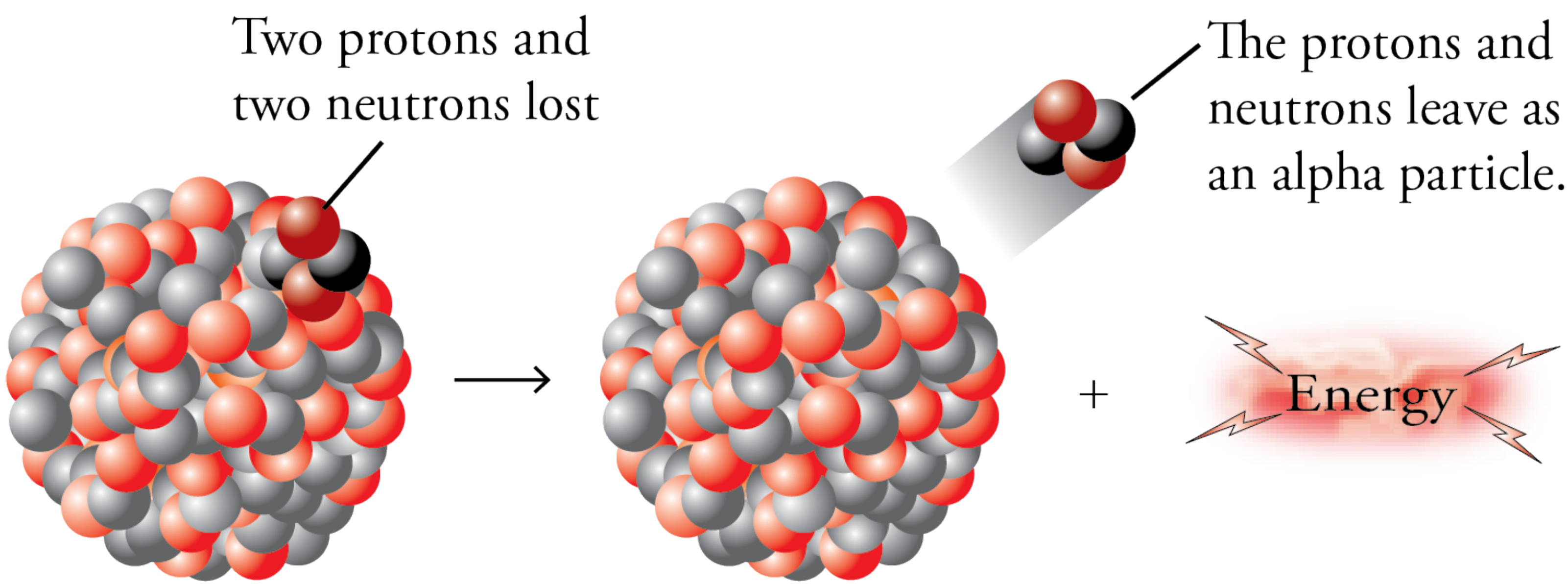
Band of Stability
Island of stability
Band of stability
One to one neutron to proton ratio
Number of neutrons
Number of protons
220
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
120



Radioactivity
Too many protons
Alpha emission
(alpha decay)
Too many neutrons
(neutron rich)
Beta emission
(beta decay)
Too few neutrons
Positron emission (positron decay)
or electron capture
Number of neutrons
220
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
120
Number of protons

Alpha Emission

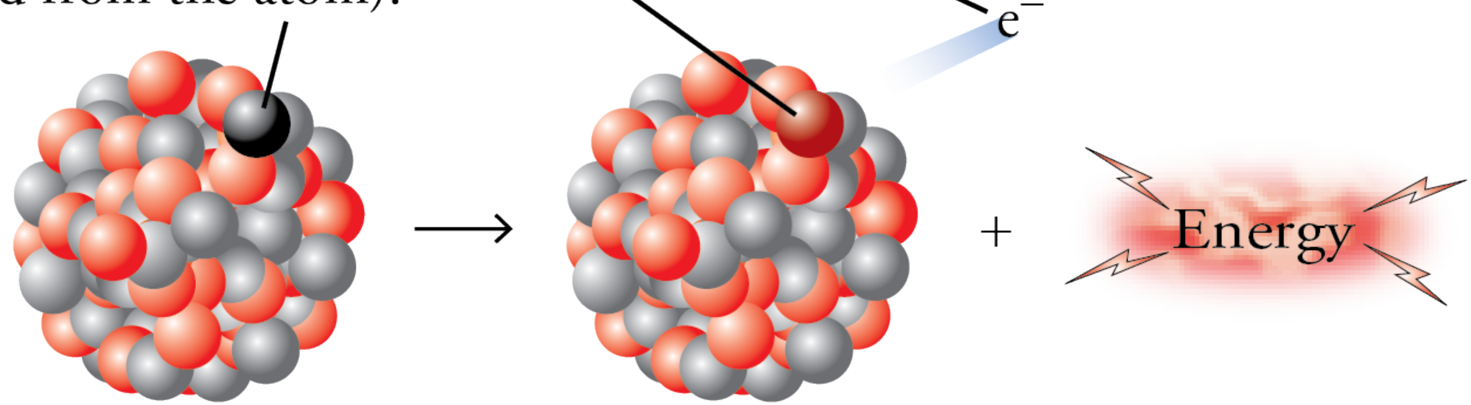
$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$



Beta Emission

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

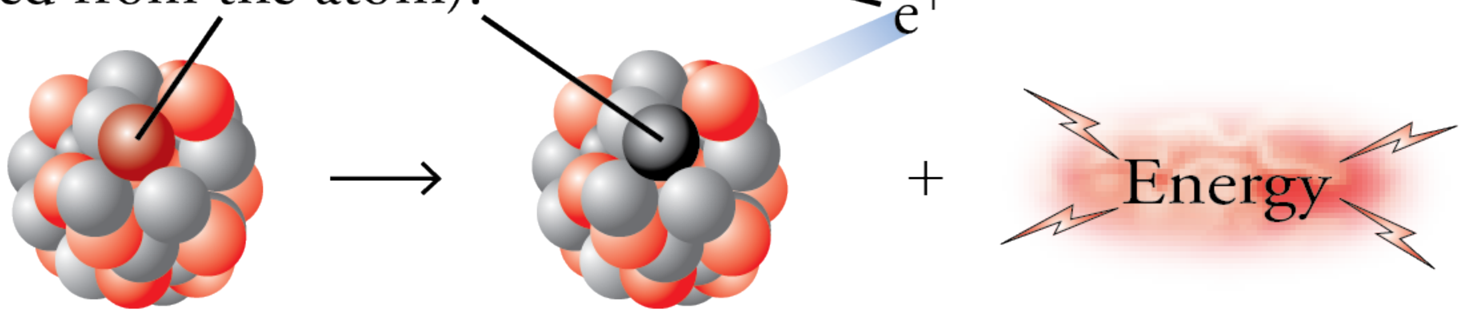
A neutron becomes a proton (which stays in the nucleus) and an electron (which is ejected from the atom).



Positron Emission

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

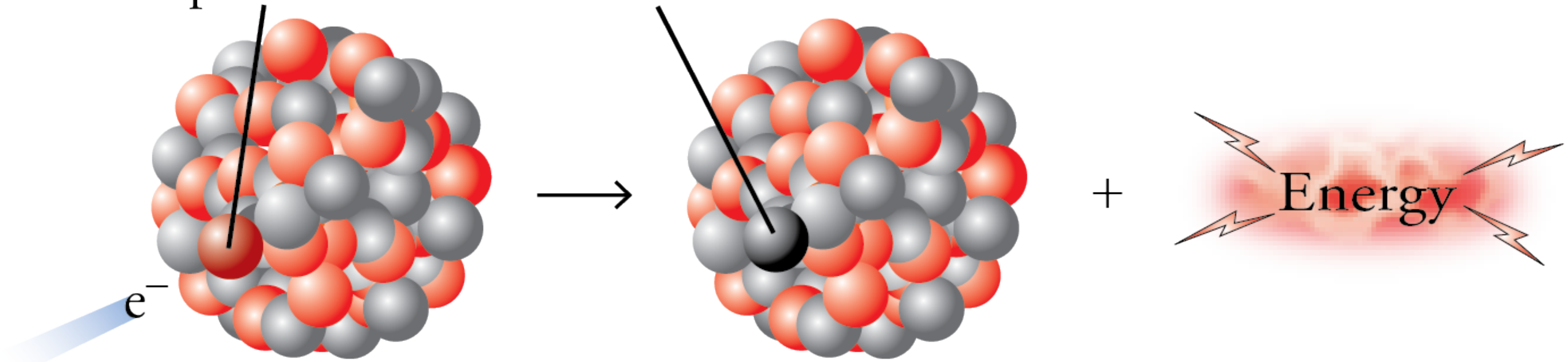
A proton becomes a neutron (which stays in the nucleus) and a positron (which is ejected from the atom).



Electron Capture

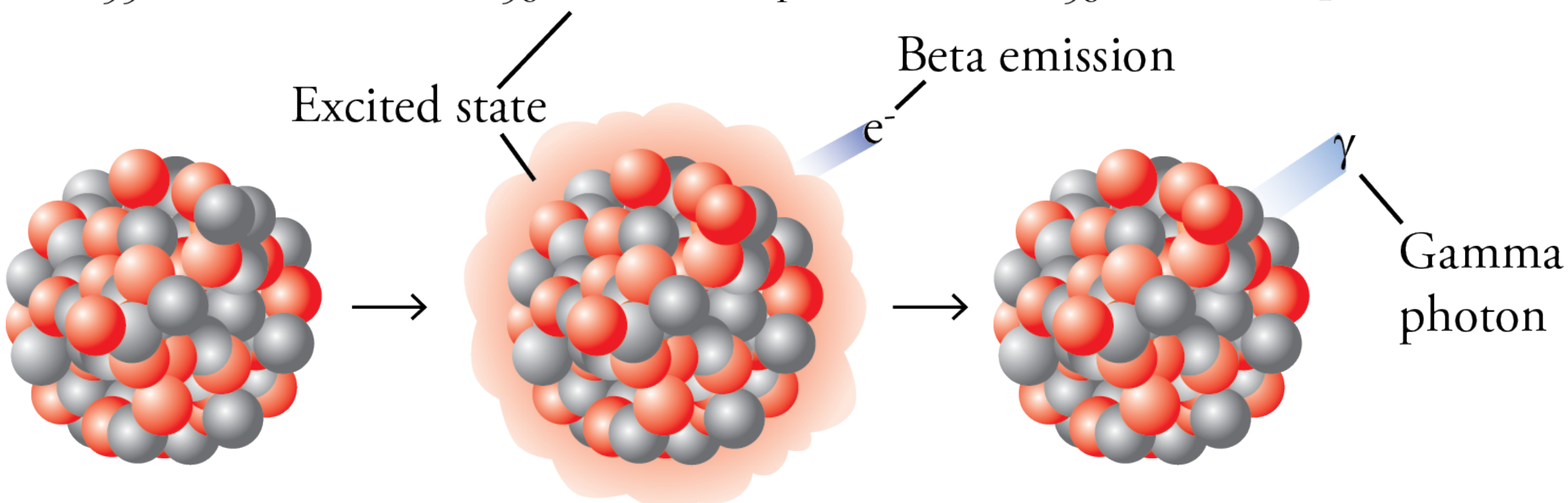
$$ {}^{0}_{-1}e + {}^{125}_{53}I \longrightarrow {}^{125}_{52}Te $$

An electron combines with a proton to form a neutron.



Gamma Emission

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



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

Beta emission

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

Positron emission

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

Electron capture

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

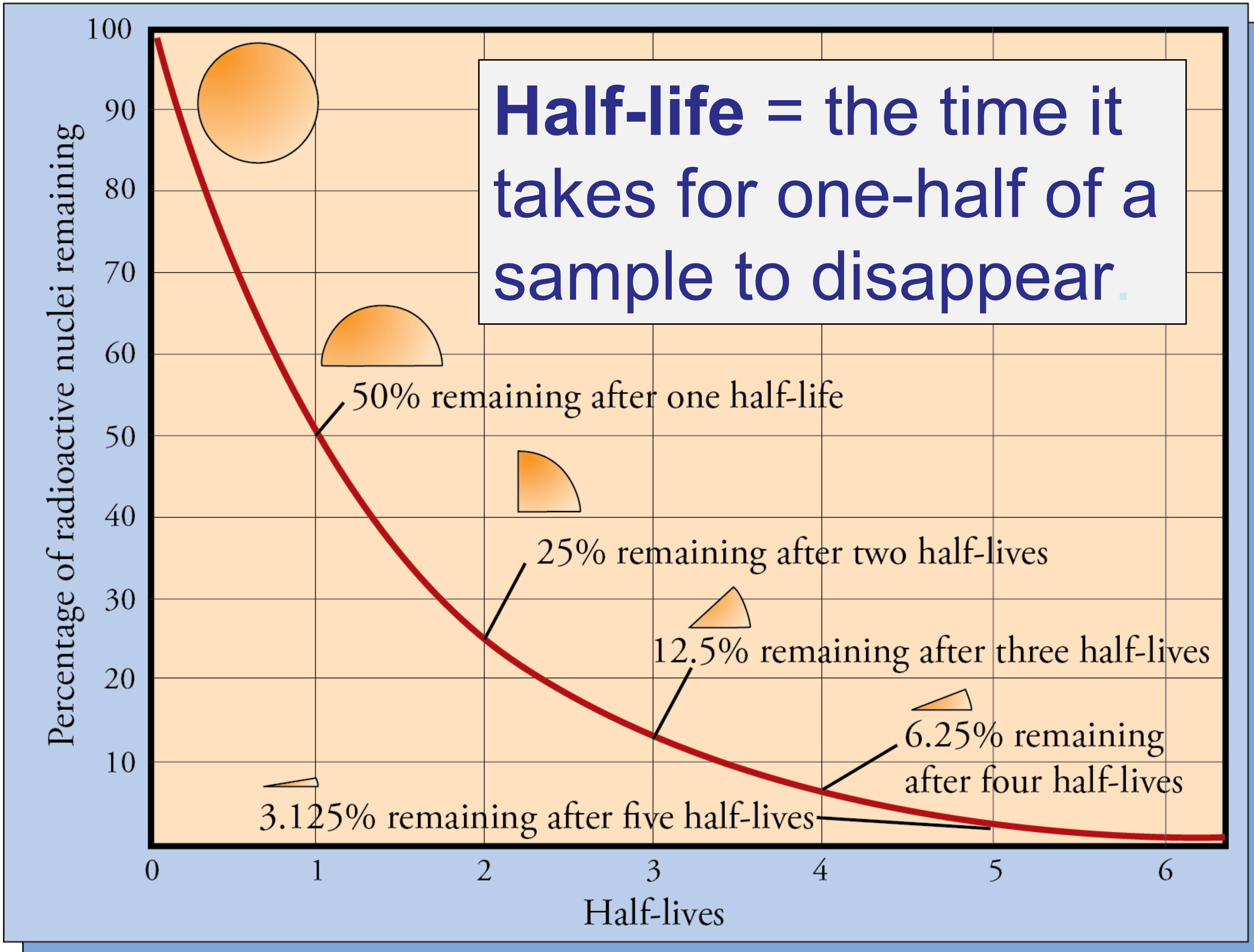
General Nuclear Equations

Alpha emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$

Beta emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$

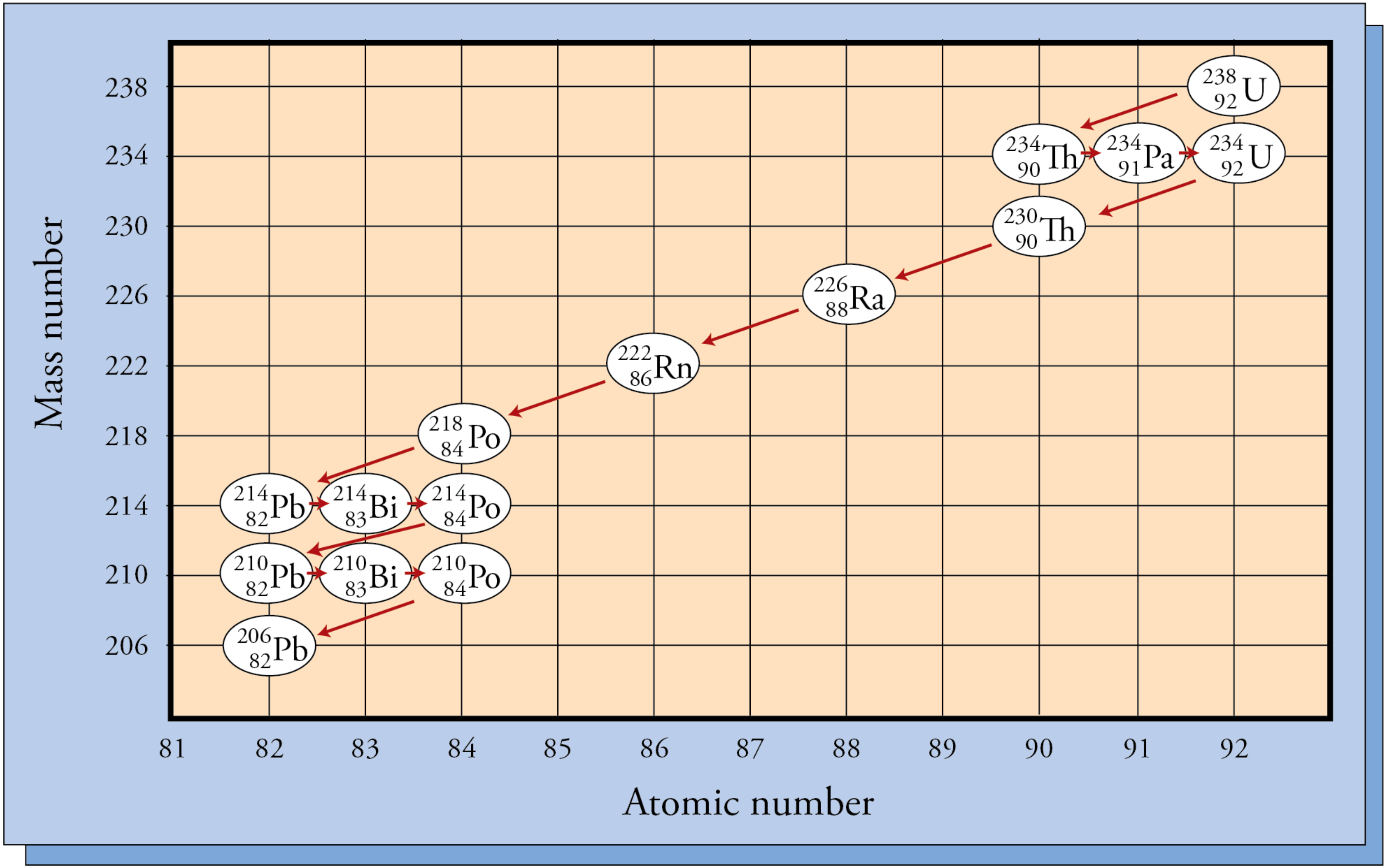
Positron emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$

Electron capture $\quad {}^{0}_{-1}e + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y$

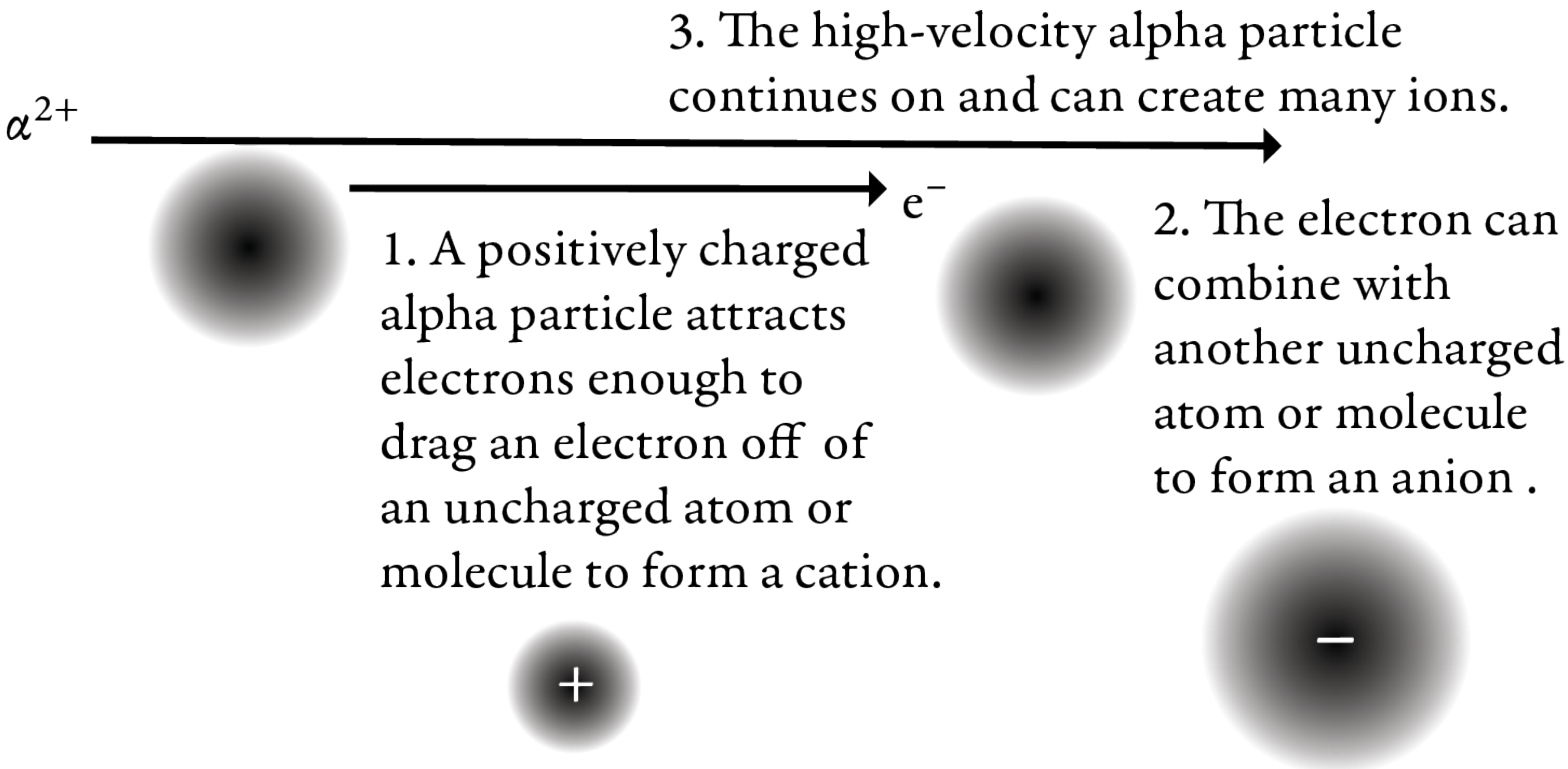


Half-life = the time it takes for one-half of a sample to disappear.
Percentage of radioactive nuclei remaining
100
90
80
70
60
50
40
30
20
10
50% remaining after one half-life
25% remaining after two half-lives
12.5% remaining after three half-lives
6.25% remaining after four half-lives
3.125% remaining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

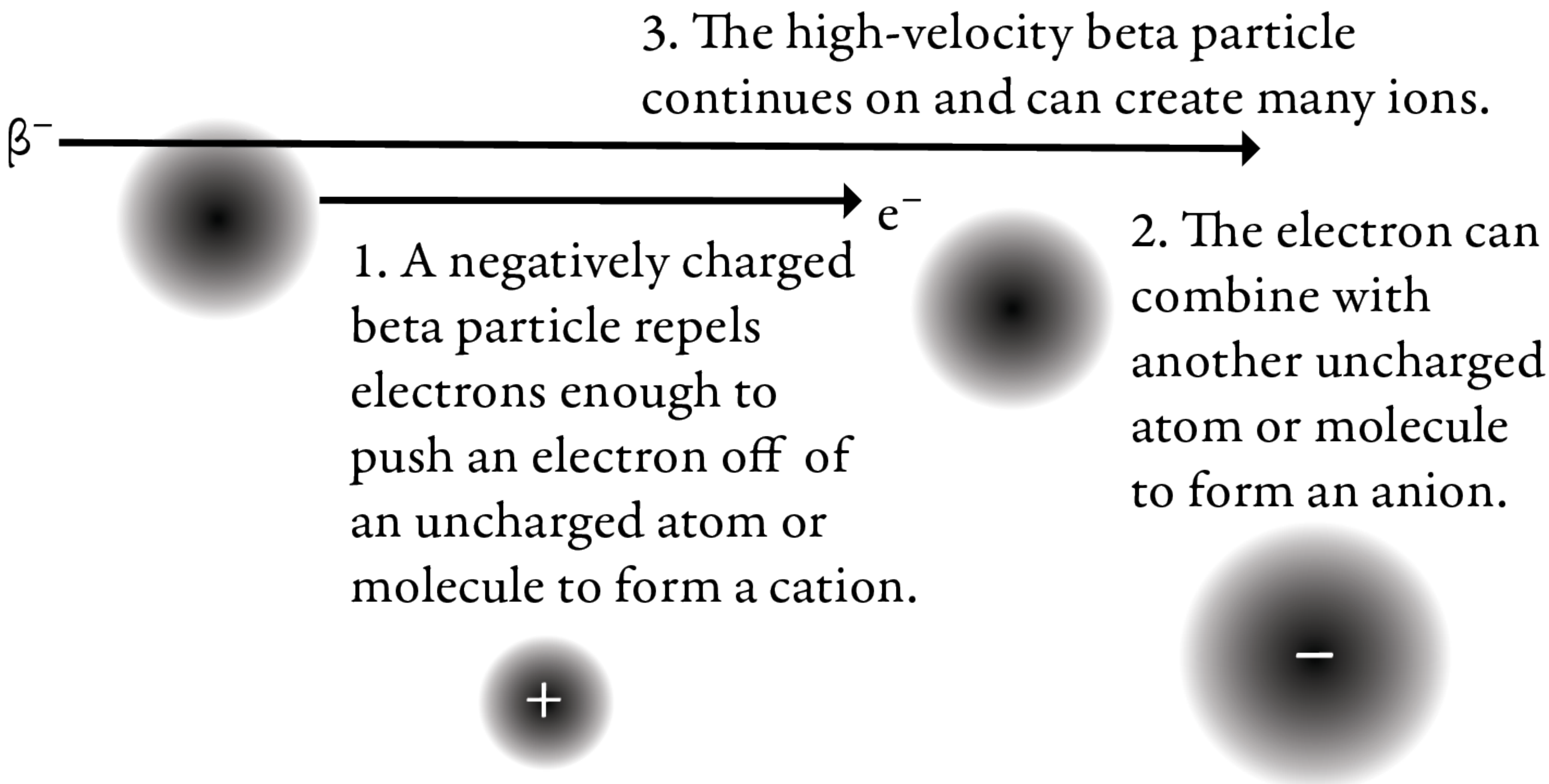
Radioactive Decay Series



Ionization by Alpha Particles

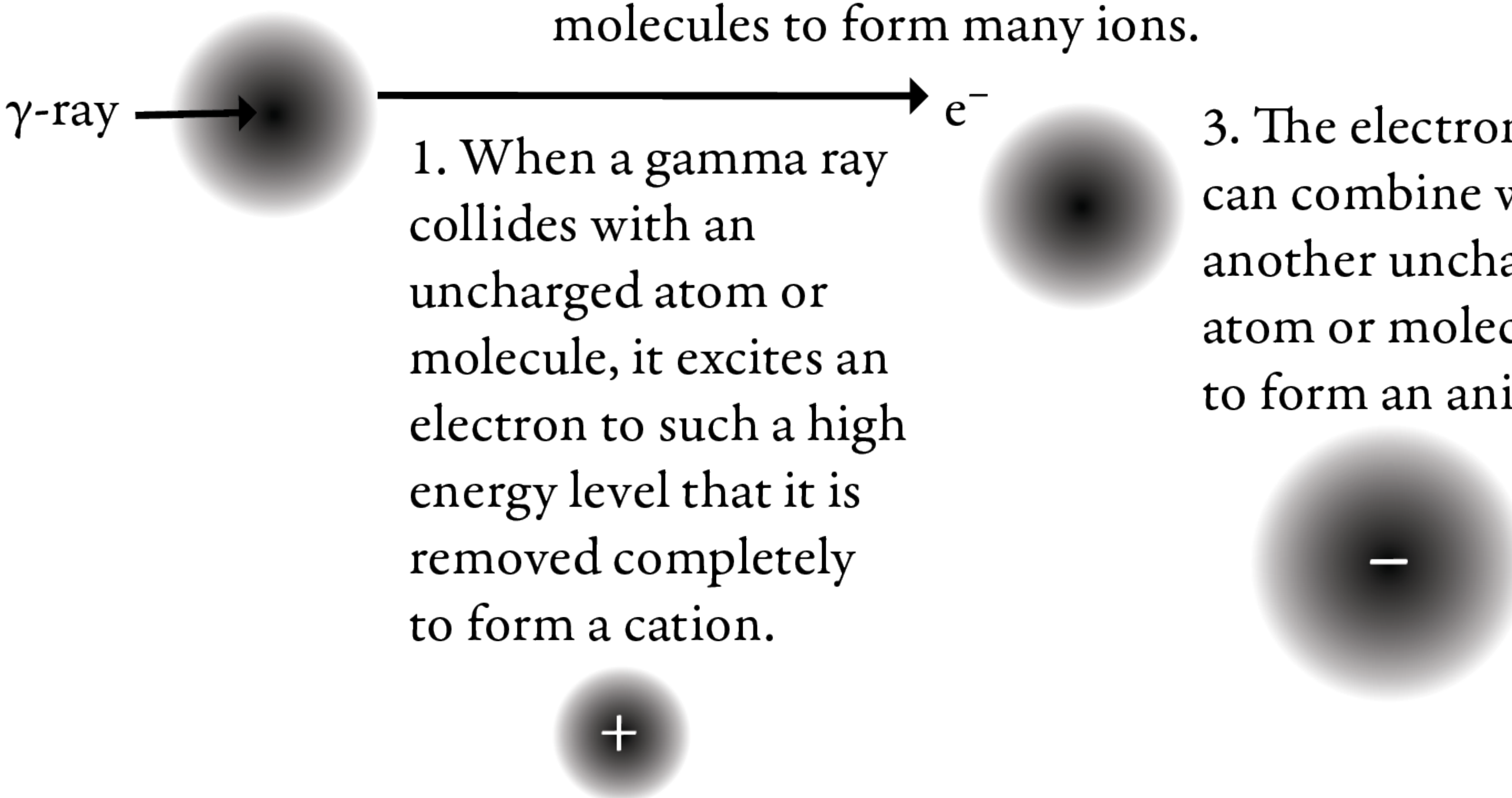


Ionization by Beta Particles



Ionization by Gamma Rays

2. The electron released might be moving fast enough to push electrons off other atoms and molecules to form many ions.



1. When a gamma ray collides with an uncharged atom or molecule, it excites an electron to such a high energy level that it is removed completely to form a cation.

3. The electron released can combine with another uncharged atom or molecule to form an anion.

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

Effects on Body from Inside and Outside

- Internal emitters = emitters of alpha and weak beta particles
  - Cannot penetrate dead outer layer of skin,
  - Dangerous if inside the body (e.g. Pu-239)
- External emitters = emitters of gamma rays, strong beta particles, or neutrons
  - Dangerous from outside the body

http://preparatorychemistry.com/radioactivity.html

Relative Biological Effectiveness

- The ratio of biological effectiveness of one type of ionizing radiation relative to another, given the same amount of absorbed energy.

Type	RBE (QF = quality factor)
x-rays	1
γ-rays	1
β-particles	1-3
α-particles	5-20
neutrons	5-20

http://en.wikipedia.org/wiki/Relative_Biological_Effectiveness

Radiation Dose

- **Physical dose** = energy absorbed per kg of tissue:
  - 1 rad = 100 erg/g = 0.01 Gy
  - 1 Gray (Gy) = 1 J/kg = 100 rad
- **Biological dose** = physical dose $\times$ biological effectiveness:
  - QF = Quality Factor
    = RBE = relative biological effectiveness
  - 1 rem = 1 rad $\times$ (QF = 1)
  - ? rem = # rad $\times$ QF
  - 1 Sievert (Sv) = 1 Gy $\times$ (QF = 1) = 100 rem
  - ? Sv = # Gy $\times$ QF

Health Effects

Sv	Effect
> 0.25	change in blood counts
> 0.50	temporary sterility
1-2	vomiting, hair loss, etc.
2-3	5-35% fatalities in 30 d
> 3	permanent sterility
4-5	50% fatalities in 30 d ($LD_{50/30}$).
6-8	95% fatalities in 30 d
>10	death in 10 d
> 50	death in 2 d
> 100	immediate death

Acute Dose Examples

98 nSv	-banana equivalent dose, a whimsical unit of radiation
0.25 µSv	-U.S. limit on effective dose from a single airport security screening
5 to 10 µSv	-one set of dental X-rays
80 µSv	-average dose to people living within 16 km of Three Mile Island accident
0.4 to 0.6 mSv	-two-view mammogram, using weighting factors updated in 2007
2 to 7 mSv	-barium fluoroscopy
10 to 30 mSv	-single full-body CT scan
68 mSv	-estimated maximum dose to evacuees who lived closest to the Fukushima I nuclear accidents
0.67 Sv	-highest dose received by a worker responding to the Fukushima emergency

http://en.wikipedia.org/wiki/Sievert

Chronic Dose Examples

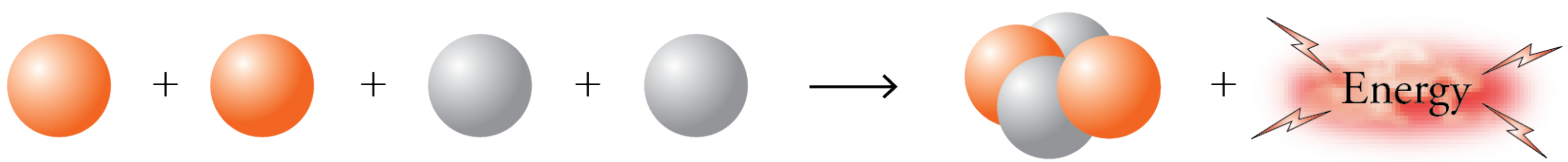
1	mSv/yr	ICRP recommended maximum for artificial irradiation of the public, excluding medical and occupational exposures.
2.4	mSv/yr	Natural background radiation, global average
24	mSv/yr	Natural background radiation at airline cruise altitude
9	Sv/yr	NRC definition of a high radiation area in a nuclear power plant, warranting a chain-link fence
>90	kSv/yr	most radioactive hotspot found in Fukushima I in areas normally accessible to workers
2.3	MSv/yr	typical PWR spent fuel bundle, after 10 year cool down, no shielding

http://en.wikipedia.org/wiki/Sievert

Nuclear Stability and Binding Energy

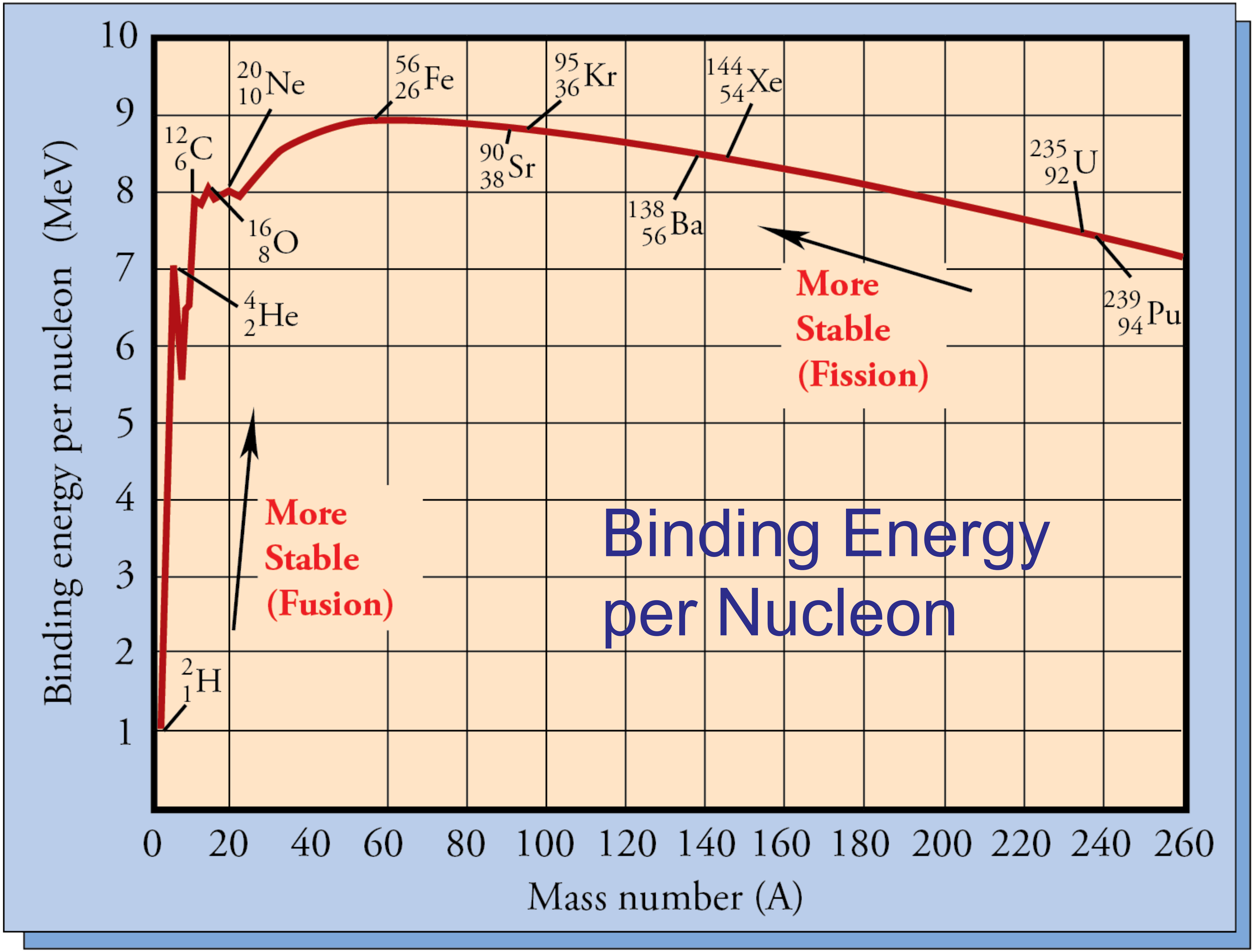
- ***Binding energy*** = the amount of energy released when a nucleus is formed.
- When two protons and two neutrons combine to form a helium nucleus, energy is released. This is the total binding energy for the helium nucleus.

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



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)
1
2
3
4
5
6
7
8
9
10
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

$$
\begin{array}{ccccccccc}
{}^{2}_{1}\mathrm{H} & + & {}^{3}_{1}\mathrm{H} & \longrightarrow & {}^{4}_{2}\mathrm{He} & + & {}^{1}_{0}\mathrm{n} \\
\text{Deuterium} & + & \text{Tritium} & \longrightarrow & \text{Helium} & + & \text{Neutron}
\end{array}
$$

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

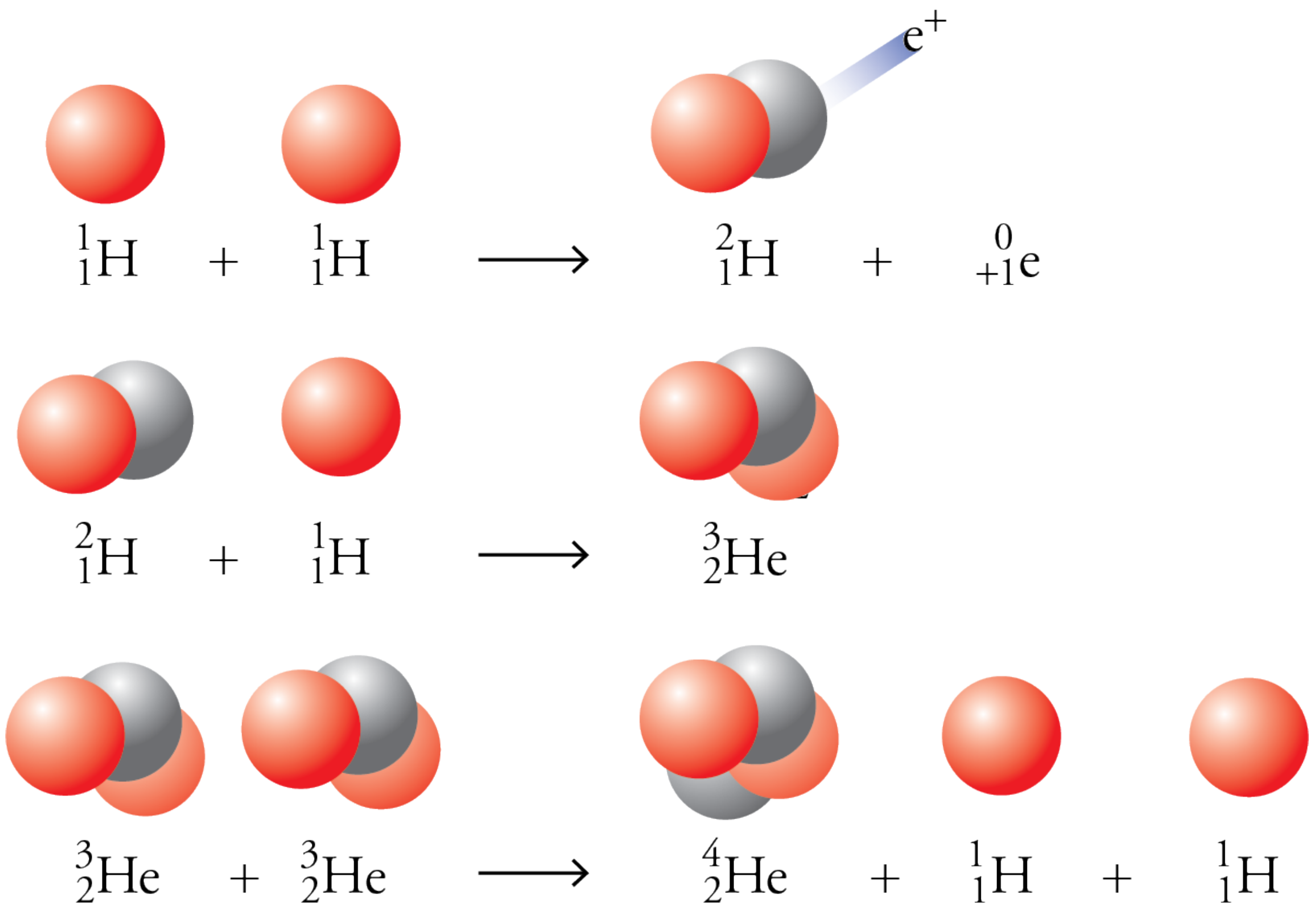
Nuclear Fusion

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

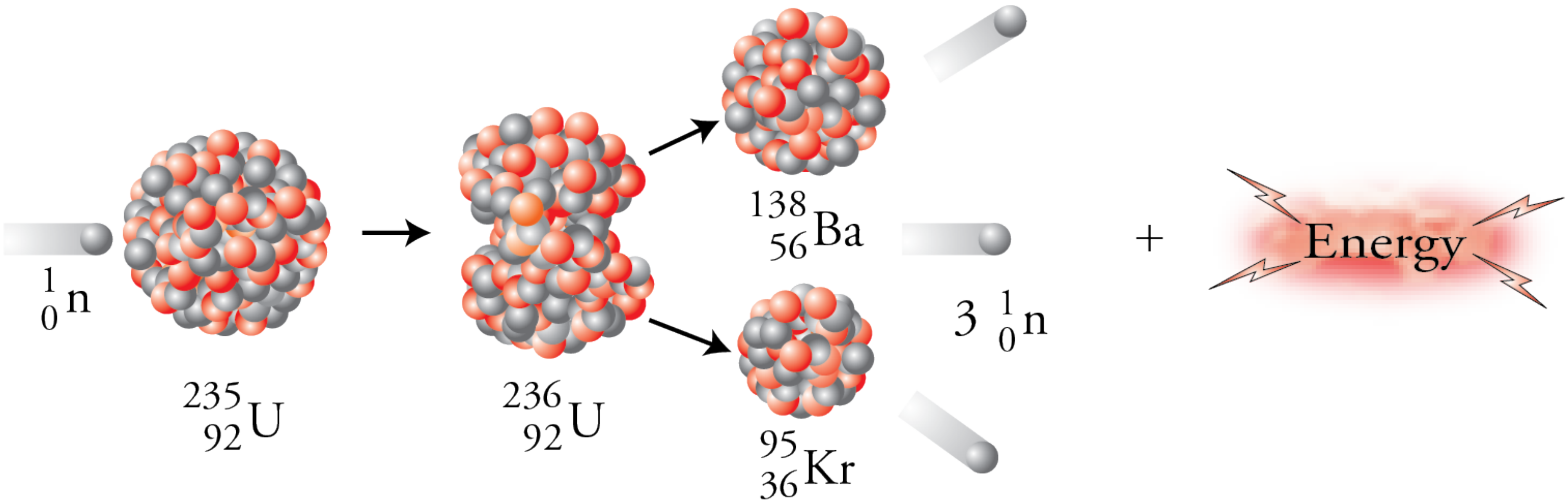
Deuterium + Tritium ⟶ Helium + Neutron

- 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.

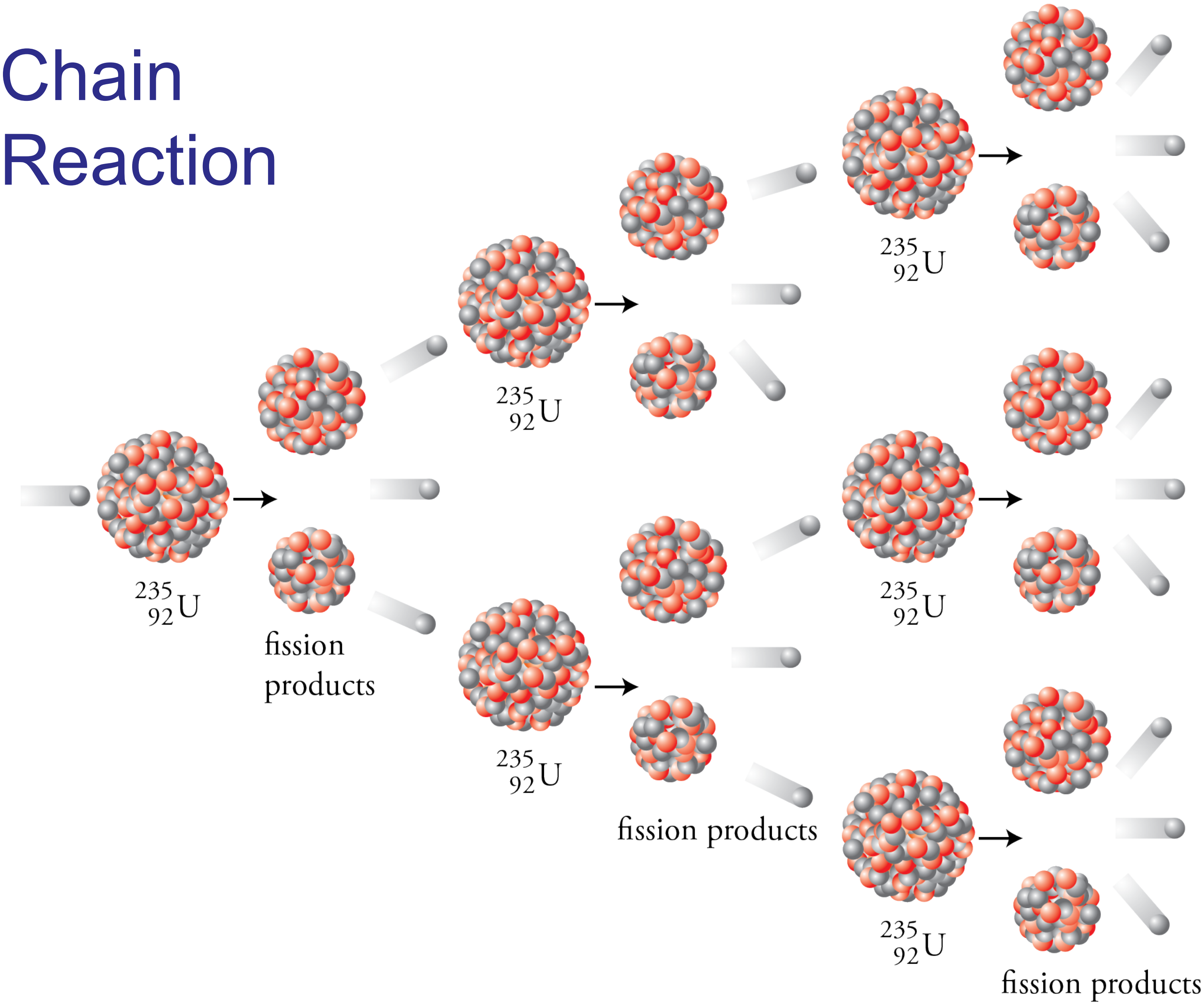
Nuclear Fusion Powers the Sun



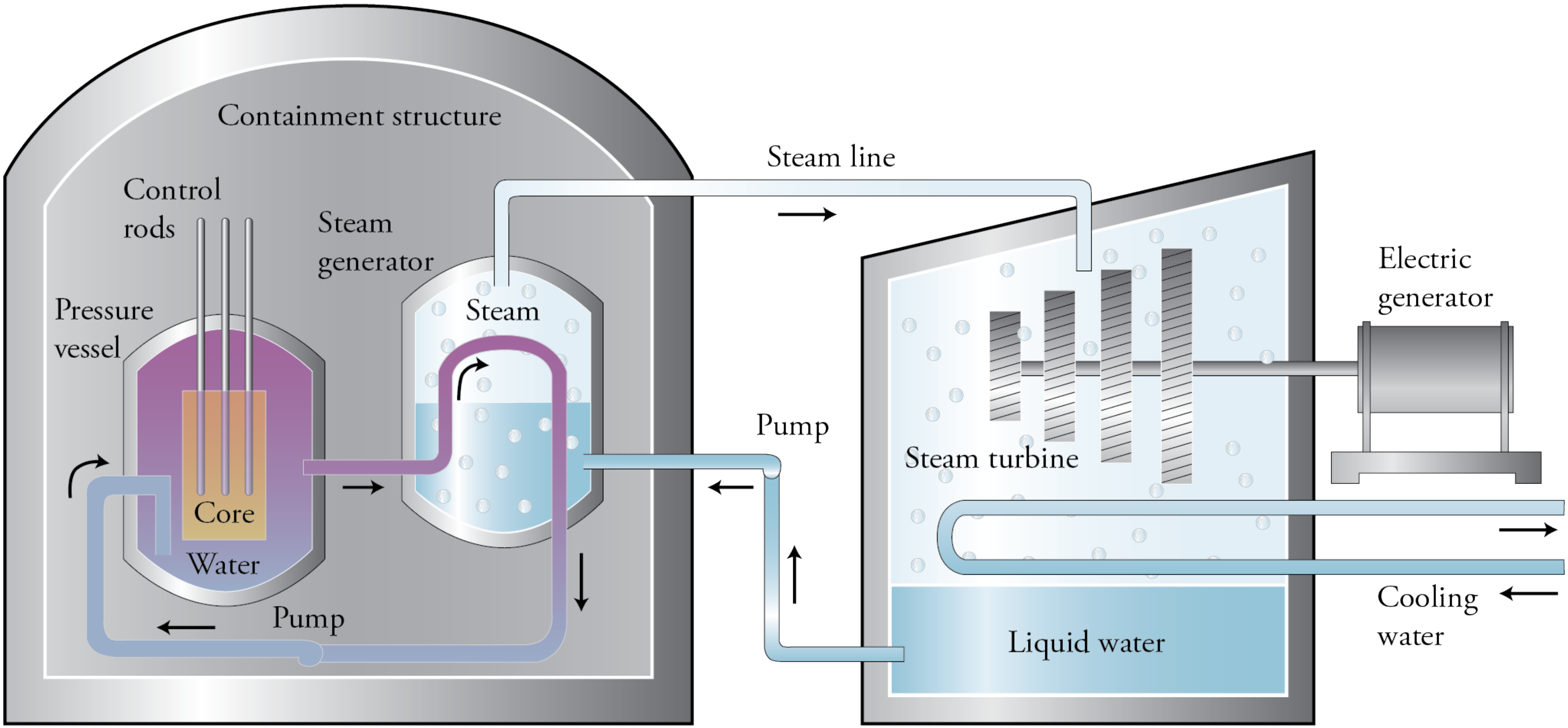
Nuclear Fission



Chain Reaction

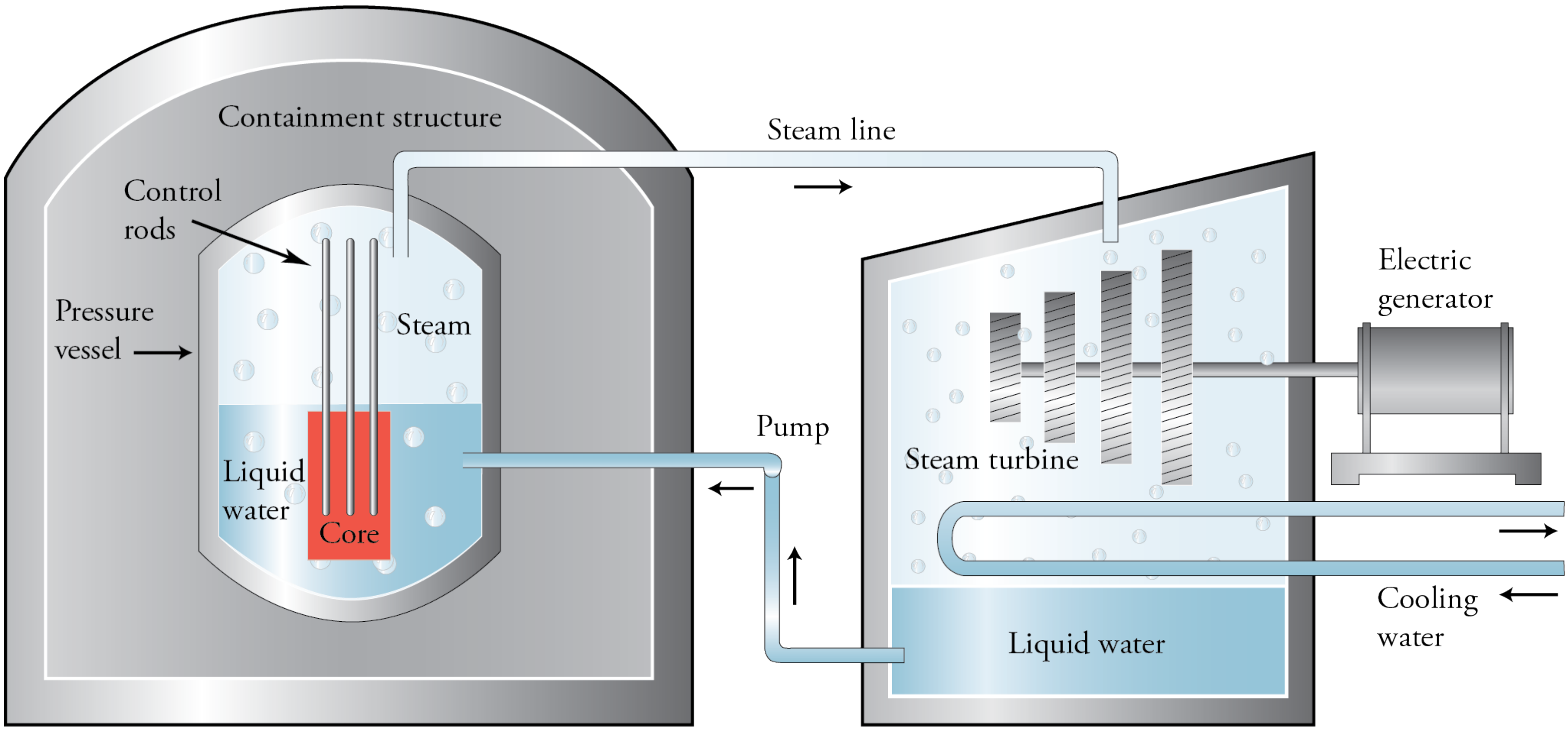


Nuclear Power Plant



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.

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

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

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

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

- Control Rods
  - Substances, such as cadmium or boron, that absorb neutrons.
  - Control rate of chain reaction
  - Dropped at first sign of trouble to stop fission reaction
- Facility includes instrumentation to monitor and control the reactor, radiation shielding, and a containment building.

Nuclear Power Plant

- Fission reactions provide heat, which is used to boil water to create steam, which turns a steam turbine to generate electricity.
- Get heat from
  - Fission reaction
  - Radioactive decay of fission products
  - Gamma rays released converted into heat

Thermal Reactors

- Thermal reactors use slowed or thermal neutrons.
- Almost all current reactors are of this type.
- A moderator slows neutrons until their kinetic energy approaches the average kinetic energy of the surrounding particles.
  - Moderator can be regular (light) water (74.8% of the world's reactors), solid graphite (20% of reactors) and heavy water (dueterium oxide - 5% of reactors).
- Thermal neutrons have a far higher probability of fissioning the fissile nuclei (^{235}U, ^{239}Pu, and ^{241}Pu), and a relatively lower probability of neutron capture by ^{238}U compared to the faster neutrons that originally result from fission, allowing use of low-enriched uranium fuel. The moderator is often also the coolant, usually water under high pressure to increase the boiling point.

Fast Neutron Reactors

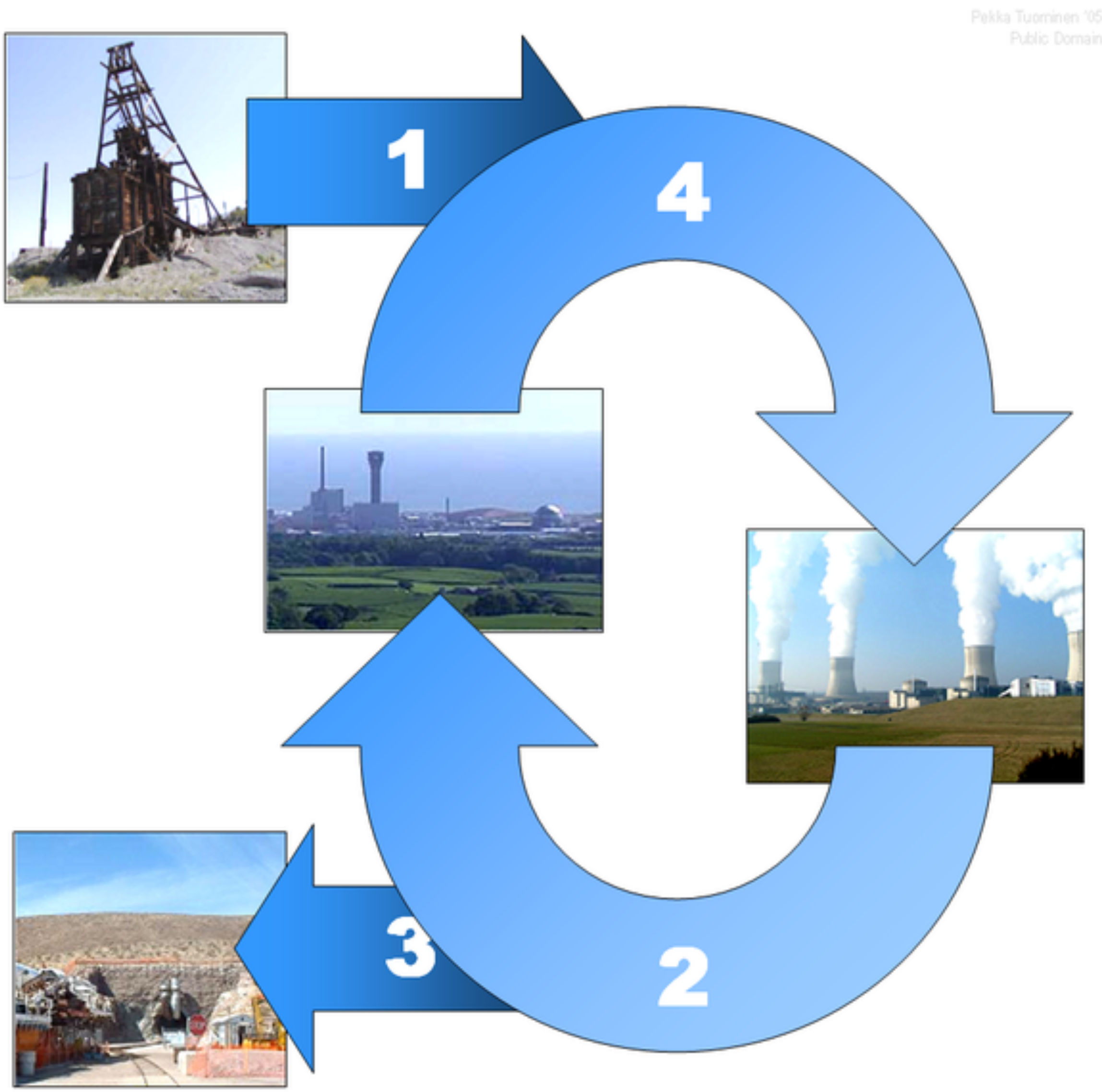
- Use fast neutrons to cause fission in their fuel.
- Do not have a neutron moderator, and use less-moderating coolants.
- Requires the fuel to be more highly enriched in fissile material (about 20% or more) due to the relatively lower probability of fission versus capture by U-238.
- More difficult to build and more expensive to operate.
- Less common than thermal reactors in most applications.

Diablo Canyon Nuclear Plant

- At Avila Beach in San Luis Obispo County, California.
- Two 1,100 MWe (MW of electrical energy produced) pressurized-water nuclear reactors operated by Pacific Gas & Electric produce about 18,000 GW·h of electricity annually, supplying the electrical needs of more than 2.2 million people.

Uranium Fuel Cycle

Uranium is mined, enriched and manufactured to make nuclear fuel (1), which is delivered to a nuclear power plant. After usage in the power plant the spent fuel might be delivered to a reprocessing plant (if fuel is recycled) (2) or to a final repository (if no recycling is done) (3) for geological disposition. In reprocessing, 95% of spent fuel can be recycled to be returned to usage in a nuclear power plant (4).



http://en.wikipedia.org/wiki/Nuclear_fuel_cycle

Uranium Ore

- Uranium is one of the more common elements in the Earth's crust, some 40 times more common than silver and 500 times more common than gold.
- The primary uranium ore is uraninite, which is is largely UO_2, but also contains UO_3 and oxides of other metals. It is commonly known as pitchblende.

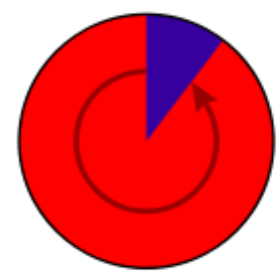
Uranium Enrichment

- Uranium in uranium ore is about 99.3% ^{238}U, which is not fissionable, and 0.7% ^{235}U, which is fissionable.
- Needs to be enriched in ^{235}U to varying degrees (depending on the reactor design) to be useful in a nuclear power plant.

Highly enriched uranium metal

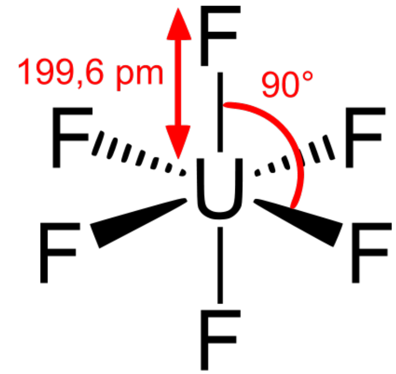
Natural uranium
> 99.2% U-238
0.72% U-235

Low-enriched uranium
(reactor grade)
3-4% U-235

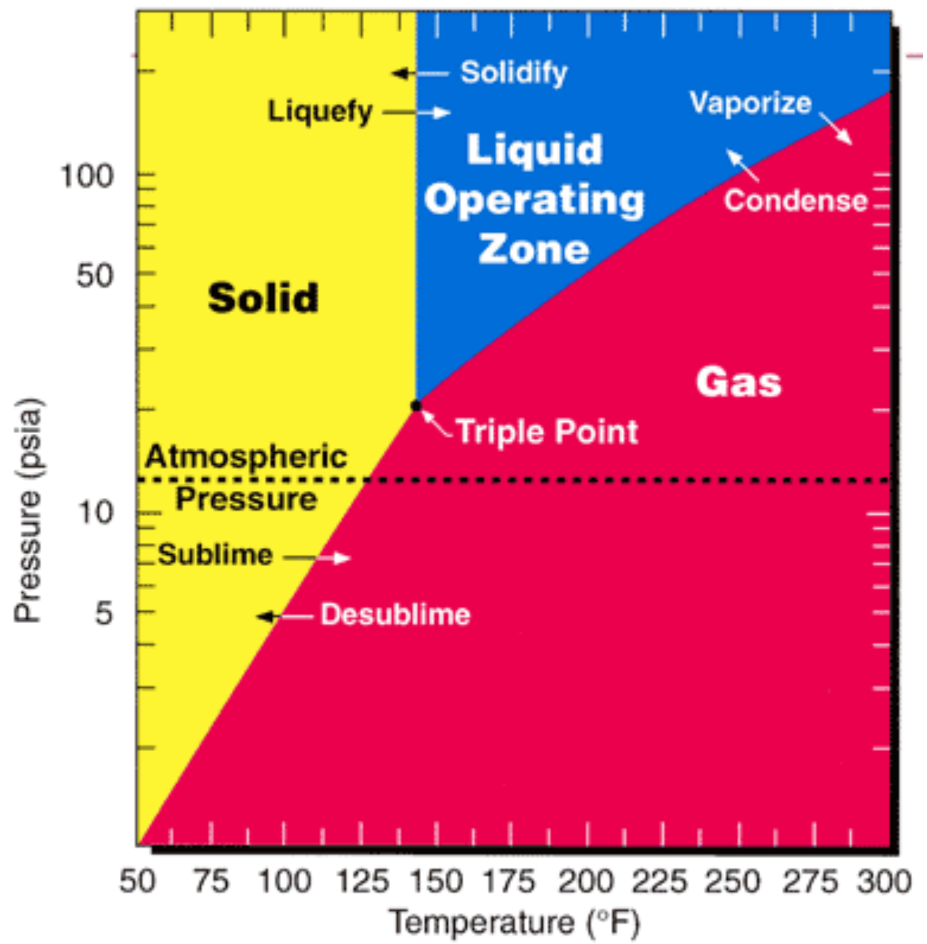


Highly enriched uranium
(weapons grade)
90% U-235

Uranium Enrichment

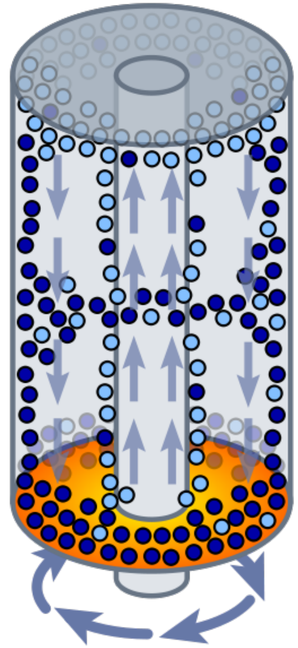


- In a series of steps, the uranium in uranium ore is converted into uranium hexafluoride, UF_6.
- It sublimes (goes directly from solid to gas) at 56.5 ° C.
- The UF_6 can be enriched in $^{235}UF_6$ by either gas diffusion (first generation) or using gas centrifuges (second generation), which requires less energy.

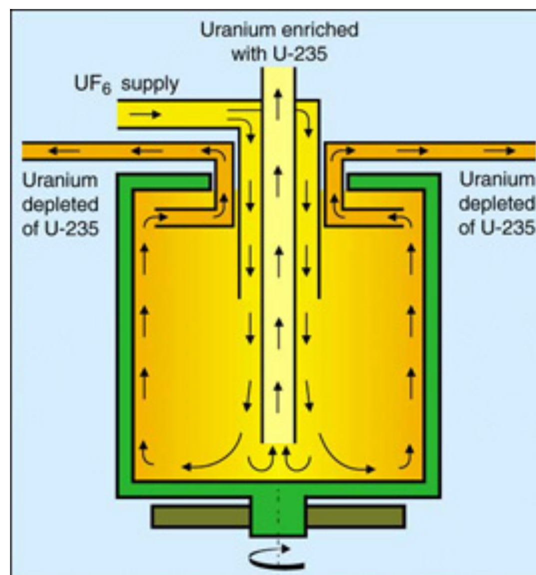


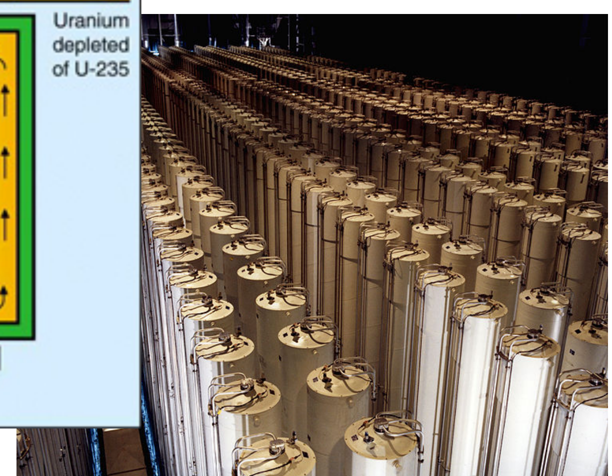
Gas Centrifuge

- Creates a strong centrifugal force so that the heavier gas molecules containing ^{238}U move toward the outside of the cylinder and the lighter gas molecules rich in ^{235}U collect closer to the center.
- A large number of rotating cylinders connected in series and parallel formations.



The bottom of the rotating cylinder can be heated, producing convection currents that move the ^{235}U up the cylinder, where it can be collected.



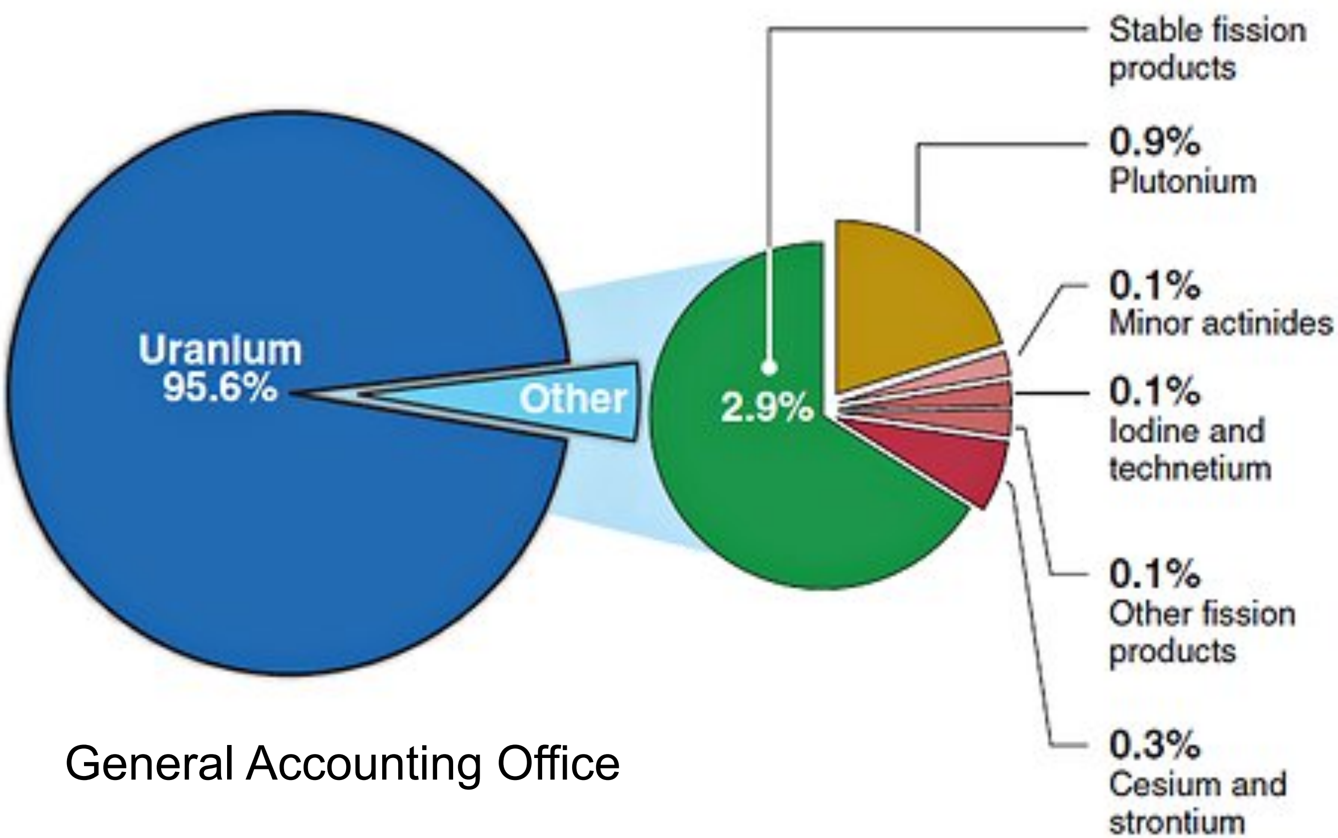


Depleted Uranium

- Most of the depleted uranium produced is stored as uranium hexafluoride, DUF_6, in steel cylinders in open air yards close to enrichment plants.

Spent Fuel Rods

Figure 1: Composition of Spent Nuclear Fuel



General Accounting Office

- Fission products that emit beta and gamma radiation
- Some fissionable U-235 and Pu-239
- Alpha emitters, such as uranium-234, neptunium-237, plutonium-238 and americium-241
- Sometimes some neutron emitters such as californium (Cf).

Nuclear Reprocessing

- Process to chemically separate and recover fissionable plutonium and uranium from irradiated nuclear fuel.
- Purposes
  - Originally reprocessing was used solely to extract plutonium for producing nuclear weapons.
  - The reprocessed plutonium can be recycled back into fuel for nuclear reactors.
  - The reprocessed uranium, which constitutes the bulk of the spent fuel material, can in principle also be re-used as fuel, but that is only economic when uranium prices are high.

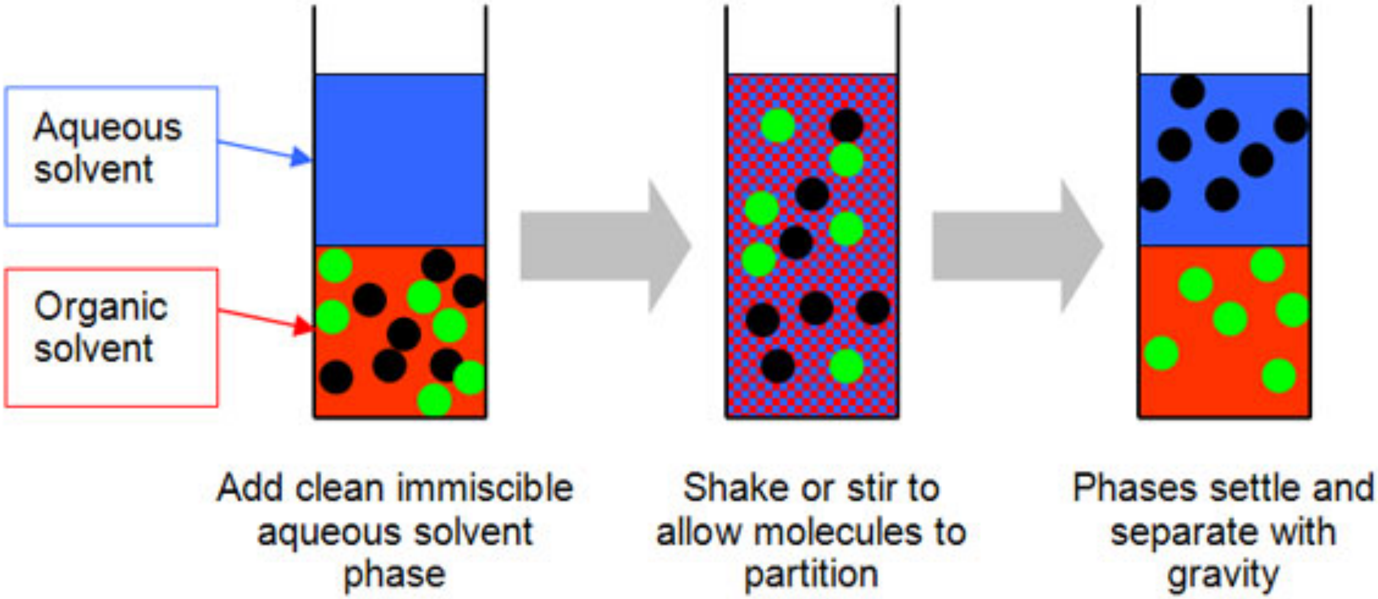
http://en.wikipedia.org/wiki/Nuclear_reprocessing

Nuclear Reprocessing

- Reprocessing of civilian fuel has long been employed in France, the United Kingdom, Russia, Japan, and India
- Briefly done at the West Valley Reprocessing Plant in the United States.
- In October 1976, concerned about nuclear weapons proliferation, President Gerald Ford indefinitely suspended the commercial reprocessing and recycling of plutonium in the U.S.
- In March 1999, the U.S. Department of Energy (DOE) reversed its policy and signed a contract with a consortium to design and operate a mixed oxide (MOX) fuel fabrication facility. There are no customers yet.

http://en.wikipedia.org/wiki/Nuclear_reprocessing

Liquid-Liquid Extraction



Polar compounds will congregate in "aqueous" layer

Non-polar compounds will congregate in "organic" layer

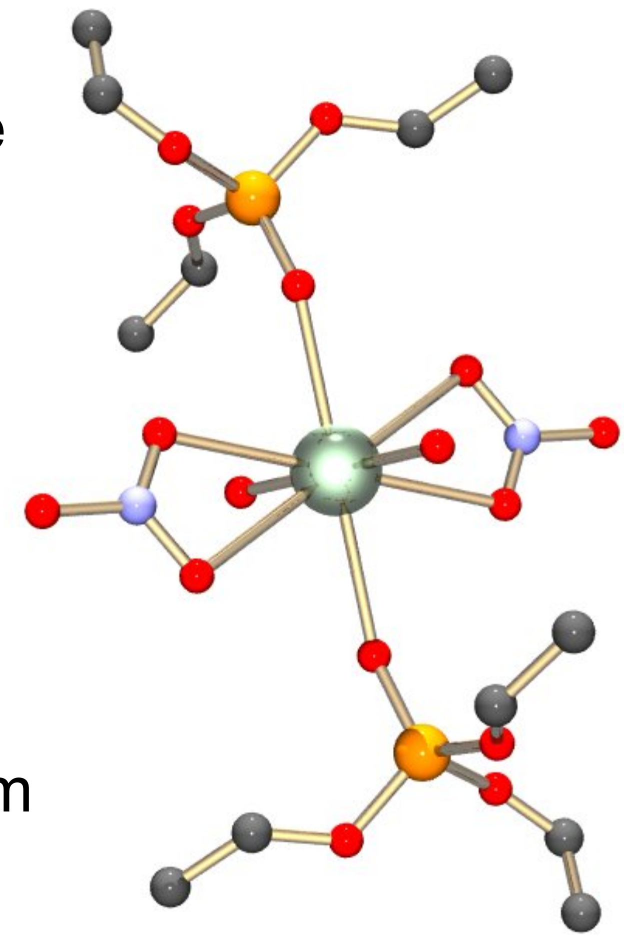
Typically performed in a separatory funnel:

Aqueous layer (polar things)

Organic layer (non-polar things)

PUREX Process

- Dissolve in 7 M HNO_3.
- Filter out solids
- Combine with 30% tributyl phosphate (TBP) to form $UO_2(NO_3)_2 \cdot 2TBP$ and $PuO_2(NO_3)_2 \cdot 2TBP$ complexes.
- Extract with an organic solvent, such as kerosene.
  - $UO_2(NO_3)_2 \cdot 2TBP$ and $PuO_2(NO_3)_2 \cdot 2TBP$ complexes in nonpolar organic solvent
  - Fission products, and transuranium elements americium and curium remain in the aqueous phase.



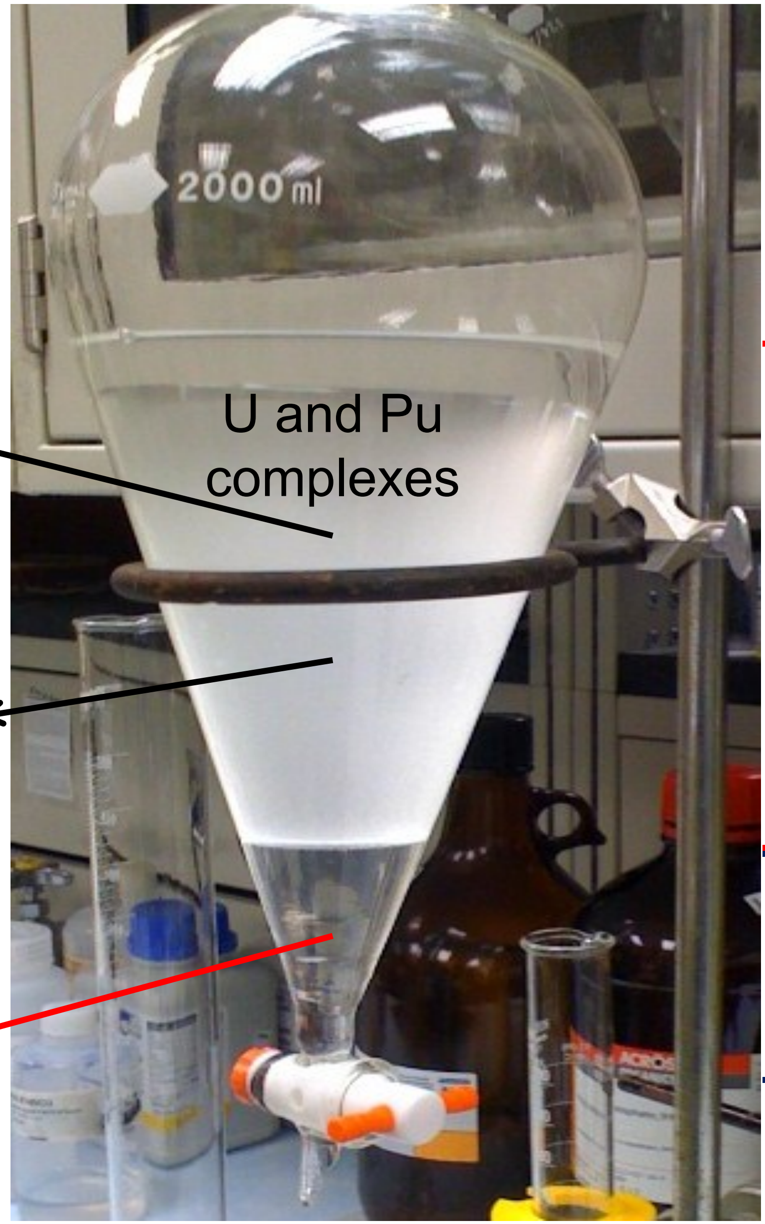
http://en.wikipedia.org/wiki/PUREX

Separation of U, Pu, and Fission Products

On to Uranium purification

On to Plutonium purification

Fission products, minor actinides: discarded as "high level waste"



Nonpolar solvent Layer

Aqueous Layer

PUREX Process

- Plutonium is separated from uranium in a separate extraction by treating the kerosene solution with aqueous iron(II) sulfamate, $Fe(SO_3NH_2)_2$, which reduces the plutonium to the +3 oxidation state. The plutonium passes into the aqueous phase.
- Variations on the PUREX process have been developed.

http://en.wikipedia.org/wiki/PUREX

One Sign of Reprocessing of Nuclear Wastes

- 2002 – China shipped about 20 tons of tributyl phosphate (TBP) to North Korea.
- Considered to be sufficient to extract enough material for three to five nuclear weapons

Nuclear Waste Storage and Disposal

- Nuclides of special concern
  - Tc-99 (half-life 220,000 years) and I-129 (half-life 17 million years), which dominate spent fuel radioactivity after a few thousand years.
  - Np-237 (half-life two million years) and Pu-239 (half-life 24,000 years).
- Needs treatment, followed by a long-term management strategy involving storage, disposal, or transformation of the waste into a non-toxic form.
- Governments around the world are considering a range of waste management and disposal options, though there has been limited progress toward long-term waste management solutions.

http://en.wikipedia.org/wiki/Nuclear_waste_storage#Management_of_waste

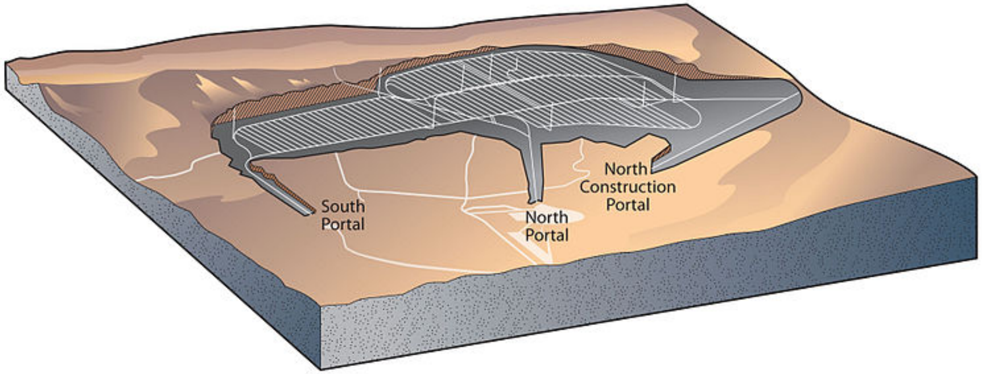
Nuclear Waste Storage/Disposal Possibilities

- "Long term above ground storage", not implemented.
- "Disposal in outer space", not implemented.
- "Deep borehole disposal", not implemented.
- "Rock-melting", not implemented.
- "Disposal at subduction zones", not implemented.
- "Ocean disposal", done by USSR, UK, Switzerland, USA, Belgium, France, Netherland, Japan, Sweden, Russia, Germany, Italy and South Korea. (1954–93) It's not permitted by international agreements.
- "Sub seabed disposal", not implemented, not permitted by international agreements.
- "Disposal in ice sheets", rejected in Antarctic Treaty
- "Direct injection“ of liquid waste, done by USSR and USA.

http://en.wikipedia.org/wiki/Nuclear_waste_storage#Management_of_waste

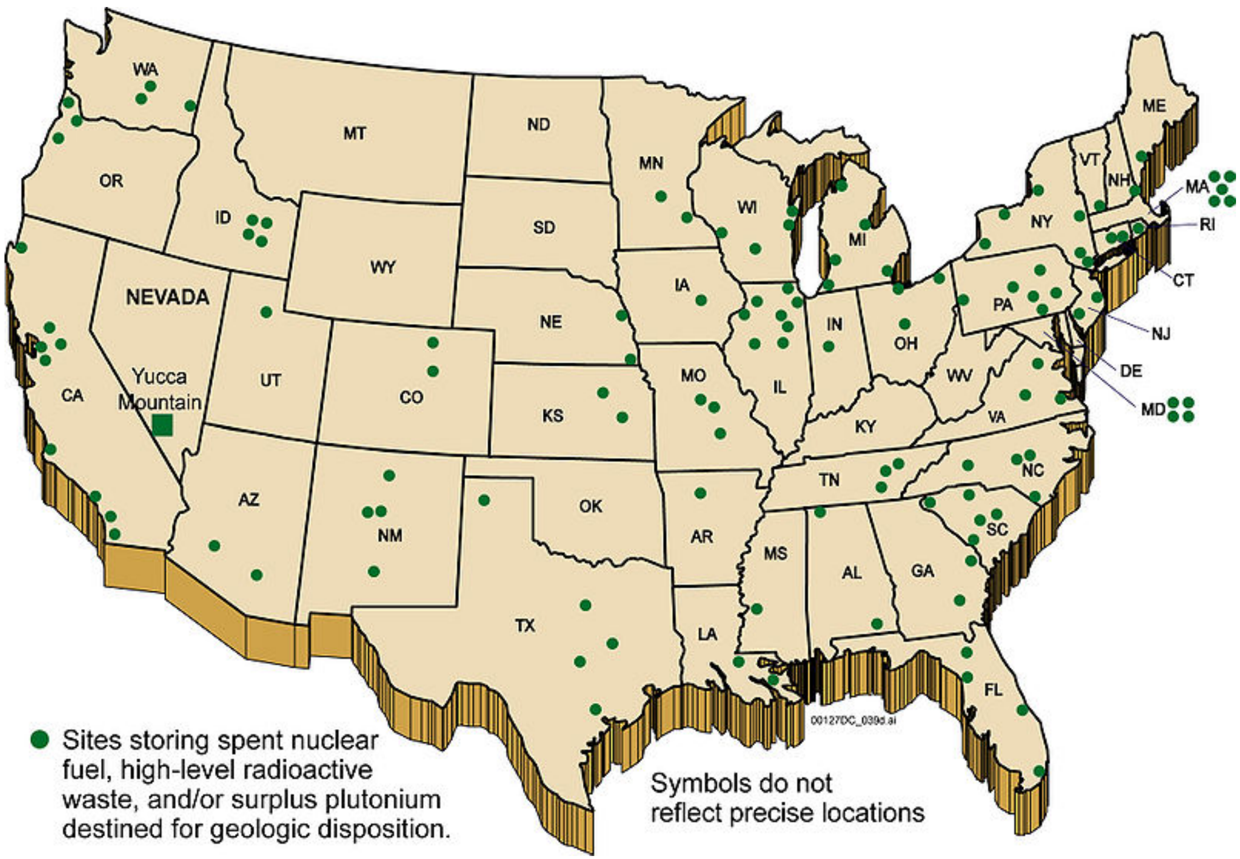
Yucca Mountain Nuclear Waste Repository

- Deep geological repository storage facility for spent nuclear reactor fuel and other high level radioactive waste,
- Approved in 2002 by the United States Congress.
- Project was defunded in 2010.
- The US Government Accountability Office stated that the closure was for political, not technical or safety reasons.



Yucca Mountain Nuclear Waste Repository

- United States without any long term storage site for high level radioactive waste, currently stored on-site at various nuclear facilities around the country



http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository

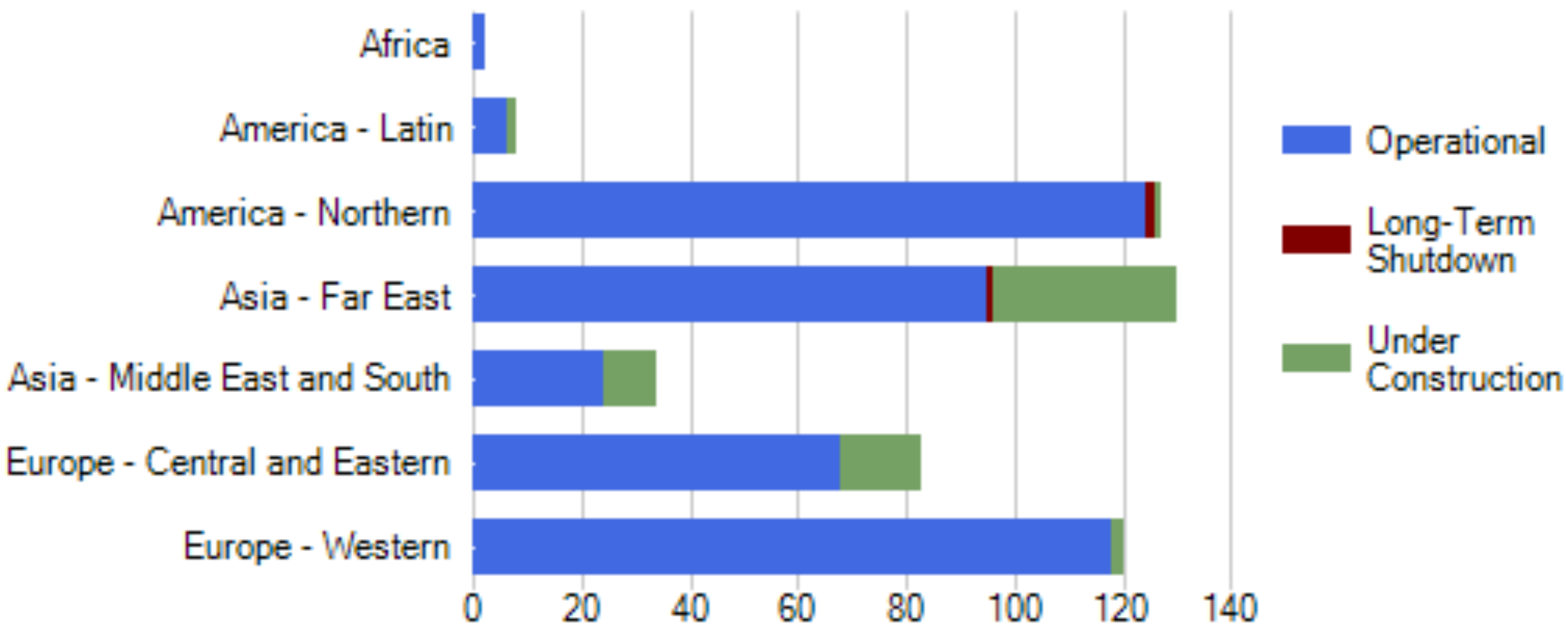
Nuclear Waste Geologic Repository

- The Blue Ribbon Commission established by the Secretary of Energy released its final report on January 26, 2012. It expressed urgency to find a consolidated, geological repository, but also that any future facility should have input from the citizens around it.

http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository

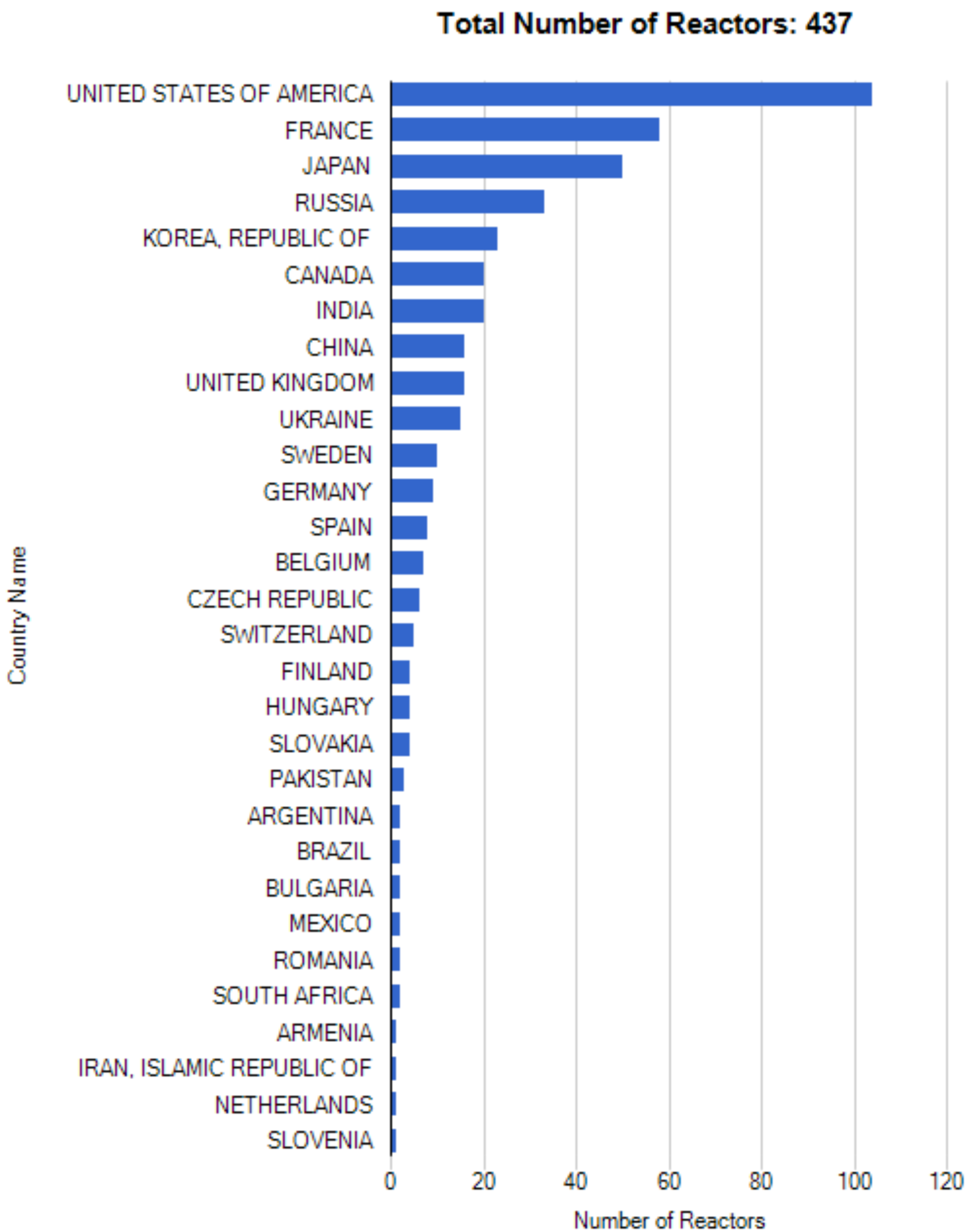
Status of Nuclear Power

- 437 nuclear power plants in operation
- 371.762 GW_e total installed capacity
- 64 Nuclear power plants under construction.



http://www.iaea.org/pris/

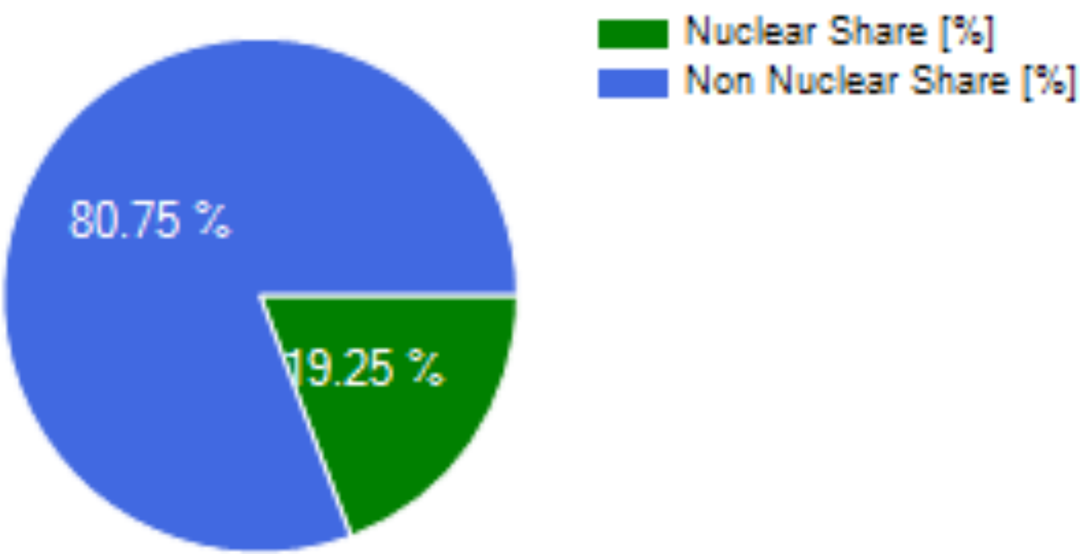
Worldwide Nuclear Reactors



http://www.iaea.org/pris/

United States

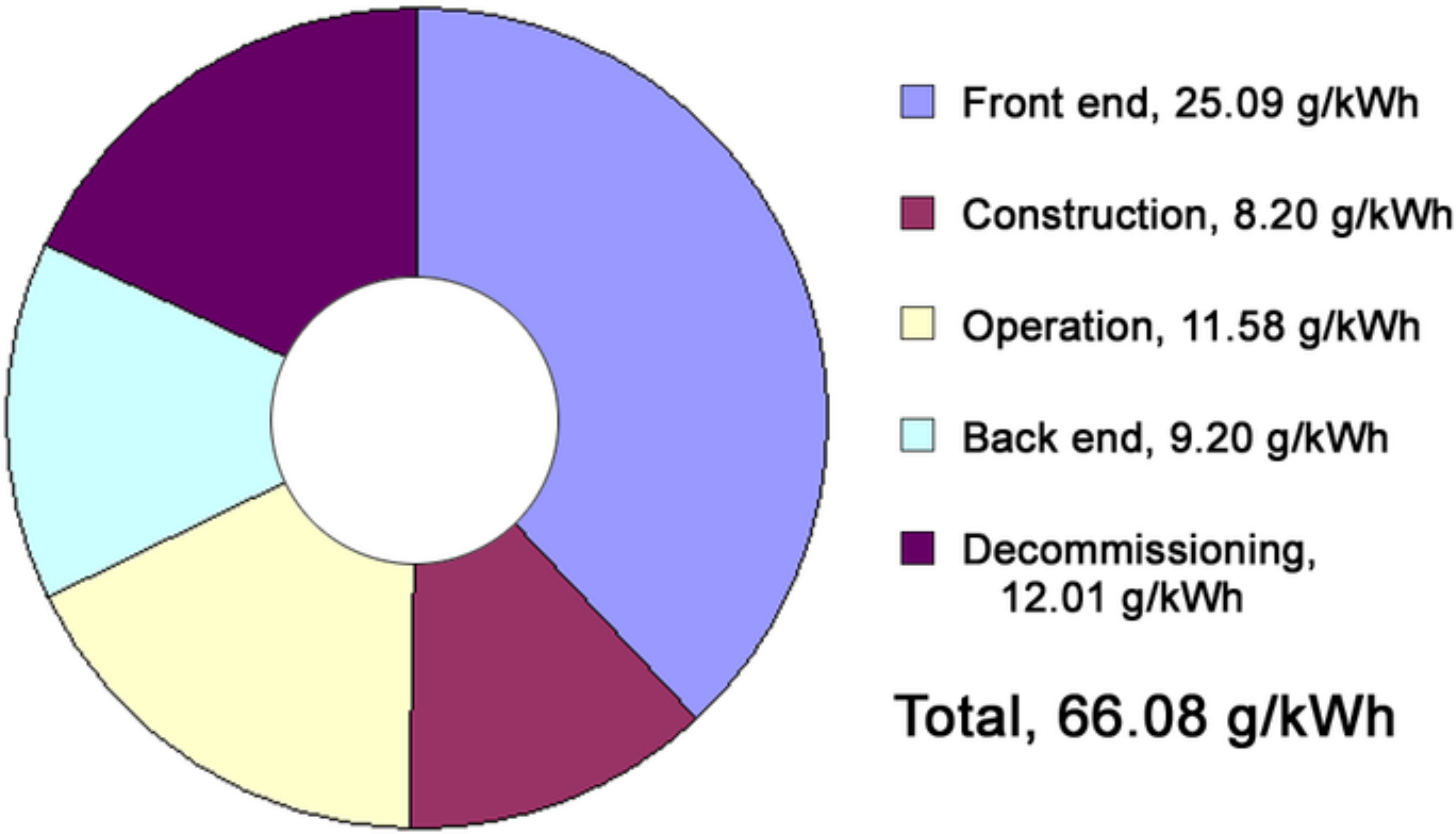
- 104 nuclear power plants
- 1 under construction
- 7.9×10^5 GWh in 2011



http://www.iaea.org/pris/

Carbon emissions from nuclear power

Sovacool life cycle study survey, 2008



Mean value of carbon dioxide emissions from qualified life cycle studies among 103 surveyed. Includes results of 1997 Vattenfall study.

Lifecycle Greenhouse Gas Emission Estimates for Electricity Generators

Technology	Description	Estimate (g CO2/kWh$_e$)
Wind	2.5 MW offshore	9
Hydroelectric	3.1 MW reservoir	10
Wind	1.5 MW onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW run-of-river	13
Solar thermal	80 MW parabolic trough	13
Biomass	various	14-35
Solar PV	Polycrystaline silicon	32
Geothermal	80 MW hot dry rock	38
Nuclear	various reactor types	66
Natural gas	various combined cycle turbines	443
Fuel Cell	hydrogen from gas reforming	664
Diesel	various generator and turbine types	778
Heavy oil	various generator and turbine types	778
Coal	various generator types with scrubbing	960
Coal	various generator types without scrubbing	1050

http://en.wikipedia.org/wiki/Comparisons_of_life-cycle_greenhouse-gas_emissions

Retiring Nuclear Power Plants