Atoms, Elements, Isotopes, Energy, Radioactivity, and Nuclear Energy

http://preparatorychemistry.com/Bishop_Book_atoms_3.pdf

http://preparatorychemistry.com/Bishop_Book_atoms_4.pdf

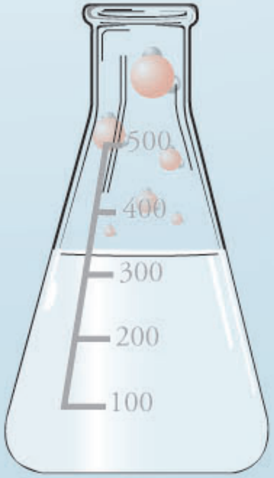
http://preparatorychemistry.com/Bishop_Book_atoms_16.pdf

Scientific Models

- A ***model*** is a simplified approximation of reality.
- Scientific models are simplified but *useful* representations of something real.

Kinetic Molecular Theory

- All matter is composed of tiny particles.
- The particles are in constant motion.
- Increased temperature reflects increased motion of particles.
- Solids, liquids and gases differ in the freedom of motion of their particles and in how strongly the particles attract each other.



http://preparatorychemistry.com/KMT_flash.htm

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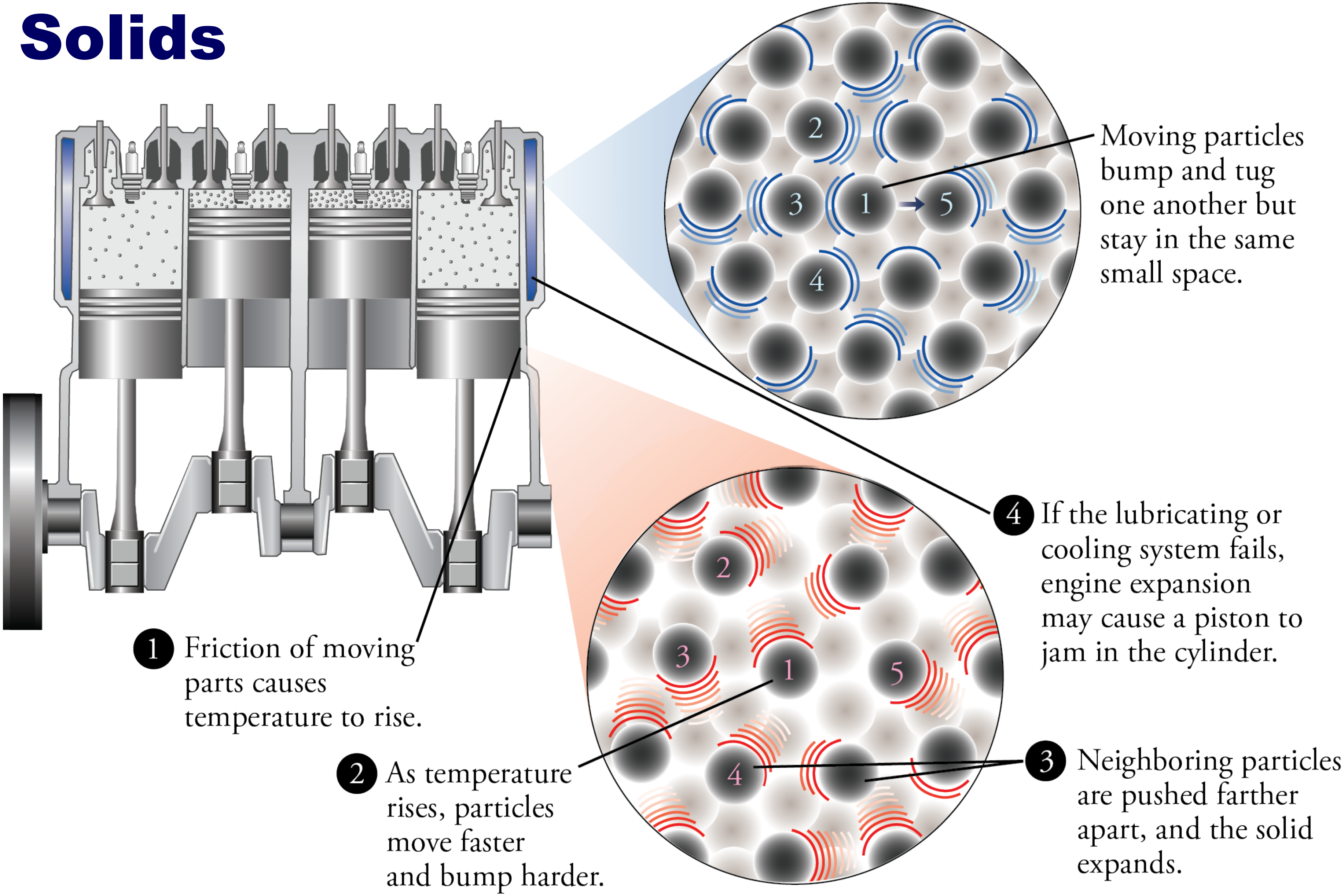
Solid

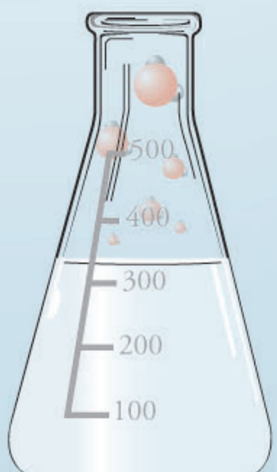
- Constant shape and volume
- The particles are constantly moving, colliding with other particles, and changing their direction and velocity.
- Each particle is trapped in a small cage whose walls are formed by other particles that are strongly attracted to each other.

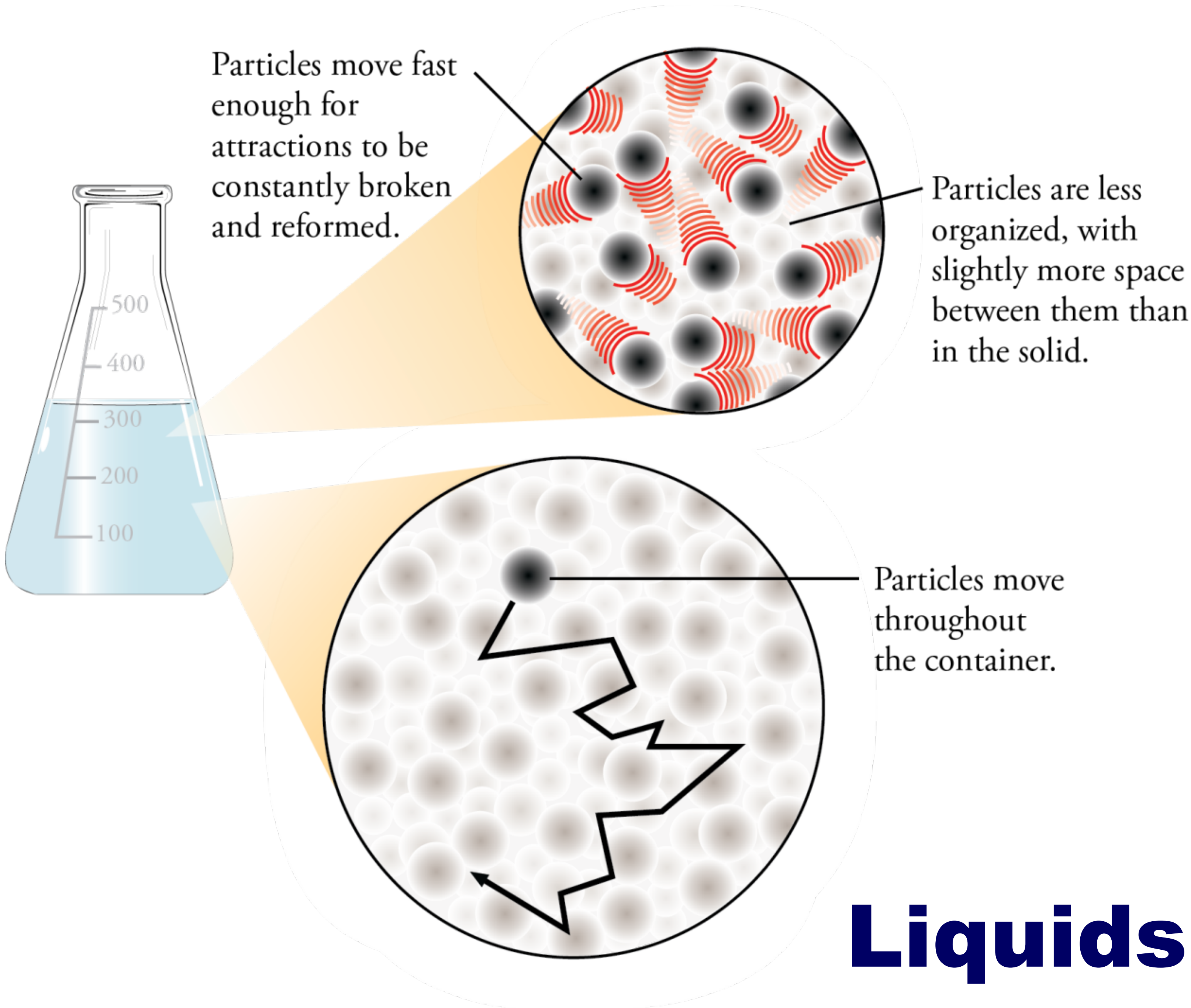
The Nature of Solids



Liquid

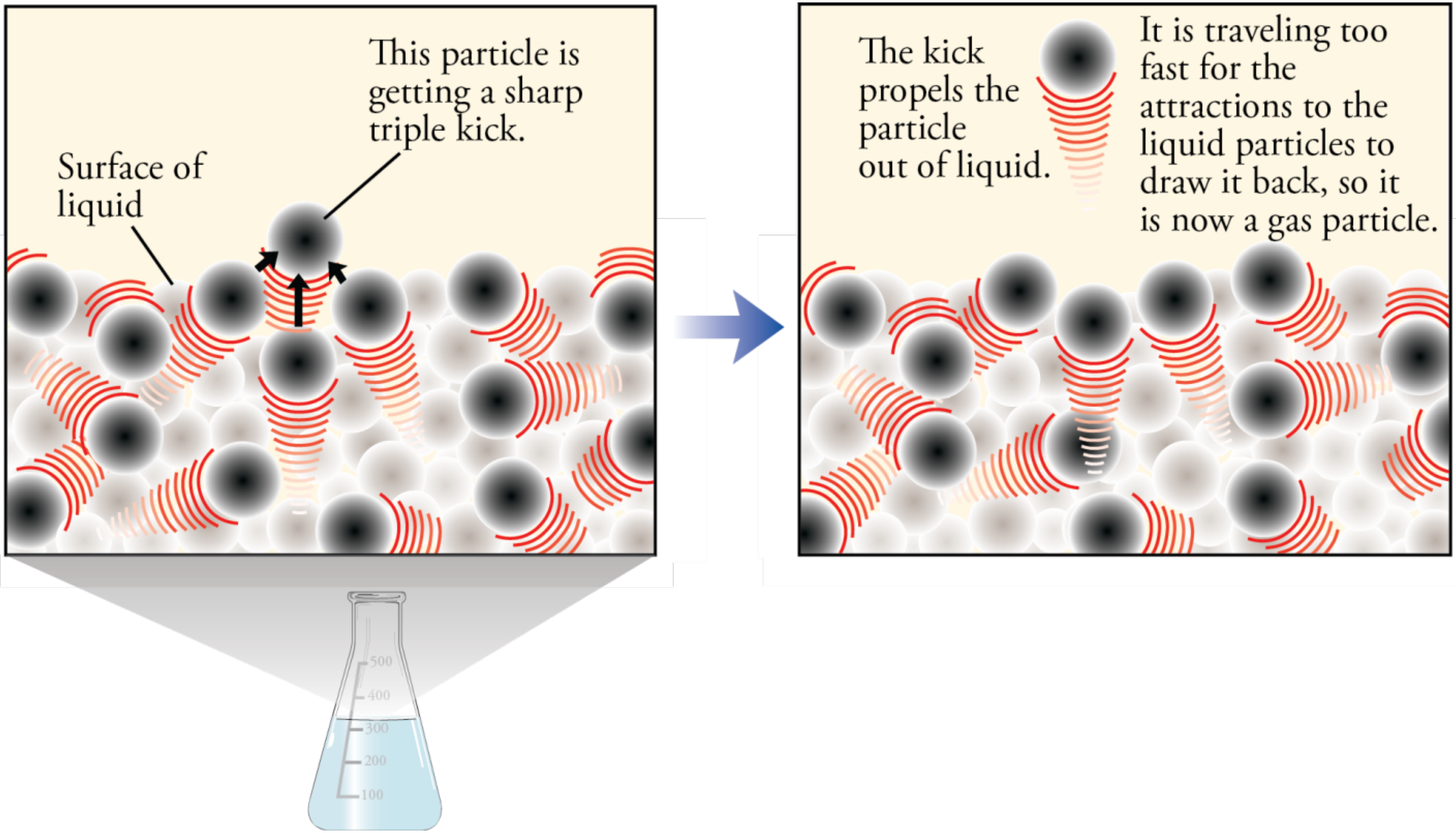
- Constant volume but variable shape
- The particles are moving fast enough to break the attractions between particles that form the walls of the cage that surround particles in the solid form.
- Thus each particle in a liquid is constantly moving from one part of the liquid to another.



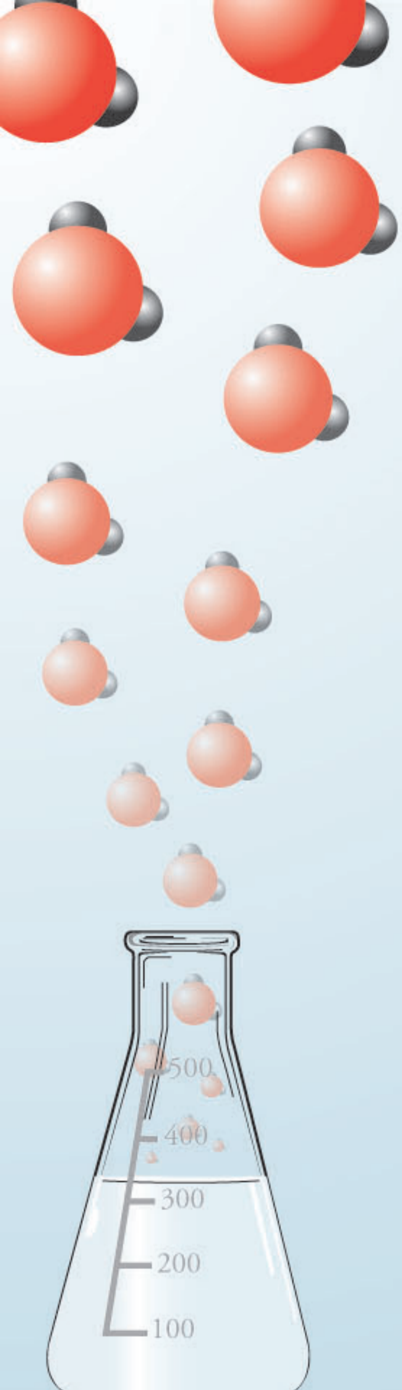

Particles move fast enough for attractions to be constantly broken and reformed.
Particles are less organized, with slightly more space between them than in the solid.
Particles move throughout the container.
500
400
300
200
100

Liquids

Evaporation

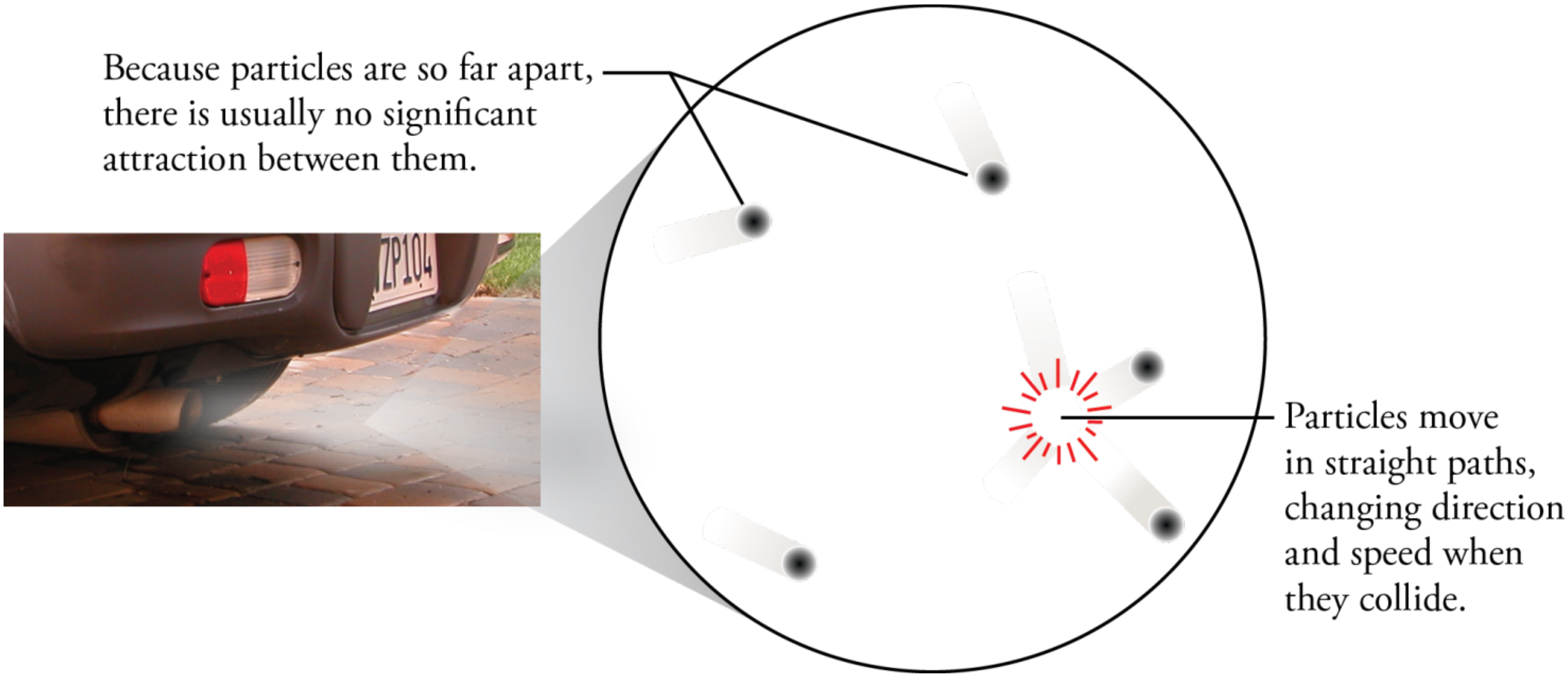


Gas



- Variable shape and volume
- Large average distances between particles
- Little attraction between particles
- Constant collisions between particles, leading to constant changes in direction and velocity

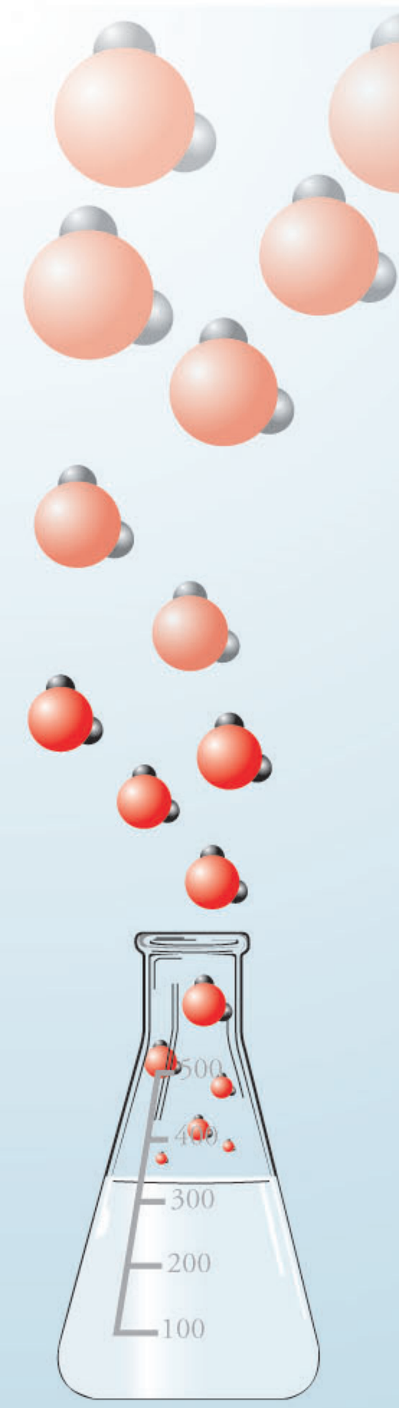
Gas


Because particles are so far apart, there is usually no significant attraction between them.
Particles move in straight paths, changing direction and speed when they collide.

Gas Model

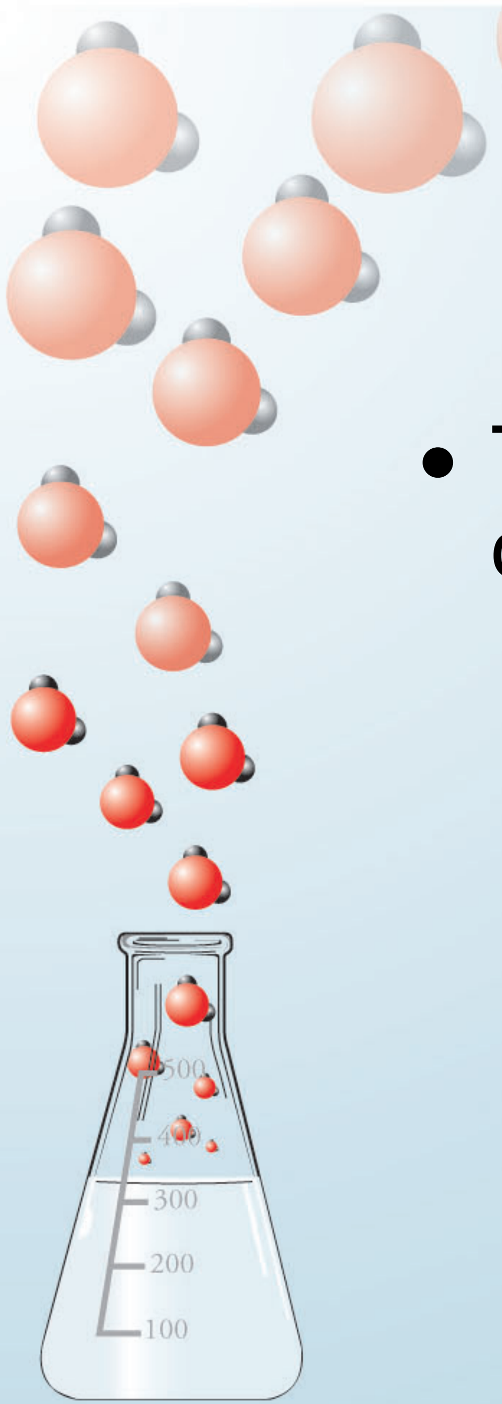
- Gases are composed of tiny, widely-spaced particles.
  - For a typical gas, the average distance between particles is about ten times their diameter.

Gas Model (cont.)



- Because of the large distance between the particles, the volume occupied by the particles themselves is negligible (approximately zero).
  – For a typical gas at room temperature and pressure, the gas particles themselves occupy about 0.1% of the total volume. The other 99.9% of the total volume is empty space. This is very different than for a liquid for which about 70% of the volume is occupied by particles.

Gas Model (cont.)



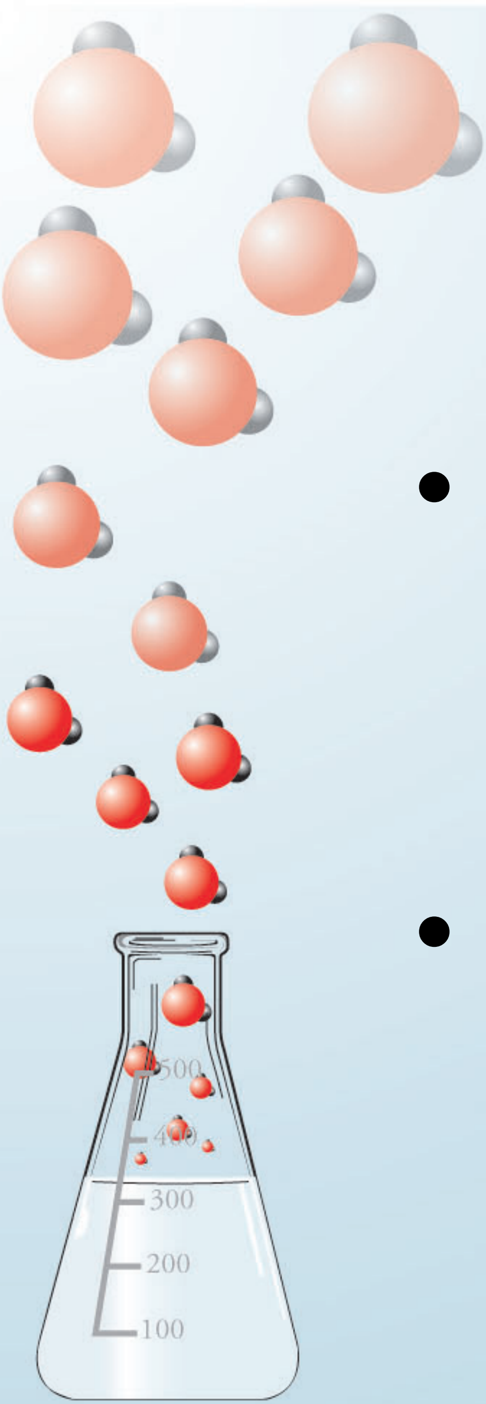
- The particles have rapid and continuous motion.
  - For example, the average velocity of a helium atom, He, at room temperature is over 1000 m/s (or over 2000 mi/hr). The average velocity of the more massive nitrogen molecules, N_2, at room temperature is about 500 m/s.
  - Increased temperature means increased average velocity of the particles.

Gas Model (cont.)

- The particles are constantly colliding with the walls of the container and with each other.
  - Because of these collisions, the gas particles are constantly changing their direction of motion and their velocity. In a typical situation, a gas particle moves a very short distance between collisions. Oxygen, O_2, molecules at normal temperatures and pressures move an average of 10^{-7} m between collisions.

Gas Model (cont.)

- There is no net loss of energy in the collisions. A collision between two particles may lead to each particle changing its velocity and thus its energy, but the increase in energy by one particle is balanced by an equal decrease in energy by the other particle.



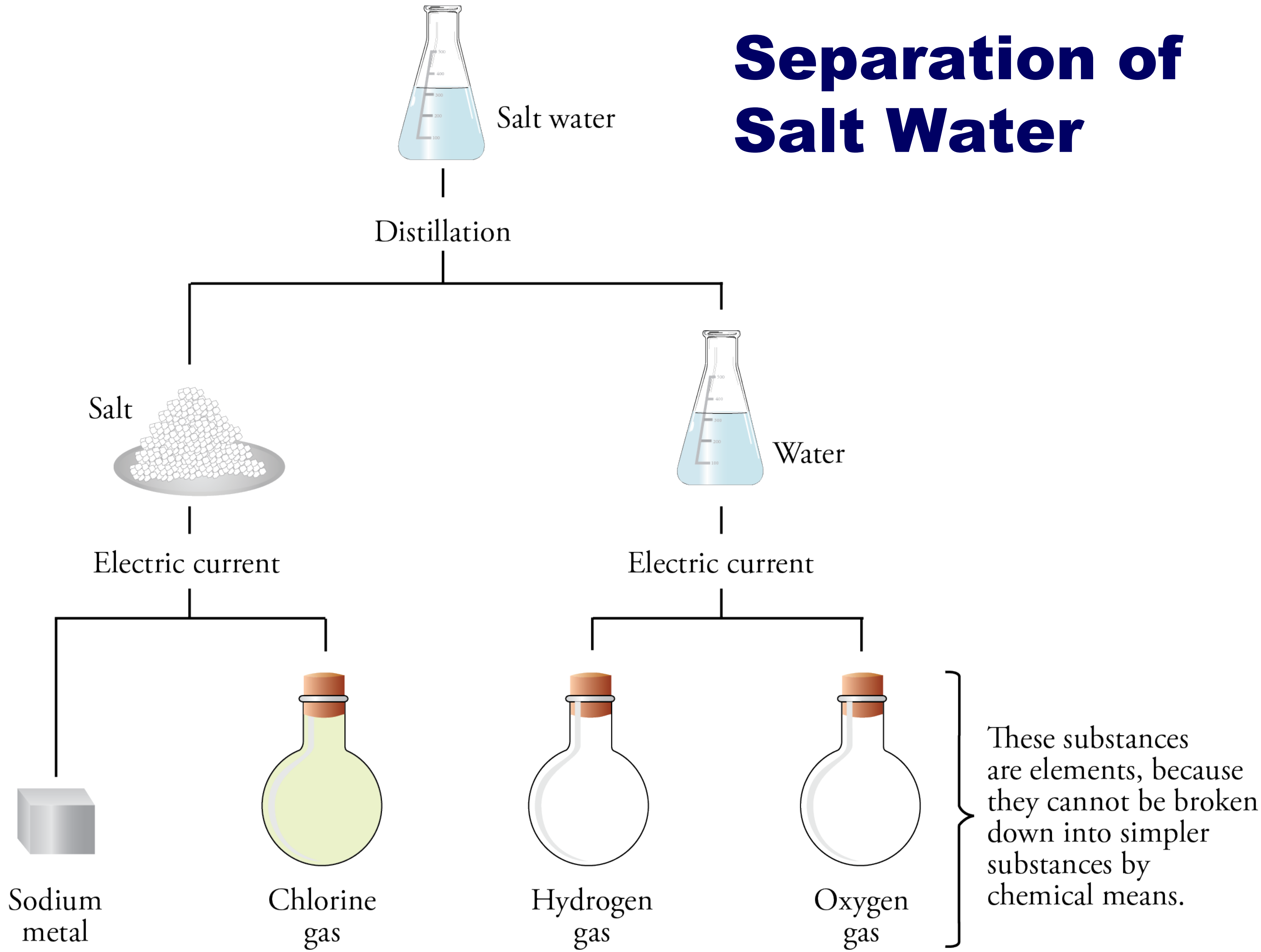
Ideal Gas

- The particles are assumed to be point-masses, that is, particles that have a mass but occupy no volume.
- There are no attractive or repulsive forces at all between the particles.

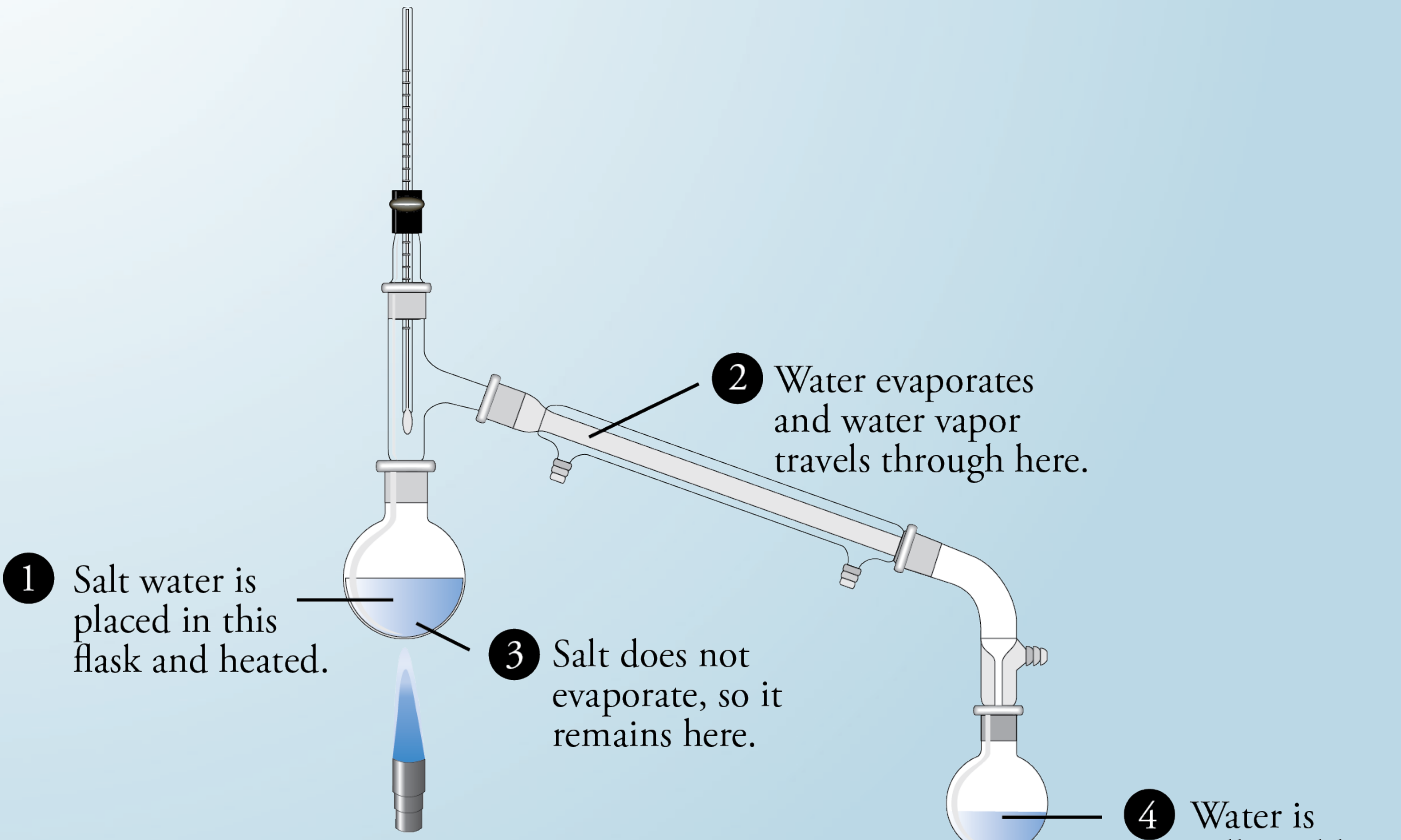
Gas Properties and their Units

- Pressure (P) = Force/Area
  - units
    - 1 atm = 101.325 kPa = 760 mmHg = 760 torr = 14.7 lb/in^2 (psi)
    - 1 bar = 100 kPa = 0.9869 atm = 750.1 mmHg
- Volume (V)
  - unit usually liters (L)
- Temperature (T)
  - ? K = --- °C + 273.15
- Number of gas particles expressed in moles (n)

Separation of Salt Water



Distillation



118 Known Elements

- 83 are stable and found in nature.
  - Many of these a very rare.
- 7 are found in nature but are radioactive.
- 28 are not natural on the earth.
  - 2 or 3 of these might be found in stars.

Group Numbers on the Periodic Table

	1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh		

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Group Names

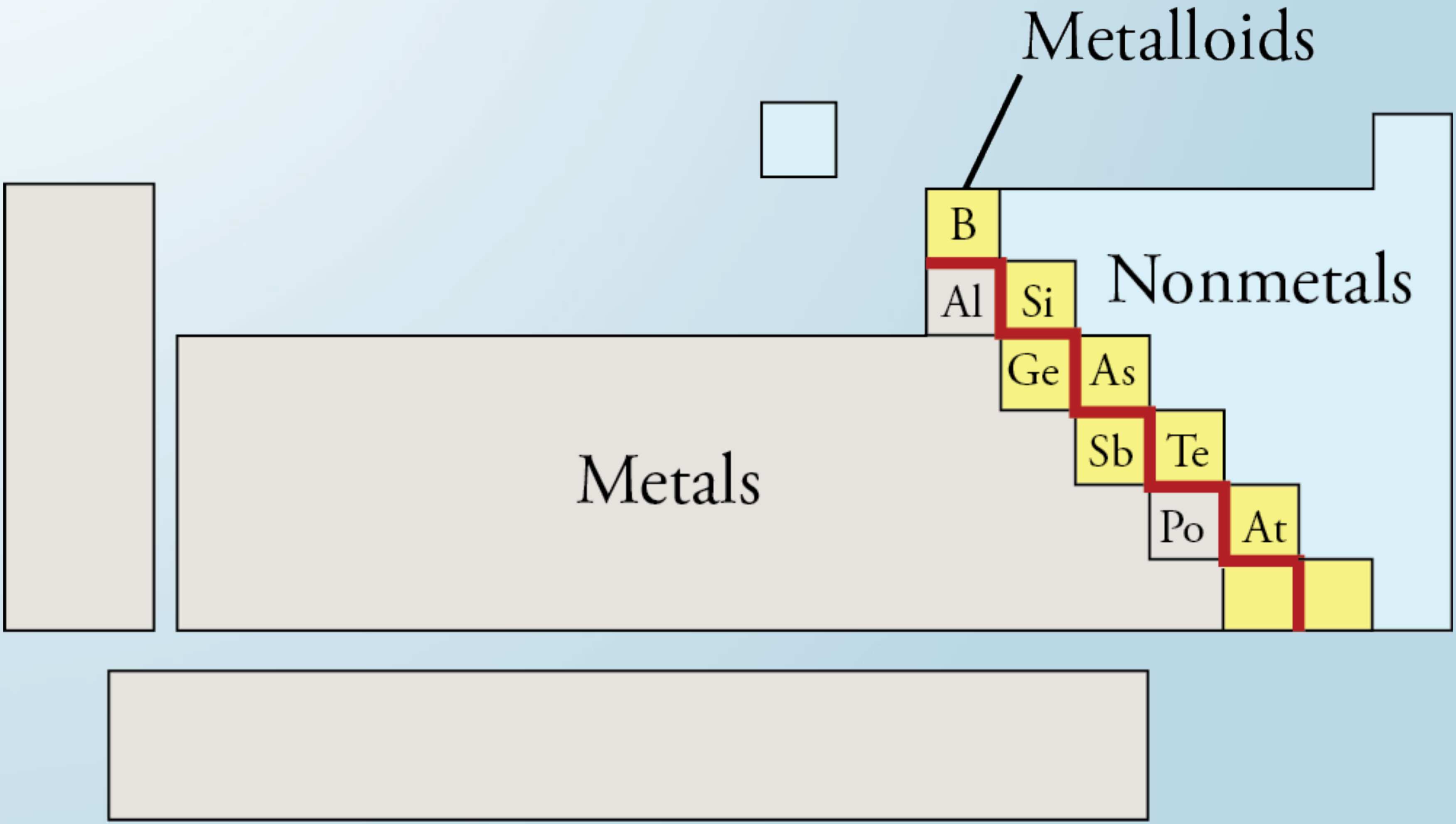
Noble Gases

Alkali Metals   Alkaline Earth Metals   Halogens

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
1											1 H							2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh		

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

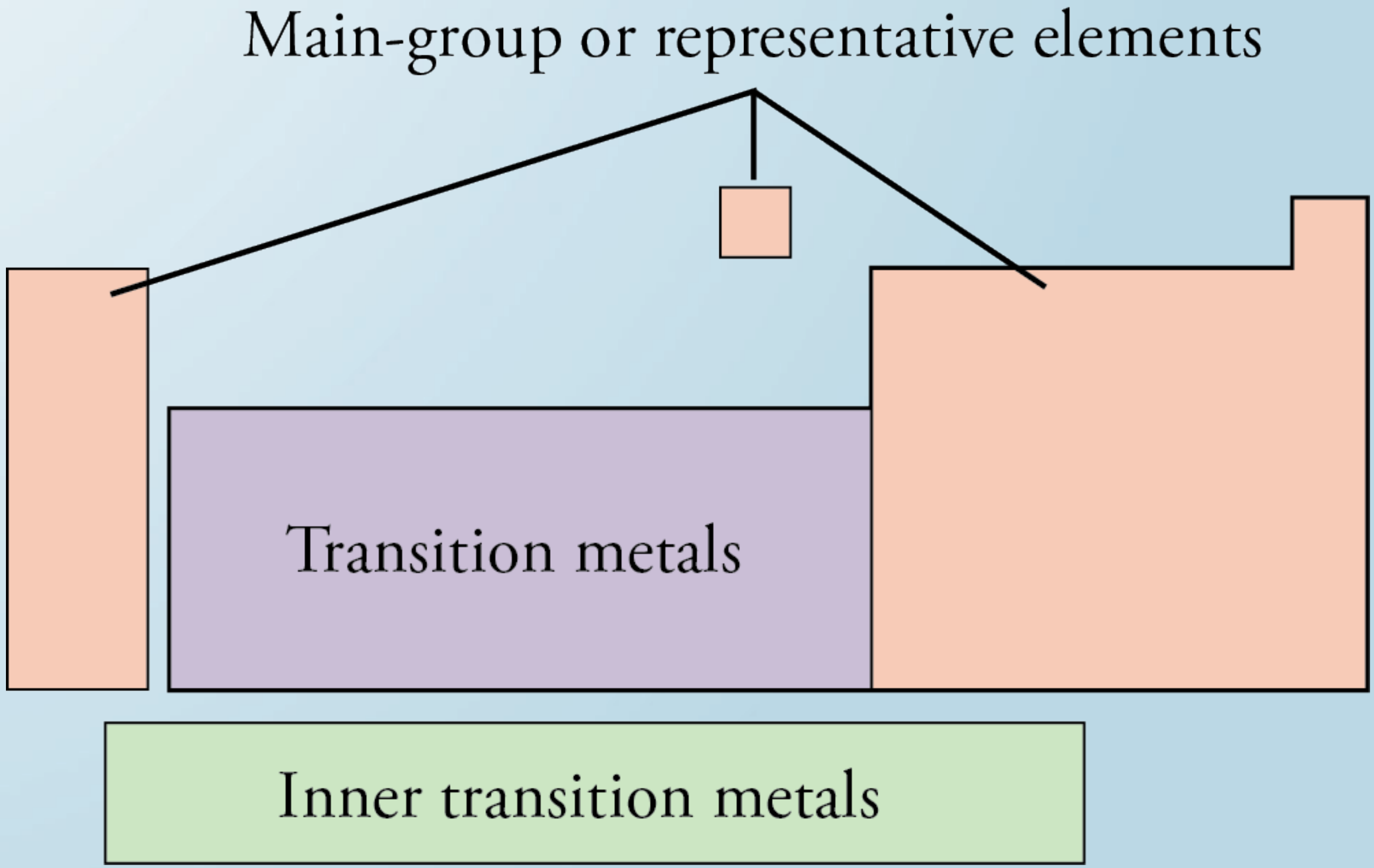
Metals, Nonmetals, and Metalloids



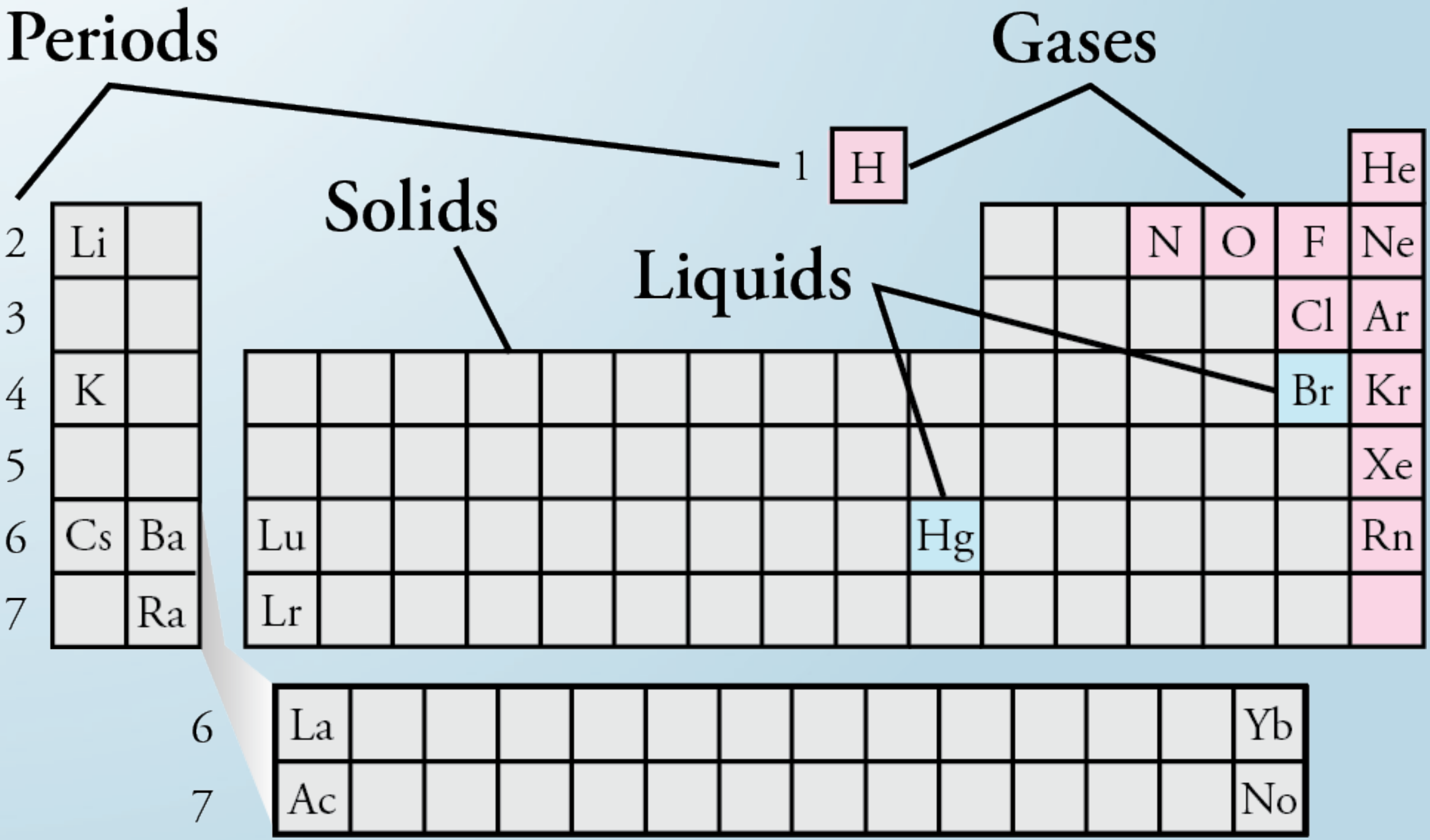
Characteristics of Metallic Elements

- Metals have a shiny metallic luster.
- Metals conduct heat well and conduct electric currents in the solid form.
- Metals are malleable.
  - For example, gold, Au, can be hammered into very thin sheets without breaking.

Classification of Elements

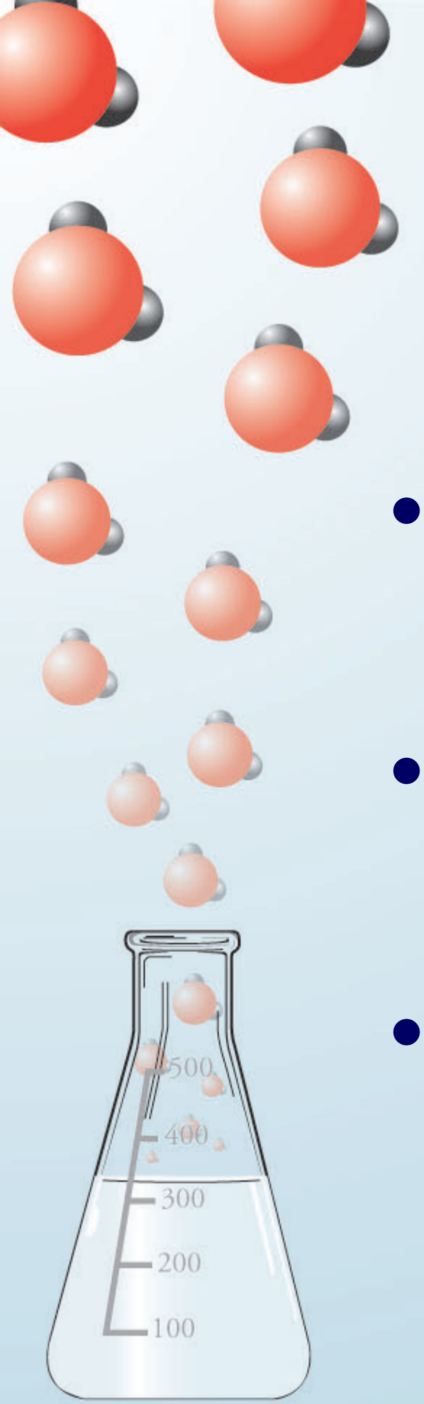


Solid, Liquid, and Gaseous Elements



Atoms

- Tiny…about 10^{-10} m
  - If the atoms in your body were 1 in. in diameter, you'd bump your head on the moon.
- Huge number of atoms in even a small sample of an element
  - 1/2 carat diamond has 5×10^{21} atoms…if lined up, would stretch to the sun.



Particles in the Atom

- Neutron (n)

  0 charge   1.00867 u   in nucleus

- Proton (p)

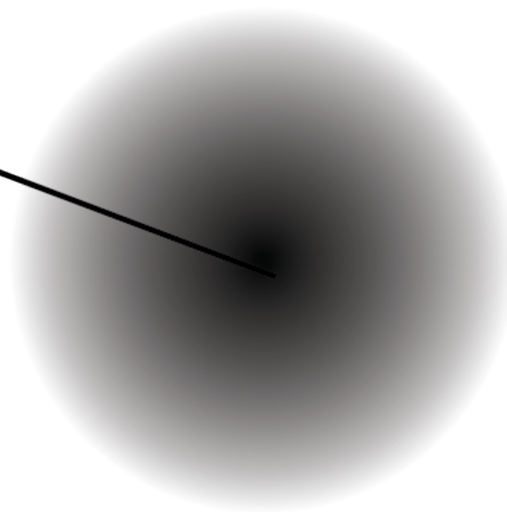
  +1 charge   1.00728 u   in nucleus

- Electron (e^-)

  –1 charge   0.000549 u   outside nucleus

Electron Cloud for Hydrogen Atom

The negative charge is most intense at the nucleus and diminishes in intensity with increased distance from the nucleus.



http://preparatorychemistry.com/Hydrogen_1.html

The Electron

"If I seem unusually clear to you, you must have misunderstood what I said."

Alan Greenspan,

Former Head of the Federal Reserve Board

"It is probably as meaningless to discuss how much room an electron takes up as to discuss how much room a fear, an anxiety, or an uncertainty takes up."

Sir James Hopwood Jeans,

English mathematician, physicist and astronomer (1877-1946)

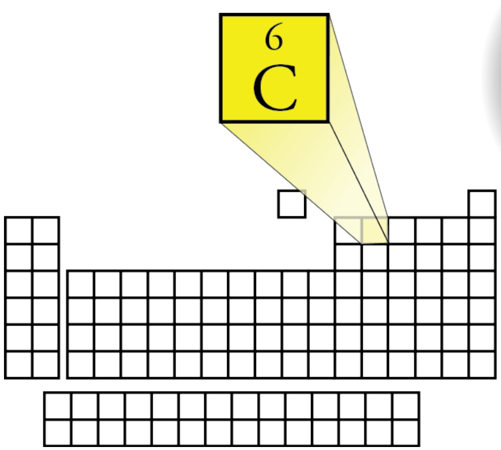
Helium Atom

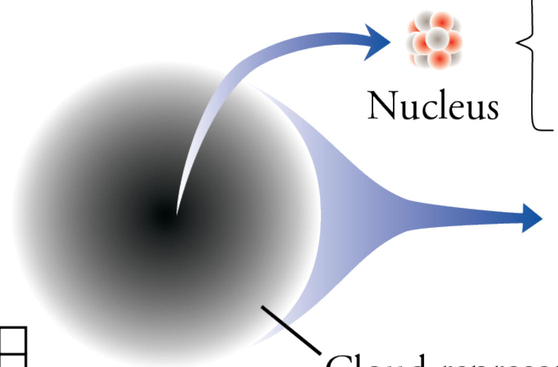
http://preparatorychemistry.com/helium_atom.html

Carbon Atom

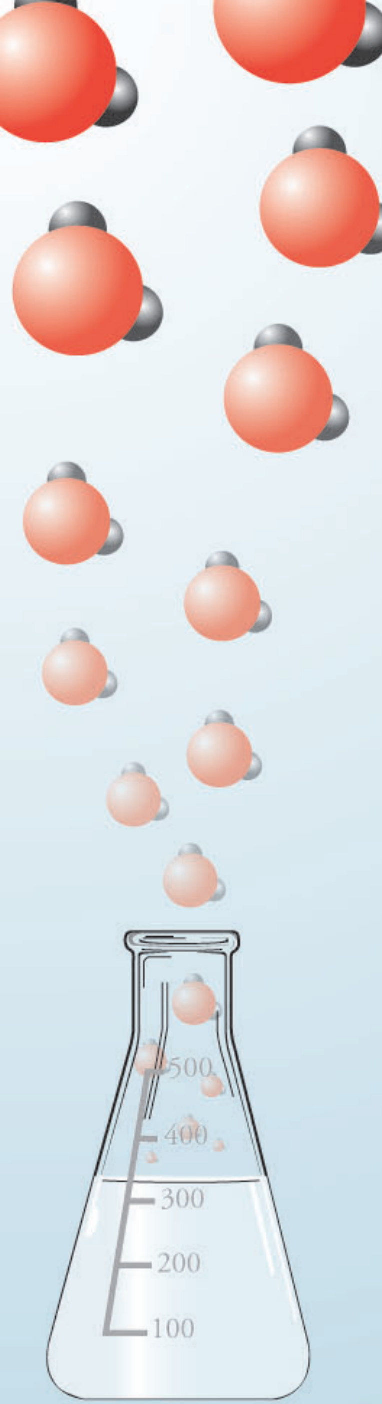
<u>Carbon atom</u>

6 protons
6 neutrons
(in most carbon atoms)
6 electrons
(in uncharged atom)





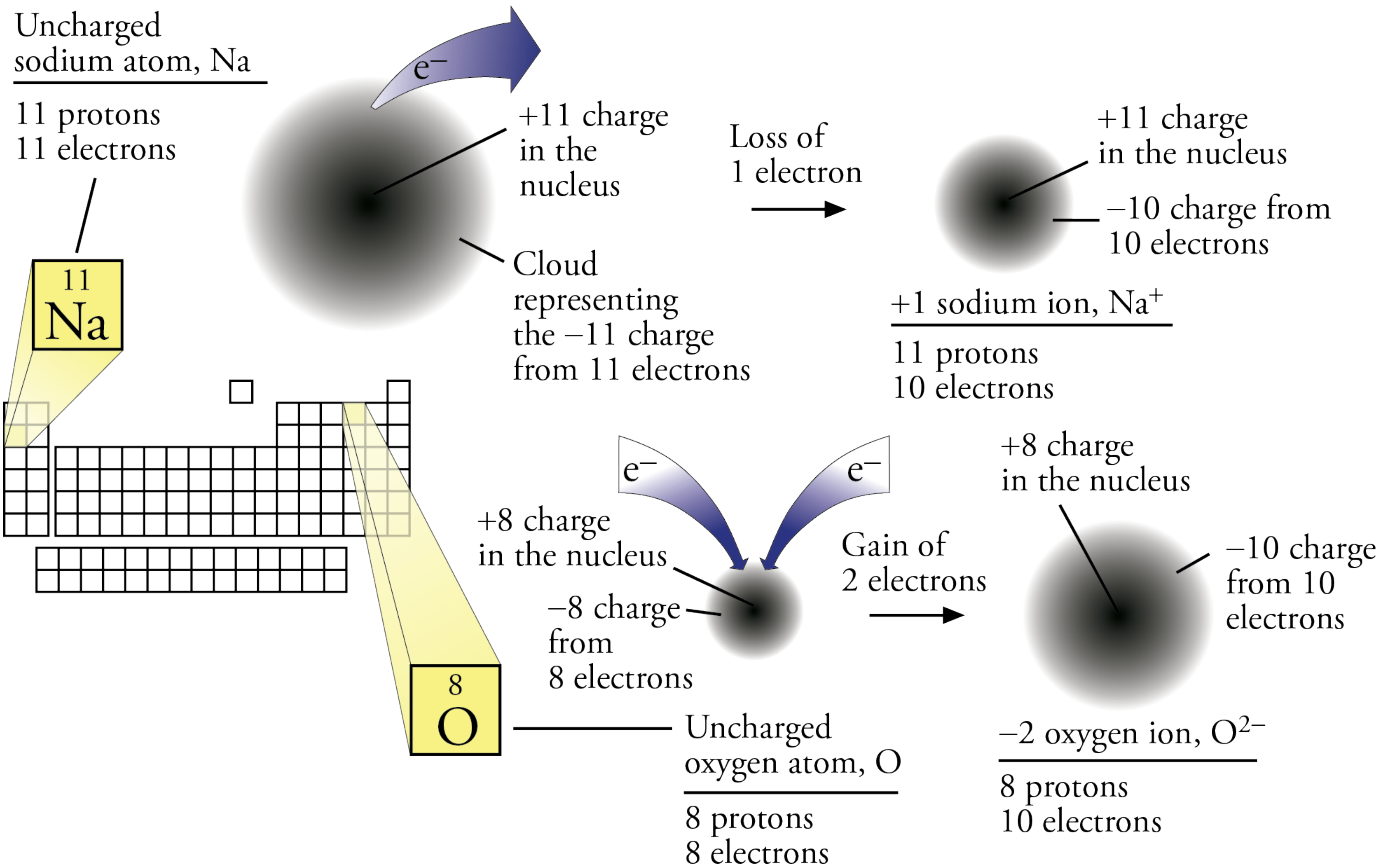
Particle	Charge	Mass
proton	+1	1.00728 u (1.6726×10^{-24} g)
neutron	0	1.00867 u (1.6750×10^{-24} g)
e^- electron	–1	0.000549 u (9.1096×10^{-28} g)



Ions

- ***Ions*** are charged particles due to a loss or gain of electrons.
- When particles lose one or more electrons, leaving them with a positive overall charge, they become ***cations***.
- When particles gain one or more electrons, leaving them with a negative overall charge, they become ***anions***.

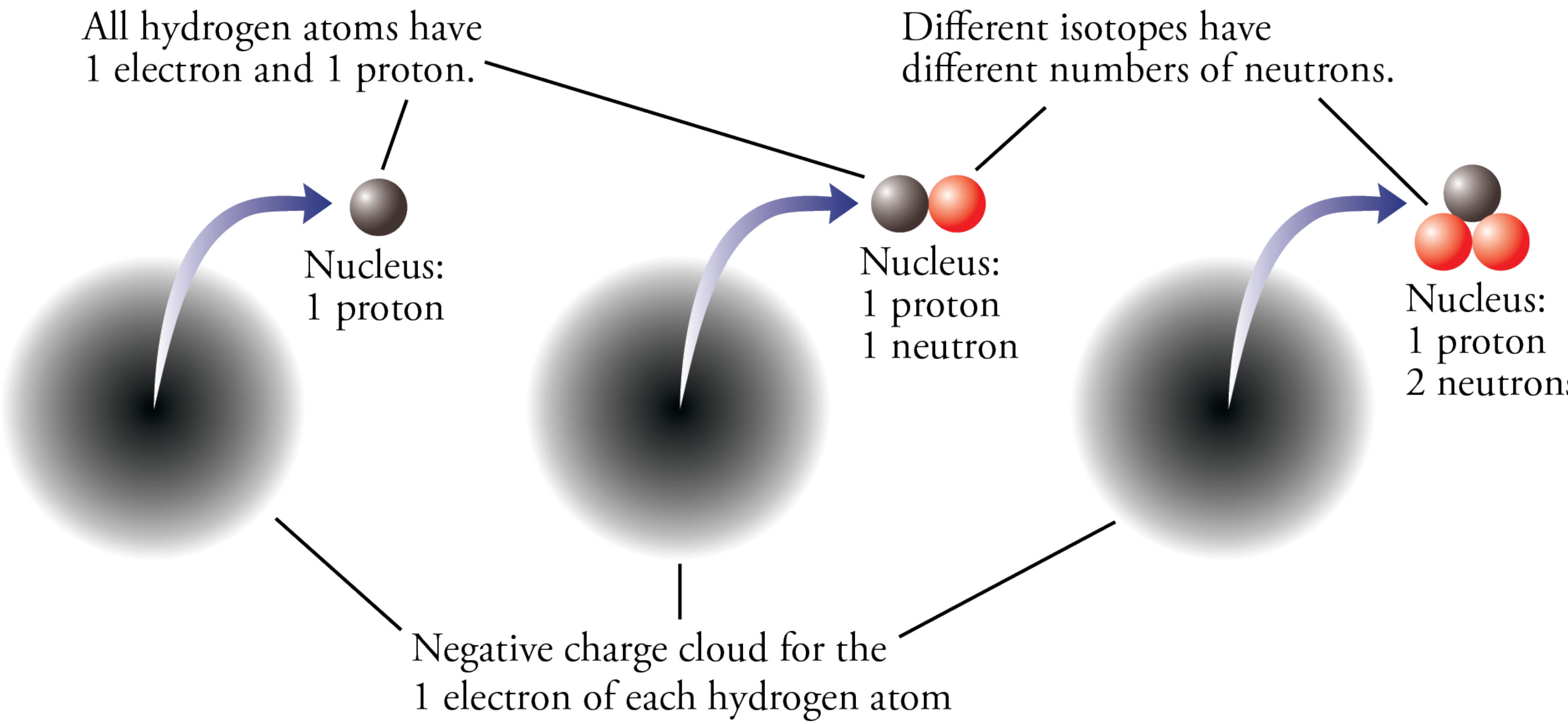
Example Ions



Effect on Chemical Changes

- Electrons
  - Can be gained, lost, or shared…actively participate in chemical changes
  - Affect other atoms through their -1 charge
- Protons
  - Affect other atoms through their +1 charge
  - Determine the number of electrons in uncharged atoms
- Neutrons
  - No charge…no effect outside the atom and no direct effect on the number of electrons.

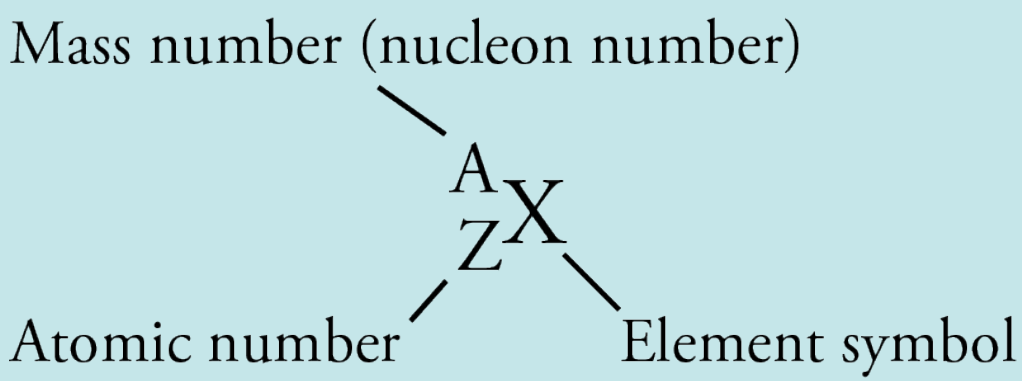
Isotopes of Hydrogen



http://preparatorychemistry.com/Hydrogen_1.html
http://preparatorychemistry.com/Hydrogen_2.html
http://preparatorychemistry.com/Hydrogen_3.html

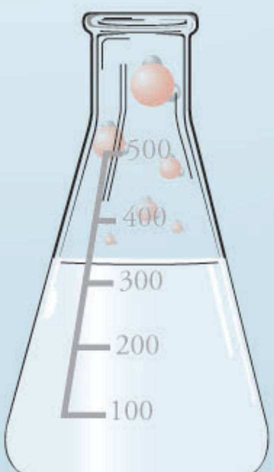
Nuclides

- ***Nuclide*** = a particular type of nucleus, characterized by 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 symbol

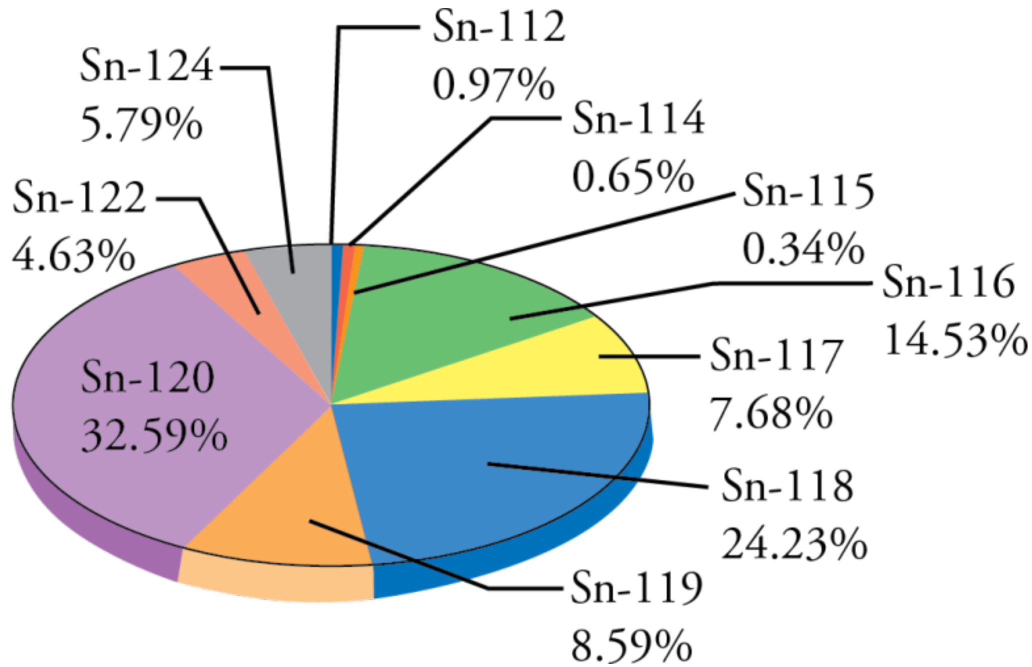


Isotopes

- ***Isotopes*** are atoms with the same atomic number but different mass numbers.
- ***Isotopes*** are atoms with the same number of protons and electrons in the uncharged atom but different numbers of neutrons.
- ***Isotopes*** are atoms of the same element with different masses.

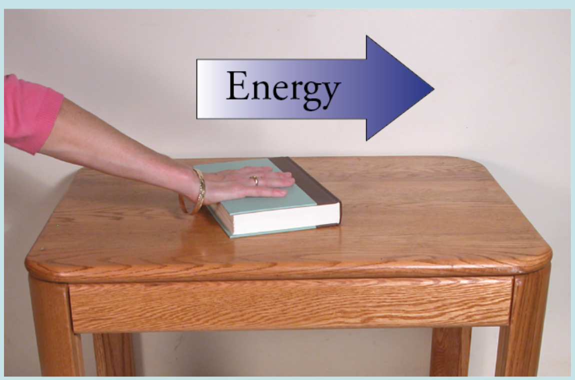


Tin has ten natural isotopes.

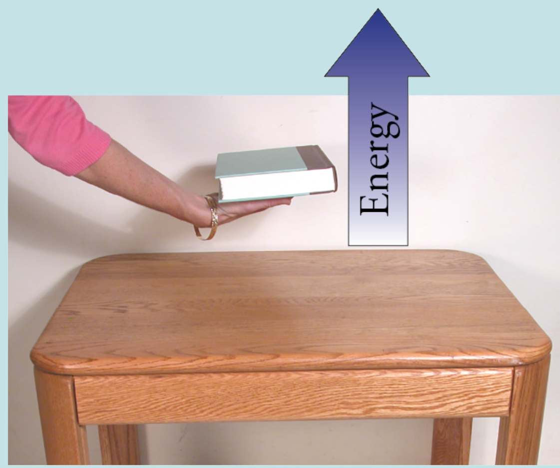


Energy Terms

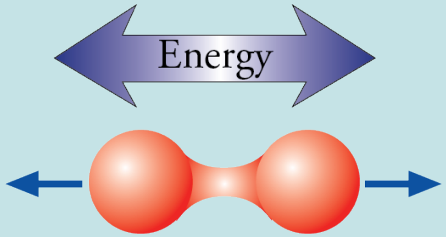
- **Energy** = the capacity to do work
- **Work**, in this context, may be defined as what is done to move an object against some sort of resistance.



Energy is required to push a book across a table and overcome the resistance to movement due to friction.



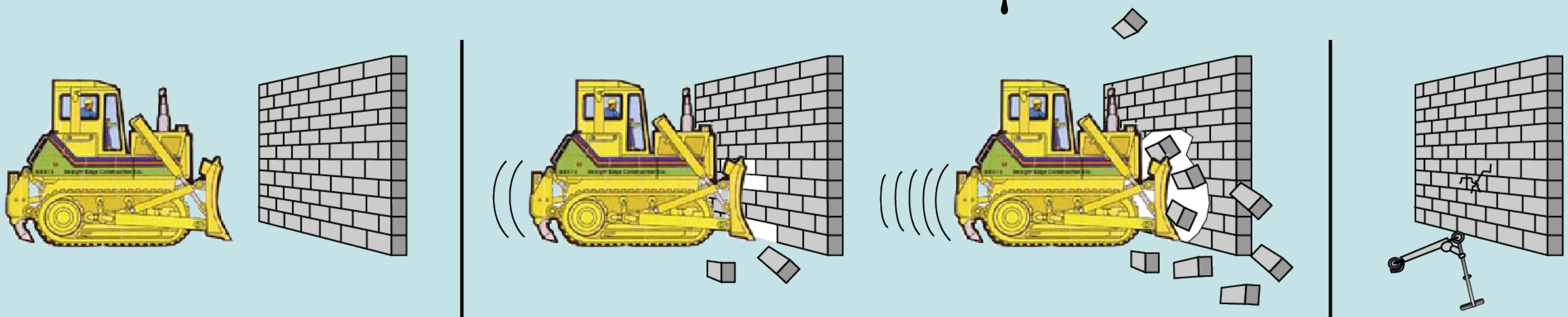
Energy is required to lift a book and overcome the resistance to movement due to gravity.



Energy is required to separate two atoms in a molecule and overcome the resistance to movement due to the chemical bond between them.

Two Types of Energy

- **Kinetic Energy** = the energy of motion
  $= 1/2\ m\mu^2$



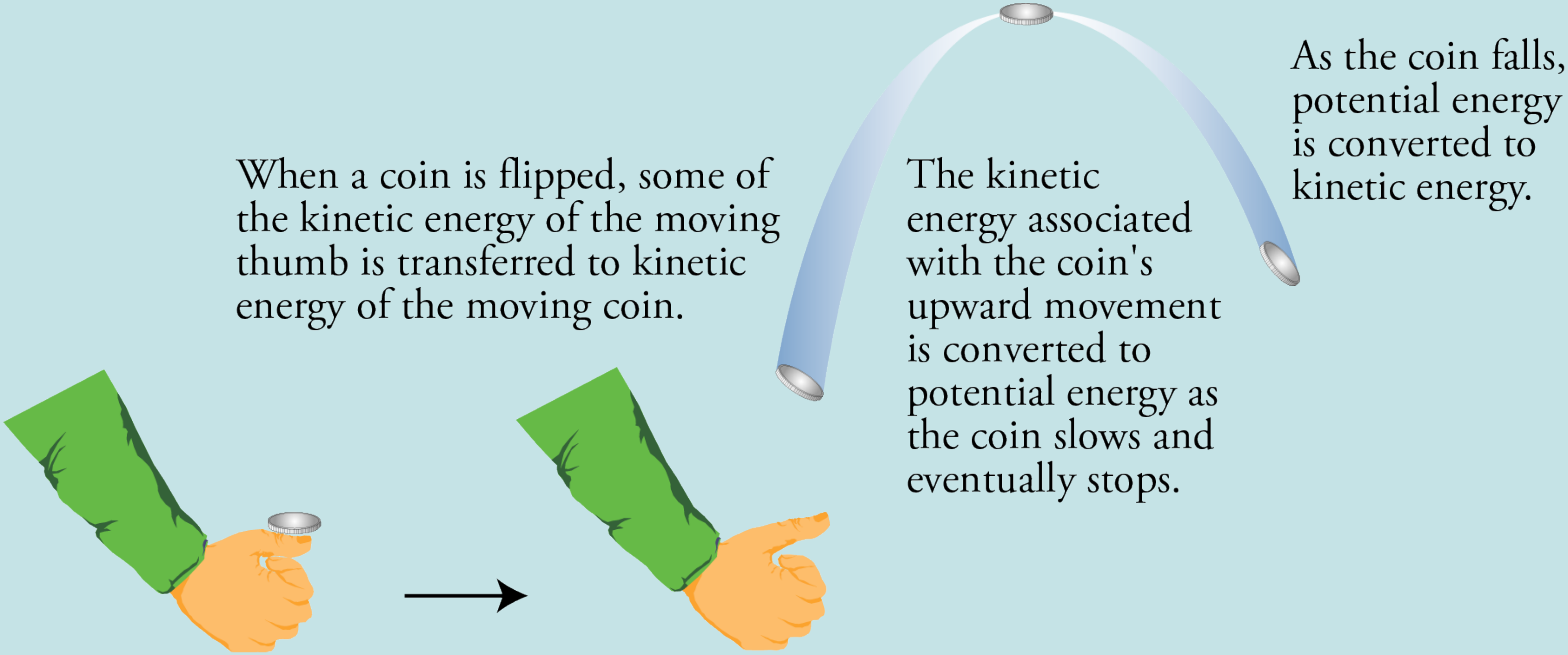
A stationary buldozer does not have the capacity to do the work of moving a wall.

The faster moving bulldozer does more of the work of moving the wall. The faster an object moves, the more work it can do, and the more kinetic energy it has.

A scooter moving at the same velocity as a bulldozer will do less work and therefore has less energy.

- **Potential Energy** = energy by virtue of position or state

Law of Conservation of Energy (First Law of Thermodynamics)



Endergonic Change

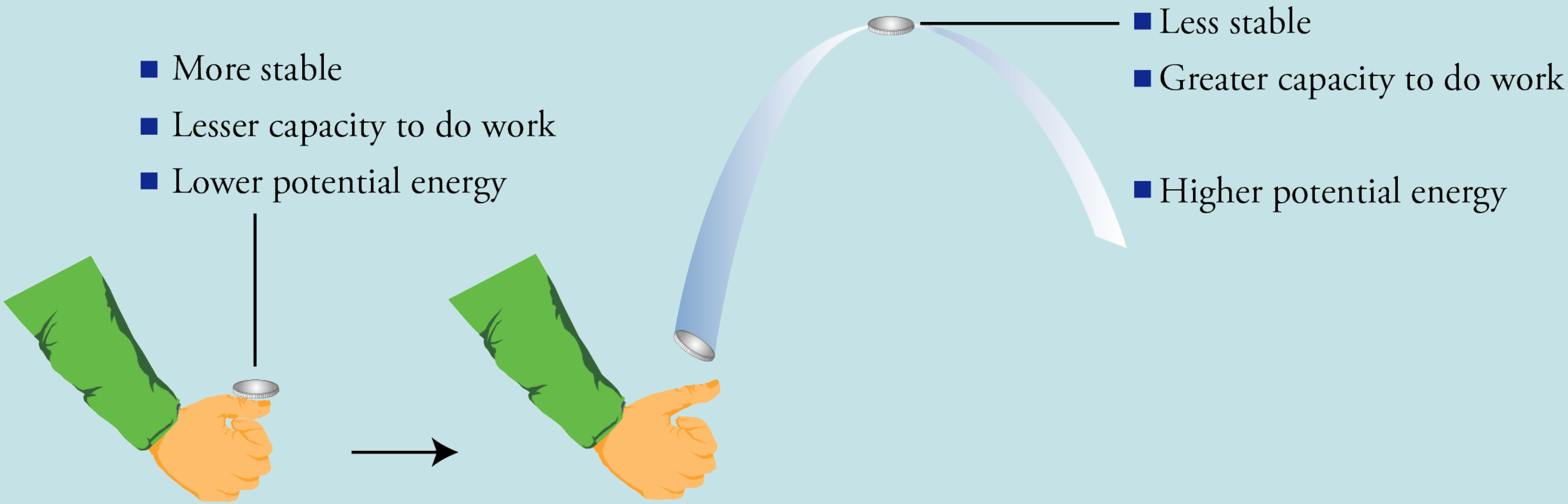
more stable + energy $\rightarrow$ less stable system

lesser capacity to do work + energy $\rightarrow$ greater capacity to do work

lower PE + energy $\rightarrow$ higher PE

coin in hand + energy $\rightarrow$ coin in air above hand

Coin and Potential Energy



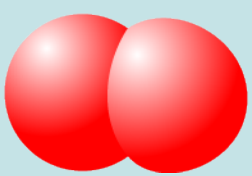
Bond Breaking and Potential Energy

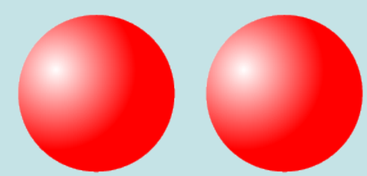
atoms in bond + Energy $\longrightarrow$ separate atoms

more stable + Energy $\longrightarrow$ less stable

lower PE + Energy $\longrightarrow$ higher PE

$$O_2(g) + \text{energy} \longrightarrow 2O(g)$$





Exergonic Change

less stable system $\rightarrow$ more stable + energy

greater capacity to do work $\rightarrow$ lesser capacity to do work + energy

higher PE $\rightarrow$ lower PE + energy

coin in air above hand $\rightarrow$ coin on ground + energy

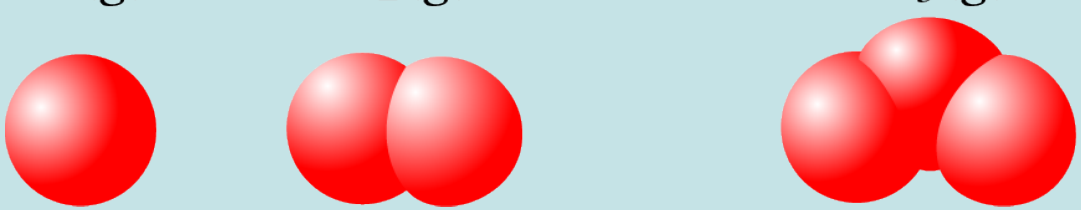
Bond Making and Potential Energy

separate atoms → atoms in bond + Energy

less stable → more stable + Energy

higher PE → lower PE + Energy

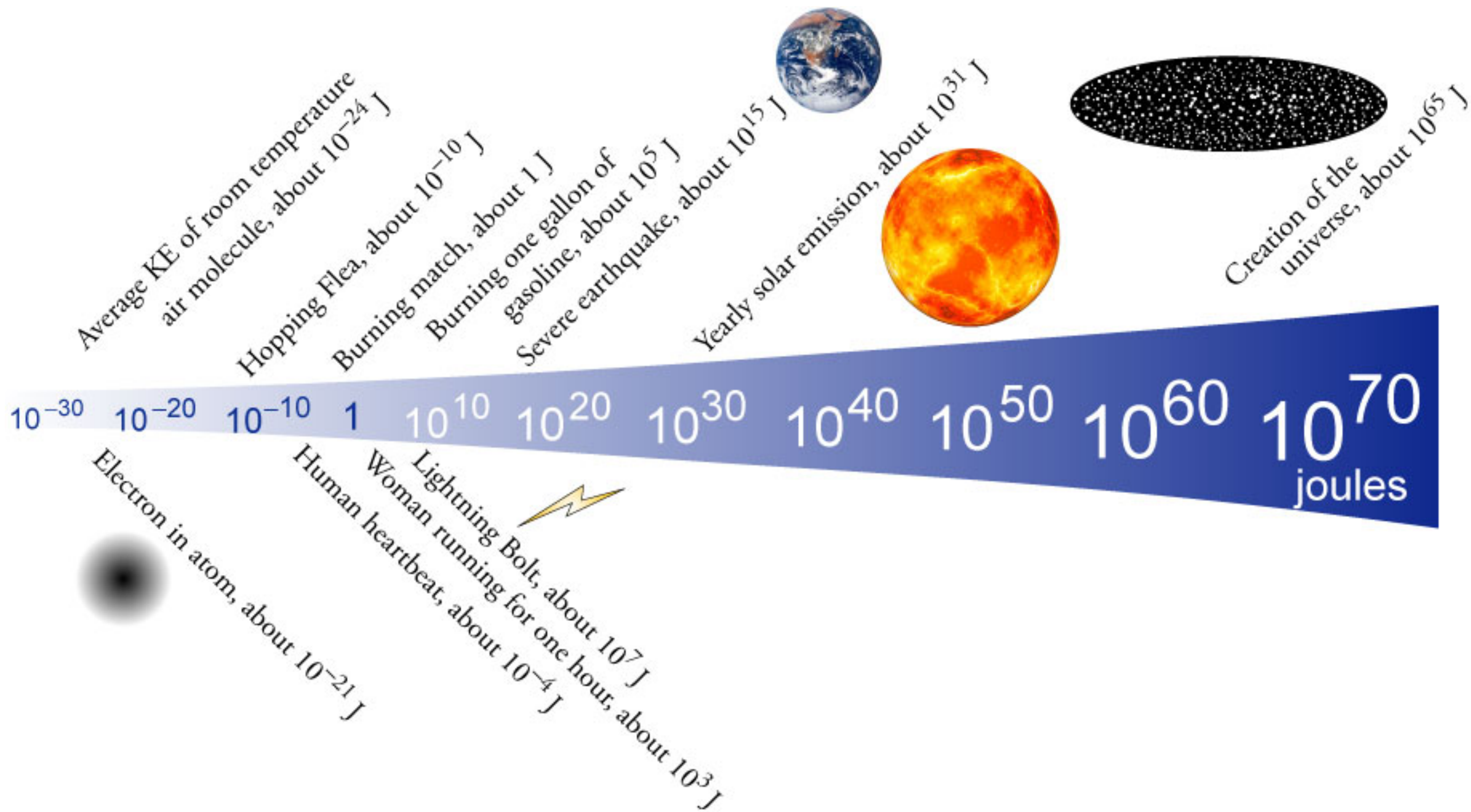
$O(g) + O_2(g) \longrightarrow O_3(g) + \text{energy}$



Units of Energy

- Joule (J) = $\dfrac{\text{kg m}^2}{\text{s}^2}$
- Some traditional units (with conversions to J) are:
  - kinetic energy: foot-pounds (1 ft-lb = 1.36 J)
  - energy of chemical reactions: kilocalories/mole (1 kcal/mol = 4.18 kJ/mole)
  - commercial chemical energy: tonnes of oil equivalent (1 toe = 42 GJ)
  - thermal energy: British thermal units (1 Btu = 1055 J)
  - electrical energy: kilowatt-hours (1 kWh = 3.6 MJ)
  - photon energy: electron volts (1 eV = 1.6×10^{-19} J)
  - energy of nuclear reactions: million electron volts (1 MeV = 1.6×10^{-13} J)
  - energy of explosions: tonnes of TNT (1 t_{TNT} = 10^9 cal = 4.18 GJ)

Approximate Energy of Various Events

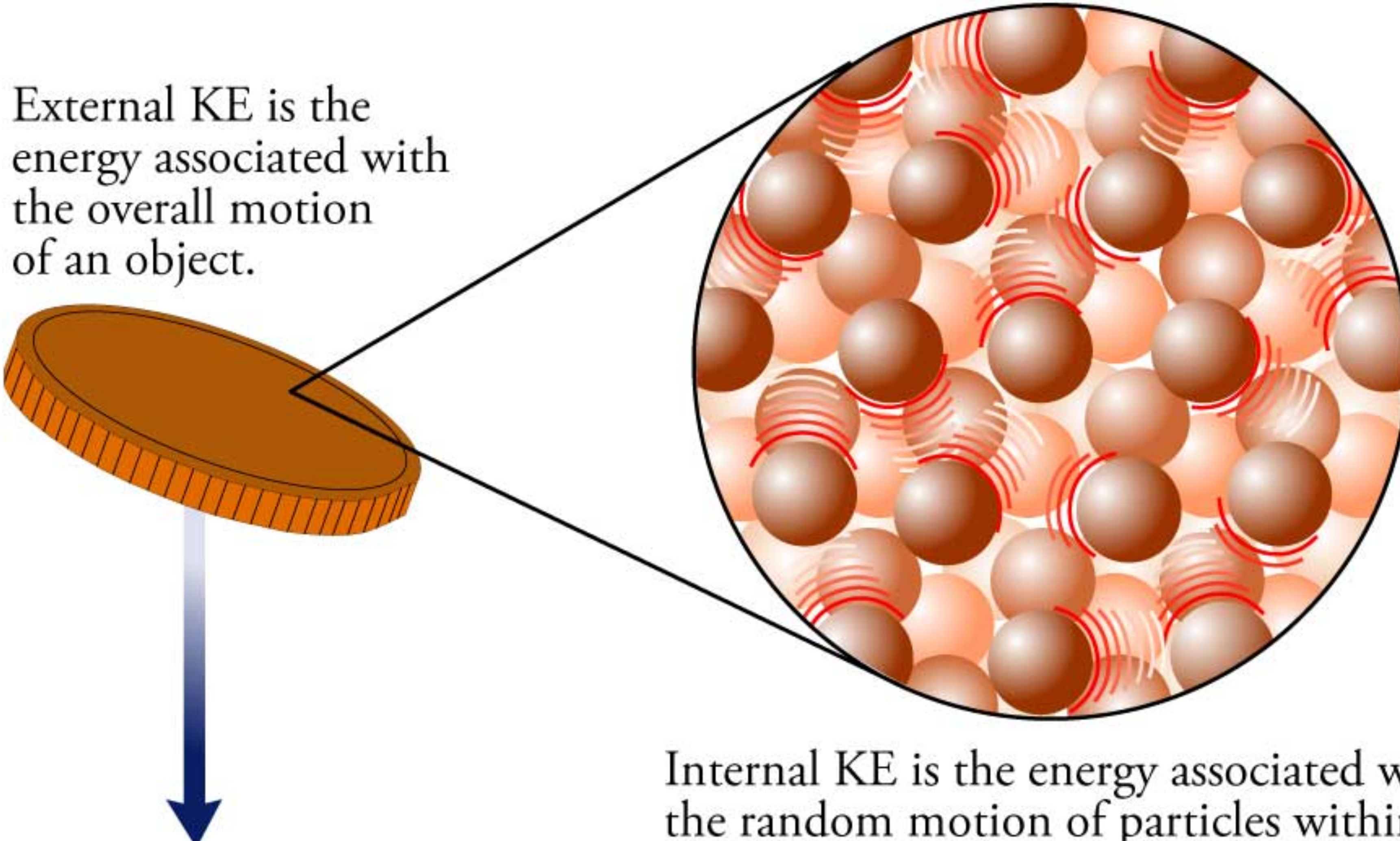


More Terms

- **External Kinetic Energy** = Kinetic energy associated with the overall movement of a body
- **Internal Kinetic Energy** = Kinetic energy associated with the random motion of the particles within a body
- **Heat** = Internal kinetic energy transfer from a region of higher temperature to a region of lower temperature due to collisions of particles.

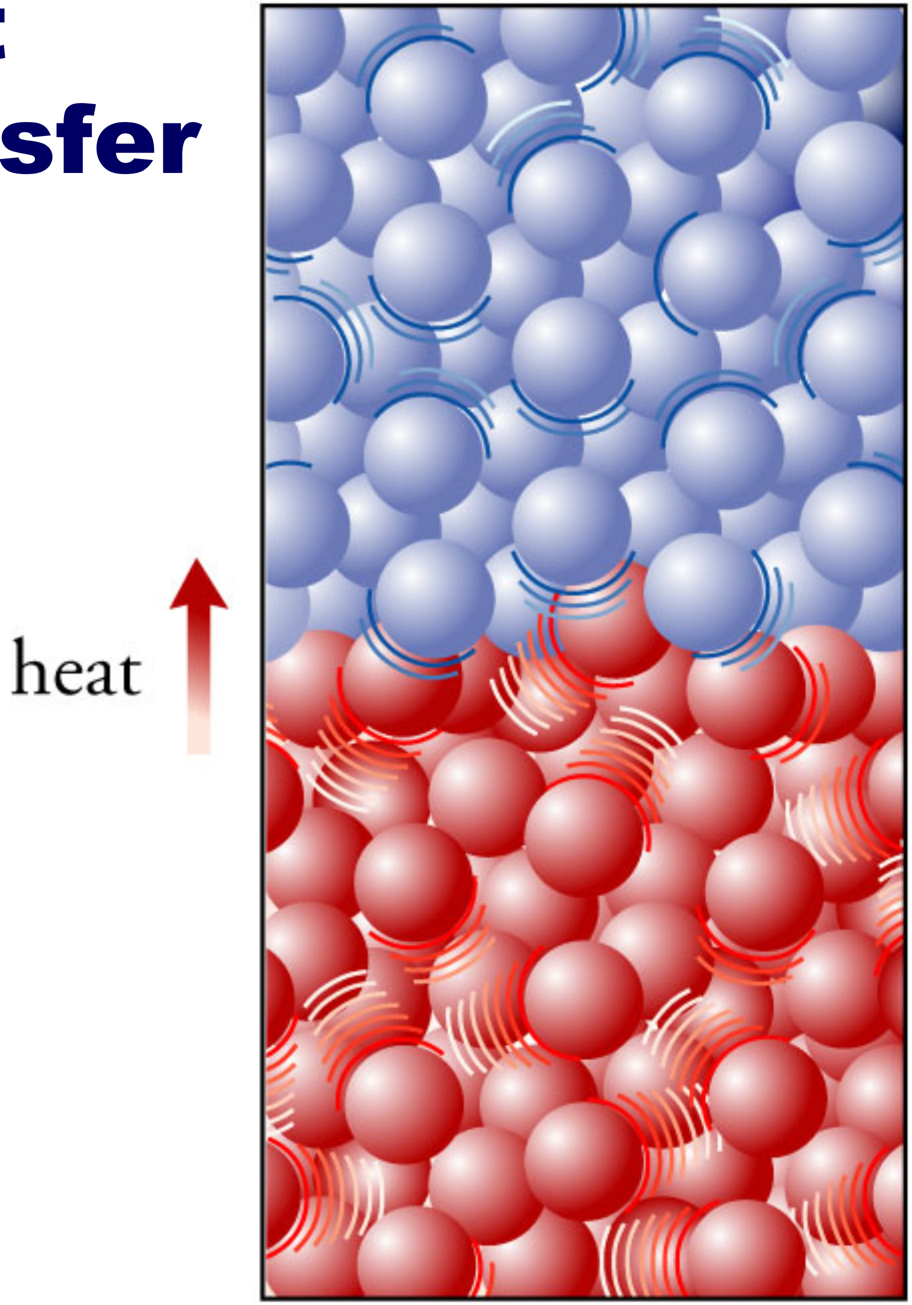
External and Internal Kinetic Energy

External KE is the energy associated with the overall motion of an object.



Internal KE is the energy associated with the random motion of particles within an object.

Heat Transfer



Lower-temperature object

↓

Lower average force of collisions

↓

Particles speed up when they collide with particles of the higher-temperature object.

↓

Increased energy

Higher-temperature object

↓

Higher average force of collisions

↓

Particles slow down when they collide with particles of the lower-temperature object.

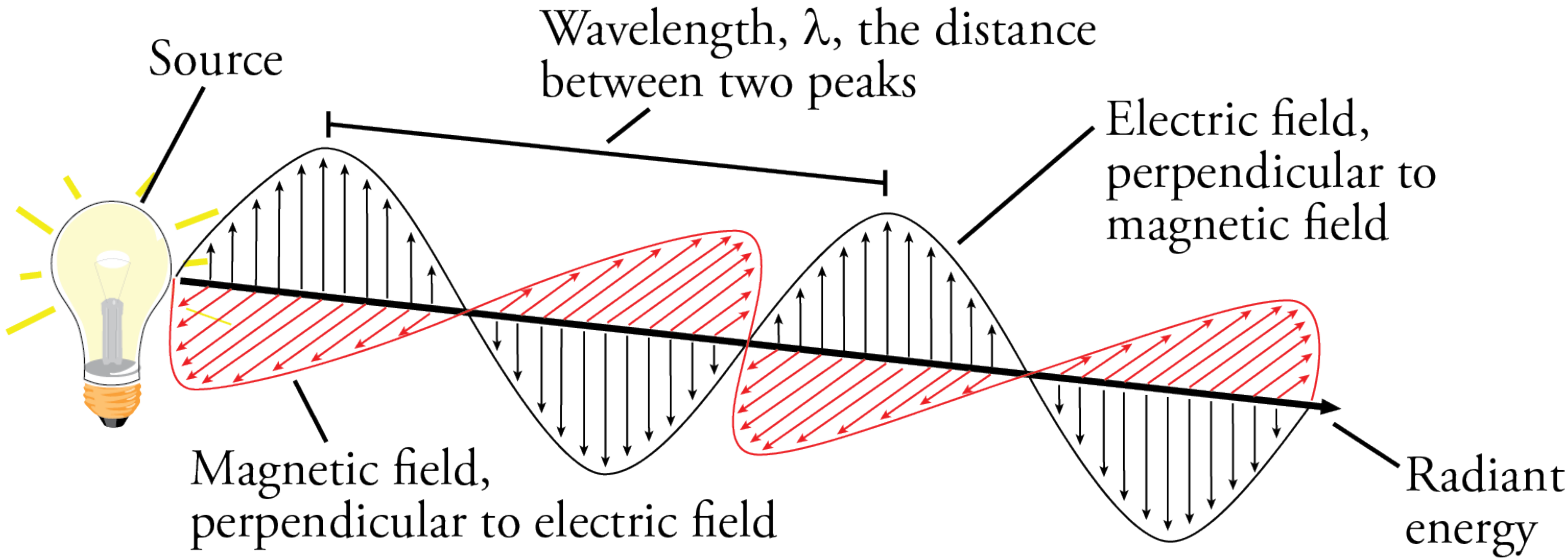
↓

Decreased energy

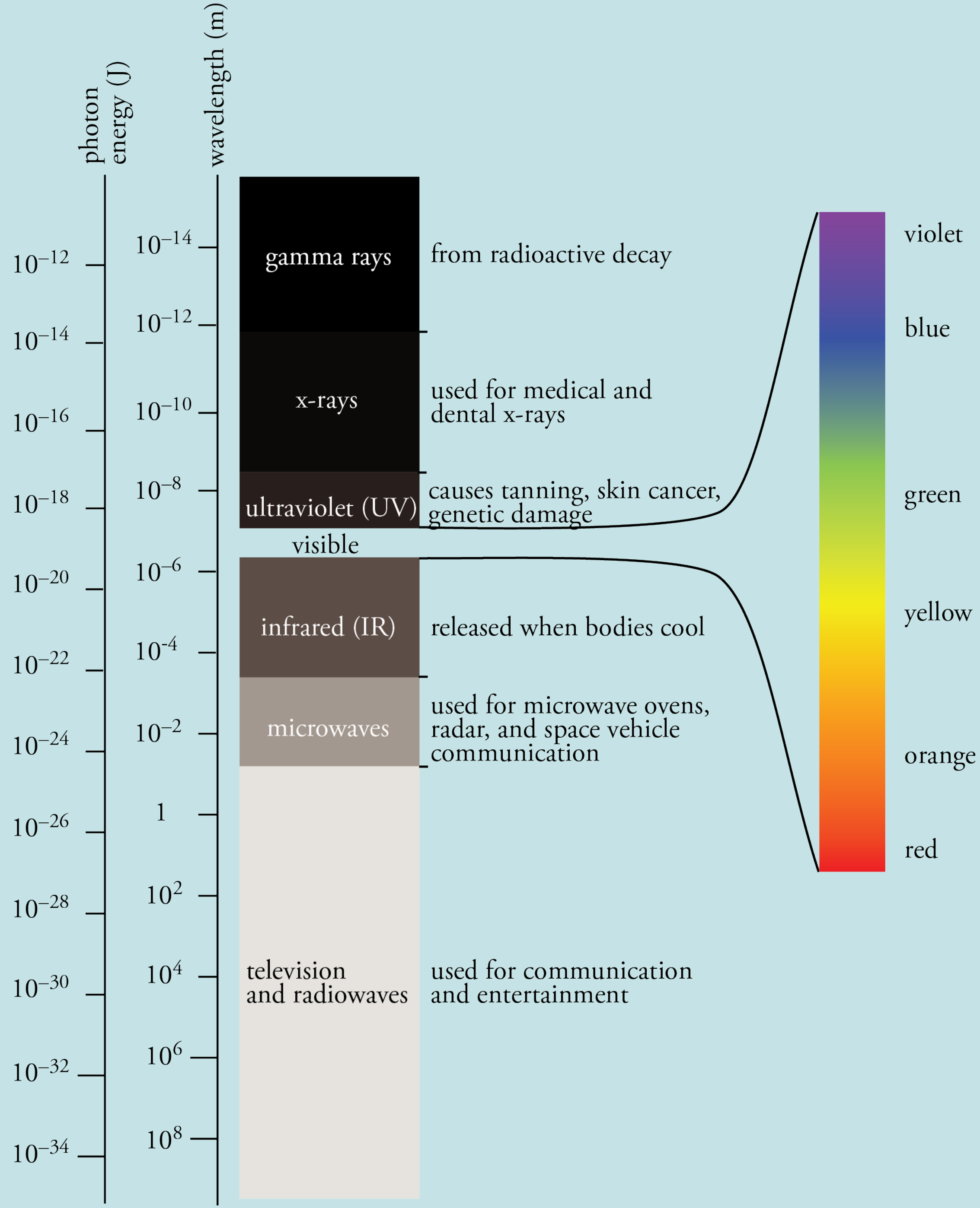
Radiant Energy

- **Radiant Energy** is electromagnetic energy that behaves like a stream of particles.
- It has a dual Nature
  - Particle
    - photons = tiny packets of radiant energy
    - 10^{17} photons/second from a flashlight bulb
  - Wave
    - oscillating electric and magnetic fields
    - describes effect on space, not true nature of radiant energy

A Light Wave's Electric and Magnetic Fields

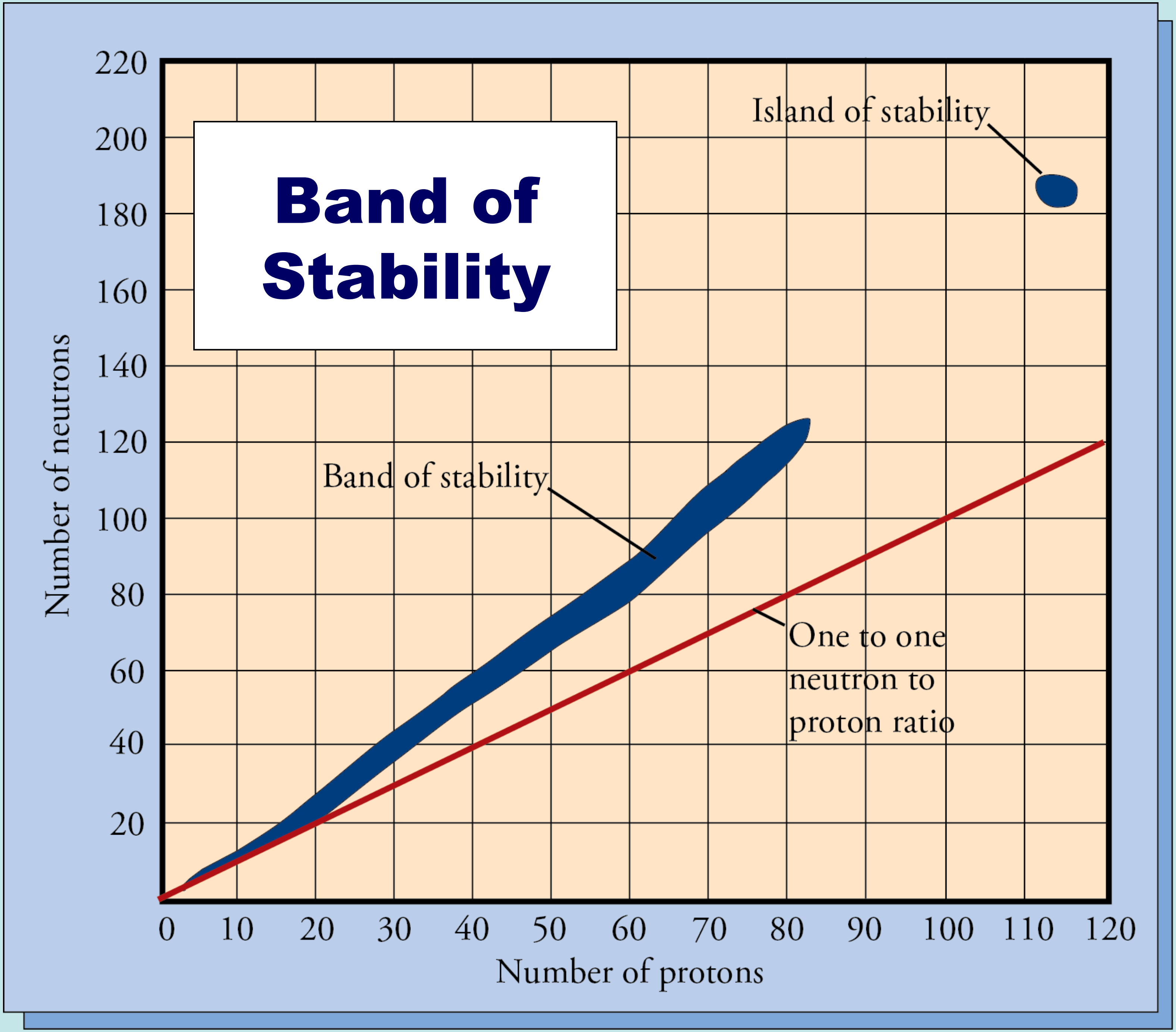


Radiant Energy Spectrum



Nuclear Stability

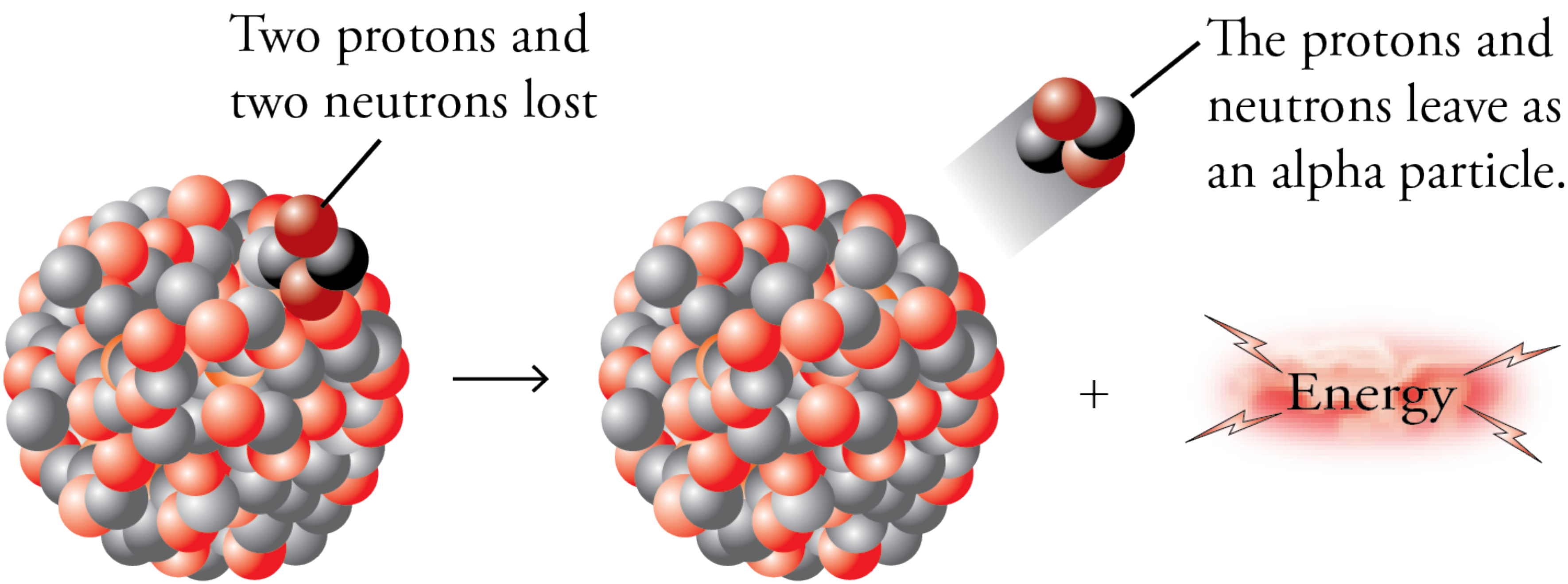
- ***Electromagnetic force*** = the force that causes opposite electrical charges to attract each other and like charges to repel.
- ***Strong force*** = the force between nucleons (protons and neutrons).
- Neutrons increase the attraction from the strong force without increasing electromagnetic repulsion between nucleons.



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
140
160
180
200
220

Alpha Emission

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

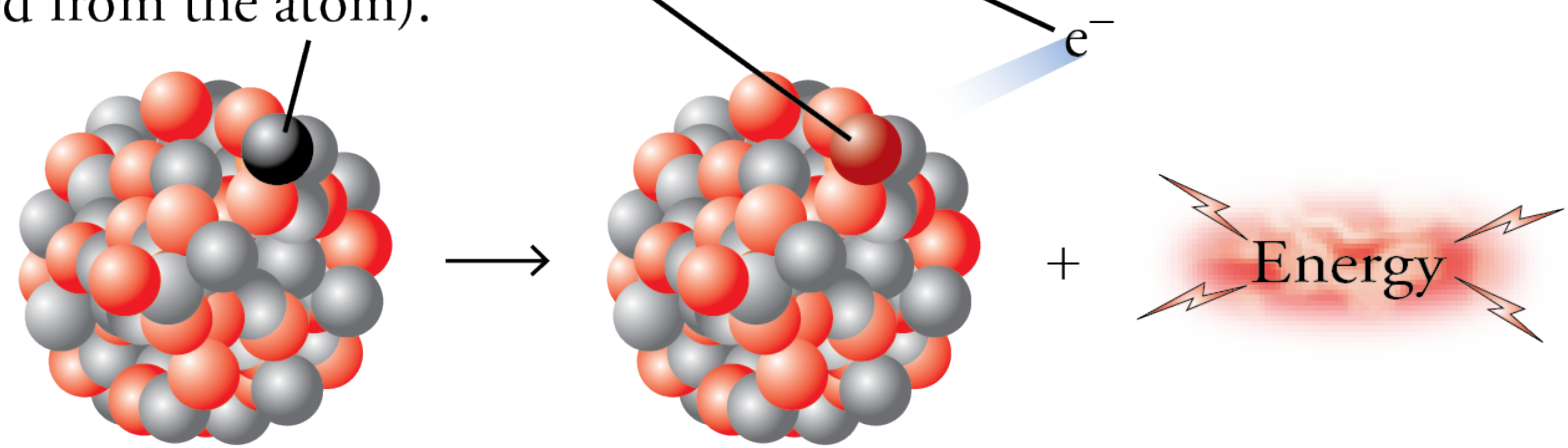


http://preparatorychemistry.com/radioactivity.html

Beta Emission

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

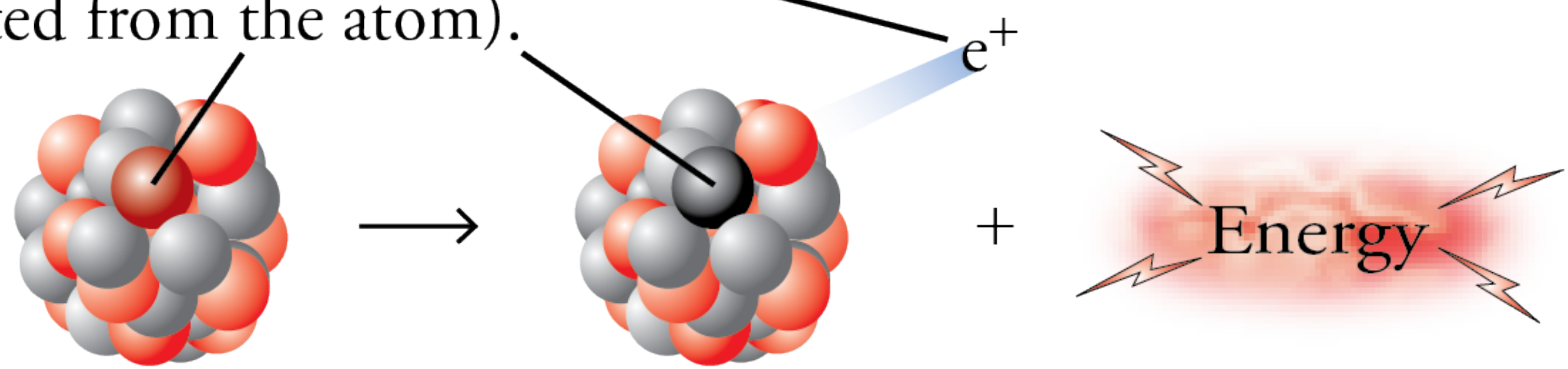
A neutron becomes a proton (which stays in the nucleus) and an electron (which is ejected from the atom).



Positron Emission

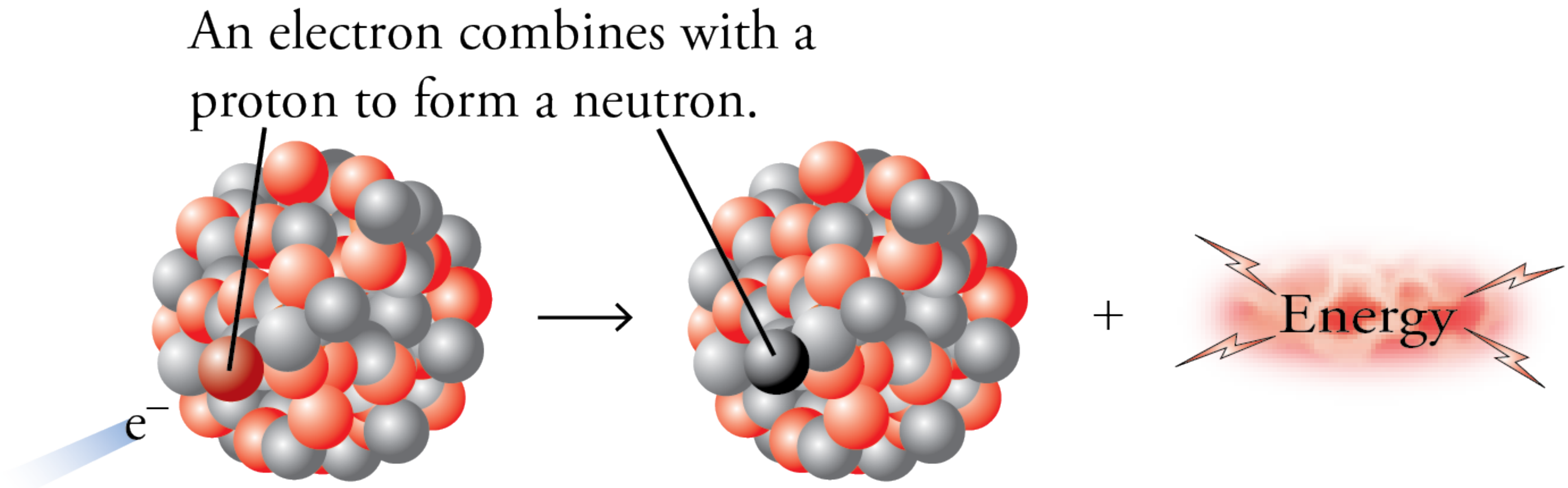
$$^{40}_{19}K \longrightarrow \; ^{40}_{18}Ar + \; ^{0}_{+1}e$$

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



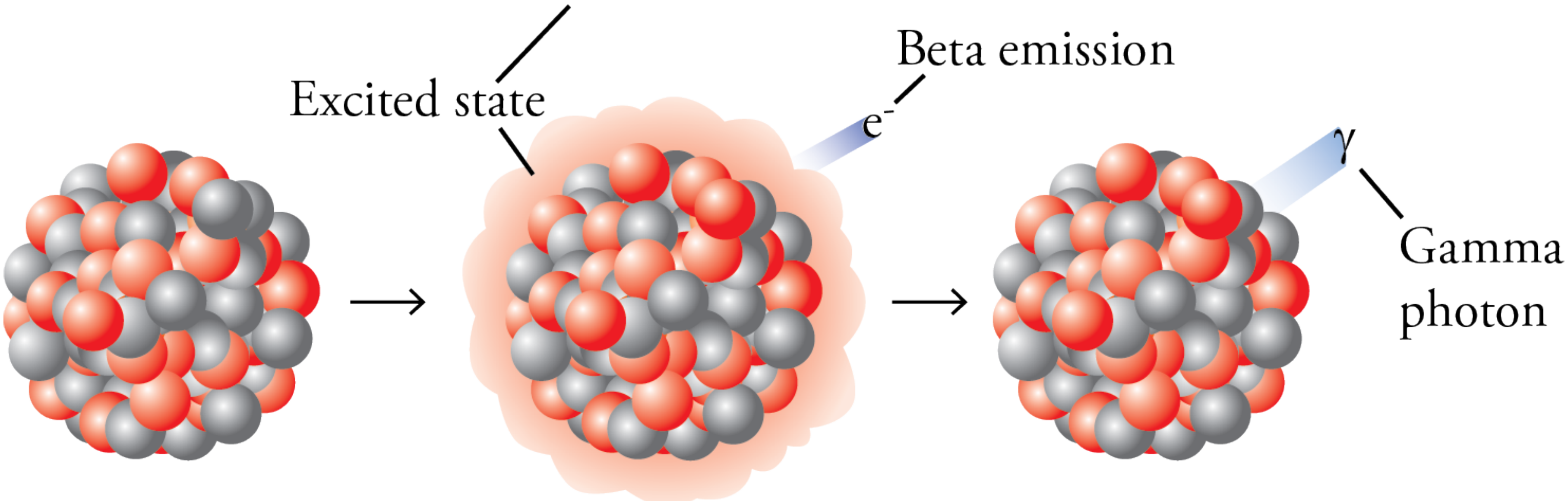
Electron Capture

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



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

Beta emission

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

Positron emission

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

Electron capture

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

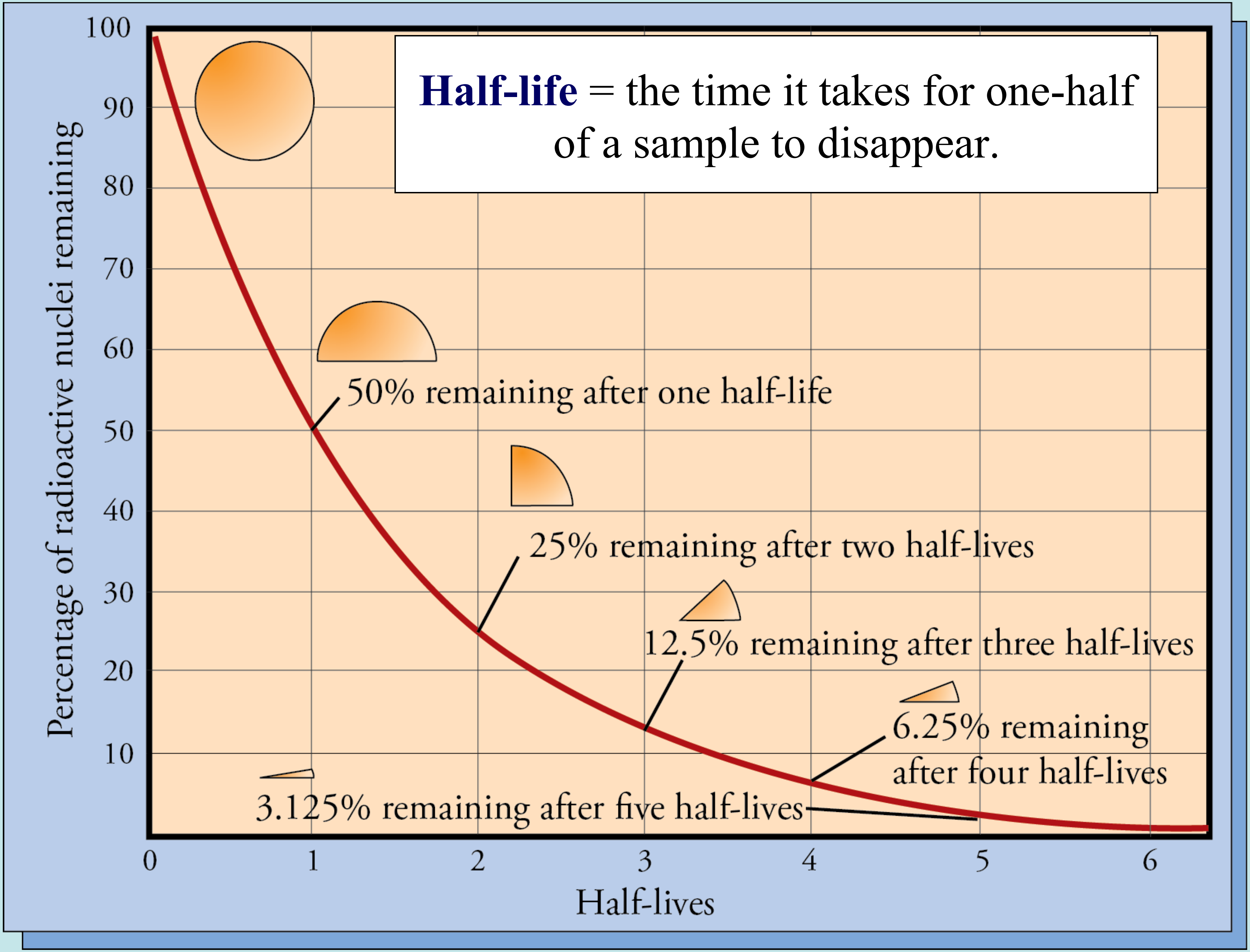
General Nuclear Equations

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

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

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

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



Half-life = the time it takes for one-half of a sample to disappear.
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
Percentage of radioactive nuclei remaining
Half-lives
0
1
2
3
4
5
6
10
20
30
40
50
60
70
80
90
100

Exponential Decline Example

- Iodine-131 has a half-life of 8.0197 days. If we start with 37 GBq (or 1 curie) of I-131, how much is left after 14 days?
  - The **becquerel** (symbol **Bq**) (pronounced: 'be-kə-rel) is the SI-derived unit of radioactivity. One Bq is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. The Bq unit is therefore equivalent to an inverse second, s^{-1}.
  - The curie is a common non-SI unit. It is now defined as 37 GBq.

Exponential Decline and Half-Life

$N(t)$ = amount at time t

N_0 = initial amount

k = rate in time^{-1}

t = time

for exponential decay **$N(t) = N_0\, e^{-kt}$**

if $N(t) = N_0/2$

so $N_0/2 = N_0\, e^{-kt_{1/2}}$

$\ln(1/2) = \ln(e^{-kt_{1/2}})$

$\ln(2^{-1}) = -kt_{1/2} \ln(e)$

$-1(\ln 2) = -kt_{1/2}$

$\ln(2) = kt_{1/2}$

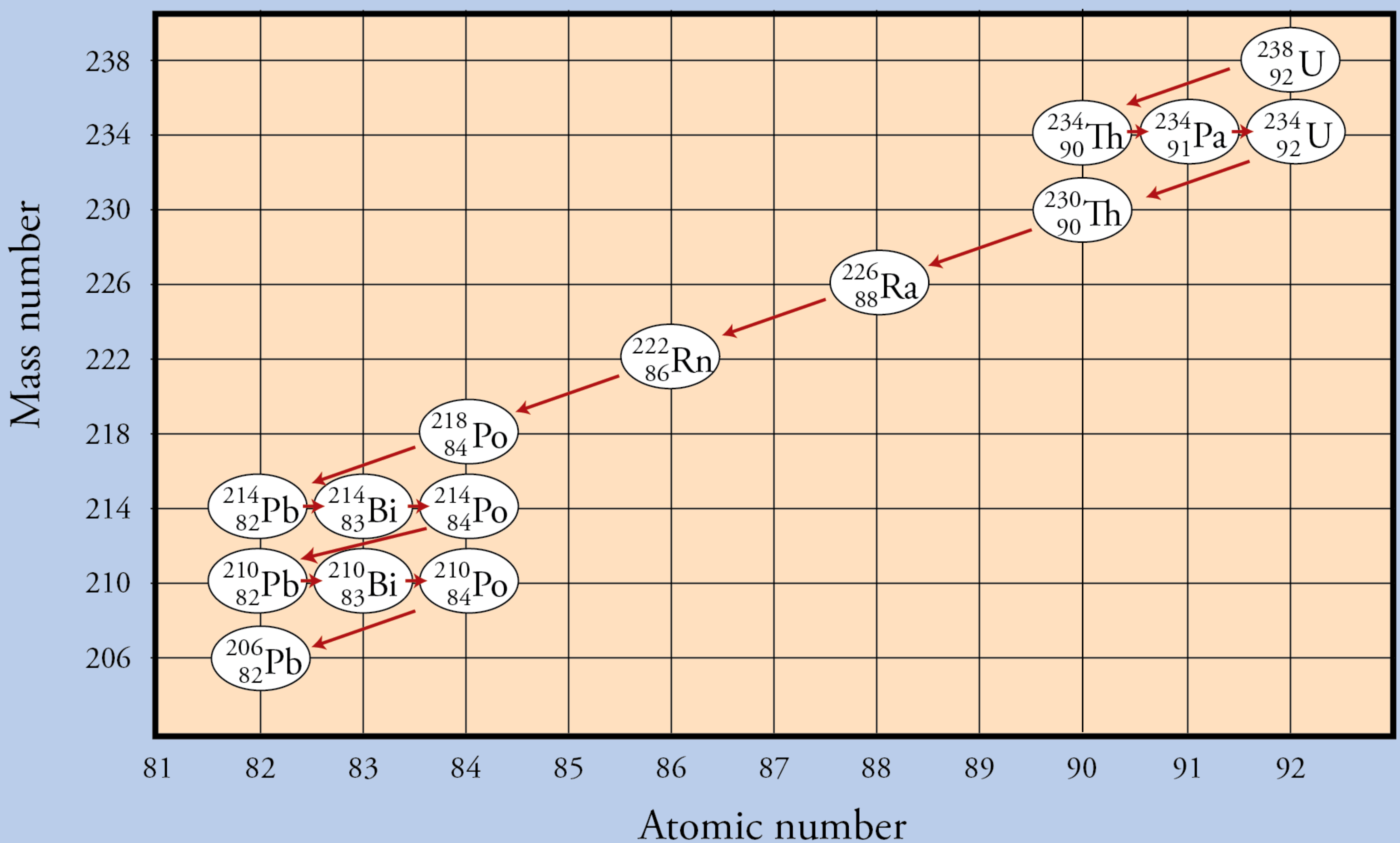
$$\mathbf{t_{1/2}} = \frac{\ln(2)}{k} = \frac{\mathbf{0.693}}{\mathbf{k}}$$

Iodine-131 has a half-life of 8.0197 days. If we start with 37 GBq (or 1 curie) of I-131, how much is left after 14 days?

$$t_{1/2} = \frac{0.693}{k} \qquad k = \frac{0.693}{t_{1/2}} = \frac{0.693}{8.0197 \text{ day}} = 0.0864 \text{ day}^{-1}$$

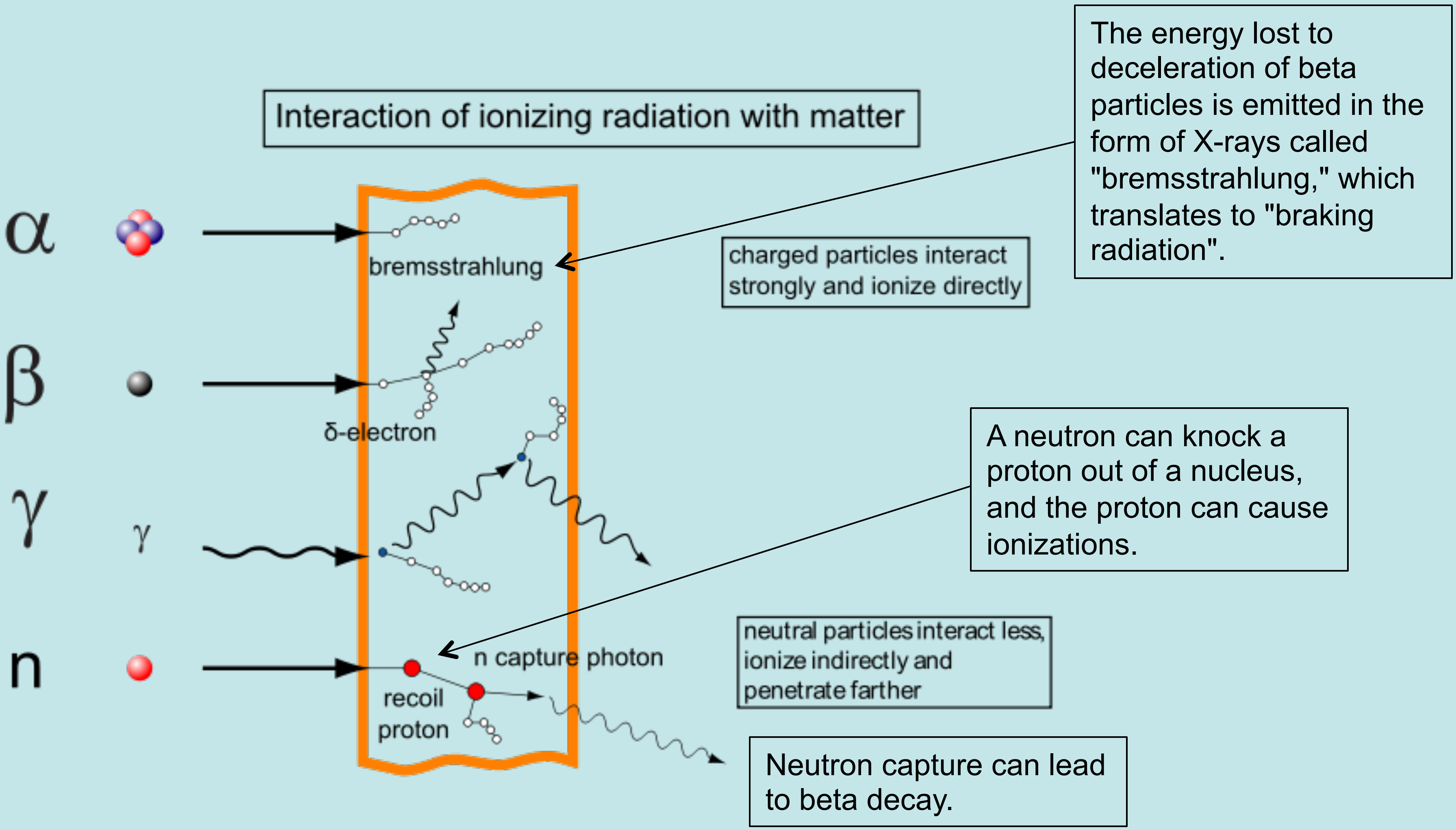
$$S(t) = S_o\, e^{-kt} = 37 \text{ GBq}\, e^{-0.0864\ 1/\text{day}(14 \text{ day})} = \mathbf{11\ GBq}$$

Radioactive Decay Series



Ionizing Radiation

- All of the forms of radioactive emissions can lead to the formation of ions.



Radiation Effect on Body

- Radioactive emissions ionize atoms and molecules. This leads to free radicals (particles with unpaired electrons). For example,

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

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

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

- Ionizing radiation is generally harmful and potentially lethal.
- High doses can cause visually dramatic radiation burns, and/or rapid death through acute radiation syndrome.

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

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 × biological effectiveness:
  - QF = Quality Factor
    = RBE = relative biological effectiveness
  - 1 rem = 1 rad × (QF = 1)
  - ? rem = # rad × QF
  - 1 Sievert (Sv) = 1 Gy × (QF = 1) = 100 rem
  - ? Sv = # Gy × 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

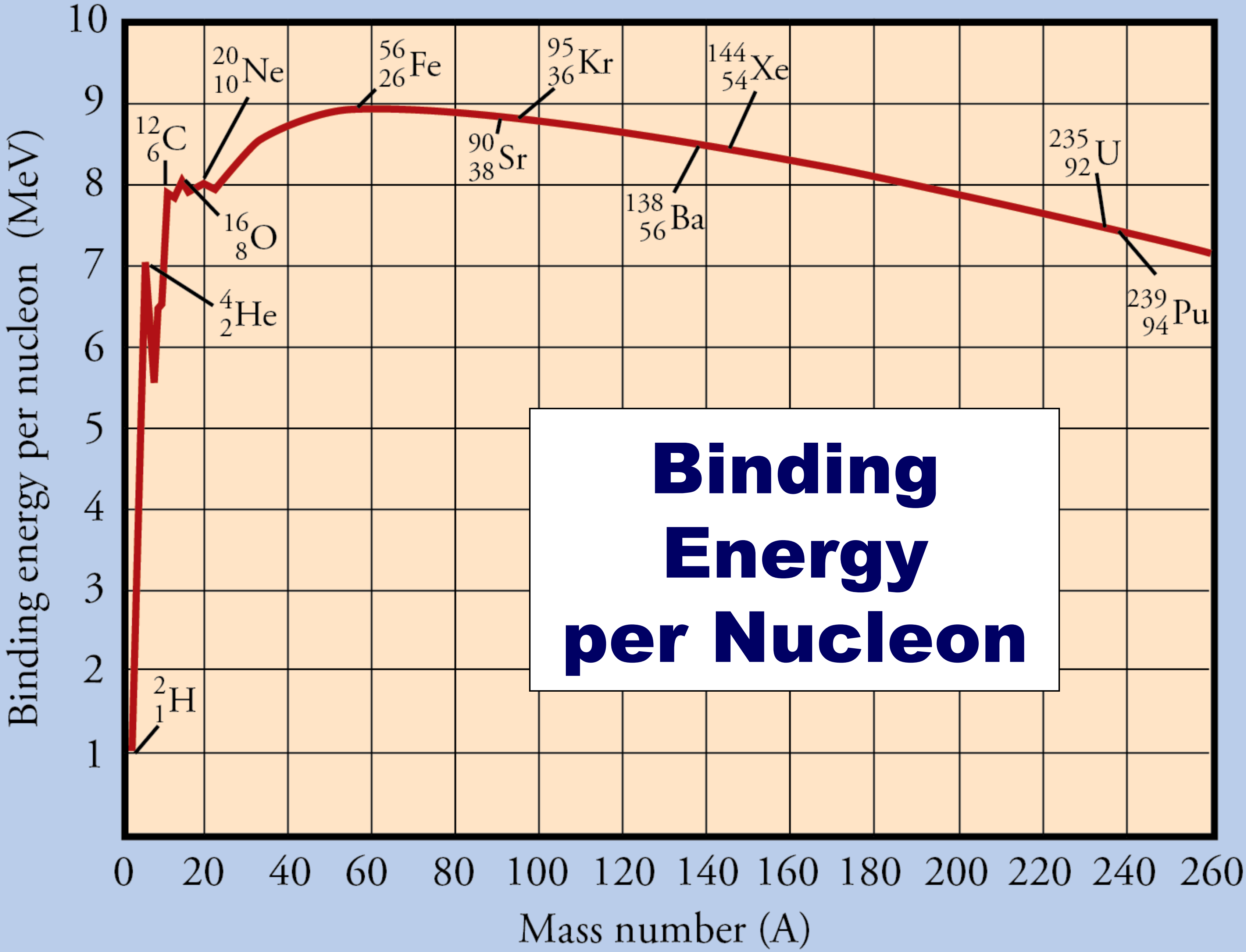
Chronic Dose Examples

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 nuclear power plant spent fuel bundle, after 10 year cool down, no shielding

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

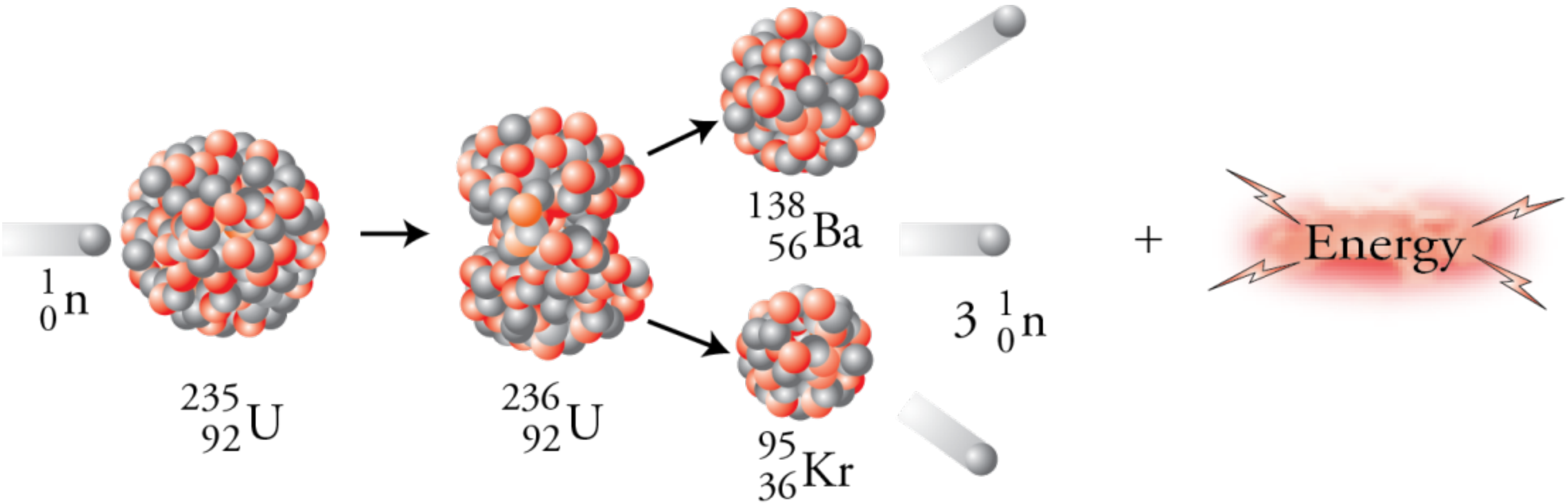
Nuclear Energy

- ***Binding energy*** = the amount of energy released when a nucleus is formed.
- Binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56. Thus fusing small atoms to form medium-sized atoms (***nuclear fusion***) releases energy.
- Binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms. Thus splitting large atoms to form medium-sized atoms (***nuclear fission***) also releases energy.

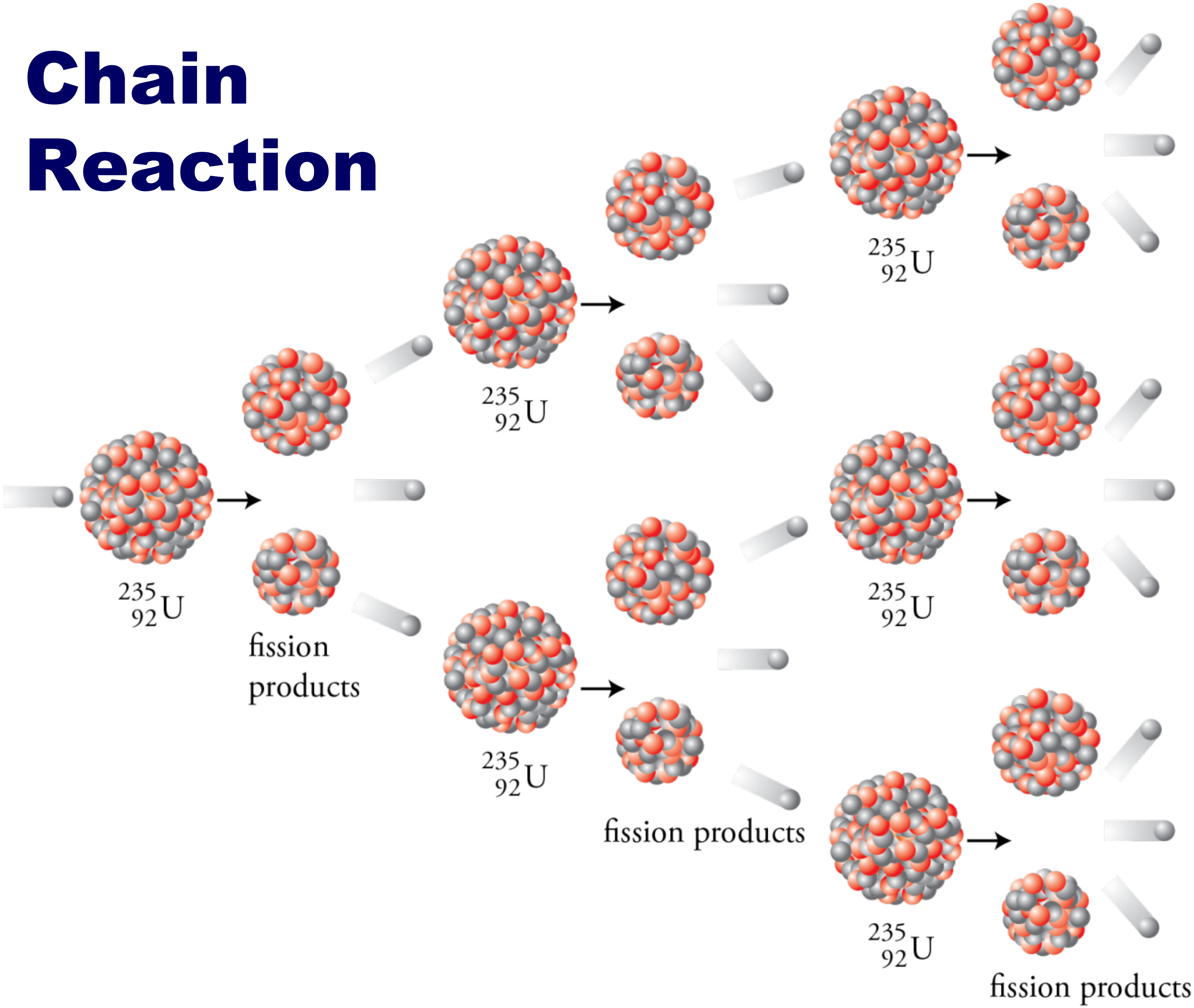


Binding Energy per Nucleon
Binding energy per nucleon (MeV)
Mass number (A)
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
$^{2}_{1}H$
$^{4}_{2}He$
$^{12}_{6}C$
$^{16}_{8}O$
$^{20}_{10}Ne$
$^{56}_{26}Fe$
$^{90}_{38}Sr$
$^{95}_{36}Kr$
$^{138}_{56}Ba$
$^{144}_{54}Xe$
$^{235}_{92}U$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

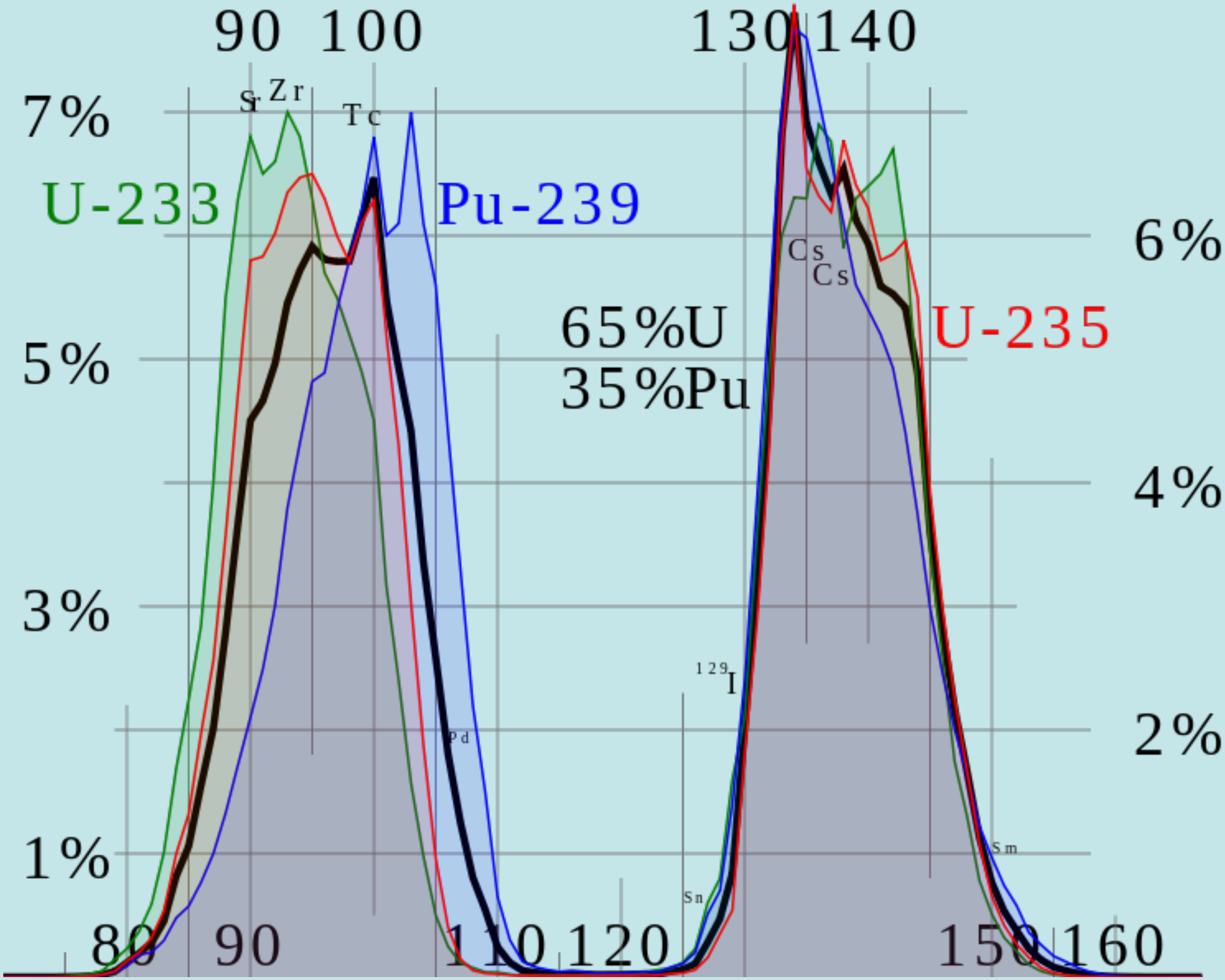
Nuclear Fission



Chain Reaction

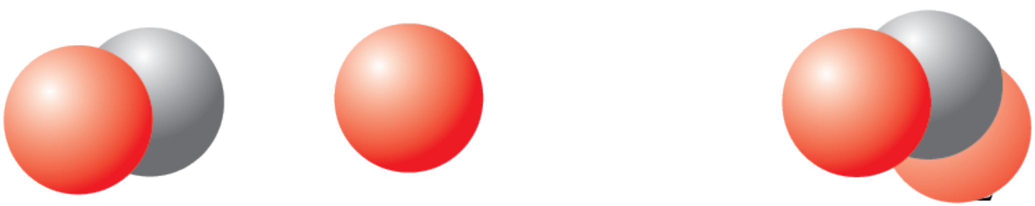


Fission Yield

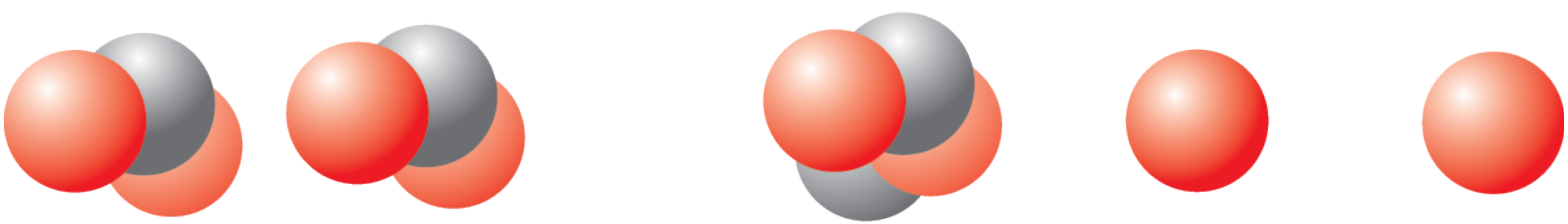


Nuclear Fusion Powers the Sun

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

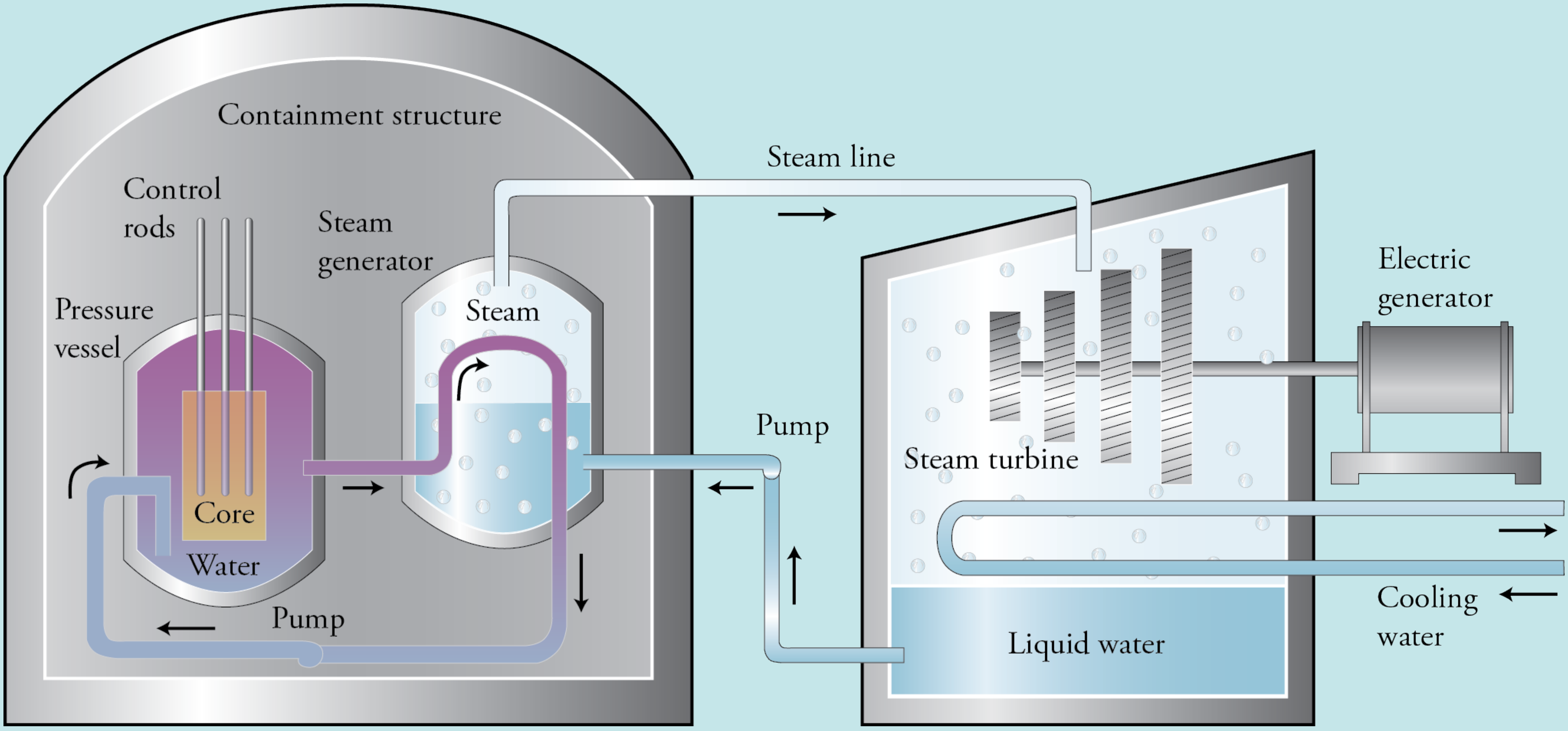


$$ {}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} $$

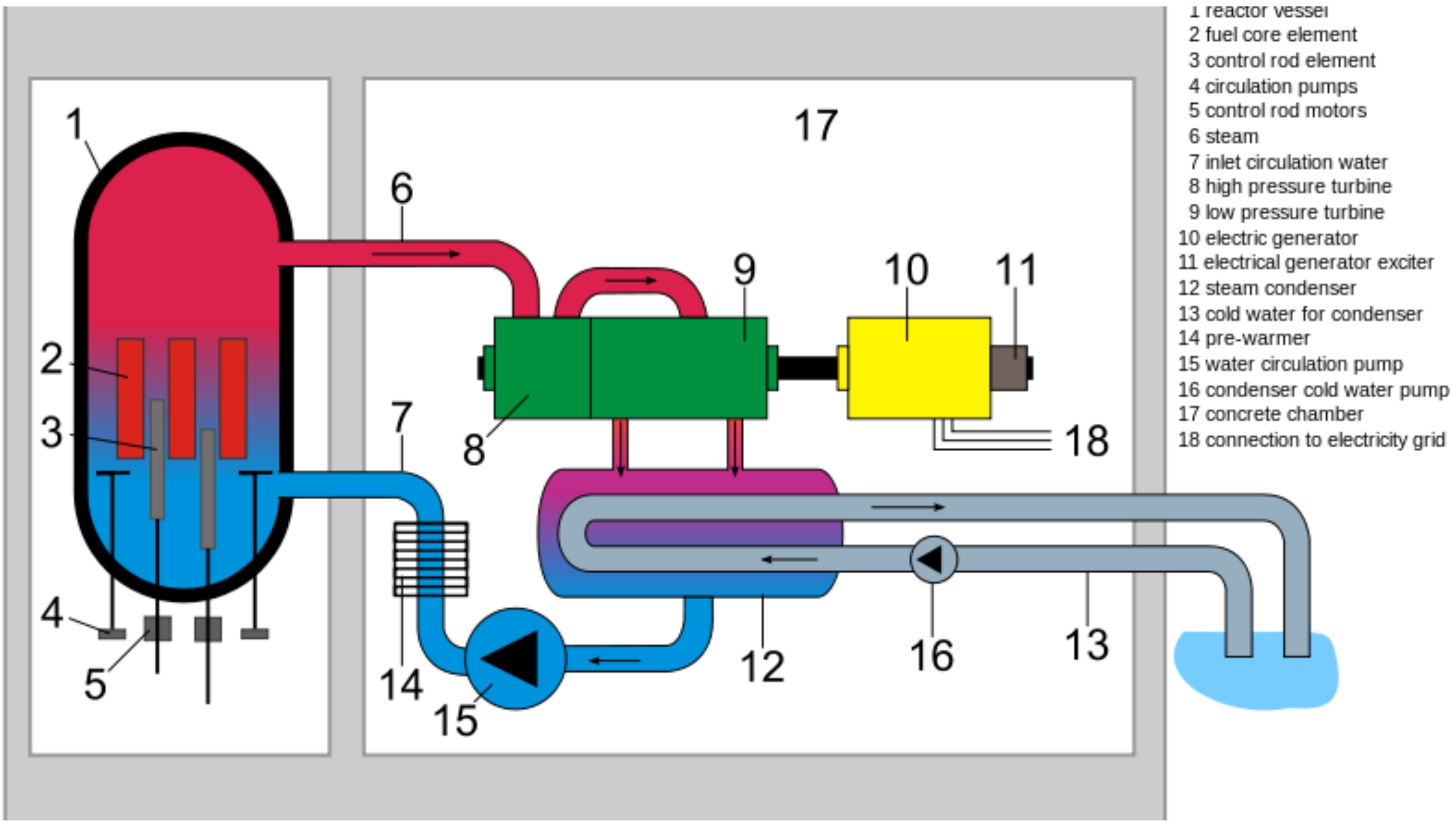


$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} $$

Nuclear Power Plant



Boiling Water Reactor



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

Nuclear Power Plant

- To get a sustained chain reaction, the percentage of ^{235}U must be increased over what is found in nature, in part because the unfissionable ^{238}U absorbs too many neutrons, and a sustained fission reaction is not reached.

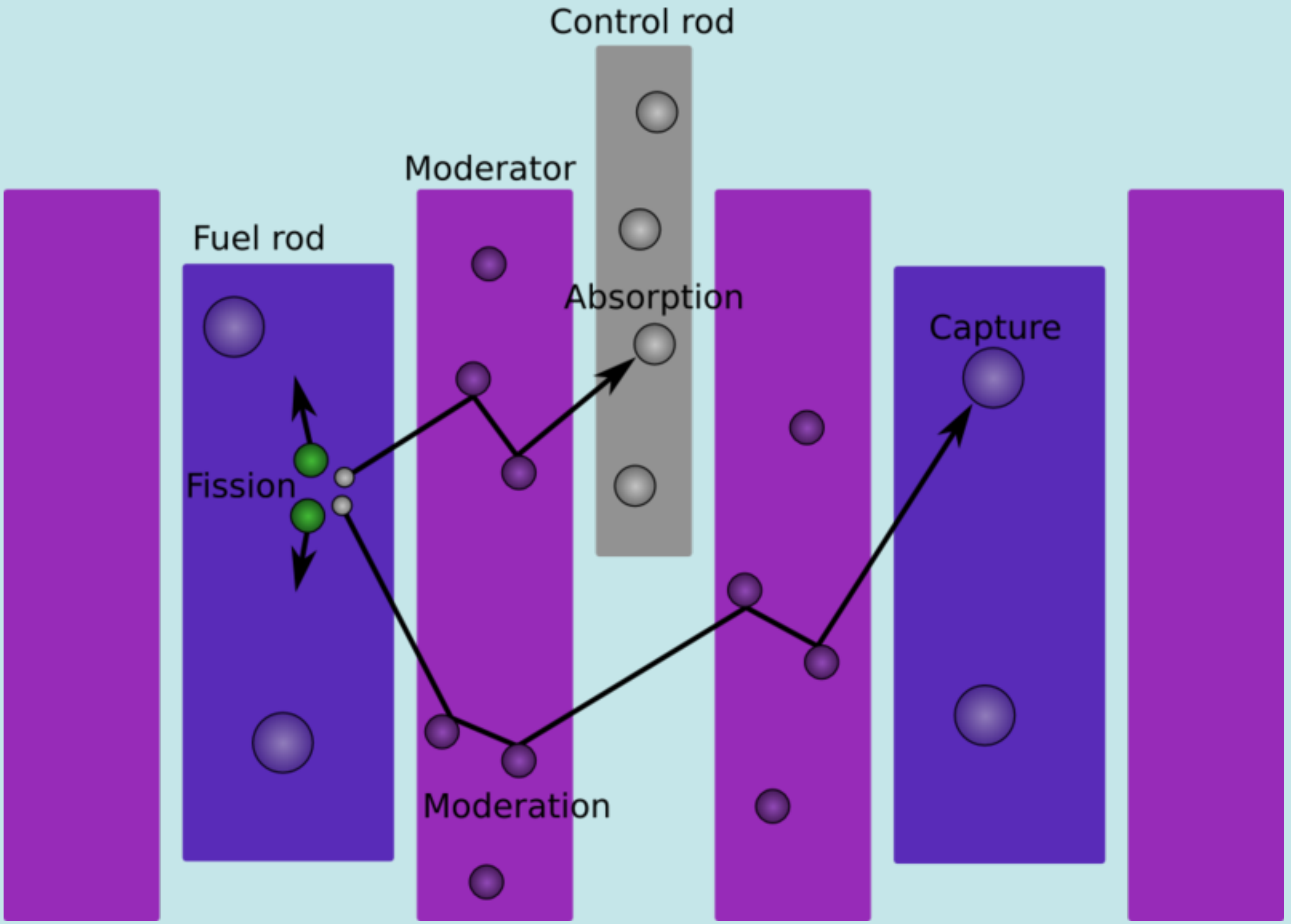
$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U}$$
$$^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}$$
$$^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}$$

- 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.

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.

Thermal Reactor



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.

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.

Prompt Critical

- **Critical** = if each fission event causes, on average, exactly one other. This causes a self-sustaining fission chain reaction.
- **Supercriticality** = if each fission event causes, on average, more than one other.
- **Prompt critical** = if for each nuclear fission event, one or more of the immediate or prompt neutrons released causes an additional fission event. This causes a rapid, exponential increase in the number of fission events. Prompt criticality is a special case of supercriticality.

Delayed Neutrons

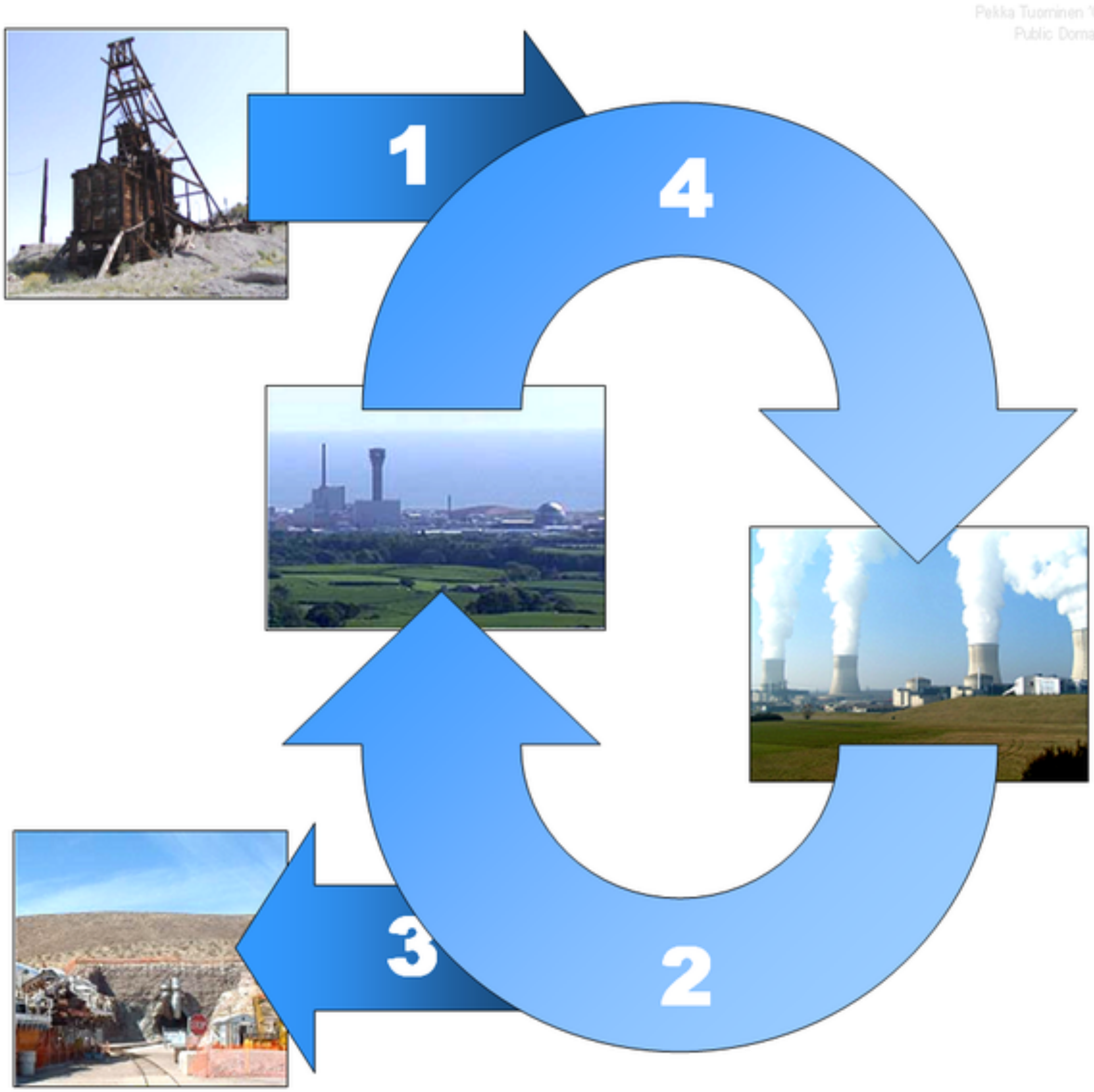
- A small fraction of the fission products that undergo beta decay are excited enough to be able to decay by emitting a neutron.
- The neutron emission happens orders of magnitude later compared to the emission of the prompt neutrons, which are released in the fission reaction.
- The ability of delayed neutrons to cause a new fission reaction is important in the design and safe operation of nuclear power plants.

Delayed Neutrons

- If a nuclear reactor happened to be prompt critical, the number of neutrons would increase exponentially, and very quickly the reactor would become uncontrollable.
- Because of the delayed neutrons, it is possible to leave the reactor in a subcritical state as far as only prompt neutrons are concerned.
- If the fission reaction begins to increase too rapidly, neutron production overall still grows exponentially, but on a time scale that is governed by the delayed neutron production, which is slow enough to be controlled.

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.

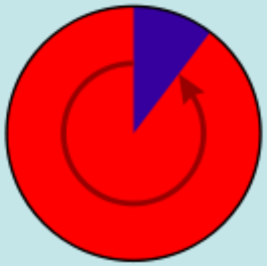
Uranium Enrichment

- 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

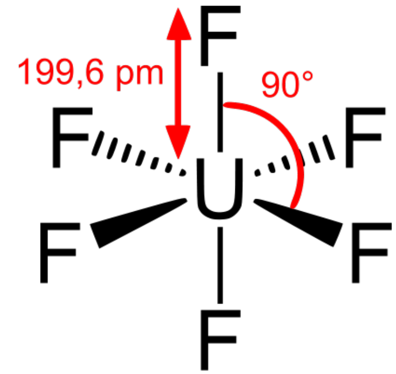
Natural uranium
> 99.2% U-238
0.72% U-235

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

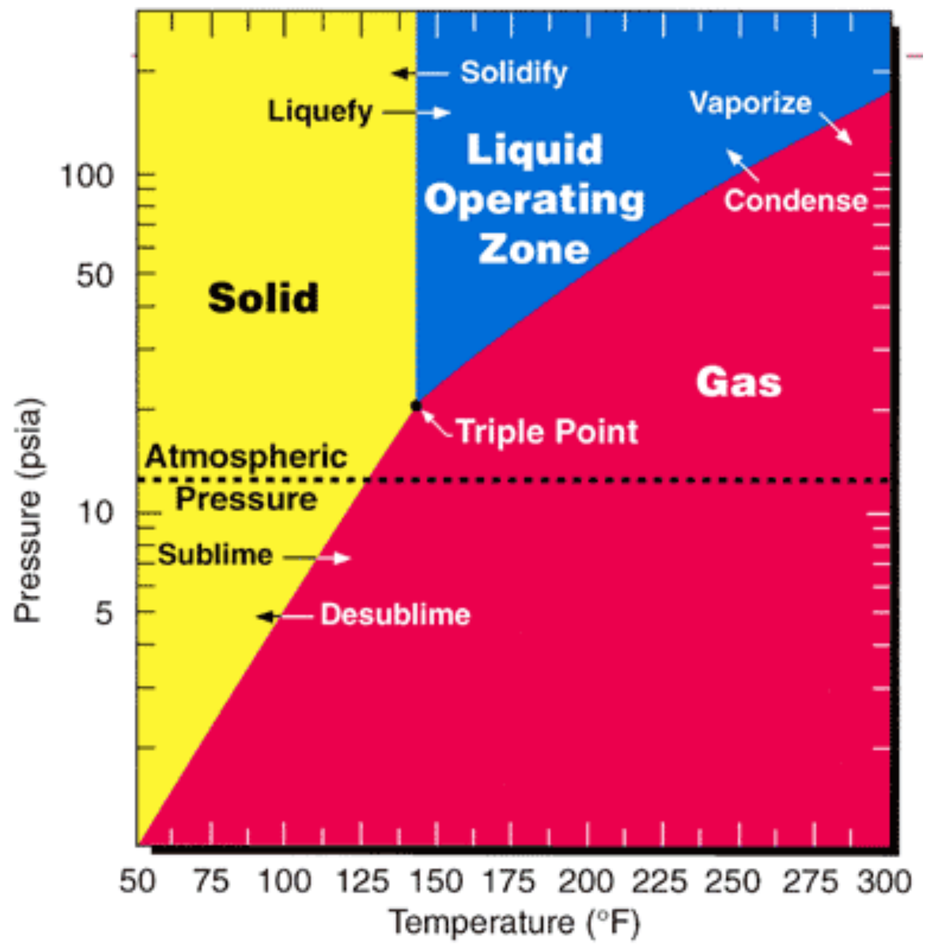


Highly enriched uranium
(weapons grade)
90% U-235

Uranium Enrichment

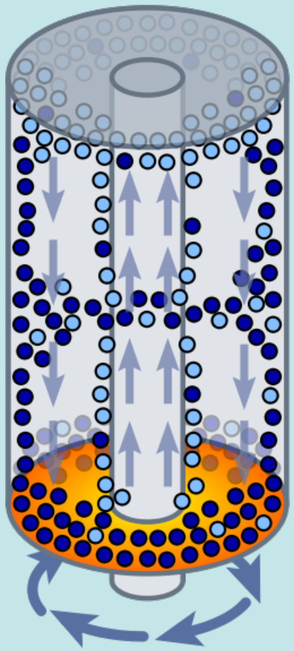


- In a series of steps, the uranium in uranium ore is converted into uranium hexafluoride, UF_6.
- It sublimes (goes directly from solid to gas) at 56.5 °C.
- The UF_6 can be enriched in $^{235}UF_6$ by either gas diffusion (first generation) or using gas centrifuges (second generation), which requires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

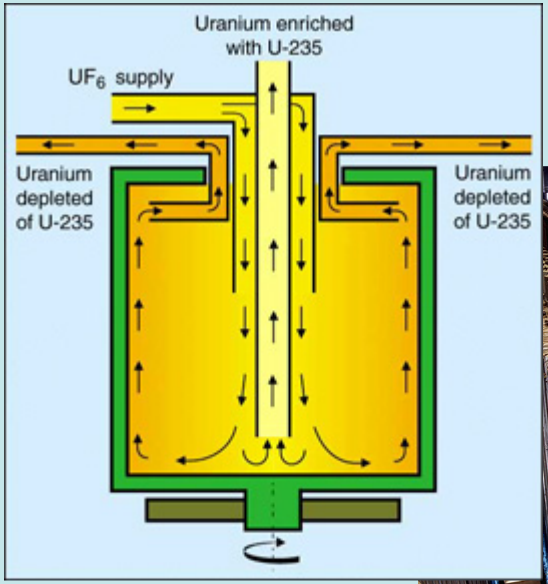


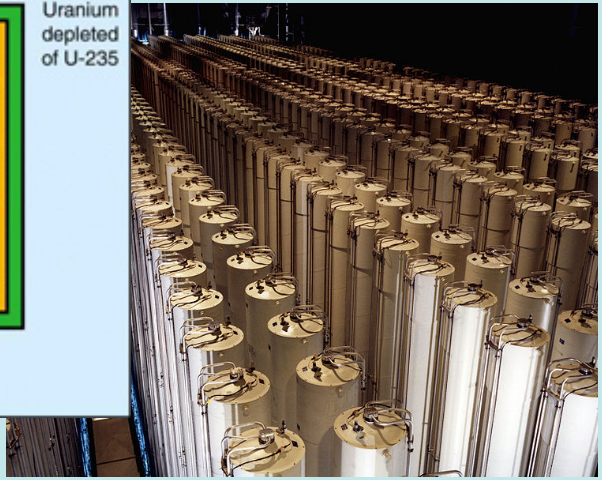
Gas Centrifuge

- 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.

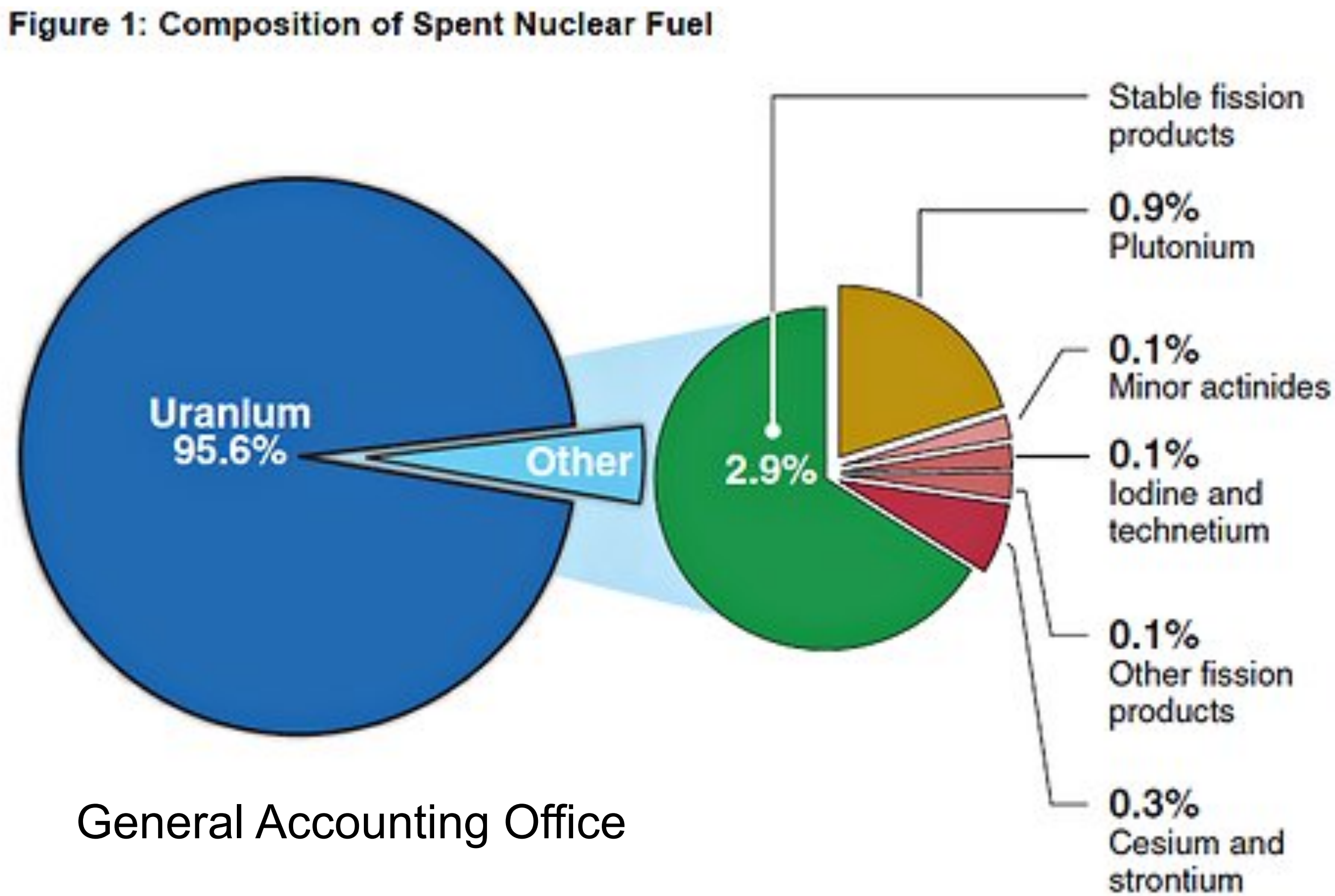




Depleted Uranium

- 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



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.

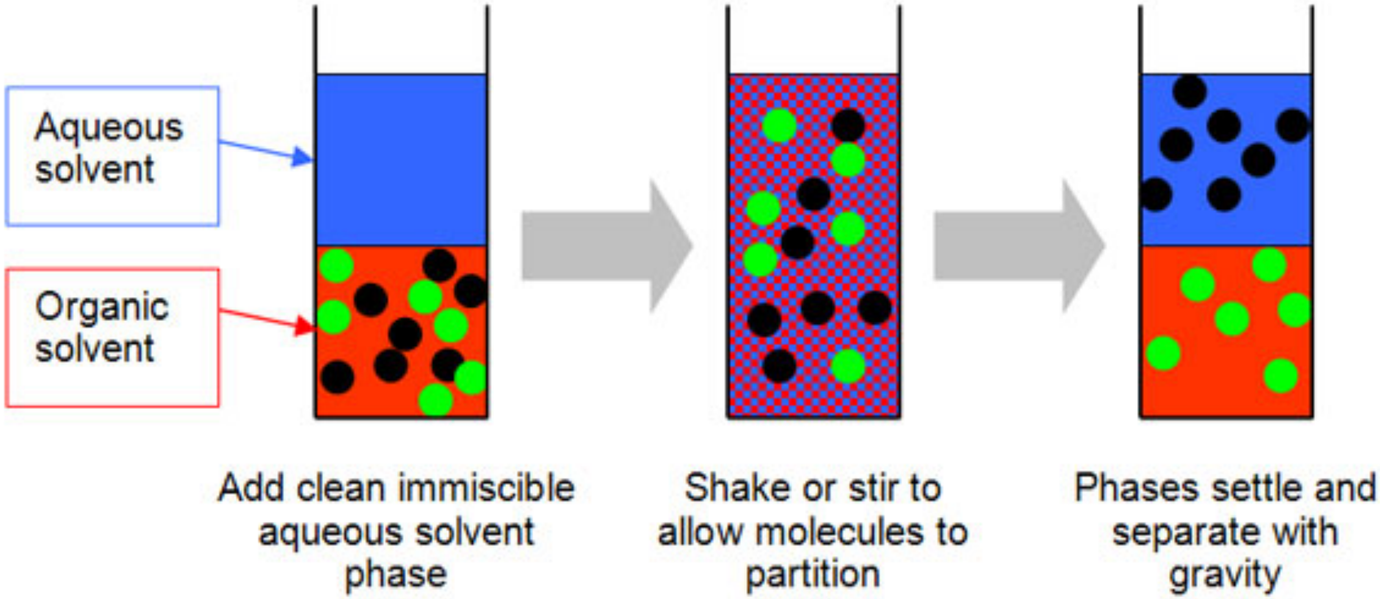
http://en.wikipedia.org/wiki/Nuclear_reprocessing

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

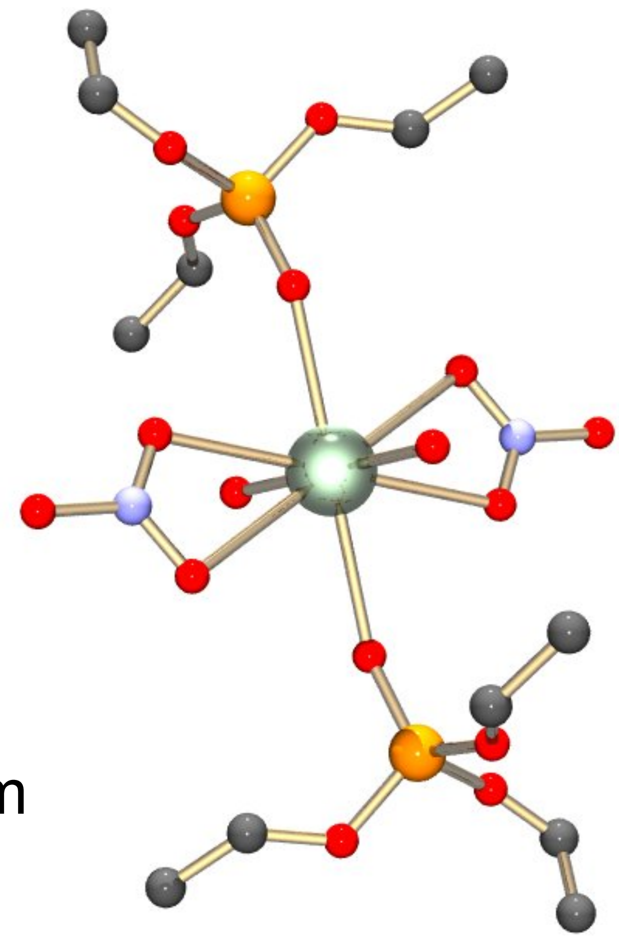
Typically performed in a separatory funnel:

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.



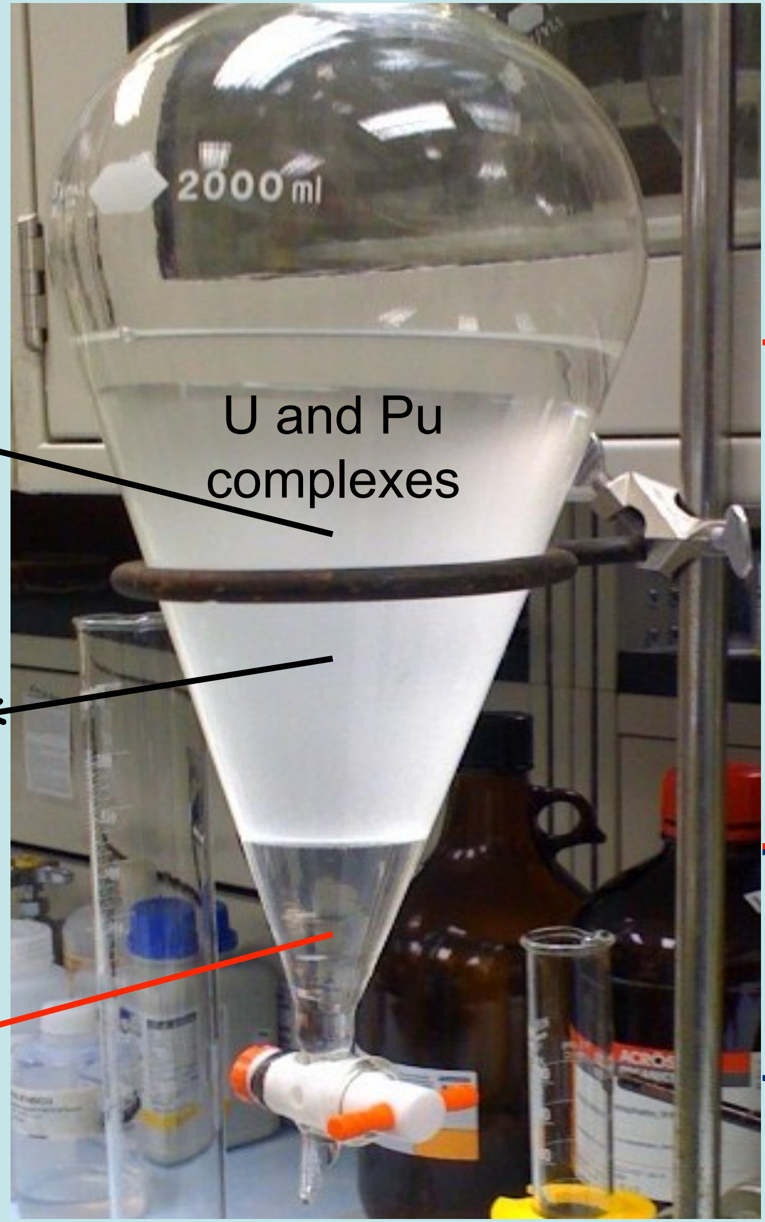
http://en.wikipedia.org/wiki/PUREX

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

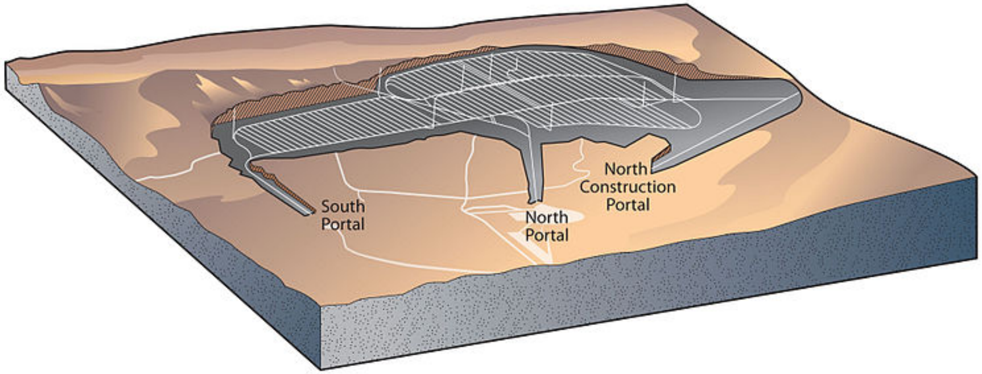
Nuclear Waste Storage/Disposal Possibilities

- "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

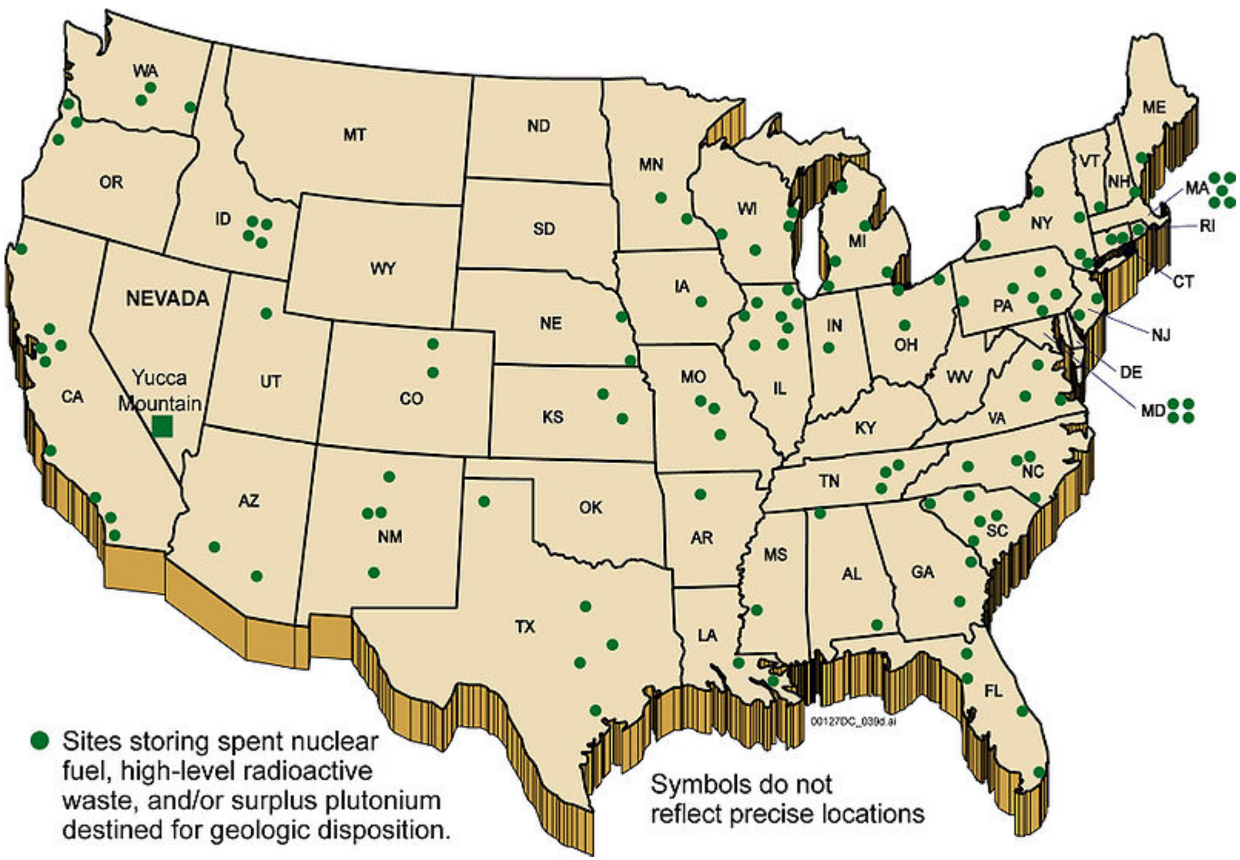
Yucca Mountain Nuclear Waste Repository

- 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