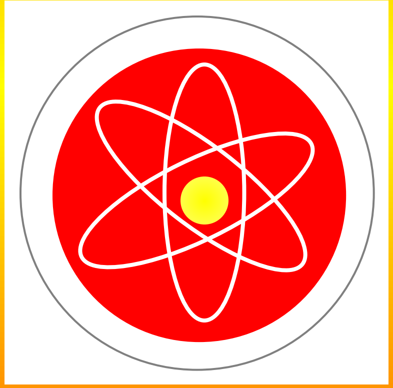
Nuclear



Guiding Questions

Is radiation dangerous?

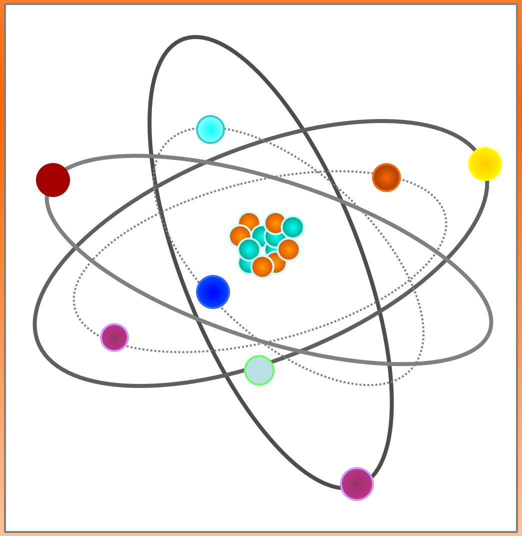
Is nuclear power a good choice?

What is nuclear energy?

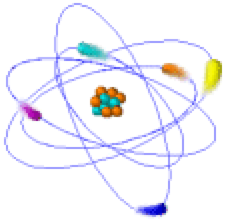
Are nuclear energy and nuclear bombs both dangerous?

Bravo – 15,000 kilotons

Development of the Atom



Nuclear



Review Background
Nuclear Radiation
Fission
Nuclear Power Plants
Half-Life
Decay Series
Fusion

Key Terms

alpha decay
alpha particles
artificial transmutation
background radiation
beta decay
beta particle
chain reaction
control rods
critical mass
curie
disintegrations per second
gamma decay
Geiger counter
half-life
ionizing radiation
irradiate
isotope
moderator
natural radioactivity
nuclear equation
nuclear fission
nuclear fusion
nuclide
plasma
positrons
rad
radioisotope
rem
roentgen
tracers
transmutation
X-rays

Radioactivity

Much of our understanding of atomic structure came from studies of radioactive elements.

Radioactivity

The process by which atoms spontaneously emit high energy particles or rays from their nucleus.

First observed by
Henri Becquerel in 1896

History: On The Human Side

1834 *Michael Faraday* - electrolysis experiments suggested electrical nature of matter

1895 *Wilhelm Roentgen* - discovered X-rays when cathode rays strike anode

1896 *Henri Becquerel* - discovered "uranic rays" and radioactivity

1896 *Marie (Marya Sklodowska) and Pierre Curie* - discovered that radiation is a property of the atom, and not due to chemical reaction. (Marie named this property *radiactivity*.)

1897 *Joseph J. Thomson* - discovered the electron through Crookes tube experiments

1898 *Marie and Piere Curie* - discovered the radioactive elements polonium and radium

1899 *Ernest Rutherford* - discovered alpha and beta particles

1900 *Paul Villard* - discovered gamma rays

1903 *Ernest Rutherford* and *Frederick Soddy* - established laws of radioactive decay and transformation

1910 *Frederick Soddy* - proposed the isosope concept to explain the existence of more than one atomic weight of radioelements

1911 *Ernest Rutherford* - used alpha particles to explore gold foil; discovered the nucleus and the proton; proposed the nuclear theory of the atom

1919 *Ernest Rutherford* - announced the first artificial transmutation of atoms

1932 *James Chadwick* - discovered the neutron by alpha particle bombardment of Beryllium

1934 *Frederick Joliet* and *Irene Joliet Curie* - produced the first artificial radioisotope

1938 *Otto Hahn, Fritz Strassmann, Lise Meitner,* and *Otto Frisch* - discovered nuclear fission of uranium-235 by neutron bombardment

1940 *Edwin M McMillan* and *Philip Abelson* - discovered the first transuranium element, neptunium, by neutron irradiation of uranium in a cyclotron

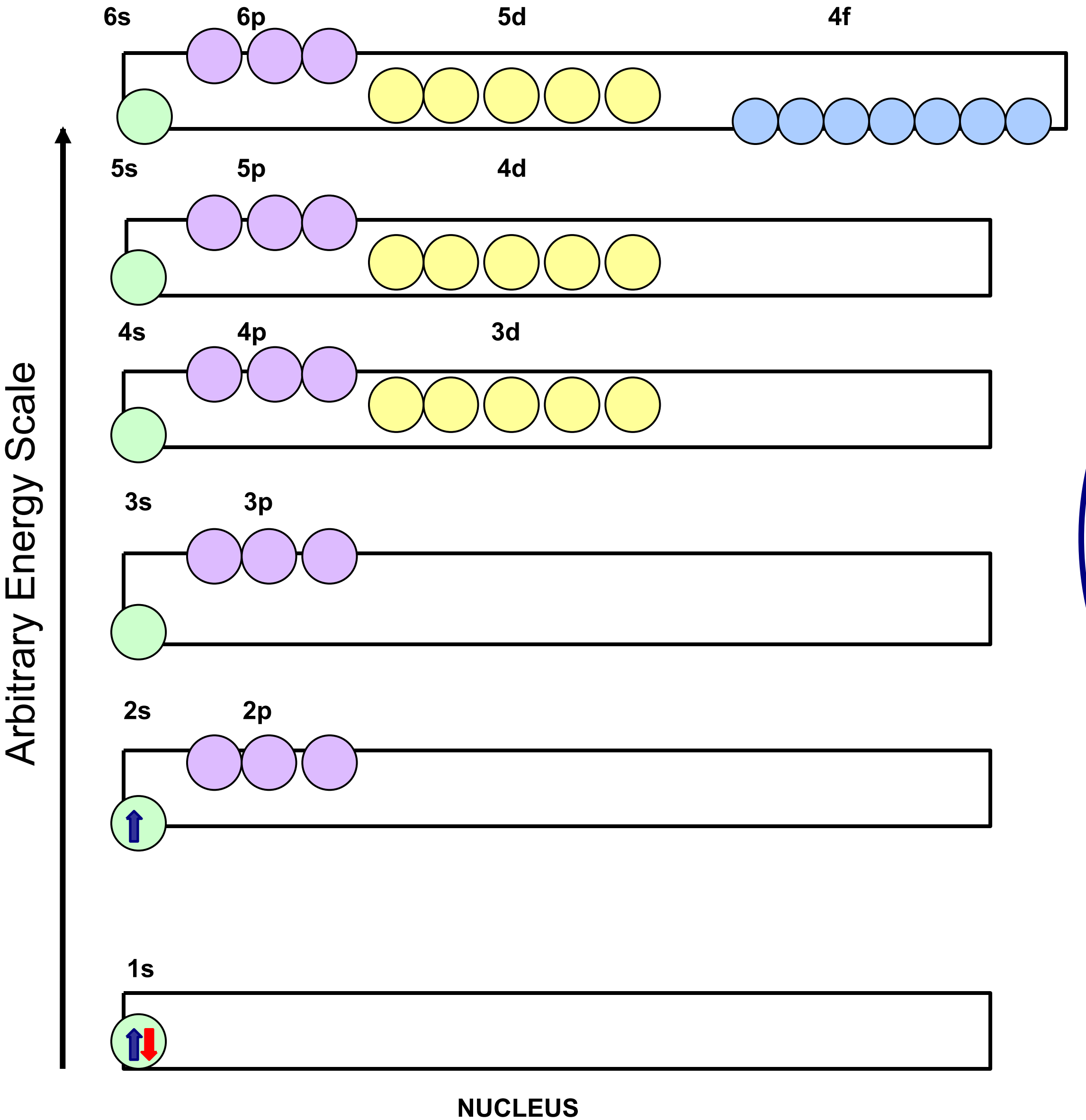
1941 *Glenn T. Seaborg, Edwin M. McMillan, Joseph W. Kennedy* and *Arthur C. Wahl* - announced discovery of plutonium from beta particle emission of neptunium

1942 *Enrico Fermi* - produced the first nuclear fission chain-reaction

1944 *Glenn T. Seaborg*- proposed a new format for the periodic table to show that a new actinide series of 14 elements would fall below and be analagous to the 14 lanthanide-series elements.

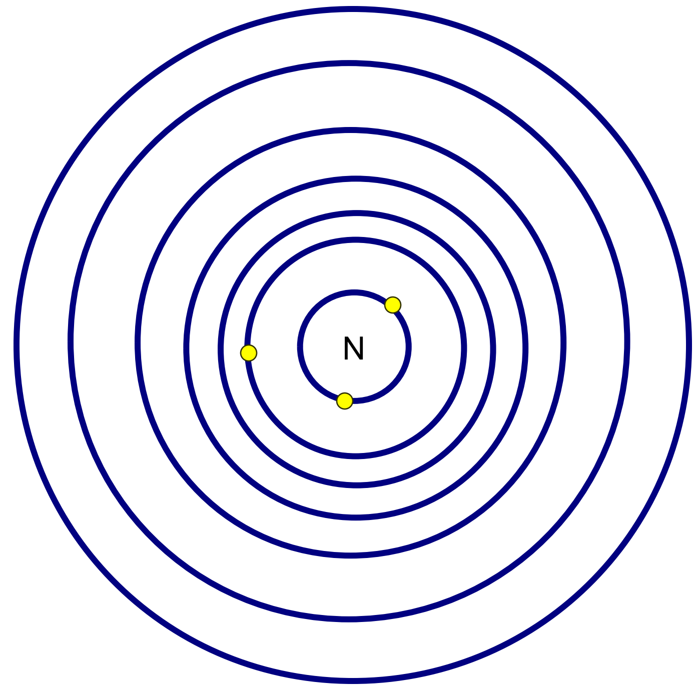
1964 *Murray Gell-Mann* hypothesized that quarks are the fundamental particles that make up all known subatomic particles except leptons.

Energy Level Diagram



Lithium

Bohr Model



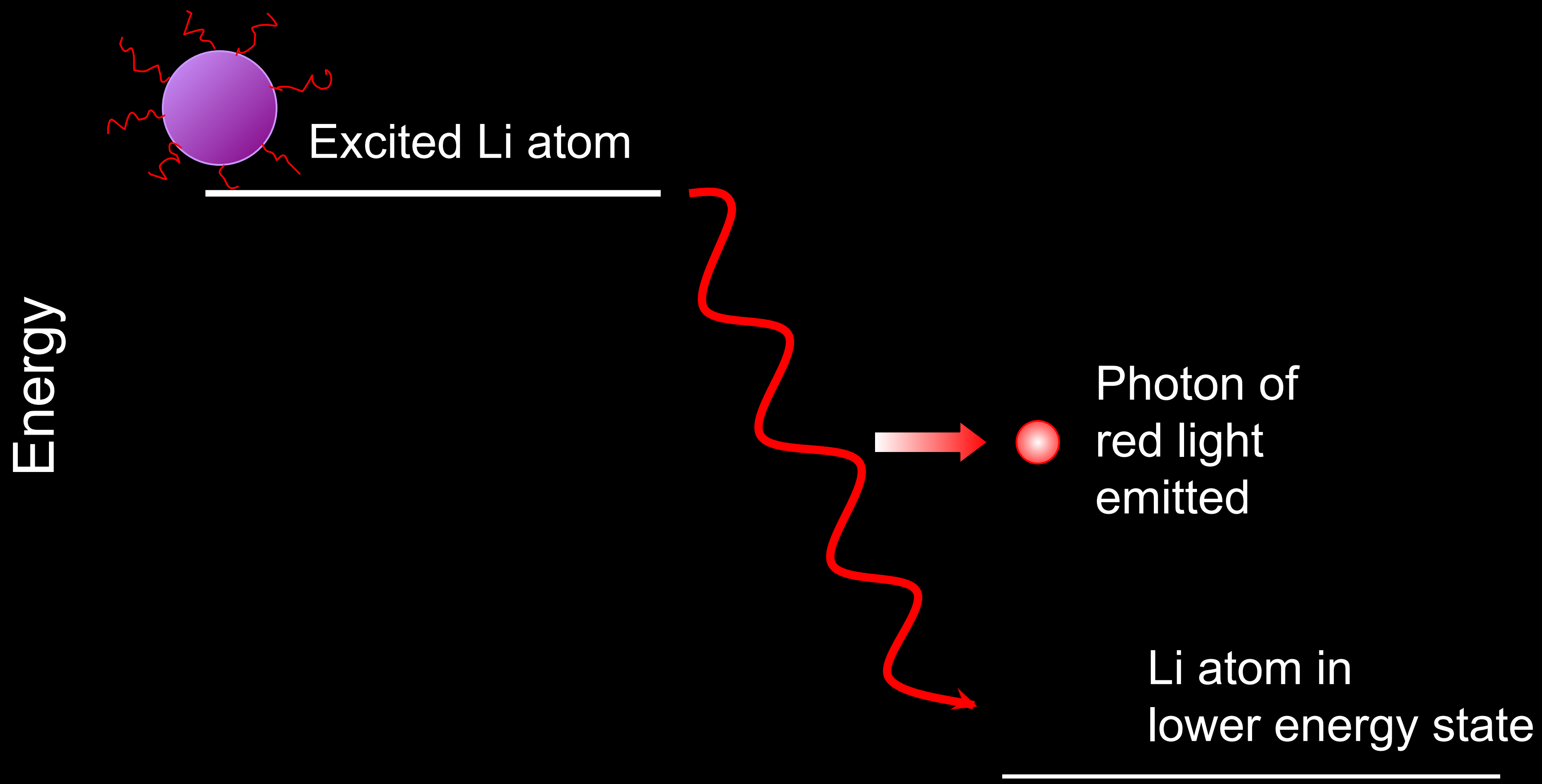
Electron Configuration

Li = $1s^2 2s^1$

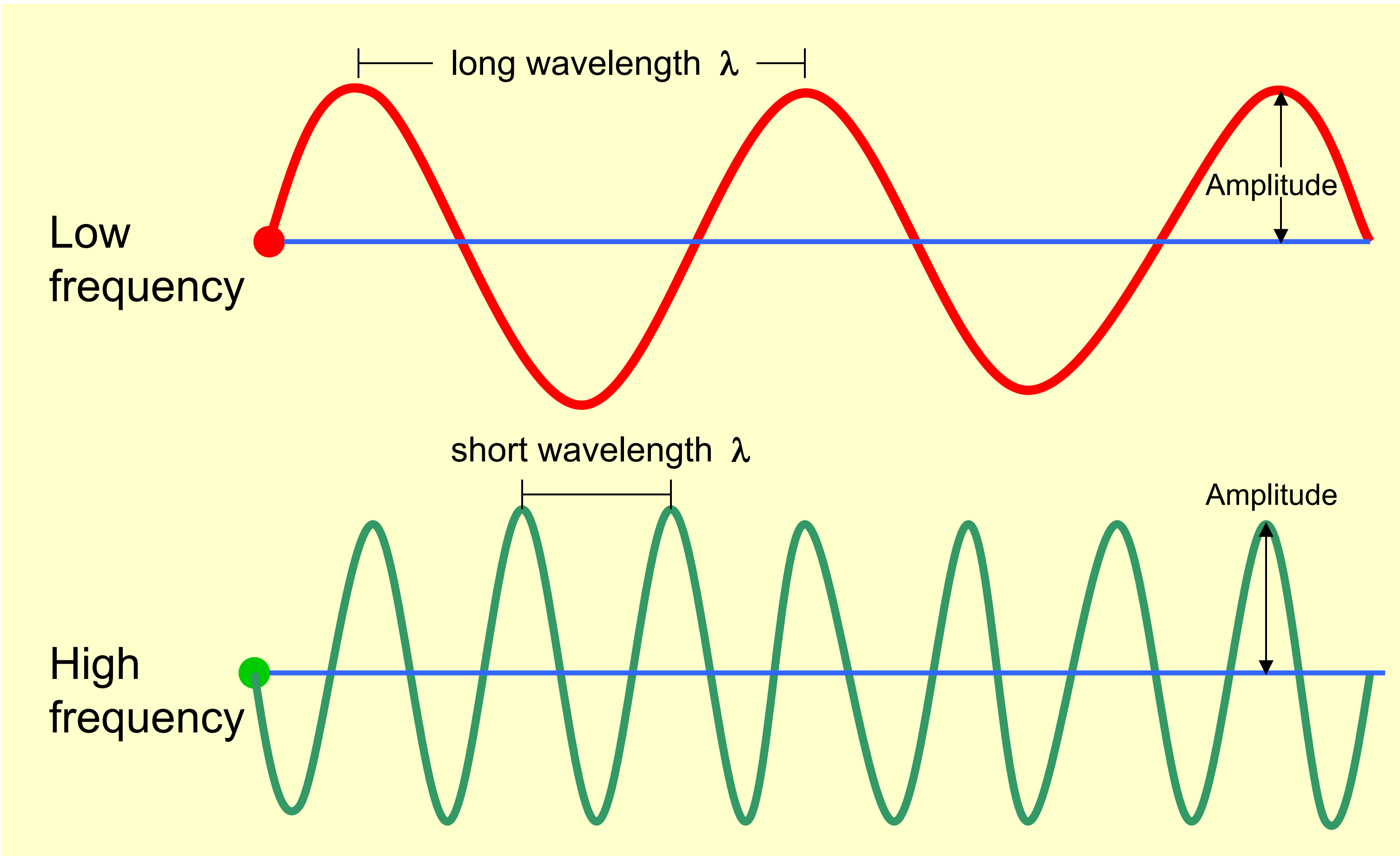
H He Li C N Al Ar F Fe La

CLICK ON ELEMENT TO FILL IN CHARTS

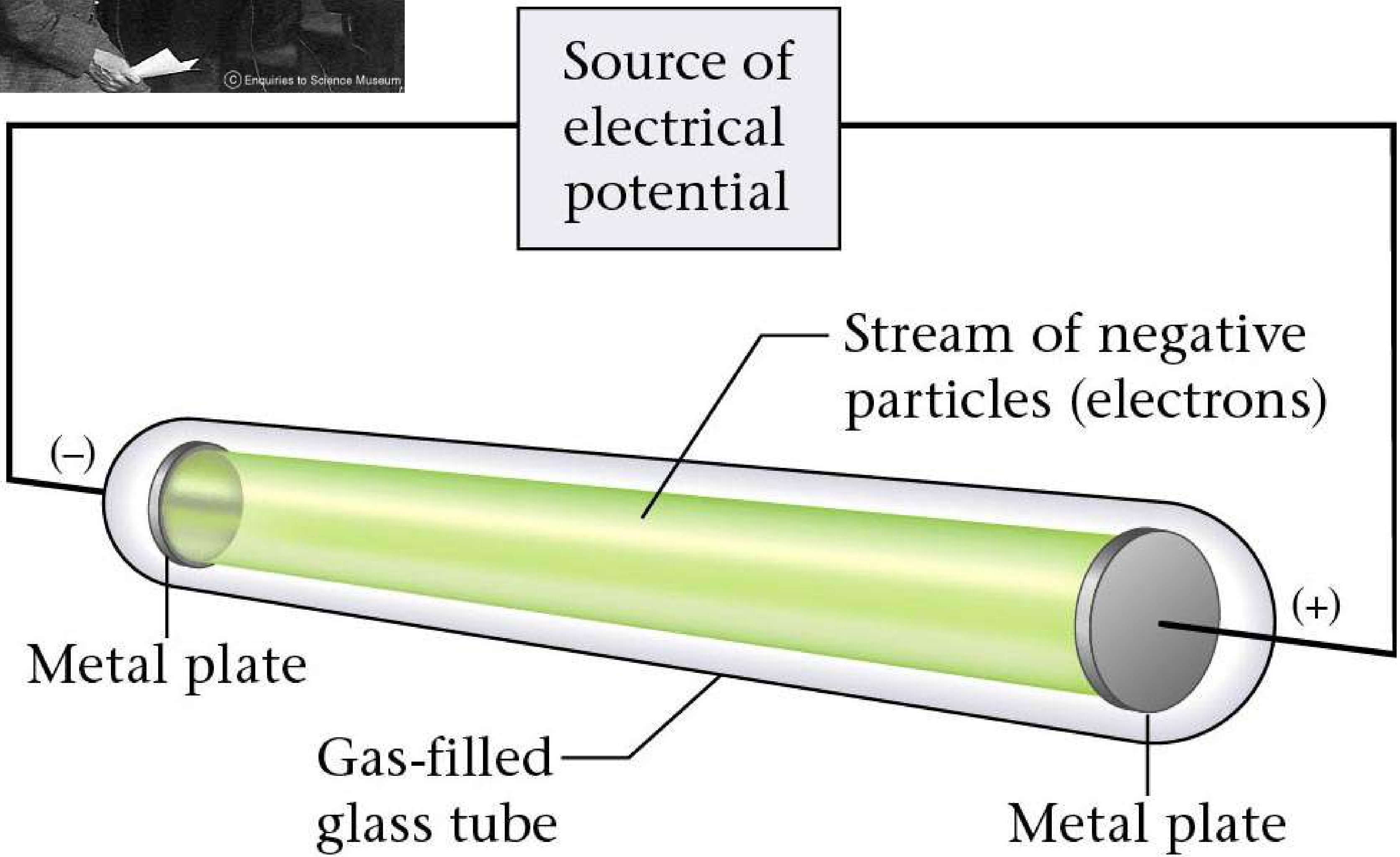
An Excited Lithium Atom



Waves

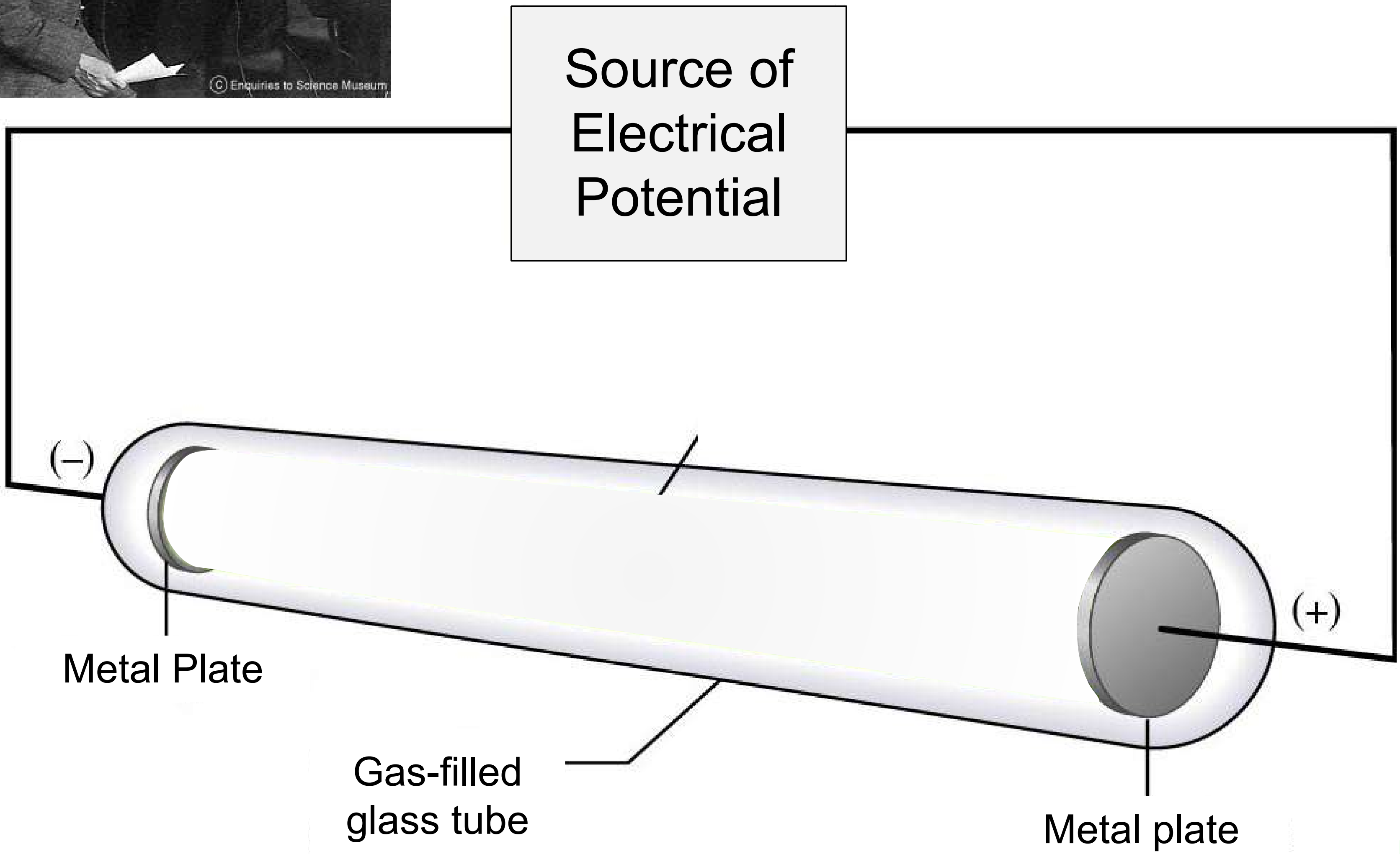

long wavelength λ
Amplitude
Low frequency
short wavelength λ
Amplitude
High frequency

A Cathode Ray Tube



Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 58

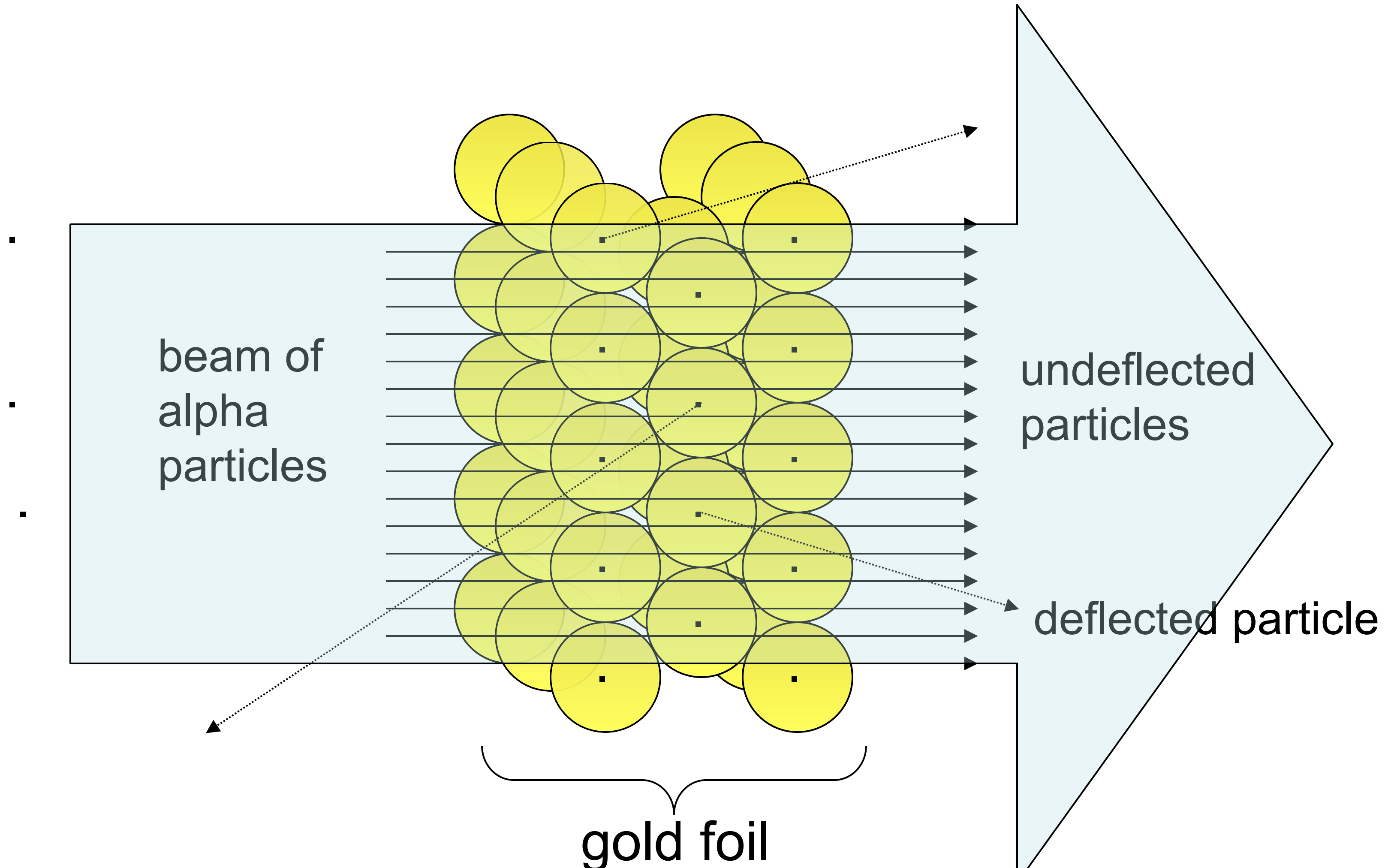
A Cathode Ray Tube



Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 58

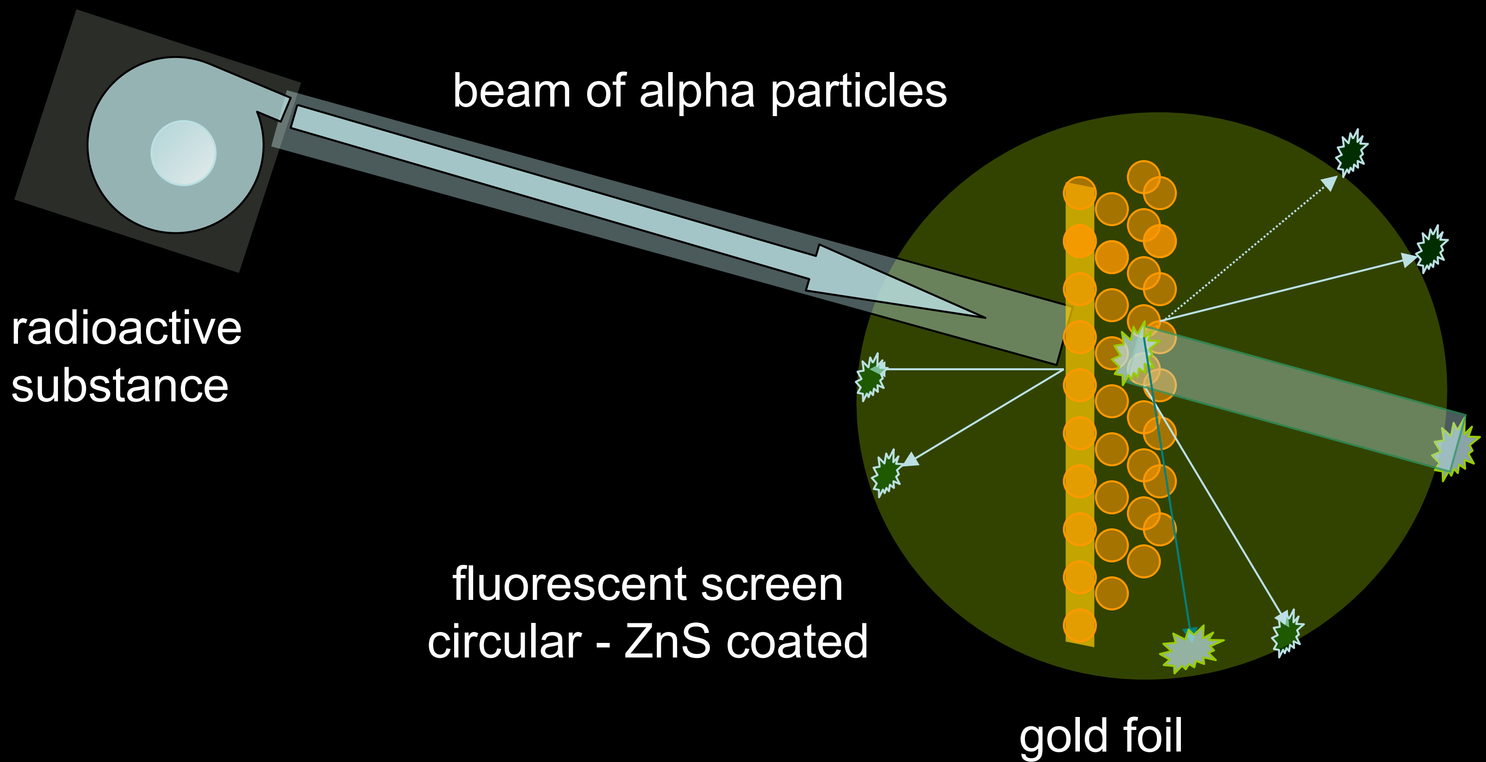
PAPER

Interpreting the Observed Deflections



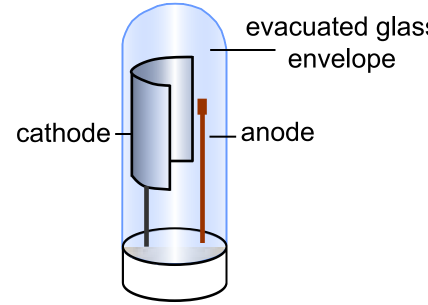
Dorin, Demmin, Gabel, Chemistry The Study of Matter , 3rd Edition, 1990, page 120

Rutherford's Apparatus

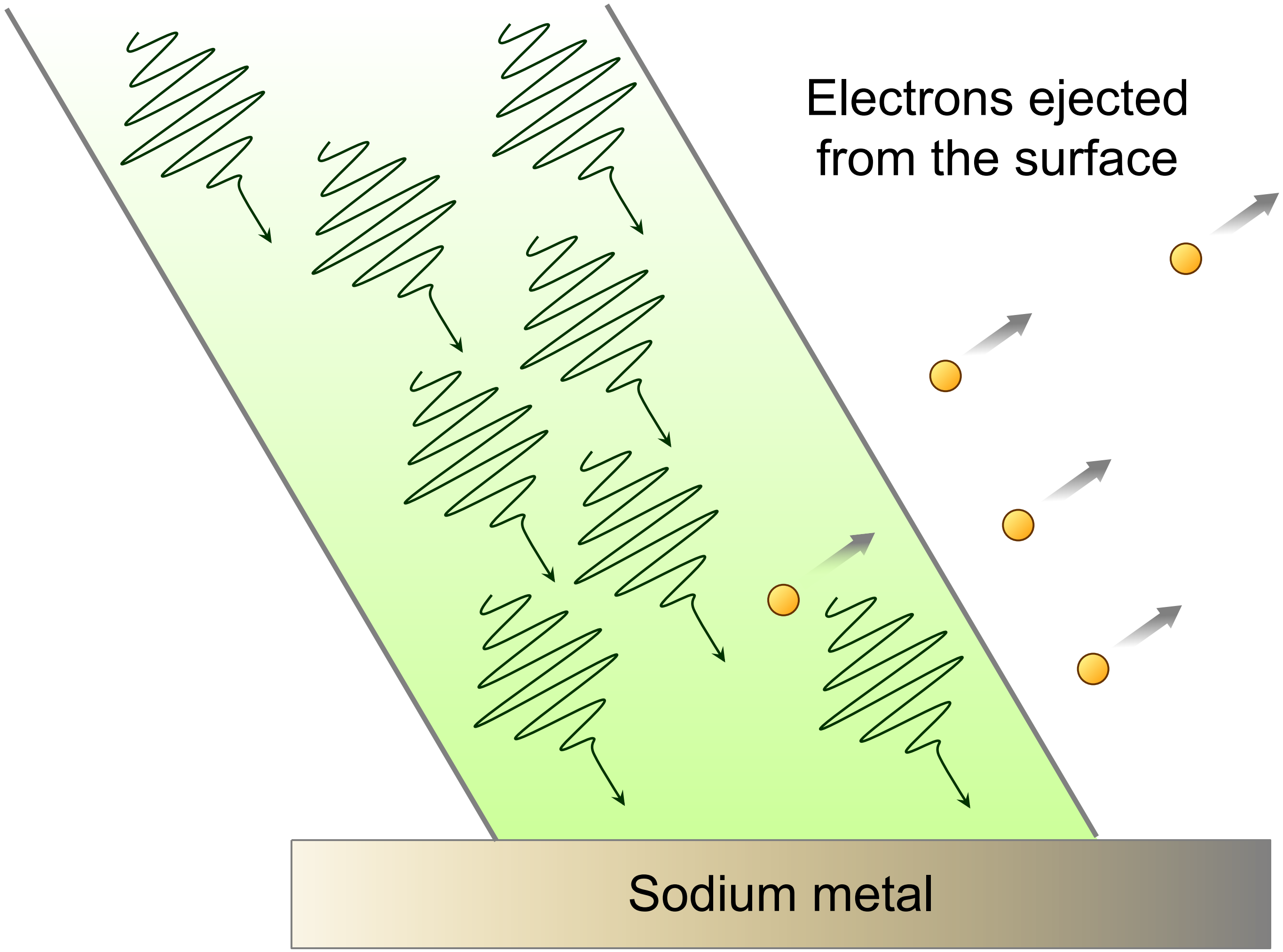


Dorin, Demmin, Gabel, Chemistry The Study of Matter , 3rd Edition, 1990, page 120

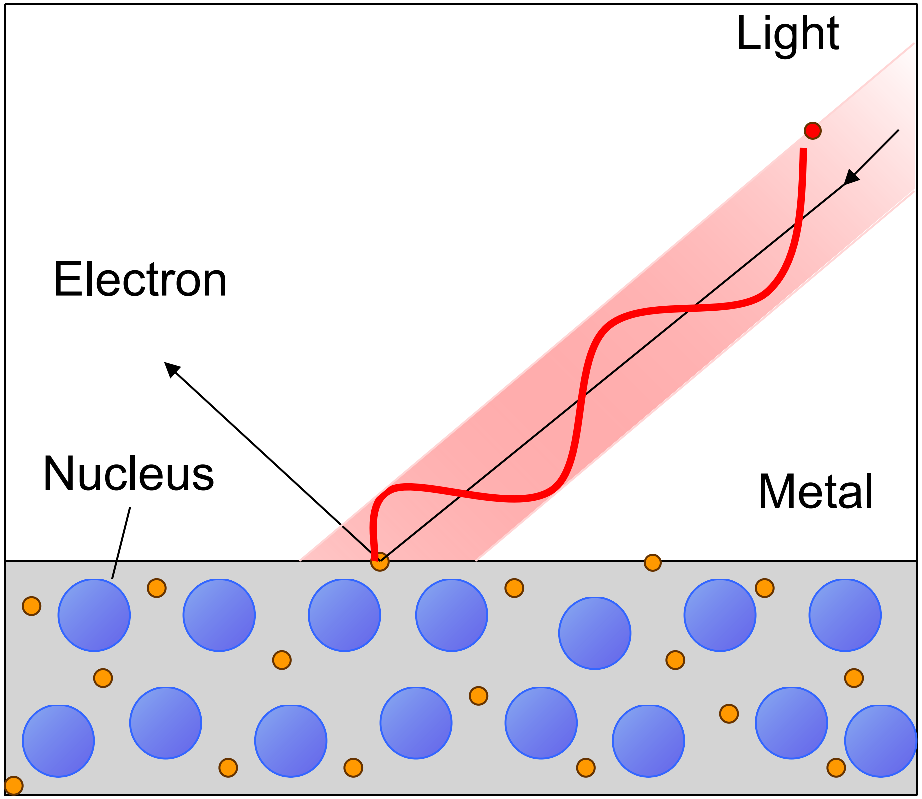
Photoelectric Effect



Photoelectric Cell

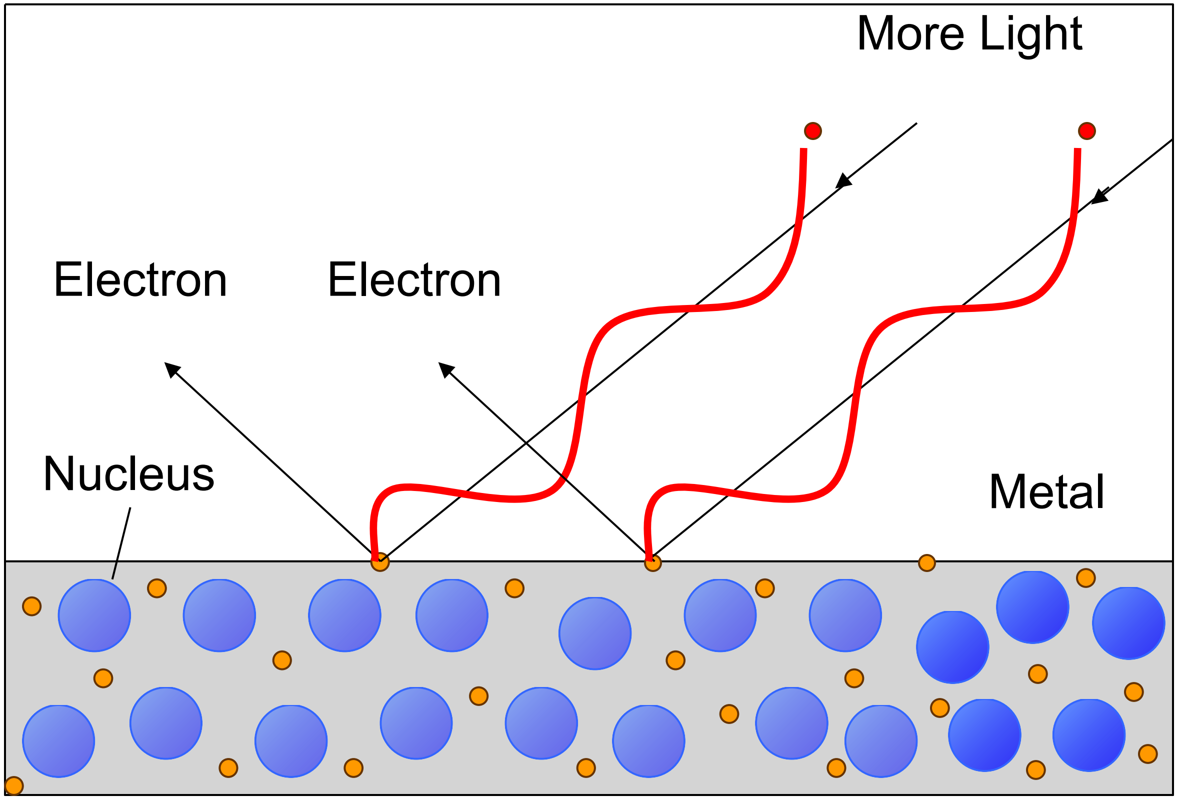


Photoelectric Effect



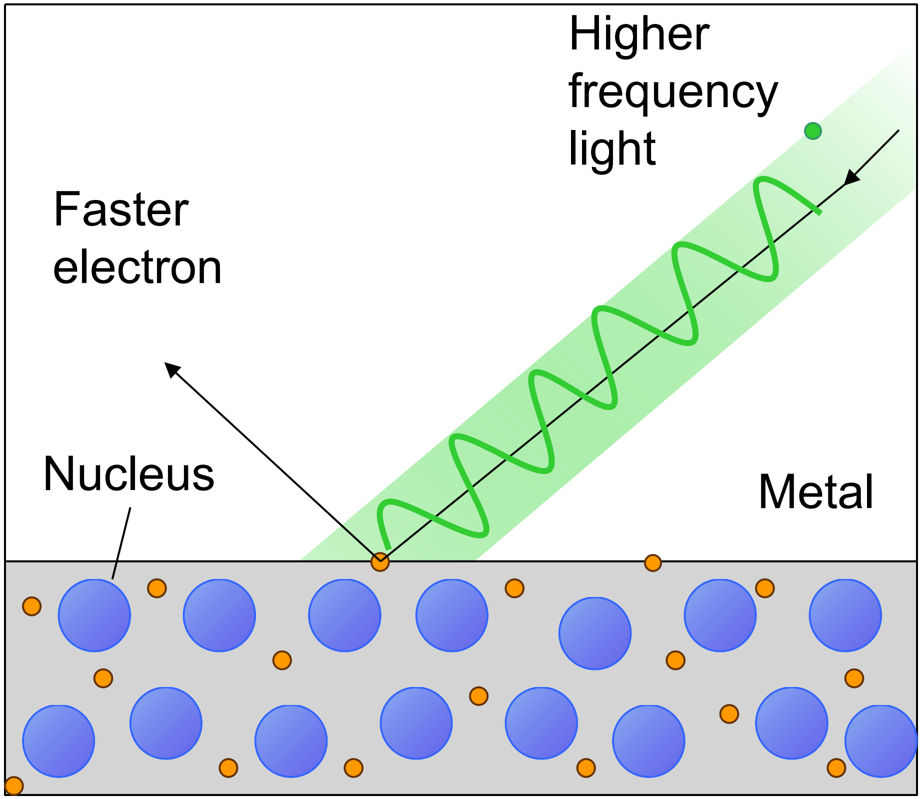
When light strikes a metal surface, electrons are ejected.

Photoelectric Effect



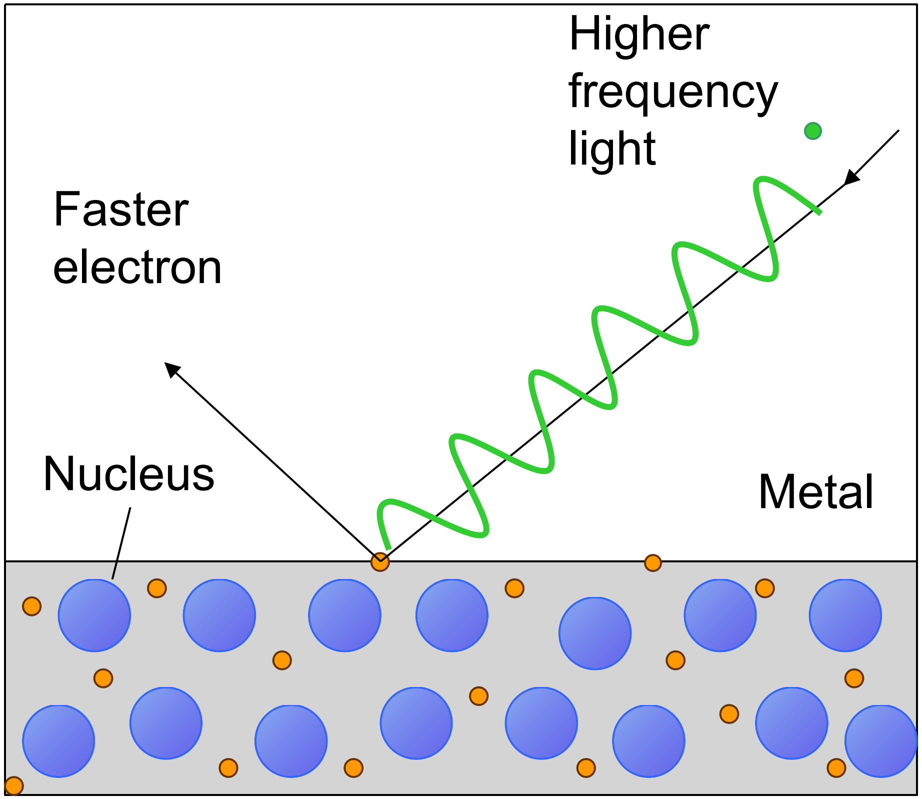
If the threshold frequency has been reached, increasing the intensity only increases the number of the electrons ejected.

Photoelectric Effect



If the frequency is increased, the ejected electrons will travel faster.

Photoelectric Effect



If the frequency is increased, the ejected electrons will travel faster.

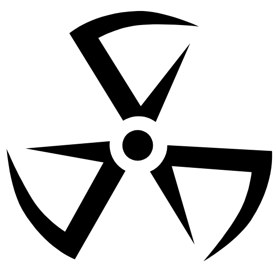
Strong vs. Weak Force

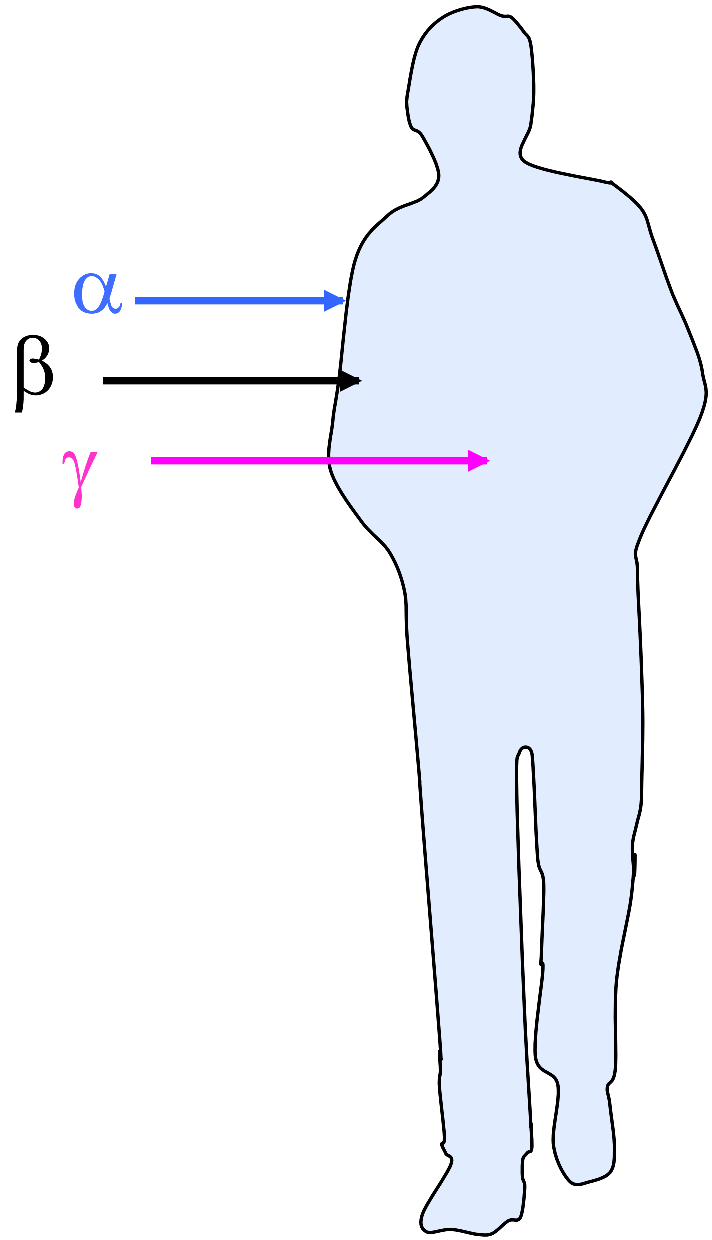
Weak force: electrostatic attractions between protons and electrons in atoms
e.g. covalent bonding, ionic bonding, hydrogen bonding

Strong force: force that holds the nucleus together.

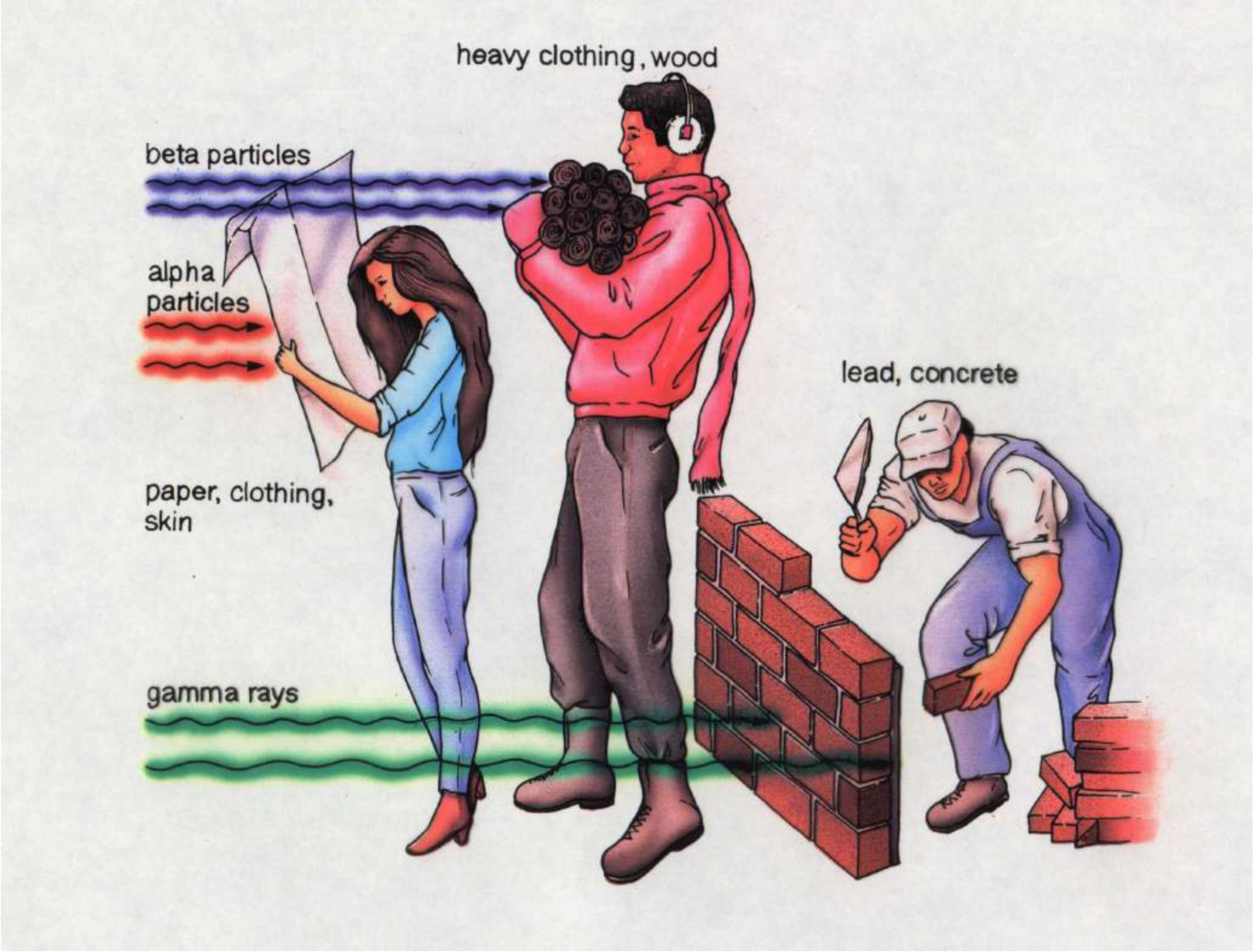
i.e. The nucleus contains protons that naturally repel each other. The *strong force* holds the nucleus together. When the nucleus is split, the energy released is the energy of the strong force.

Absorption of Radiation





Absorption of Radiation



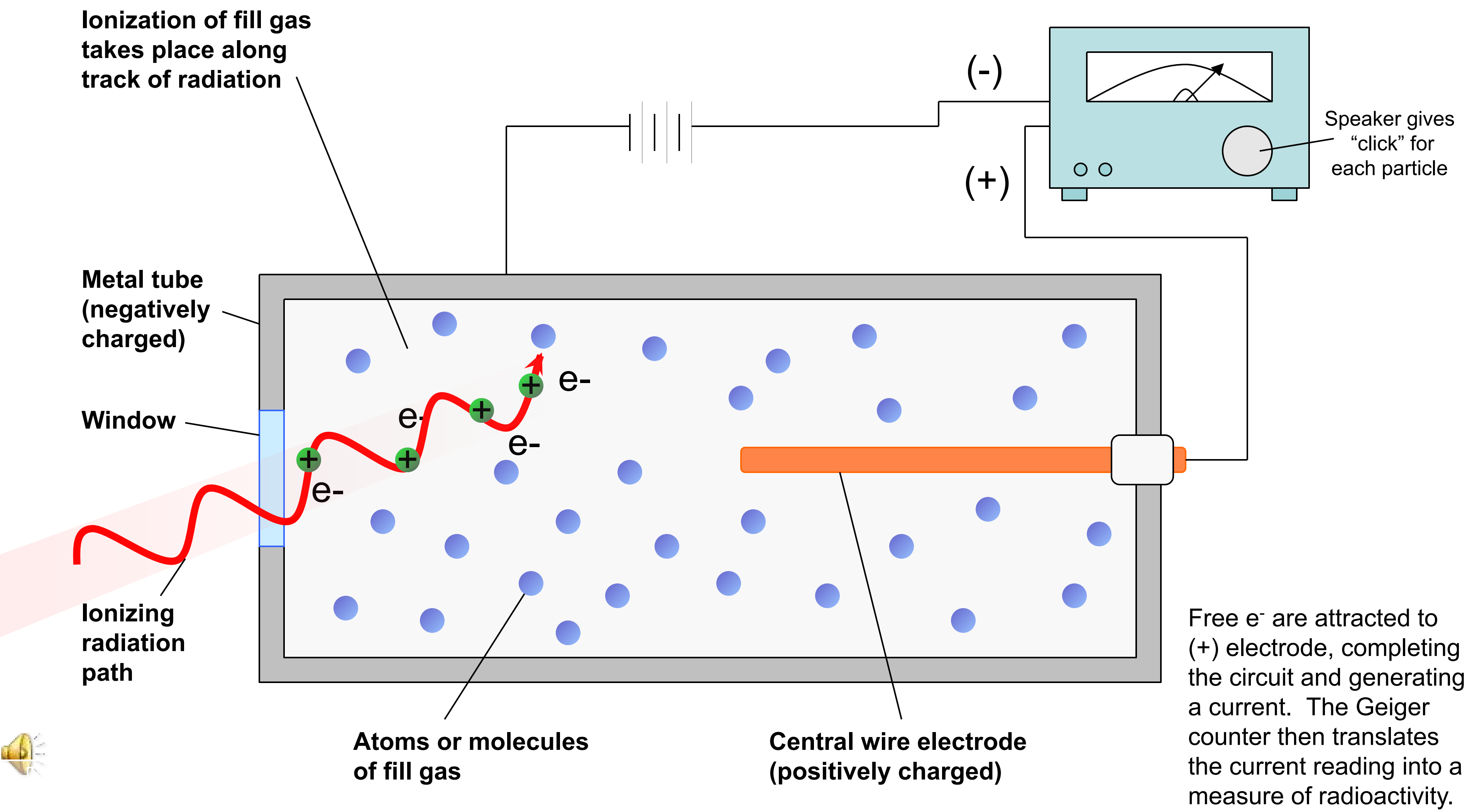
Timberlake, Chemistry 7th Edition, page 84

Typical Radiation Exposure per Person per Year in the United States			
Source	**Radiation**	**Source**	**Radiation**
atmosphere at sea level*	26 mrem	dental X-ray	1 mrem
ground	30 mrem	chest X-ray	6 mrem
foods	20 mrem	X-ray of hip	65 mrem
air travel above 1,800 m	4 mrem	CAT scan	110 mrem
construction site	7 mrem	nuclear power plant nearby	0.02 mrem
X-ray of arm or leg	1 mrem	TV and computer use	2 mrem

*Add 3 mrem for every 300 m of elevation

Packard, Jacobs, Marshall, Chemistry Pearson AGS Globe, page 341

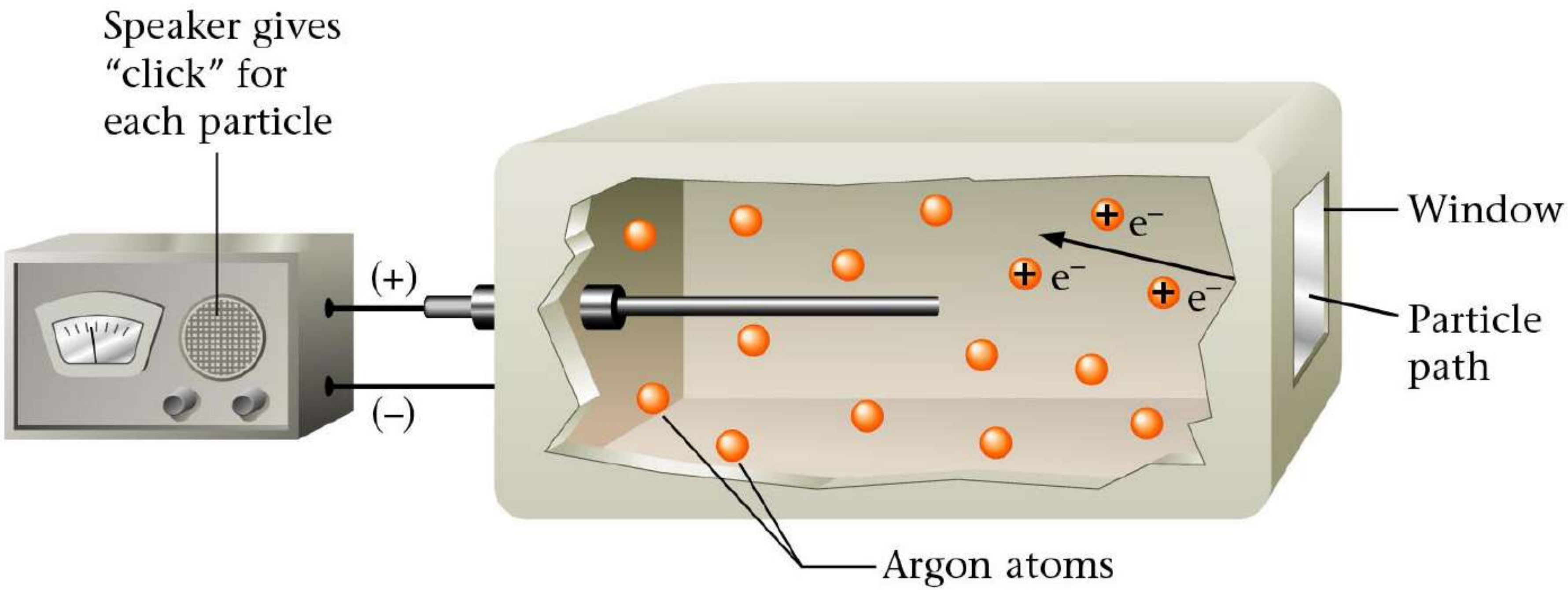
Geiger Counter



Free e^- are attracted to (+) electrode, completing the circuit and generating a current. The Geiger counter then translates the current reading into a measure of radioactivity.

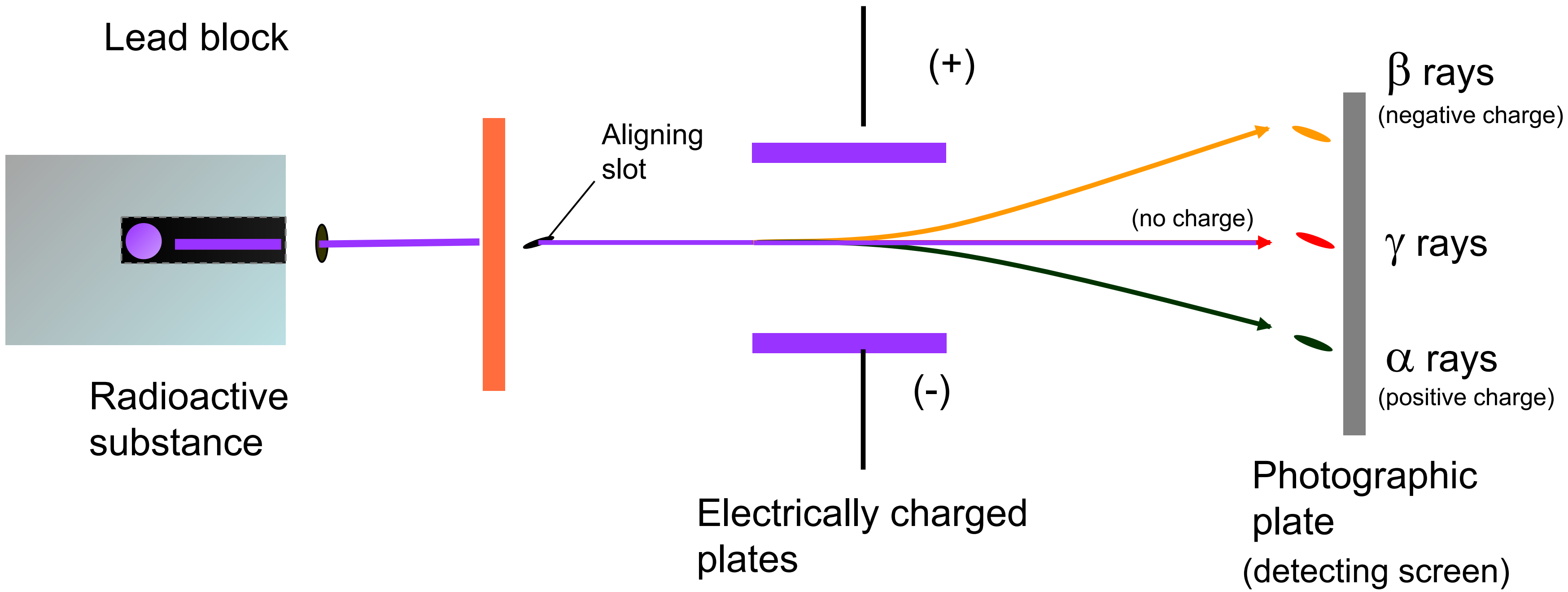
Wilbraham, Staley, Matta, Waterman, Chemistry, 2002, page 857

Geiger-Muller Counter



Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 614

Alpha, Beta, Gamma Rays



Animation by Raymond Chang

Types of Radiation

Type	Symbol	Charge	Mass (amu)
Alpha particle	${}^{4}_{2}He$	2+	4.015062
Beta particle	${}^{0}_{-1}\beta$	1-	0.0005486
Positron	${}^{0}_{+1}\beta$	1+	0.0005486
Gamma ray	γ	0	0

Characteristics of Some Ionizing Radiations			
Property	***Alpha radiation***	***Beta radiation***	***Gamma radiation***
Composition	Alpha particle (helium nucleus)	Beta particle (electron)	High-energy electro-magnetic radiation
Symbol	α, He-4	β, e	γ
Charge	2+	1-	0
Mass (amu)	4	$^{1}/_{1837}$	0
Common source	Radium-226	Carbon-14	Cobalt-60
Approximate energy	5 MeV*	0.05 to 1 MeV	1 MeV
Penetrating power	Low (0.05 mm body tissue)	Moderate (4 mm body tissue)	Very high (penetrates body easily)
Shielding	Paper, clothing	Metal foil	Lead, concrete (incomplete shields)

***(1 MeV = 1.60 x 10^{-13} J)**

Nuclear reactions

Nuclear equations show how atoms decay.

Similar to chemical equations.

- *must still balance mass and charge.*

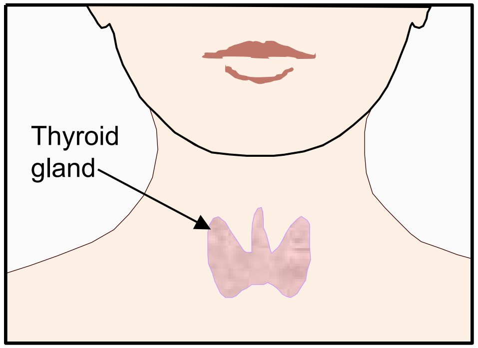
Differ from chemical equations because

- *we can change the elements.*

  …transmutation
- *the type of isotope is important.*

A patient is given radioactive iodine to test thyroid function. What happens to the iodine?

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



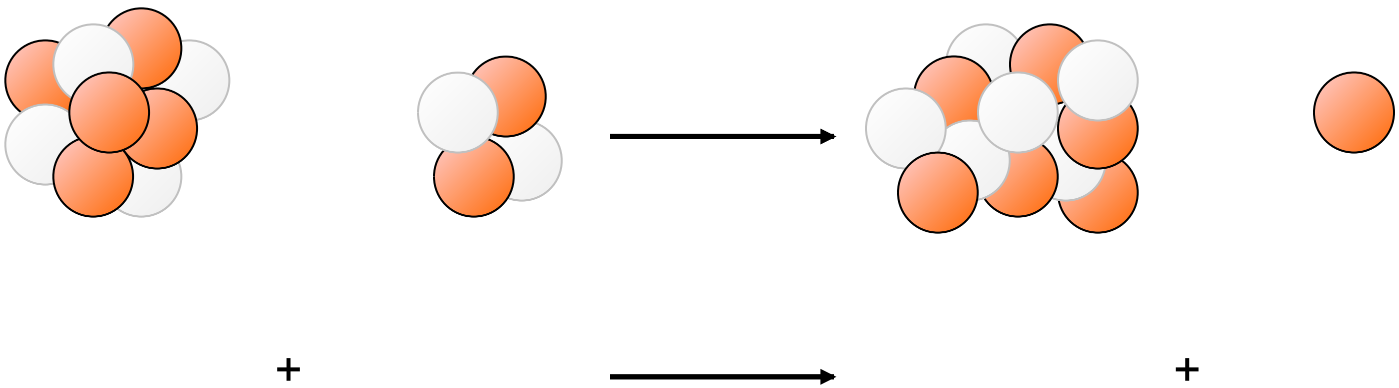
Is this equation balanced?

You must see if the mass and charge are the same on both sides.

Mass		Charge	
53 protons	54 protons	+53, protons	+54, protons
78 neutrons	77 neutrons		-1 charge from β^-
131 total mass	131 total mass	+53 total charge	+53 total charge

Yes – it's balanced

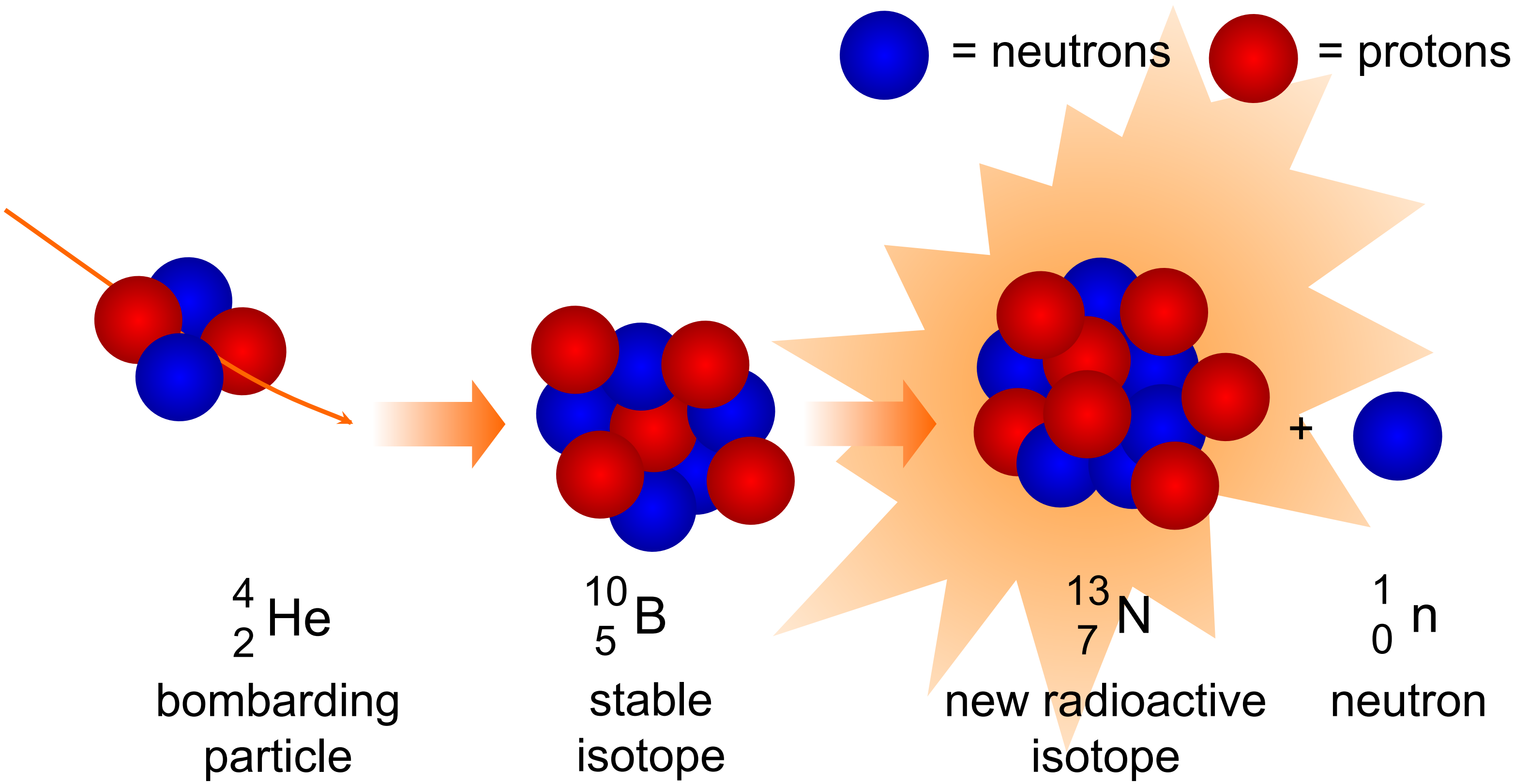
Discovery of the Neutron



James Chadwick bombarded beryllium-9 with alpha particles, carbon-12 atoms were formed, and neutrons were emitted.

Dorin, Demmin, Gabel, Chemistry The Study of Matter 3rd Edition, page 764

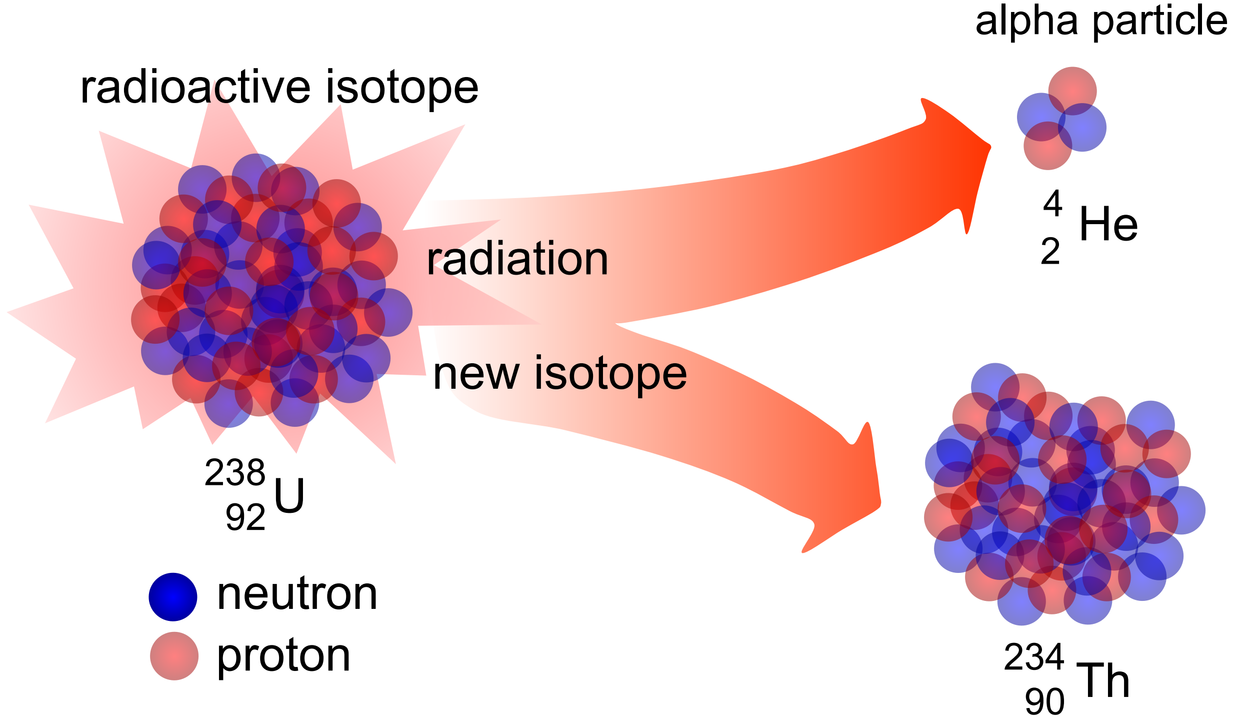
New Radioactive Isotope



$$^{4}_{2}He + ^{10}_{5}B \rightarrow ^{13}_{7}N + ^{1}_{0}n$$

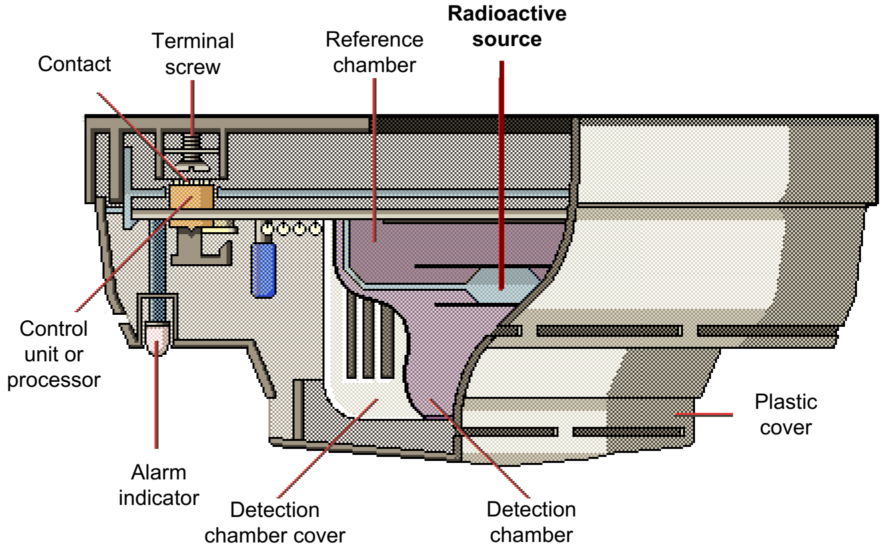
Timberlake, Chemistry 7th Edition, page 92

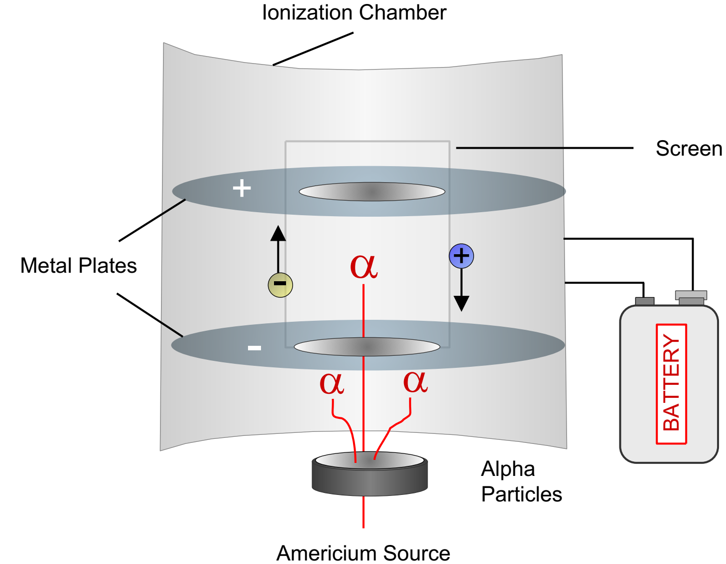
Alpha Decay



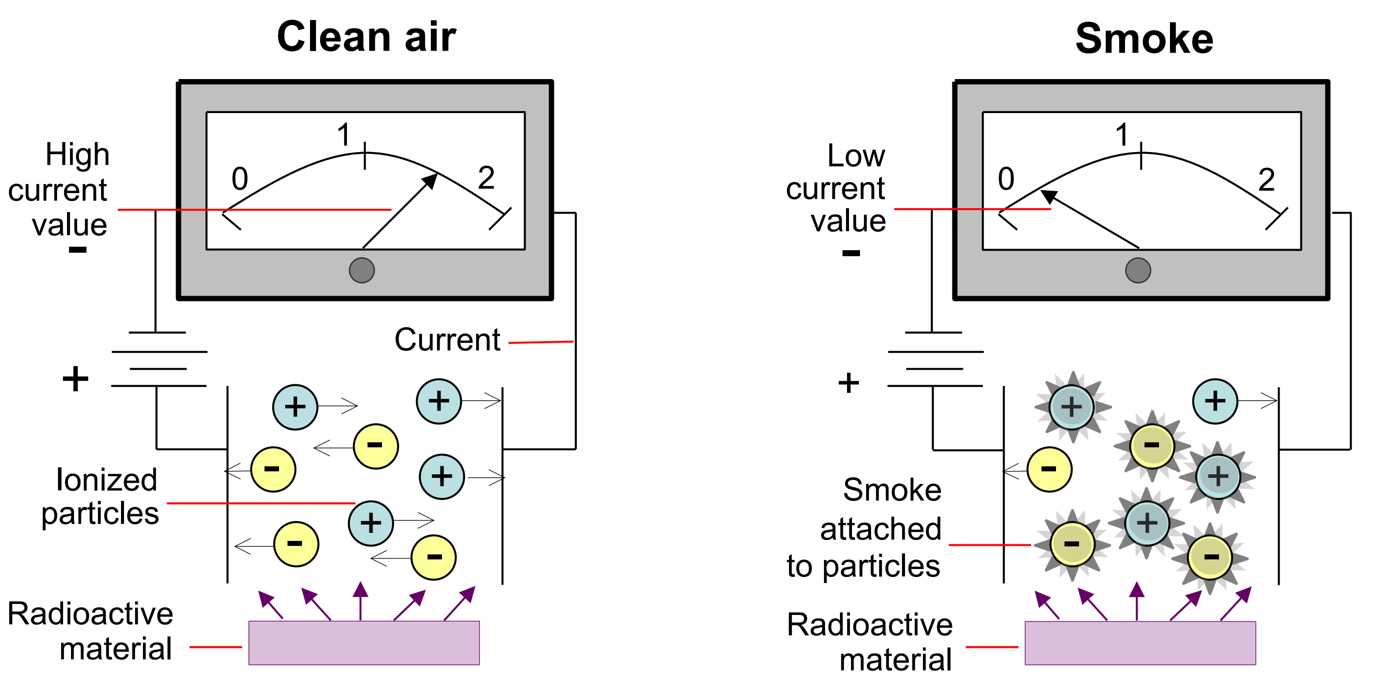
$$^{238}_{92}U \longrightarrow {}^{4}_{2}He^{2+} + {}^{234}_{90}Th$$

Timberlake, Chemistry 7th Edition, page 87

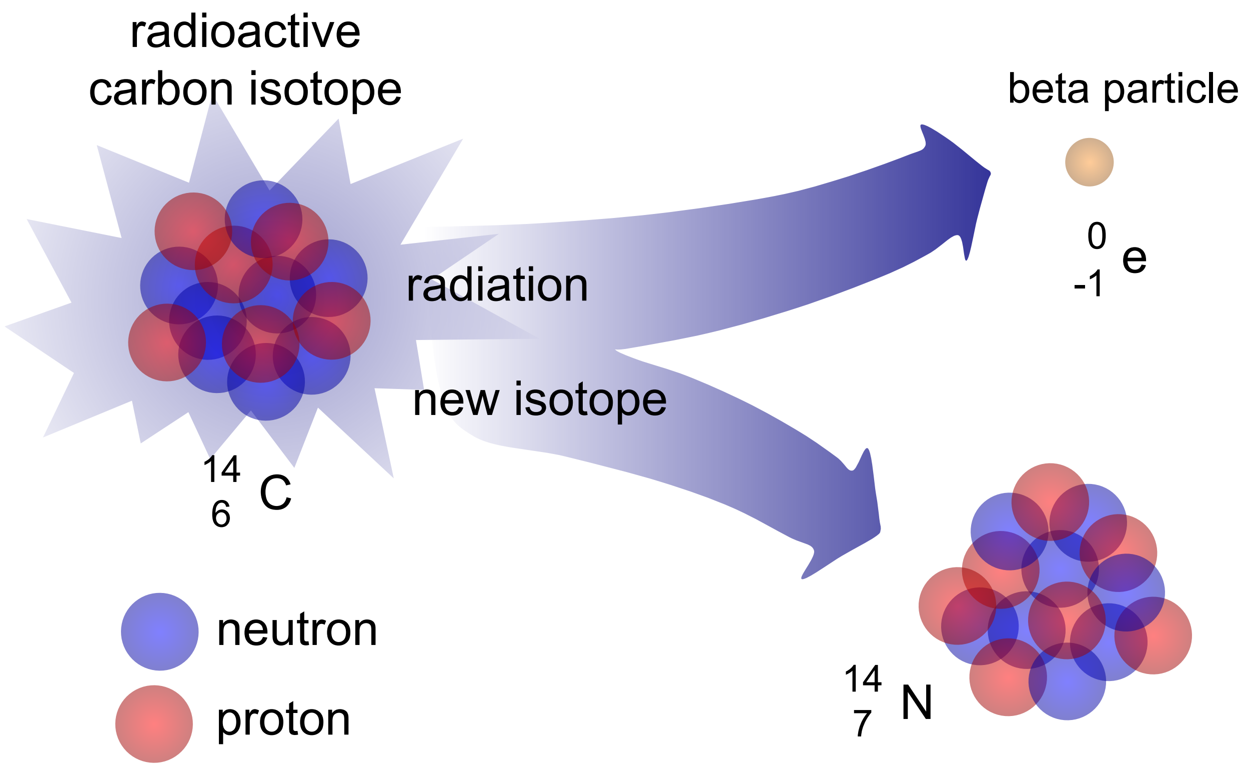




Measuring Circuit in Detection Chamber



Beta Decay



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

Timberlake, Chemistry 7th Edition, page 90

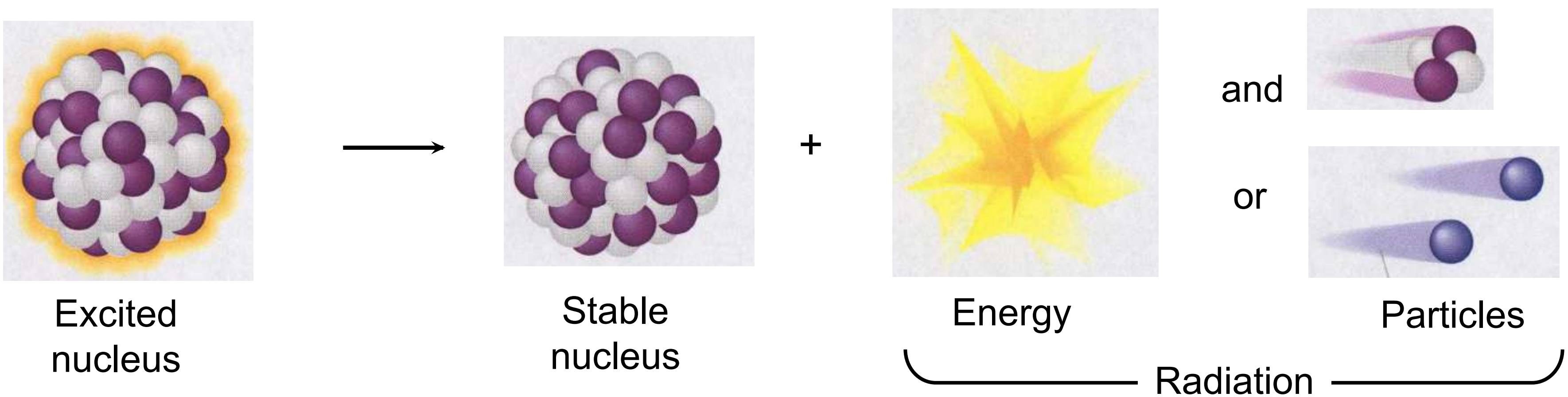
Bombardment of aluminum-27 by alpha particles produces phosphorous-30 and one other particle. Write the nuclear equation and identify the other particle.

$$^{27}_{13}\mathrm{Al} + \,^{4}_{2}\mathrm{He} \longrightarrow \,^{30}_{15}\mathrm{P} + \,^{1}_{0}n$$

Plutonium-239 can be produced by bombarding uranium-238 with alpha particles. How many neutrons will be produced as a by product of each reaction. Write the nuclear equation for this reaction.

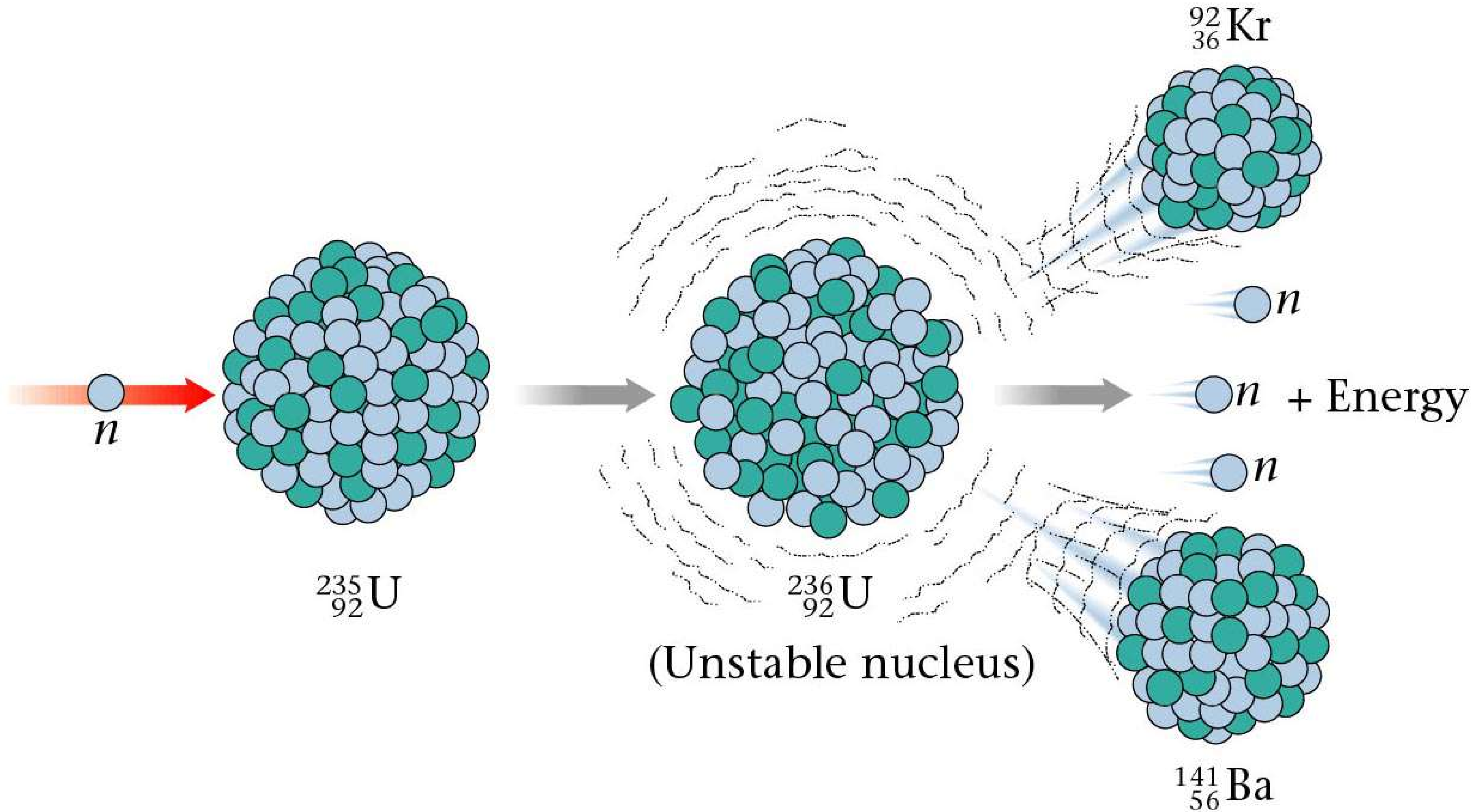
$$^{238}_{92}\mathrm{U} + \,^{4}_{2}\mathrm{He} \longrightarrow \,^{239}_{94}\mathrm{Pu} + 4\,^{1}_{0}n$$

Unstable Isotopes



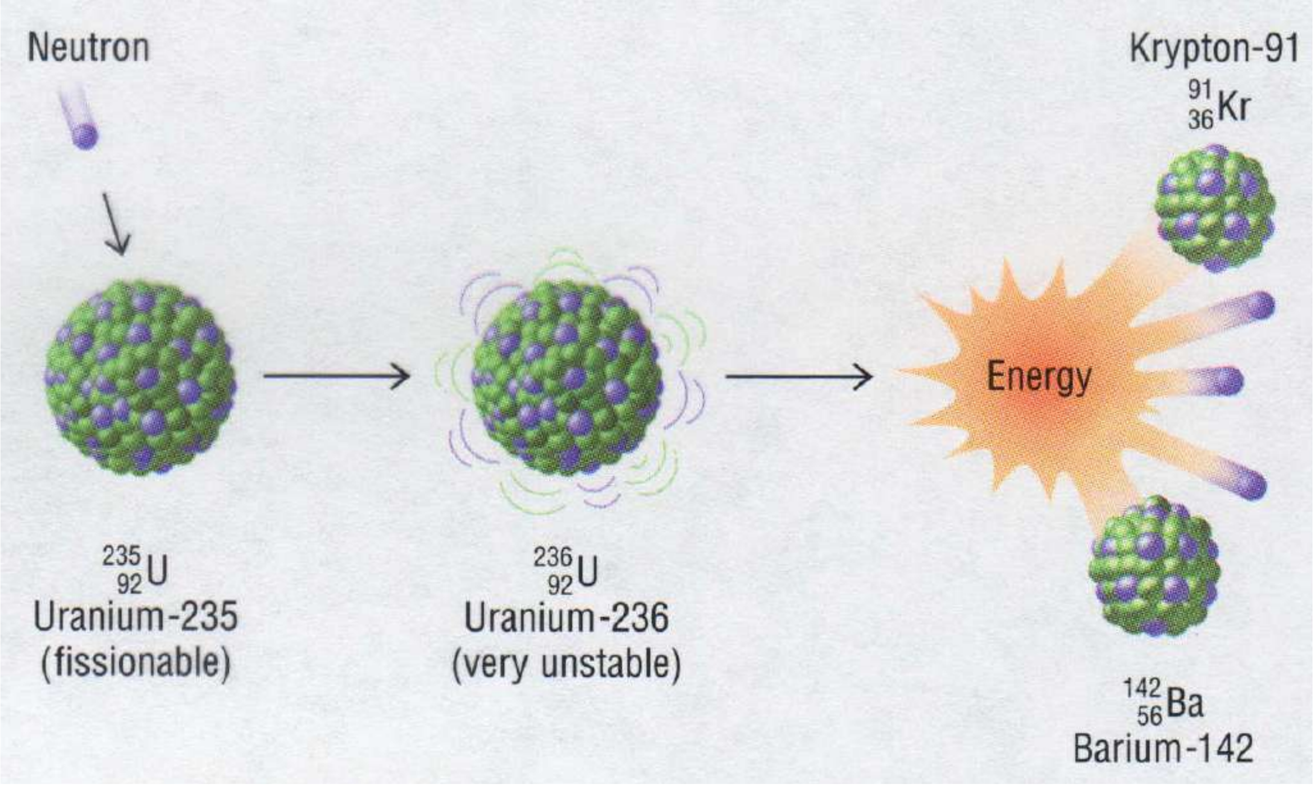
Kelter, Carr, Scott, Chemistry A World of Choices 1999, page 439

Unstable Nucleus

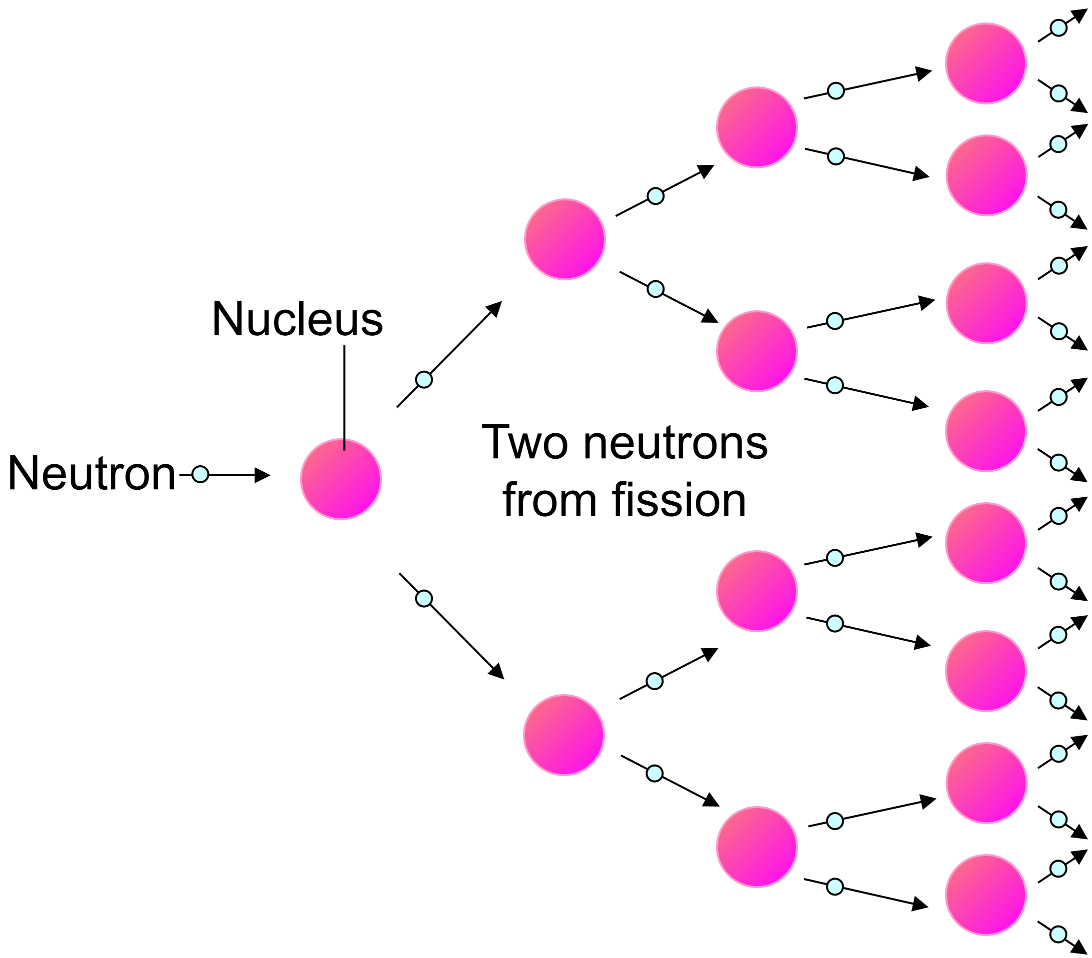


Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 620

Fissionable U-235

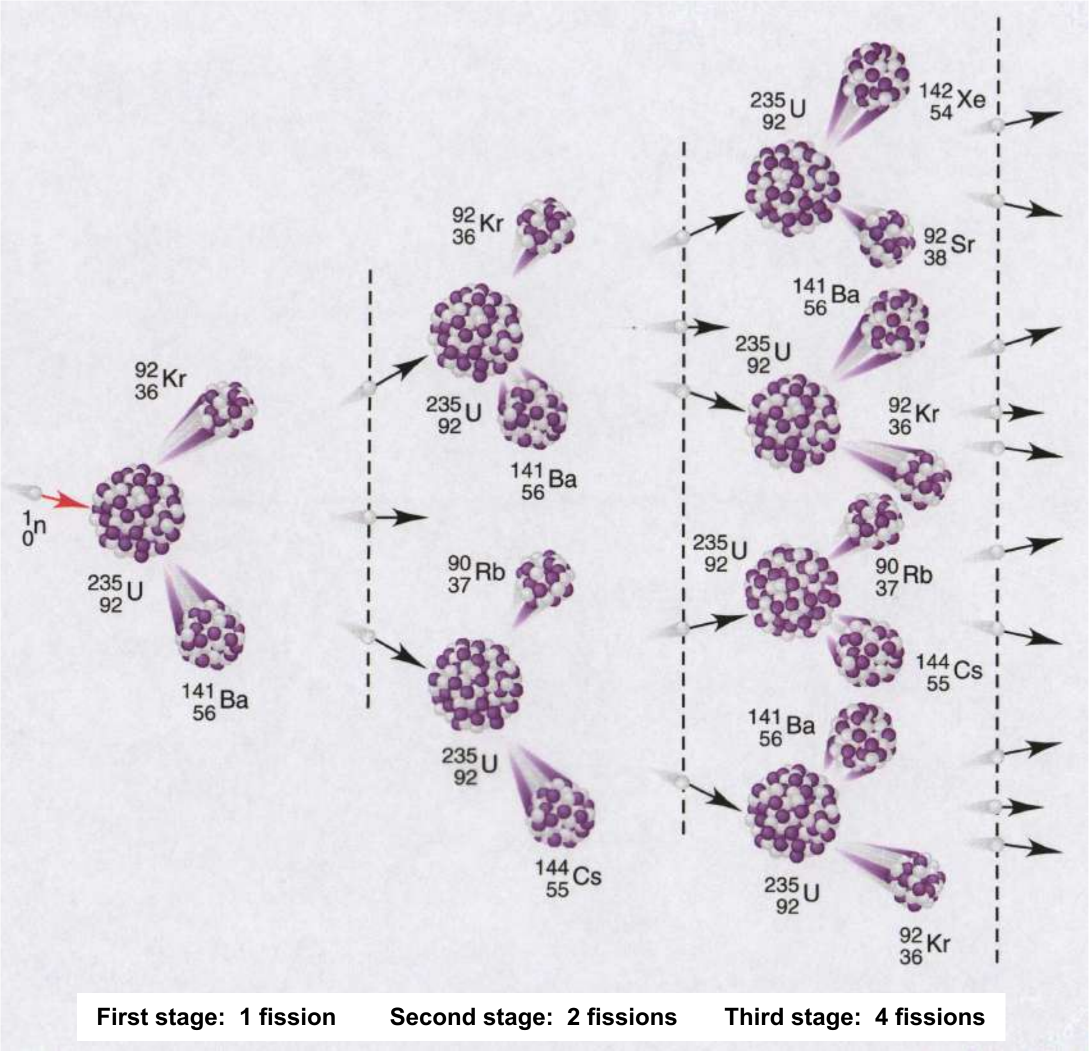


Fission Process



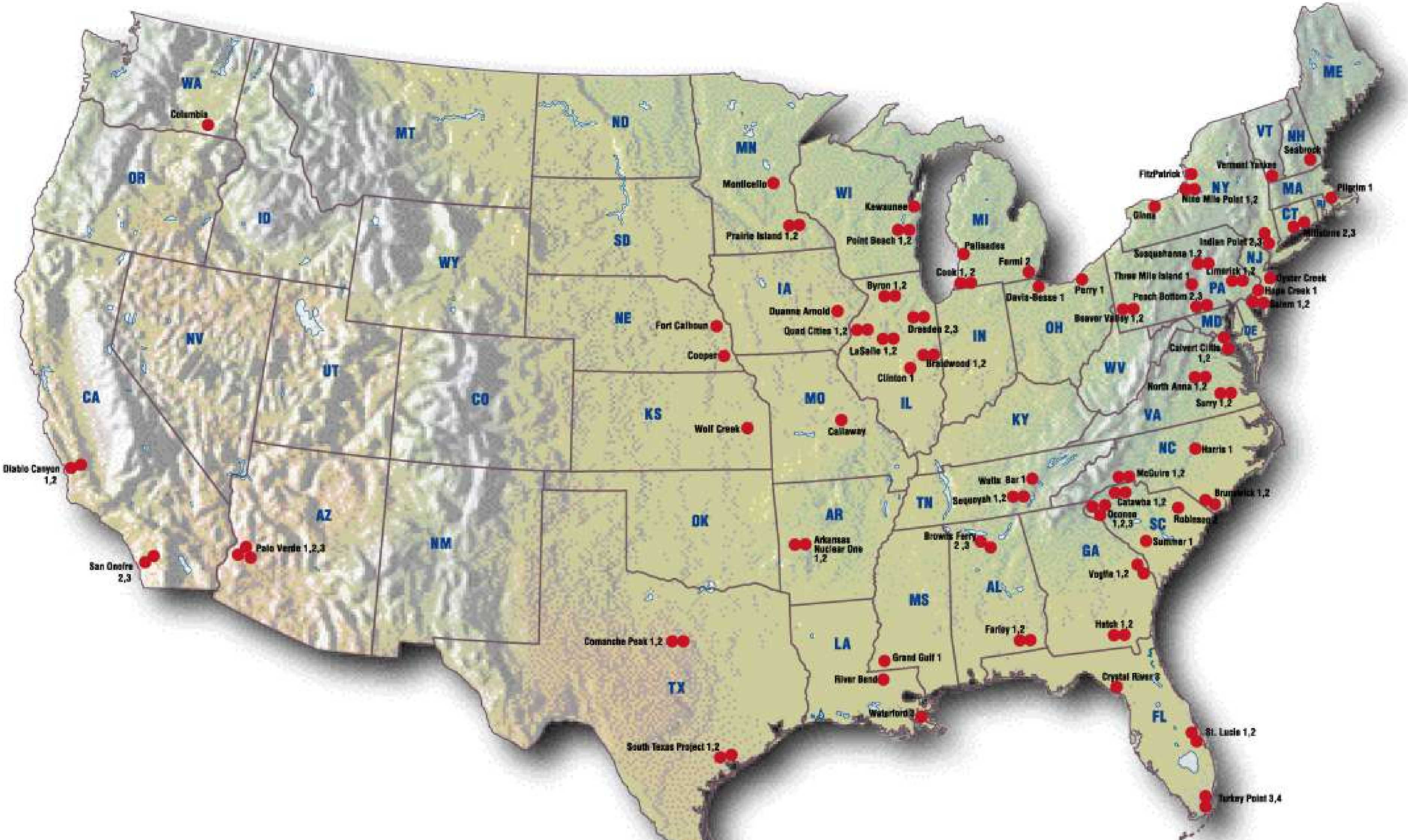
Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 620

Stages of Fission



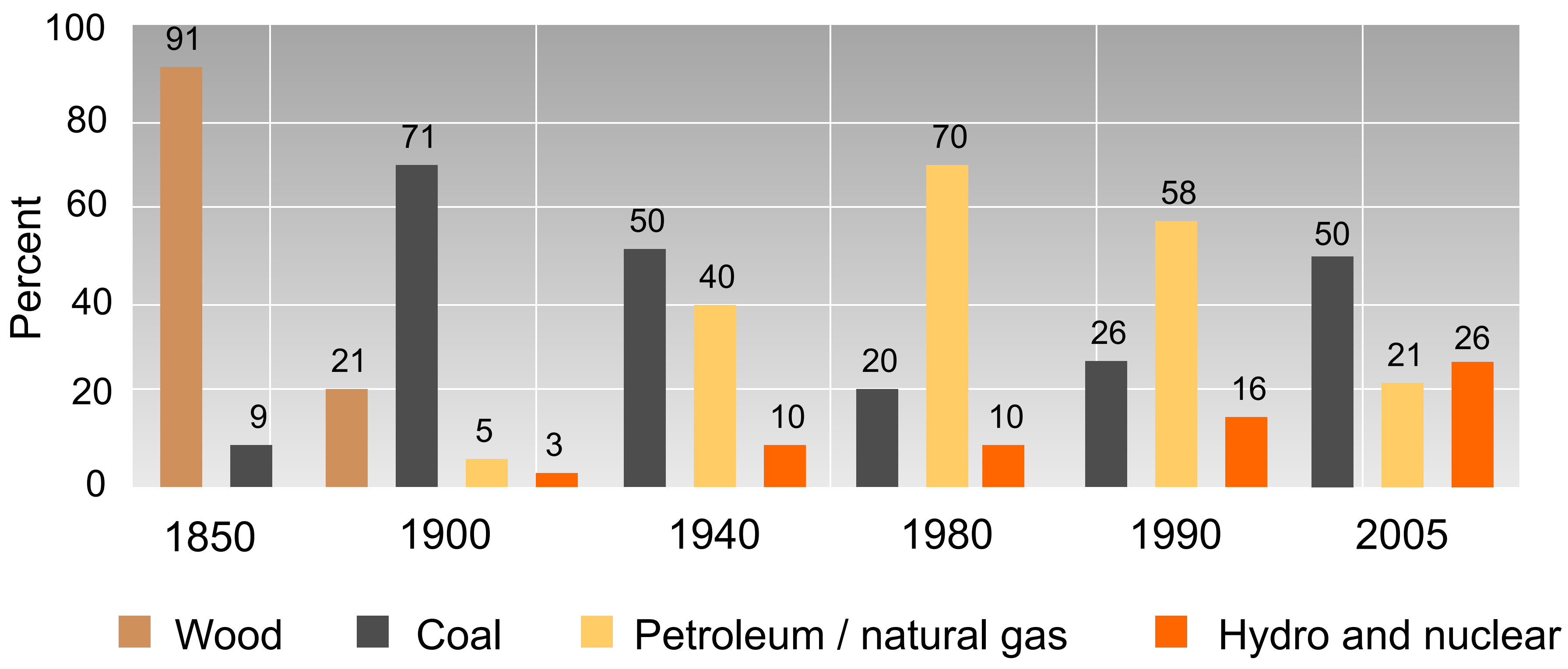
Kelter, Carr, Scott, <u>Chemistry A World of Choices</u> 1999, page 454

Nuclear Power Plants



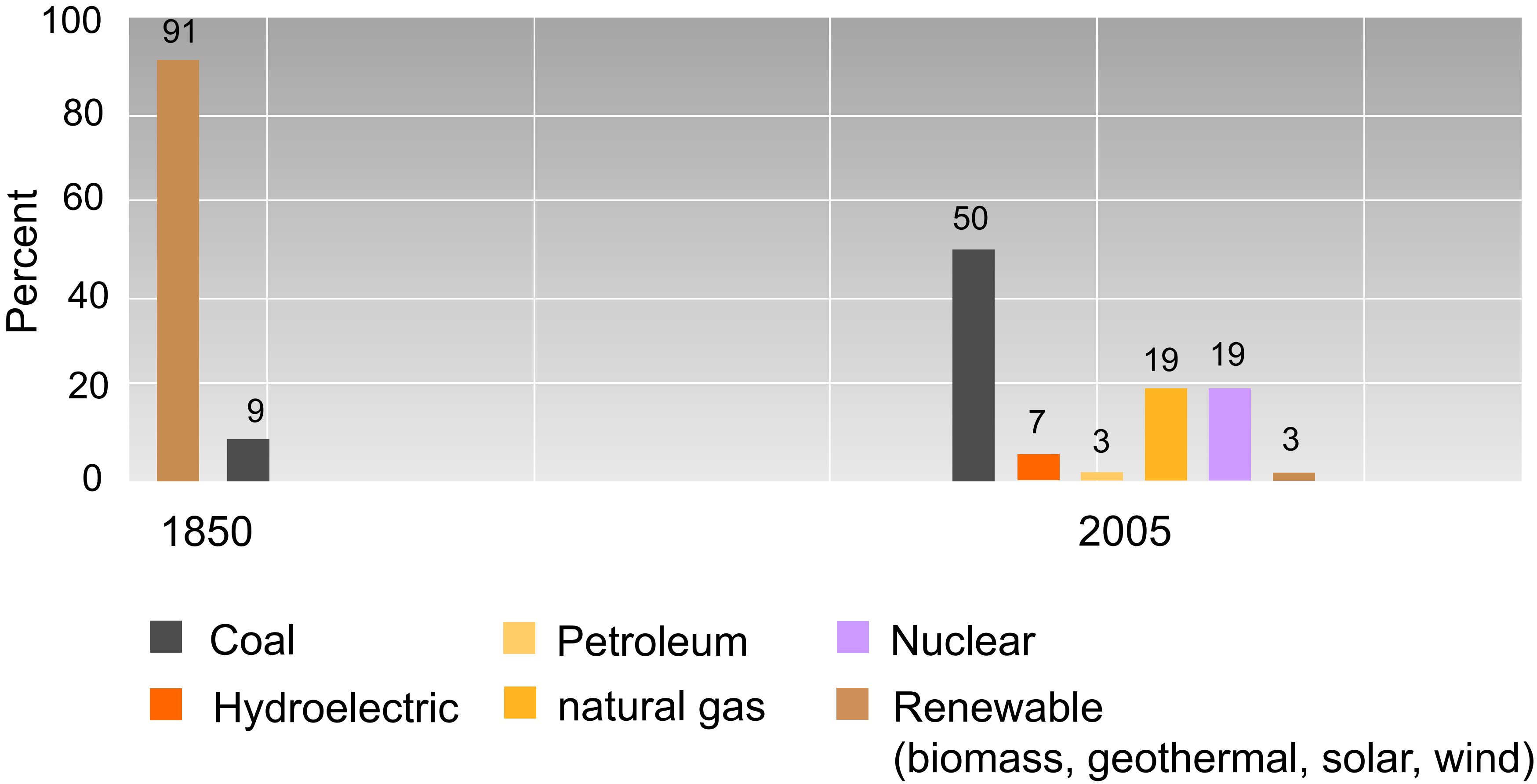
map: Nuclear Energy Institute

Energy Sources in the United States



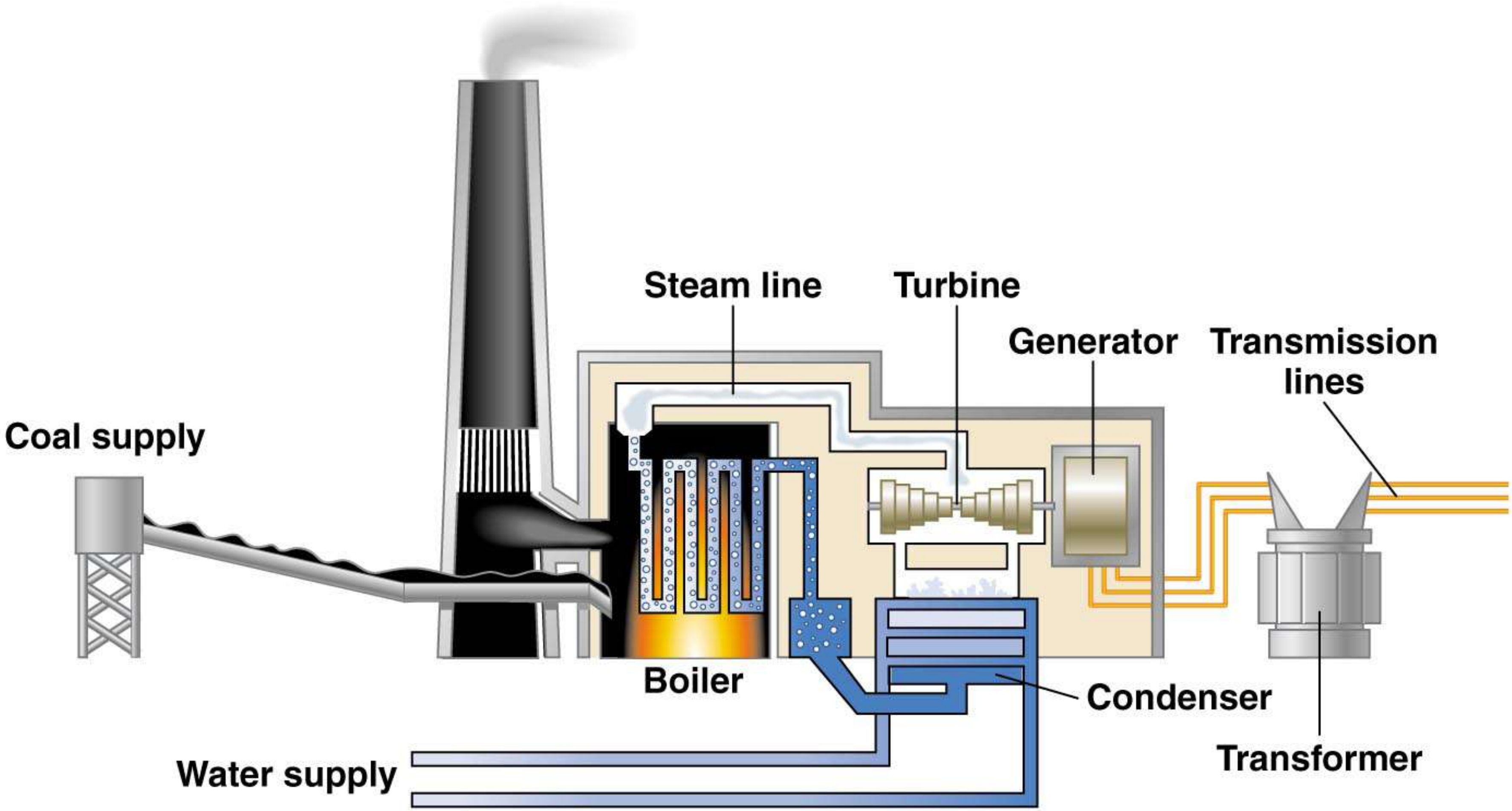
Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 307

Energy Sources in the United States

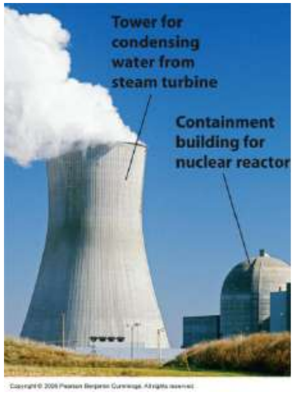


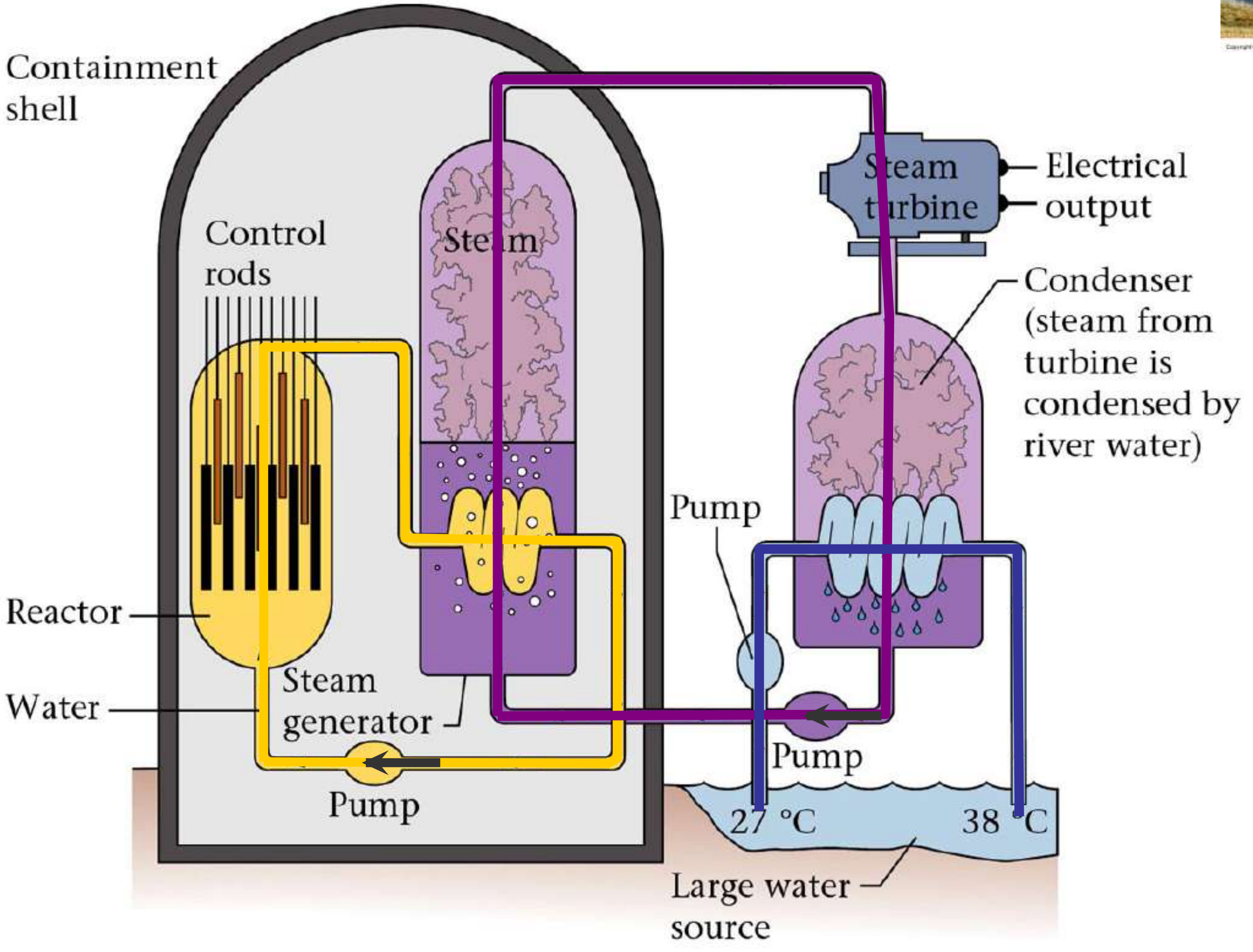
Source: *US Energy Information Administration* (2005 Electricity Generation)

Coal Burning Power Plant



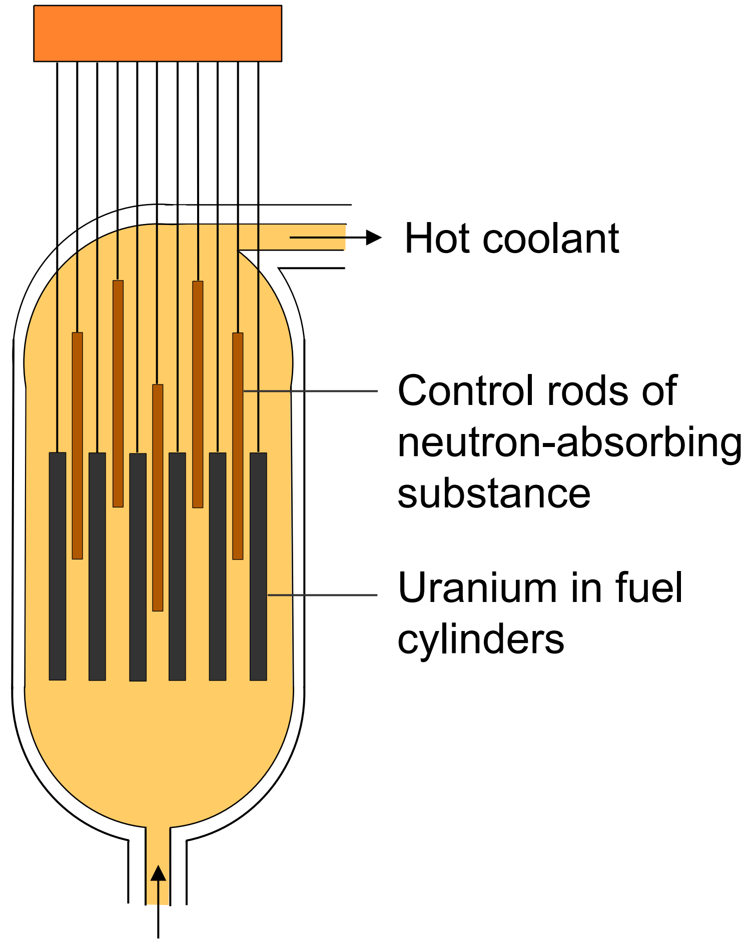
Nuclear Power Plant





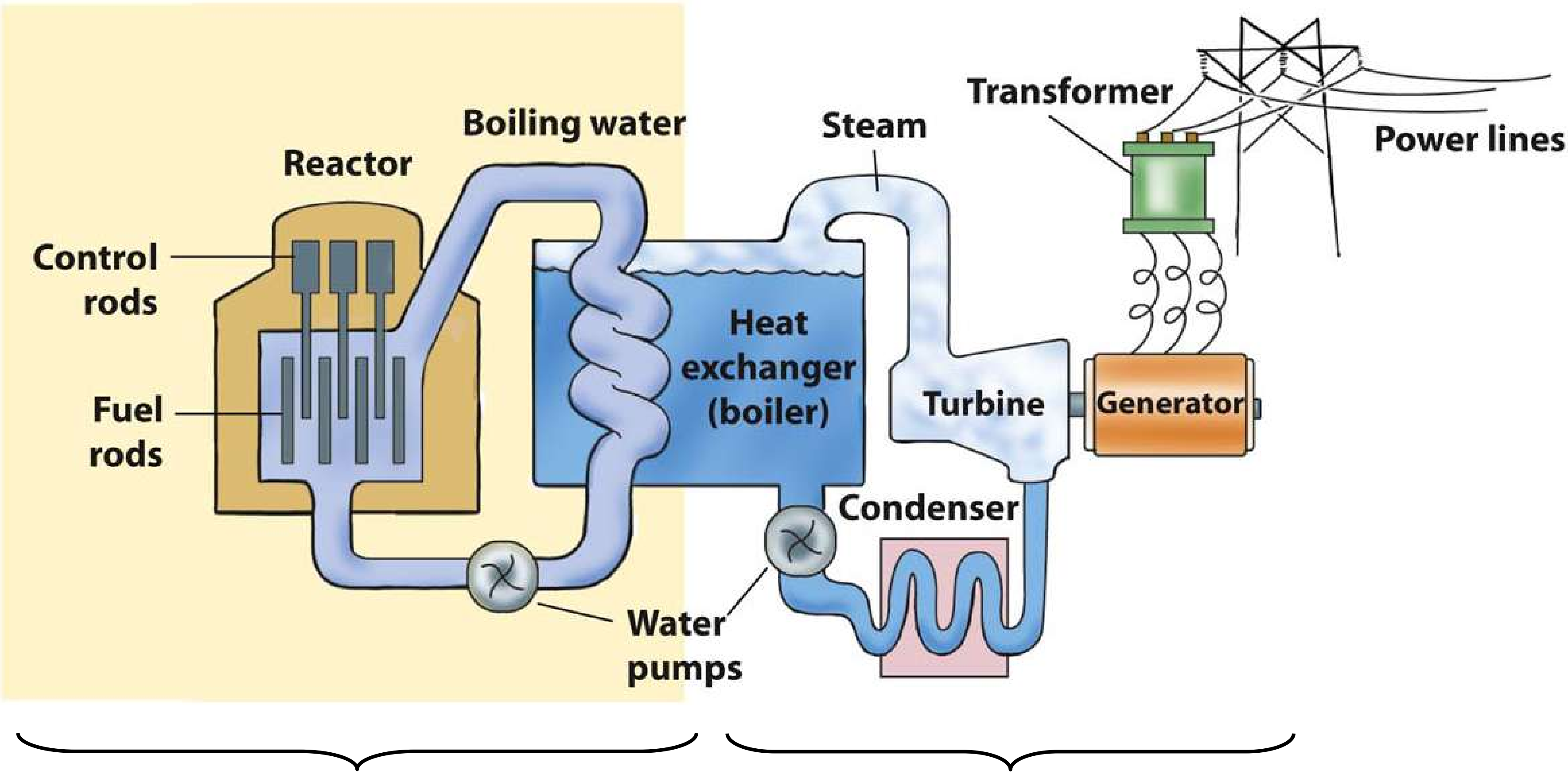
Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 621

Reactor Core



Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 622

Nuclear Power Plant

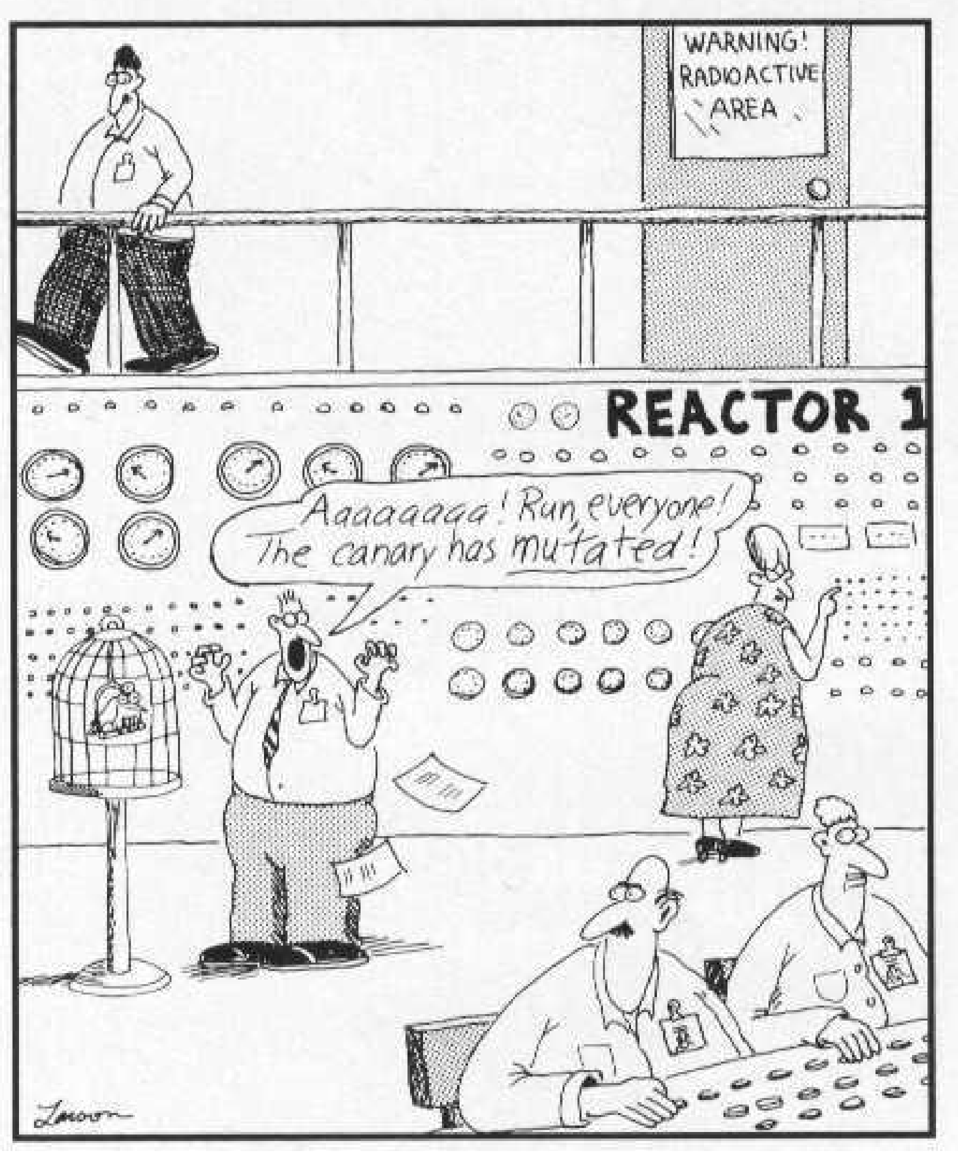


Production of heat

Production of electricity

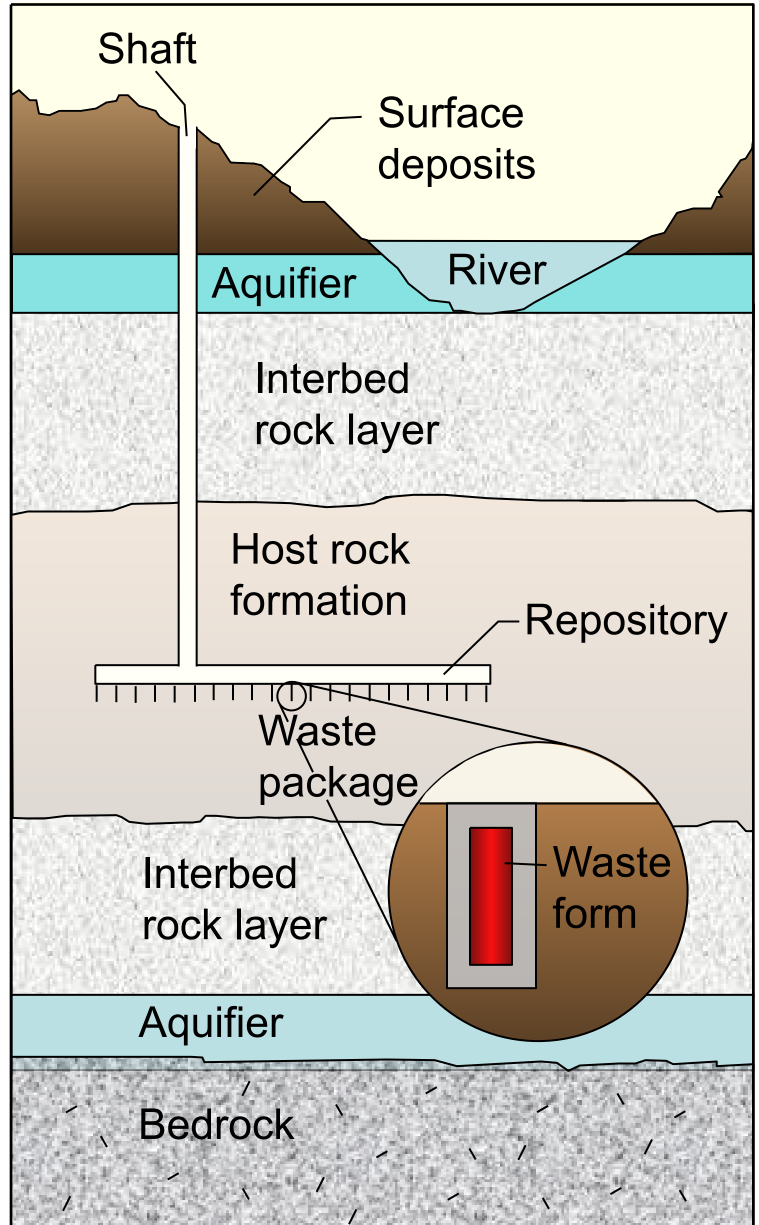
Chant of the Radioactive Workers

We're not afraid of the alpha ray.
A sheet of paper will keep it away!
A beta ray needs much more care,
Place sheets of metal here and there.
And as for the powerful gamma ray
(Pay careful heed to what we say)
Unless you wish to spend weeks in bed
Take cover behind thick slabs of lead!
Fast neutrons pass through everything.
Wax slabs remove their nasty sting.
These slow them down, and even a moron
Knows they can be absorbed by boron.
Remember, remember all that we've said,
Because it's no use remembering when you're dead.



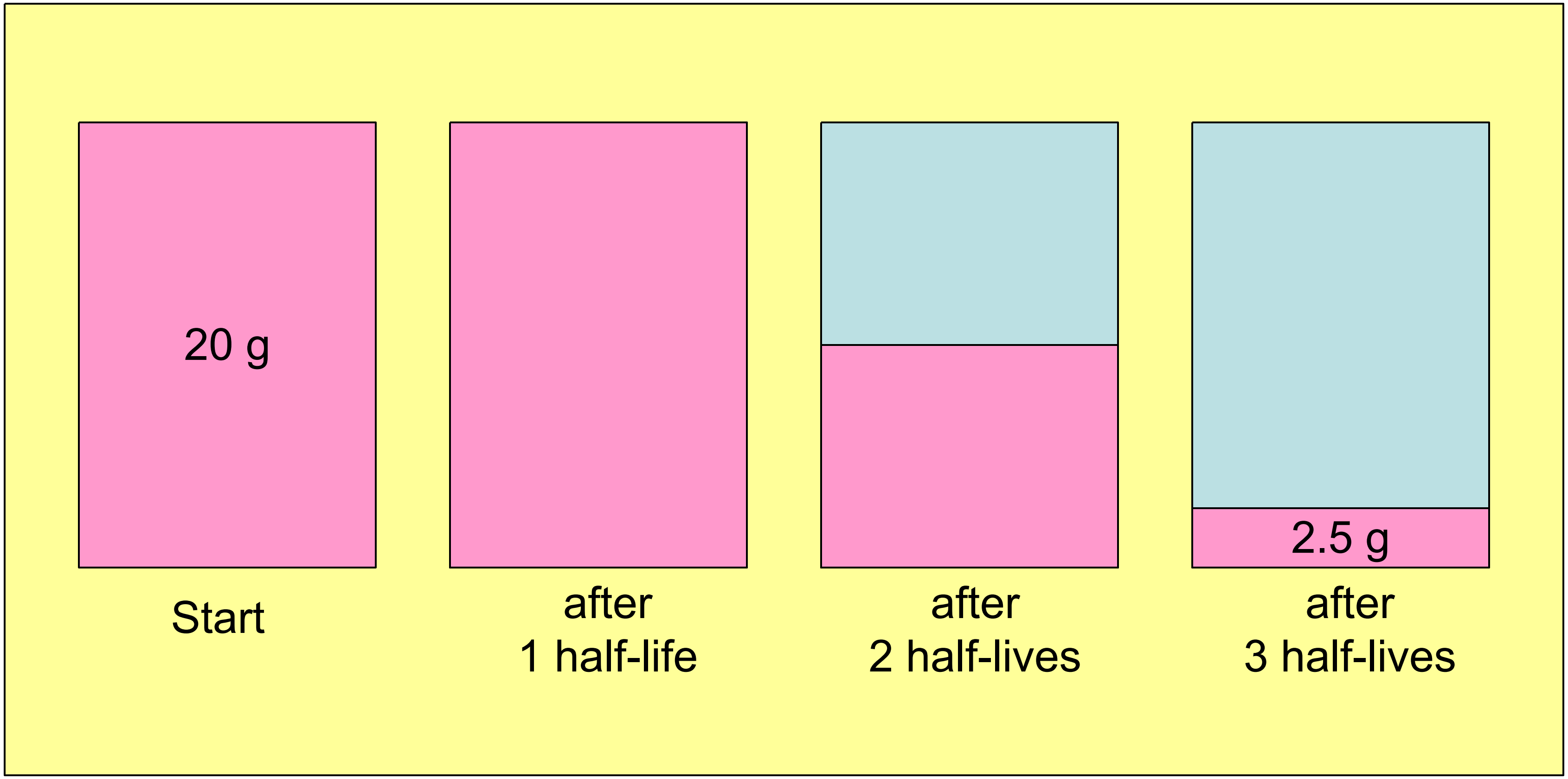
Inside a nuclear power plant.

Nuclear Waste Disposal



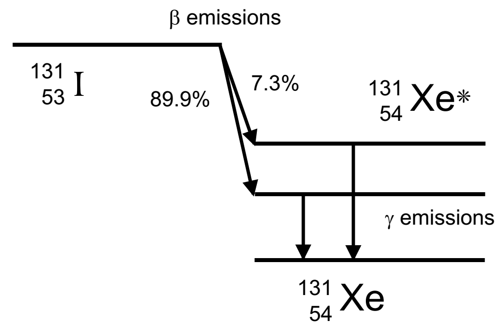
Zumdahl, Zumdahl, DeCoste, World of Chemistry 2002, page 626

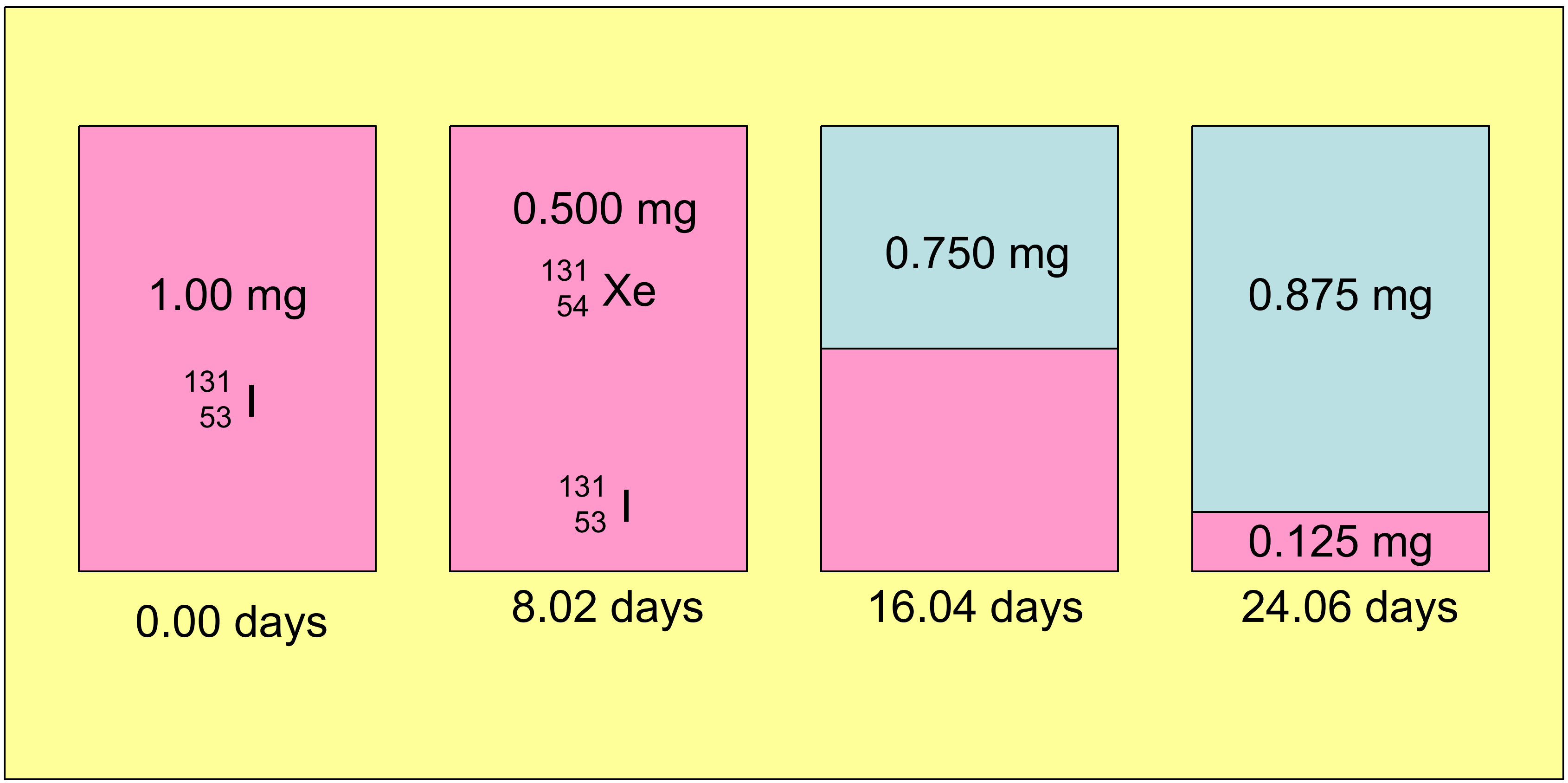
Half-Life



Dorin, Demmin, Gabel, Chemistry The Study of Matter 3rd Edition, page 757

Half-Life

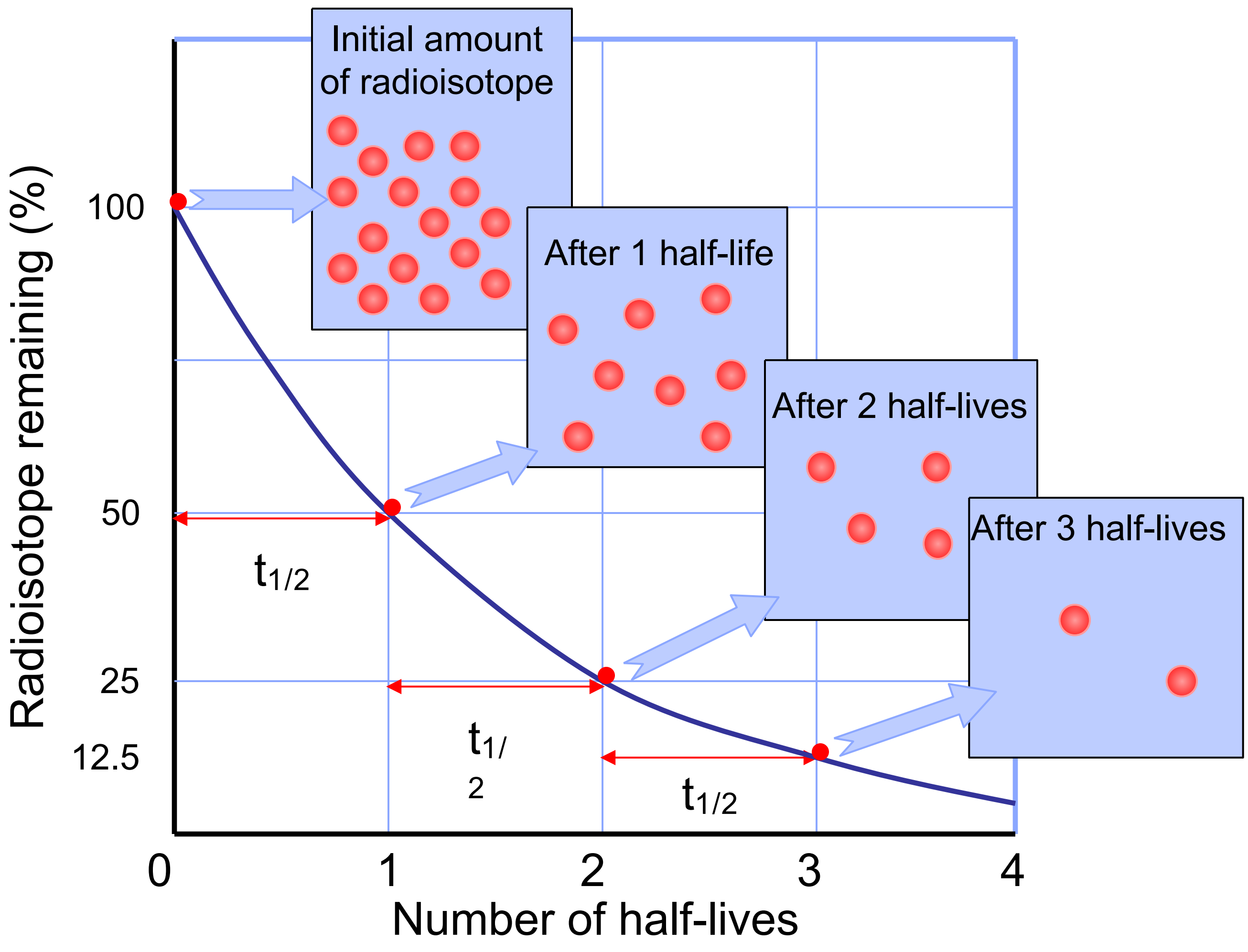




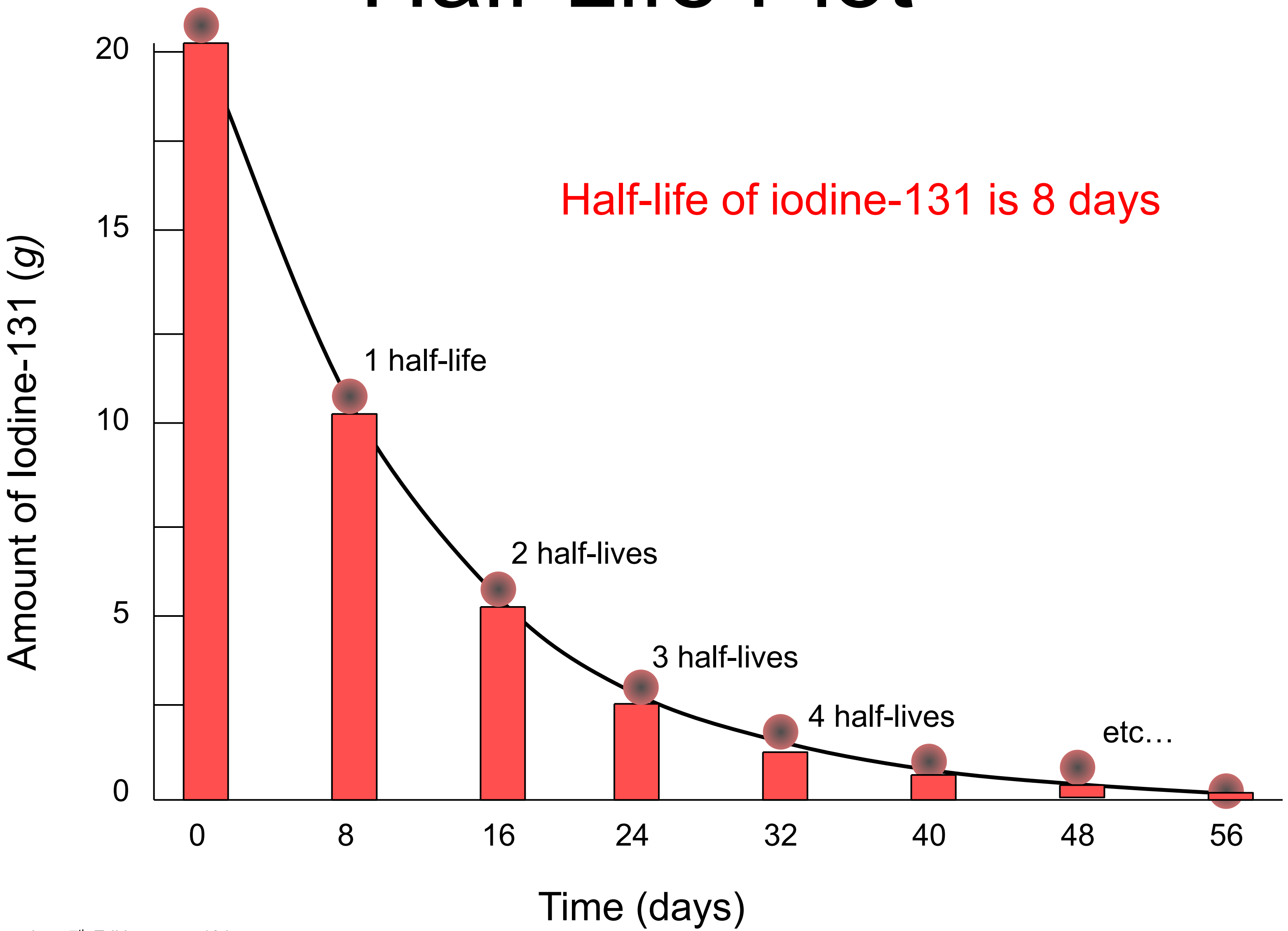
$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\beta^{-} + \gamma$$

Dorin, Demmin, Gabel, Chemistry The Study of Matter 3rd Edition, page 757

Half-life of Radiation



Half-Life Plot

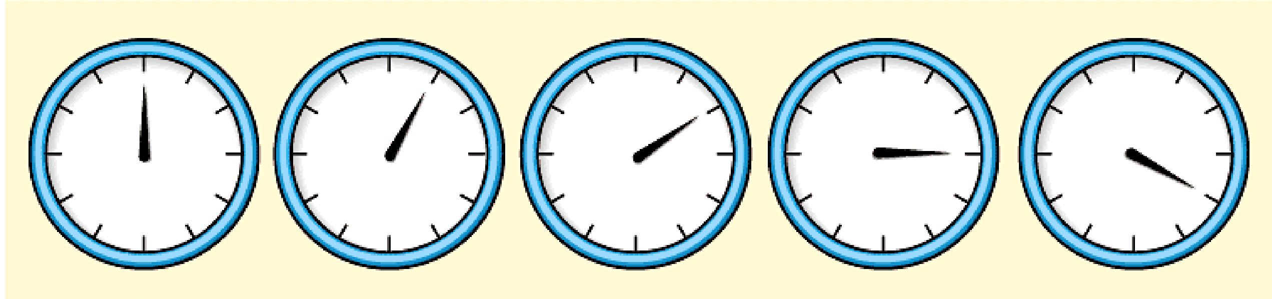


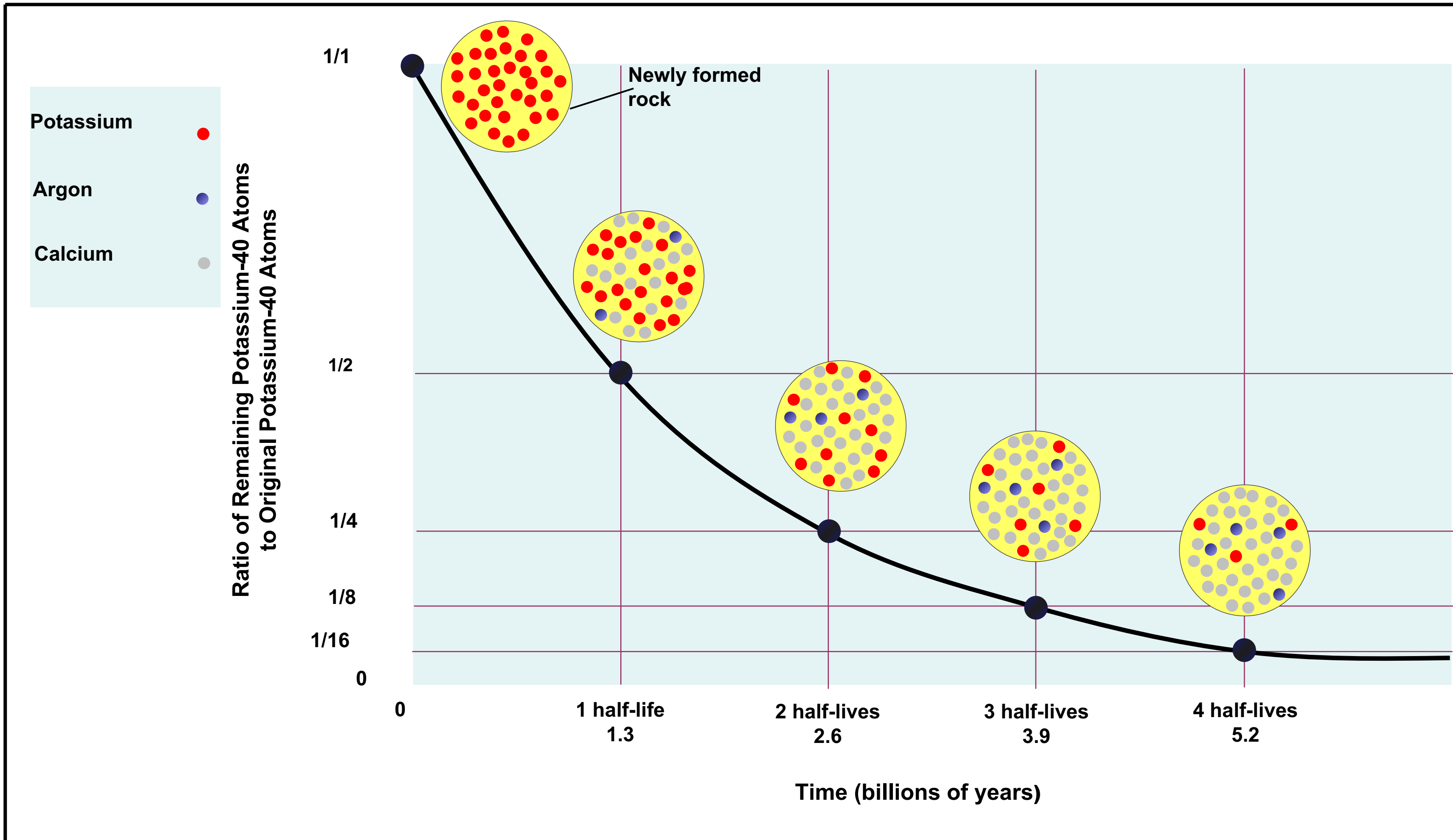
Timberlake, Chemistry 7th Edition, page 104

Half-Life of Isotopes

Half-Life and Radiation of Some Naturally Occurring Radioisotopes		
Isotope	**Half-Live**	**Radiation emitted**
Carbon-14	5.73×10^3 years	β
Potassium-40	1.25×10^9 years	β, γ
Radon-222	3.8 days	α
Radium-226	1.6×10^3 years	α, γ
Thorium-230	7.54×10^4 years	α, γ
Thorium-234	24.1 days	β, γ
Uranium-235	7.0×10^8 years	α, γ
Uranium-238	4.46×10^9 years	α

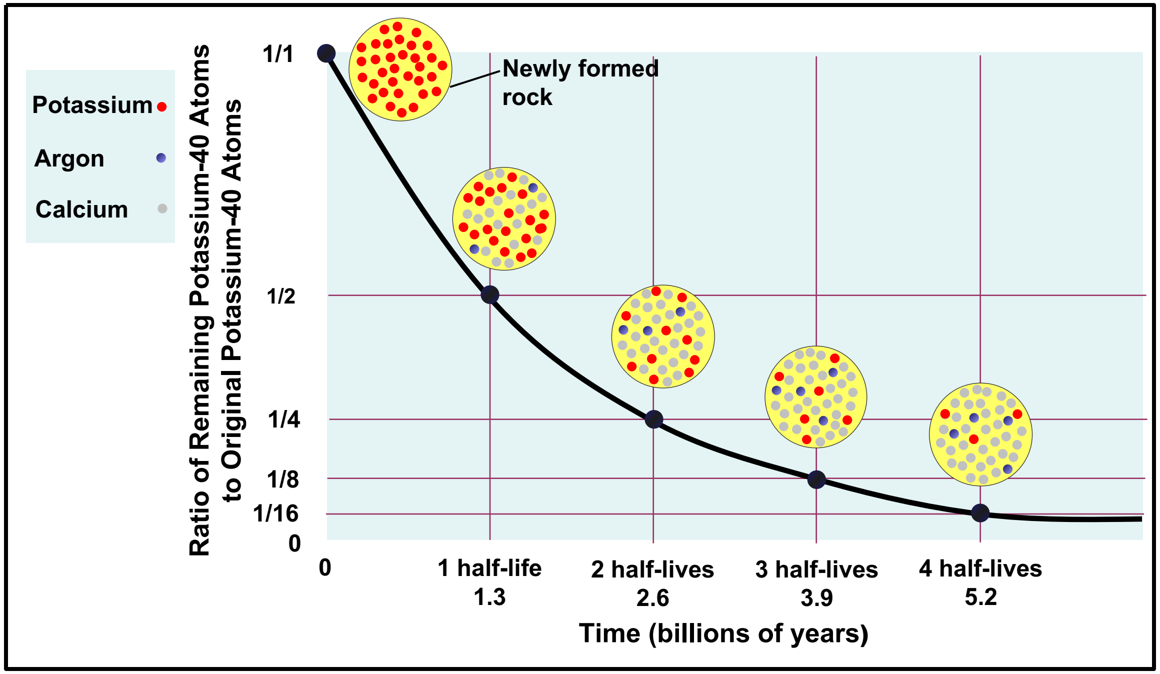
Half-life ($t_{1/2}$)





Half-life ($t_{1/2}$)

- Time required for half the atoms of a radioactive nuclide to decay.
- Shorter half-life = less stable.



How Much Remains?

After **one** half-life, $\frac{1}{2}$ of the original atoms remain.

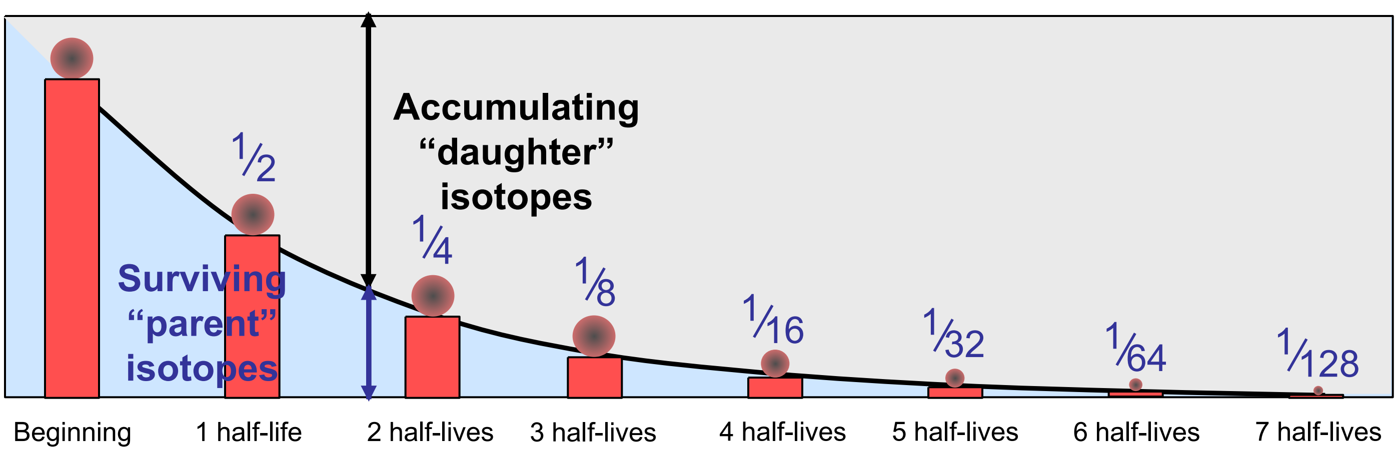
After **two** half-lives, ½ x ½ = $1/(2^2)$ = $\frac{1}{4}$ of the original atoms remain.

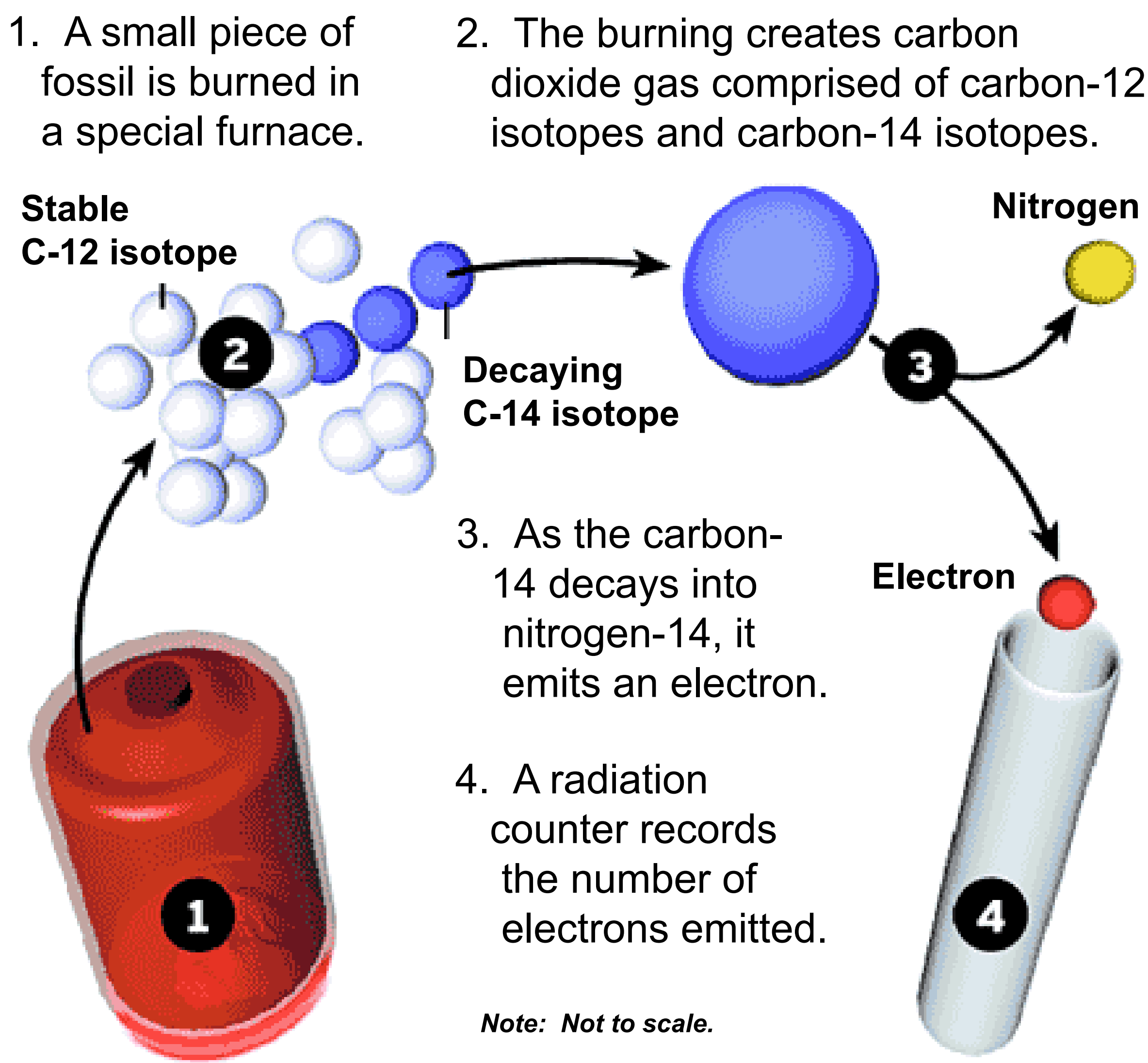
After **three** half-life, ½ x ½ x ½ = $1/(2^3)$ = $\frac{1}{8}$ of the original atoms remain.

After **four** half-life, ½ x ½ x ½ x ½ = $1/(2^4)$ = $\frac{1}{16}$ of the original atoms remain.

After **five** half-life, ½ x ½ x ½ x ½ x ½ = $1/(2^5)$ = $\frac{1}{32}$ of the original atoms remain.

After **six** half-life, ½ x ½ x ½ x ½ x ½ x ½ = $1/(2^6)$ = $\frac{1}{64}$ of the original atoms remain.





SOURCE: Collaboration for NDT Education MATT PERRY / Union-Tribune

The iodine-131 nuclide has a half-life of 8 days. If you originally have a 625-g sample, after 2 months you will have approximately?

a. 40 g
b. 20 g
c. 10 g
☆ d. 5 g
e. less than 1 g

Data Table: Half-life Decay

~ Amount	Time	# Half-Life
625 g	0 d	0
312 g	8 d	1
156 g	16 d	2
78 g	24 d	3
39 g	32 d	4
20 g	40 d	5
10 g	48 d	6
5 g	56 d	7
2.5 g	64 d	8
1.25 g	72 d	9

$$N = N_o(^1/_2)^n$$

N = amount remaining
N_o = original amount
n = # of half-lives

Assume 30 days = 1 month

$$\frac{60 \text{ days}}{8 \text{ days}} = 7.5 \text{ half-lives}$$

$$N = (625 \text{ g})(^1/_2)^{7.5}$$

$$N = 3.45 \text{ g}$$

Given that the half-life of carbon-14 is 5730 years, consider a sample of fossilized wood that, when alive, would have contained 24 g of carbon-14. It now contains 1.5 g of carbon-14.

How old is the sample?

$$\ln \frac{N}{N_o} = -k\,t$$

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

$$5730 \text{ y} = \frac{0.693}{k}$$

$$k = 1.209 \times 10^{-4}$$

Data Table: Half-life Decay

Amount	Time	# Half-Life
24 g	0 y	0
12 g	5,730 y	1
6 g	11,460 y	2
3 g	17,190 y	3
1.5 g	22,920 y	4

$$\ln \frac{1.5 \text{ g}}{24 \text{ g}} = -(1.209 \times 10^{-4})\,t$$

$$t = 22{,}933 \text{ years}$$

Half-Life Practice Calculations

- The half-life of carbon-14 is 5730 years. If a sample originally contained 3.36 g of C-14, how much is present after 22,920 years?

  0.21 g C-14

- Gold-191 has a half-life of 12.4 hours. After one day and 13.2 hours, 10.6 g of gold-19 remains in a sample. How much gold-191 was originally present in the sample?

  84.8 g Au-191

- There are 3.29 g of iodine-126 remaining in a sample originally containing 26.3 g of iodine-126. The half-life of iodine-126 is 13 days. How old is the sample?

  39 days old

- A sample that originally contained 2.5 g of rubidium-87 now contains 1.25 g. The half-life of rubidium-87 is 6×10^{10} years. How old is the sample? Is this possible? Why or why not?

  6×10^{10} years

(60,000,000,000 billions years old)

What is the age of Earth???

Demo: Try to cut a string in half seven times (if it begins your arm's length).

The half-life of carbon-14 is 5730 years. If a sample originally contained 3.36 g of C-14, how much is present after 22,920 years?

$t_{1/2}$ = 5730 years

$$n = \frac{22{,}920 \text{ years}}{5{,}730 \text{ years}}$$

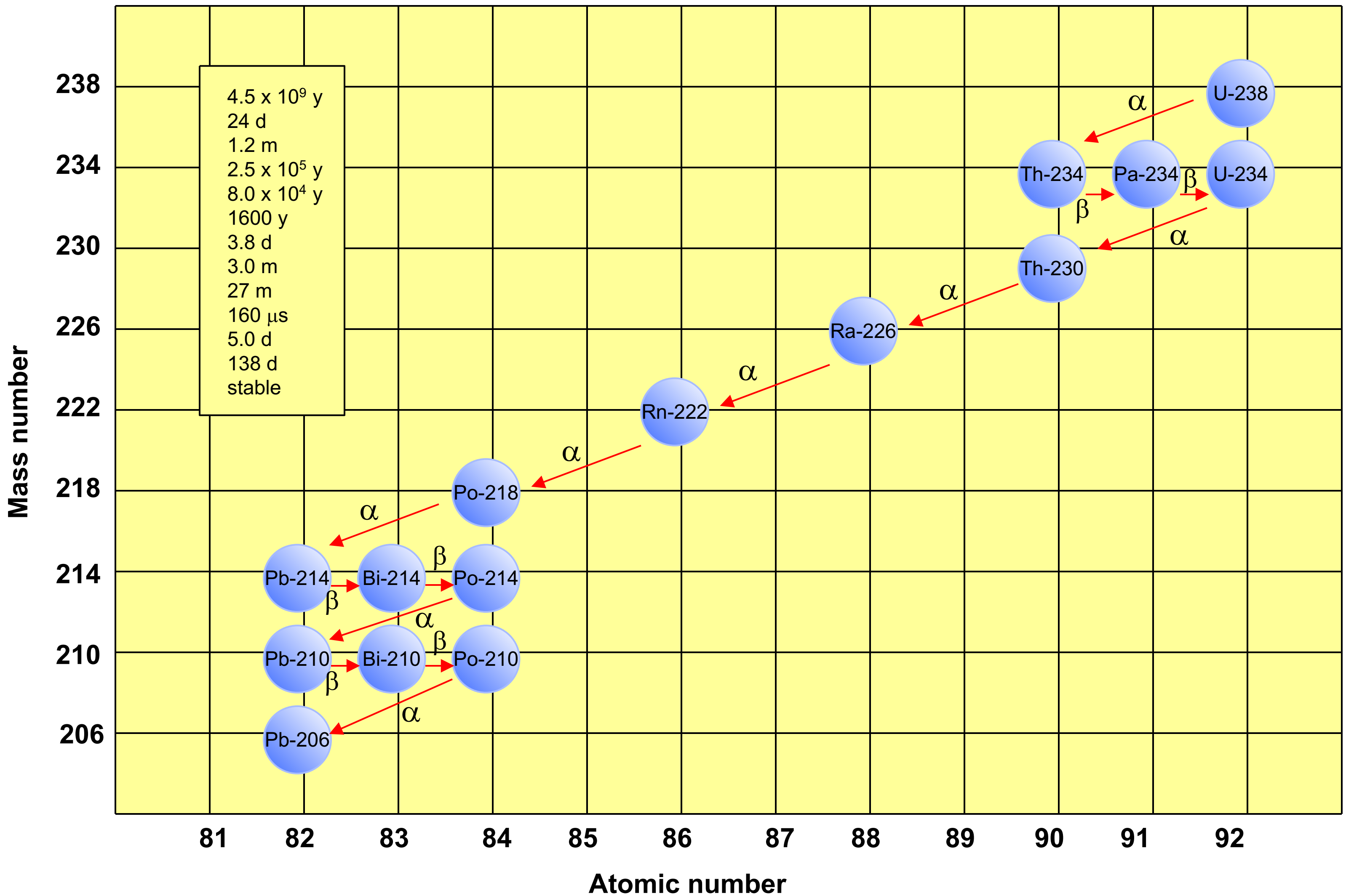
n = 4 half-lives

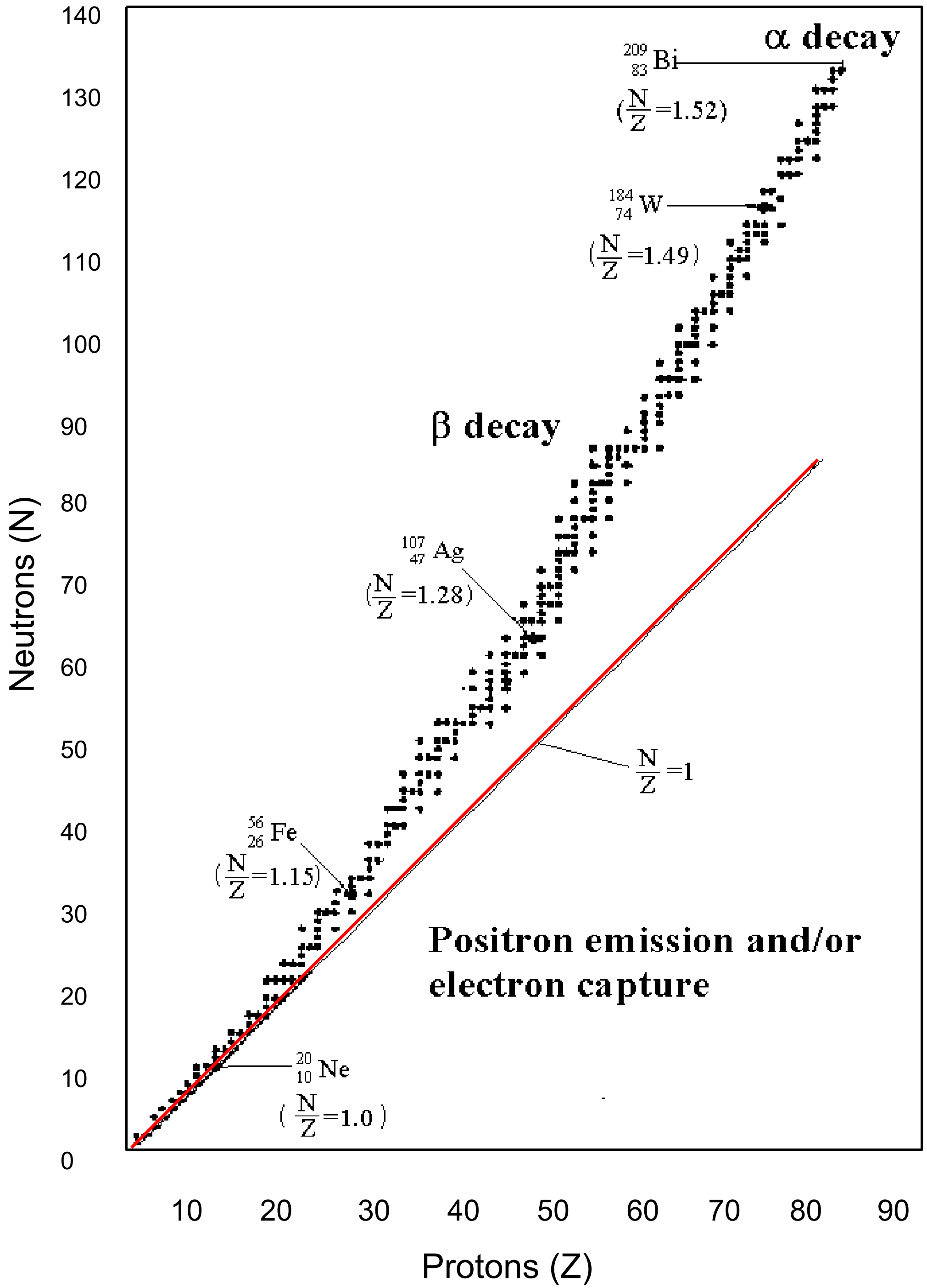
(# of half-lives)(half-life) = age of sample

(4 half-lives)(5730 years) = age of sample

22,920 years

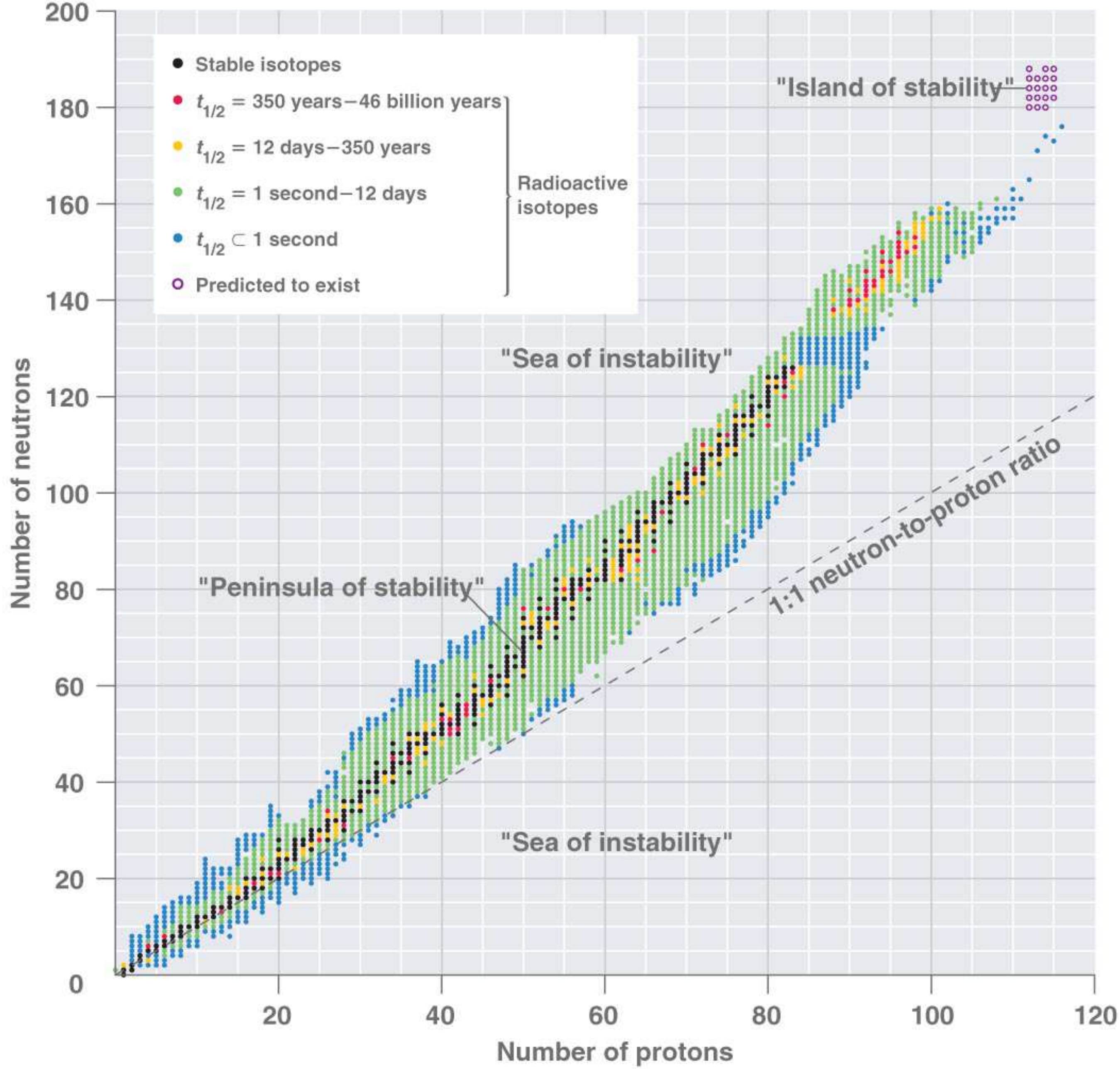
Uranium Radioactive Decay



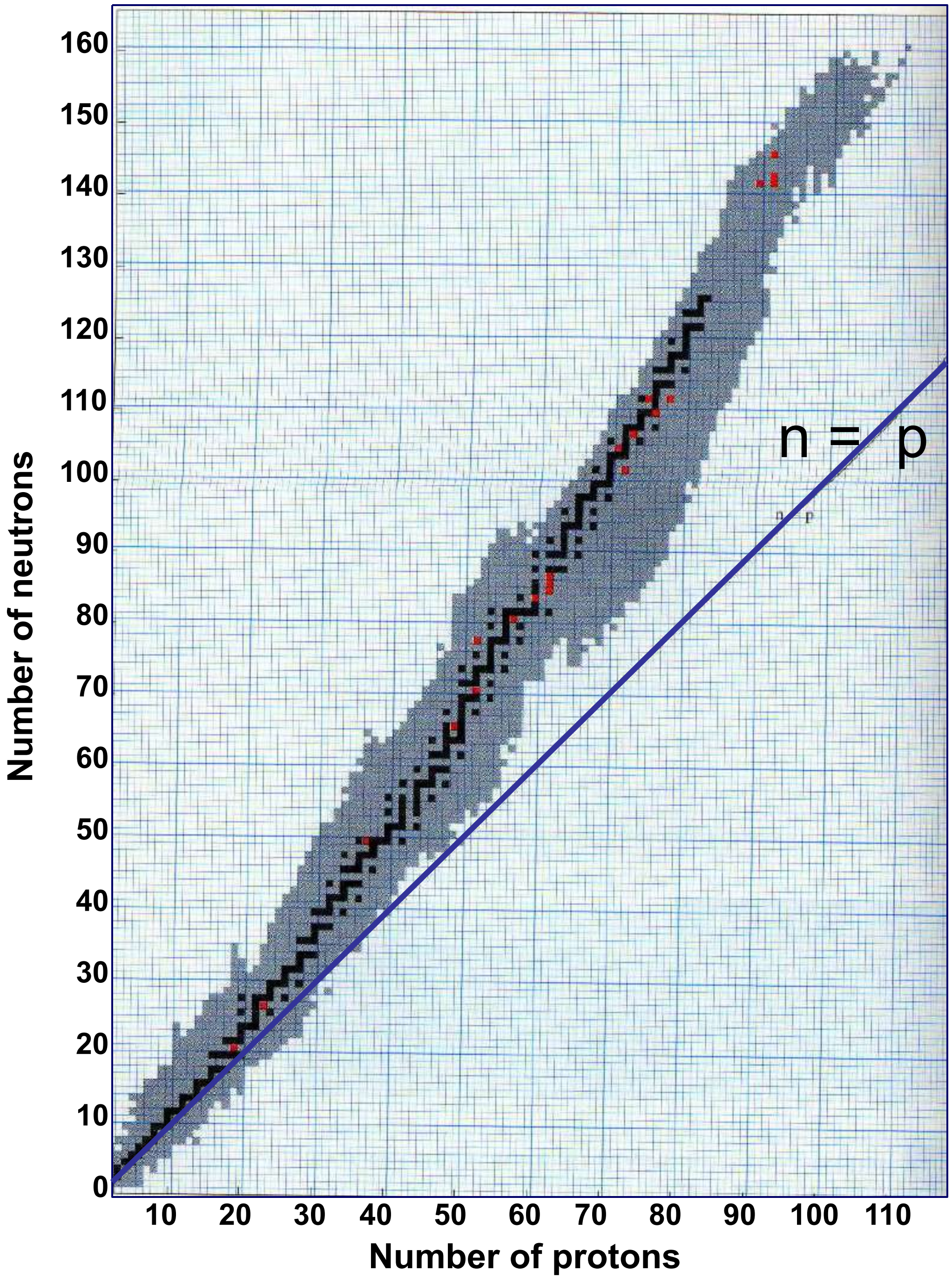


Nuclear Stability

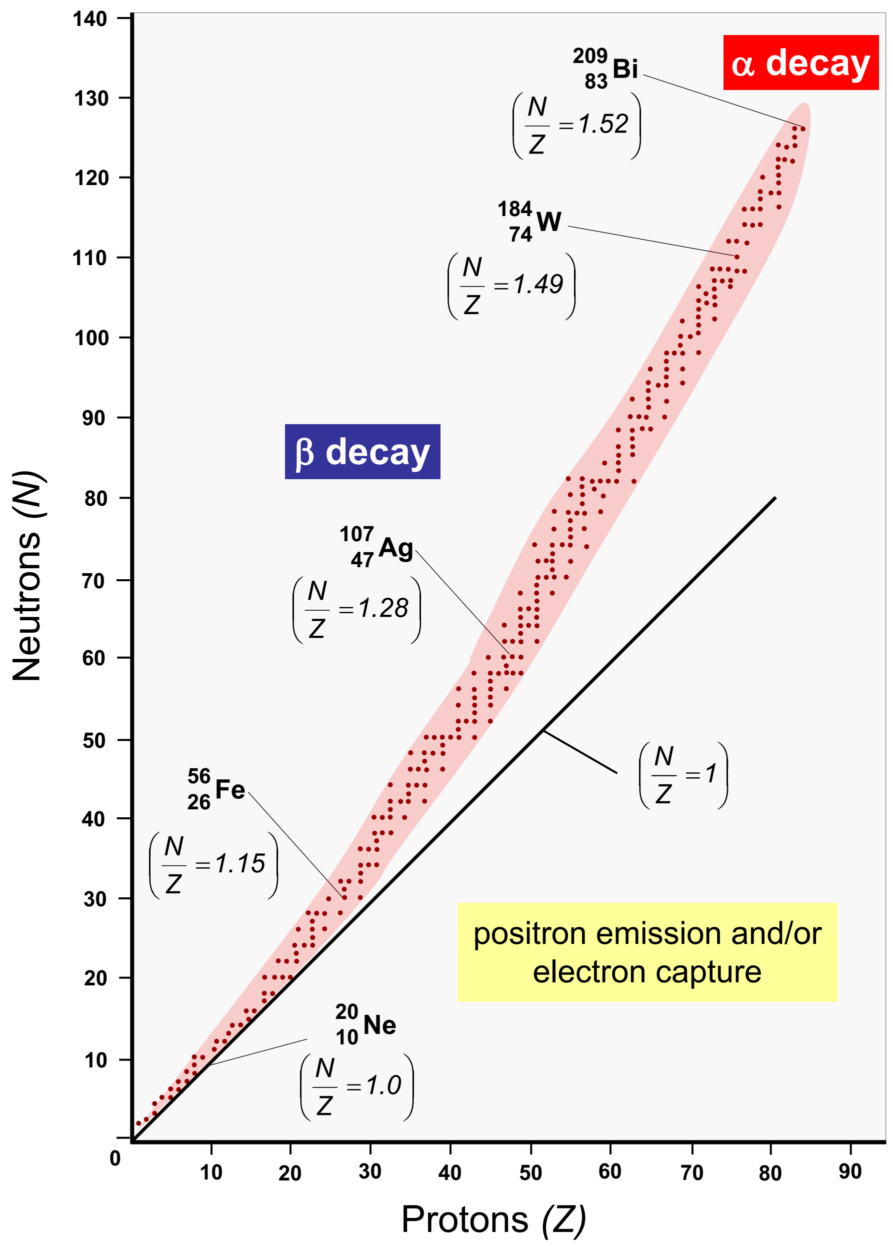
Decay will occur in such a way as to return a nucleus to the band (line) of stability.


Stable isotopes
$t_{1/2}$ = 350 years−46 billion years
$t_{1/2}$ = 12 days−350 years
$t_{1/2}$ = 1 second−12 days
$t_{1/2}$ ⊂ 1 second
Predicted to exist
Radioactive isotopes
"Island of stability"
"Sea of instability"
"Peninsula of stability"
1:1 neutron-to-proton ratio
"Sea of instability"
Number of neutrons
Number of protons
0
20
40
60
80
100
120
140
160
180
200

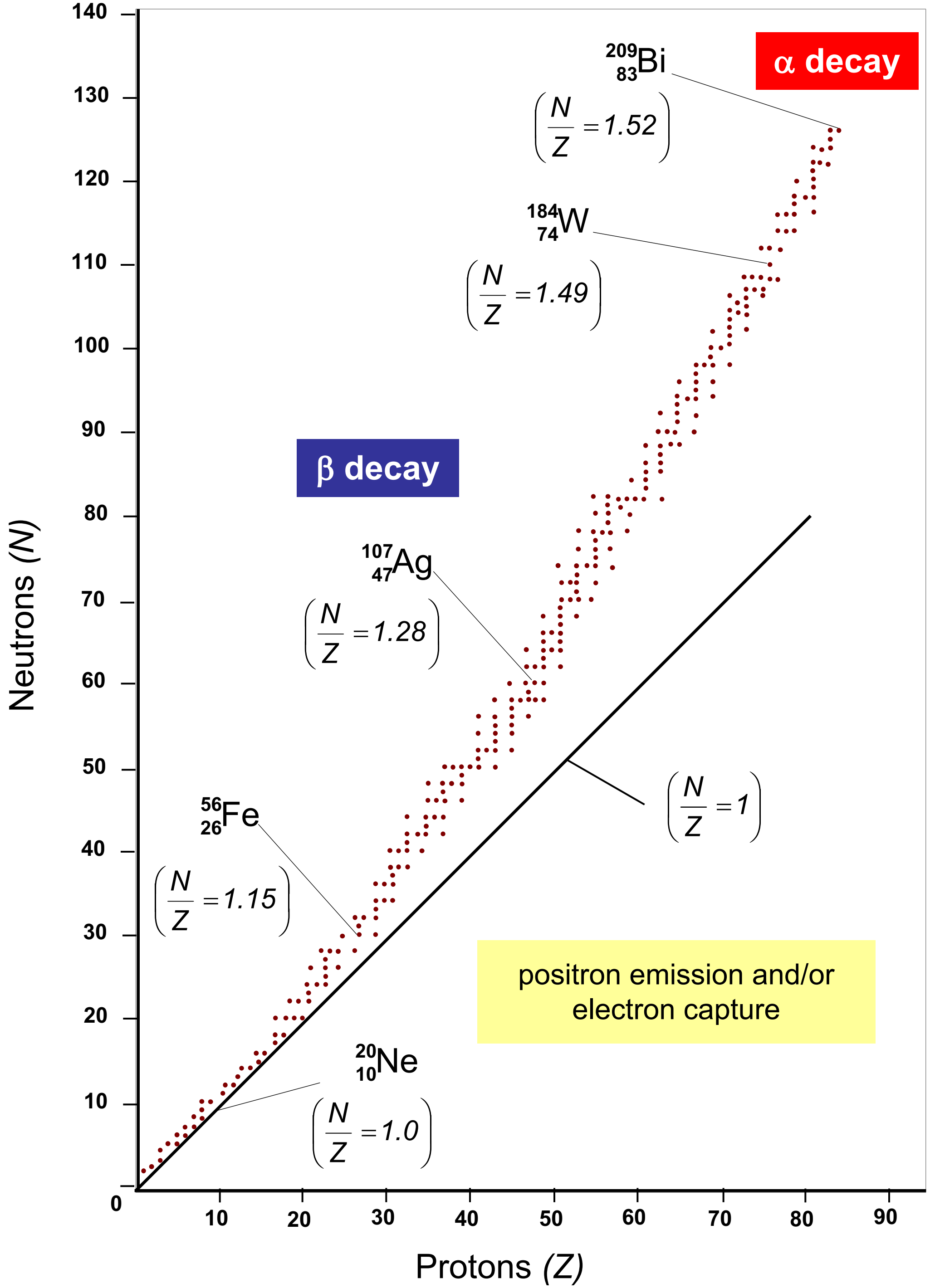
Band of Stability



- Stable nuclides
- Naturally occurring radioactive nuclides
- Other known nuclides



α decay
β decay
positron emission and/or electron capture
$^{209}_{83}$Bi
$\left(\frac{N}{Z} = 1.52\right)$
$^{184}_{74}$W
$\left(\frac{N}{Z} = 1.49\right)$
$^{107}_{47}$Ag
$\left(\frac{N}{Z} = 1.28\right)$
$^{56}_{26}$Fe
$\left(\frac{N}{Z} = 1.15\right)$
$^{20}_{10}$Ne
$\left(\frac{N}{Z} = 1.0\right)$
$\left(\frac{N}{Z} = 1\right)$
Neutrons (N)
Protons (Z)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140



Nuclear Stability

Decay will occur in such a way as to return a nucleus to the band (line) of stability.

Half-Lives of Some Isotopes of Carbon

Nuclide	Half-Life
Carbon-9	0.127 s
Carbon-10	19.3 s
Carbon-11	10.3 m
Carbon-12	Stable
Carbon-13	Stable
Carbon-14	5715 y
Carbon-15	2.45 s
Carbon-16	0.75 s

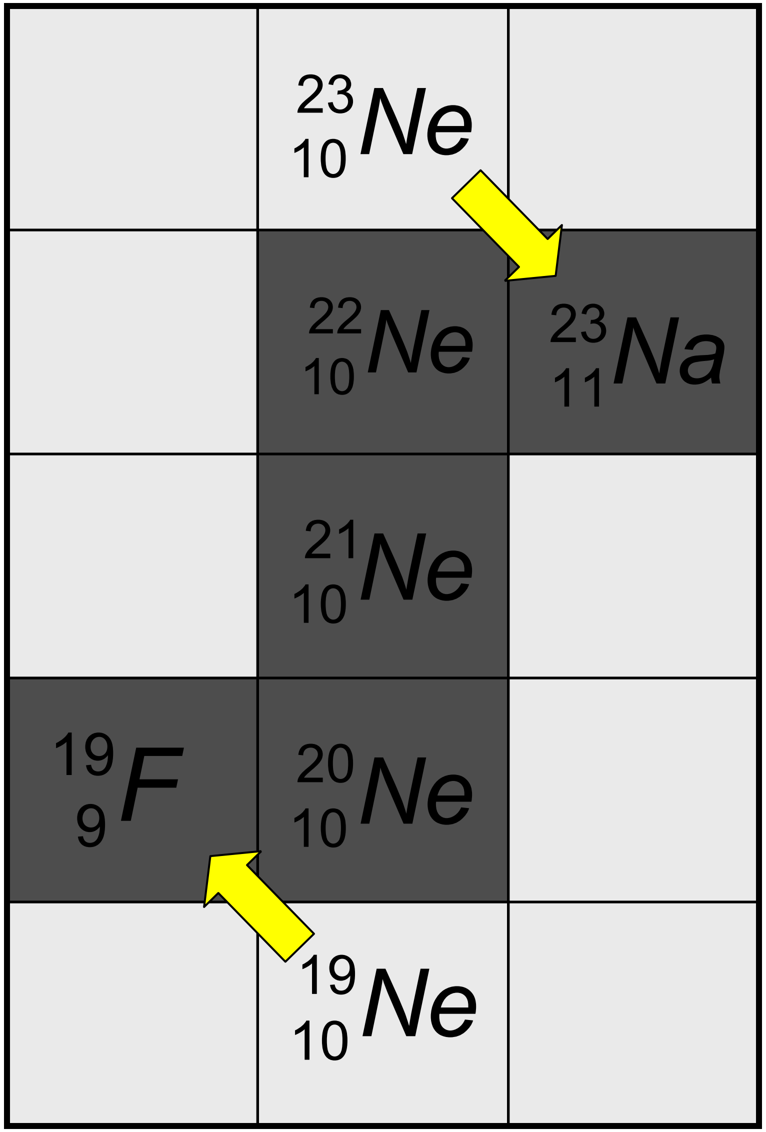
Enlargement of part of band of stability around Neon

moves into band of stability by beta decay.

$$^{23}_{10}\text{Ne} \rightarrow {}^{0}_{-1}\beta + {}^{23}_{11}\text{Na}$$

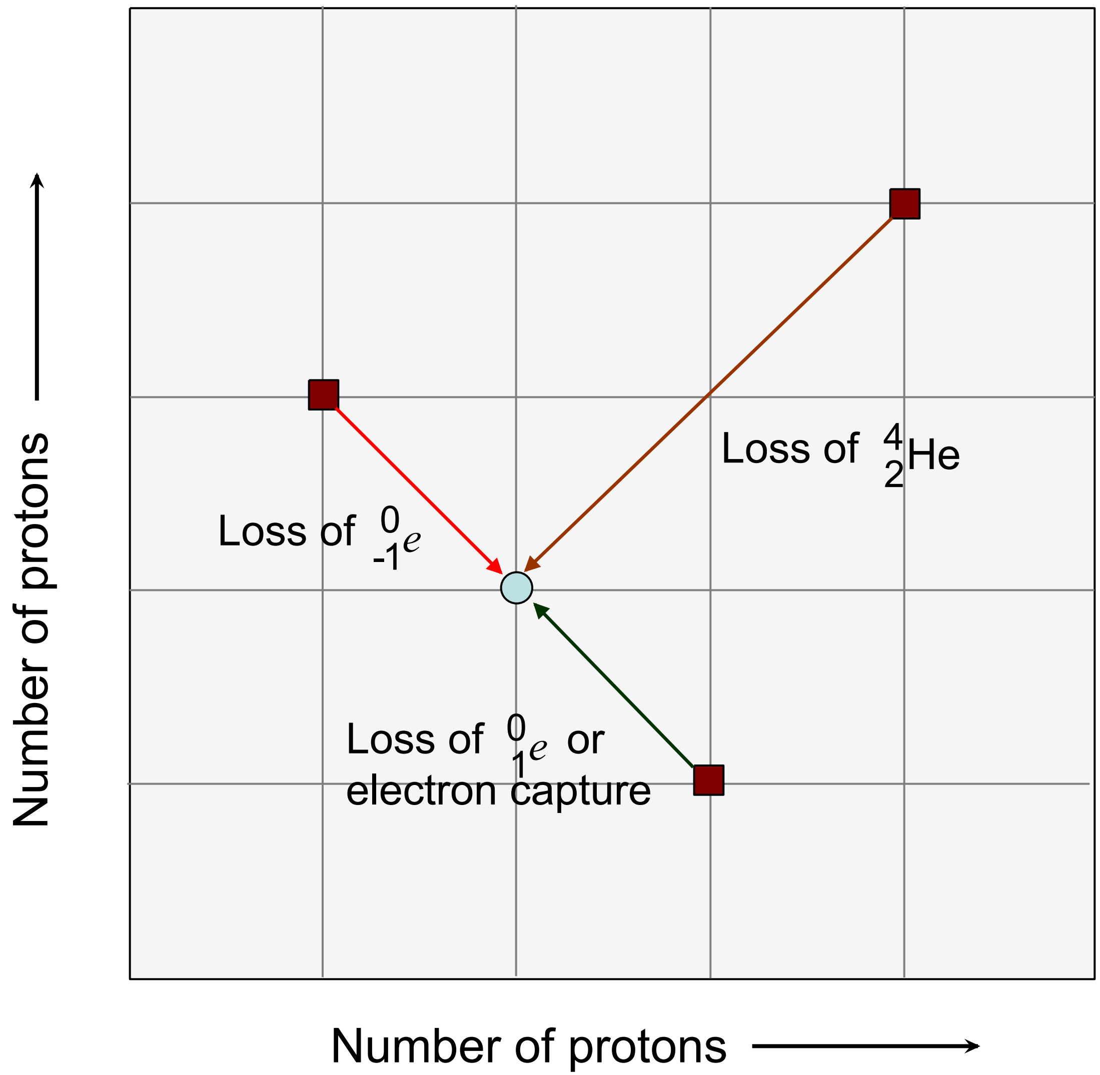
moves into band of stability by positron emission. Electron capture would also move into the band of stability.

$$^{19}_{10}\text{Ne} \rightarrow {}^{0}_{1}\beta + {}^{19}_{9}\text{F}$$



Umland and Bellama, General Chemistry 2nd Edition, page 773

Effects of Radioactive Emissions on Proton and Neutrons



Nuclear Decay

"absorption", "bombardment" vs. "production", "emission"

$$^{223}_{88}Ra \longrightarrow {}^{4}_{2}\alpha^{2+} + \underline{{}^{219}_{86}Rn}$$

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

$$^{4}_{2}\alpha^{2+} + {}^{14}_{7}N \longrightarrow \underline{{}^{17}_{8}O} + {}^{1}_{1}H$$

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

$$^{87}_{37}Rb \longrightarrow \underline{{}^{0}_{-1}\beta} + {}^{87}_{38}Sr$$

$$^{14}_{6}C \longrightarrow {}^{0}_{-1}\beta + \underline{{}^{17}_{7}N}$$

Alpha: $^{4}_{2}\alpha^{2+}$

Beta: $^{0}_{-1}\beta$

Positron: $^{0}_{+1}\beta$

Gamma: $^{0}_{0}\gamma$

neutron: $^{1}_{0}n$

proton: $^{1}_{1}H^{1+}$

Units Used in Measurement of Radioactivity

Units	Measurements
 Curie (C)	radioactive decay
 Becquerel (Bq)	radioactive decay
 Roentgens (R)	exposure to ionizing radiation
Rad (rad)	energy absorption caused by ionizing radiation
Rem (rem)	biological effect of the absorbed dose in humans

Effects of Instantaneous Whole-Body Radiation Doses on People

Alexander Litvinenko

Dose, Sv (rem)	Effect
$\geq$10 (1000)	Death within 24 h from destruction of the neurological system.
7.5 (750)	Death within 4-30 d from gastrointestinal bleeding.
1.5 – 7.5 (150 – 750)	Intensive hospital care required for survival. At the higher end of range, death through infection resulting from destruction of white-blood cell-forming organs usually takes place 4 – 8 weeks after accident. Those surviving this period usually recover.
< 0.5 (50)	Only proven effect is decrease in white blood cell count.

The intensity of radiation is proportional to $^{1}/_{d}{}^{2}$, where d is the distance from the source.

Alpha, Beta, Positron Emission

Examples of Nuclear Decay Processes		
α emission (alpha)	**β⁻ emission** (beta)	**β⁺ emission** (positron)
$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th$	$^{27}_{12}Mg \rightarrow {}^{0}_{-1}e + {}^{27}_{13}Al$	$^{14}_{8}O \rightarrow {}^{0}_{+1}e + {}^{14}_{7}N$
$^{230}_{90}Th \rightarrow {}^{4}_{2}He + {}^{226}_{88}Ra$	$^{35}_{16}S \rightarrow {}^{0}_{-1}e + {}^{35}_{17}Cl$	$^{32}_{17}Cl \rightarrow {}^{0}_{+1}e + {}^{32}_{16}S$
$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{86}Rn$	$^{40}_{19}K \rightarrow {}^{0}_{-1}e + {}^{40}_{20}Ca$	$^{14}_{8}O \rightarrow {}^{0}_{+1}e + {}^{14}_{7}N$

Although beta emission involves electrons, those electrons come from the nucleus. Within the nucleus, a neutron decays into a proton and an electron. The electron is emitted, leaving behind a proton to replace the neutron, thus transforming the element. (A neutrino is also produced and emitted in the process.)

Herron, Frank, Sarquis, Sarquis, Schrader, Kulka, Chemistry, Heath Publishing,1996, page 275

Nuclear Reactions

First recognized natural transmutation of an element (Rutherford and Soddy, 1902)

$$^{226}_{88}\text{Ra} \rightarrow \,^{4}_{2}\text{á} + \,^{222}_{86}\text{Rn}$$

First artificial transmutation of an element (Rutherford, 1919)

$$^{14}_{7}\text{N} + \,^{4}_{2}\alpha \rightarrow \textbf{?} + \,^{1}_{1}\text{p}$$

Discovery of the neutron (Chadwick, 1932)

$$^{9}_{4}\text{Be} + \,^{4}_{2}\alpha \rightarrow \,^{12}_{6}\text{C} + \textbf{?}$$

Discovery of nuclear fission (Otto Hahn and Fritz Strassman, 1939)

$$^{235}_{92}\text{U} + \,^{1}_{0}\text{n} \rightarrow \,^{141}_{56}\text{Ba} + \,^{92}_{36}\text{Kr} + 3\,^{1}_{0}\text{n}$$

Bailar, Chemistry, pg 361

Preparation of Transuranium Elements

Atomic Number	Name	Symbol	Year Discovered	Reaction
93	**Neptunium**	Np	1940	${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$
94	**Plutonium**	Pu	1940	${}^{238}_{92}U + {}^{2}_{1}H \rightarrow {}^{238}_{93}Np + 2{}^{1}_{0}n$ ${}^{238}_{93}Np \rightarrow {}^{238}_{94}Pu + {}^{0}_{-1}e$
95	**Americium**	Am	1944	${}^{239}_{94}Pu + {}^{1}_{0}n \rightarrow {}^{240}_{95}Am + {}^{0}_{-1}e$
96	**Curium**	Cm	1945	${}^{239}_{94}Pu + {}^{4}_{2}He \rightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$
97	**Berkelium**	Bk	1949	${}^{241}_{95}Am + {}^{4}_{2}He \rightarrow {}^{243}_{97}Bk + 2{}^{1}_{0}n$
98	**Californium**	Cf	1950	${}^{242}_{96}Cm + {}^{4}_{2}He \rightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$

Ralph A. Burns, Fundamentals of Chemistry 1999, page 553

Preparation of Transuranium Elements

Atomic Number	***Name***	***Symbol***	***Year Discovered***	***Reaction***
93	**Neptunium**	Np	1940	$^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$
94	**Plutonium**	Pu	1940	$^{238}_{92}U + {}^{2}_{1}H \rightarrow {}^{238}_{93}Np + 2{}^{1}_{0}n$
				$^{238}_{93}Np \rightarrow {}^{238}_{94}Pu + {}^{0}_{-1}e$
95	**Americium**	Am	1944	$^{239}_{94}Pu + {}^{1}_{0}n \rightarrow {}^{240}_{95}Am + {}^{0}_{-1}e$
96	**Curium**	Cm	1945	$^{239}_{94}Pu + {}^{4}_{2}He \rightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$
97	**Berkelium**	Bk	1949	$^{241}_{95}Am + {}^{4}_{2}He \rightarrow {}^{243}_{97}Bk + 2{}^{1}_{0}n$
98	**Californium**	Cf	1950	$^{242}_{96}Cm + {}^{4}_{2}He \rightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$

Ralph A. Burns, Fundamentals of Chemistry 1999, page 553

Additional Transuranium Elements

99	Einsteinium	Es	1952	
100	Fermium	Fm	1952	
101	Mendelevium	Md	1955	
102	Nobelium	Nb	1958	
103	Lawrencium	Lr	1961	
104	Rutherfordium	Rf	1964	
105	Dubnium	Db	1970	
106	Seaborgium	Sg	1974	
107	Bohrium	Bh	1981	
108	Hassium	Hs	1984	
109	Meitnerium	Mt	1988	
110	DarmstadtiumDs		1994	
111	Unununium	Uun1994		
112	Ununbium	Uub1996		
114		Uuq	1999	(Russia)
116			2002	(Russia)
118			2006	

CHAPTER 22

Nuclear Chemistry

I

II

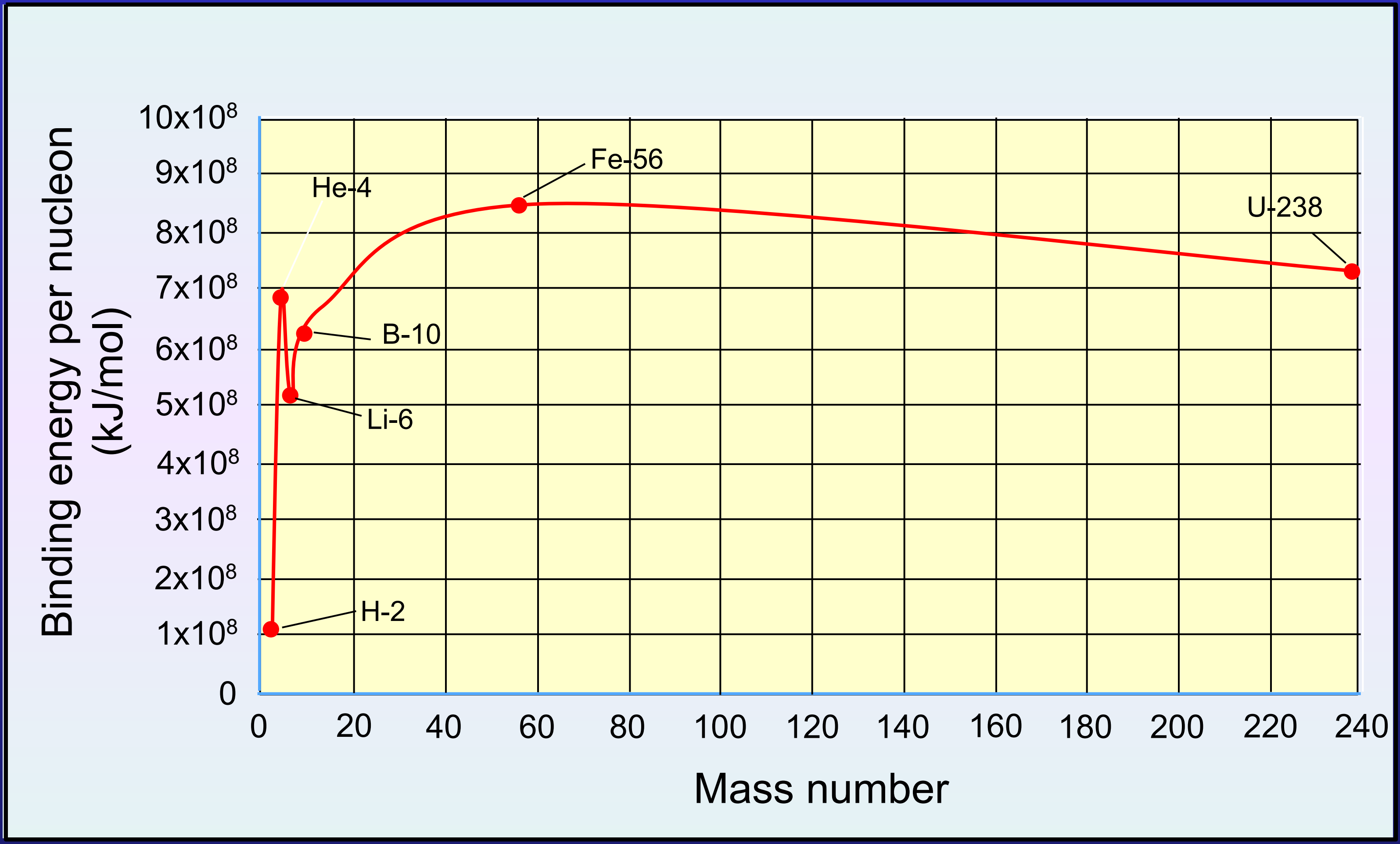
III

IV

I. The Nucleus

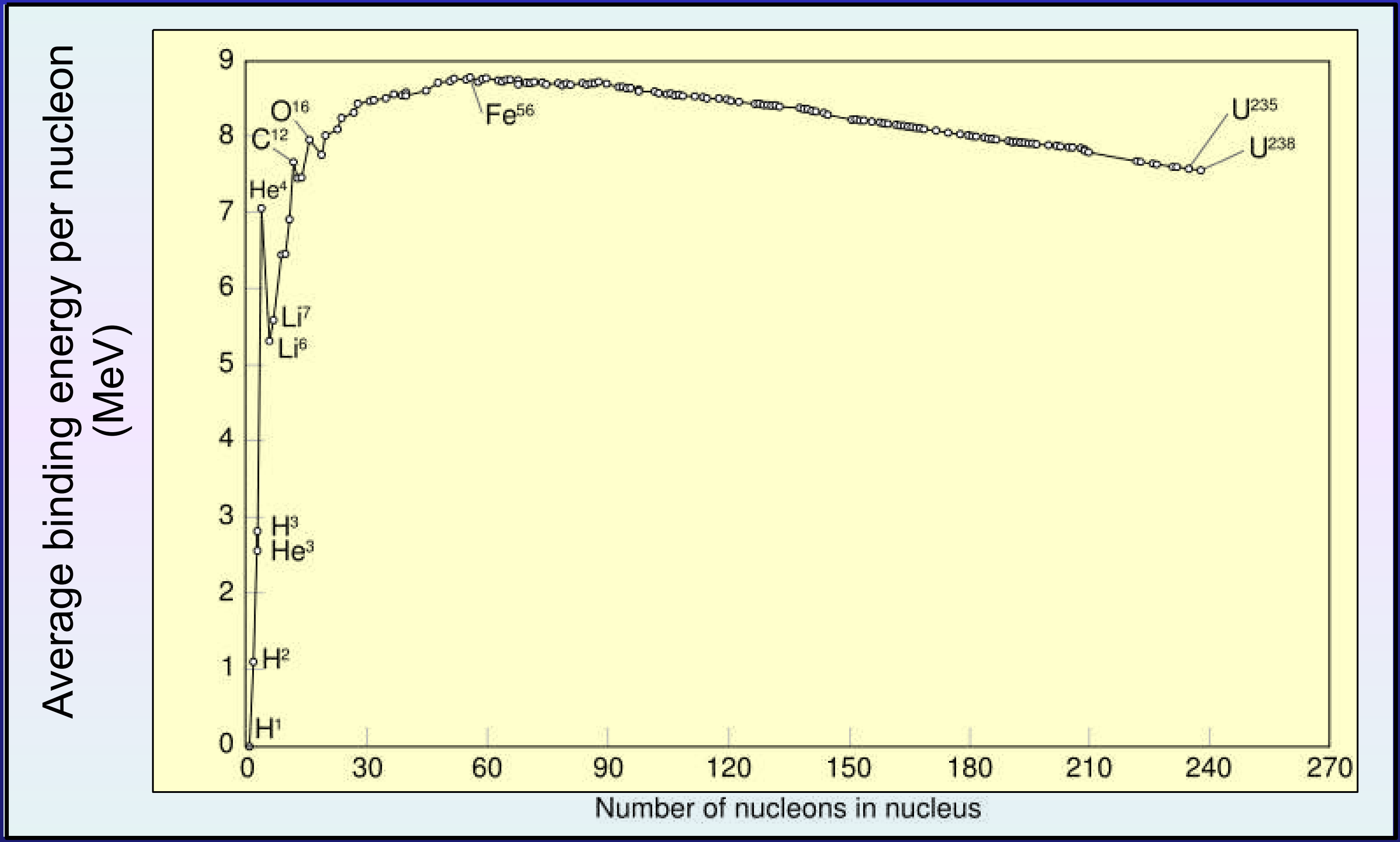
(p. 701 - 704)

Nuclear Binding Energy



Unstable nuclides are radioactive and undergo radioactive decay.

Nuclear Binding Energy



Unstable nuclides are radioactive and undergo radioactive decay.

CHAPTER 22

Nuclear Chemistry

I

II

III

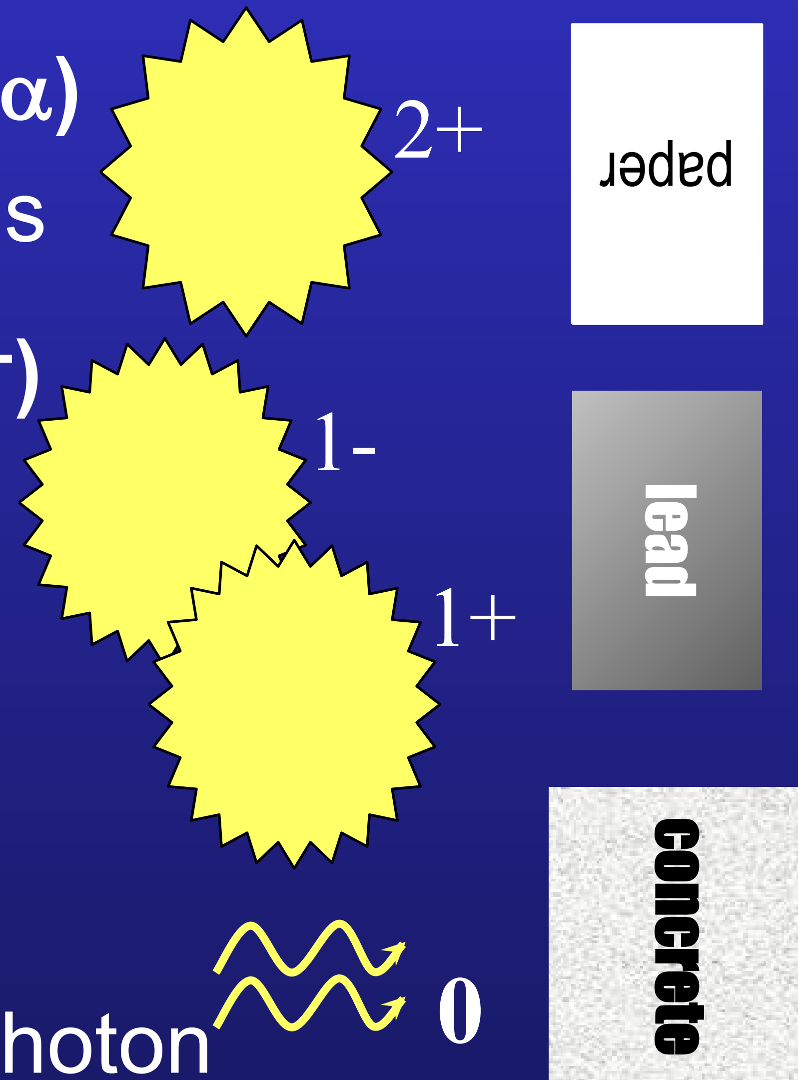
IV

II. Radioactive Decay

(p. 705 - 712)

Types of Radiation

- Alpha particle (α)
  - helium nucleus
- Beta particle (β^-)
  - electron
- Positron (β^+)
  - positron
- Gamma (γ)
  - high-energy photon



Nuclear Decay

- Alpha Emission

Numbers must balance!!

Nuclear Decay

- Beta Emission

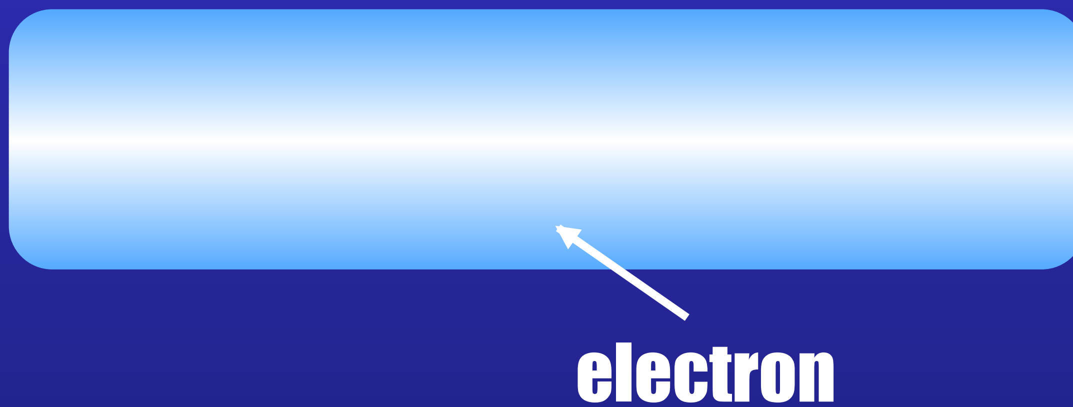
electron

- Positron Emission

positron

Nuclear Decay

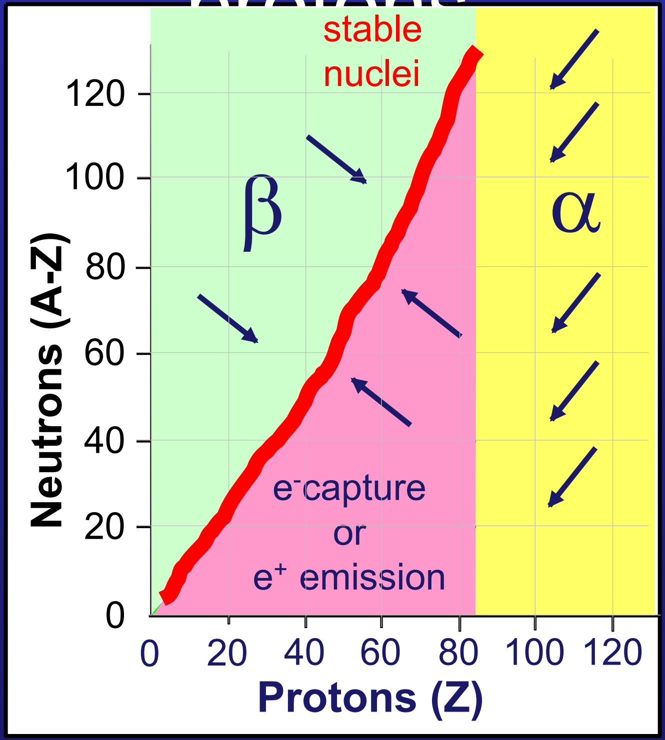
- Electron Capture



- Gamma Emission
  - Usually follows other types of decay.
- Transmutation
  - One element becomes another.

Nuclear Decay

- **Why nuclides decay…**
  - need stable ratio of neutrons to protons

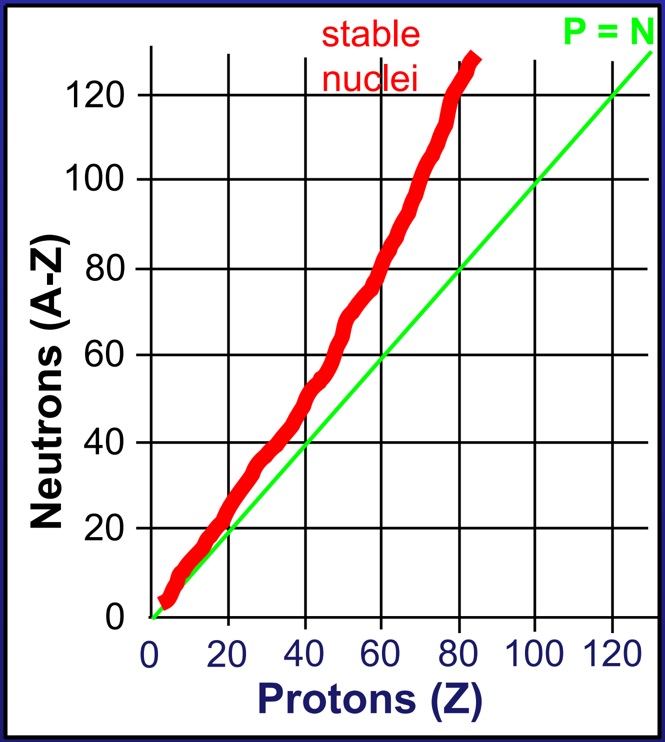


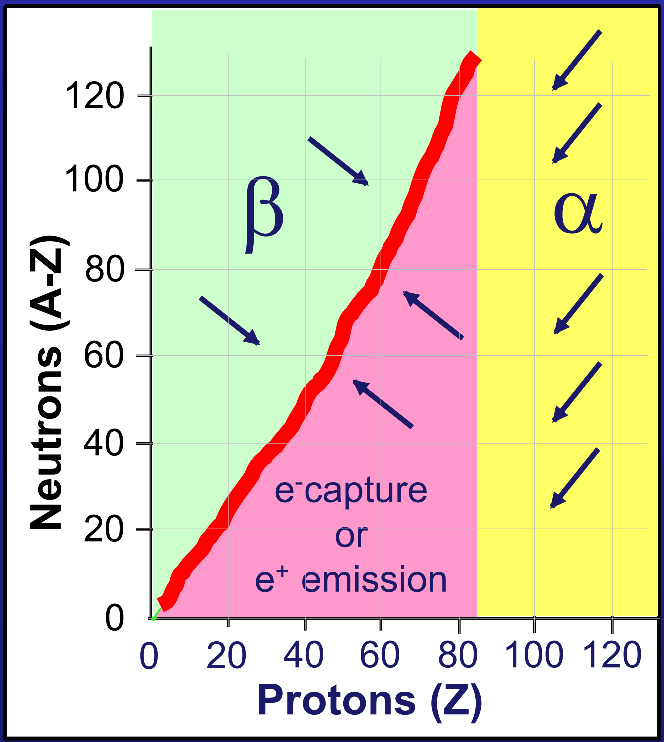
Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

DECAY SERIES TRANSPARENCY

Nuclear Decay

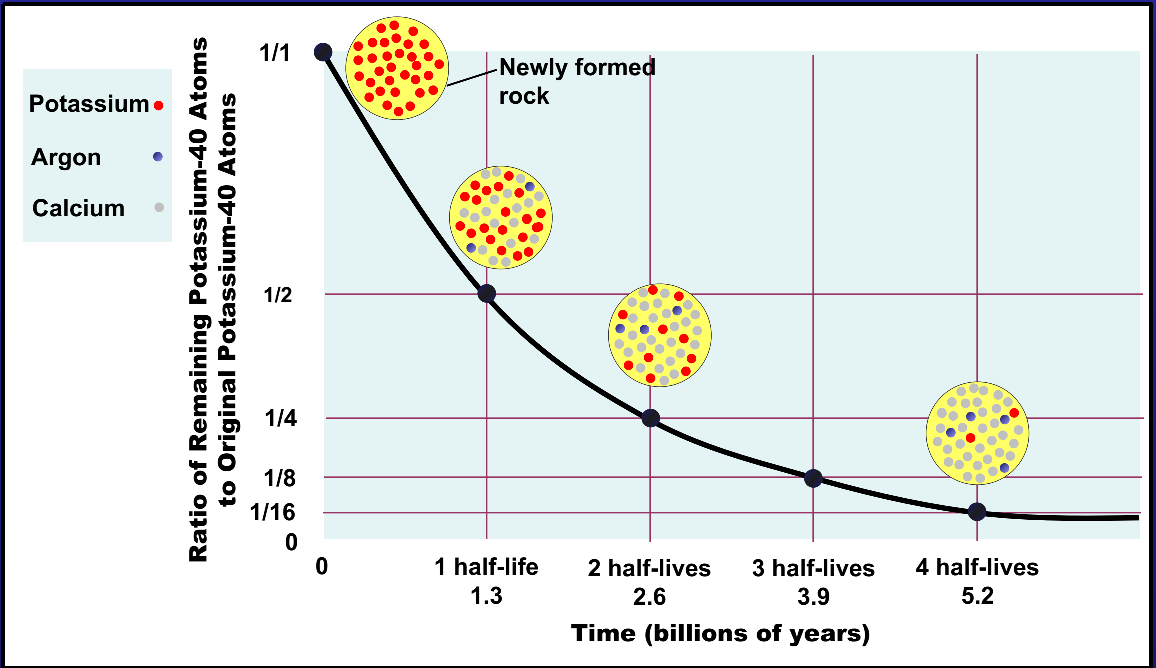
- **Why nuclides decay…**
  - need stable ratio of neutrons to protons





Half-life

- **Half-life ($t_{1/2}$)**
  - Time required for half the atoms of a radioactive nuclide to decay.
  - Shorter half-life = less stable.



Half-life

m_f: final mass

m_i: initial mass

n: # of half-lives

Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Half-life

- Fluorine-21 has a half-life of 5.0 seconds. If you start with 25 g of fluorine-21, how many grams would remain after 60.0 s?

GIVEN:	WORK:
$t_{½} = 5.0$ s $m_i = 25$ g $m_f = ?$ total time = 60.0 s n = 60.0s ÷ 5.0s =12	$m_f = m_i (½)^n$ $m_f = (25 \text{ g})(0.5)^{12}$ **$m_f = 0.0061$ g**

CHAPTER 22

Nuclear Chemistry

I

II

III

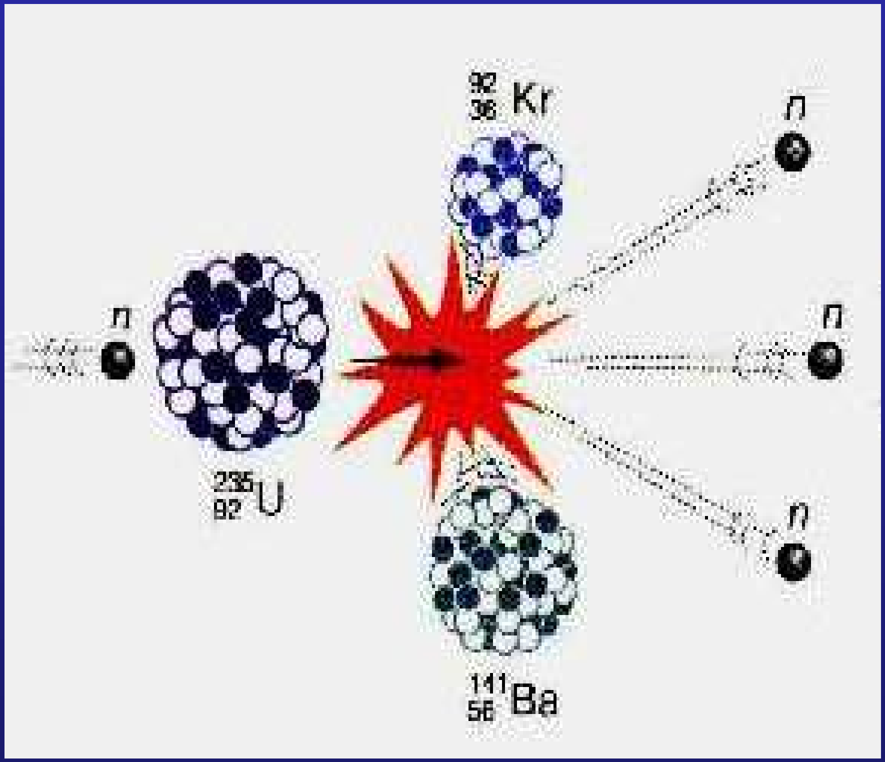
IV

III. Fission & Fusion

(p. 717 - 719)

Fission

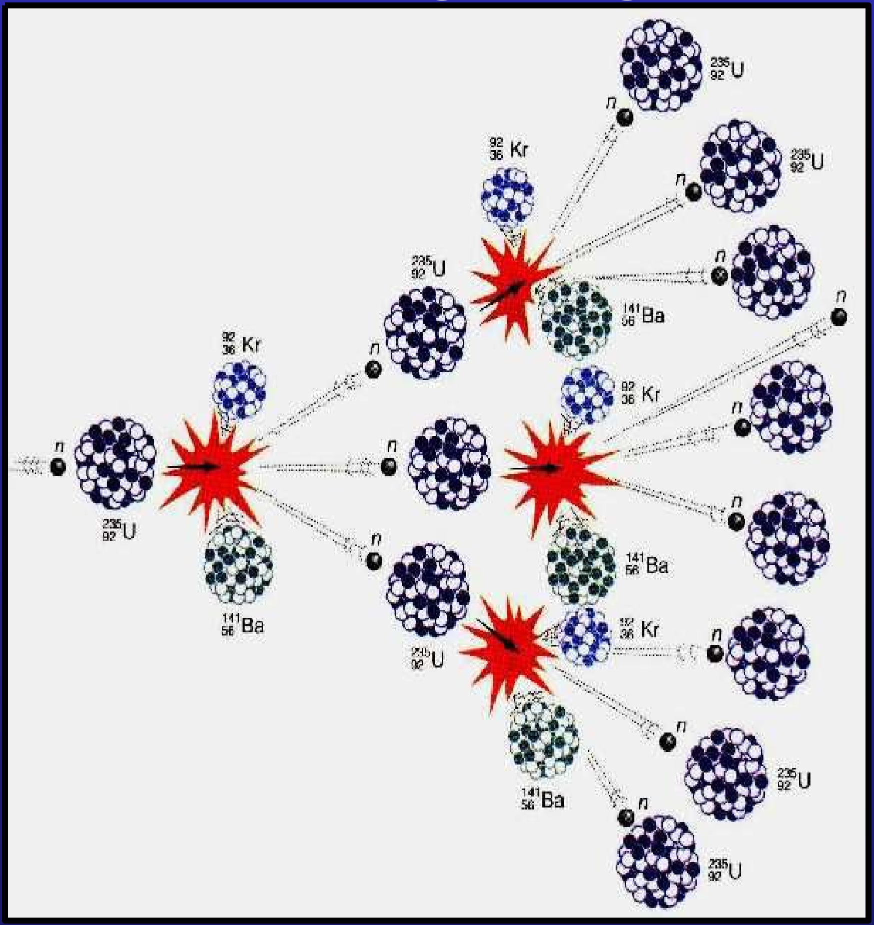
- splitting a nucleus into two or more smaller nuclei
- 1 g of ^{235}U = 3 tons of coal



Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Fission

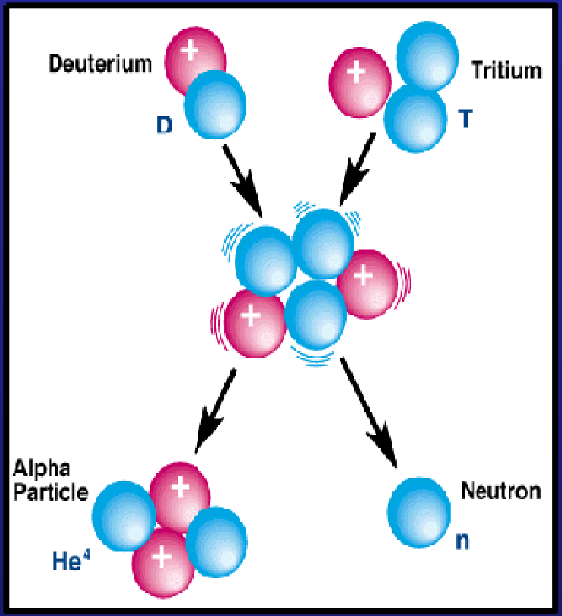
- chain reaction - self-propagating reaction
- critical mass - mass required to sustain a chain reaction



Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Fusion

- combining of two nuclei to form one nucleus of larger mass
- thermonuclear reaction – requires temp of 40,000,000 K to sustain
- 1 g of fusion fuel = 20 tons of coal
- occurs naturally in stars

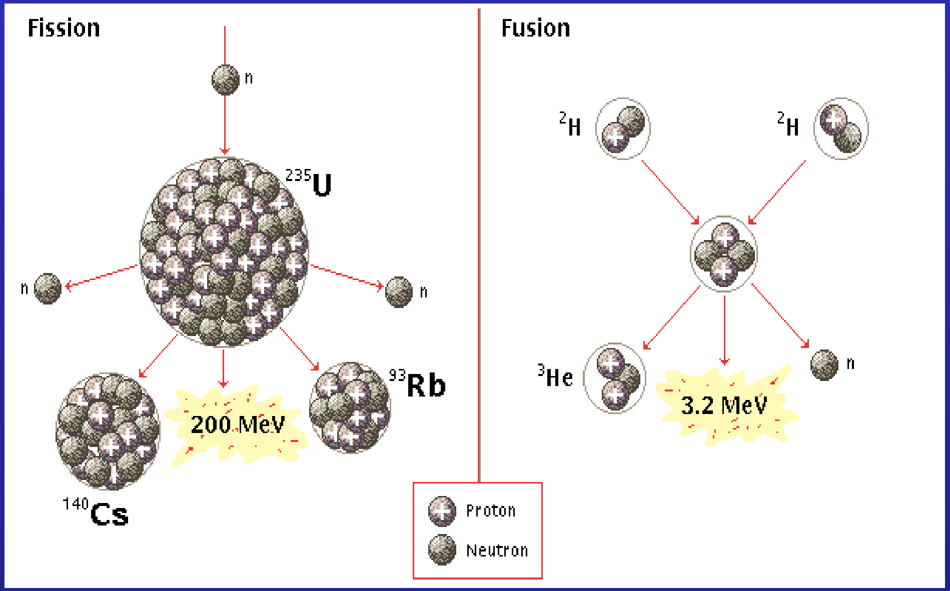


Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Fission vs. Fusion

Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

FISSION



FUSION

- ^{235}U is limited
- danger of meltdown
- toxic waste
- thermal pollution

- fuel is abundant
- no danger of meltdown
- no toxic waste
- not yet sustainable

CHAPTER 22

Nuclear Chemistry

I

II

III

IV

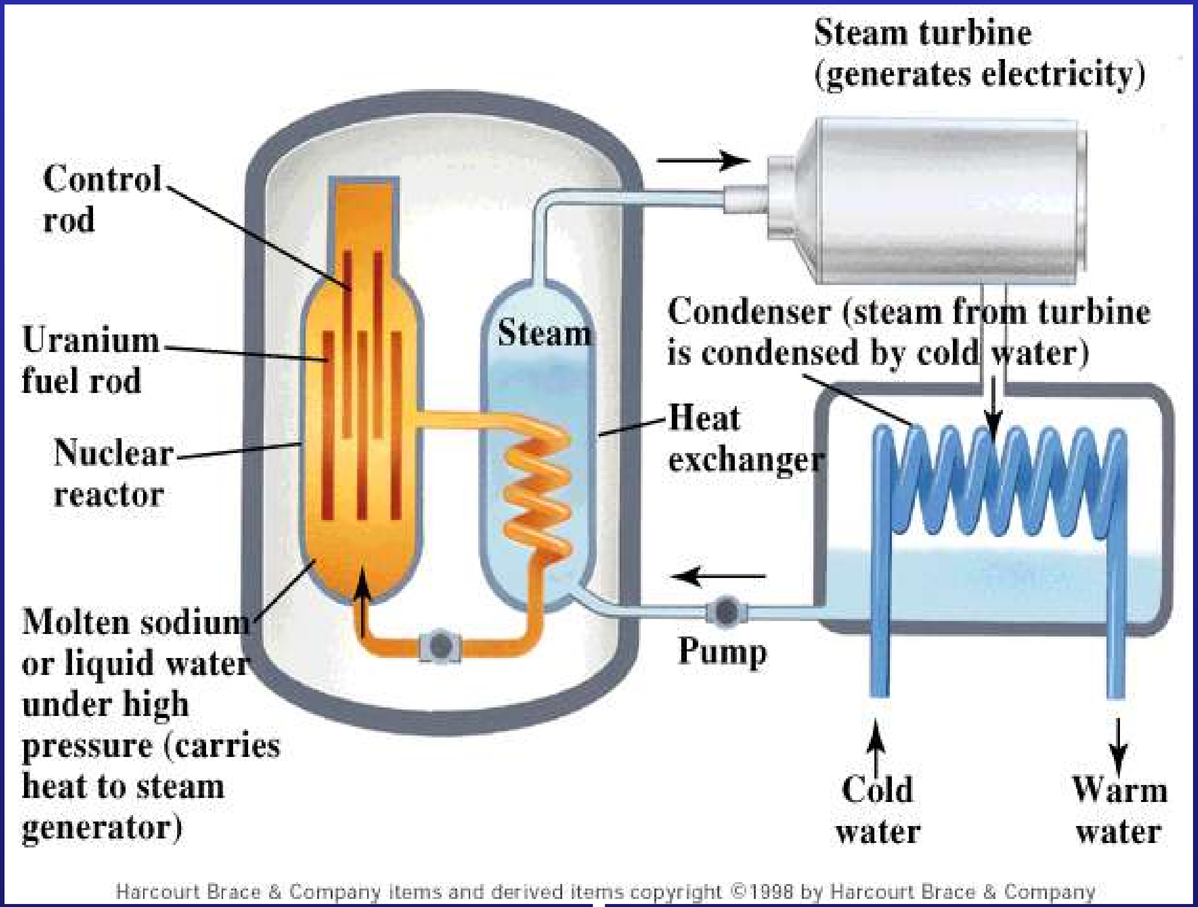
IV. Applications

(p. 713 - 716)

Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Nuclear Power

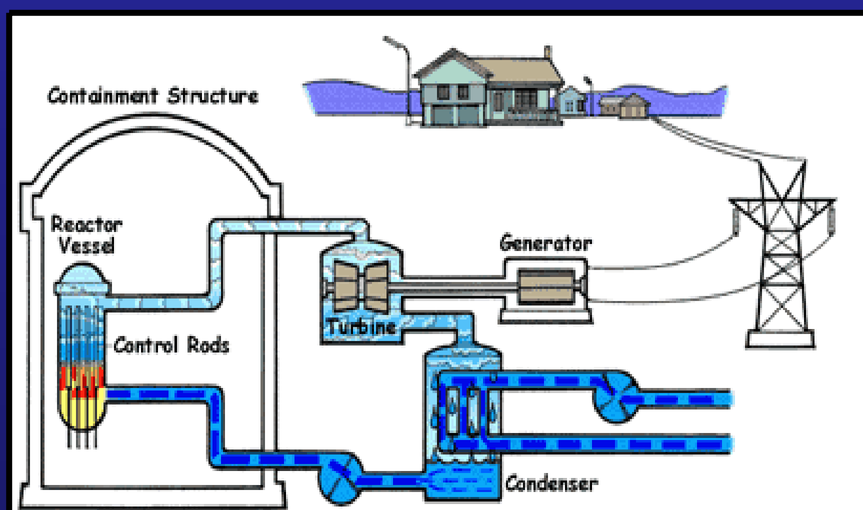
- Fission Reactors

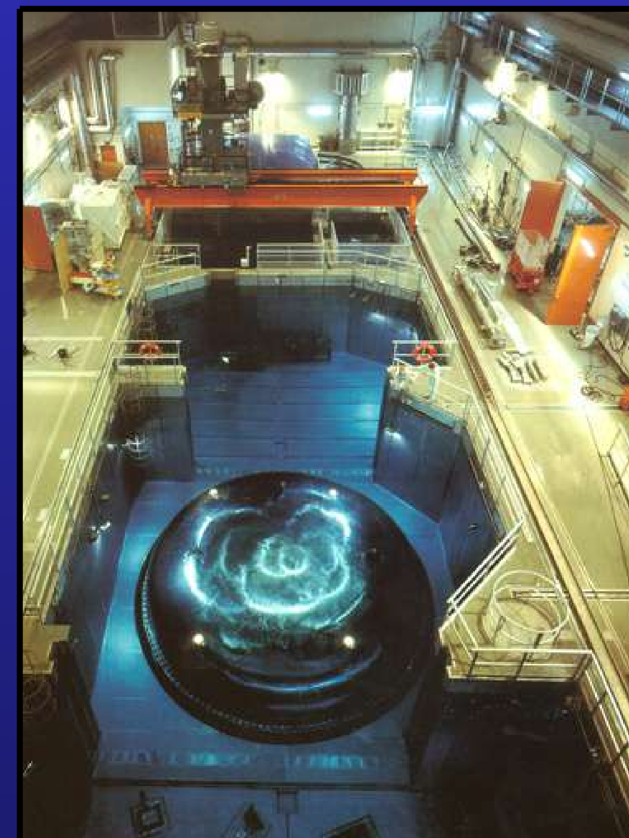


Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Nuclear Power

- Fission Reactors

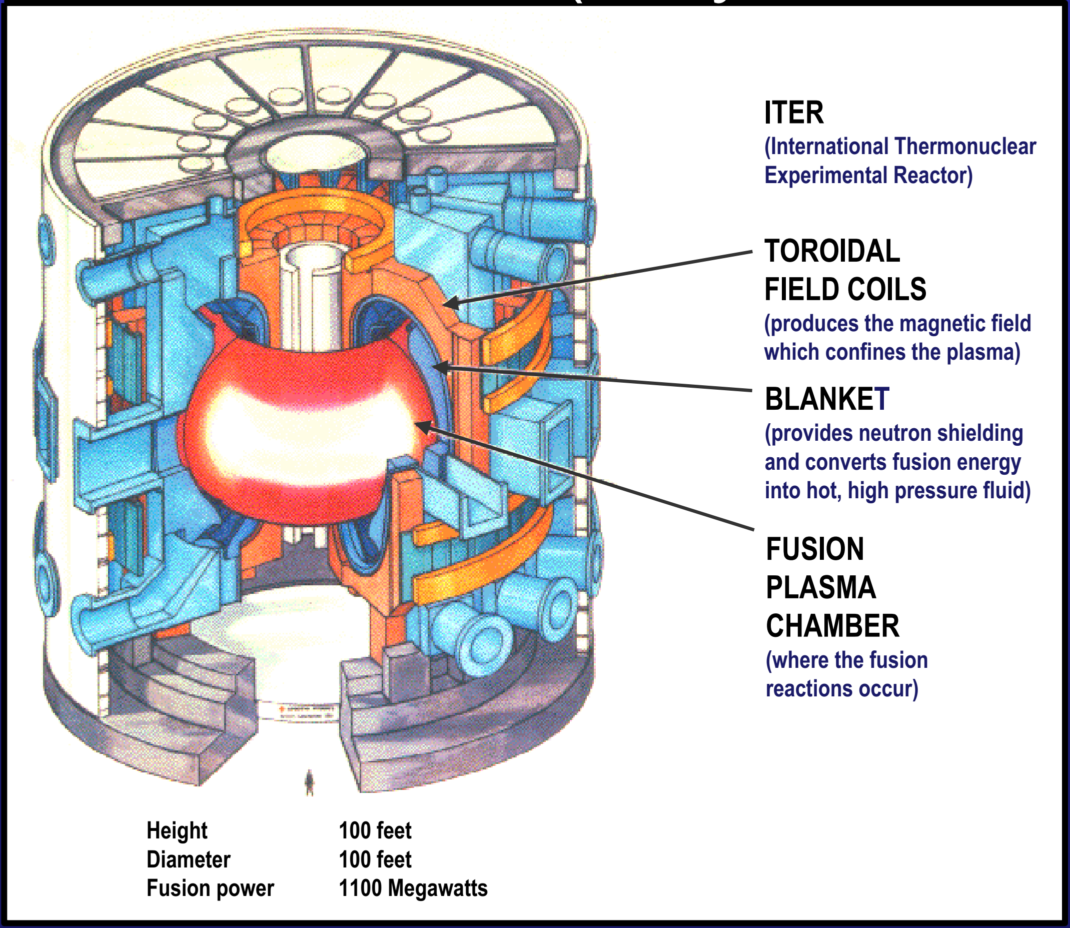




Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Nuclear Power

- Fusion Reactors (not yet sustainable)



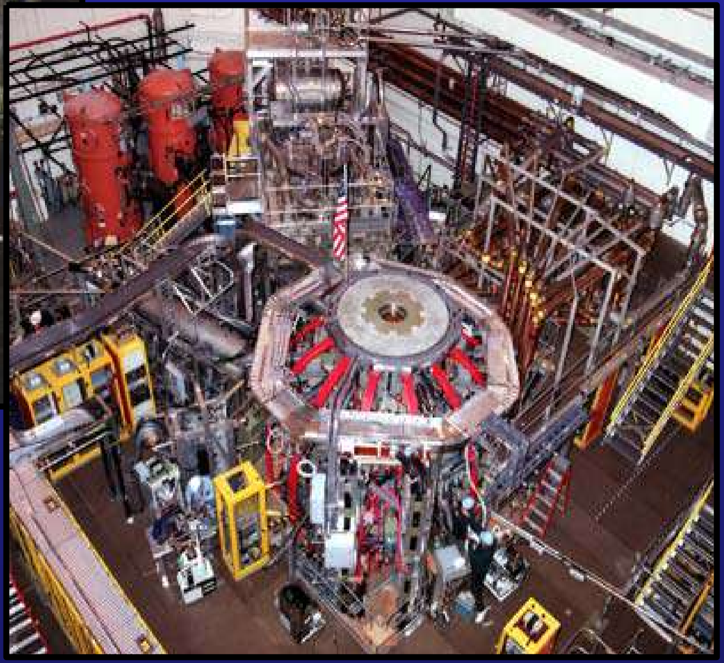
Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

Nuclear Power

- **Fusion Reactors** (not yet sustainable)

Tokamak Fusion Test Reactor

National Spherical Torus Experiment



Princeton University

Synthetic Elements

- **Transuranium Elements**
  - elements with atomic #s above 92
  - synthetically produced in nuclear reactors and accelerators
  - most decay very rapidly

Natural and artificial radioactivity

Natural radioactivity

Isotopes that have been here since the earth formed.

Example - Uranium

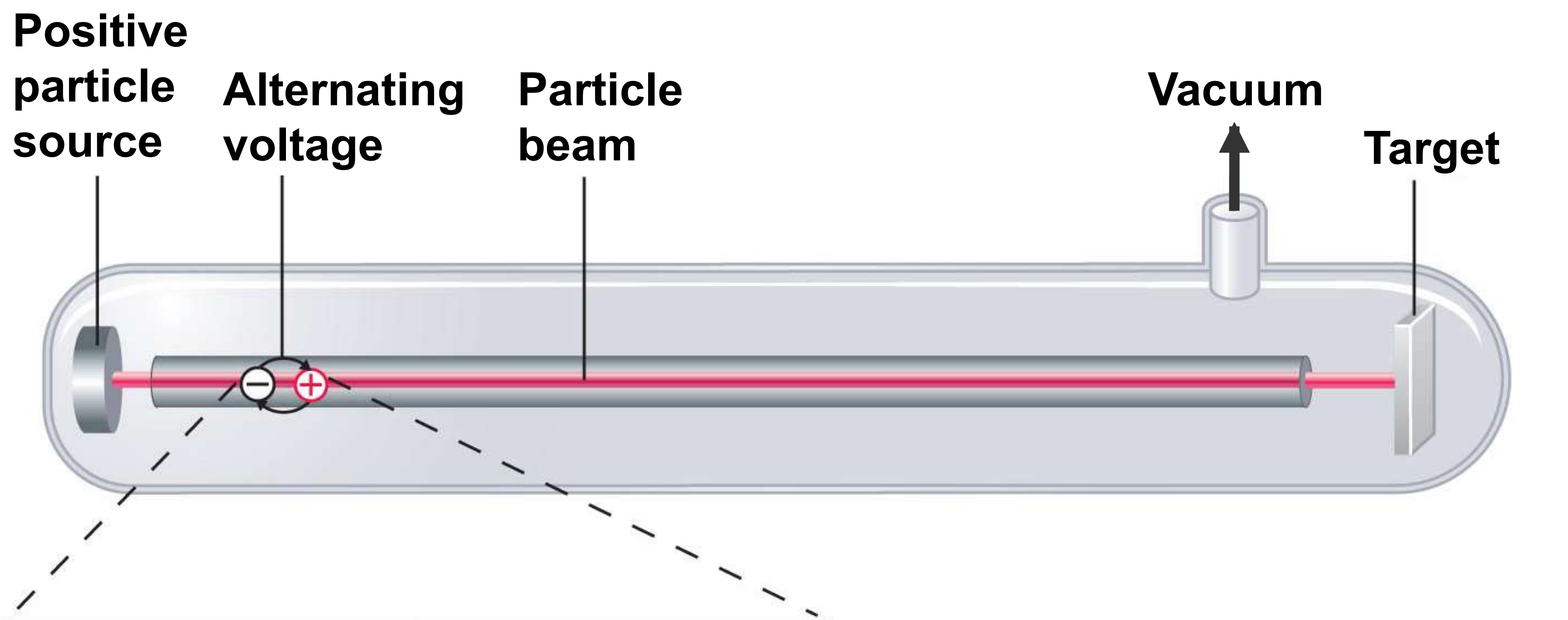
Produced by cosmic rays from the sun.

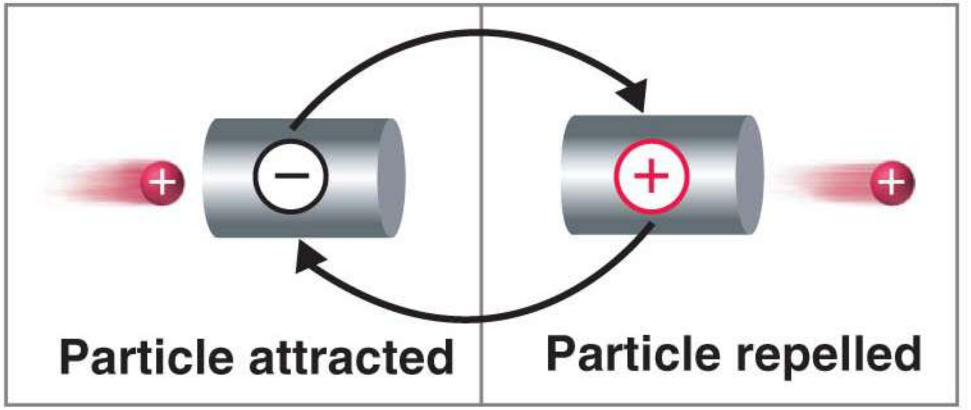
Example – carbon-14

Man-made Radioisotopes

Made in nuclear reactors when we split atoms (fission).

Produced using cyclotrons, linear accelerators,…


Positive particle source
Alternating voltage
Particle beam
Vacuum
Target


Particle attracted
Particle repelled

Radioactive Dating

- half-life measurements of radioactive elements are used to determine the age of an object
- decay rate indicates amount of radioactive material
- EX: ^{14}C - up to 40,000 years
  ^{238}U and ^{40}K - over 300,000 years

Nuclear Medicine

- **Radioisotope Tracers**
  - absorbed by specific organs and used to diagnose diseases
- **Radiation Treatment**
  - larger doses are used to kill cancerous cells in targeted organs
  - internal or external radiation source

Radiation treatment using γ-rays from cobalt-60.

Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

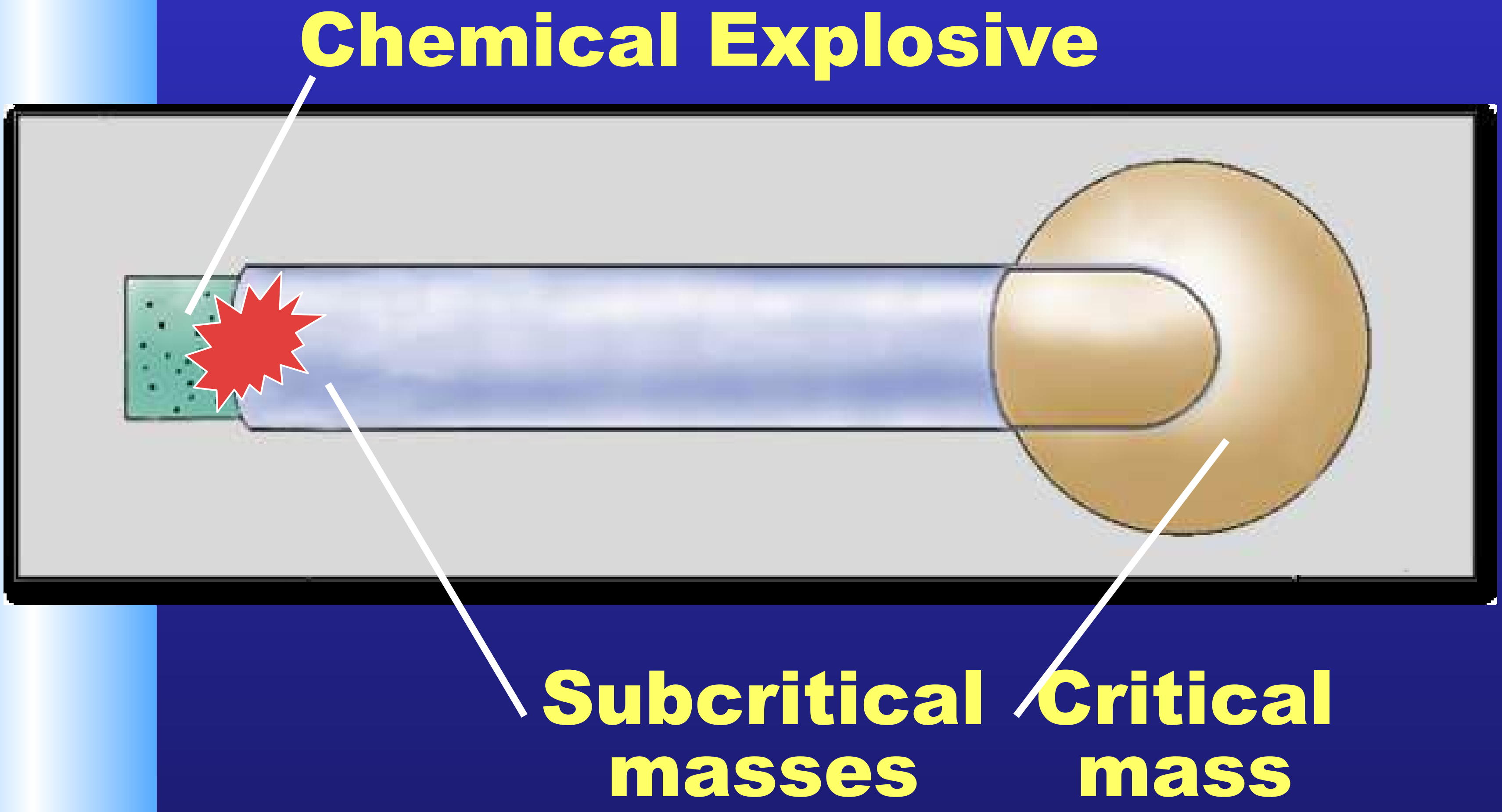
Nuclear Weapons

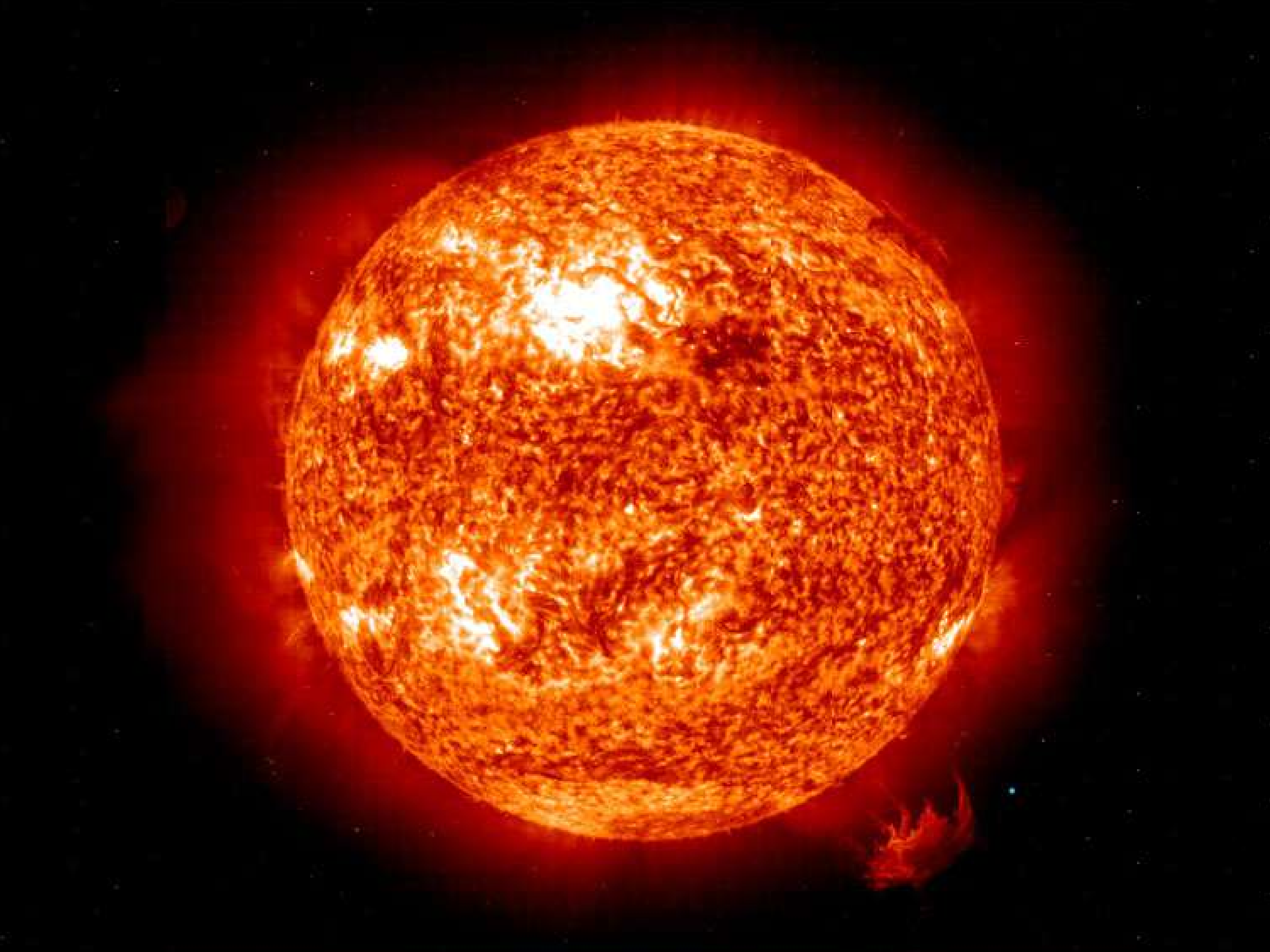
- **Atomic Bomb**
  - chemical explosion is used to form a critical mass of ^{235}U or ^{239}Pu
  - fission develops into an uncontrolled chain reaction
- **Hydrogen Bomb**
  - chemical explosion → fission → fusion
  - fusion increases the fission rate
  - more powerful than the atomic

Others

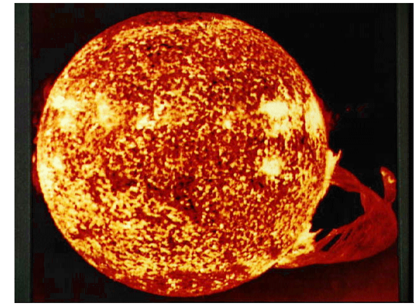
- **Food Irradiation**
  - γ radiation is used to kill bacteria
- **Radioactive Tracers**
  - explore chemical pathways
  - trace water flow
  - study plant growth, photosynthesis
- **Consumer Products**
  - ionizing smoke detectors - ^{241}Am

Simplified diagram of fission bomb

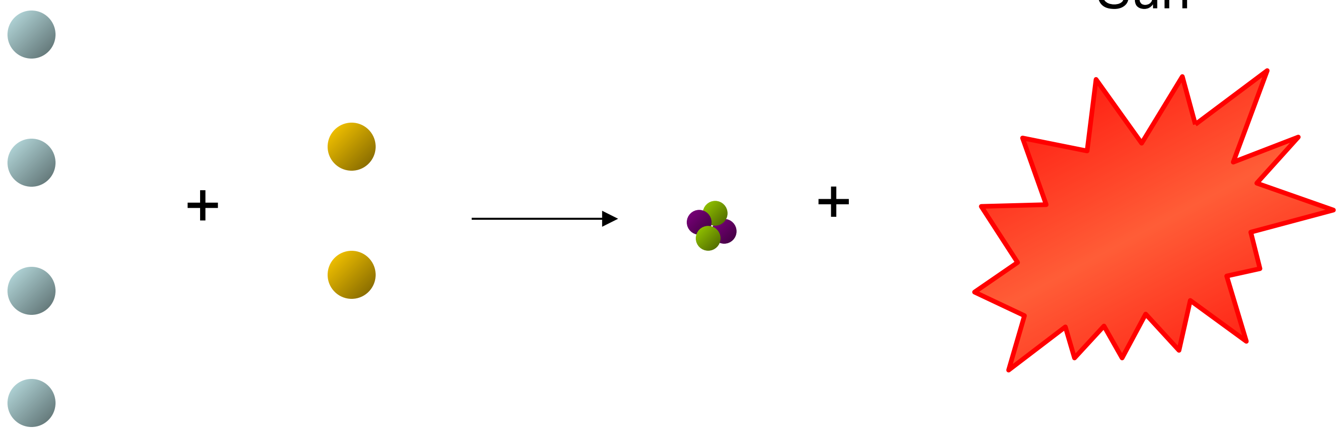




Nuclear Fusion



Sun



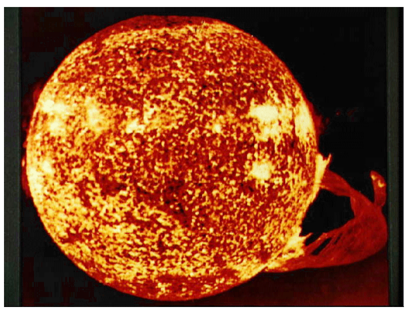
$$4\,{}^{1}_{1}\mathrm{H} + 2\,{}^{0}_{-1}\mathrm{e} \longrightarrow {}^{4}_{2}\mathrm{He} + \text{Energy}$$

Four hydrogen nuclei (protons)	Two beta particles (electrons)	One helium nucleus	

Conservation of Mass

…mass is converted into energy

Hydrogen (H_2) — H = 1.008 amu
Helium (He) — He = 4.004 amu



FUSION

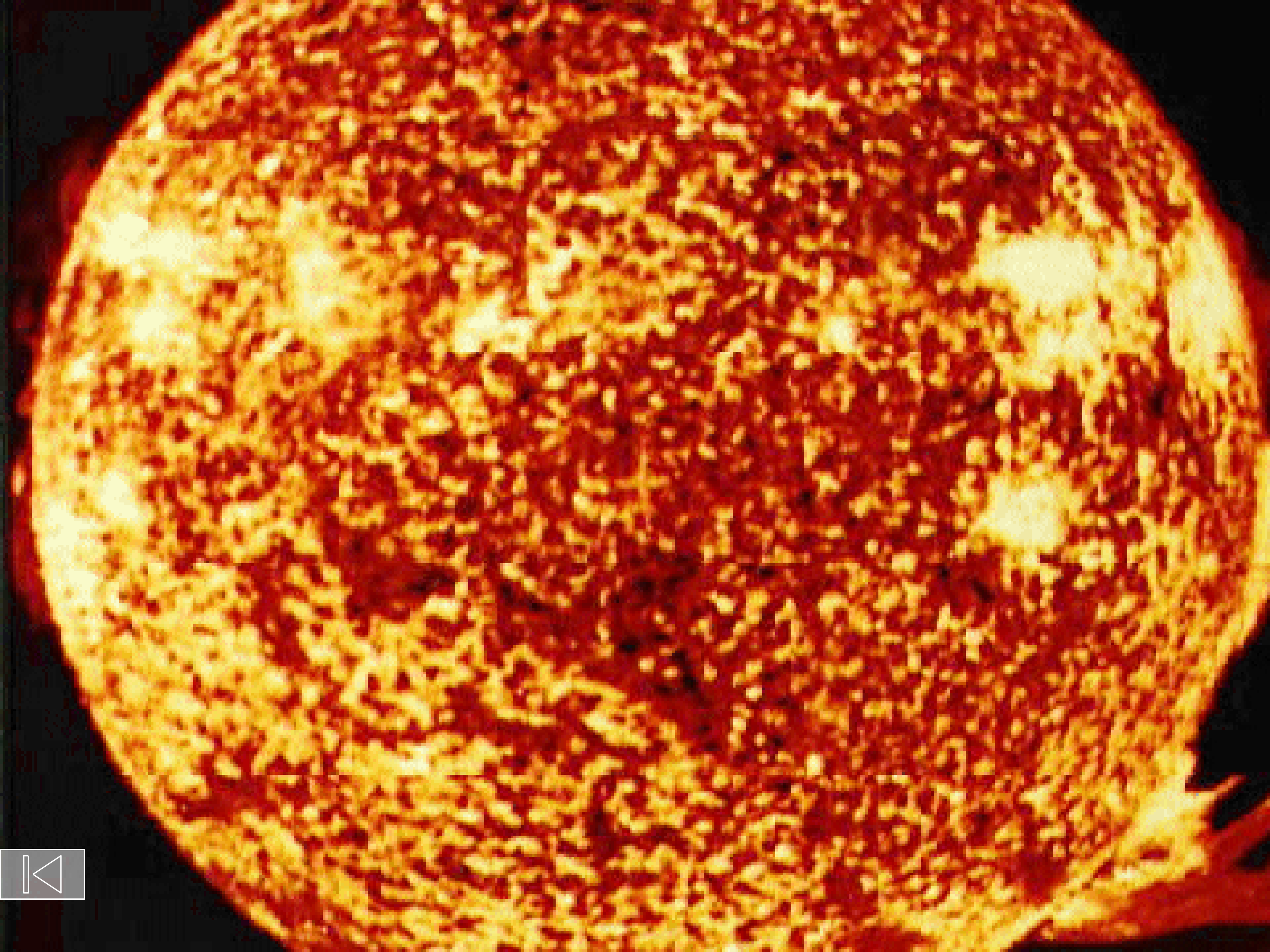
$2\ H_2$	→	1 He	+	ENERGY

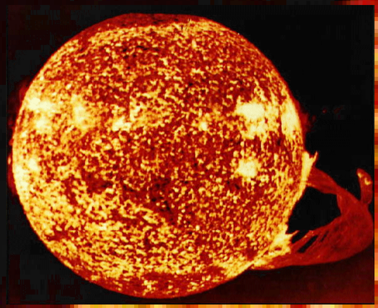
1.008 amu
x 4
4.0032 amu = 4.004 amu + 0.028 amu

This relationship was discovered by Albert Einstein

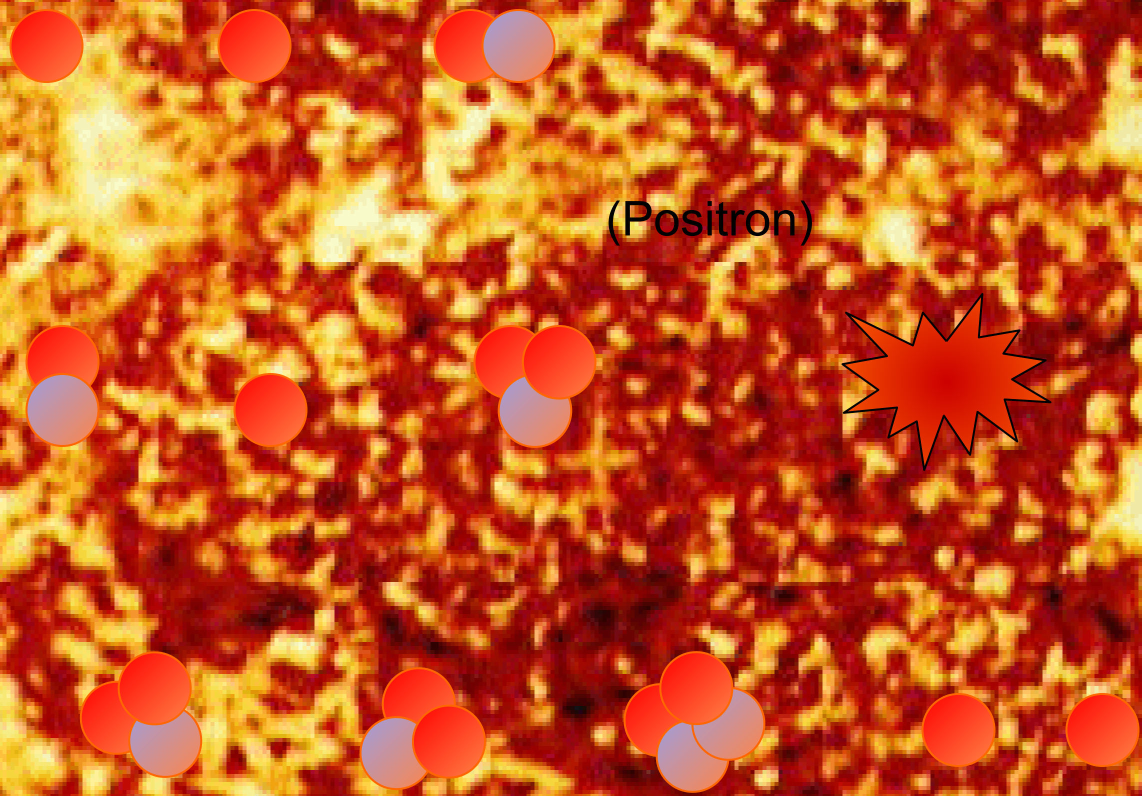
$$E = mc^2$$

Energy= (mass) (speed of light)^2





Nuclear Fusion

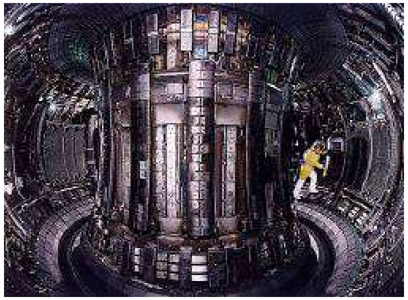


Cold Fusion

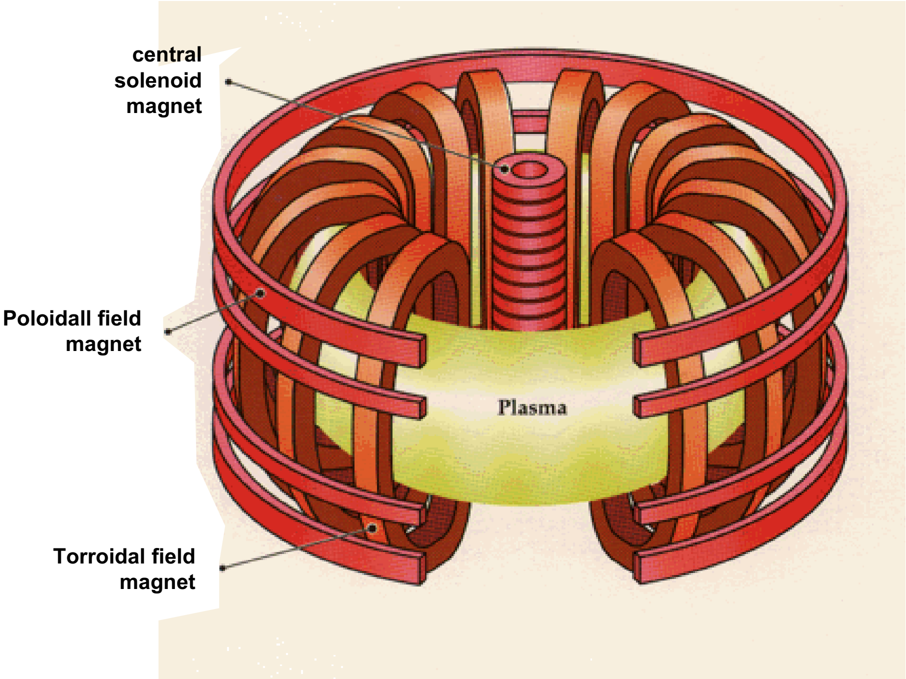
- Fraud?
- Experiments must be repeatable to be valid

Stanley Pons and
Martin Fleischman

Tokamak Reactor

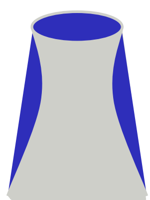


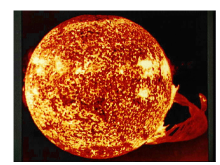
- Fusion reactor
- 10,000,000 º Celsius
- Russian for torroidial (doughnut shaped) ring
- Magnetic field contains *plasma*



Fission vs. Fusion

Different	Topic	Alike	Topic	Different
Split large atoms U-235	Fission	Change Nucleus of Atoms	Fusion	Fuse small atoms $2H_2 \rightarrow He$
Radioactive waste (long half-life)		Create Large Amounts of Energy $E = mc^2$		NO Radioactive waste
Nuclear Power Plants		Transmutation of Elements Occurs		Very High Temperatures ~5,000,000 °C (SUN)





Atomic Structure

- **ATOMS**
  - Differ by number of ***protons***

carbon vs. oxygen

6 protons 8 protons

- **IONS**
  - Differ by number of ***electrons***

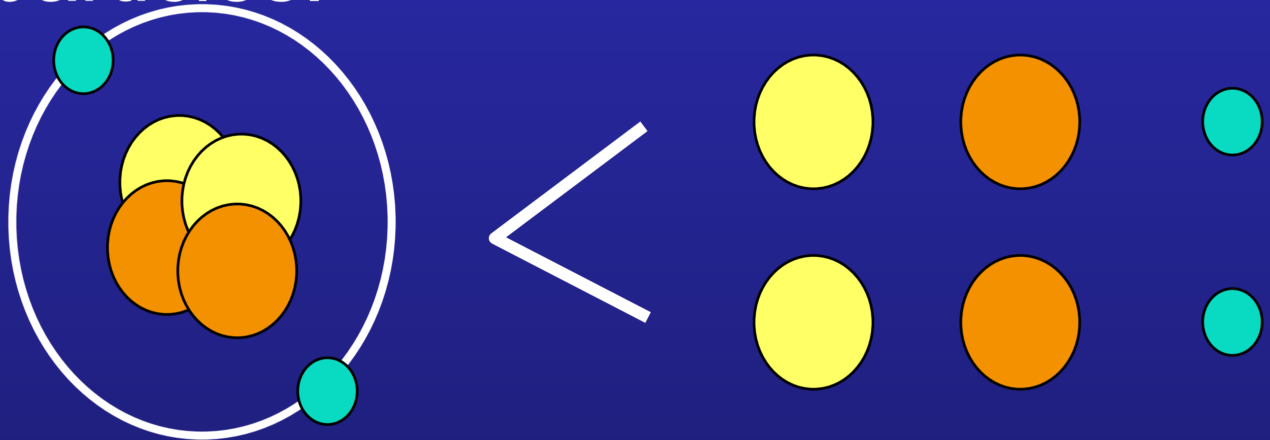
C	C^{4+}	C^{4-}
6 e^-	2 e^-	10 e-
6 p+	6 p^+	6 p^+

- **ISOTOPES**
  - Differ by number of ***neutrons***

C-12	vs.	C-14
6 e^-		6 e-
6 p+		6 p^+
6 n^0		8 n^0

Mass Defect

- Difference between the mass of an atom and the mass of its individual particles.



4.00260 amu

4.03298 amu

Courtesy Christy Johannesson www.nisd.net/communicationsarts/pages/chem

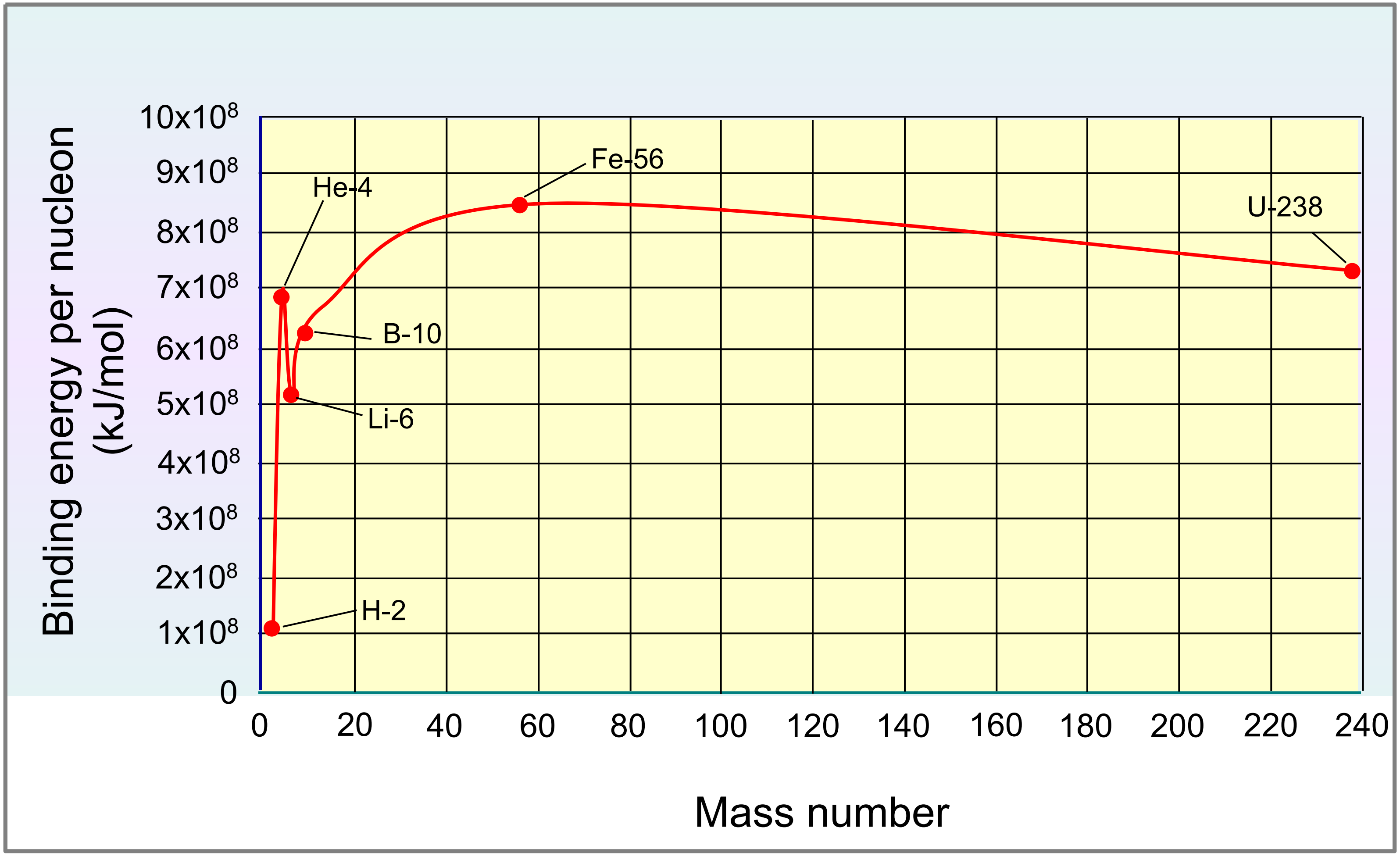
Nuclear Binding Energy

- Energy released when a nucleus is formed from nucleons.
- High binding energy = stable nucleus.

$$E = mc^2$$

E: energy (J)
m: mass defect (kg)
c: speed of light (3.00×10^8 m/s)

Nuclear Binding Energy



Unstable nuclides are radioactive and undergo radioactive decay.

Mass Defect and Nuclear Stability

2 protons:	(2 x 1.007276 amu) =	2.014552 amu
2 neutrons:	(2 x 1.008665 amu) =	2.017330 amu
2 electrons:	(2 x 0.0005486 amu) =	0.001097 amu
	Total combined mass:	4.032979 amu $\neq$ 4.002602 amu

The atomic mass of He atom is 4.002602 amu.
This is 0.030368 amu *less* than the combined mass.

This difference between the mass of an atom and the sum of the masses of its protons, neurons, and electrons is called the mass defect.

Nuclear Binding Energy

What causes the loss in mass?

According to Einstein's equation $E = mc^2$

Convert mass defect to energy units

$$0.030368 \text{ amu} \left(\frac{1.6605 \times 10^{-27} \text{ kg}}{1 \text{ amu}} \right) = 5.0426 \times 10^{-29} \text{ kg}$$

The energy equivalent can now be calculated

$$E = m\,c^2$$

$$E = (5.0426 \times 10^{-29} \text{ kg})\,(3.00 \times 10^{8} \text{ m/s})^2$$

$$E = (4.54 \times 10^{-12} \text{ kg m}^2/\text{s}^2) = 4.54 \times 10^{-12} \text{ J}$$

This is the NUCLEAR BINDING ENERGY, the energy released when a nucleus is formed from nucleons.

Binding Energy per Nucleon

1) Calculate mass defect

protons: 1.007276 amu

neutrons: 1.008665 amu

electrons: 0.0005486 amu

mass number
(# of protons
+ neutrons)

7
Li
3

atomic number
(# of protons)

Li - 7

2) Convert amu ⟶ kg

$$\_\_\_\_\_\_\_\_ \text{ amu} \left(\frac{1.6605 \times 10^{-27} \text{ kg}}{1 \text{ amu}} \right) = \_\_\_\_\_\_\_\_ \text{ kg}$$

3) $E = mc^2$

speed of light (c) 3.00×10^{8} m/s

4) Divide binding energy by number of nucleons

The Energy of Fusion

The fusion reaction releases an enormous amount of energy relative to the mass of the nuclei that are joined in the reaction. Such an enormous amount of energy is released because some of the mass of the original nuclei is converted to energy. The amount of energy that is released by this conversion can be calculated using Einstein's relativity equation $E = mc^2$.

Suppose that, at some point in the future, controlled nuclear fusion becomes possible. You are a scientist experimenting with fusion and you want to determine the energy yield in joules produced by the fusion of one mole of deuterium (H-2) with one mole of tritium (H-3), as shown in the following equation:

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

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

2.01345 amu 3.01550 amu 4.00150 amu 1.00867 amu

5.02895 amu **5.01017 amu**

First, you must calculate the mass that is *"lost"* in the fusion reaction. The atomic masses of the reactants and products are as follows:
deuterium (2.01345 amu), tritium (3.01550 amu), helium-4 (4.00150 amu), and a neutron (1.00867 amu).

Mass defect:

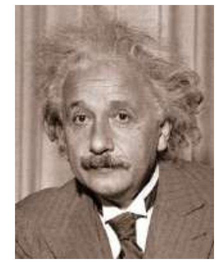
-

0.01878 amu

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

Mass defect = 0.01878 amu

According to Einstein's equation $E = mc^2$



Convert mass defect to energy units

$$ 0.01878 \text{ amu} \left(\frac{1.6605 \times 10^{-27} \text{ kg}}{1 \text{ amu}} \right) = 3.1184 \times 10^{-29} \text{ kg} $$

The energy equivalent can now be calculated

$$ E = m\, c^2 $$

$$ E = (3.1184 \times 10^{-29}\ kg)\ (3.00 \times 10^{8}\ m/s)^2 $$

$$ E = (2.81 \times 10^{-12}\ kg\ m^2/s^2) = 2.81 \times 10^{-12}\ J $$

This is the NUCLEAR BINDING ENERGY, for the formation of a single Helium atom from a deuterium and tritium atom.

Therefore, one mole of helium formed by the fusion of one mole of deuterium and one mole of hydrogen would be 6.02×10^{23} times greater energy.

$$
\begin{array}{rl}
 & 2.81 \times 10^{-12}\ J \\
\times & 6.02 \times 10^{23} \\
\hline
 & 1.69 \times 10^{12}\ J \text{ of energy released per mole of helium formed}
\end{array}
$$

1,690,000,000,000 J

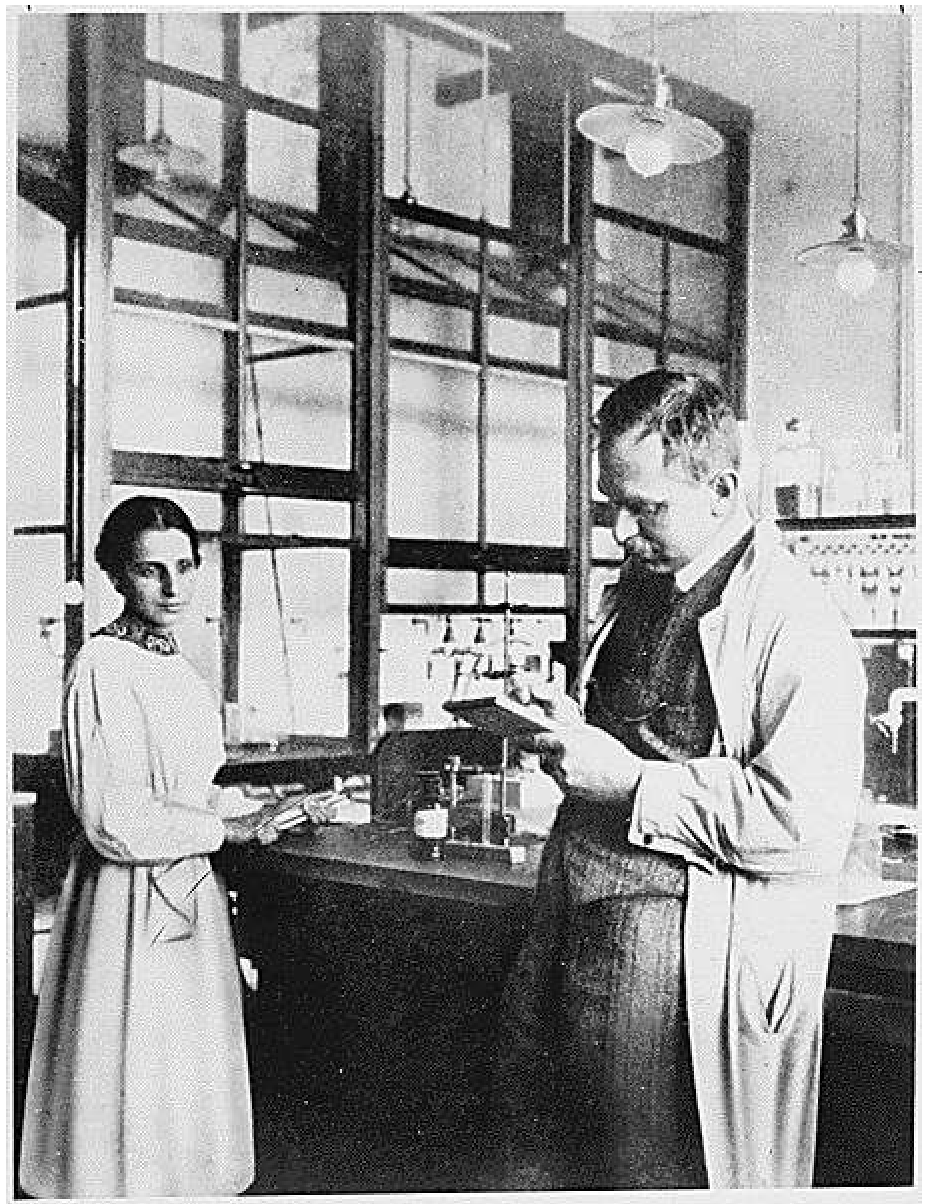
The combustion of one mole of propane (C_3H_8), which has a mass of 44 g, releases 2.043×10^6 J. How does this compare to the energy released by the fusion of deuterium and tritium, which you calculated?

$$C_3H_8 + O_2 \longrightarrow H_2O + CO_2 + 2.043 \times 10^6\ J \quad \text{(unbalanced)}$$

44 g

4 g He	1,690,000,000,000 J	Fusion produces ~1,000,000 x
44 g C_3H_8	2,043,000 J	more energy/mole

Lise Meitner and Otto Hahn

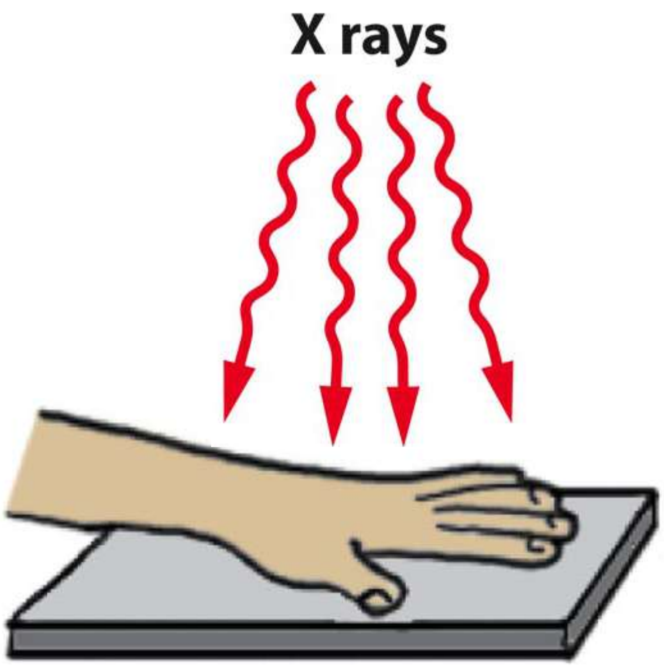


Atoms for Peace

Bombing of Japan in WW II

- Eisenhower
  - Show nuclear science is not evil
  - Has good uses, too.
- Food irradiation
- Cancer treatment
- PET & CAT scan
- Destroy ANTHRAX bacteria

Radiology



Photographic film enclosed in lightproof holder

Exposed and developed photographic film

X-rays

Chest X-ray showing scoliosis corrected with steel rod

Radioisotopes

- Radioactive isotopes
- Many uses
  - Medical diagnostics
  - Optimal composition of fertilizers
  - Abrasion studies in engines and tires

Radioisotope is injected into the bloodstream to observe circulation.

Isotopes of Three Common Elements

Element	Symbol	Mass Number	Mass (amu)	Fractional Abundance	Average Atomic Mass
Carbon	$^{12}_{6}C$	12	12 (exactly)	99.89%	12.01
	$^{13}_{6}C$	13	13.003	1.11%	
Chlorine	$^{35}_{17}Cl$	35	34.969	75.53%	35.45
	$^{37}_{17}Cl$	37	36.966	24.47%	
Silicon	$^{28}_{14}Si$	28	27.977	92.21%	28.09
	$^{29}_{14}Si$	29	28.976	4.70%	
	$^{30}_{14}Si$	30	29.974	3.09%	

LeMay Jr, Beall, Robblee, Brower, Chemistry Connections to Our Changing World , 1996, page 110

Radioactivity and Nuclear Energy

Practice Quiz

1. Which of the following is *not* an example of spontaneous radioactive process?
   - a. alpha-decay
   - b. beta-decay
   - c. positron production
   - ★ d. autoionization
   - e. electron capture

2. If a nucleus captures an electron, describe how the atomic number will change.
   - a. It will increase by one
   - ★ b. It will decrease by one
   - c. It will not change because the electron has such a small mass
   - d. It will increase by two
   - e. It will decrease by two

mass number

$$^{14}_{7}N + ^{0}_{-1}\beta \longrightarrow ^{14}_{6}C$$

atomic number

Radioactivity and Nuclear Energy

3. Polonium is a naturally radioactive element decaying with the loss of an alpha particle. ${}^{210}_{84}Po \longrightarrow {}^{4}_{2}He \quad + \quad$ _?_. What is the second product of this decay?

   a. Rn-214
   ☆ b. Pb-206
   c. At-206
   d. Hg-208
   e. none of these

$${}^{210}_{84}Po + {}^{4}_{2}\alpha \longrightarrow {}^{214}_{86}Rn$$

alpha *absorption*

$${}^{210}_{84}Po \longrightarrow {}^{4}_{2}\alpha + {}^{206}_{82}Pb$$

alpha *emission*

4. Thorium-234 undergoes beta particle production. What is the other product?

   ☆ a. ${}^{234}_{91}Pa$
   b. ${}^{234}_{89}Ac$
   c. ${}^{233}_{90}Th$
   d. ${}^{233}_{91}Th$
   e. none of these

$${}^{234}_{90}Th \longrightarrow {}^{0}_{-1}\beta + {}^{234}_{91}Pa$$

Radioactivity and Nuclear Energy

5. The element curium (*Z* = 242, *A* = 96) can be produced by positive-ion bombardment when an alpha particle collides with which of the following nuclei? Recall that a neutron is also a product of this bombardment.

   a. $^{249}_{98}\text{Cf}$

   b. $^{241}_{94}\text{Pu}$

   c. $^{241}_{95}\text{Am}$

   d. $^{239}_{92}\text{U}$

   ★ e. $^{239}_{94}\text{Pu}$

$$^{239}_{94}\text{Pu} + {}^{4}_{2}\alpha^{2+} \longrightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}n$$

6. When $^{14}_{7}\text{N}$ is bombarded by (and absorbs) a proton, a new nuclide is produced plus an alpha particle. The nuclide produced is ______?

$$^{14}_{7}\text{N} + {}^{1}_{1}p \longrightarrow {}^{11}_{6}\text{C} \;\text{C-11} + {}^{4}_{2}\alpha$$

Radioactivity and Nuclear Energy

7. When the uranium-235 nucleus is struck with a neutron, the cesium-144 and strontium-90 nuclei are produced with some neutrons and electrons. a) How many neutrons are produced? b) How many electrons are produced?

a)

☆ a. 2
b. 3
c. 4
d. 5
e. 6

b)

☆ a. 1
b. 2
c. 3
d. 4
e. 5

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{144}_{55}Cs + ^{90}_{38}Sr + 2\,^{1}_{0}n + ^{0}_{-1}\beta$$

8. When the palladium-106 nucleus is struck with an alpha particle, a proton is produced along with a new element. What is the new element?

a. cadmium-112
b. cadmium-109
c. silver-108
☆ d. silver-109
e. none of these

$$^{106}_{46}Pd + ^{4}_{2}\alpha \longrightarrow ^{1}_{1}p + ^{109}_{47}Ag$$

Radioactivity and Nuclear Energy

9. Strontium-90 from radioactive fallout is a health threat because, like __________, it is incorporated into bone.

   a. iodine
   b. cesium
   c. iron
   ☆ d. calcium
   e. uranium

Strontium (Sr) and calcium (Ca) are alkaline earth metals. Strontium is chemically more reactive than calcium.

10. Nuclear fusion uses heavy nuclides such as $^{235}_{92}U$ as fuel. **True / False**

FALSE,
Nuclear fission *splits heavy nuclides such as U-235 for fuel in nuclear reactors.*
Nuclear fusion *joins light nuclides such as H-1 into He-4 (on the Sun).*

Textbook Problems

Modern Chemistry

Chapter 22

Pg 704 #1-4 Section Review
Pg 712 #1-5 Section Review
Pg 715 #1-4
Pg 719 #1-4
End of Chapter #25-47 (pg 723-724)

25. The mass of a Ne-20 atom is 19.99244 amu.
    Calculate its mass defect.

26. The mass of Li-7 is 7.01600 amu.
    Calculate its mass defect.

27. Calculate the nuclear binding energy of one lithium-6 atom.
    The measured atomic mass of lithium-6 is 6.015 amu.