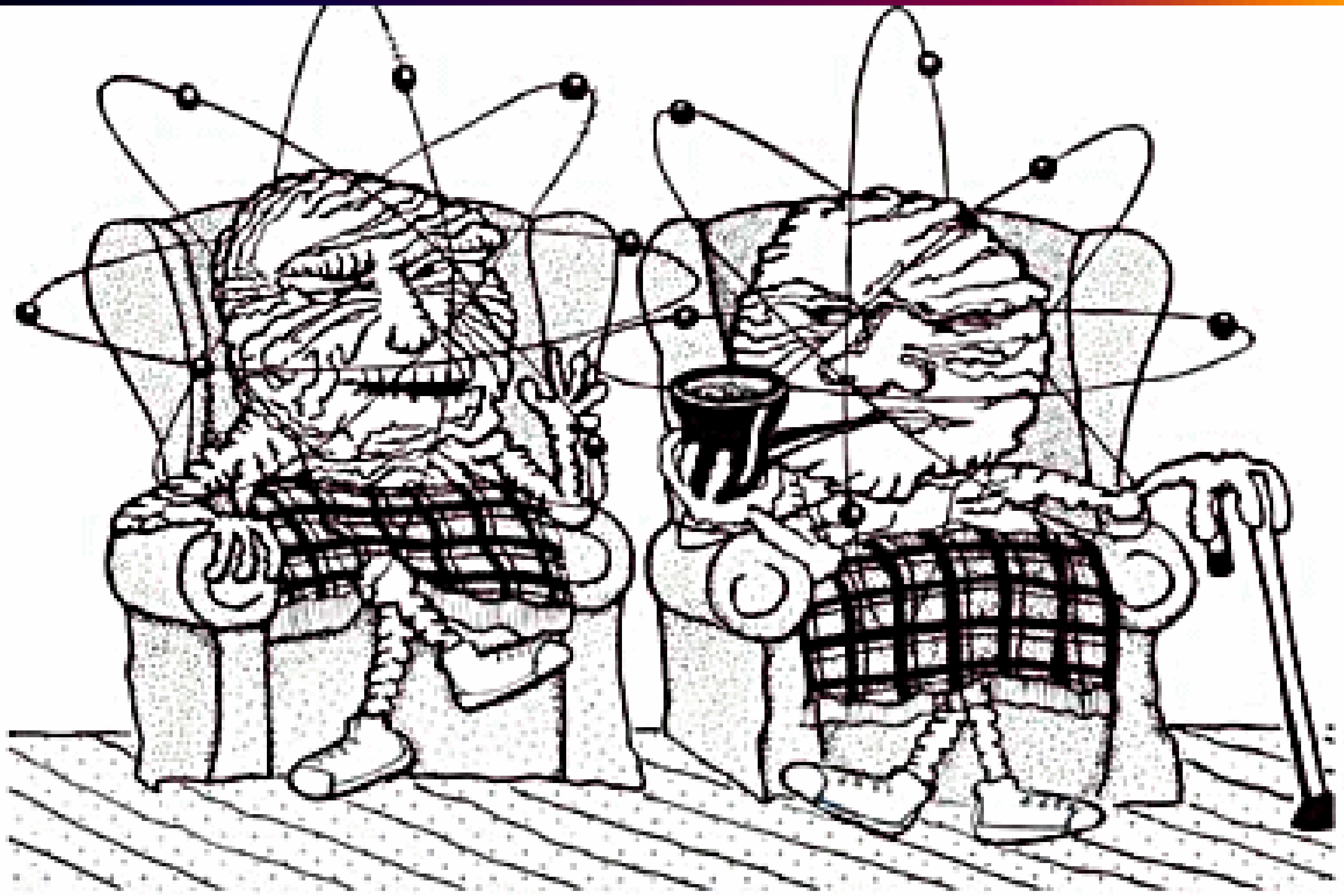
Nuclear Chemistry

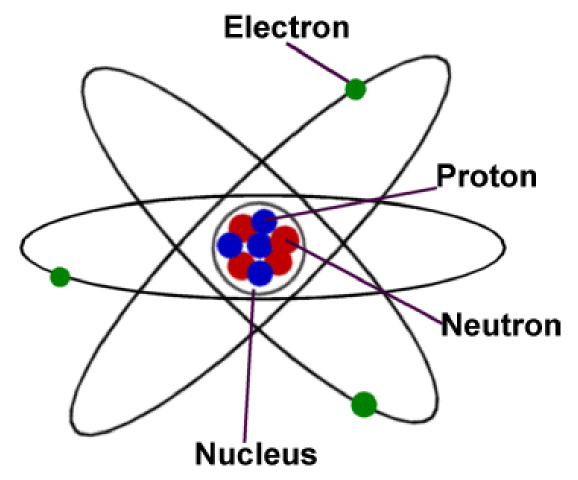


"When I was young I used to feel so alive, so dangerous! In fact, would you believe I started life as a Uranium-238? Then one day I accidentally ejected an alpha particle....now look at me, a spent old atom of Lead-206. Seems that all my life since then has been nothing but decay, decay, decay..."

Atomic Structure

- INSIDE the Nucleus:
  - Protons (+)
  - Neutrons (no charge)
  - 99.9% of the mass of the atom (Rutherford – central dense nucleus)

- OUTSIDE the Nucleus:
  - Electrons (-)
  - Little mass
  - Located in electron clouds



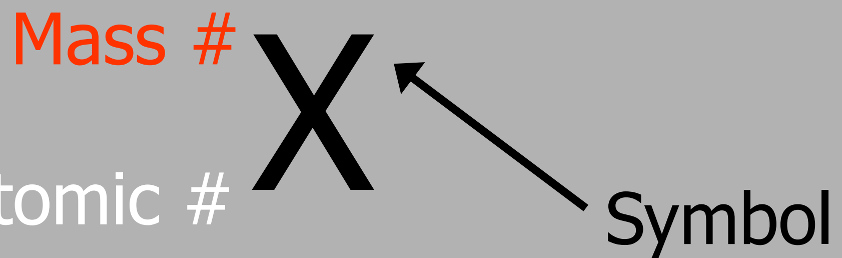
Atomic Structure

- Atomic number = number of protons (p^+)
  - Every atom of an element has the same atomic number because the number of protons defines the element

- Mass number (or atomic mass) =sum of p^+ & n°

  The number of neutrons (n°) may vary without changing the element

- Atomic notation:



Mass #

Atomic #

X

Symbol

Ex: Magnesium Atom: $^{25}_{12}\text{Mg}$

Atomic Structure

- Number of electrons = number of protons in a neutral atom
- To calculate the number of electrons for an ion:
  - Cation: lost electron(s)

    Ca^{2+} 20 protons

    20 electrons → 18 electrons
  - Anion: gained electron(s)

    F^{1-} 9 protons

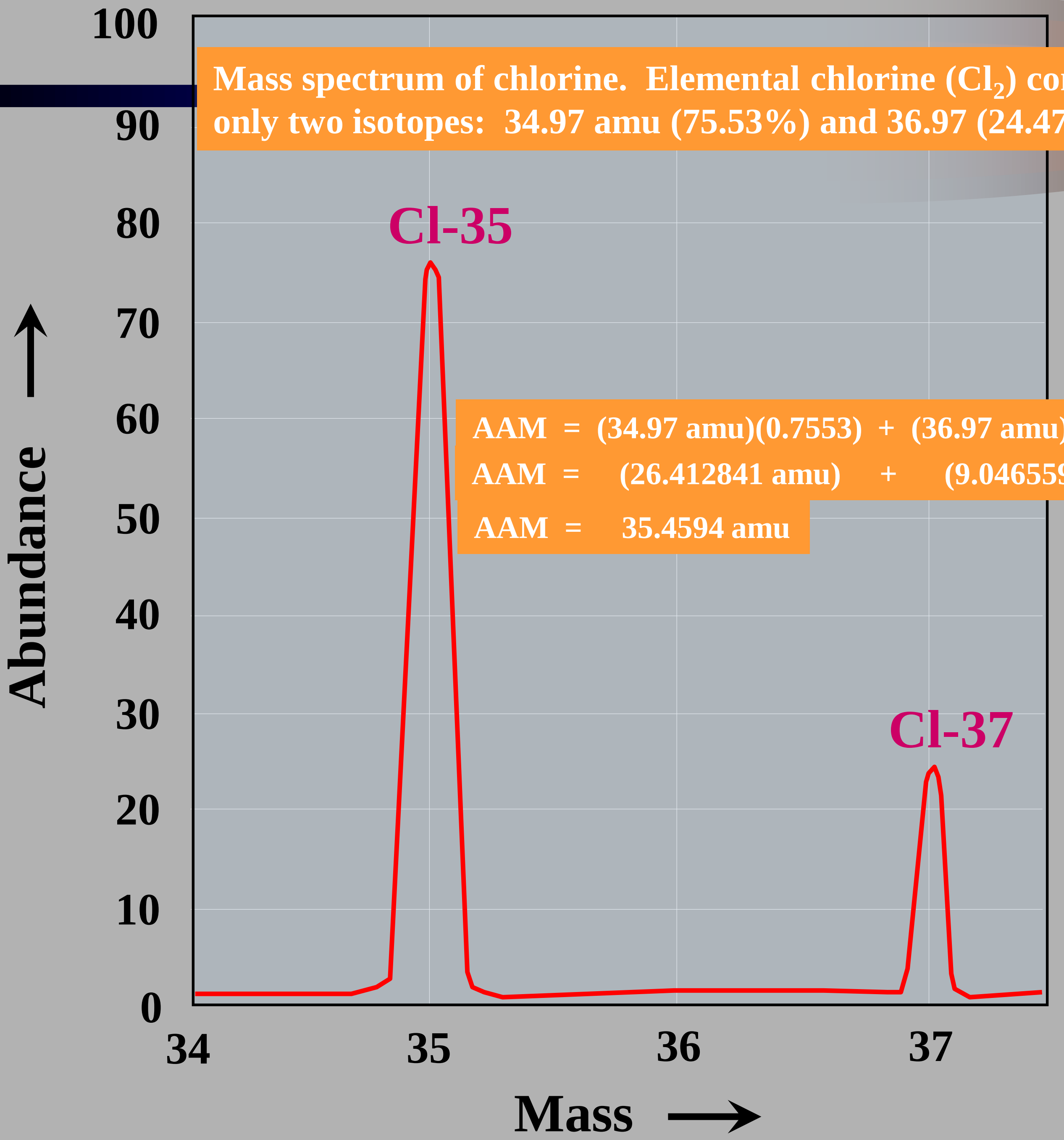
    9 electrons → 10 electrons

Practice

Fill in the blanks:

Name	**Symbol**	**# p**	**# n**
Hydrogen-1	$^{1}_{1}\text{H}$	1	0
Helium-5	$^{5}_{2}\text{He}$	2	3
Carbon-13	$^{13}_{6}\text{C}$	6	7

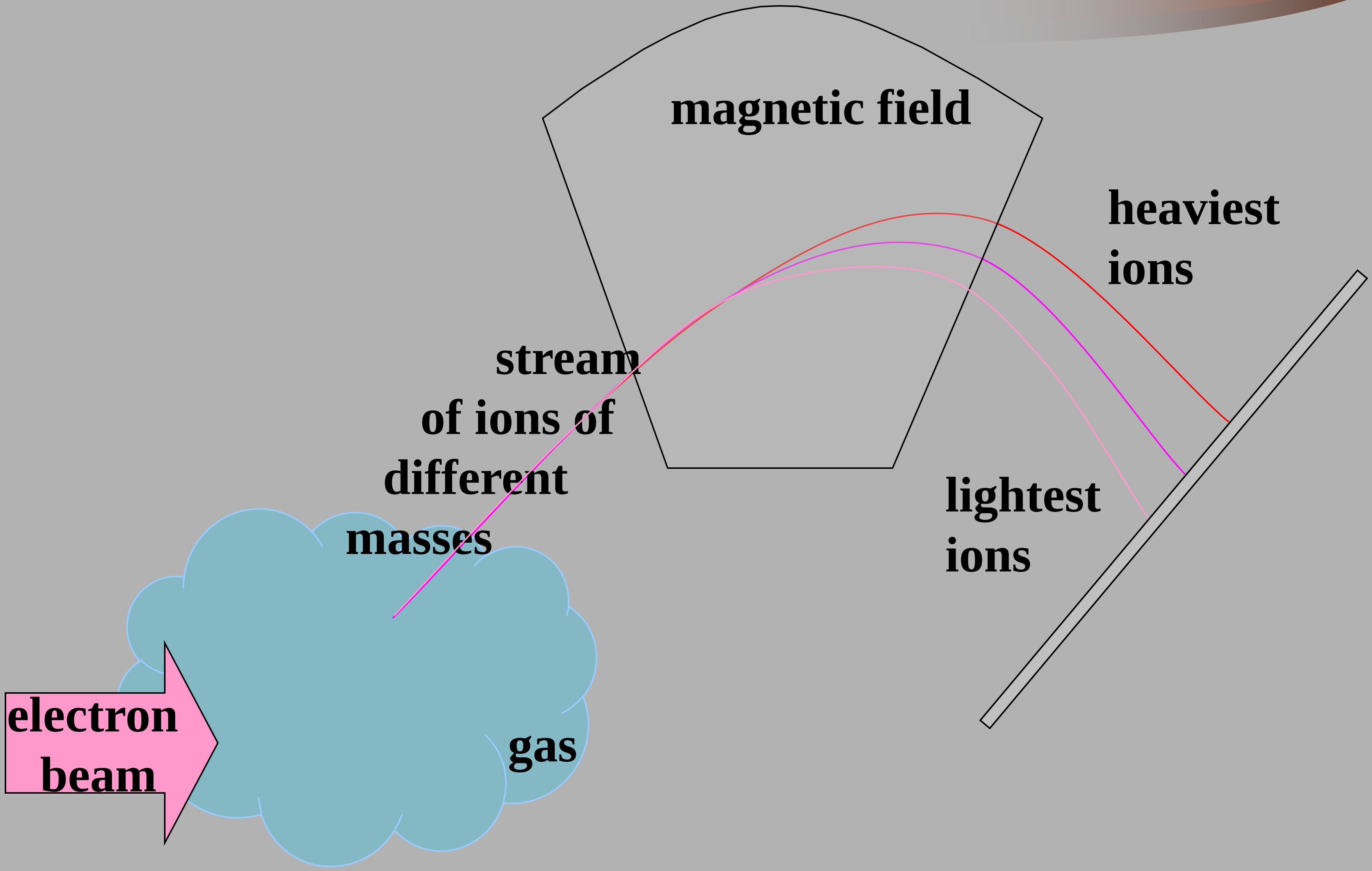
Mass spectrum of chlorine. Elemental chlorine (Cl_2) contains only two isotopes: 34.97 amu (75.53%) and 36.97 (24.47%)



AAM = (34.97 amu)(0.7553) + (36.97 amu)(0.2447)
AAM = (26.412841 amu) + (9.046559 amu)
AAM = 35.4594 amu

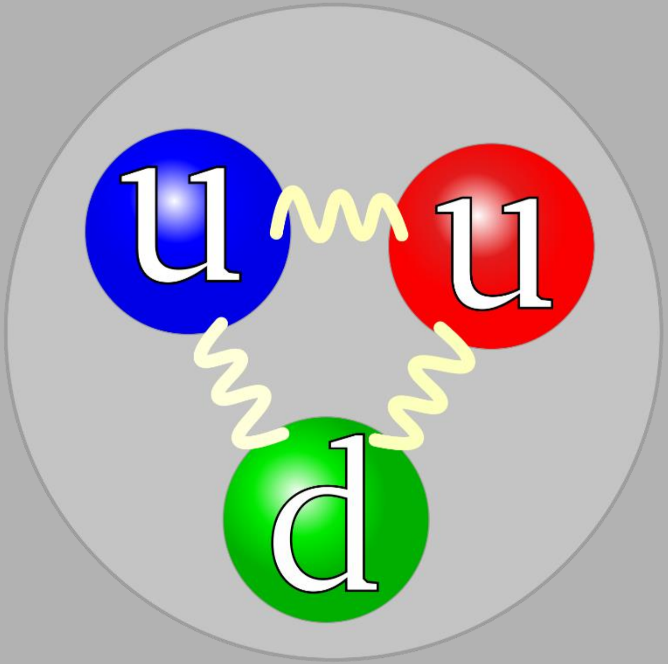
17
Cl
35.4594

Mass Spectrophotometer



Quark

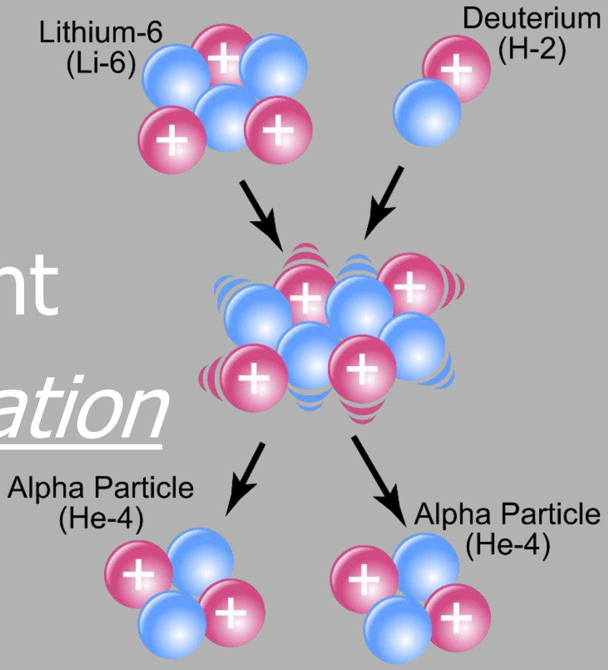
- An elementary particle of matter
- Quarks combine to form protons and neutrons



Nuclear Reactions

- Unstable nuclei undergo SPONTANEOUS changes that alter the numbers of protons and neutrons
- This gives off large amounts of energy and increases their stability
- Called a *Nuclear Reaction*
- The changing of one element

to another is called *Transmutation*



Lithium-6 – Deuterium Reaction

Natural Radioactivity

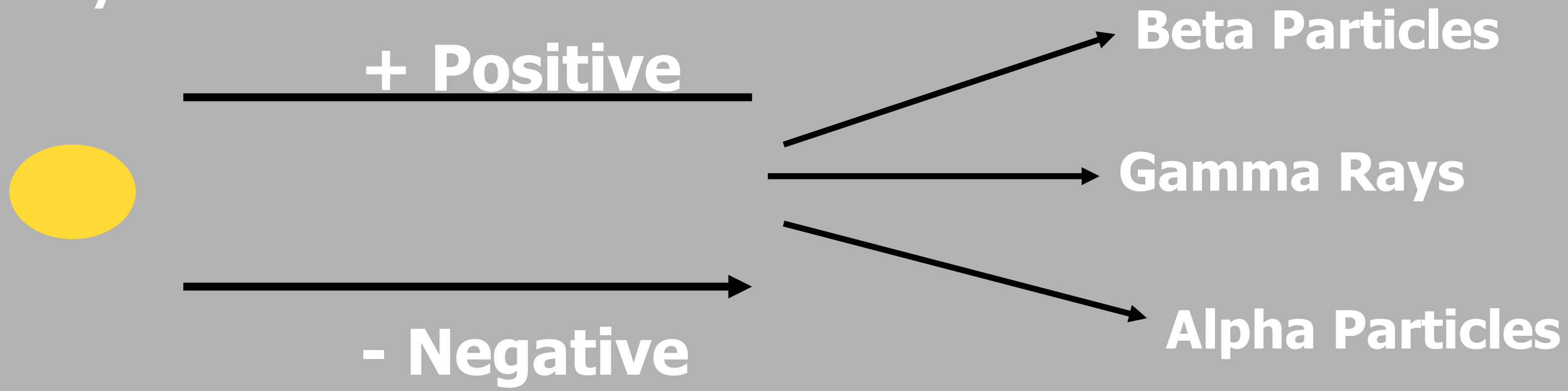
* Discovered in 1896 by Antoine Henri Becquerel, who observed that a uranium caused a photographic plate to fog up as if it had been exposed to light (therefore emitting radiation)

* The term *radioactivity* was coined in 1898 by Marie Curie, a Polish physicist, who was doing research with her husband Pierre. (They eventually died of radiation-related illnesses.) There are four noble prizes in the Curie family!

Radioactivity: spontaneous emission of particles and/or energy from the nucleus of an atom

Lord Ernest Rutherford

- Isolates and identifies what “radioactivity” really is.



+ Positive

- Negative

Beta Particles

Gamma Rays

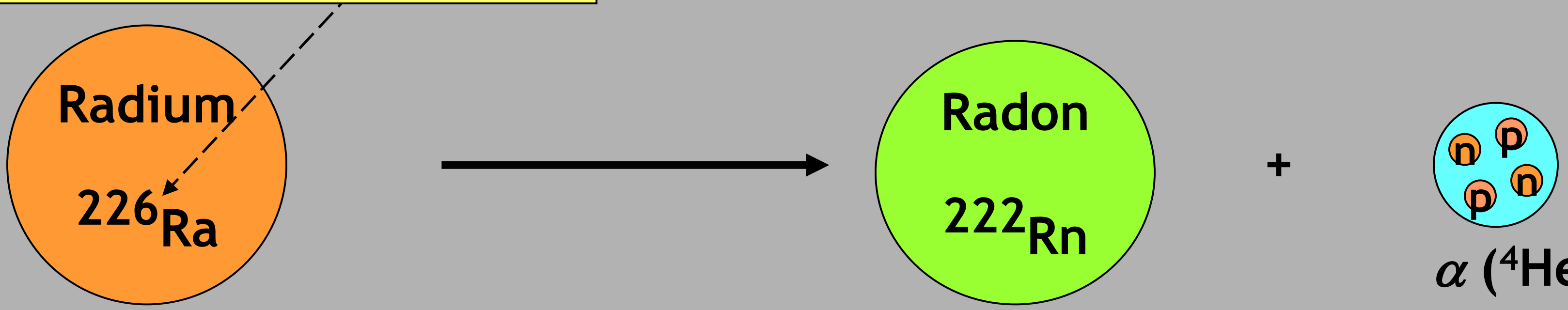
Alpha Particles

Types of Radioactive Decay

Type	Symbol	Charge	Interesting Fact
alpha α	$^{4}_{2}He$ Helium nucleus	2+	If ingested, is harmful to lungs
beta β	$^{0}_{-1}\mathbf{e}$ An electron	1-	Causes damage to sensitive tissues like eyes
gamma γ	γ High energy photon	0	Causes severe damage to body tissues

Alpha Particles (α)

Note: This is the atomic mass, which is the number of protons plus neutrons



Radium

^{226}Ra

88 protons
138 neutrons

$\rightarrow$

Radon

^{222}Rn

86 protons
136 neutrons

+

α (^{4}He)

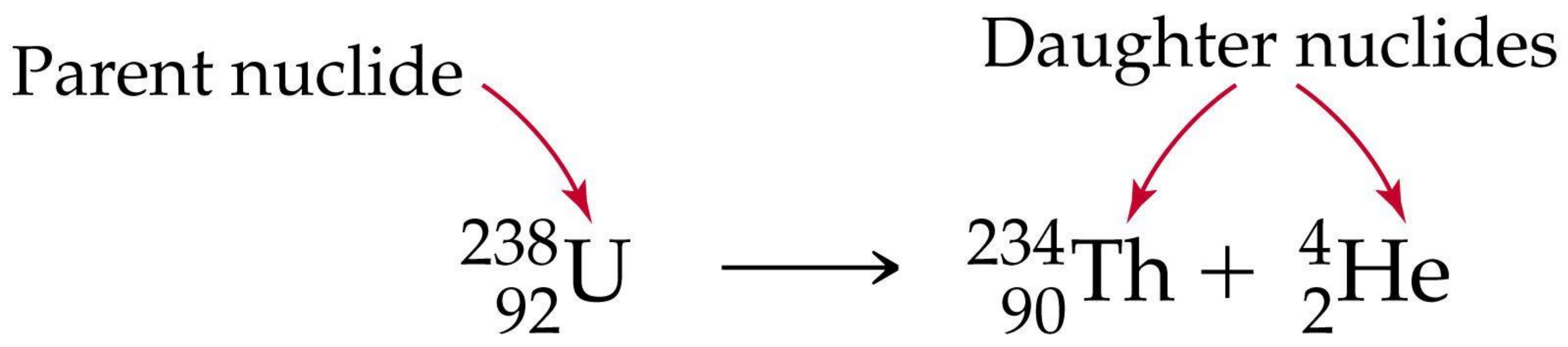
2 protons
2 neutrons

The alpha-particle (α) is a Helium nucleus.

It's the same as the element Helium, with the electrons stripped off!

Alpha Emission/Decay

- Two protons & two neutrons bound together and emitted from the nucleus

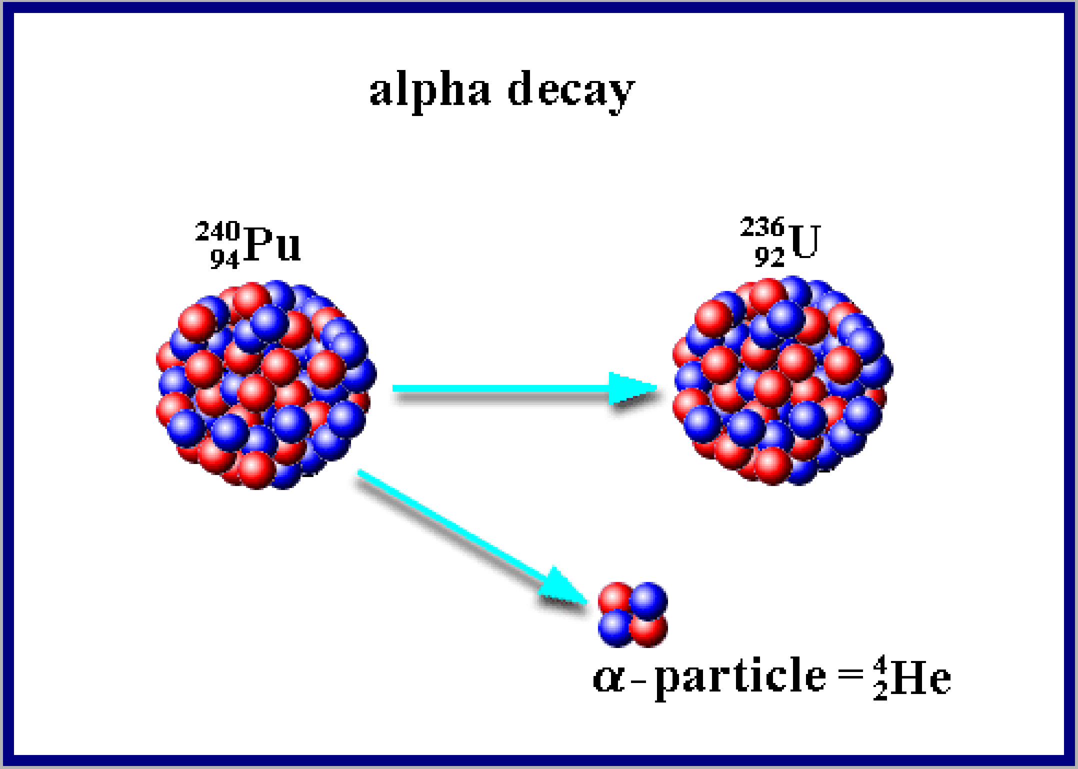


$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

Alpha Decay

Example:

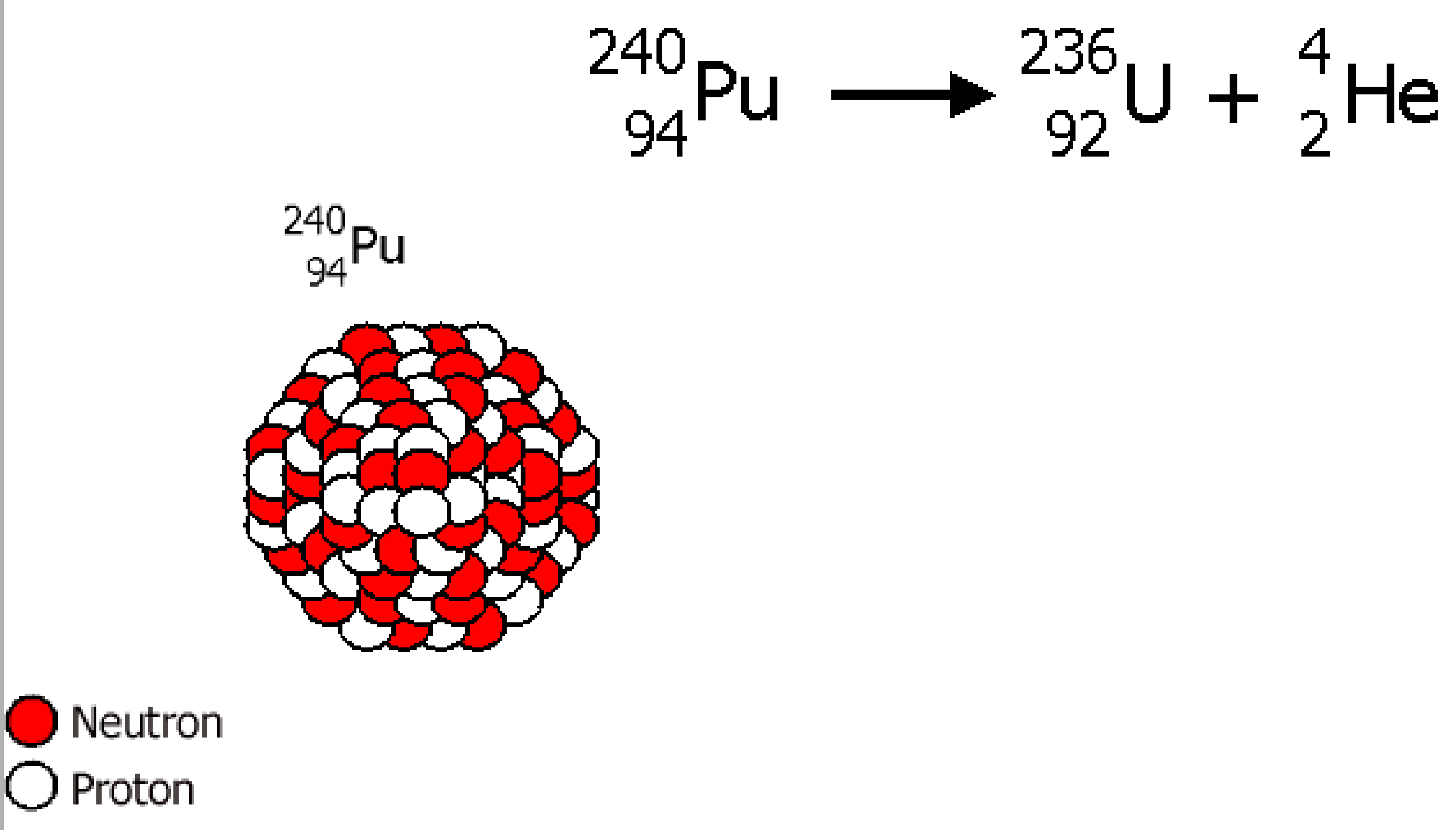
$$^{240}_{94}\mathrm{Pu} \longrightarrow \ ? \ + \ ^{4}_{2}\mathrm{He}$$



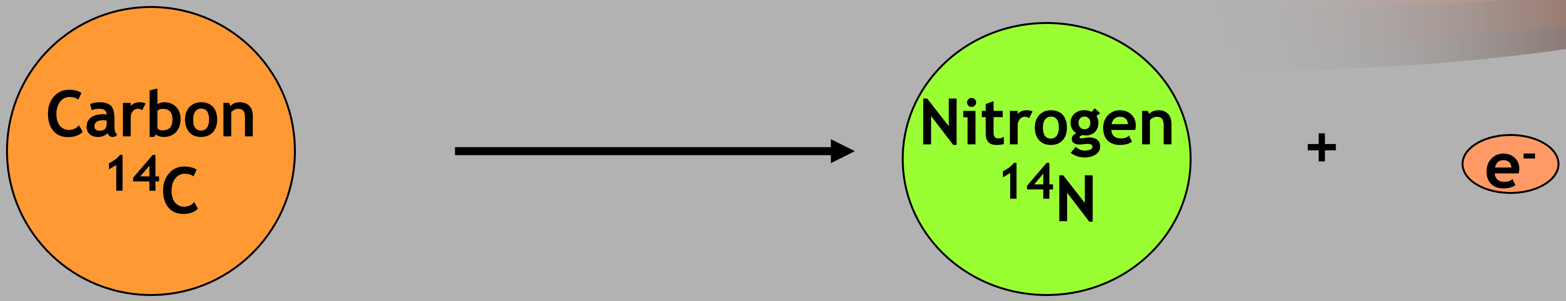
Alpha Decay

Example:

$$^{240}_{94}\text{Pu} \longrightarrow \, ^{236}_{92}\text{U} \quad + \quad ^{4}_{2}\text{He}$$



Beta Particles (β)



6 protons
8 neutrons

7 protons
7 neutrons

electron
(beta-particle)

We see that one of the neutrons from the C^{14} nucleus “converted” into a proton, and an electron was ejected. The remaining nucleus contains 7p and 7n, which is a nitrogen nucleus. In symbolic notation, the following process occurred:

$$n \rightarrow p + e \quad (+ n)$$

Yes, the same neutrino we saw previously

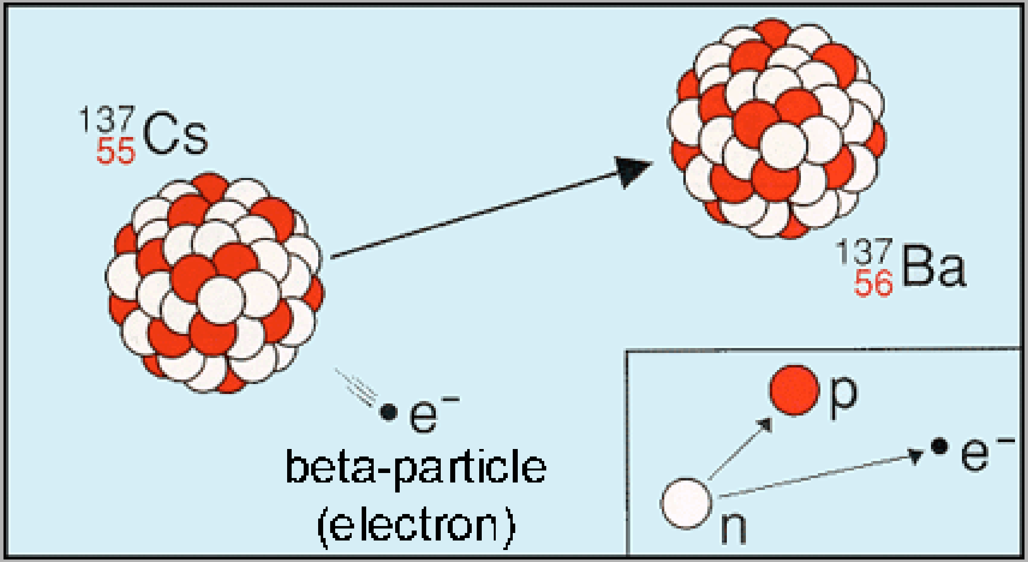
<u>Beta Emission</u>: e- emitted from the nucleus as a beta particle

- **Ex:**

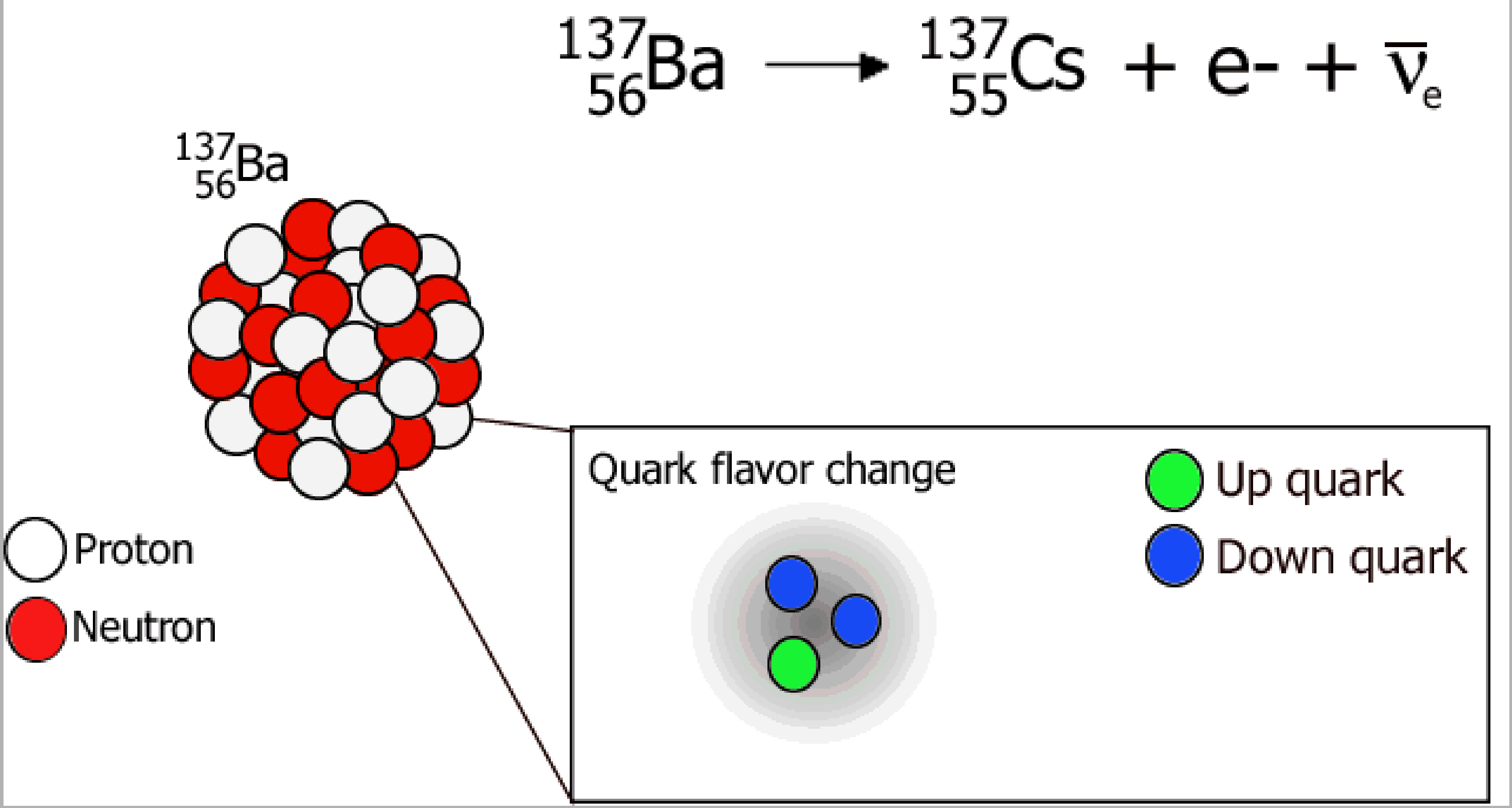
$$^{137}_{55}\mathrm{Cs} \longrightarrow \;?\; + \;^{0}_{-1}\mathrm{e}$$

$$^{1}_{0}\mathrm{n} \longrightarrow \;?\; + \;^{0}_{-1}\mathrm{e}$$

(One of Cs’s neutrons converts to a proton and electron.)

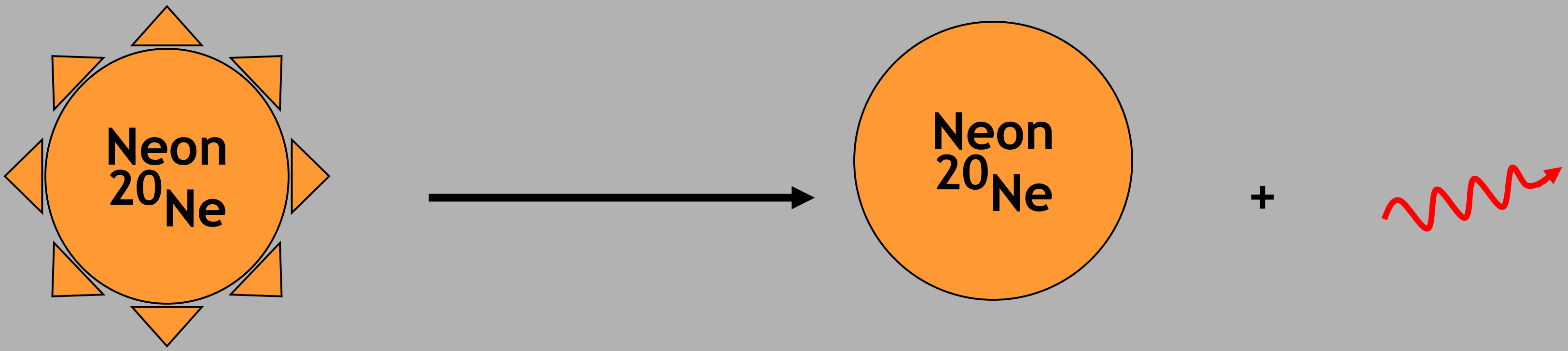


Beta Emission/Decay



Gamma Particles (γ)

In much the same way that electrons in atoms can be in an *excited state*, so can a nucleus.



10 protons
10 neutrons
(in excited state)

10 protons
10 neutrons
(lowest energy state)

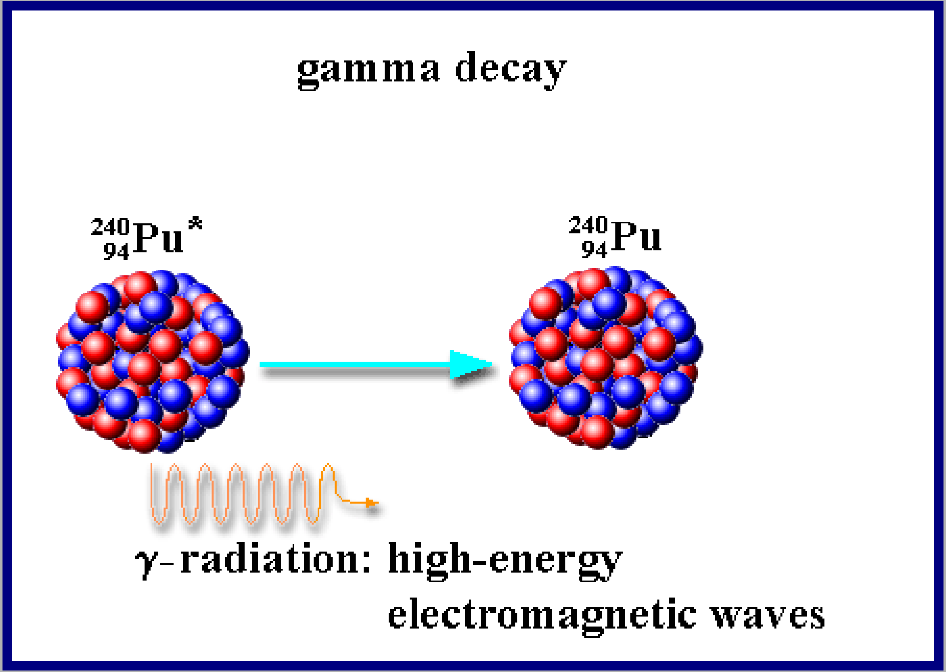
gamma

A *gamma* is a high energy *light particle*.

It is NOT visible by your naked eye because it is not in the visible part of the electromagnetic spectrum.

Gamma Ray Emission

- High-energy electromagnetic waves emitted from a nucleus as it changes from an excited state to a ground state
- **Ex:** Pu* (energized) → Pu (stable)



Your turn!

Write the balanced equation for the following nuclear reactions:

1. Beta decay of Phosphorus-32

$$^{32}_{15}\mathrm{P} \longrightarrow \boxed{^{32}_{16}\mathrm{S}} + {}^{0}_{-1}\mathrm{e}$$

2. Alpha decay of U-238

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

3. Decay of Oxygen-17 into Nitrogen-17

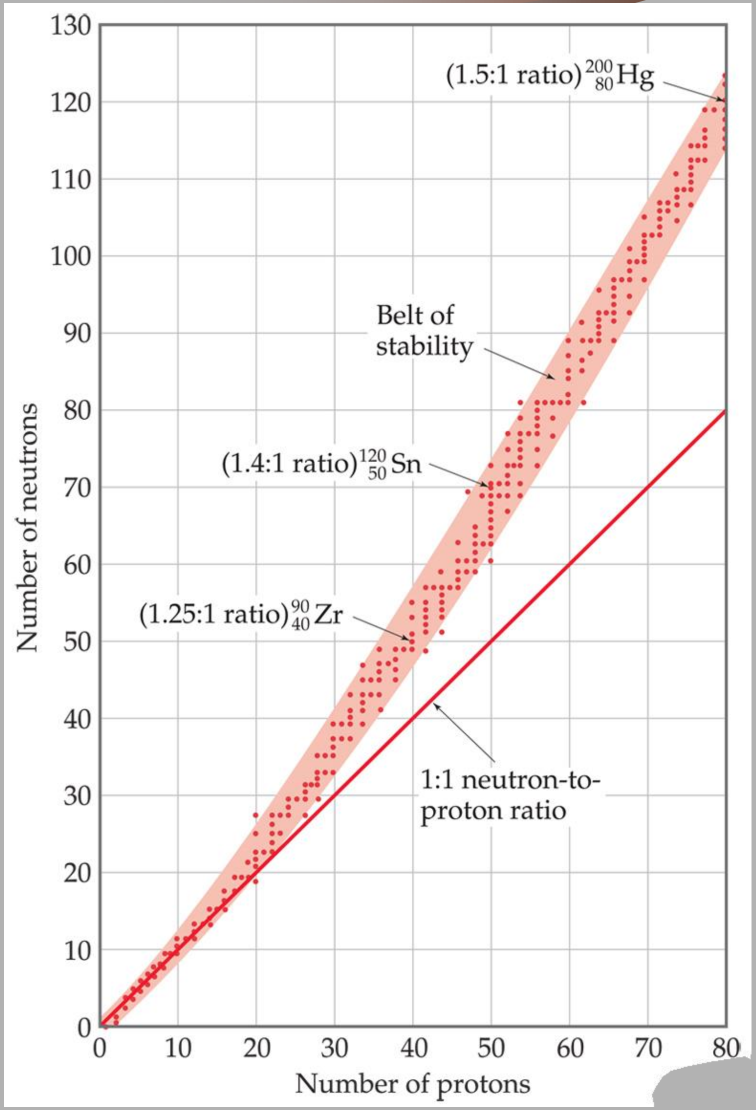
$$^{17}_{8}\mathrm{O} \longrightarrow {}^{17}_{7}\mathrm{N} + \boxed{^{0}_{+1}\mathrm{e}}$$

4. Decay of Potassium-42 into Calcium-42

$$^{42}_{19}\mathrm{K} \longrightarrow {}^{42}_{20}\mathrm{Ca} + \boxed{^{0}_{-1}\mathrm{e}}$$

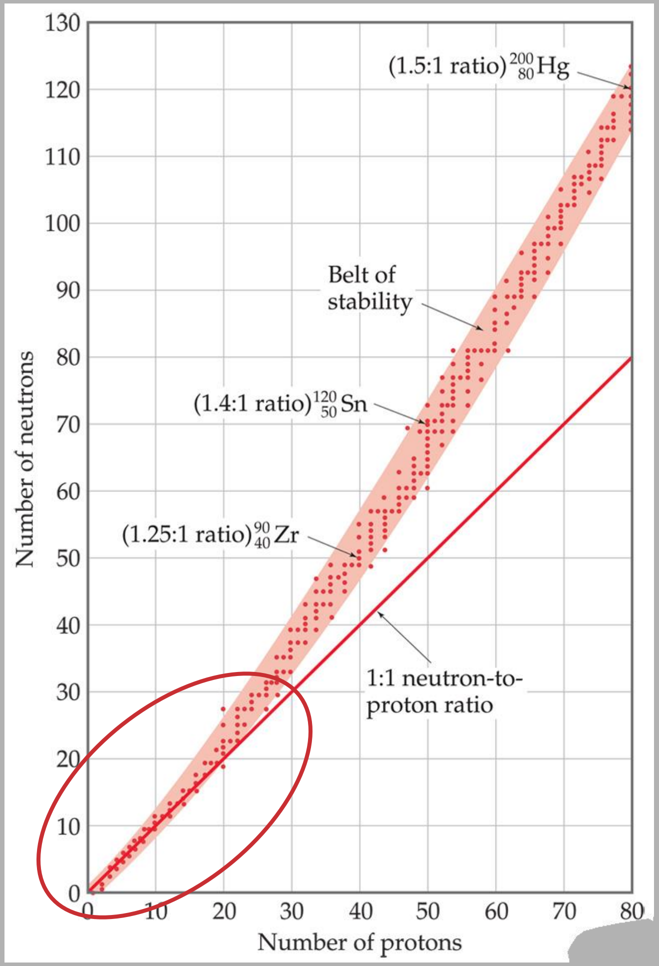
Neutron-Proton Ratios

- Any element with more than one proton (i.e., anything but hydrogen) will have repulsions between the protons in the nucleus
- A strong nuclear force helps keep the nucleus from flying apart
- Neutrons play a key role stabilizing the nucleus
- Therefore, the *ratio of neutrons to protons is an important factor*



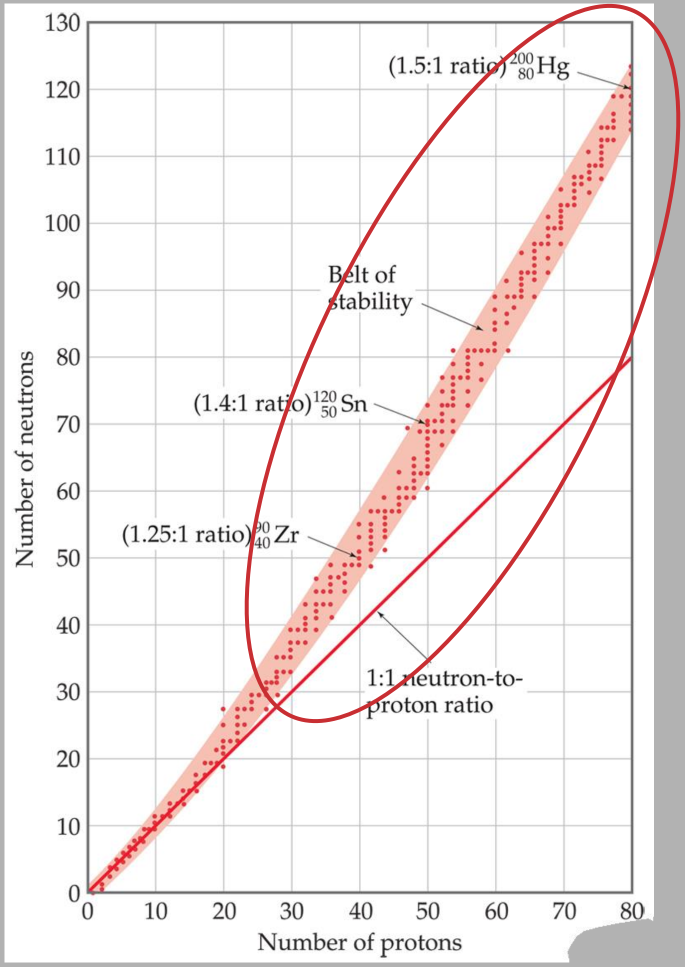
Neutron-Proton Ratios

For smaller nuclei (Atomic Number ≤ 20) stable nuclei have a neutron-to-proton ratio close to 1:1



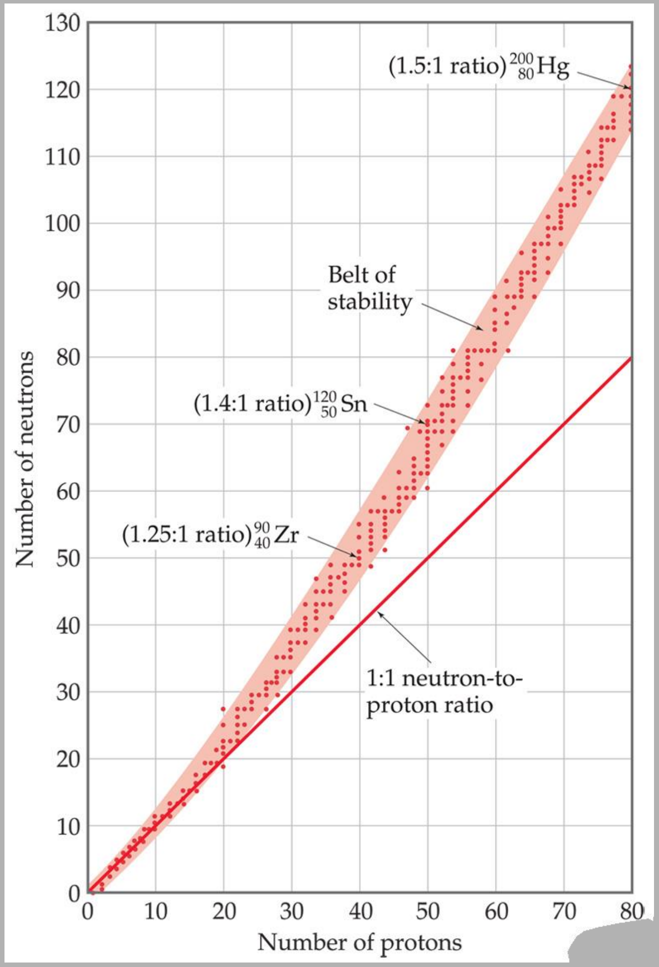
Neutron-Proton Ratios

As nuclei get larger, it takes a greater number of neutrons to stabilize the nucleus



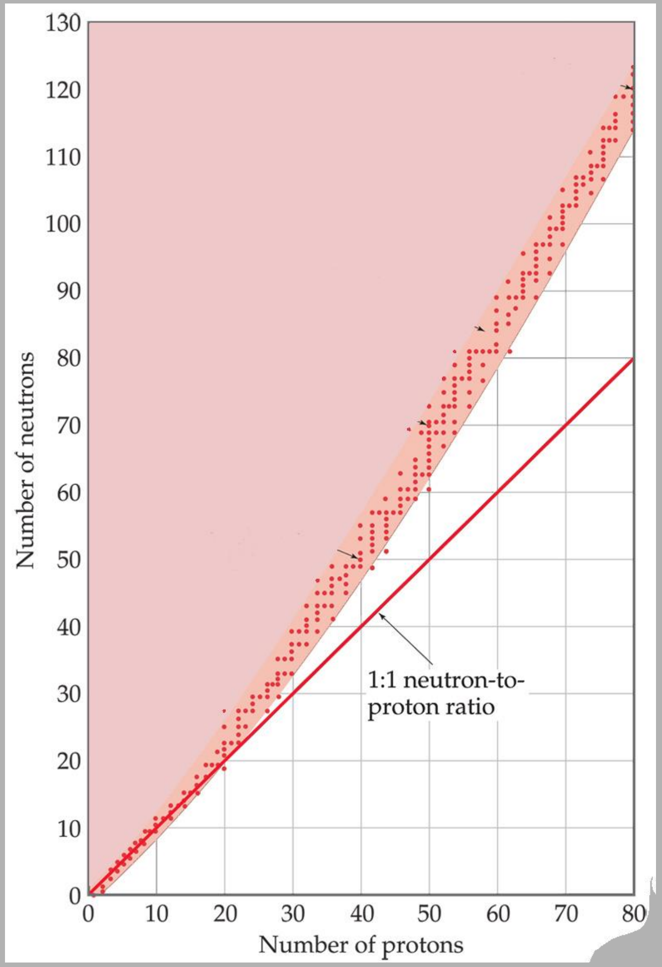
Stable Nuclei

The shaded region in the figure shows what nuclides would be stable, the so-called belt of stability



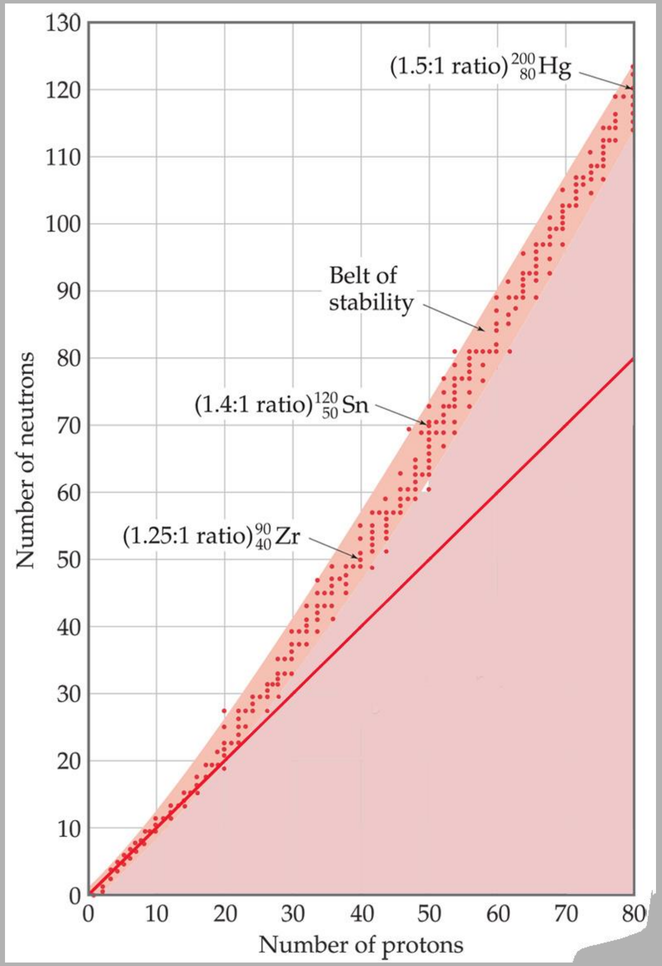
Stable Nuclei

- Nuclei above this belt have too many neutrons
- They tend to decay by emitting beta particles



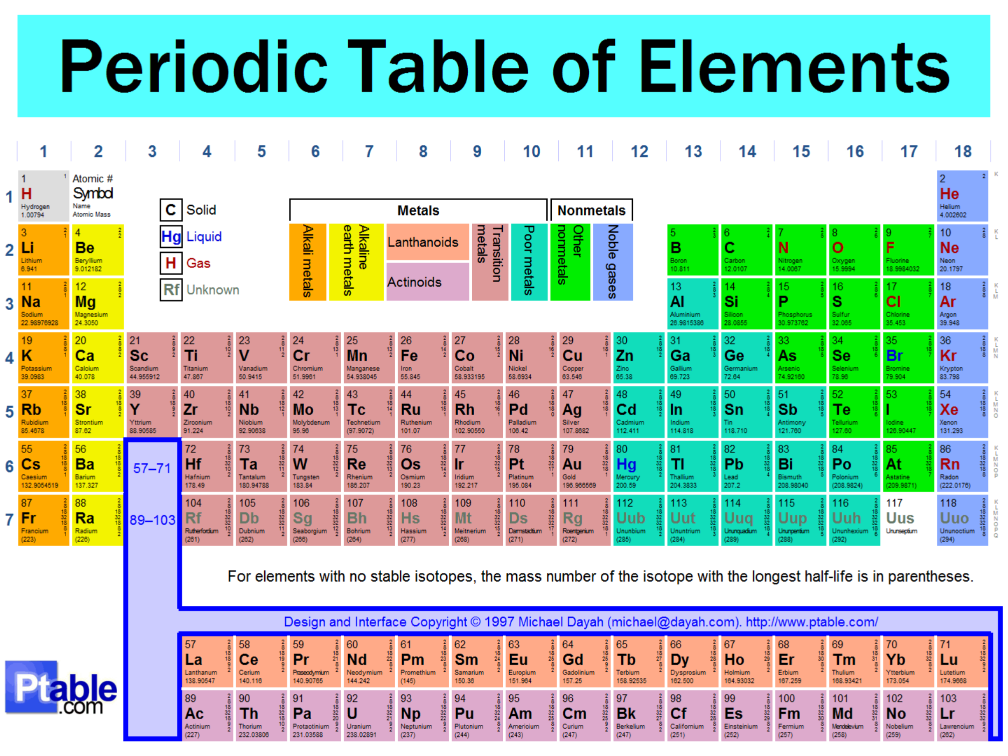
Stable Nuclei

- Nuclei below the belt have too many protons
- They tend to become more stable by positron emission or electron capture



Stable Nuclei

- There are no stable nuclei with an atomic number greater than 83.
- These nuclei tend to decay by alpha emission.



Periodic Table of Elements

Atomic #
Symbol
Name
Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals

Nonmetals: Other nonmetals, Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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	57–71	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	89–103	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	117 Uus	118 Uuo

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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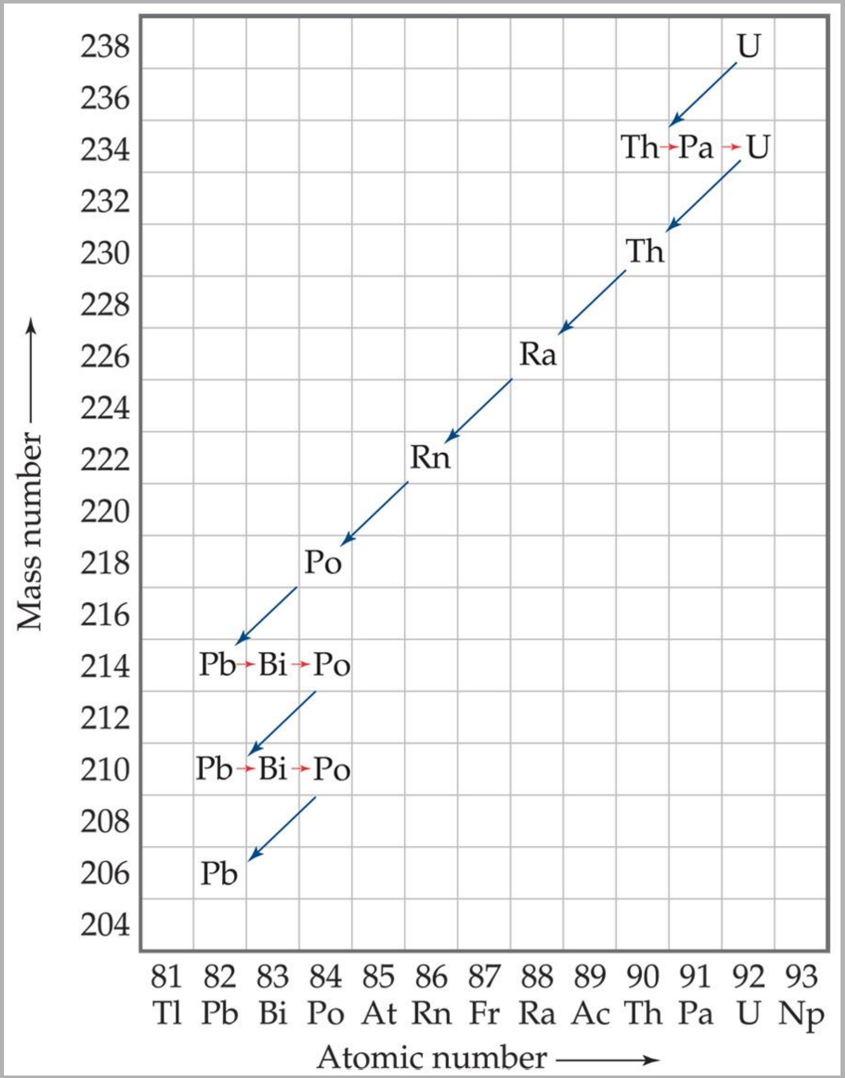
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Ptable.com

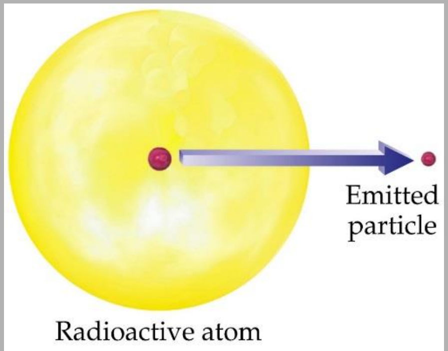
Radioactive Series



- Large radioactive nuclei cannot stabilize by undergoing only one nuclear transformation
- They undergo a series of decays until they form a stable nuclide (often a nuclide of lead)

Radioactive Decay & Half-life

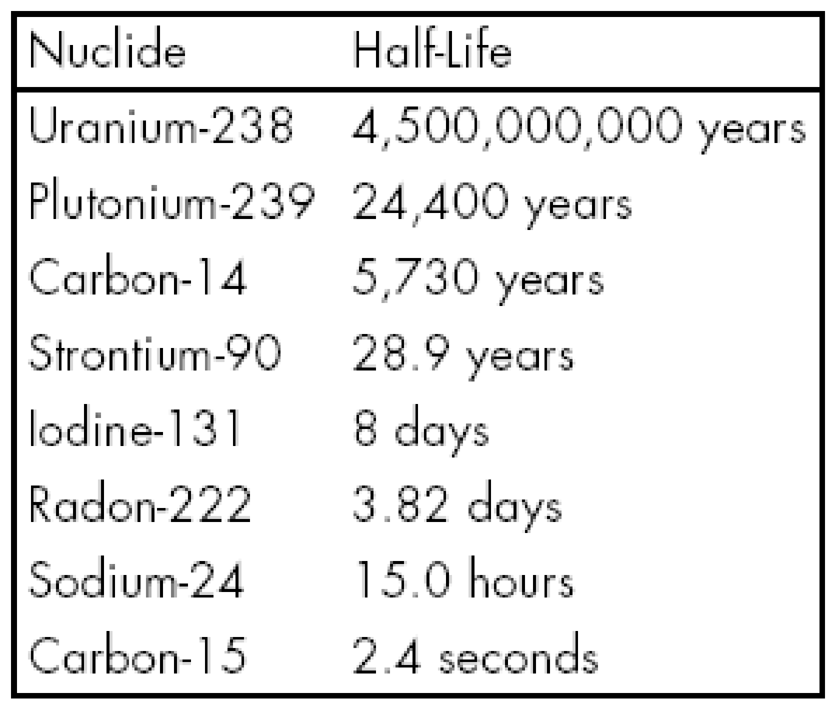
Radioactive Decay: process in which a radioactive atom disintegrates into a different element



Half-life: the time required for ½ the amount of a radioactive material to disintegrate

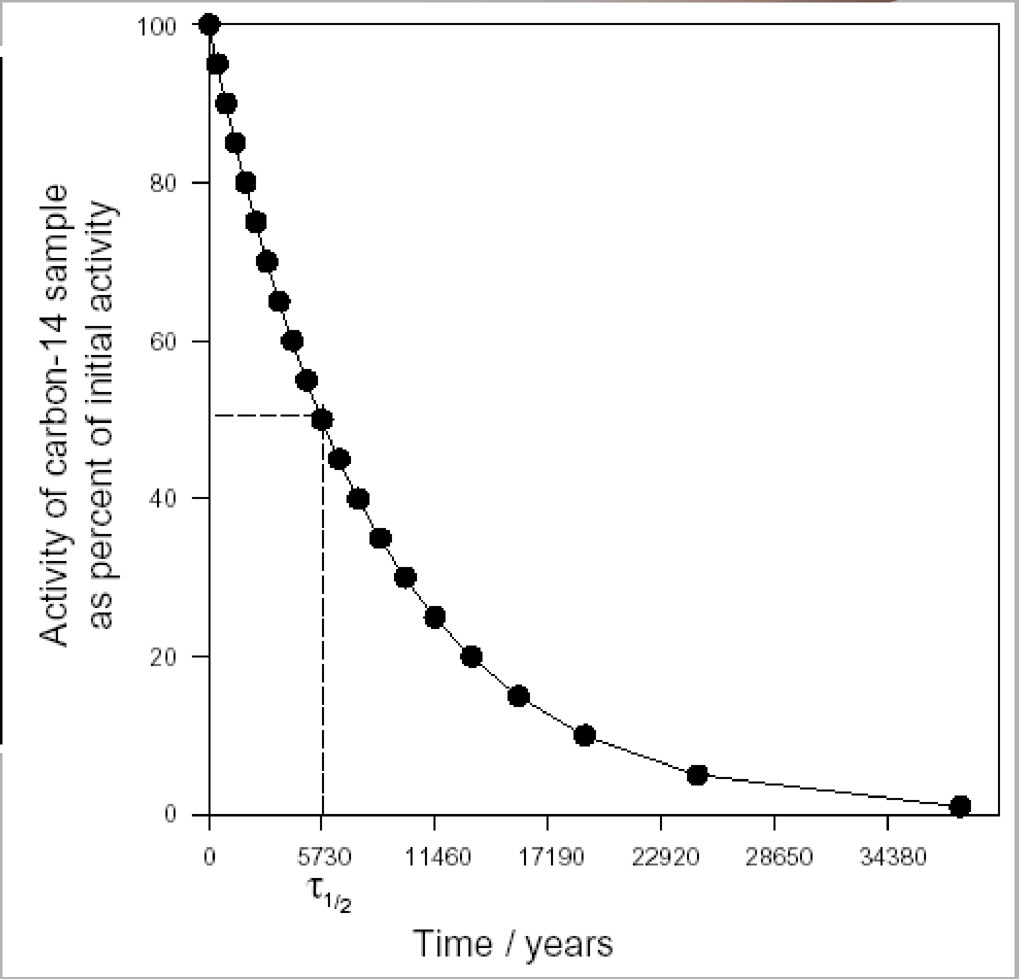
- Could be a fraction of a second or billions of years.

Decay and Half-Life



Nuclide	Half-Life
Uranium-238	4,500,000,000 years
Plutonium-239	24,400 years
Carbon-14	5,730 years
Strontium-90	28.9 years
Iodine-131	8 days
Radon-222	3.82 days
Sodium-24	15.0 hours
Carbon-15	2.4 seconds

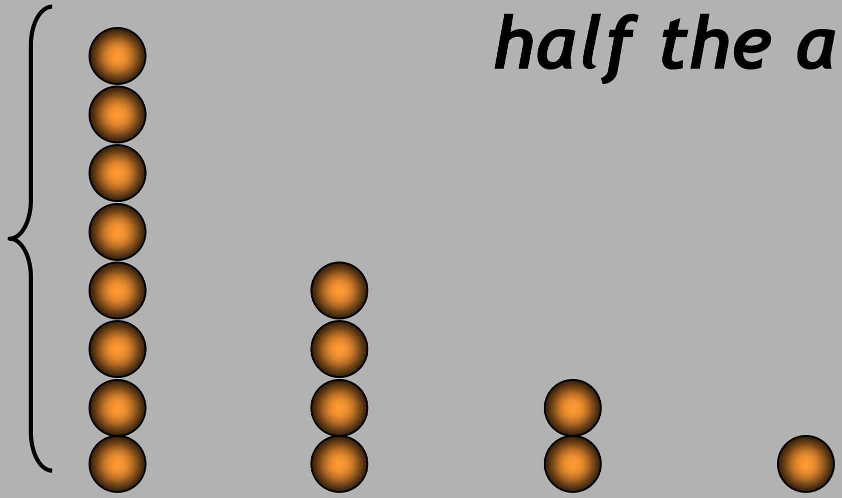
J. Chem. Ed. (2000)



J. Chem. Ed. (2000)

Radioactive half-life

Every half-life,
half the atoms decay



Undecayed nuclei

t=0

t=1 yr

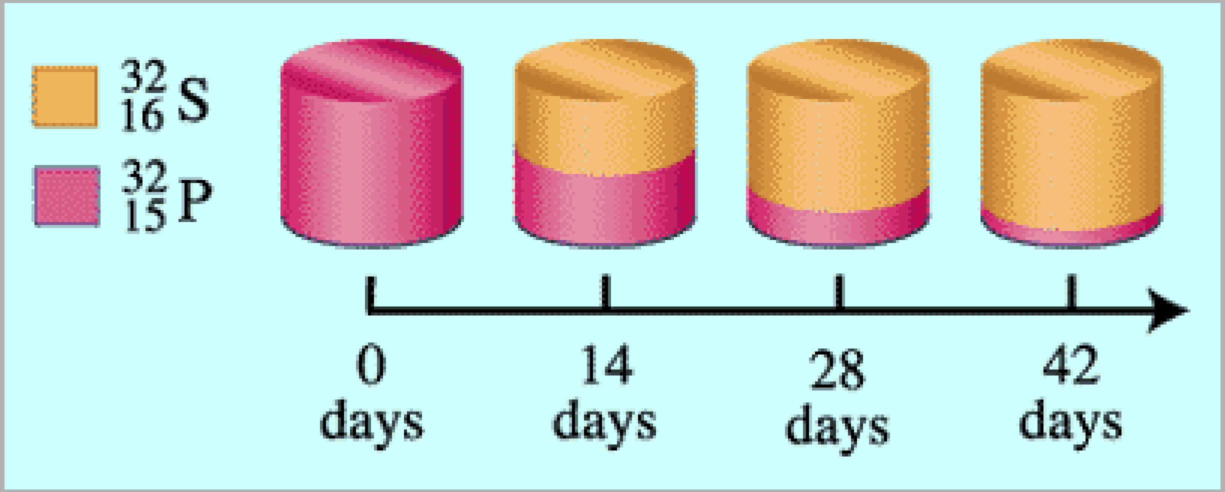
t=2 yr

t=3 yr

Half Life

Example:

- Phosphorus-32 radioactively decays to form Sulfur-32
- Half life ^{32}P = 14 days



Half-Life Calculation #1

- You have 400 mg of a radioisotope with a half-life of 5 minutes. How much will be left after 30 minutes?

Half-Life Calculation #2

- Suppose you have a 100 mg sample of Au-191, which has a half-life of 3.4 hours. How much will remain after 10.2 hours?

Half-Life Calculation # 3

- Cobalt-60 is a radioactive isotope used in cancer treatment. Co-60 has a half-life of 5 years. If a hospital starts with a 1000 mg supply, how many mg will need to be purchased after 10 years to replenish the original supply?

Half-Life Calculation # 4

- A radioisotope has a half-life of 1 hour. If you began with a 100 g sample of the element at noon, how much remains at 3 PM? At 6 PM? At 10 PM?

Half-Life Calculation # 5

- How many half-lives have passed if 255 g of Co-60 remain from a sample of 8160 g?

Half-Life Calculation # 6

- Suppose you have a sample containing 400 nuclei of a radioisotope. If only 25 nuclei remain after one hour, what is the half-life of the isotope?

Answers to Half-Life Calculations:

- Half-Life Calculation #1
  - 6.25 mg
- Half-Life Calculation #2
  - 12.5 mg
- Half-Life Calculation #3
  - 750 mg

Answers to Half-Life Calculations:

- Half-Life Calculation #4
  - 12.5 g, 1.5625 g, 0.09765625 g
- Half-Life Calculation #5
  - 5 half-lives
- Half-Life Calculation #6
  - 15 minutes

Radioactive Decay Question

A piece of radioactive material is initially observed to have 10,000 radioactive nuclei.

3 hours later, you measure 1,250 radioactive nuclei.

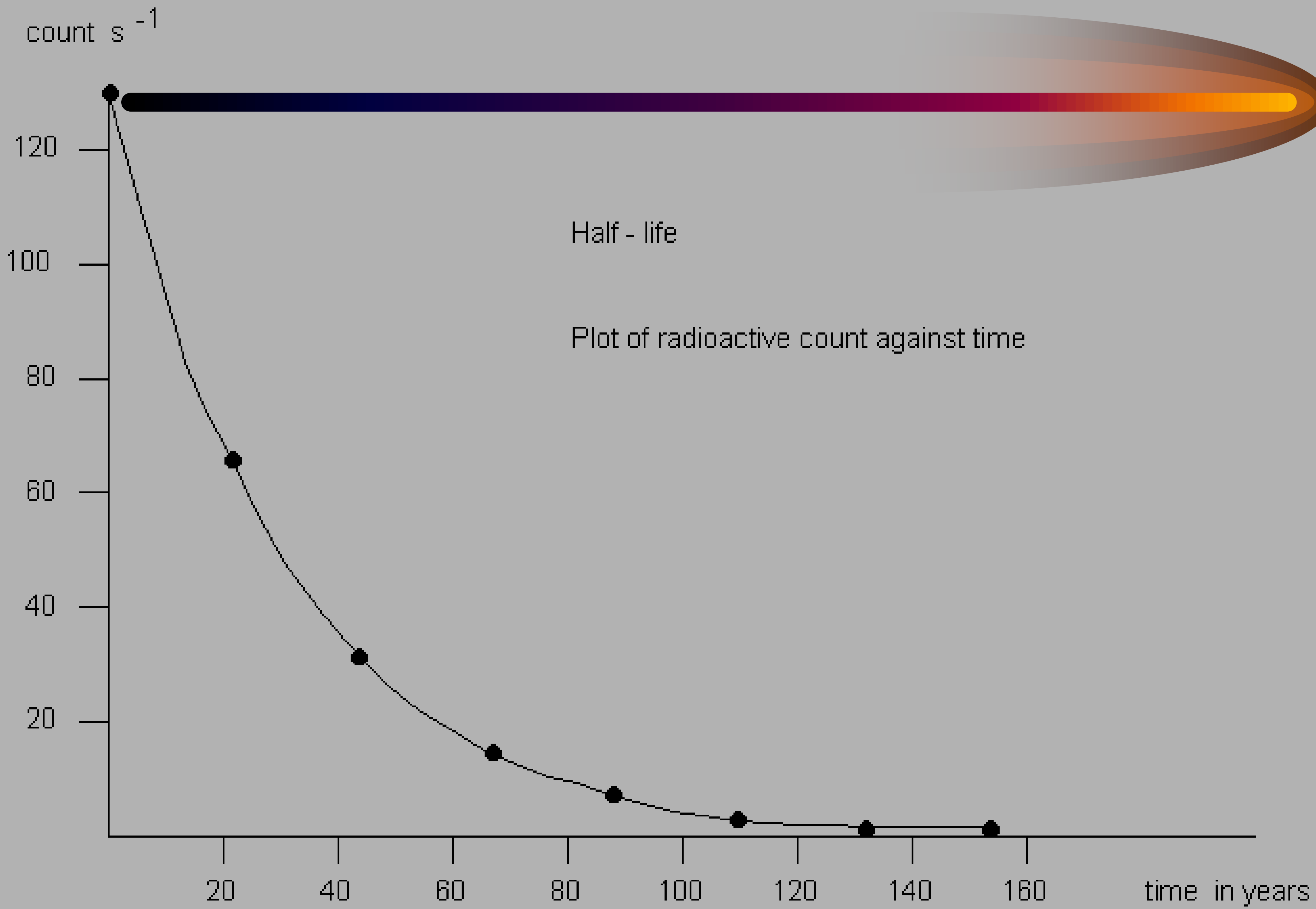
The half-life is:

A. 1/2 hour
[✓ B. 1 hour]
C. 3 hours
D. 8 hours

In each half-life,
the number of radioactive nuclei,
and hence the number of decays / second,
drops by a factor of two.

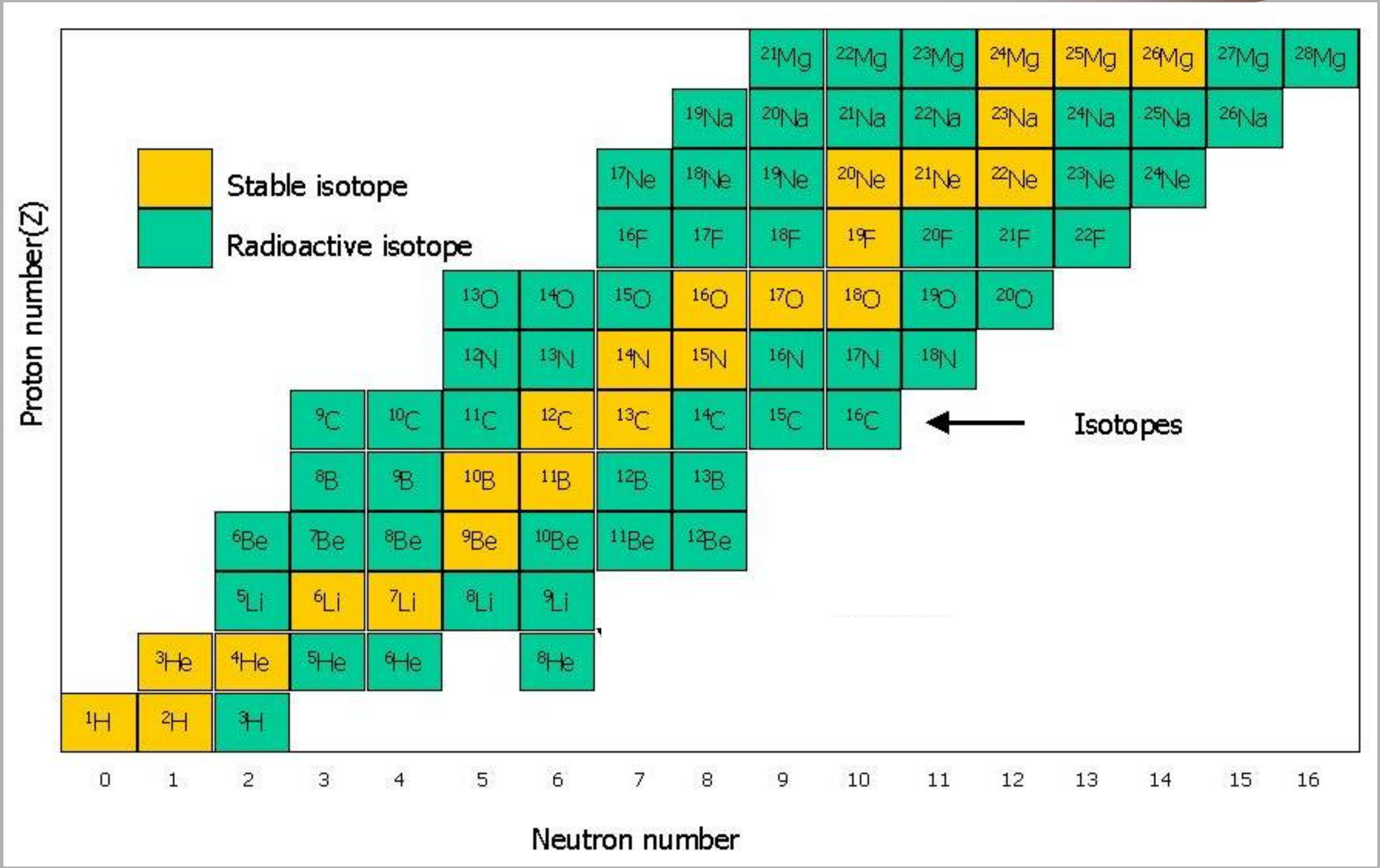
After 1 half life, 5000 are left undecayed.
After 2 half lives, 1/2 of these are left: 2,500
After 3 half lives there are 1,250 left.

Half - life



Plot of radioactive count against time

Radioactive Nuclei



🟨 Stable isotope

🟩 Radioactive isotope

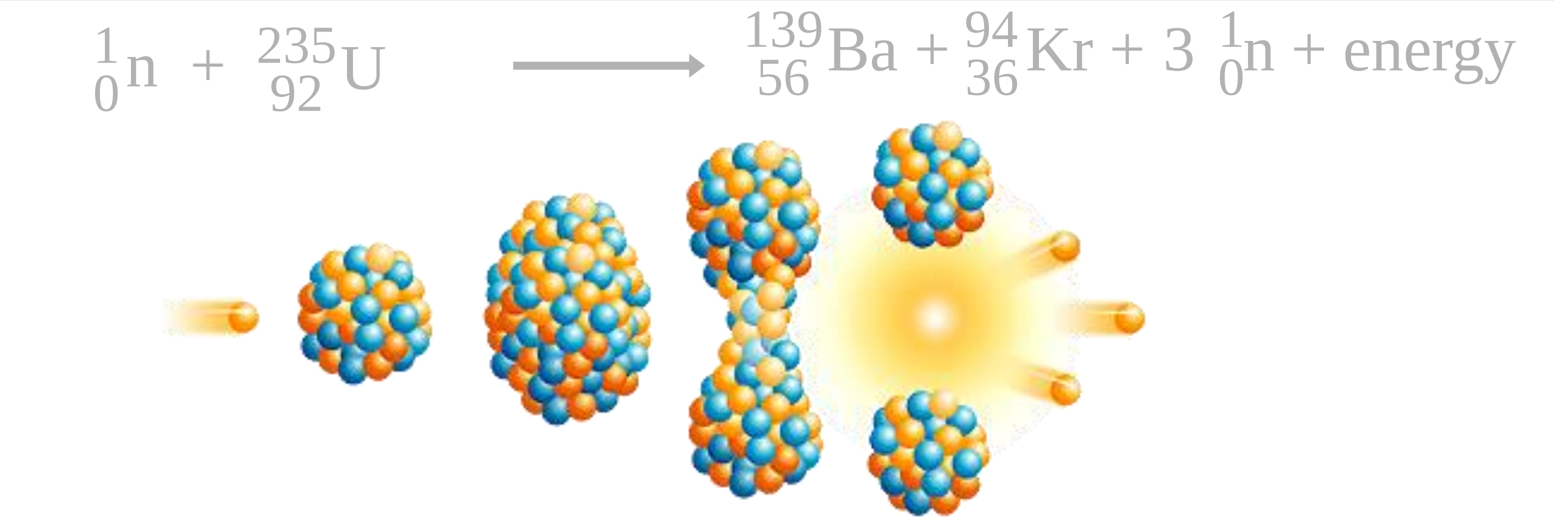
Proton number(Z)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
										🟩 ^{21}Mg	🟩 ^{22}Mg	🟩 ^{23}Mg	🟨 ^{24}Mg	🟨 ^{25}Mg	🟨 ^{26}Mg	🟩 ^{27}Mg	🟩 ^{28}Mg
									🟩 ^{19}Na	🟩 ^{20}Na	🟩 ^{21}Na	🟩 ^{22}Na	🟨 ^{23}Na	🟩 ^{24}Na	🟩 ^{25}Na	🟩 ^{26}Na	
								🟩 ^{17}Ne	🟩 ^{18}Ne	🟩 ^{19}Ne	🟨 ^{20}Ne	🟨 ^{21}Ne	🟨 ^{22}Ne	🟩 ^{23}Ne	🟩 ^{24}Ne		
								🟩 ^{16}F	🟩 ^{17}F	🟩 ^{18}F	🟨 ^{19}F	🟩 ^{20}F	🟩 ^{21}F	🟩 ^{22}F			
						🟩 ^{13}O	🟩 ^{14}O	🟩 ^{15}O	🟨 ^{16}O	🟨 ^{17}O	🟨 ^{18}O	🟩 ^{19}O	🟩 ^{20}O				
						🟩 ^{12}N	🟩 ^{13}N	🟨 ^{14}N	🟨 ^{15}N	🟩 ^{16}N	🟩 ^{17}N	🟩 ^{18}N					
				🟩 ^{9}C	🟩 ^{10}C	🟩 ^{11}C	🟨 ^{12}C	🟨 ^{13}C	🟩 ^{14}C	🟩 ^{15}C	🟩 ^{16}C						
				🟩 ^{8}B	🟩 ^{9}B	🟨 ^{10}B	🟨 ^{11}B	🟩 ^{12}B	🟩 ^{13}B								
			🟩 ^{6}Be	🟩 ^{7}Be	🟩 ^{8}Be	🟨 ^{9}Be	🟩 ^{10}Be	🟩 ^{11}Be	🟩 ^{12}Be								
			🟩 ^{5}Li	🟨 ^{6}Li	🟨 ^{7}Li	🟩 ^{8}Li	🟩 ^{9}Li										
		🟨 ^{3}He	🟨 ^{4}He	🟩 ^{5}He	🟩 ^{6}He		🟩 ^{8}He										
	🟨 ^{1}H	🟨 ^{2}H	🟩 ^{3}H														

← Isotopes

Neutron number

Nuclear Fission

- **Fission:** process in which the nucleus of a large, radioactive atom splits into 2 or more smaller nuclei
  - Caused by a collision with an energetic neutron.

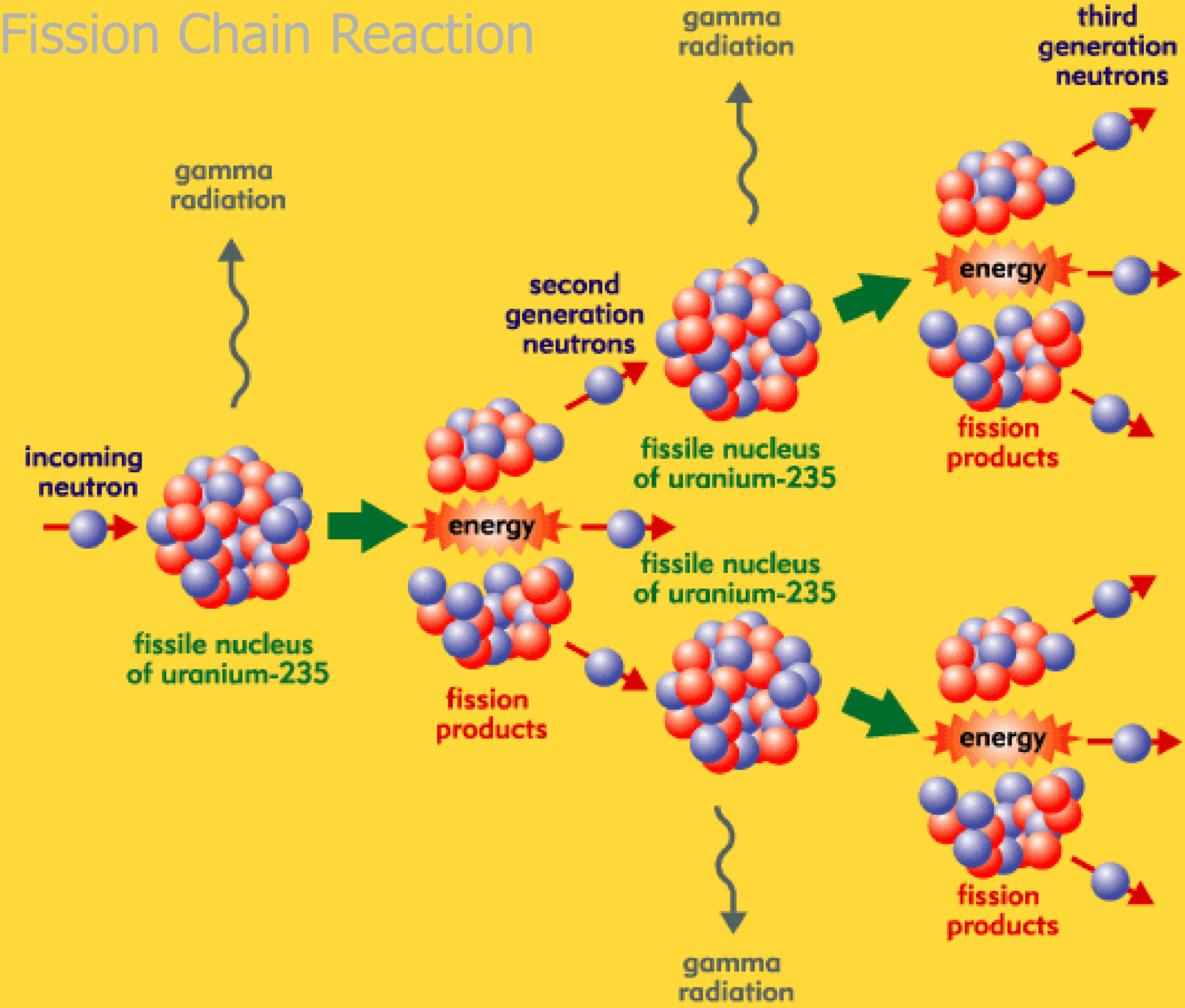


$$ {}_{0}^{1}\mathrm{n} + {}_{92}^{235}\mathrm{U} \longrightarrow {}_{56}^{139}\mathrm{Ba} + {}_{36}^{94}\mathrm{Kr} + 3\,{}_{0}^{1}\mathrm{n} + \text{energy} $$

A neutron is absorbed by a U-235 nucleus. The nucleus is now less stable than before. It then splits into 2 parts and energy is released.

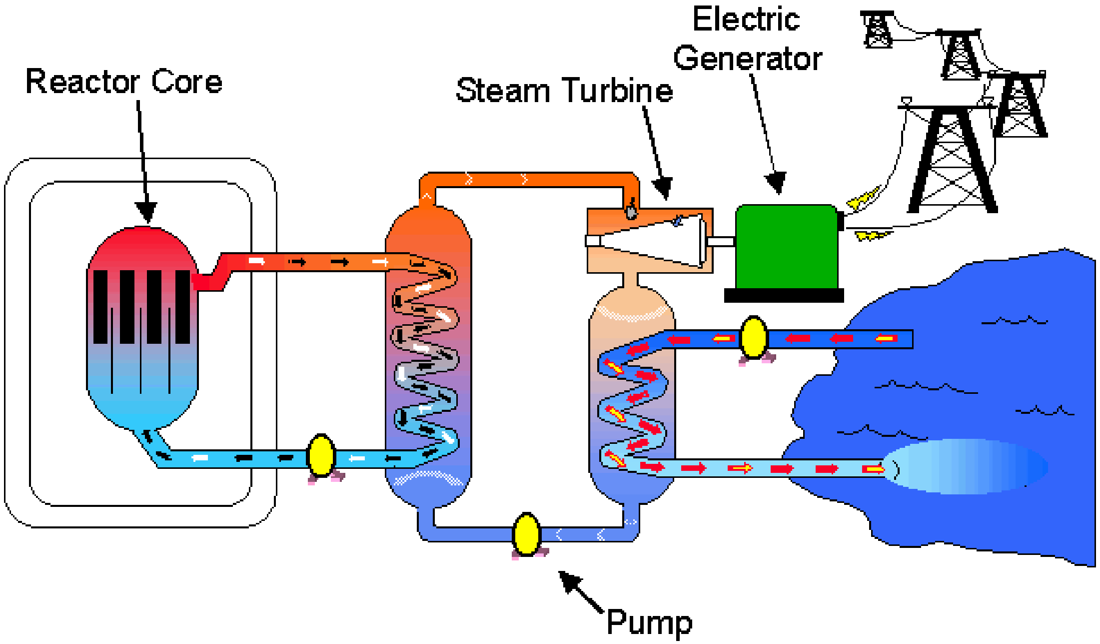
- Fission has been occurring in the universe for billions of years

*A Fission Chain Reaction



Harnessing Fission: A nuclear power plant

- Nuclear PP utilize the energy released in a controlled fission reaction in the **core** to heat water in one pipe
- The heat then vaporizes water in another pipe
- The steam drives a **turbine** and generates electricity



- The steam is in a closed circuit that is never exposed any radiation
- The speed of the fission chain reaction is regulated using carbon **control rods** which can absorb extra neutrons

Nuclear Power

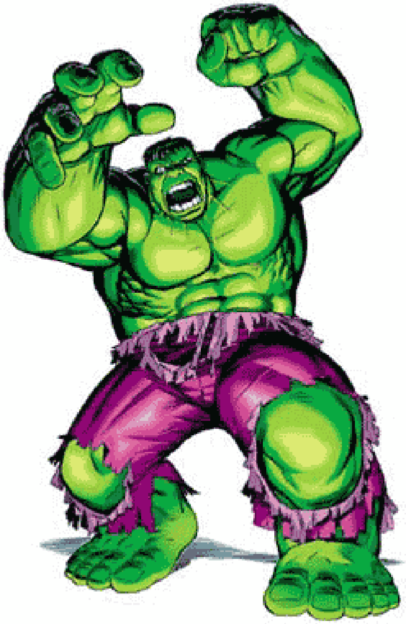
- The United States currently imports over 58% of its oil supply. There is a need to develop alternative energy sources, such as nuclear, wind, geothermal, solar, …

- By 2020 it is expected to be 67%.

- At present about 20% of the electrical energy used in the U.S. is generated from power plants using uranium. In France the percentage is 75% .

Nuclear Chemistry

North Anna – Nuclear Power Plant is located in Louisa County in central Virginia, northwest of Richmond.



Marvel Comics' "The Incredible Hulk" was created in 1962 by Stan Lee and artist Jack Kirby. The Hulk's powers began when nuclear scientist Dr. Bruce Banner was accidentally bombarded with gamma rays from a "gamma bomb" he had invented.

The Atomic Bomb

- Uses an unregulated fission reaction in a very fast chain reaction that releases a tremendous amount of energy.

- Site of fission reaches temperatures believed to be about 10,000,000°C.

- Produces shock waves and α, β, γ, x-rays, and UV radiation.

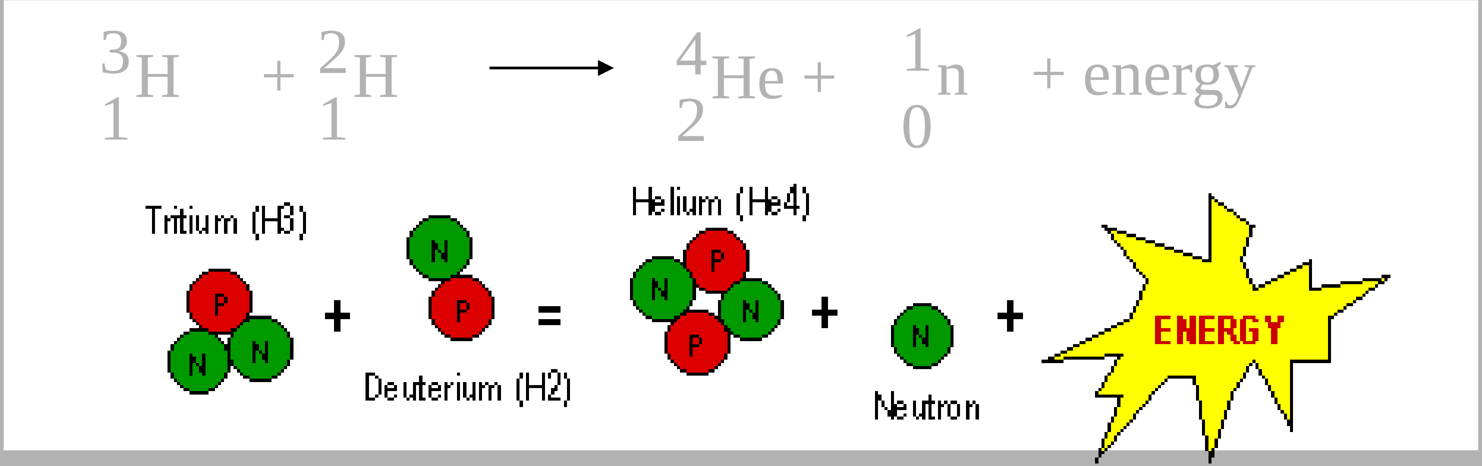
The classic “mushroom cloud” is a result of dust and debris lifted into the air as a result of the detonation

*US Army aerial photograph from 80 km away, taken about 1 hour after detonation over Nagasaki, Japan, August 9, 1945

Nuclear Fusion

Fusion: process in which 2 nuclei of small elements are united to form one heavier nucleus

- * Requires temperatures on the order of tens of millions of degrees for initiation.
- * The mass difference between the small atoms and the heavier product atom is liberated in the form of energy.
- Responsible for the tremendous energy output of stars (like our sun) and the devastating power of the hydrogen bomb.



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

Stars & the Hydrogen Bomb

- The first thermonuclear bomb was exploded in 1952 in the Marshall islands by the United States; the second was exploded by Russia (then the USSR) in 1953.
- “H bombs” utilize a fission bomb to ignite a fusion reaction.