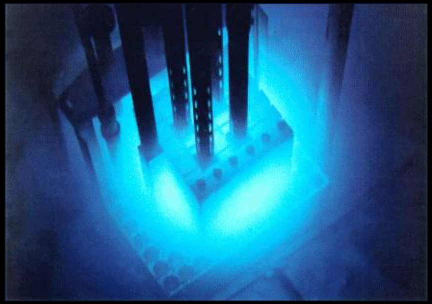
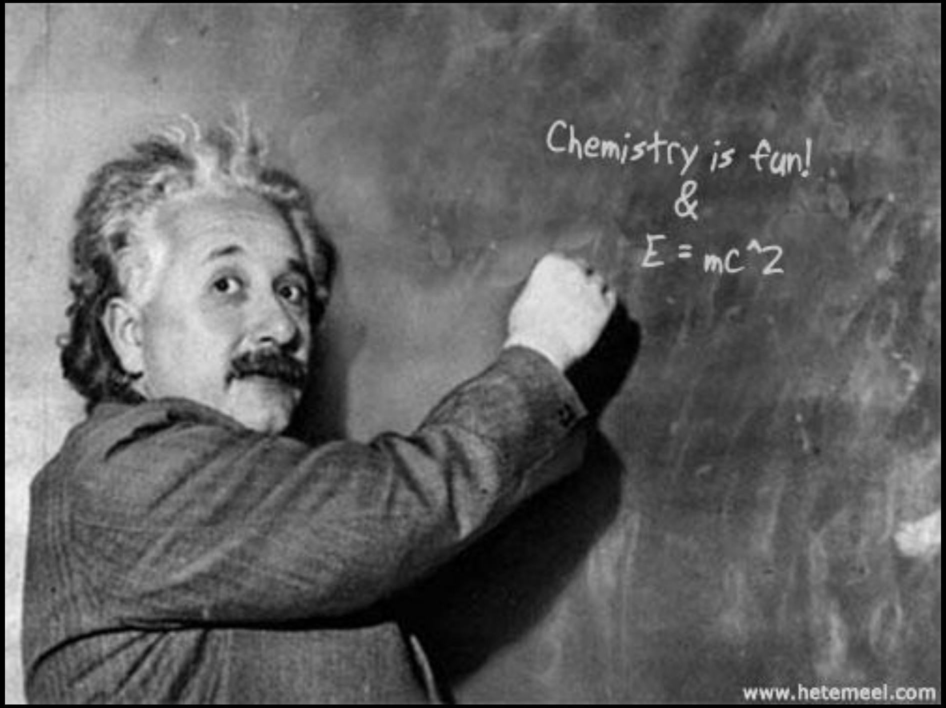
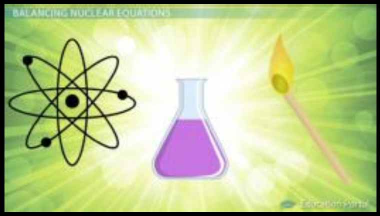
Nuclear Chemistry





Nuclear Chemistry



Nuclear chemistry: study of changes in the atomic nucleus

Recall:

Z: Atomic Number; number of protons in nucleus

A: Atomic Mass number; sum of protons and neutrons in nucleus

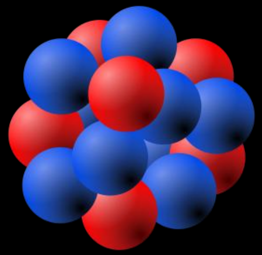
Isotopes: atoms with same Z, but different A

Nuclide: a single atom type

Nuclide Symbol: $^{A}_{Z}X$ **where X = symbol of the element**

Nuclide Name: Element - A (Example: $^{14}_{6}C$ **= Carbon-14)**

Nucleon: collective name for protons & neutrons



Proton: positive charge

Neutron: no charge

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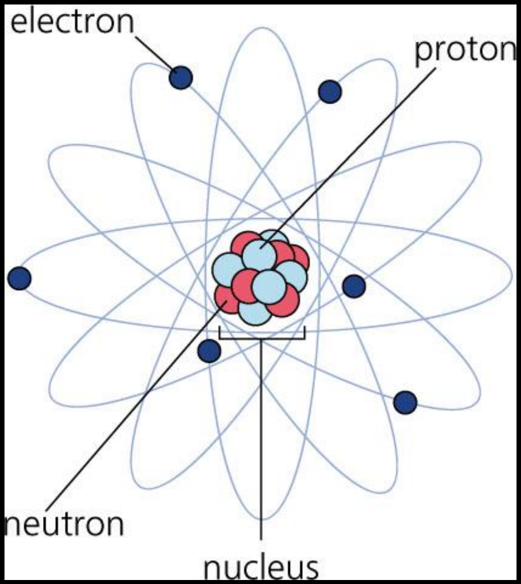
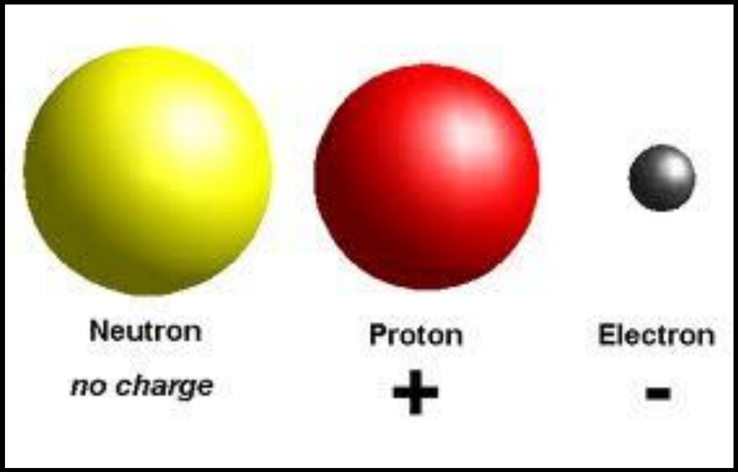
Primary Subatomic Particles

Particle	Location (Nucleus)	Charge	Mass (g)	Mass (amu)
Neutron (n^0)	Inside	0	1.675×10^{-24}	1.00867 (~1)
Proton (p^+)	Inside	+1	1.673×10^{-24}	1.00728 (~ 1)
Electron (e^-)	Outside	-1	9.11×10^{-28}	0.000549 (~0)





Mass Order: n > p >> e

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The Nucleus

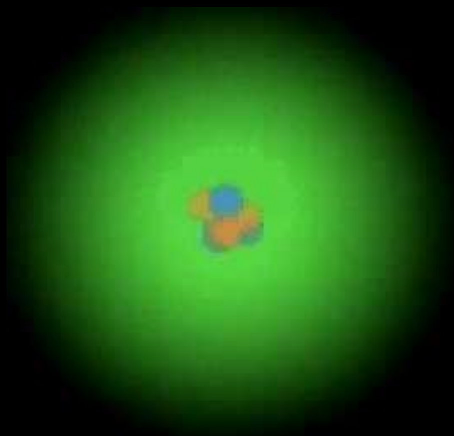
Most mass concentrated in a small, dense core (the nucleus)

Positively charged

Nucleus Radius: ~ 10^{-15} m

Atomic Radius: ~ 10^{-10} m

Atomic Density: ~ 1.8×10^{14} g/cm^3



For He atom: If nucleus equals the size of a penny
Atomic sphere diameter equals the size of the pentagon

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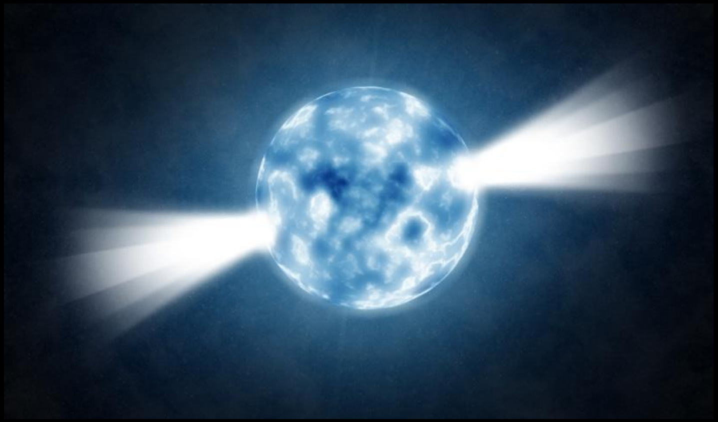
Density of Neutron Star

Supernova collapse creates neutron star (most dense stars known)

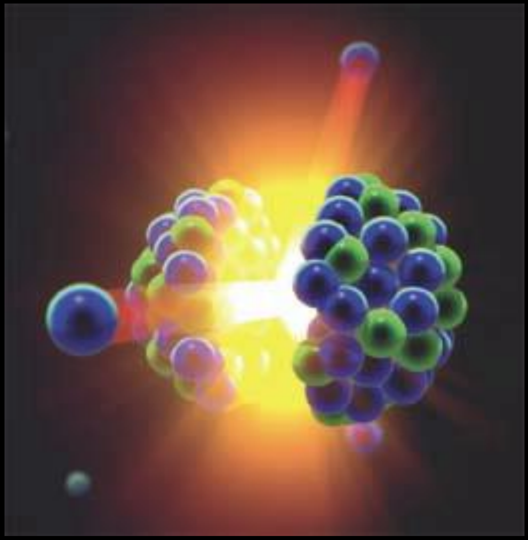
What is the density of the neutron star:
Mass: 1.99×10^{30} kg
Diameter: 26 km



$$D = \frac{1.99 \times 10^{30} \text{ kg}}{4/3\ \pi\ (26 / 2 \text{ km})^3}$$

$D = 5.2 \times 10^{17}\ \text{kg/m}^3$

What is the density of a uranium - 235 nucleus:
Mass: 235 amu (1.66×10^{-27} kg / amu)
Radius: 7.5×10^{-15} m



$$D = \frac{235 \text{ amu } (1.66 \times 10^{-27} \text{ kg / amu})}{4/3\ \pi\ (7.5 \times 10^{-15} \text{m})^3}$$

$D = 2.2 \times 10^{17}\ \text{kg/m}^3$

Nucleus is about 2 x density of neutron star

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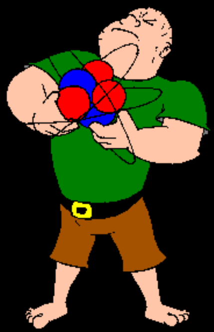
Strong Nuclear Force



Holds strongly repulsive positive charges (protons) together
Only relevant at extremely short (nuclear) distances

Theoretical mass of the Helium - 4 Atom:

Total mass: sum of mass of 2 protons, 2 neutrons and 2 electrons
Total mass: (2 x 1.0072 amu) + (2 x 1.0087 amu) + (2 x 0.00055 amu)
Total mass: 4.0331 amu

Value of Helium – 4 atom by mass spectroscopy

4.0026 amu

Difference: 4.0331 amu – 4.0026 amu = 0.0305 amu

Mass Defect:

Mass loss represents conversion to energy
This energy holds nucleus together

Nuclear Binding Energy (of He - 4)

Mass to Energy conversion defined by Einstein's $E = mc^2$

To use energy term of Joules ($1\ J = 1\ kg\ m^2 / s^2$), need to express mass in kg:

$0.0305\ g/mol \times 1\ kg / 1000\ g = 3.05 \times 10^{-5}\ kg / mol$

$E = mc^2$ (where $c = 2.998 \times 10^8\ m/s$)

$$E = \frac{3.05 \times 10^{-5}\ kg}{mol} \times \left(\frac{2.998 \times 10^8\ m}{s}\right)^2 = 2.74 \times 10^{12}\ kg\ m^2\ s^{-2}\ mol^{-1}$$

$E = 2.74 \times 10^{12}\ J\ mol^{-1}$

Molar Binding Energy:

$$E = 2.74 \times 10^{12}\ J\ mol^{-1} \times \frac{1\ mol}{6.02 \times 10^{23}\ nuclei} = 4.55 \times 10^{-12}\ J$$

Energy in terms of electron volts:

$$E = 4.55 \times 10^{-12}\ J \times \frac{1\ eV}{1.602 \times 10^{-19}\ J} = 2.84 \times 10^{7}\ eV \rightarrow 28.4\ MeV$$

Problem: Binding Energy (MeV) of F - 19

Theoretical mass of the Fluorine-19Atom:

Total mass: sum of mass of 9 protons, 10 neutrons and 9 electrons

Total mass: (9 x 1.0072 amu) + (10 x 1.0087 amu) + (9 x 0.00055 amu)

Total mass: 9.0648 amu + 10.087 amu + 0.0050 amu (only allowed 2 sig figs here)

Total mass: 19. 157 amu

Mass spectroscopy value of fluorine – 19 atom:

18.9984 amu

Difference: 19.157 amu – 18.9984 amu = 0.163 amu

Energy Equivalent in Joules:

$$E = \frac{1.63 \times 10^{-4}\ \text{kg}}{\text{mol}} \times \left(\frac{2.998 \times 10^{8}\ \text{m}}{\text{s}}\right)^2 = 1.47 \times 10^{13}\ \text{kg m}^2\ \text{s}^{-2}\ \text{mol}^{-1} = 1.47 \times 10^{13}\ \text{J mol}^{-1}$$

Molar Energy Equivalent:

$$E = 1.47 \times 10^{13}\ \text{J mol}^{-1} \times \frac{1\ \text{mol}}{6.02 \times 10^{23}\ \text{nuclei}} = 2.43 \times 10^{-11}\ \text{J}$$

Energy in electron volts:

$$E = 2.43 \times 10^{-11}\ \text{J} \times \frac{1\ \text{eV}}{1.602 \times 10^{-19}\ \text{J}} = 1.51 \times 10^{8}\ \text{eV} \rightarrow 151\ \text{MeV}$$

Nuclear Stability

Nucleus is stable: does not change (transform) without outside energy

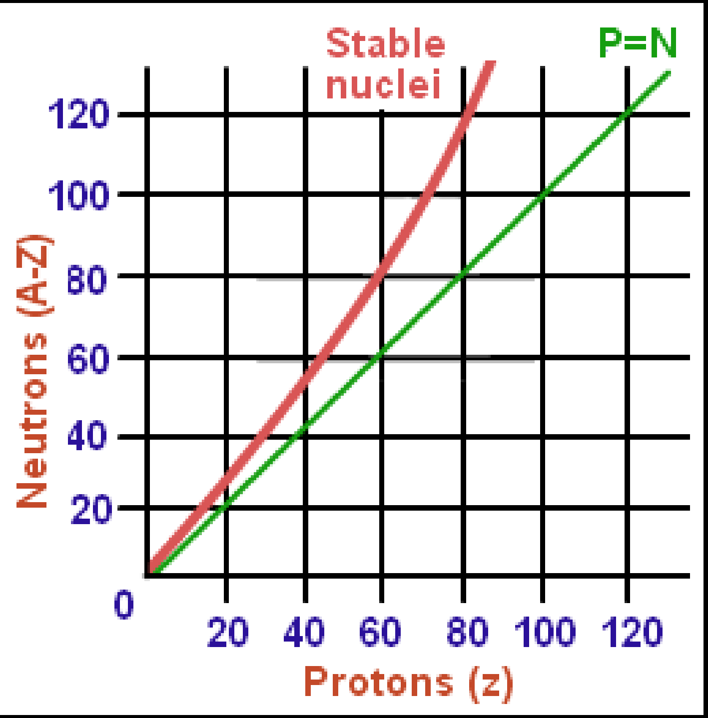
~ 250 nuclei are stable ~ 3100 nuclei known

Nucleus is unstable: changes composition by emitting nuclear particles

- radioactivity: emission of particles to move towards a more stable nucleus
- radioactive: an atom that will spontaneously emit nuclear particles
- radioactive decay: emission of nuclear particle
- radioisotope: nucleus that spontaneous decays

Larger Z nuclei have more:

- protons
- proton repulsions
- neutrons to overcome electrostatics



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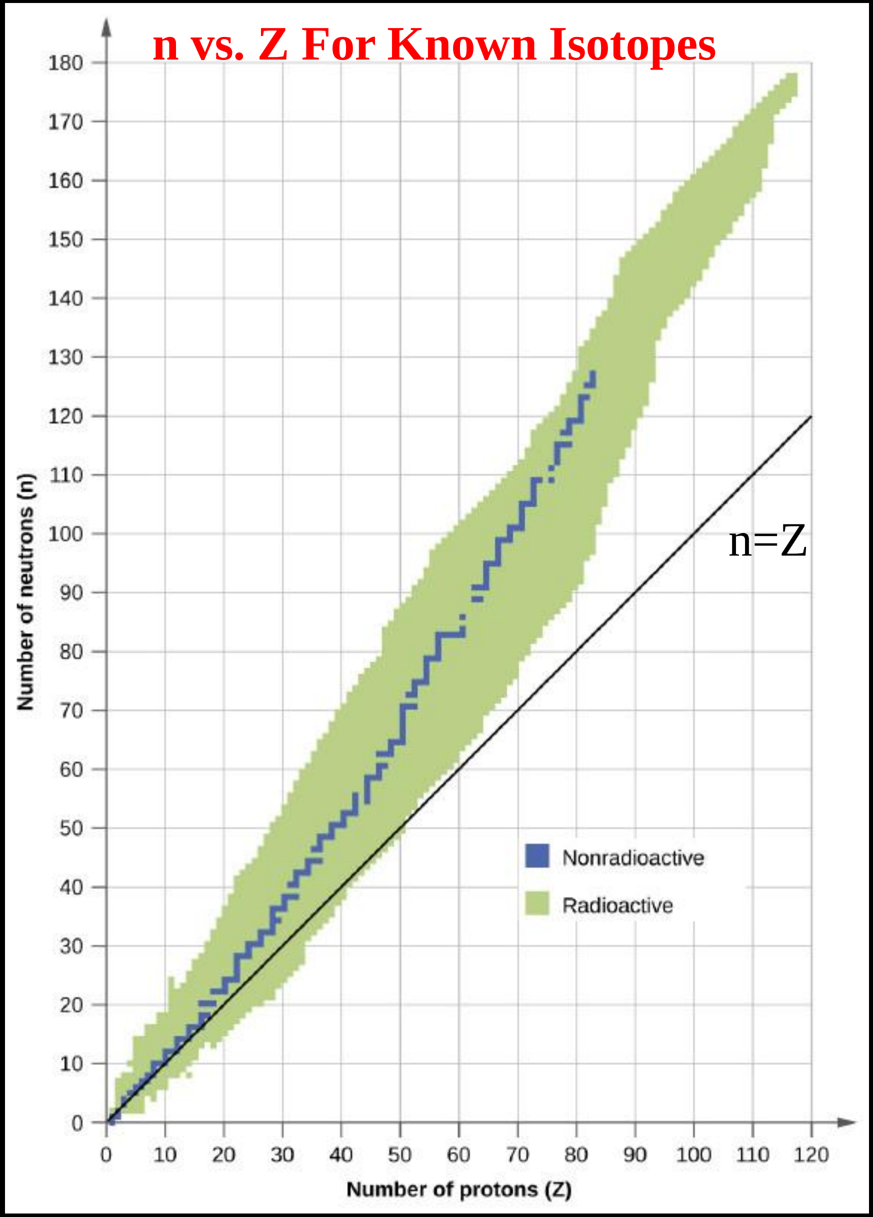
Nuclear Stability



All nuclei with Z > 83 are unstable

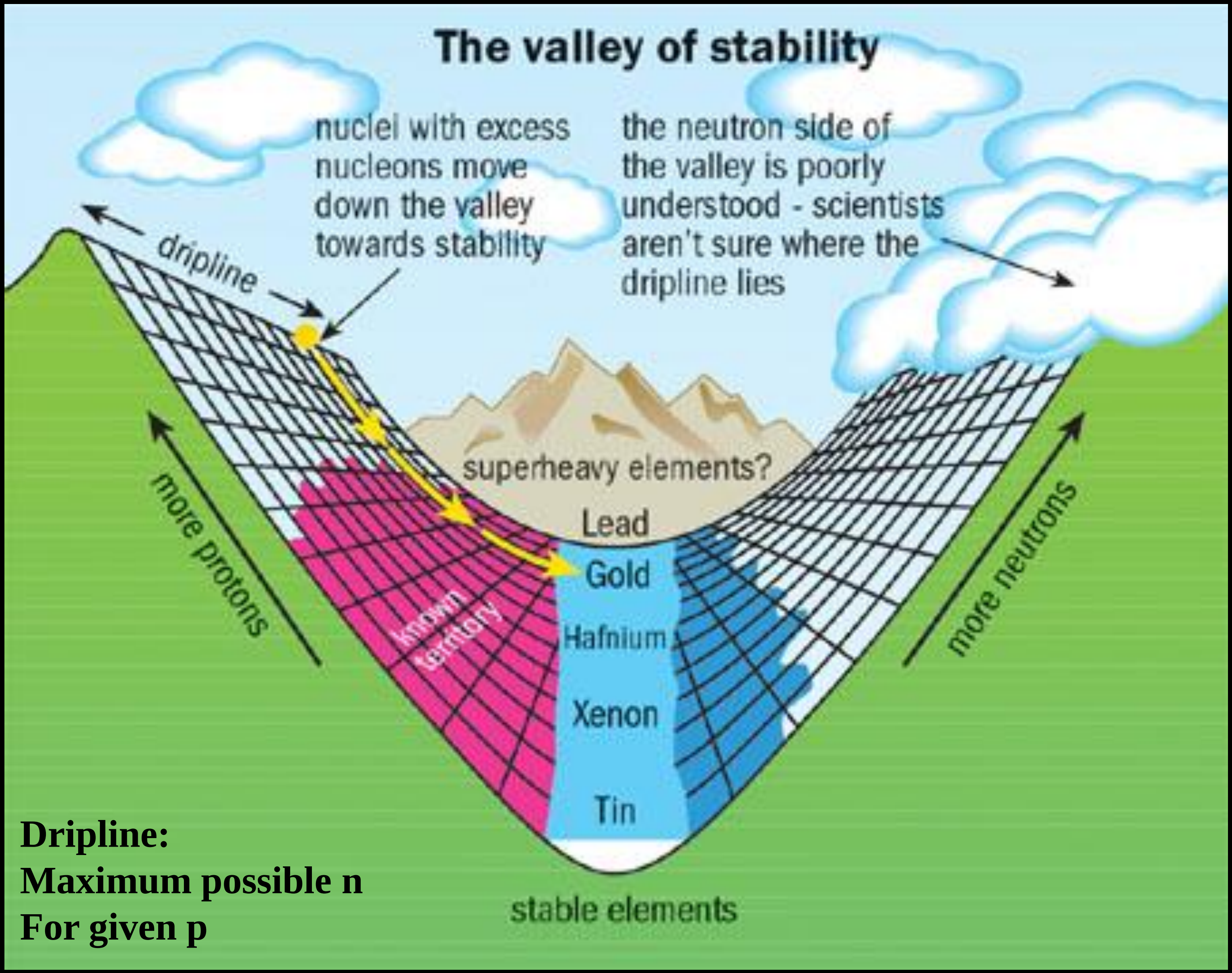
Nuclei likely to be stable:
- Even # n
- Even # p
- Even # both

"Magic Numbers" (protons or neutrons)
(2, 8, 20, 28, 50, 80, 126)
Nucleons stable against nuclear decay

"Double Magic"
Magic number of both n and Z

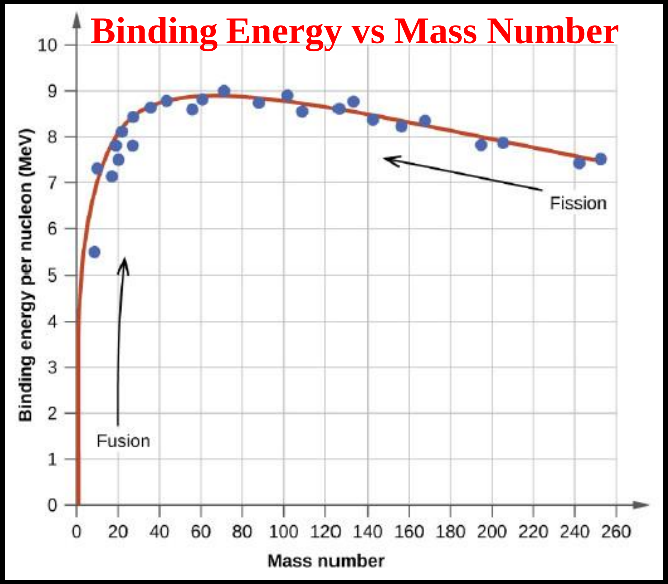
Number of Stable Isotopes	Proton Number	Neutron Number
157	even	even
53	even	odd
50	odd	even
5	odd	odd

Nuclear Stability



Dripline:
Maximum possible n
For given p

Nucleon Binding Energy



Nucleon Binding Energy = $\frac{\text{Nuclear Binding Energy}}{\text{\# Nucleons}}$

For $^{4}_{2}He$: Nuclear Binding Energy of 28.4 MeV

$$\frac{28.4 \text{ MeV}}{4 \text{ nucleons}} = 7.10 \text{ MeV}$$

Nucleon Binding Energy greatest about mass number 56

Stars do not create elements (Fusion) beyond Iron

For Fe 56: Nucleon Binding Energy: 8.820 MeV

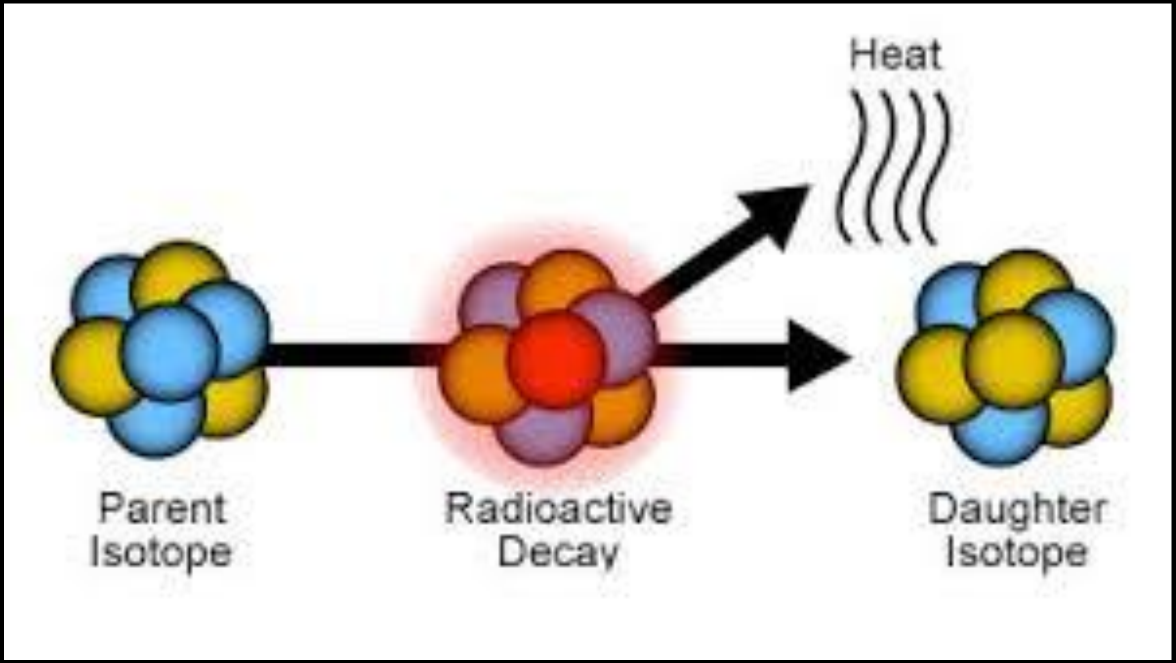
~ 25% larger than He-4

Nuclear Decay Events

Decay: Radioisotopes move towards a more stable nucleus

Emission of material from nucleus

Changes nucleus



Heat from radioactive decay: adds heat to earth's core

Nuclear Reactions

Nuclear reaction represents the decay process of nuclear rearrangement

Nuclear reaction conservation laws:

- **sum of mass numbers for reactants and products identical**
- **sum of charges for reactants and products identical**

Radioactive decay of polonium-210 can be summarized by the following:

$$^{210}_{84}Po \rightarrow {}^{206}_{82}X + \text{a radioactive particle: } {}^{amass}_{anumber}Y$$

What is element X? Pb What is element Y? He

amass = 4 anumber = 2

The radioactive particle (He nucleus without electrons): α particle

All of the Helium found on earth comes from radioactive decay

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Historical Nuclear Reactions

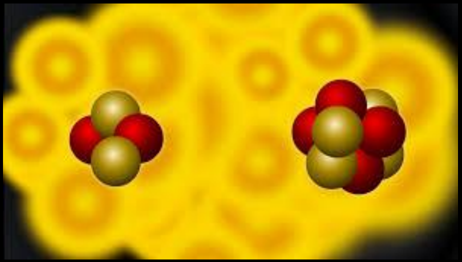
First naturally occurring radioisotope (1898) Marie & Pierre Curie:

$$^{212}_{84}\text{Po} \rightarrow \; ^{208}_{82}\text{Pb} + \; ^{4}_{2}\alpha$$

First artificial nuclide prepared (1919) Ernst Rutherford:

$$^{14}_{7}\text{N} + \; ^{4}_{2}\alpha \rightarrow \; ^{17}_{8}\text{O} + \; ^{1}_{1}\text{H} \quad (^{1}_{1}\text{H} = \text{proton})$$

Neutron discovered (1932) by James Chadwick



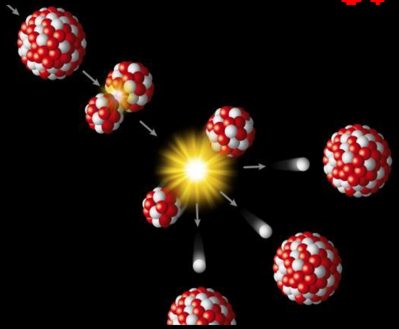
$$^{9}_{4}\text{Be} + \; ^{4}_{2}\alpha \rightarrow \; ^{12}_{6}\text{C} + \; ^{1}_{0}\text{n}$$

First artificial element (1937) Technetium:

$$^{2}_{1}\text{H} + \; _{42}\text{Mo} \rightarrow 2 \; ^{1}_{0}\text{n} + \; ^{97}_{43}\text{Tc}$$

First controlled sustained chain reaction (1942) at U of Chicago

$$^{235}\text{U} + \; ^{1}_{0}\text{n} \rightarrow \; ^{87}_{35}\text{Br} + \; ^{146}_{57}\text{La} + 3 \; ^{1}_{0}\text{n}$$



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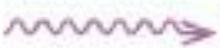
Nuclear Decay Events

Name	Symbol(s)	Representation	Description
Alpha particle	${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$		(High-energy) helium nuclei consisting of two protons and two neutrons
Beta particle	${}^{0}_{1}e$ or ${}^{0}_{-1}\beta$		(High-energy) electrons
Positron	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta$		Particles with the same mass as an electron but with 1 unit of positive charge
Proton	${}^{1}_{1}H$ or ${}^{1}_{1}p$		Nuclei of hydrogen atoms
Neutron	${}^{1}_{0}n$		Particles with a mass approximately equal to that of a proton but with no charge
Gamma ray	γ	 γ	Very high-energy electromagnetic radiation

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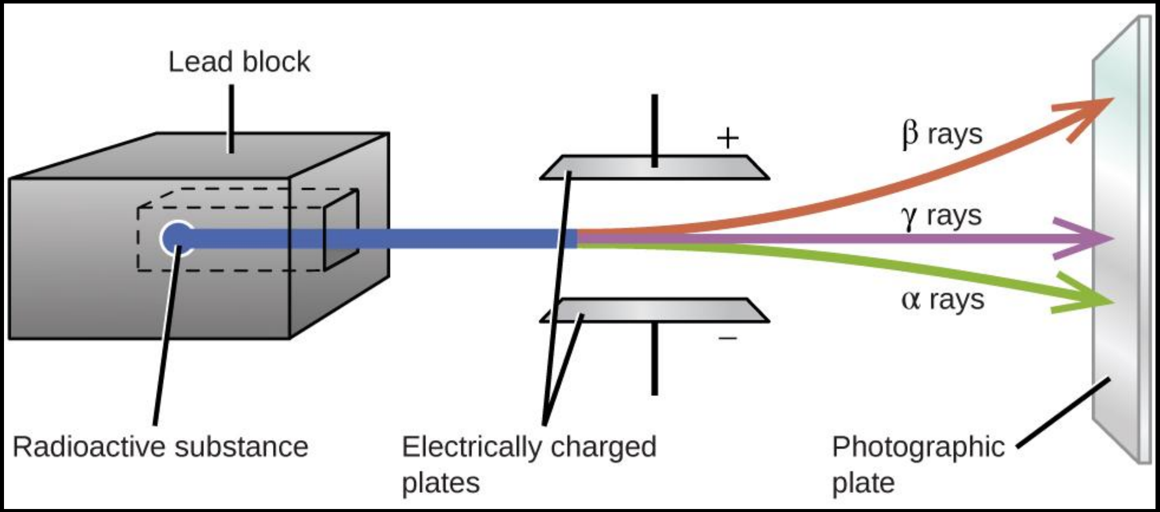
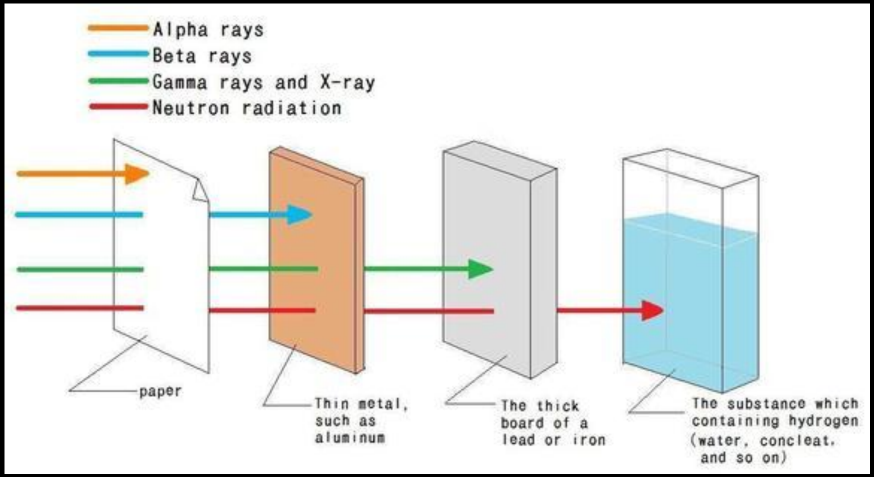
Types of Radioactive Decay

Rutherford's Determination of radioactive charge



Relative Penetration Energy



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Types of Radioactive Decay

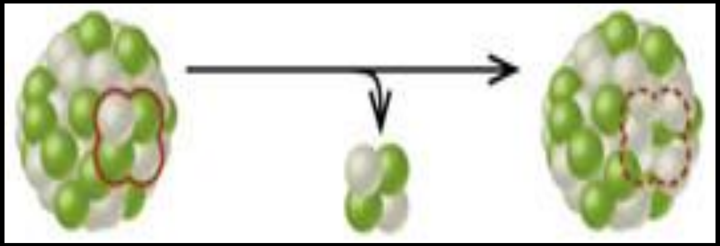
Alpha Particle

Parent nucleus: Emits 2 protons & 2 neutrons (He nucleus)

Daughter nucleus: A -4; Z -2

has higher n:p ratio than parent

Typically from heavier nuclei (A > 200; Z > 83)



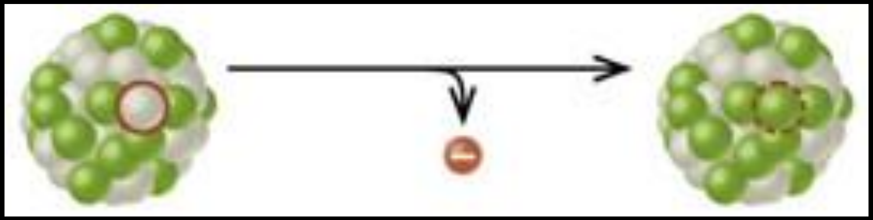
Beta Particle

Parent nucleus: Emits electron

Daughter nucleus: A unchanged; Z +1

has lower n:p ratio than parent

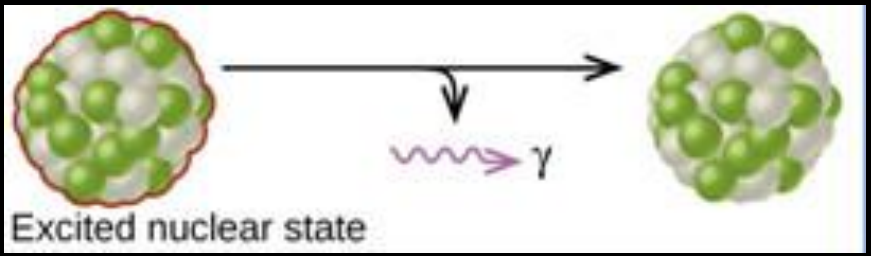
Typically from heavier nuclei (A > 200; Z > 83)



Gamma Emission

Parent nucleus: emits high energy photon

No effect on either A or Z



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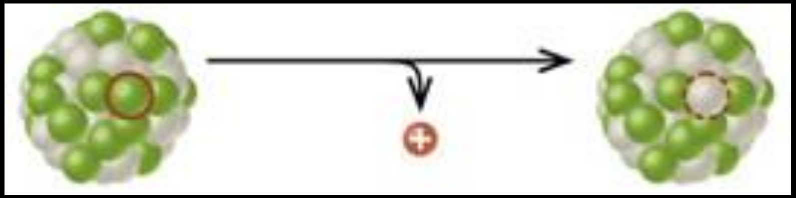
Types of Radioactive Decay

Positron Emission

Parent Nucleus: emits positron

low n:p ratio

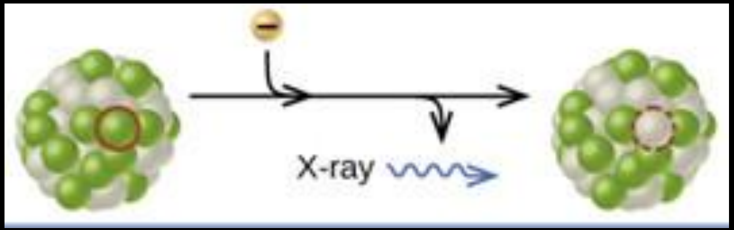


Daughter Nucleus: closer to stability band

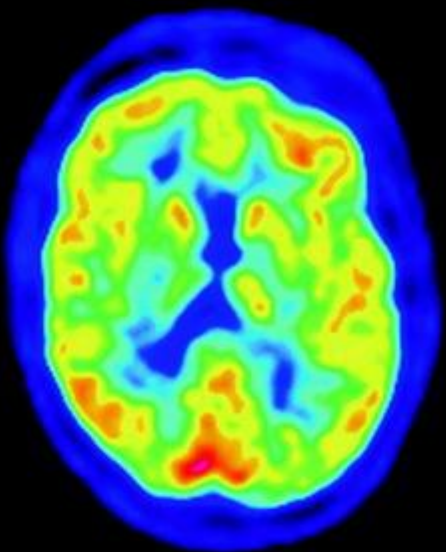
Electron Capture

Parent Nucleus: captures inner shell electron

Daughter: A unchanged; Z -1



Positron Emission Tomography



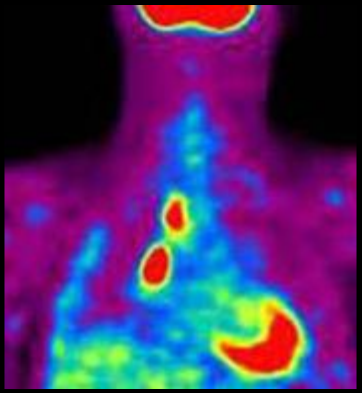
Radioactive F-18 incorporated into glucose

Radioactive decay (gamma radiation) detected

Used to study brain chemistry

highlights increased metabolism

Used to spot cancerous growth



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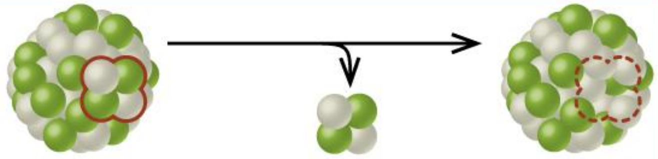
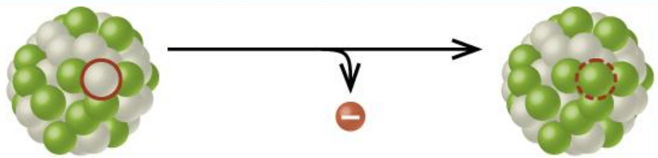
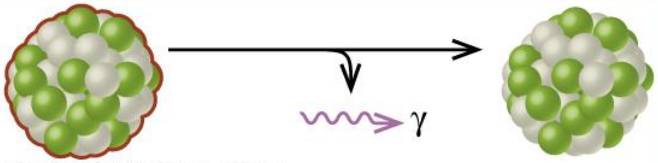
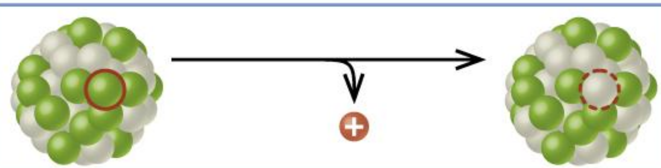
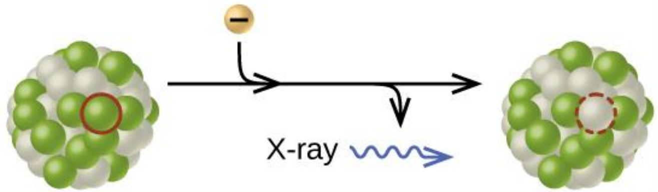
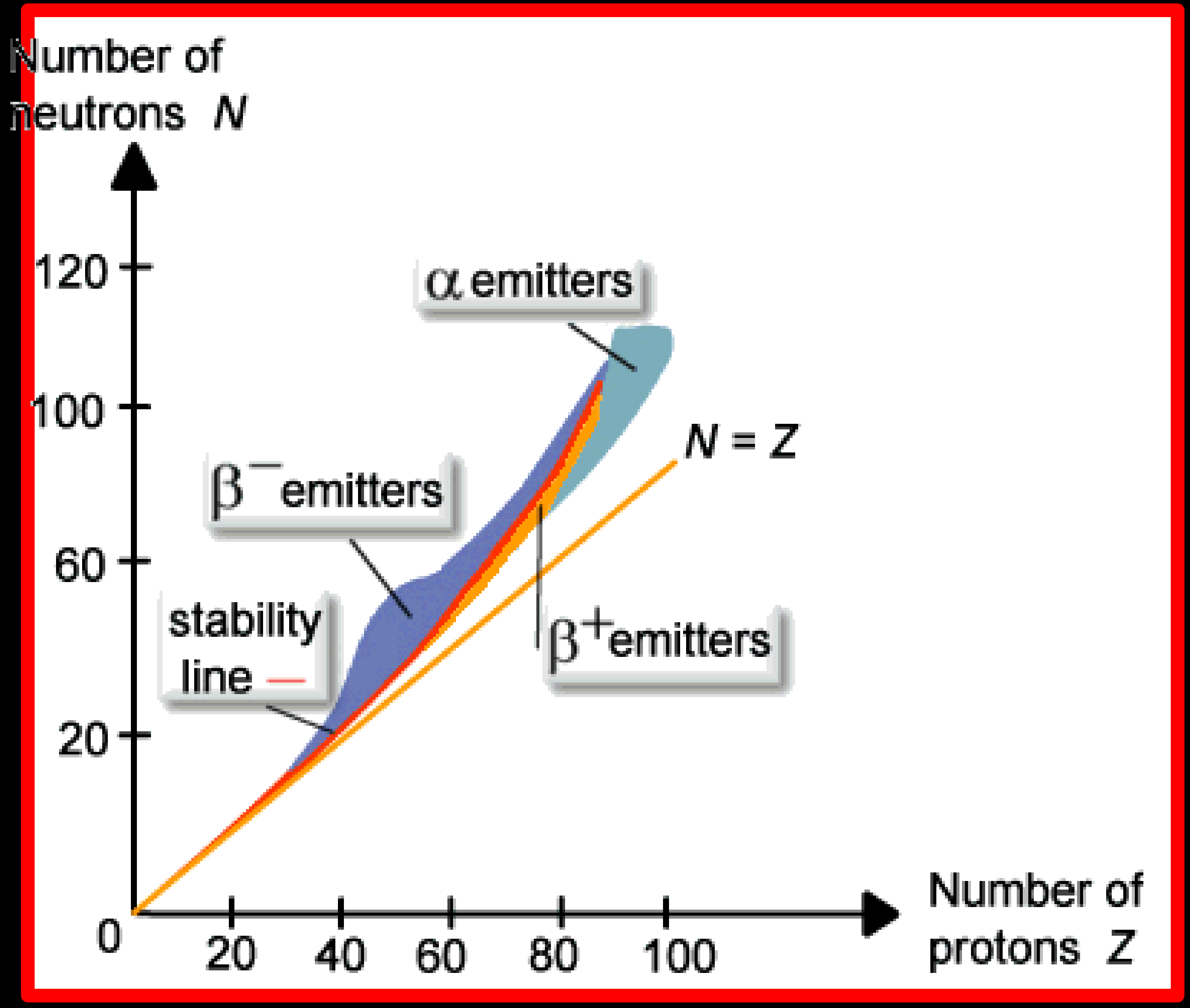
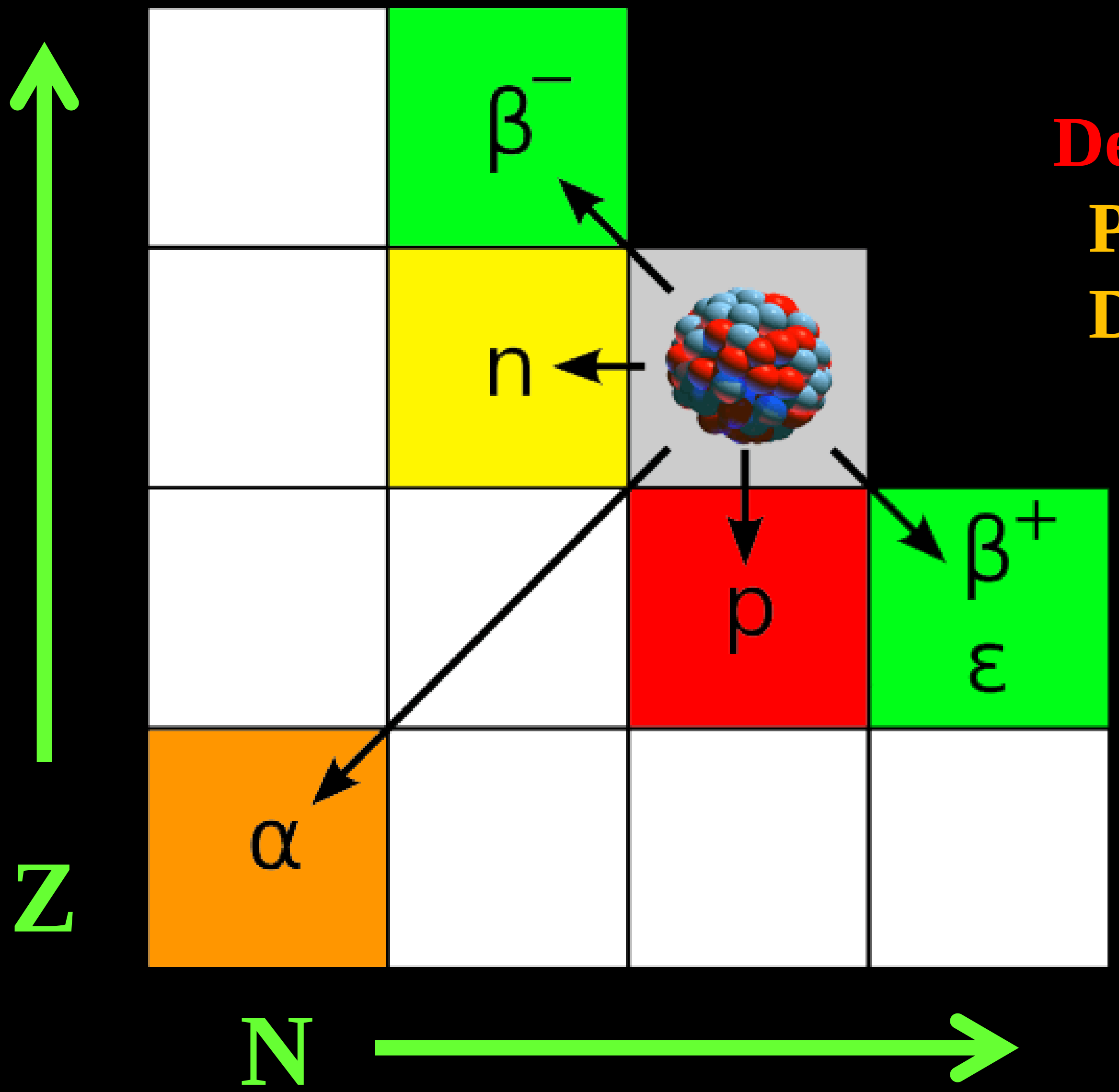
Nuclear Decay Events

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X$ $\quad$ $^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X$ $\quad$ $^{0}_{-1}e + ^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X$ $\quad$ $^{0}_{0}\gamma + ^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X$ $\quad$ $^{0}_{+1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X$ $\quad$ $^{0}_{-1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Nuclear Decay Events



Nuclear Decay Events



Decay alters nucleus

Parent decays

Daughter results

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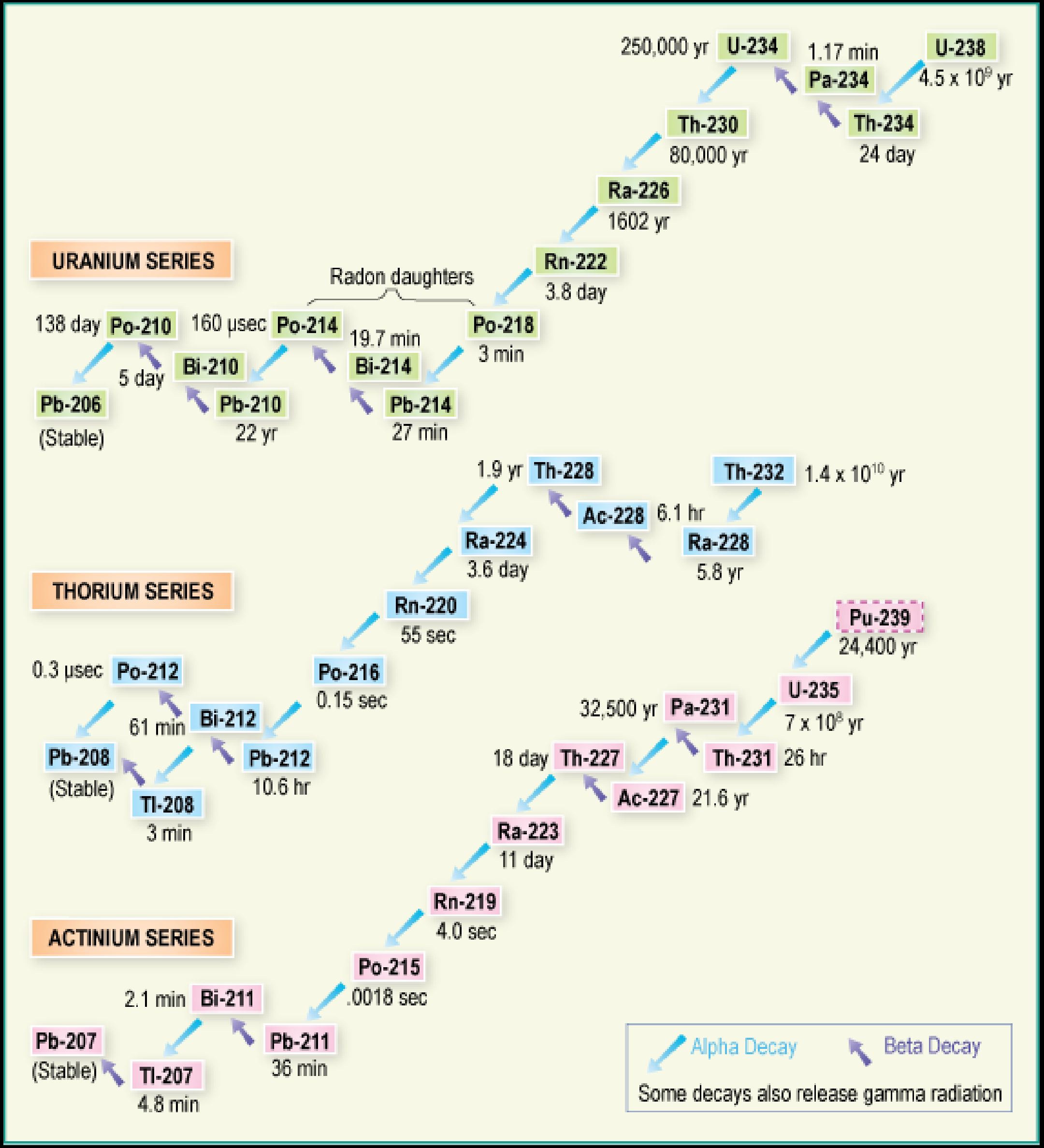
Naturally Occurring Radioactive Decay Series



Chains of successive decays

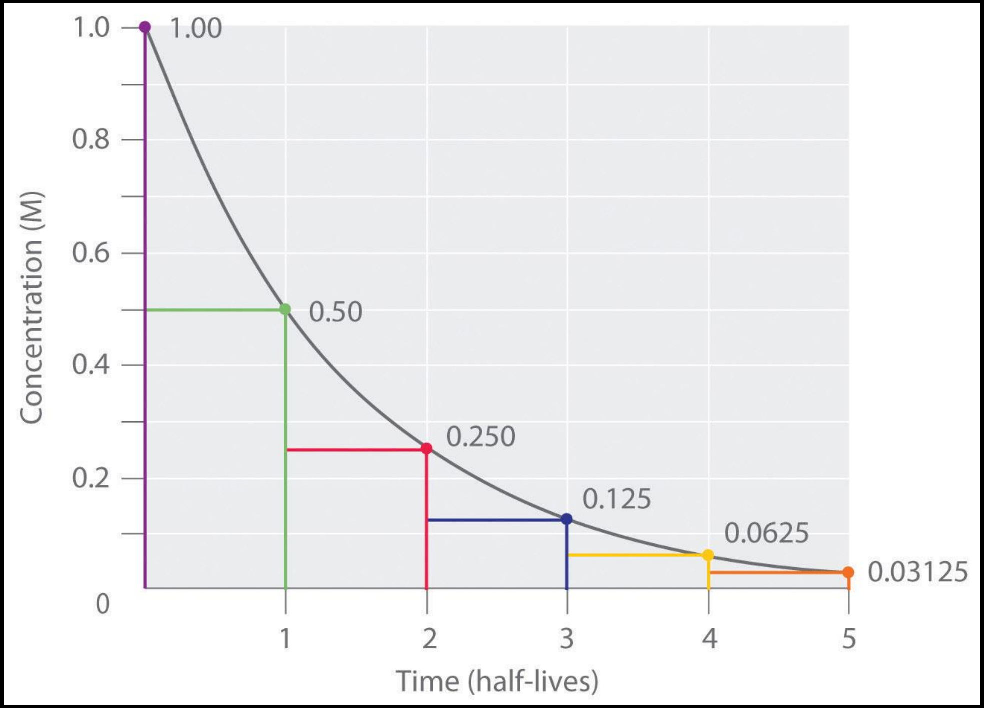
Named for Parent Isotope

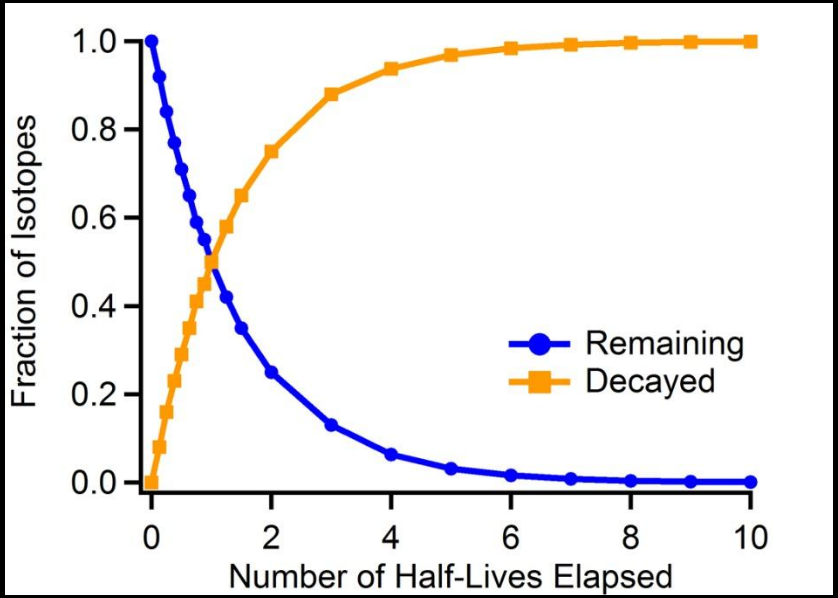
All decay to stable lead

Radioactive Half-Lives

Radioactive decay follows first order kinetics

Half-time ($t^{1/2}$): time for one-half of sample to decay





$$N_t = N_0\, e^{-kt}$$

$$t = -1/2 \ln \left(\frac{N_t}{N_o}\right)$$

N = number of atoms

n = isotope decay constant

t = time

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Radioactive Half-Lives

Cobalt -60 decays with a half-life of 5.27 years to produce Ni- 60.

The decay (rate) constant:

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{5.27\ y} = 0.132\ y^{-1}$$

Calculate amount remaining after 15 years:

$$\frac{N^t}{N_o} = e^{-\lambda t} = e^{-(0.132y)(15.0y)} = 0.138 \rightarrow 13.8\ \%$$

How long to decay to 2 % of the original sample

$$t = -\frac{1}{\lambda} \ln\left(\frac{N_t}{N_o}\right) = -(1 / 0.132\ y^{-1}) \ln (0.0200\ N_0/N_0)$$

$$t = 29.6\ y$$

Radioactive Half-Life Problem

Radon-222 has a half-life of 3.823 days. How long will it take a sample of radon-222 with a mass of 0.750 g to decay to 0.100 g of the original radon-333

Fraction Remaining:

0.100 / 0.750 = 0.1333

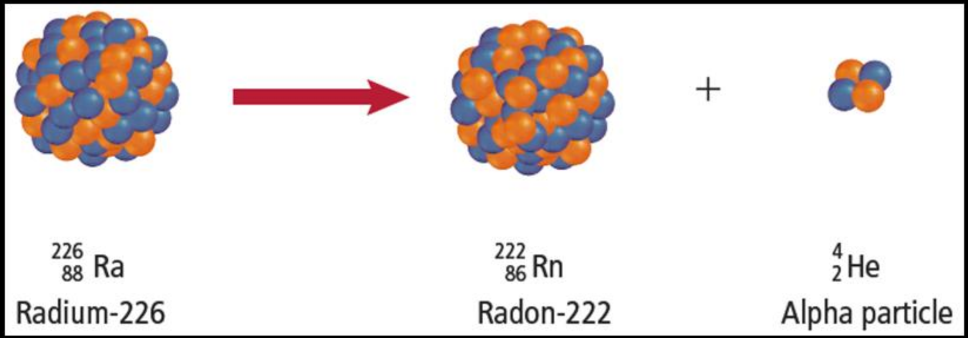
Determine number of half-times:

$(1/2)^n = 0.1333$

$n \log(0.5) = \log(0.1333)$

$n(-0.301) = -0.876$

$n = 2.91$



Determine time elapsed:

$$2.91 \text{ half-lives} \times \frac{3.823 \text{ days}}{\text{half-live}} = 11.1 \text{ days}$$

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Medically Important Radioactive Half-Lives

Type[1]	Decay Mode	Half-Life	Uses
F-18	β^+ decay	110. minutes	PET scans
Co-60	β decay, γ decay	5.27 years	cancer treatment
Tc-99m	γ decay	8.01 hours	scans of brain, lung, heart, bone
I-131	β decay	8.02 days	thyroid scans and treatment
Tl-201	electron capture	73 hours	heart and arteries scans; cardiac stress tests

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Radioisotopes in the News

Xe-129 found in Mars atmosphere
Implies ancient nuclear explosion

He-3 found on the moon
Potential fusion energy source

Sr-90 found in atmosphere
Indicates nuclear processes
Health concern since animals incorporate Sr for Ca

Co-60 gamma ray source
Used in radiation therapy to kill cancer cells

Half-Life Demo

m&m's EXPERIMENT

The following experiment is designed to simulate a natural occurrence.

I. **Data Collection:**

a. Quality control: Check each m&m to be sure that it has an "m" on one side *only* – eat any that don't! You may also consume any m&m's that are not whole.

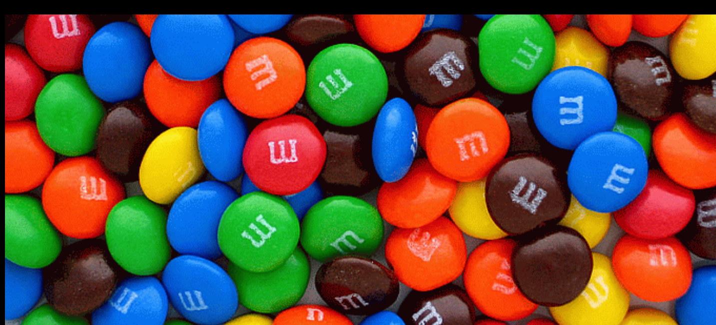
b. Count the m&m's in the cup and record as the beginning number in the table at the right.

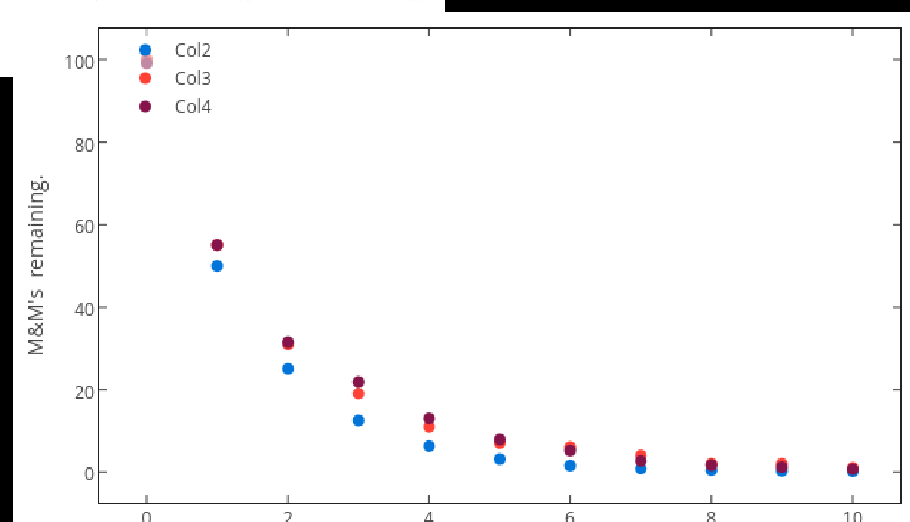
c. Shake the cup and carefully dump the m&m's on the napkin on your desktop. Remove those candies that landed with the "m" showing and eat them! Count the ones remaining and record this number in the chart at the right. Place these candies back into the cup.

d. Repeat step c until no m&m's are left.

e. Graph the data from the table below – label and use an appropriate scale.

Toss	# remaining
Beginning	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	



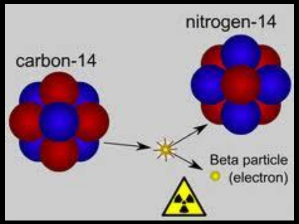


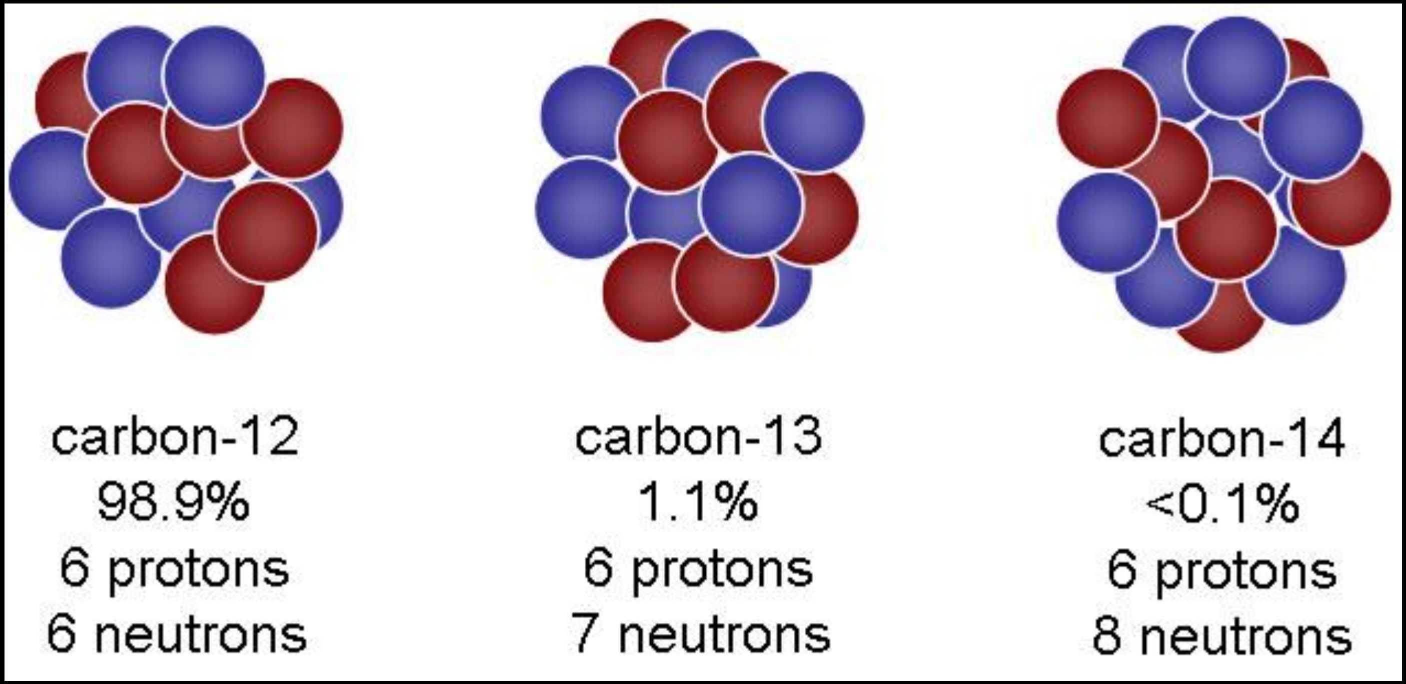
LPT

Radiometric Dating

Radioactive decay has become a powerful dating technique

Carbon-14: useful for former living materials
- **reliable to 30,000 years ago**
- **limit 50,000 years ago**





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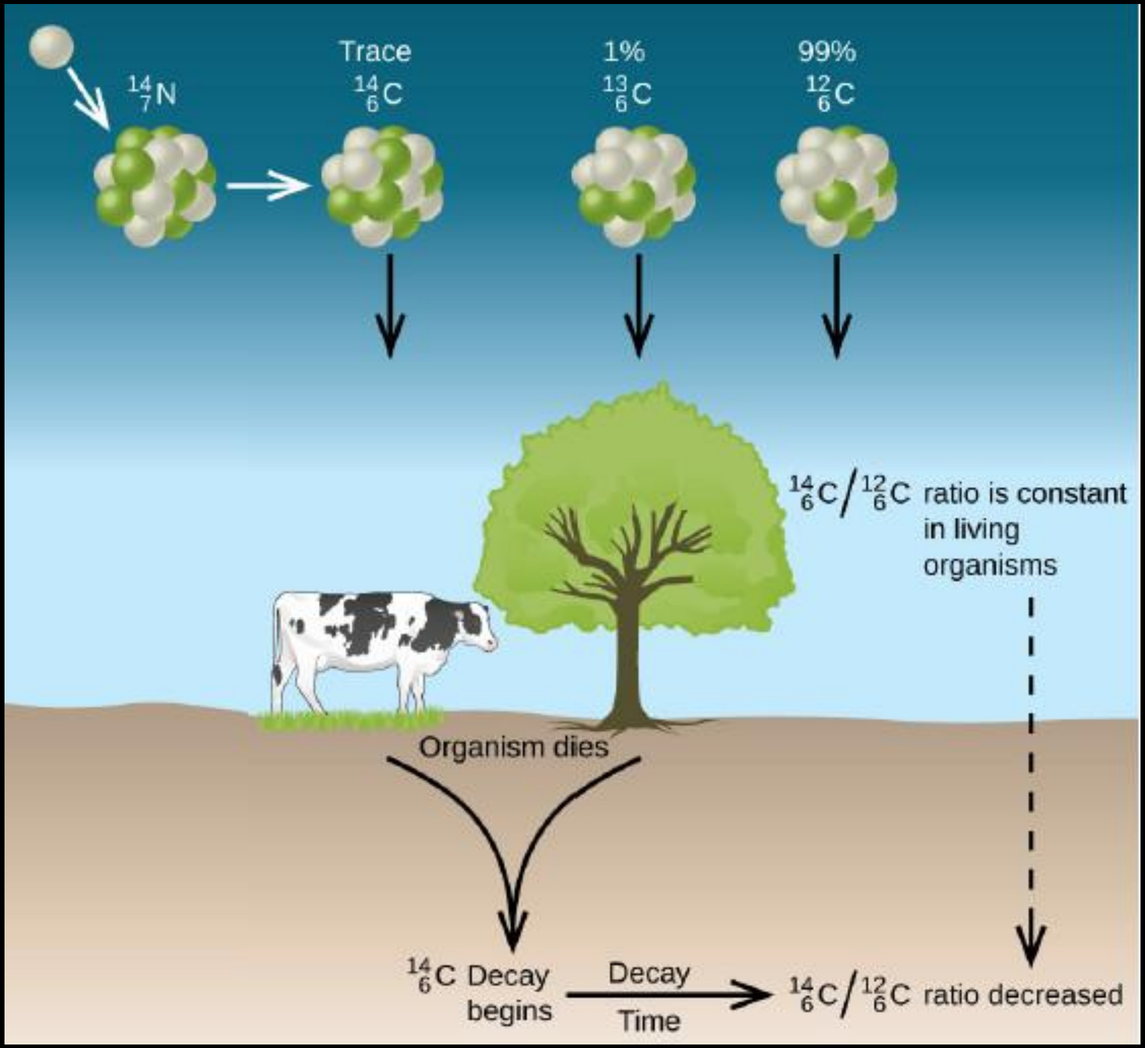
Radiometric Dating: Carbon-14



Half-life C-14:
5730 years

Six half-lives:
34,380 years

During Life:
C-14 Constant
C-12

After death
As C-14 decays

C-14 Decreases
C-12

Ratio ~ Age

Increasing CO_2 levels may affect C-14 data; validate with other methods

LPT

Radiometric Dating: Carbon-14

A piece of the dead sea scrolls has an activity of 10.8 disintegrations per gram of C-14. If initial activity was 13.6 disintegrations per minute, estimate scroll age.

Determine λ:

$\lambda = \ln 2 / t_{1/2}$

$\lambda = 0.693 / 5730\ y$

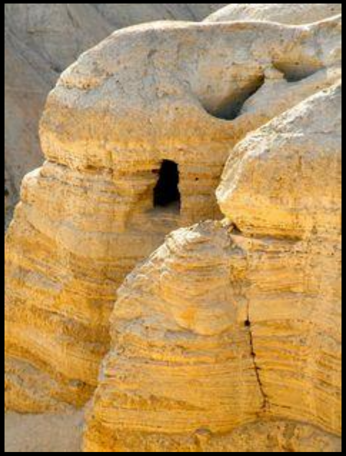
$\lambda = 1.21 \times 10^{-4}\ y^{-1}$

Estimate age:

$t = -\ 1/\lambda\ \ \ln(\text{rate}_t / \text{rate}_0)$

$t = -\ (1/\ 1.21 \times 10^{-4}\ y^{-1})\ \ln(10.8\ \text{dis/min/g C} / 13.6\ \text{dis/min/g C})$

t = 1905 years → 1910 years



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Radiometric Dating:

Seeds from Egyptian tombs have a C-14 disintegration rate of 9.07 dis/min/g C. Determine the age of the seeds

Determine λ:

$\lambda = \ln 2 / t_{1/2}$

$\lambda = 0.693 / 5730\ y$

$\lambda = 1.21 \times 10^{-4}\ y^{-1}$

Estimate age:

$t = -\ 1/\lambda\ \ln(rate_t / rate_0)$

$t = -\ (1/\ 1.21 \times 10^{-4}\ y^{-1})\ \ln(9.07\ dis/min/g\ C\ /\ 13.6\ dis/min/g\ C)$

t = 3347 years ➔ 3350 years

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Radiometric Dating: Other nucleotides

Isotope selected depends on date range needed

ISOTOPES		HALF-LIFE OF PARENT (YEARS)	EFFECTIVE DATING RANGE (YEARS)	MINERALS AND OTHER MATERIALS THAT CAN BE DATED
PARENT	DAUGHTER			
Uranium-238	Lead-206	4.5 billion	10 million-4.6 billion	Zircon Uraninite
Potassium-40	Argon-40	1.3 billion	50,000 - 4.6 billion	Muscovite Biotite Hornblende Whole volcanic rock
Rubidium-87	Strontium-87	47 billion	10 million - 4.6 billion	Muscovite Biotite Potassium feldspar Whole metamorphic or igneous rock
Carbon-14	Nitrogen-14	5730	100 -70,000	Wood, charcoal, peat Bone and tissue Shell and other calcium carbonate Groundwater, ocean water, and glacier ice containing dissolved carbon dioxide

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Radiometric Dating: Rocks

Ratio of parent / daughter used to estimate age

Rock sample contains 9.58×10^{-5} g of U-235 and 2.51×10^{-5} g of Pb-206.
Determine the age of the rock. (Assume all Pb-206 produced by decay of U-238.)

Amount of U-238 currently in the rock:

$$9.58 \times 10^{-5}\ \text{g U} \times \frac{1\ \text{mol U}}{238\ \text{g U}} = 4.03 \times 10^{-7}\ \text{mole U-238}$$

Amount of Pb produced converted to moles uranium:

$$2.51 \times 10^{-5}\ \text{g Pb} \times \frac{1\ \text{mol Pb}}{206\ \text{g Pb}} \times \frac{1\ \text{mol U-238}}{1\ \text{mol Pb}} = 1.22 \times 10^{-7}\ \text{mole U-238}$$

Total U-238 present in original sample:

$$(4.03 + 1.22) \times 10^{-7}\ \text{mole} = 5.25 \times 10^{-7}\ \text{mole U-238}$$

Amount of time passed for this decay process:

$$t = -1/\lambda \ \ln (N_t/N_0)$$

$$t = (1/1.54 \times 10^{-10}\ \text{y}^{-1}) \ \ln \frac{(4.03 \times 10^{-7}\ \text{mol U})}{(5.25 \times 10^{-7}\ \text{mol U})}$$

$$t = 1.7 \times 10^{9}\ \text{years}$$

Need Lamda:

$\lambda = \ln 2 / 4.5 \times 10^{9}$ y

$\lambda = 1.54 \times 10^{-10}\ \text{y}^{-1}$

Oldest earth rocks ~ 4.4 billion years old

LPT

Problem: Radiometric Dating of Rocks

Rock sample contains 6.14×10^{-4} g of Rb-87 and 3.51×10^{-5} g of Sr-87. Determine the age of the rock. (Half-life of Rb-87 = 4.7×10^{10} y.)

Amount of Rb-87 currently in the rock:

$$6.14 \times 10^{-4} \text{ g Rb} \times \frac{1 \text{ mol Rb}}{87 \text{ g Rb}} = 7.06 \times 10^{-6} \text{ mole Rb}$$

Amount of Sr produced converted to moles Rb:

$$3.51 \times 10^{-5} \text{ g Sr} \times \frac{1 \text{ mol Sr}}{87 \text{ g Sr}} \times \frac{1 \text{ mol Rb}}{1 \text{ mol Sr}} = 4.03 \times 10^{-7} \text{ mole Rb}$$

Total Rb present in original sample:

$$7.06 \times 10^{-6} + 4.03 \times 10^{-7} \text{ mole} = 7.46 \times 10^{-6} \text{ mole Rb}$$

Amount of time passed for this decay process:

$$t = -1/\lambda \ \ln (N_t/N_0)$$

$$t = -(1/1.47 \times 10^{-11} \text{ y}^{-1}) \ \ln \frac{(7.06 \times 10^{-6} \text{ mol Rb})}{(7.46 \times 10^{-6} \text{ mol Rb})}$$

$$t = 3.7 \times 10^{9} \text{ years}$$

Need Lamda:

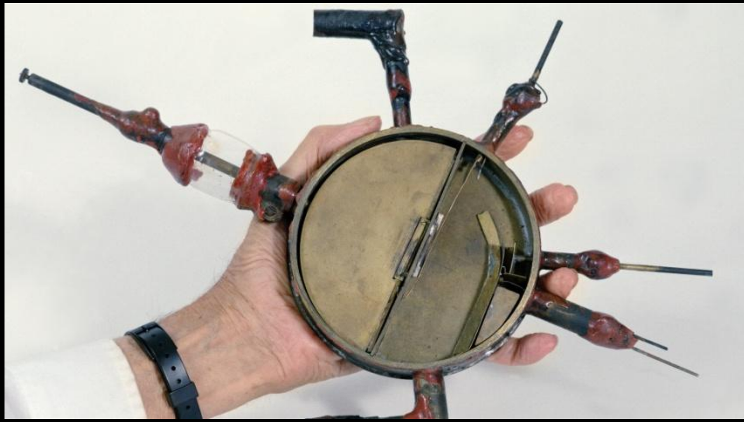
$$\lambda = \ln 2 / 4.7 \times 10^{10} \text{ y}$$

$$\lambda = 1.47 \times 10^{-11} \text{ y}^{-1}$$

Oldest earth rocks ~ 4.4 billion years old

Transmutation of Elements

Transmutation:
Changing one nucleotide to another via nuclear reactions



Requires enormous kinetic energy:
Originally called “atom smashers”
Now: particle accelerators or colliders

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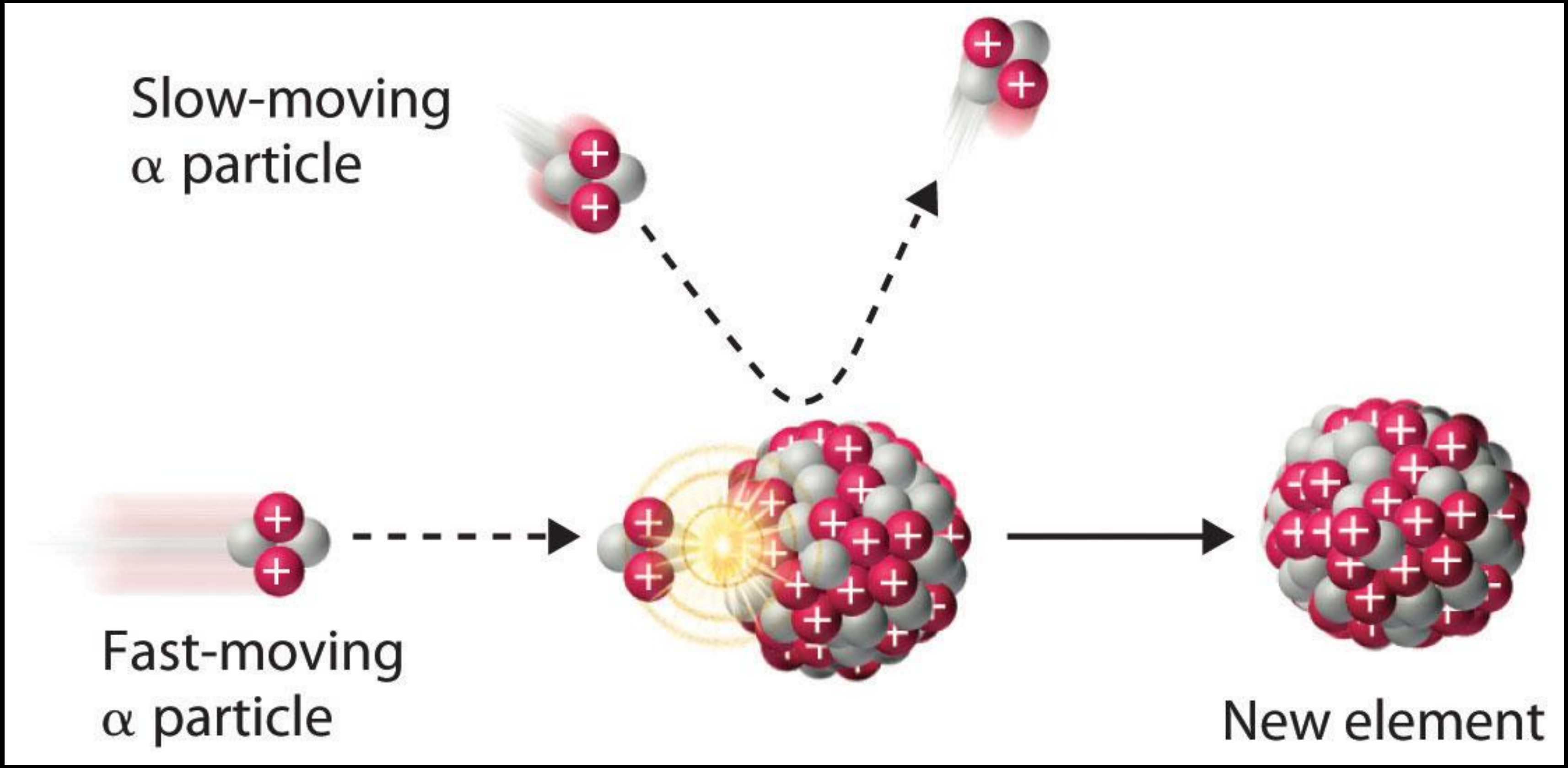
Transmutation of Elements

Requires enormous kinetic energy

Must overcome forces holding nucleus together



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Transmutation of Elements

All elements beyond Uranium are man-made
First man-made element: Neptunium (Neptune follows Uranus)

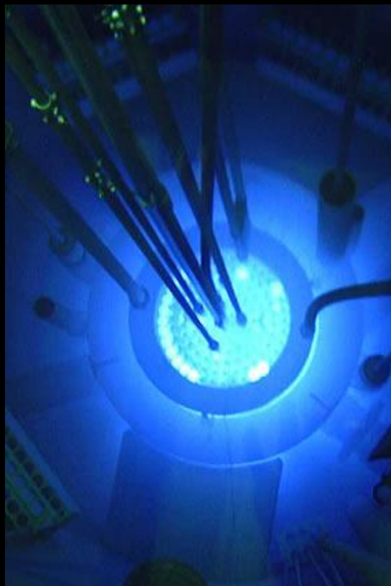
$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U$$

$${}^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e \qquad t_{1/2} = 23.5 \text{ min}$$

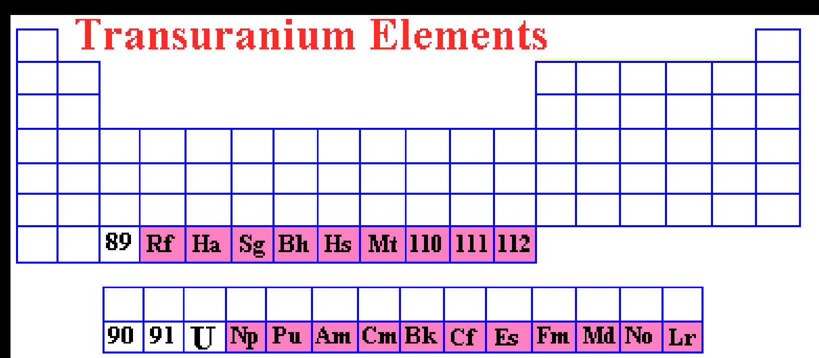
$${}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e \qquad t_{1/2} = 2.36 \text{ days}$$

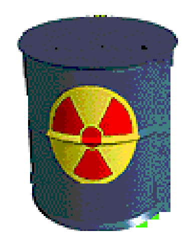
Most Plutonium created in “breeder reactors” using U-238

Transmutation of Elements



Name	Symbol	Atomic Number	Reaction
americium	Am	95	$^{239}_{94}\text{Pu} + ^{1}_{0}\text{n} \longrightarrow ^{240}_{95}\text{Am} + ^{0}_{-1}\text{e}$
curium	Cm	96	$^{239}_{94}\text{Pu} + ^{4}_{2}\text{He} \longrightarrow ^{242}_{96}\text{Cm} + ^{1}_{0}\text{n}$
californium	Cf	98	$^{242}_{96}\text{Cm} + ^{4}_{2}\text{He} \longrightarrow ^{243}_{97}\text{Bk} + 2^{1}_{0}\text{n}$
einsteinium	Es	99	$^{238}_{92}\text{U} + 15^{1}_{0}\text{n} \longrightarrow ^{253}_{99}\text{Es} + 7^{0}_{-1}\text{e}$
mendelevium	Md	101	$^{253}_{99}\text{Es} + ^{4}_{2}\text{He} \longrightarrow ^{256}_{101}\text{Md} + ^{1}_{0}\text{n}$
nobelium	No	102	$^{246}_{96}\text{Cm} + ^{12}_{6}\text{C} \longrightarrow ^{254}_{102}\text{No} + 4^{1}_{0}\text{n}$
rutherfordium	Rf	104	$^{249}_{98}\text{Cf} + ^{12}_{6}\text{C} \longrightarrow ^{257}_{104}\text{Rf} + 4^{1}_{0}\text{n}$
seaborgium	Sg	106	$^{249}_{98}\text{Cf} + ^{18}_{8}\text{O} \longrightarrow ^{263}_{106}\text{Sg} + 4^{1}_{0}\text{n}$
meitnerium	Mt	107	$^{209}_{83}\text{Bi} + ^{58}_{26}\text{Fe} \longrightarrow ^{266}_{109}\text{Mt} + ^{1}_{0}\text{n}$





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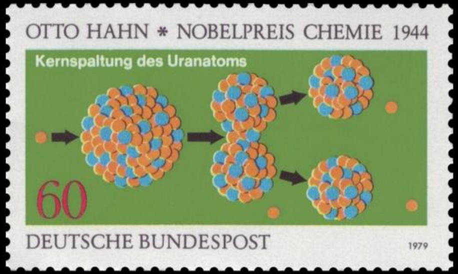
Nuclear Fission

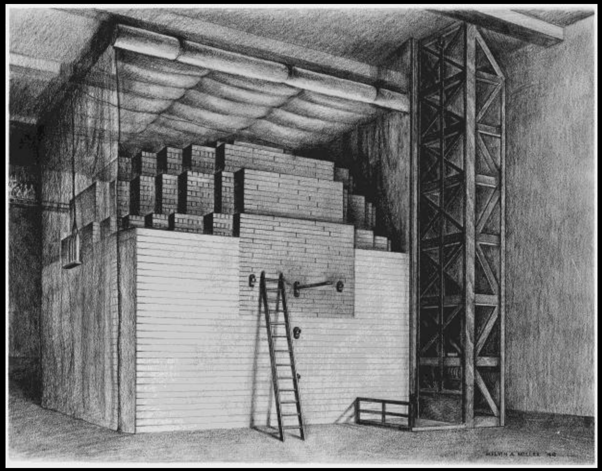


Fission (splitting):

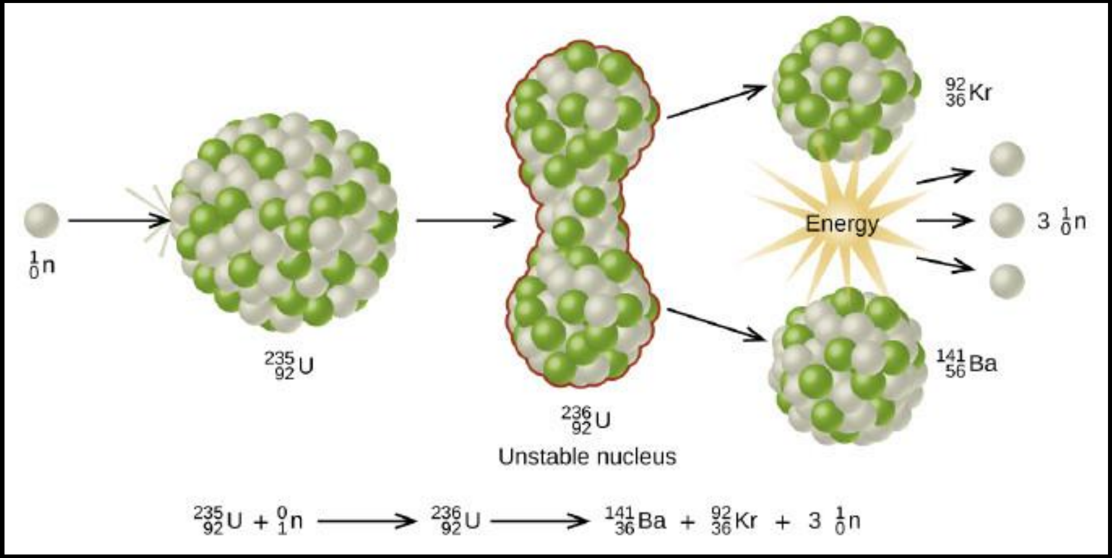
Heavy element nuclei with small nuclear binding energy spontaneously decompose to nuclei with smaller binding energy

Typically, a random, low probability event

First artificial fission (Hahn, 1939)



12/2/1942



Process releases large amount of energy

1 kg U-235: 2.5 x 10^6 more energy than 1 kg coal

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Nuclear Fission: Typical products

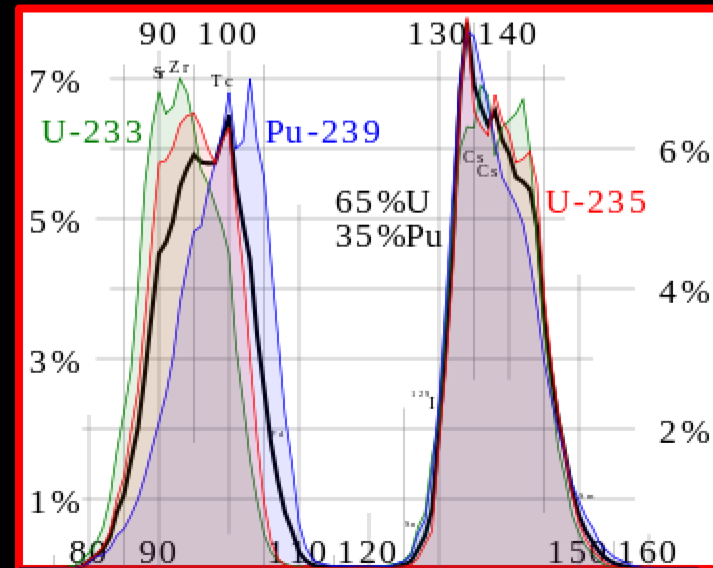
$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \longrightarrow {}^{90}_{38}Sr + {}^{144}_{54}Xe + 2\,{}^{1}_{0}n$$

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \longrightarrow {}^{87}_{35}Br + {}^{146}_{57}La + 3\,{}^{1}_{0}n$$

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \longrightarrow {}^{96}_{37}Rb + {}^{137}_{55}Cs + 3\,{}^{1}_{0}n$$

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \longrightarrow {}^{137}_{52}Te + {}^{97}_{40}Zr + 2\,{}^{1}_{0}n$$

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$$



Fission can produce elements from Zn to Lanthanides
Most appear in two peaks: 85-105 and 130-150

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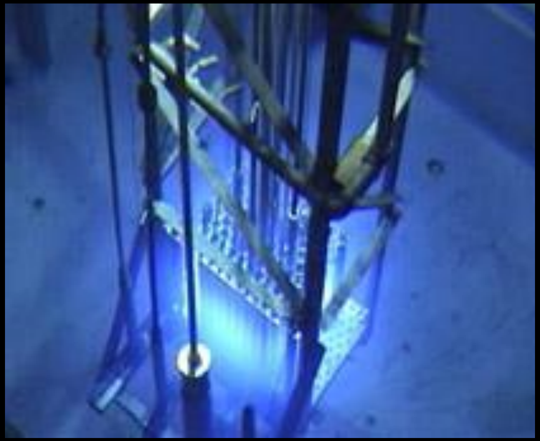
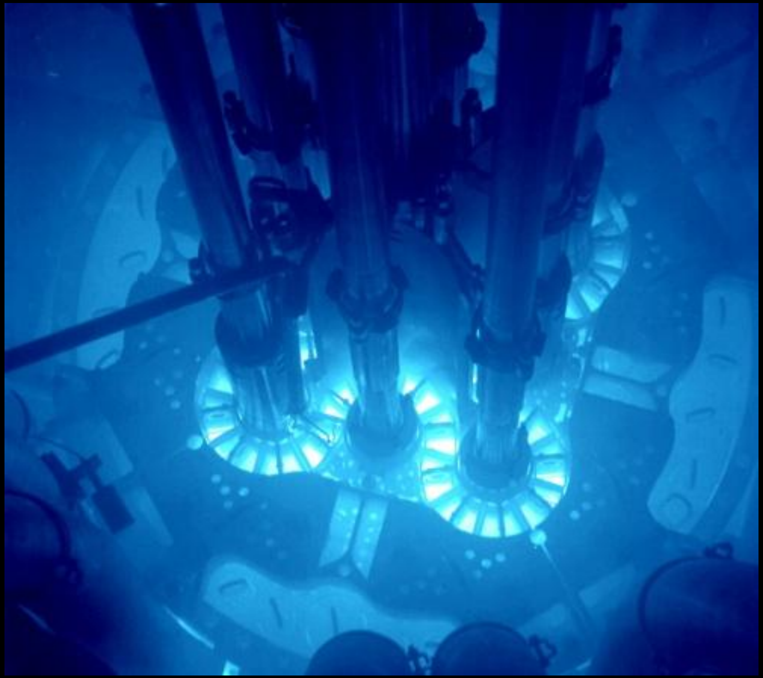
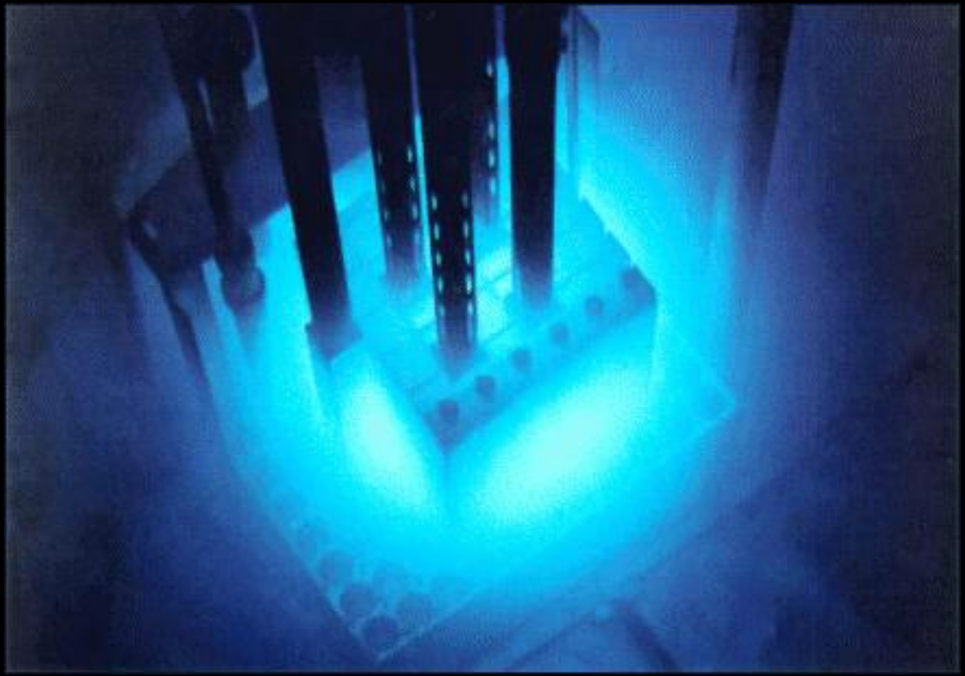
Cherenkov Radiation

Blue glow that results from electrically charged particle moving thru media faster than speed of light in that media







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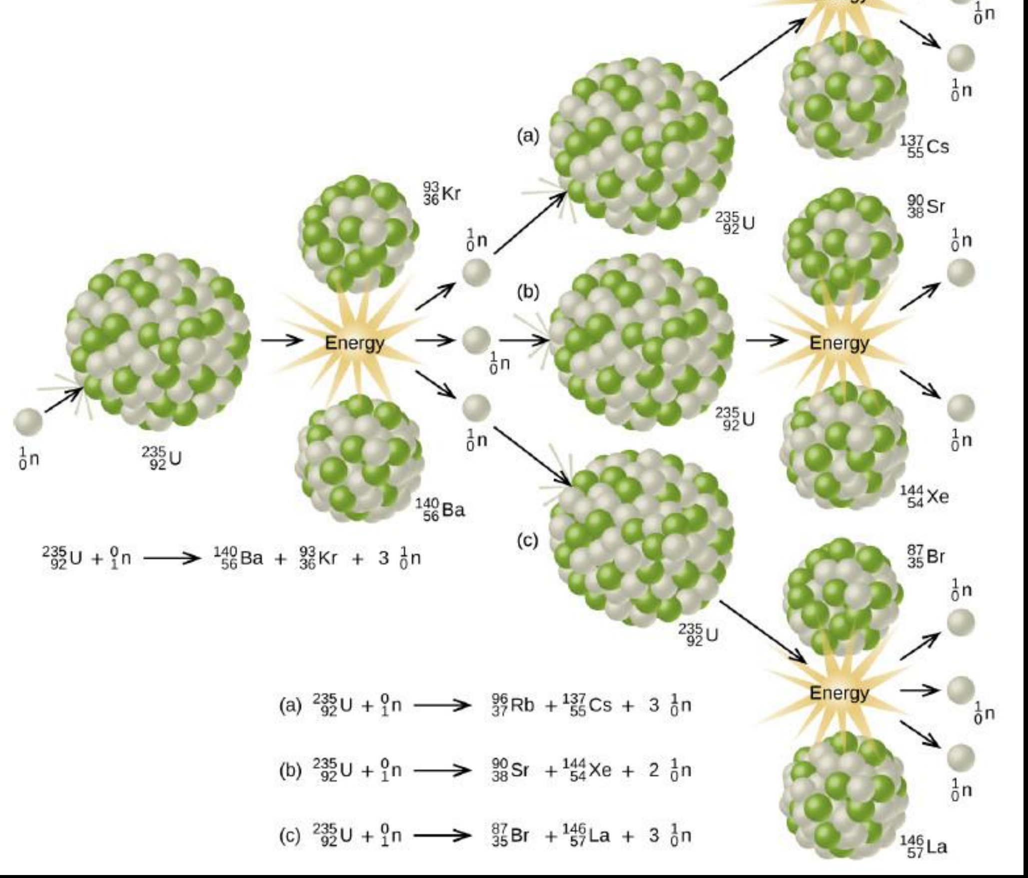
Nuclear Fission: Chain Reaction

Chain Reaction:
Multiplication of neutrons
More fissions



Releases enormous (explosive) energy

Nuclear Fission: Definitions

Fissile: material that will undergo fission as a result of any neutron source

U-233 (from Thorium) U-235 Pu-239   Pu-241

Most actinides with odd number of neutrons

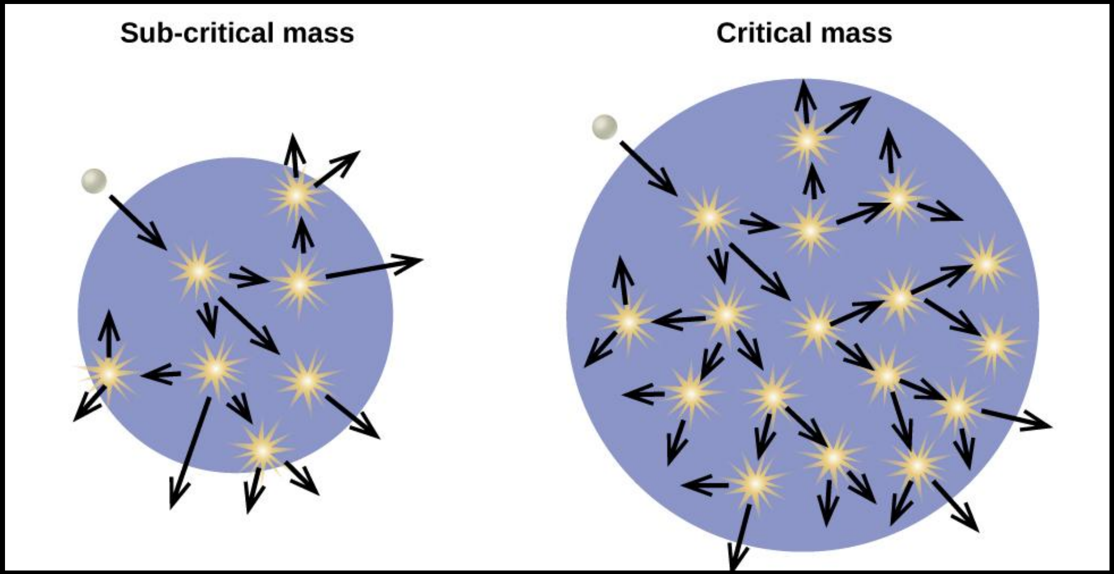
Fissionable: material that requires a high energy neutron source.

Pu-240   U-238

Fission is self-sustaining when neutrons produced exceed neutrons absorbed

Critical Mass: amount of material needed to sustain a chain reaction

Sub-critical mass: less than critical mass (not self-sustaining)



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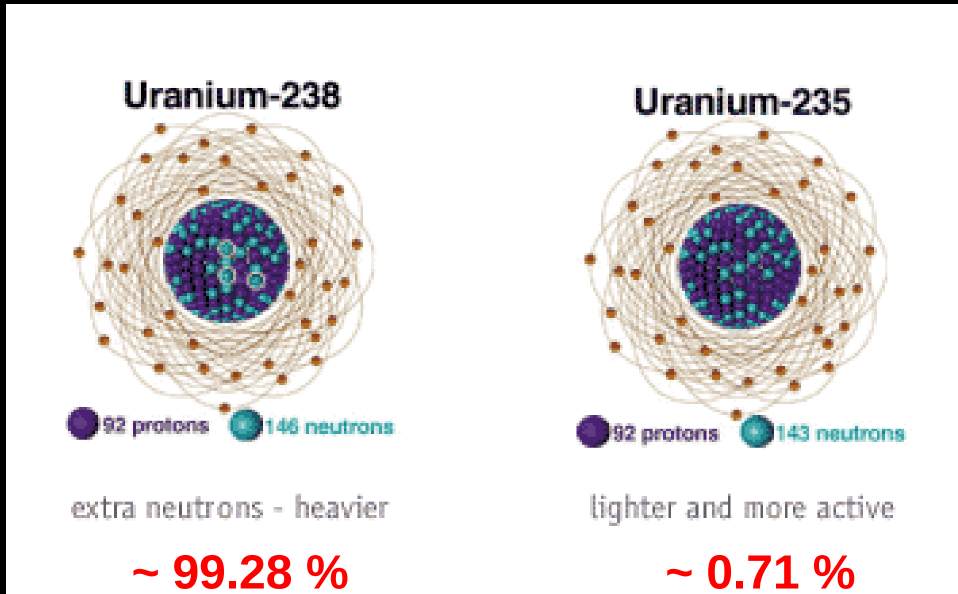
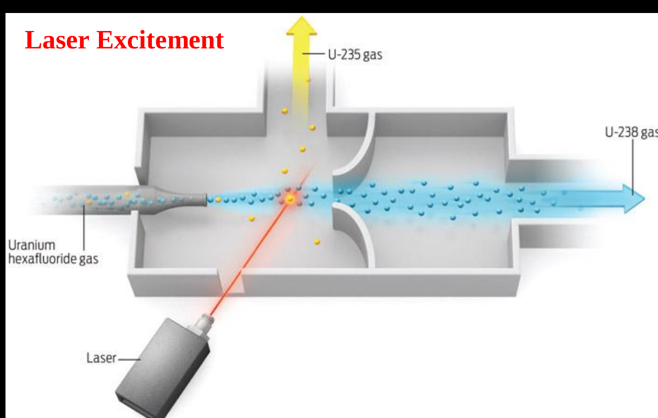
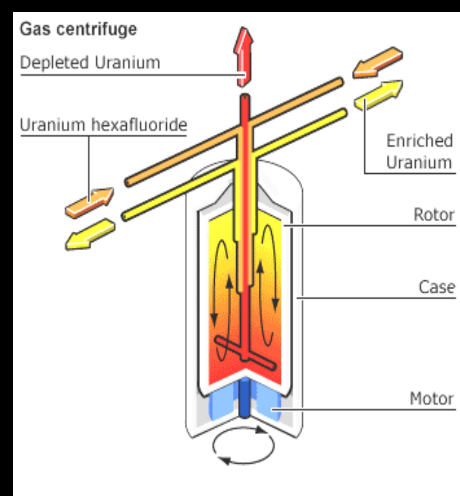
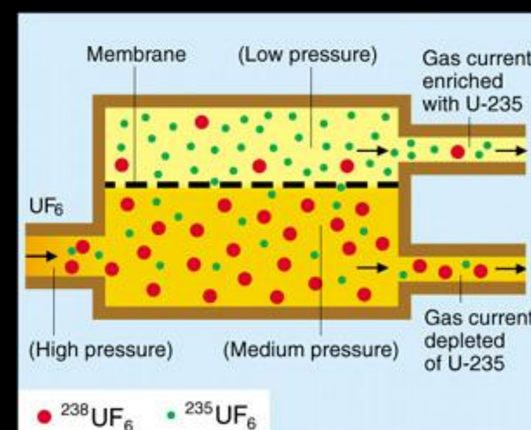
Isotopes of Uranium



Since Z is the same, chemical properties of the isotopes are identical







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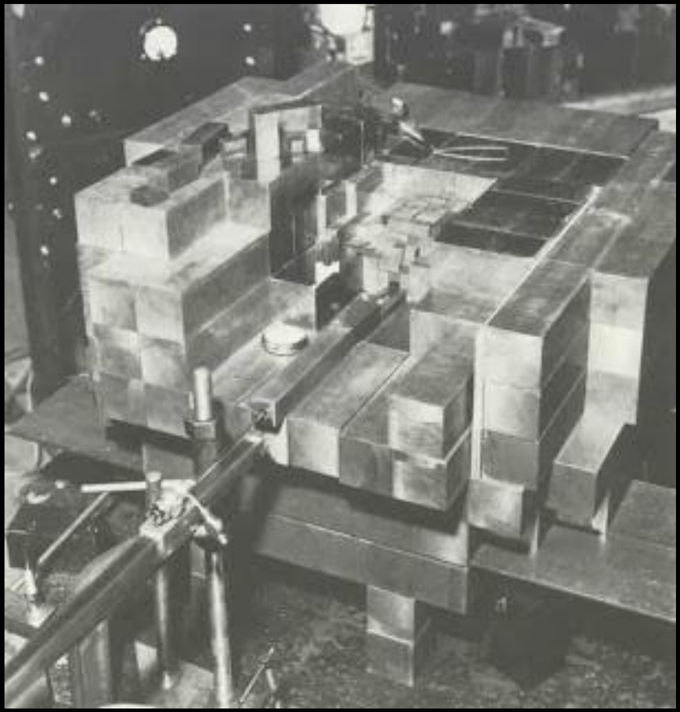
Tickling The Dragon's Tail

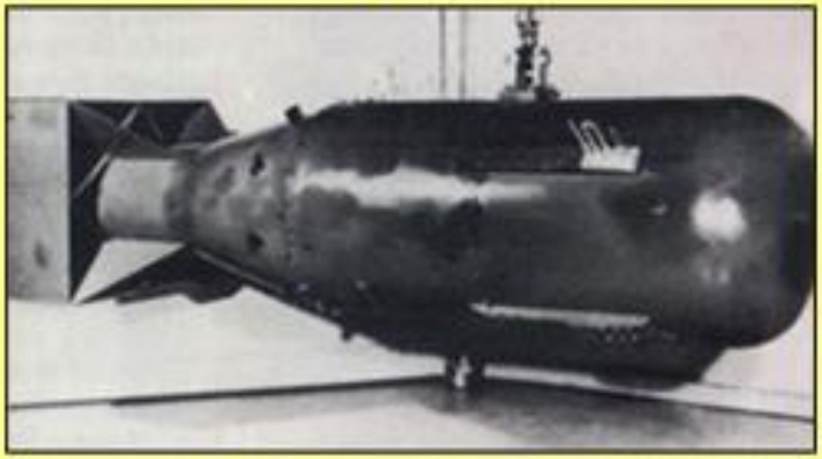
Manhattan Project Experiment to determine critical mass
Sub-critical masses brought together on a rail

Device failed, Louis Sloton held Uranium spheres apart
Died 5 days latter
Refused medications to allow detailed observations



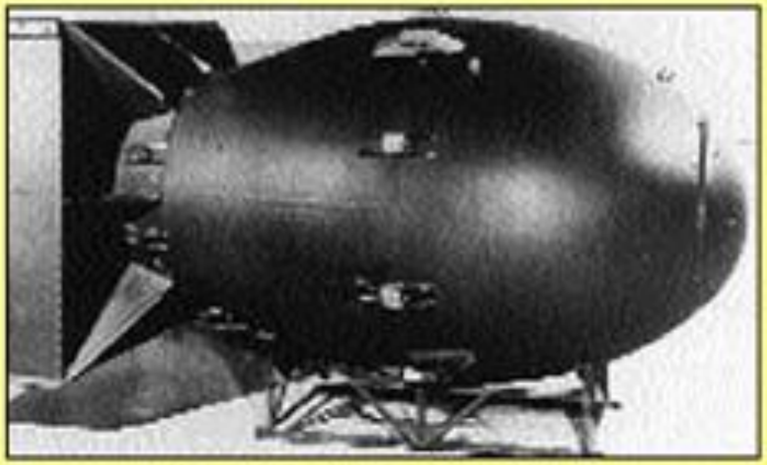
Atomic Bomb

Little boy : Hiroshima

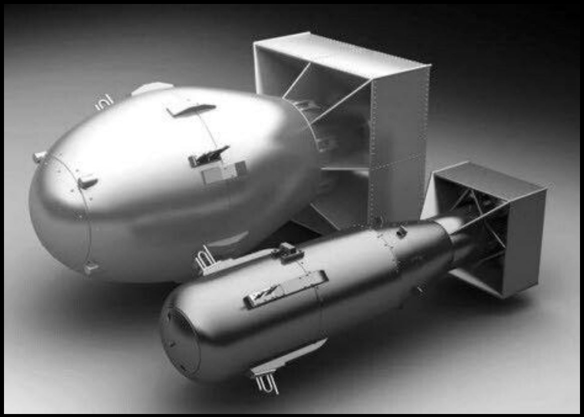


Fission uranium-235
Weight : 4400 kg
Power : 15,000 tons of TNT

Fat Man : Nagasaki

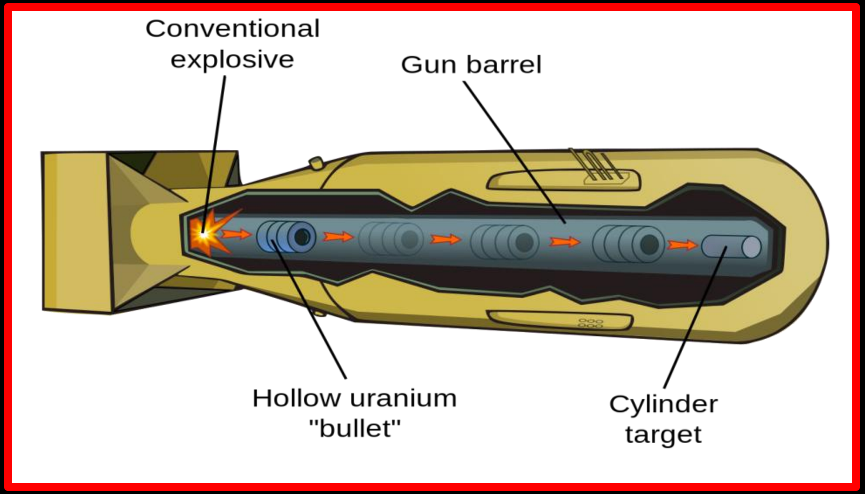


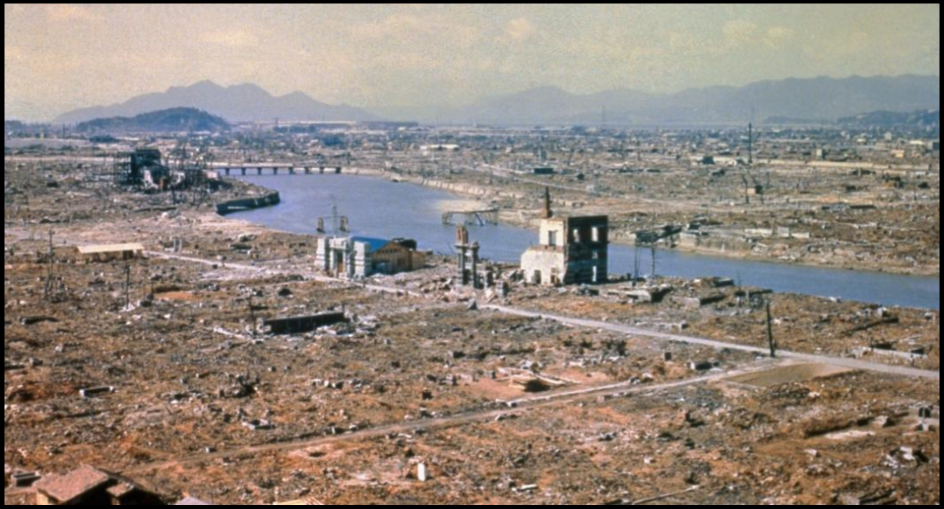
Fission plutonium-239
Weight: 4535 kg
Power : 21,000 tonnes de TNT

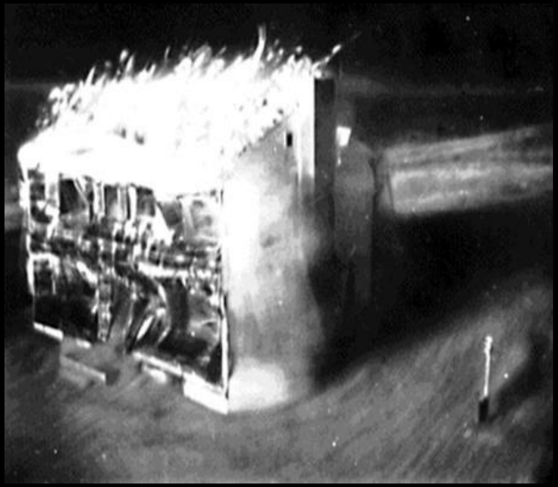


Enola Gay

Atomic Bomb







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Fission Reactors

Nuclear reactions that is controlled and sustained can be harnessed for power

Reactors control fission of U-235 or Pu 239 with 5 components:

- Nuclear fuel
- Moderator (slows neutrons)
- Reactor coolant
- Control rods
- Radiation shield and containment

Nuclear fuel is separated (diluted) to prevent chain reaction
Neutron flux controlled by neutron absorbing material
Heat released used to boil water
Steam turns turbine and generator

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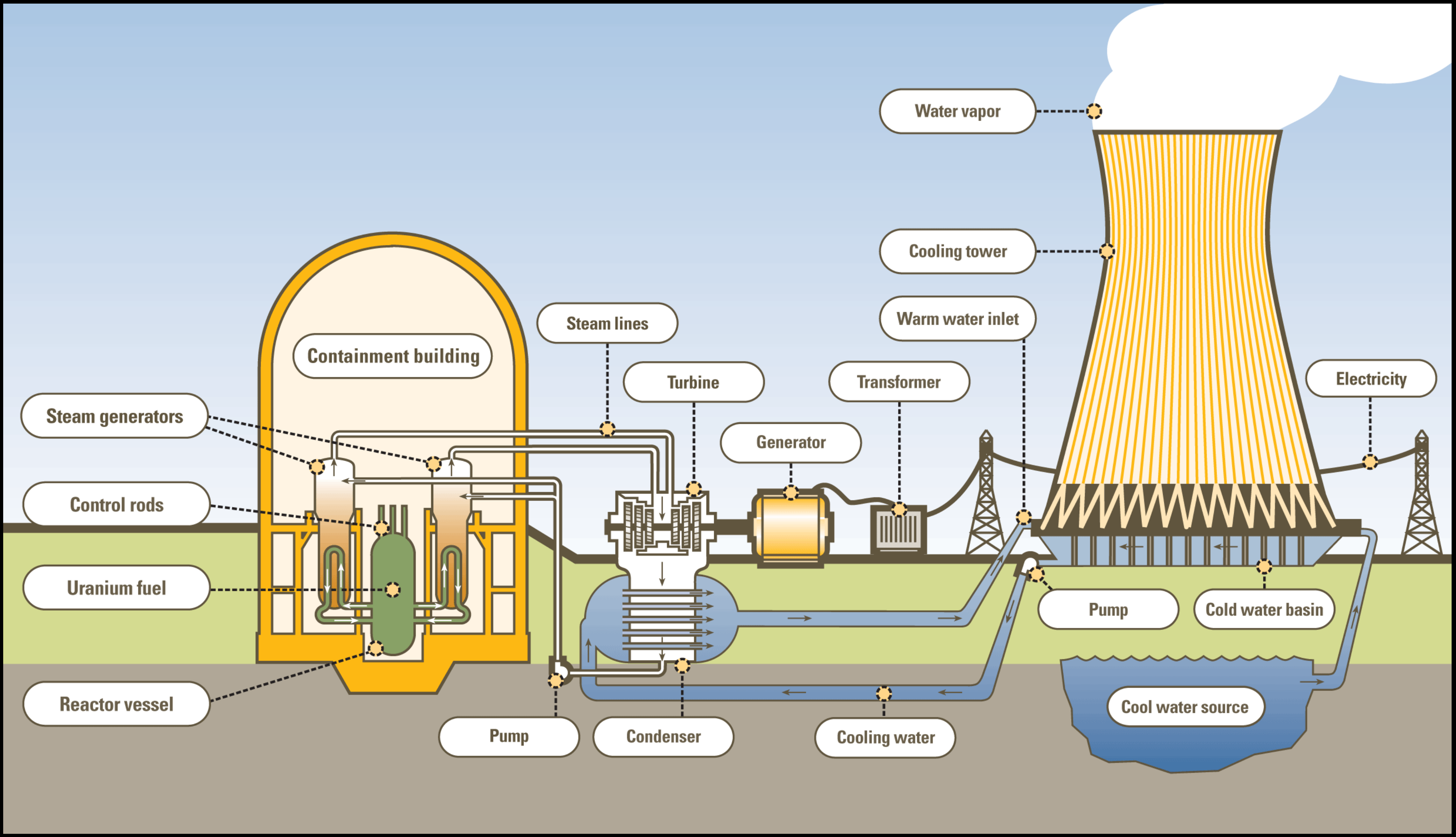
Power Plant Schematic



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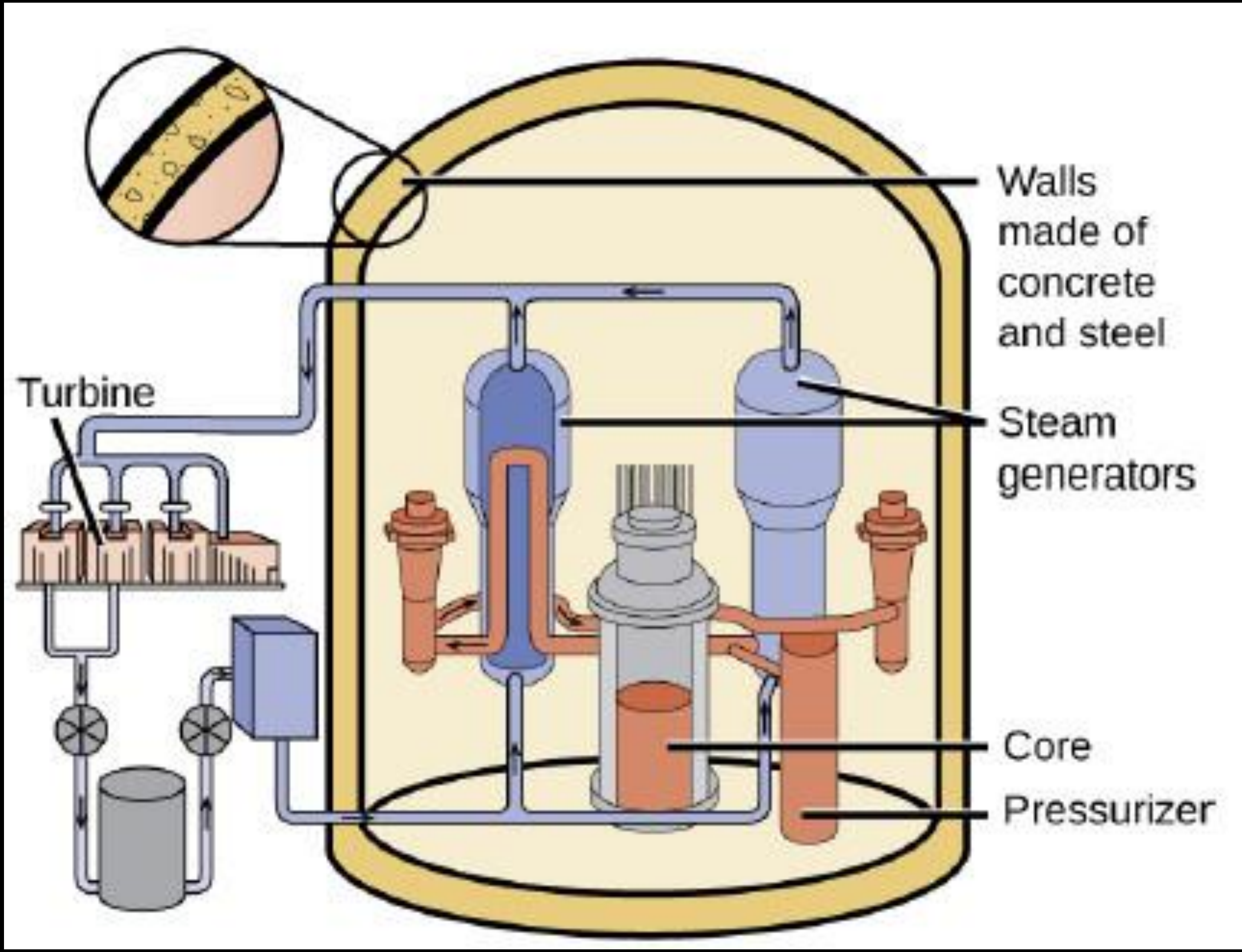
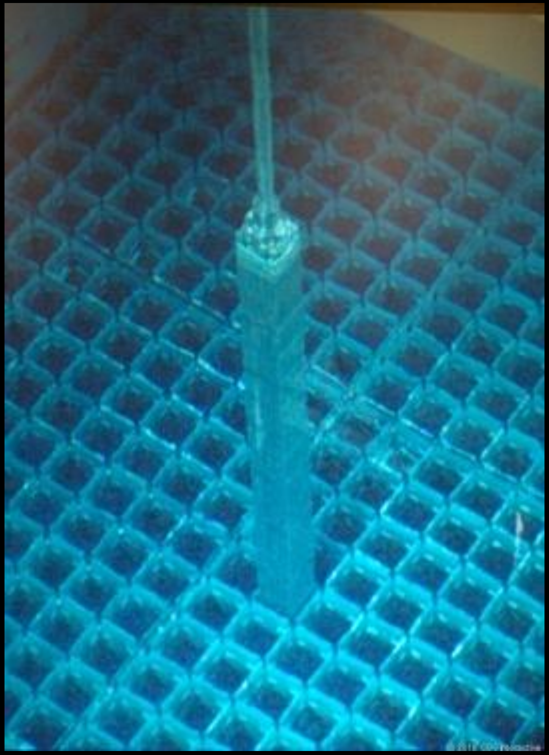
Fission Reactor Schematic



Nuclear Fuel Rods



Need fissionable material to sustain chain reaction

U-235

Uranium ore: ~ 0.05 – 0.3 % U-235

Fuel rods: enriched uranium ~ 5 % U-235

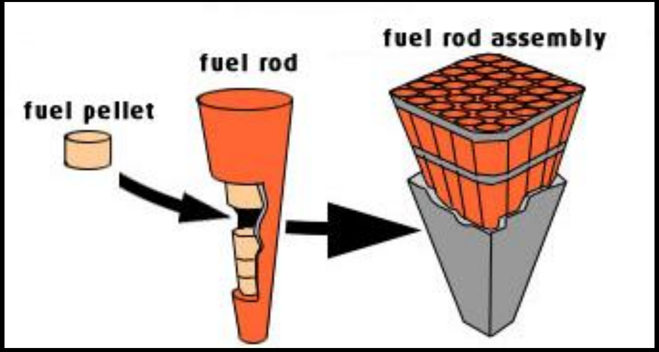
Well below level needed for atomic weapons

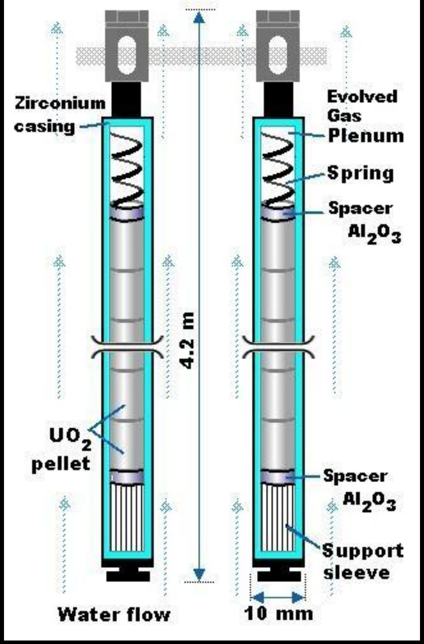
Eventually, consumed fuel drops efficiency

Depleted rods stored (thousands of years to decay)

Some material used for "depleted uranium" artillery shells

Also used to isolate a variety of radio-isotopes





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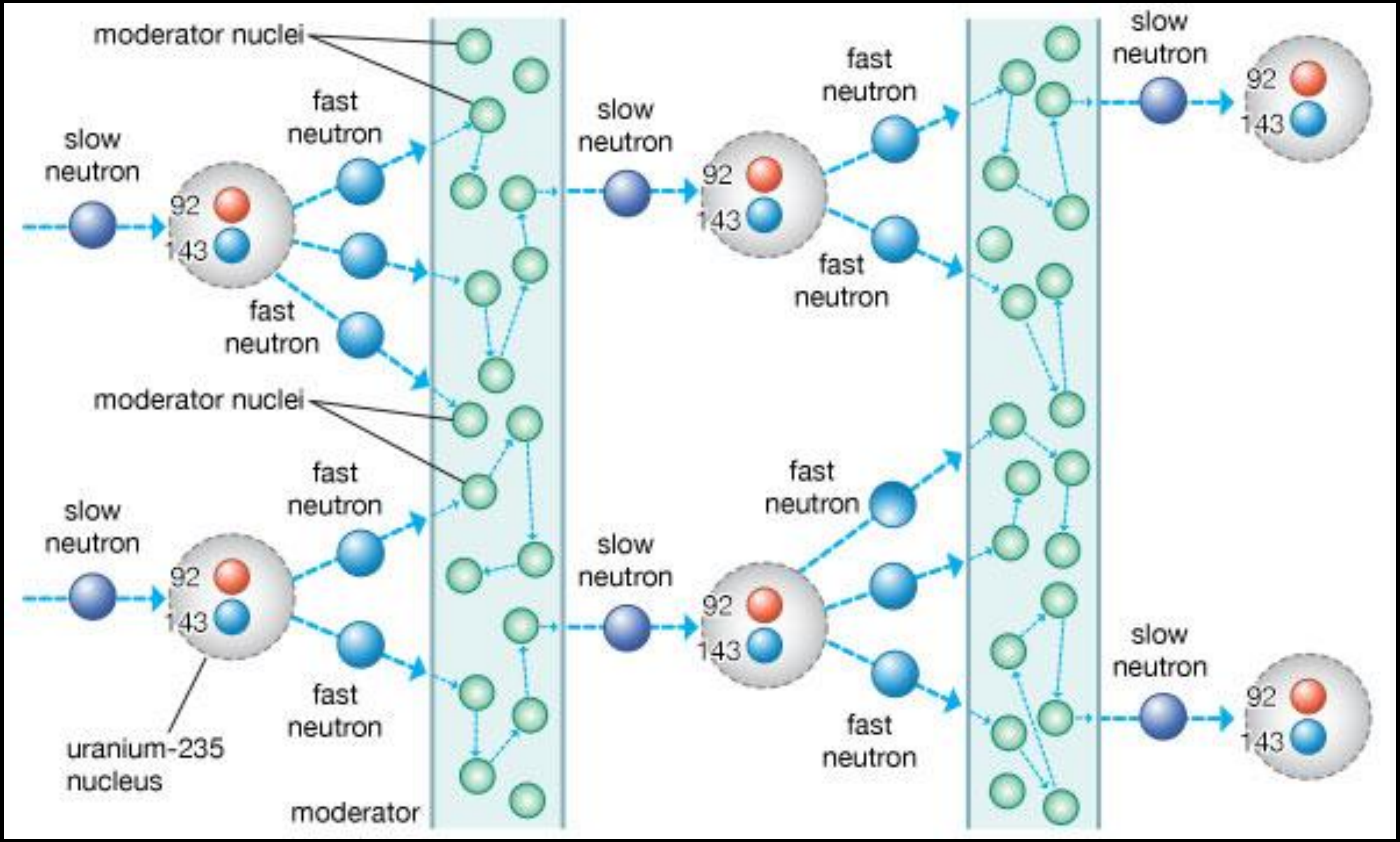
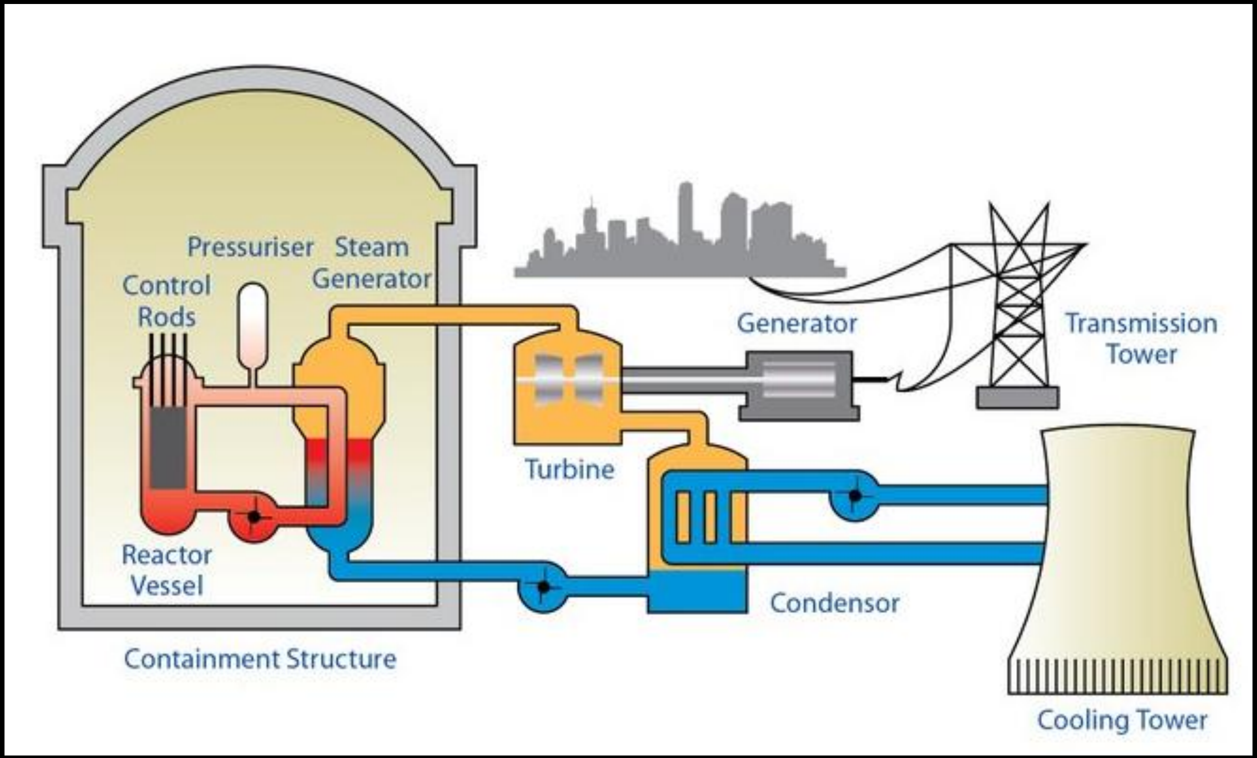
Nuclear Moderator



Slows neutron speed: reaction more efficient

Graphite, Be, CO_2, H_2O, D_2O

Reactor Coolant



Removes heat from reactor

Two/Three loops:

- From reactor to boiler
- From boiler (steam) to turbine
- From Turbine to Tower

H_2O, Na, Pb-Bi, molten salts

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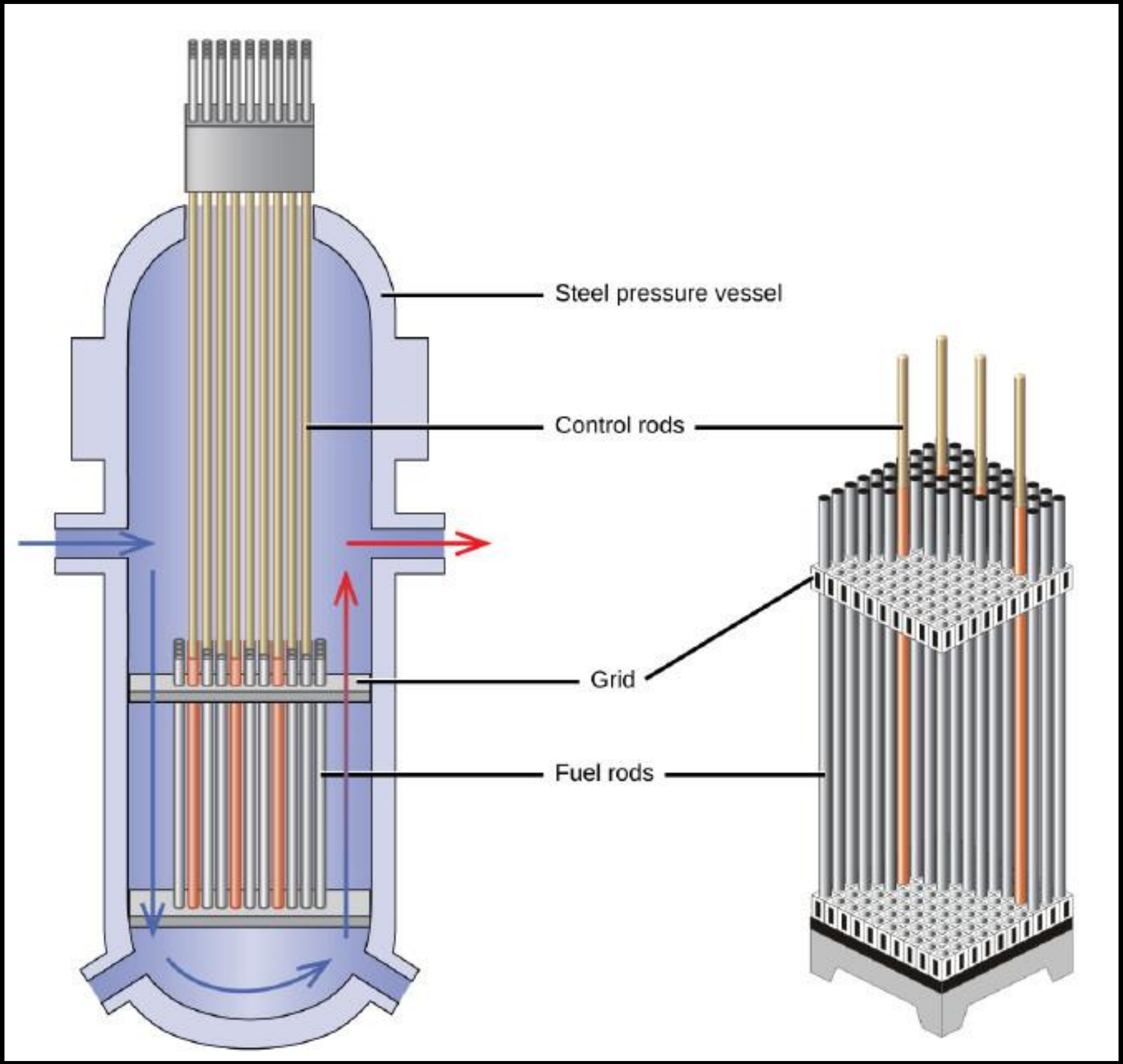
Control Rods

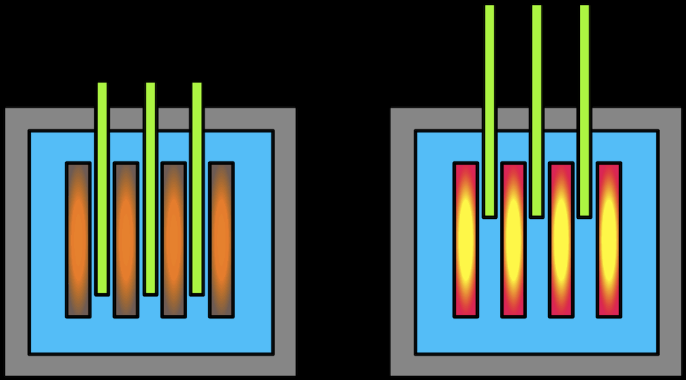


Neutron absorbing materials

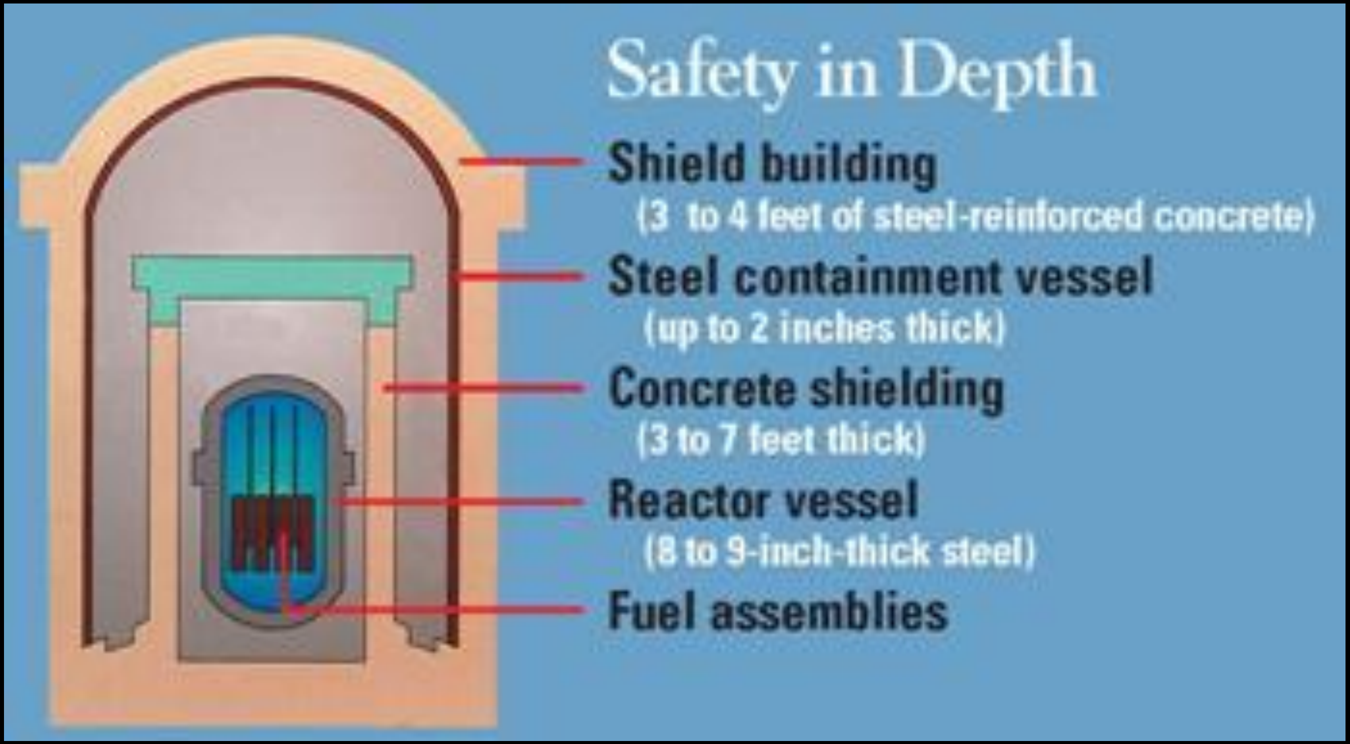
B, Cd, Hf

Control neutron flux

Control amount of fission



Shield and Containment System



Reactors contain and produce a variety of radioactive materials
Shielding and Containment: protects operating personnel

Reactors in USA must have containment shells

Nuclear Accidents: Three Mile Island

Nuclear power stations do not explode

Accidents release radiation into environment

- March 1979
- Cooling pump failed
- Water flooded containment building
- Water superheated
- Produced H_2 gas
- Gases (H_2, Kr, Xe) vented to atmosphere

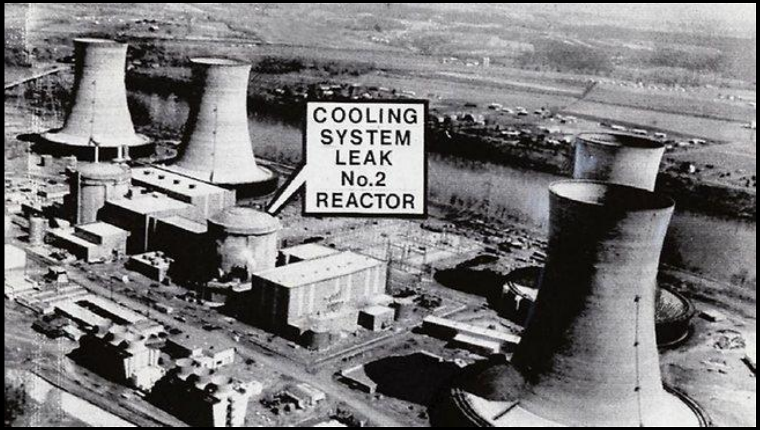
- Took 10 years to clean
- Nothing "hazardous" was released

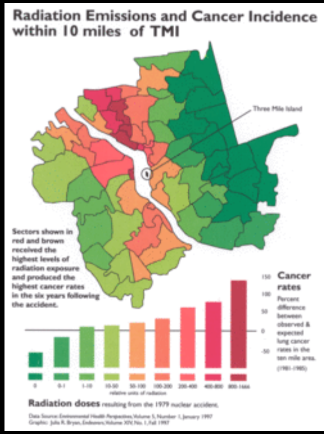
MARCH 29, 1979— 88 PAGES

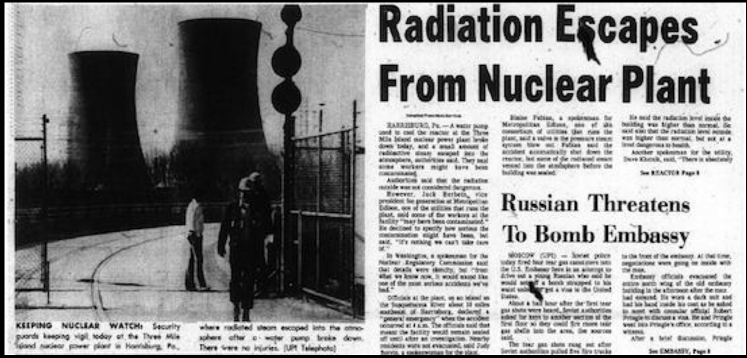
Nuclear Plant Shut By Radiation Leak

HARRISBURG, Pa. (AP) — An accident at the Three Mile Island nuclear power plant forced radioactive steam into the air at levels that could be measured 16 miles away, but caused no damage to the reactor core, goverment investigators said late Wednesday.

Charles Gallina, a Nuclear Regulatory Commission investigator who spent all day







Radiation Escapes From Nuclear Plant

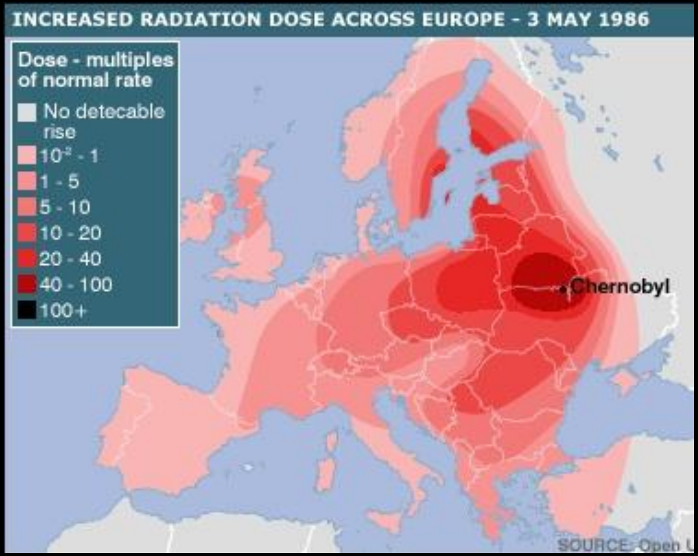
Russian Threatens To Bomb Embassy

KEEPING NUCLEAR WATCH: Security guards keeping vigil today at the Three Mile Island nuclear power plant in Harrisburg, Pa., where radiated steam escaped into the atmosphere after a water pump broke down. There were no injuries. (UPI Telephoto)

LPT

Nuclear Accidents: Chernobyl

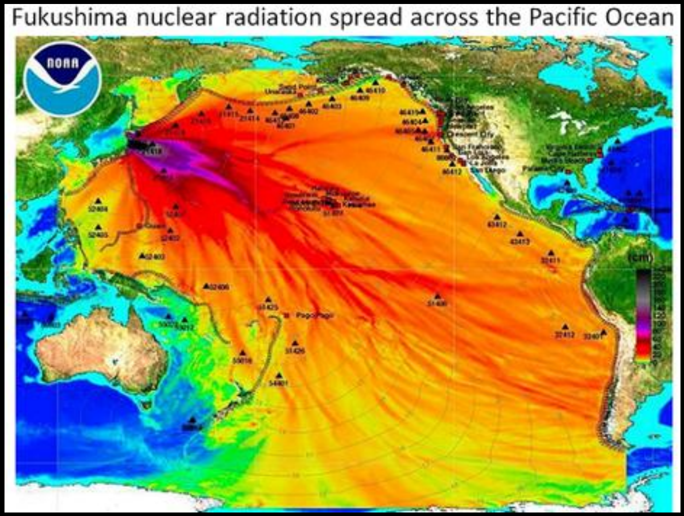
April, 1986
Unauthorized experiment
Minimum safety devices
Reactor became uncontrolled
Superheated water ruptured reactor
Massive release of radioactivity
Graphite moderator ignited
Thousands died
Area is still a wasteland
Russian reactors have no containment



LPT

Nuclear Accidents: Fukushima

March, 2011
9.0 Earthquake, followed by Tsunami
3 reactor meltdowns
Hydrogen explosions / fire
~ 200,000 people displaced



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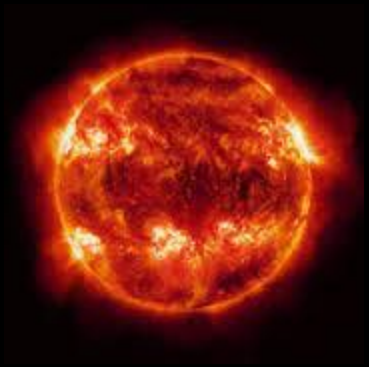
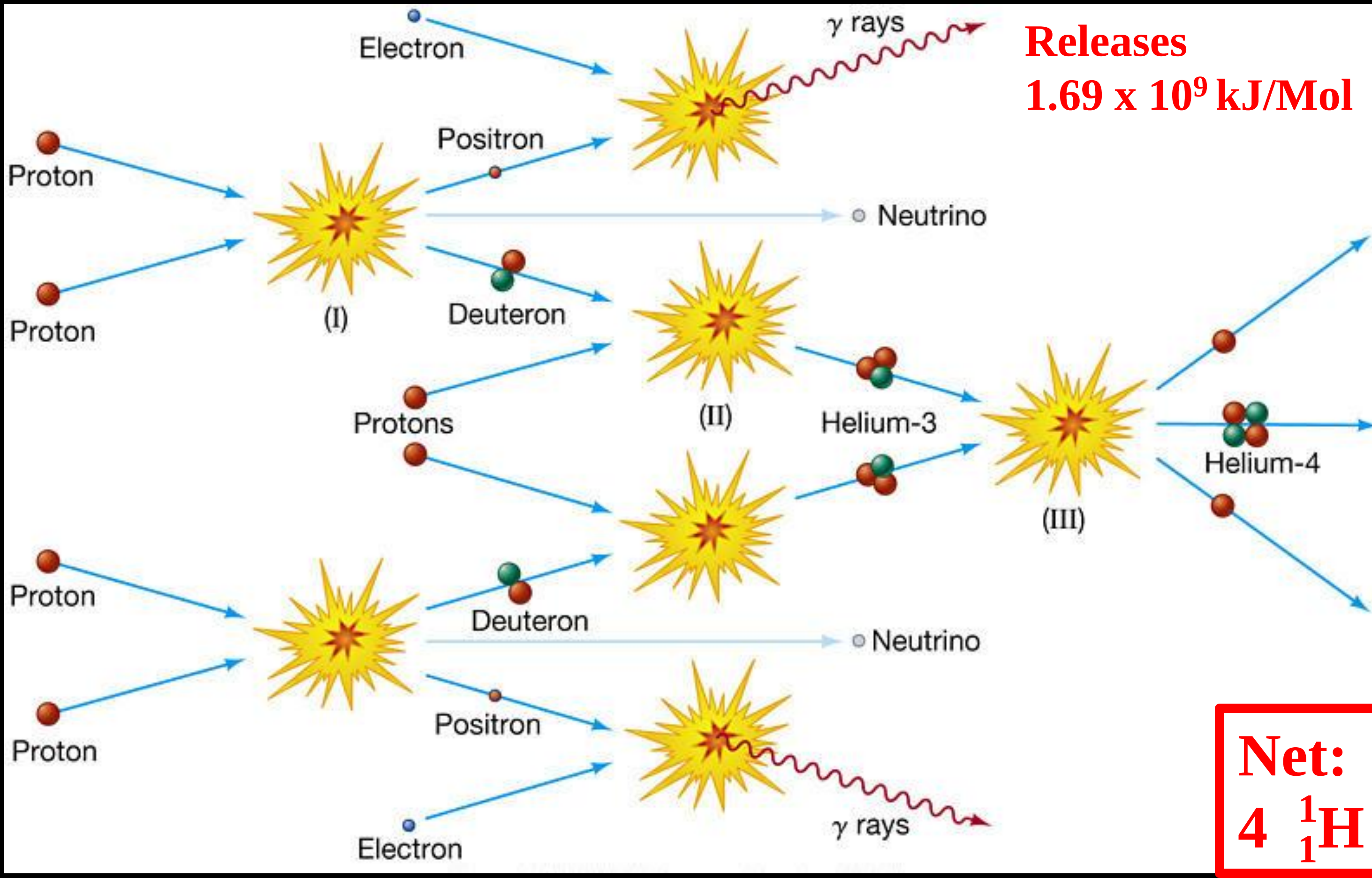
Thermonuclear Fusion



Fusion:

colliding small atoms together to form larger atoms

Energy source of stars



Releases
1.69 x 10^9 kJ/Mol

Requires:
15 M K

Net:

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

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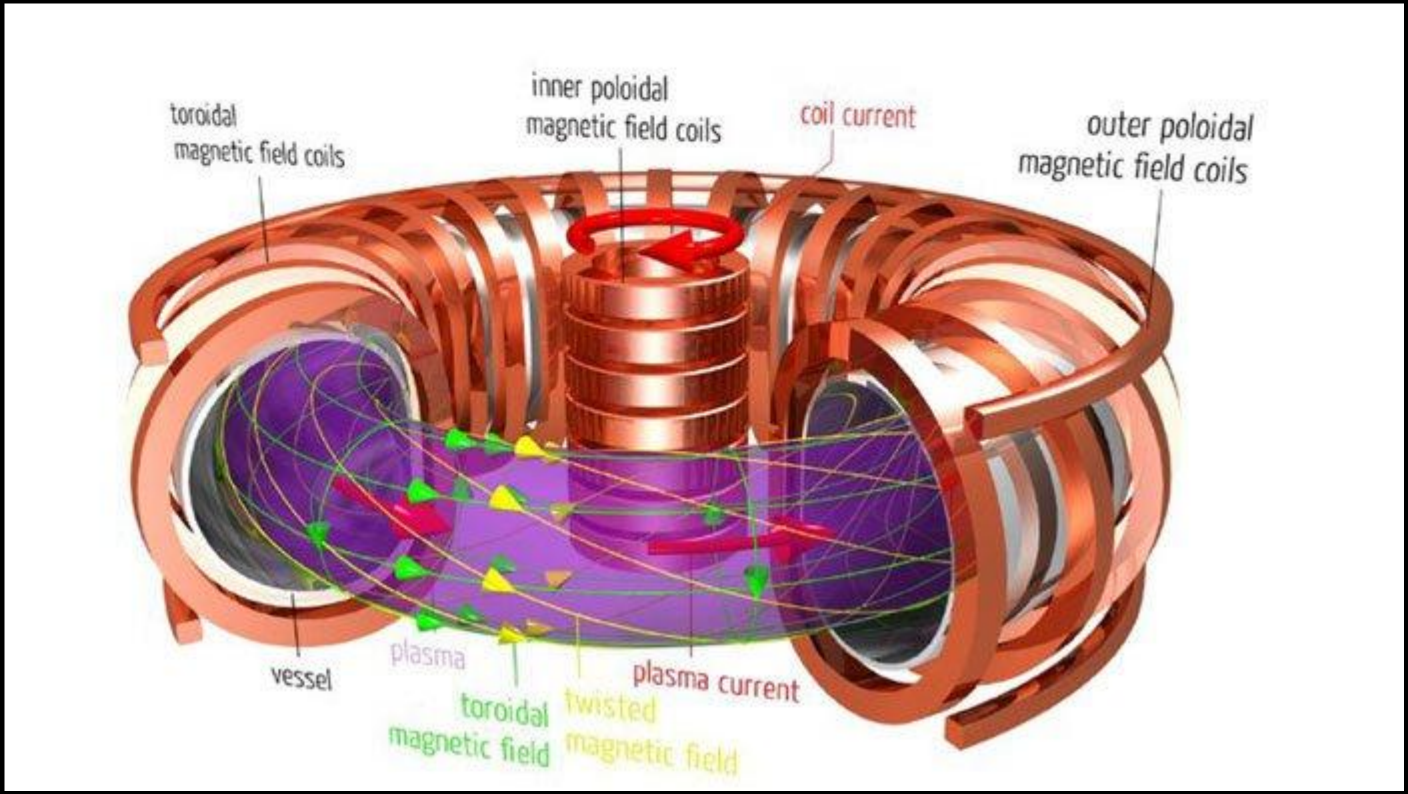
Fusion Reactors

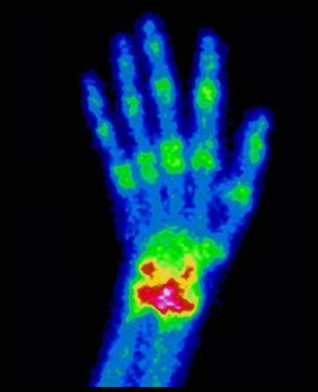
Theory: contain plasma in magnetic field
So far, only brief episodes successful



Uses of Radioisotopes

Radioisotopes have same chemistry as stable isotopes

- Radioactivity allows detection
- Allows radioisotopes to be effective tracers
- Used in medical diagnosis and treatment



Common Medical Isotopes:

- Technecium-99
- Thallium-201
- Iodine-131
- Sodium-24

Annually:

10 million nuclear medicine procedures

100 million nuclear medical tests

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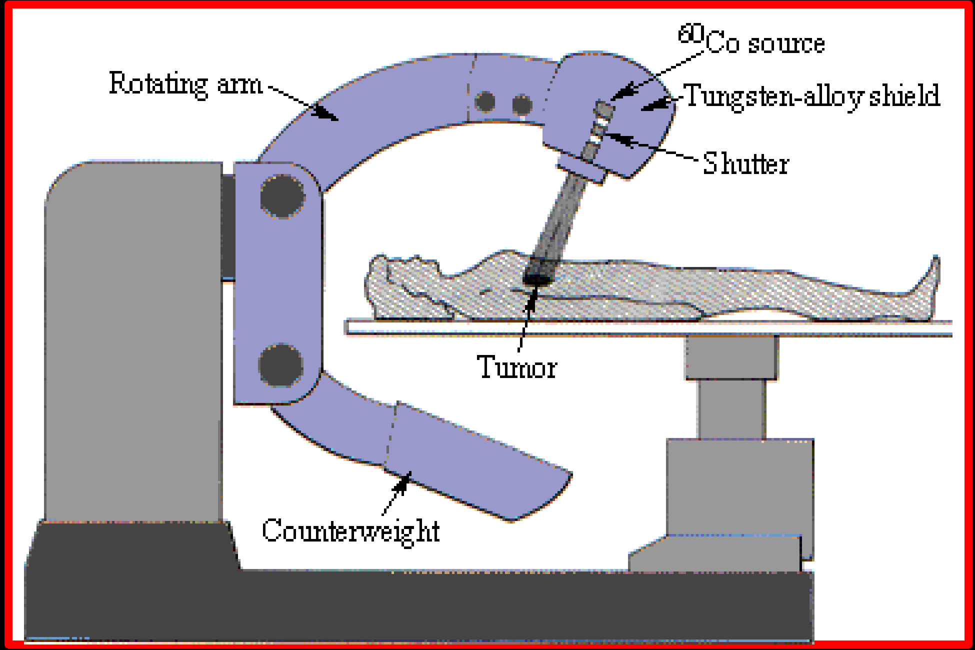
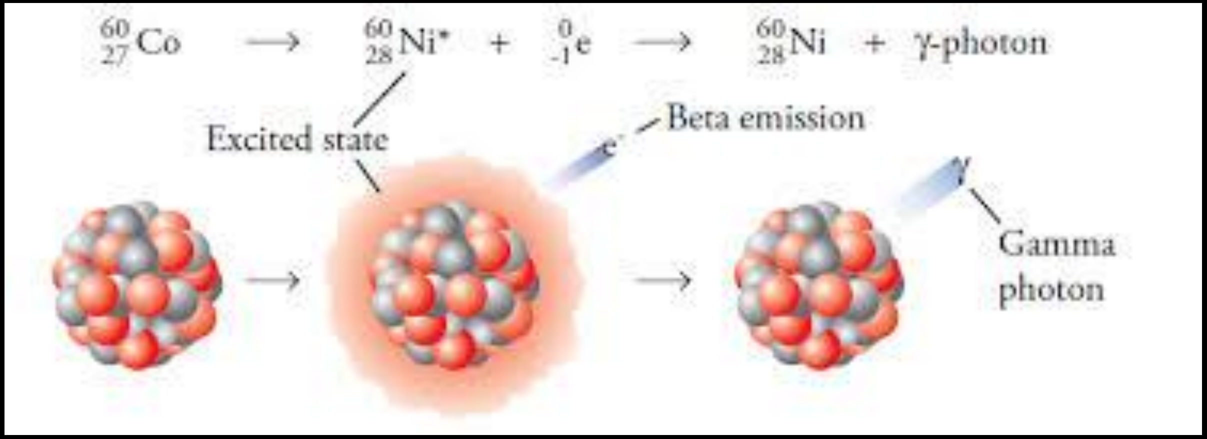
Uses of Radioisotopes

Radioactive Isotope	Applications in Medicine
Cobalt-60	Radiation therapy to prevent cancer
Iodine-131	Locate brain tumors, monitor cardiac, liver and thyroid activity
Carbon-14	Study metabolism changes for patients with diabetes, gout and anemia
Carbon-11	Tagged onto glucose to monitor organs during a PET scan
Sodium-24	Study blood circulation
Thallium-201	Determine damage in heart tissue, detection of tumors
Technetium-99m	Locate brain tumors and damaged heart cells, radiotracer in medical diagnostics (imaging of organs and blood flow studies)

Short Half-lives … often made on-site

Cobalt-60 Used in Radiation Therapy





Gamma radiation kills cancer cells

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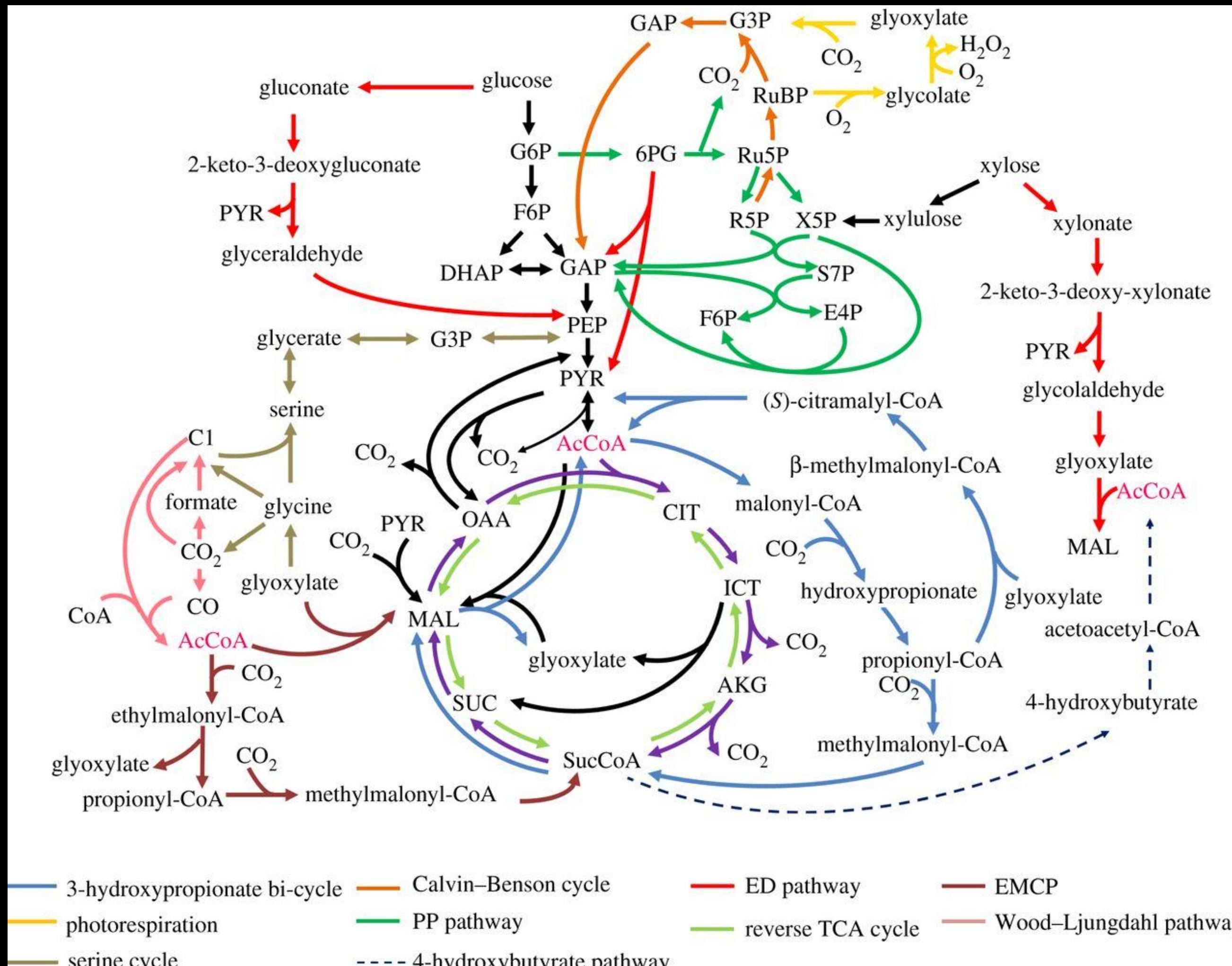
Carbon-14 Used as Tracer: Determines Biochemical Pathways



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

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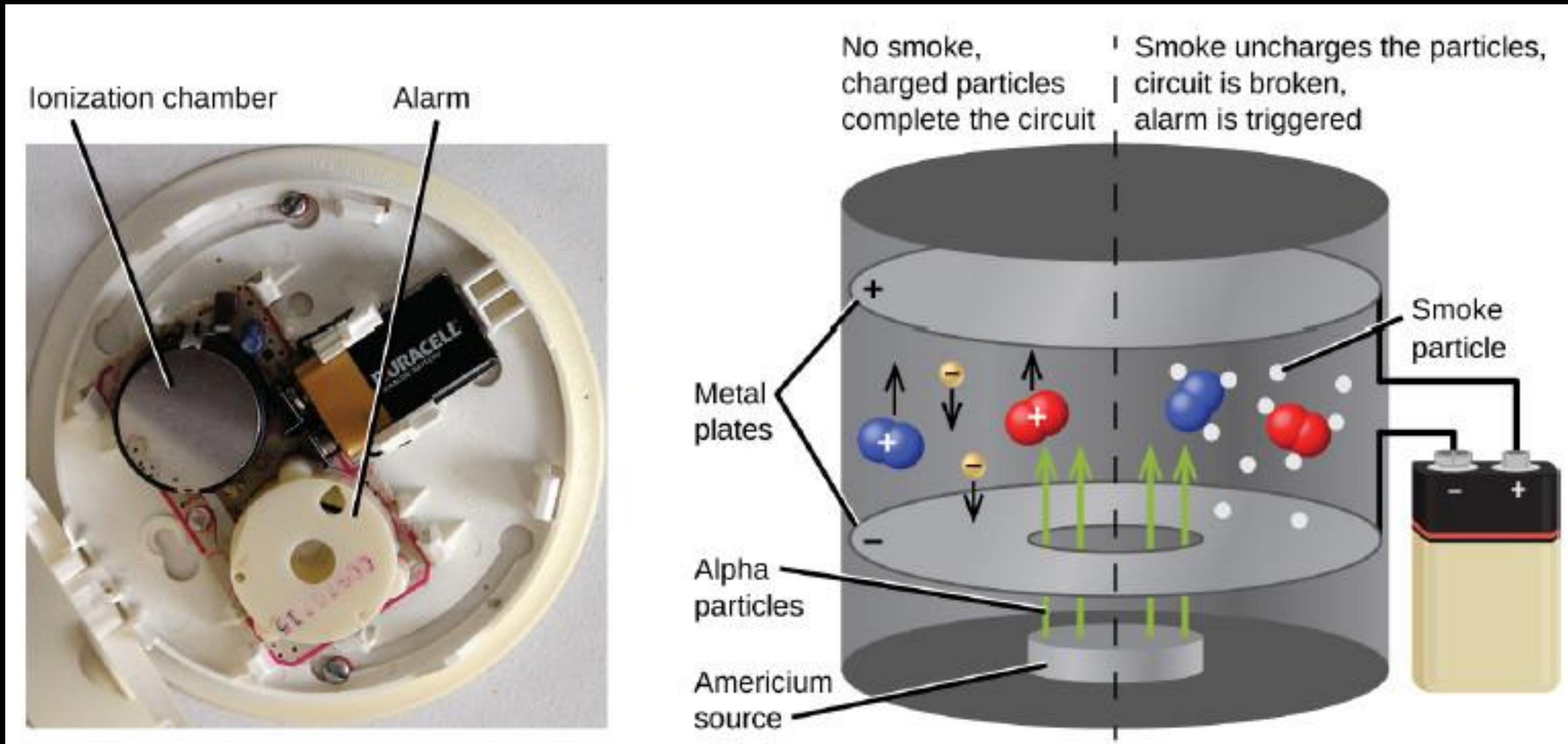
Americium-241: Smoke Detectors



$$^{241}_{95}\mathrm{Am} \dashrightarrow\ ^{237}_{93}\mathrm{Np} + ^{4}_{2}\alpha$$

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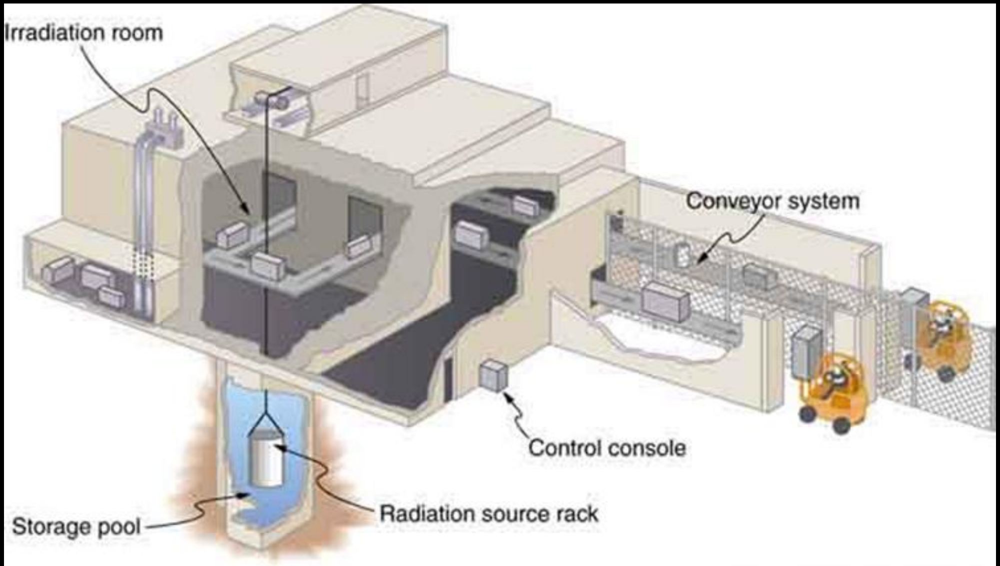
Food Sterilization: C - 60 & Cs - 137



Objects exposed to γ-radiation
- Food
- Medical instruments
- Bulk Cargo

Ions produced attack DNA

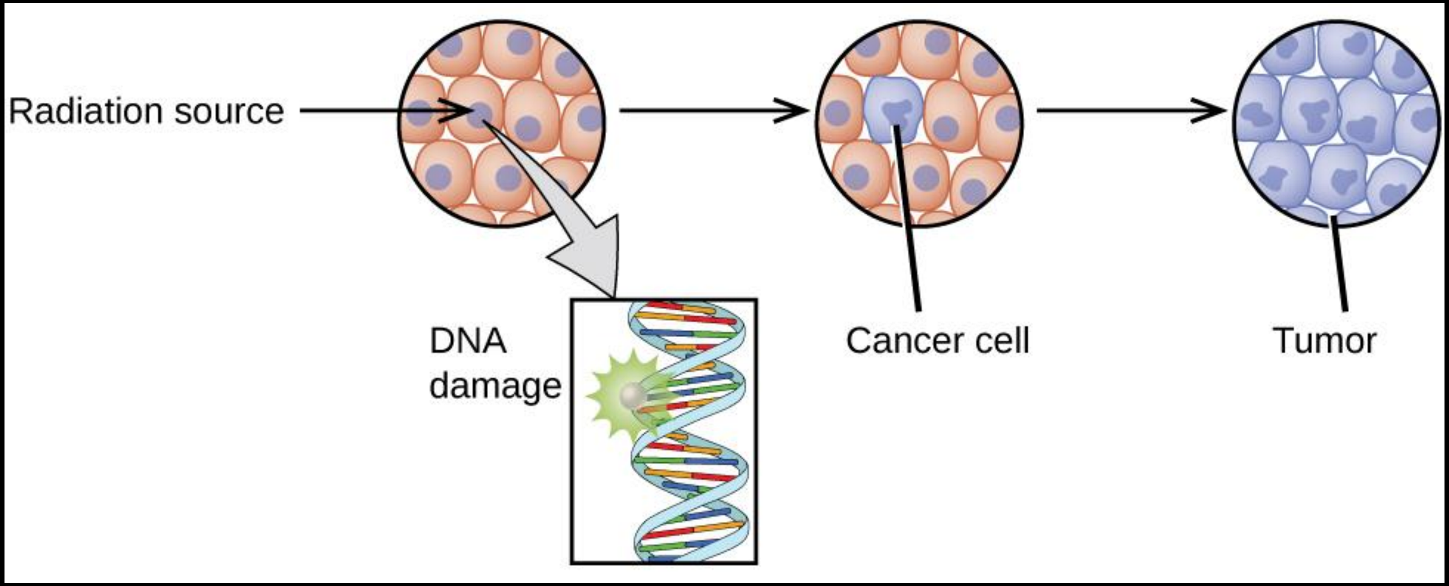
Biological dies

Biological Effects of Radiation

All radioactive materials emit high energy particles or electromagnetic waves

This radiation may:

- thermal heating
- chemical bond breaking
- ionize molecules



No natural defenses against incoming radiation

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Ionizing vs. Non-Ionizing Radiation

Ionizing

Higher energy electromagnetic waves (x-ray, γ – ray)

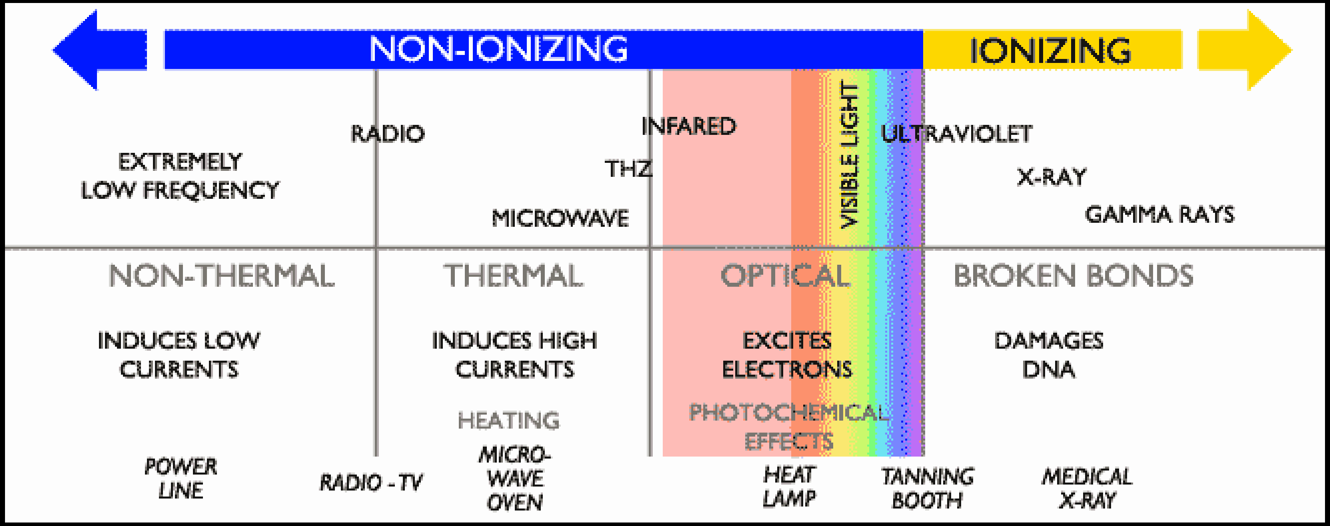
High energy particles (α, β particles)

Energy sufficient to pull electrons away from nucleus

Non-Ionizing

Lower energy electromagnetic waves

Insufficient energy to ionize, but does excite electrons



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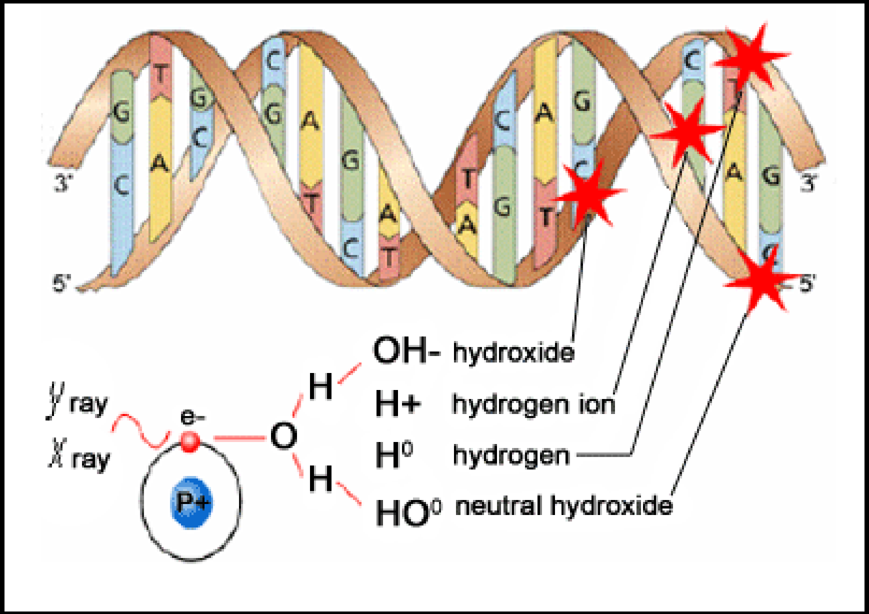
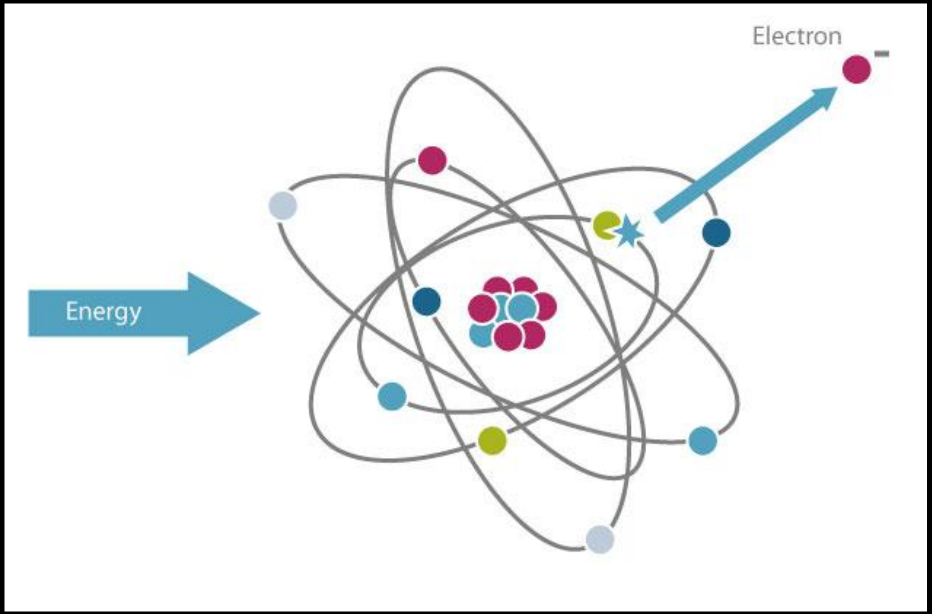
Ionizing Radiation: Direct Effect



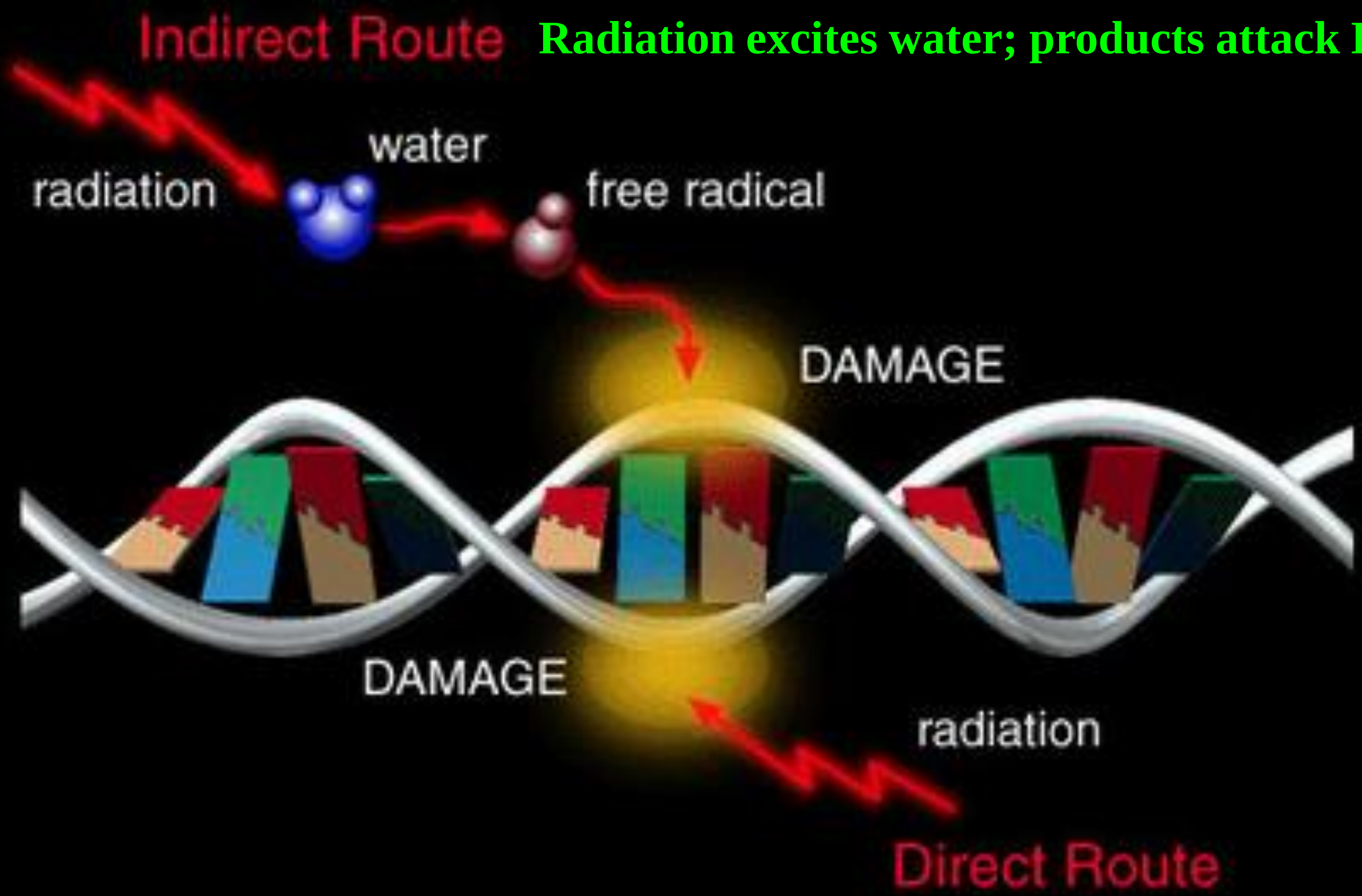


High energy radiation removes electron
Resultant ion has high energy
Biological structure altered

DNA is the primary target of radiation exposure

Non-Ionizing Radiation: Indirect Effect

Radiation excites water; products attack DNA

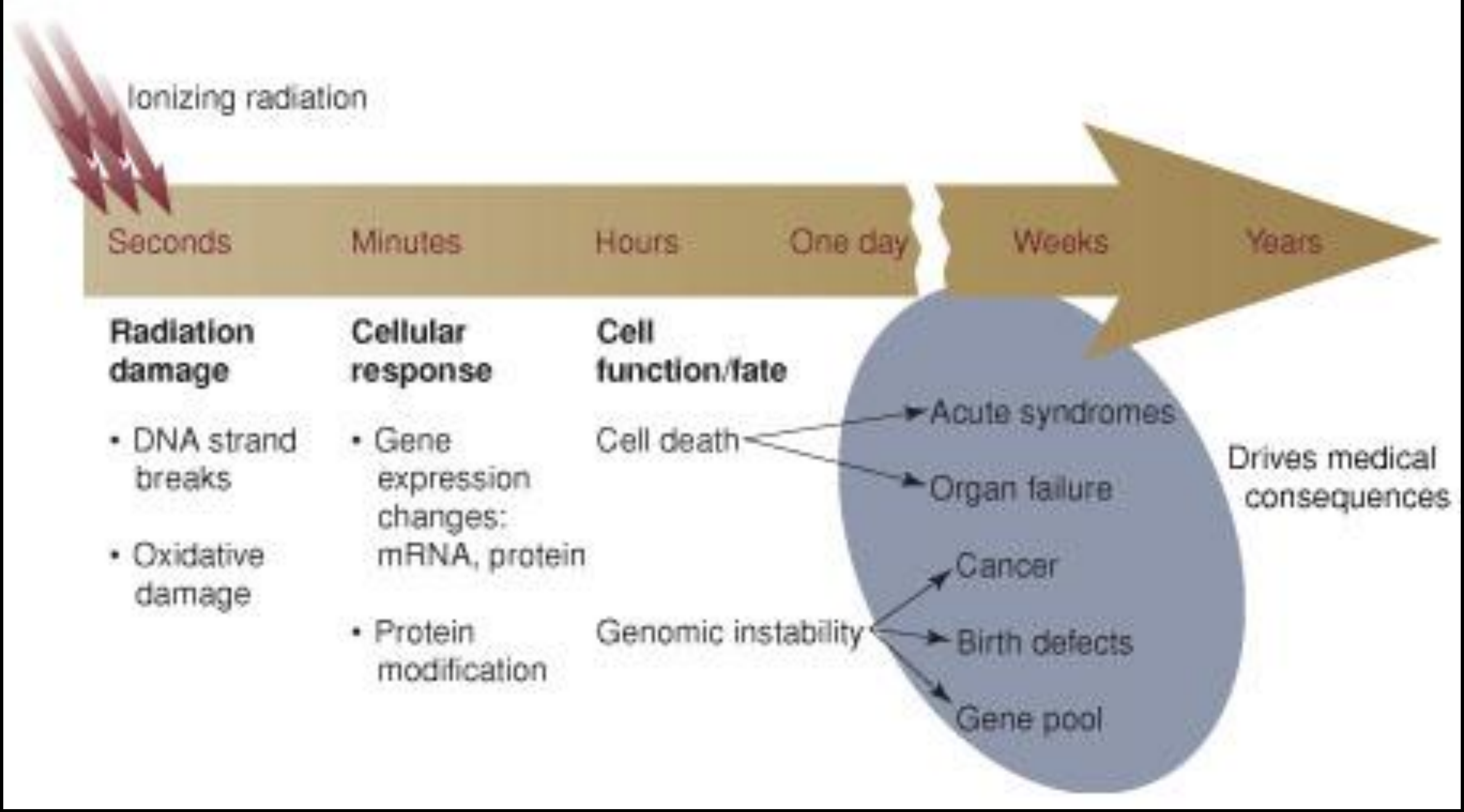


Radiation directly attacks DNA

LPT

Biological Effects of Radiation

Insidious since damage may take years to manifest



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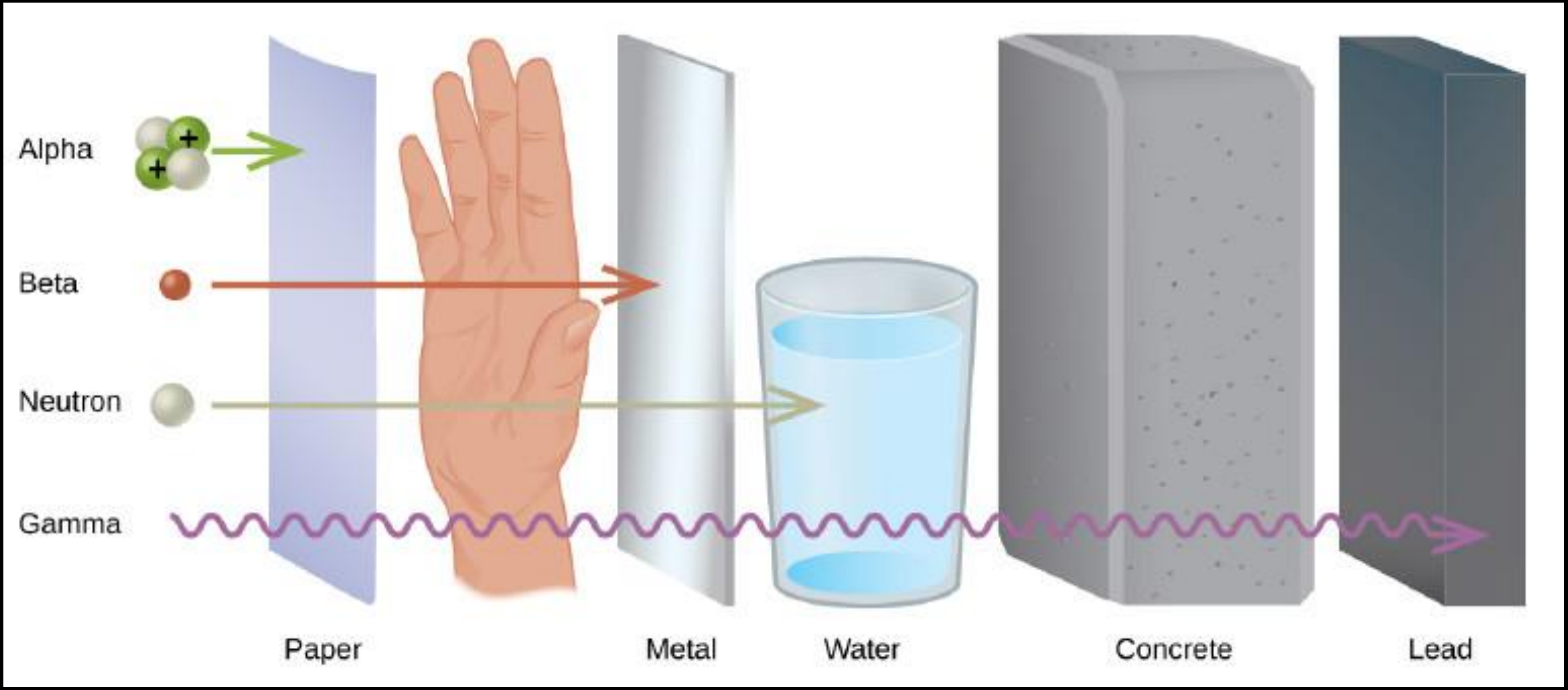
Radiation Penetration

> The energy, the > the penetration



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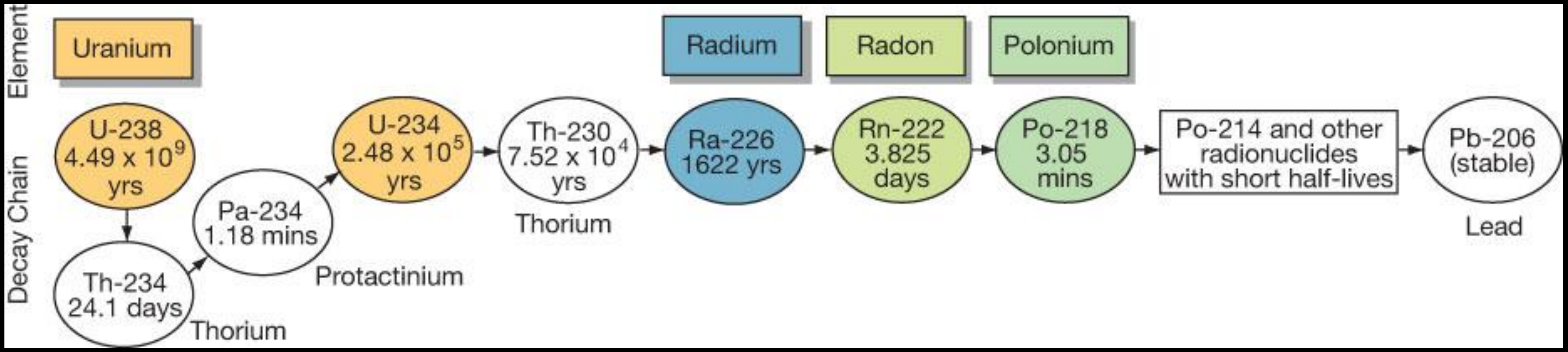
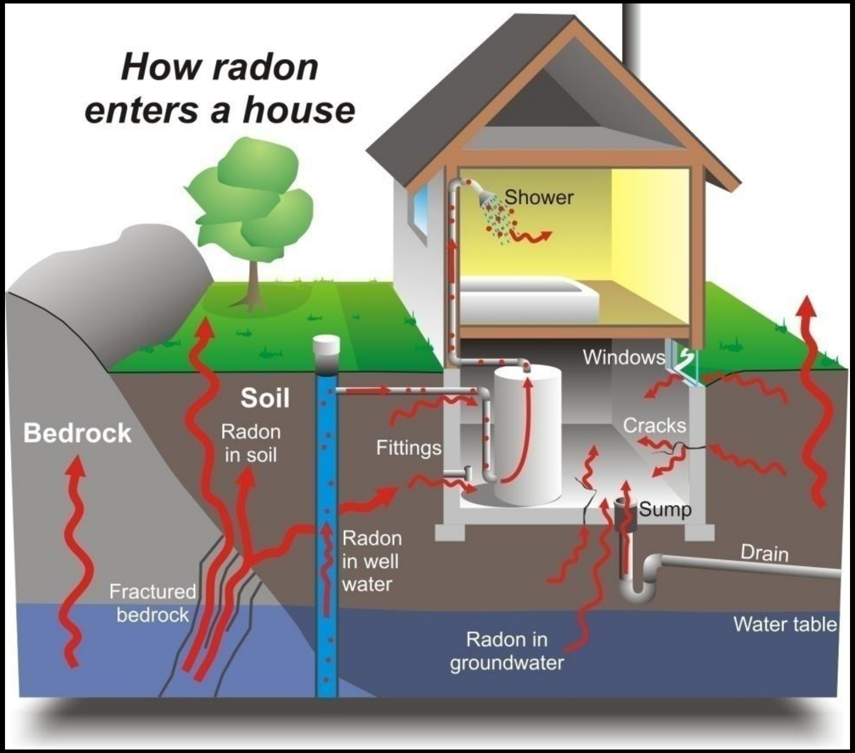
Radon: Health Hazard in Michigan

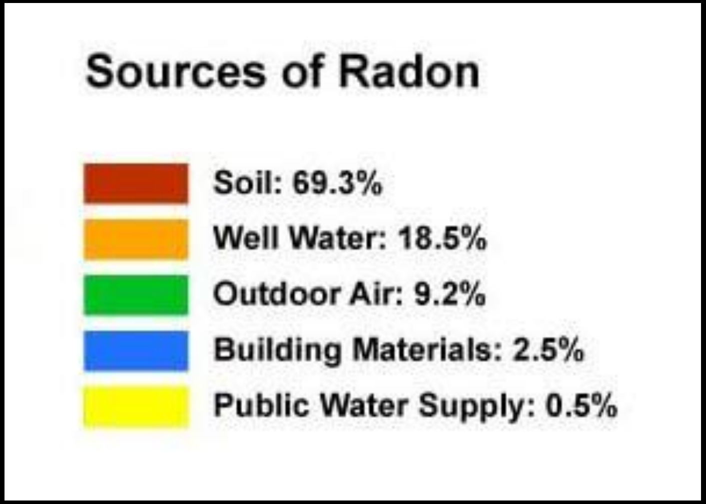




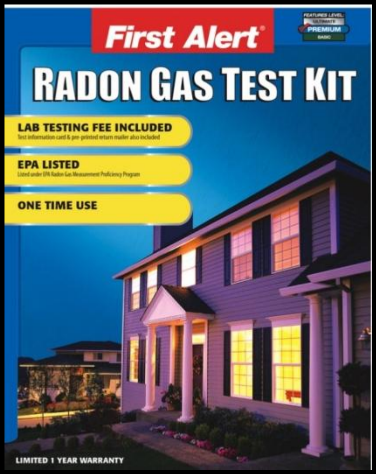
Major radiation exposure source

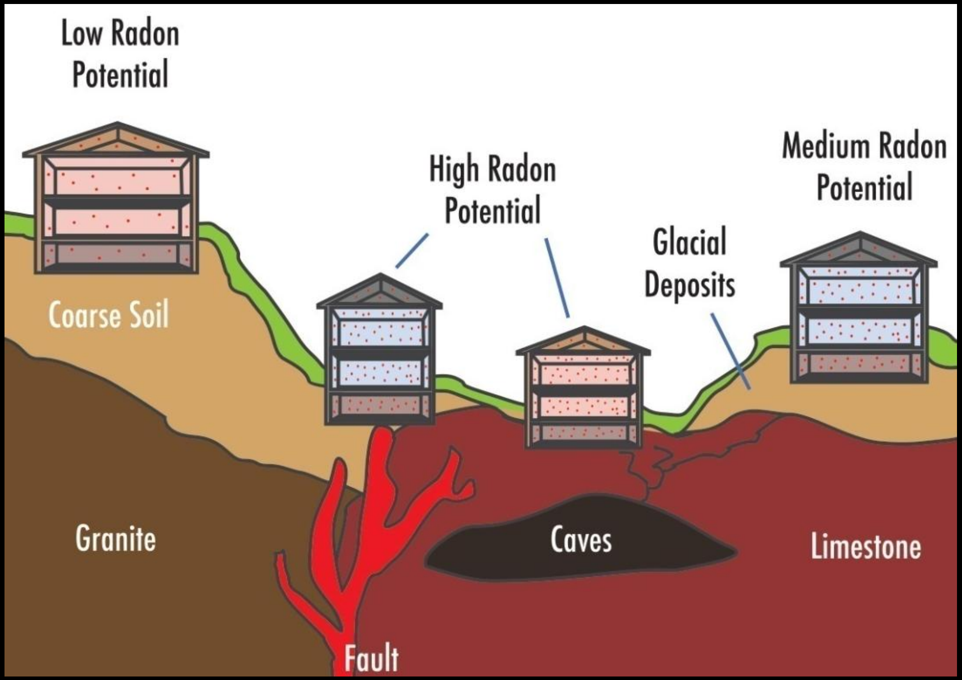
A Gas: An alpha emitter

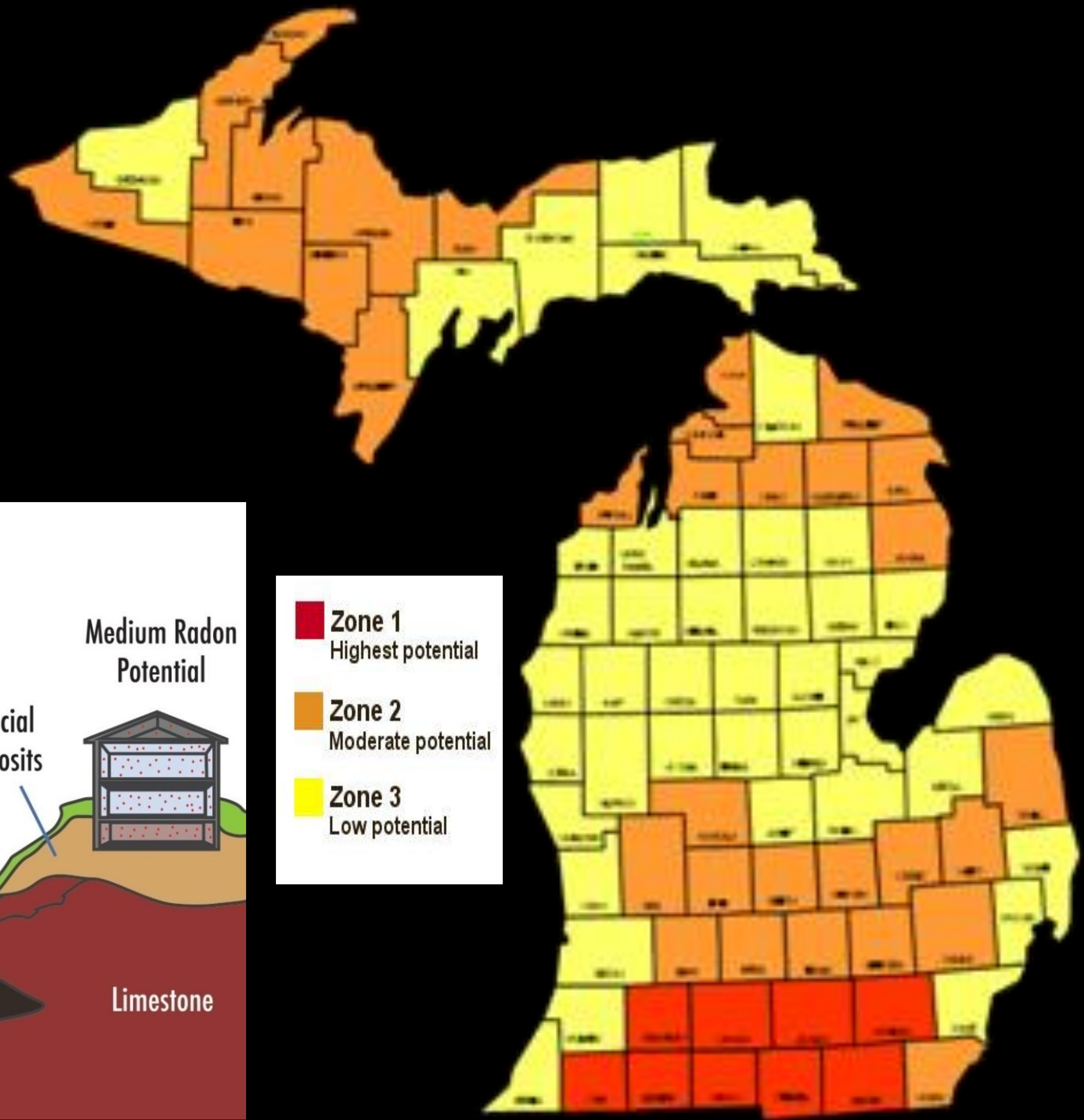
Considered major risk for lung cancer



Radon: Health Hazard in Michigan







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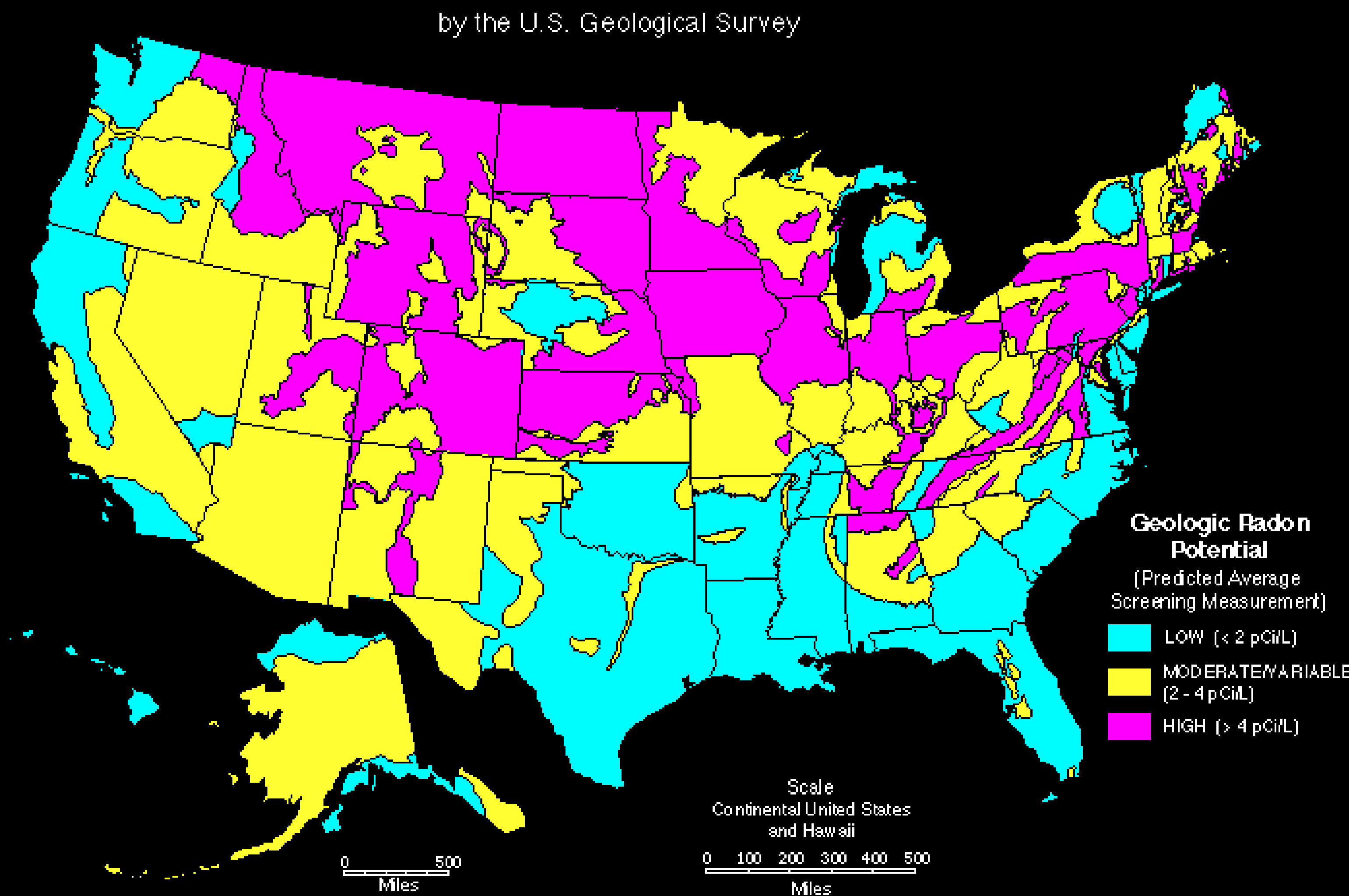
Radon: Health Hazard in United States



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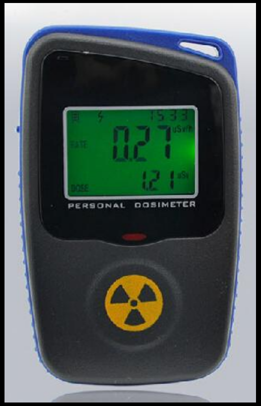
Measuring Radiation Exposure

Geiger Counter
Gas filled tube
Radiation ionized the gas
Amount of radiation proportion to level of ionization

Scintillation Detector
Substance emits light when struck by radiation
Amount of radiation proportion to level of emitted light

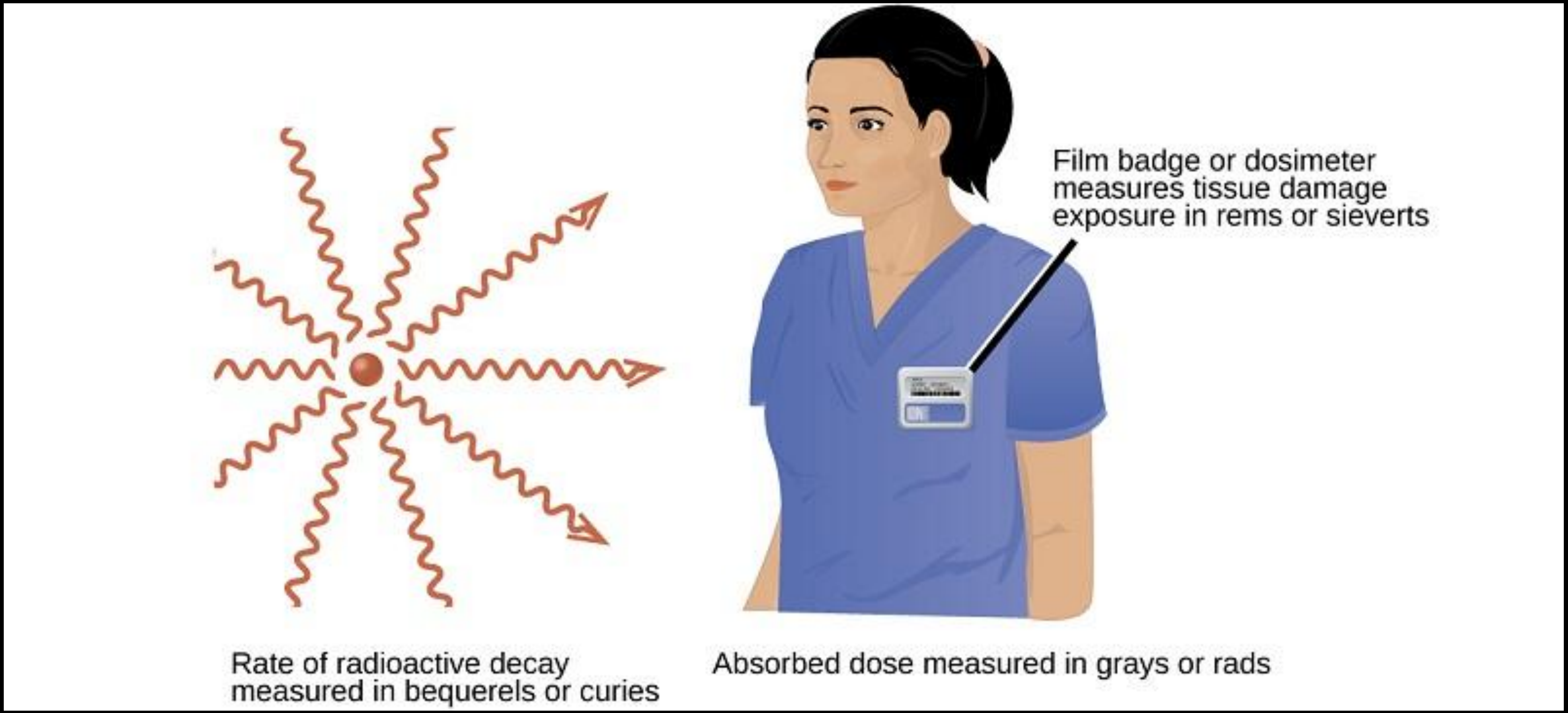
Dosimeter (Dose meter)
Measure personal exposure
Many types:
- film badge
- electronic
- thermoluminescence
- quartz fiber



Units of Radiation Measurement

Measurement Purpose	Unit	Quantity Measured	Description
activity of source	becquerel (Bq)	radioactive decays or emissions	amount of sample that undergoes 1 decay/second
activity of source	curie (Ci)	radioactive decays or emissions	amount of sample that undergoes 3.7×10^{10} decays/second
absorbed dose	gray (Gy)	energy absorbed per kg of tissue	1 Gy = 1 J/kg tissue
absorbed dose	radiation absorbed dose (rad)	energy absorbed per kg of tissue	1 rad = 0.01 J/kg tissue
biologically effective dose	sievert (Sv)	tissue damage	Sv = RBE $\times$ Gy
biologically effective dose	roentgen equivalent for man (rem)	tissue damage	Rem = RBE $\times$ rad

Units of Radiation Measurement



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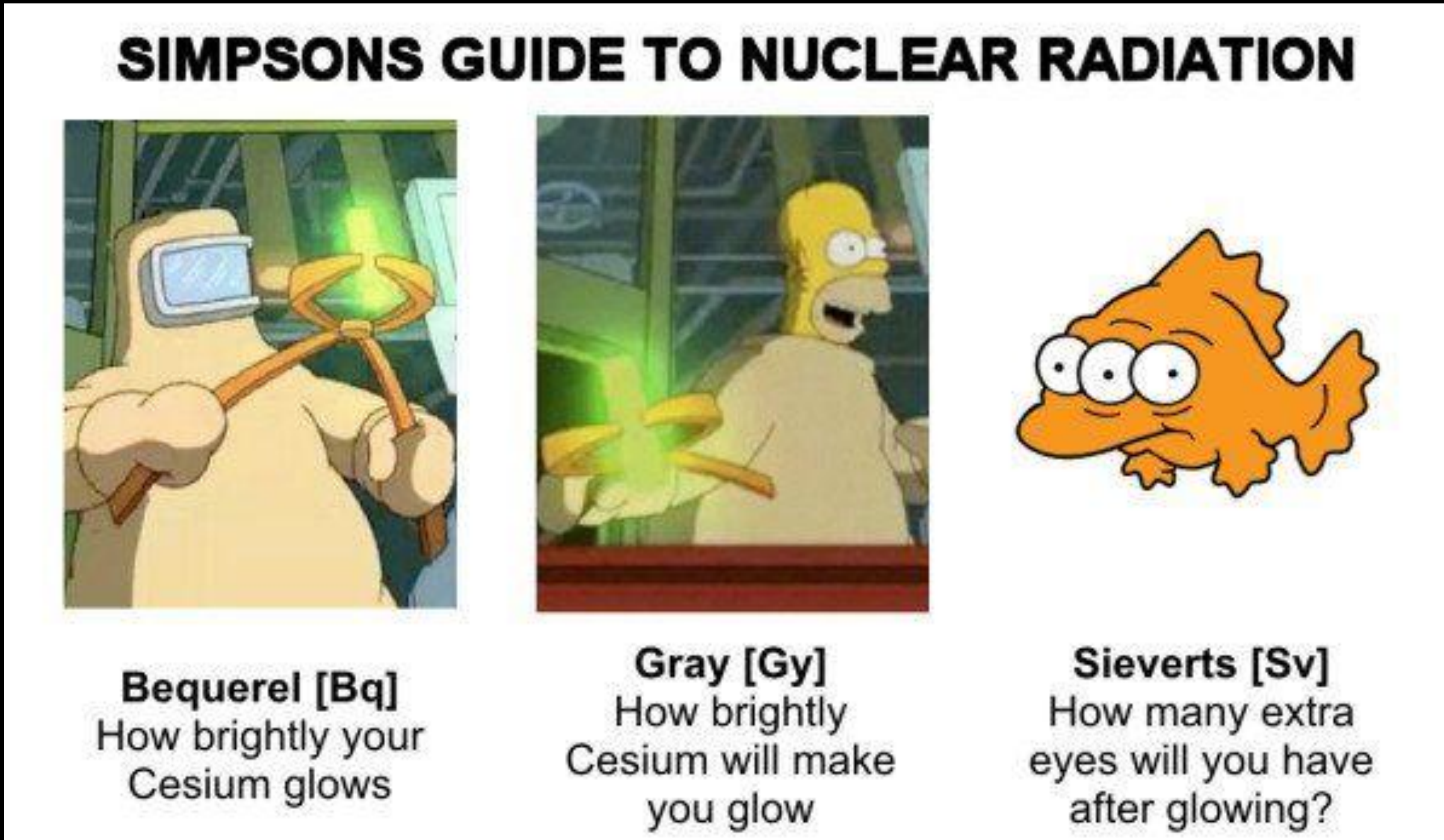
SIMPSONS GUIDE TO NUCLEAR RADIATION
Bequerel [Bq]
How brightly your Cesium glows
Gray [Gy]
How brightly Cesium will make you glow
Sieverts [Sv]
How many extra eyes will you have after glowing?

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Amount of Radiation

Co-60 ($t^{1/2}$ = 5.26 y) is the γ source for cancer therapy
For a 5.00 gram sample, what is the activity?

Activity:

$$\lambda N = (\ln 2/\ t^{1/2})\ N = (\ln 2/\ 5.26\ \text{y})\ 5.00\ \text{g} = 0.659\ \text{g/y that decays}$$

Converting this activity to decays per second:

$$\frac{0.659\ \text{g}}{\text{year}} \times \frac{1\ \text{year}}{365\ \text{d}} \times \frac{1\ \text{day}}{24\ \text{hr}} \times \frac{1\ \text{hour}}{3600\ \text{s}} \times \frac{1\ \text{mol}}{59.9\ \text{g}} \times \frac{6.02 \times 10^{23}\ \text{atoms}}{\text{mol}} \times \frac{1\ \text{decay}}{\text{atom}} = 2.10 \times 10^{14}\ \frac{\text{decay}}{\text{s}}$$

Since 1 decay/sec = 1 Bq, activity in Bq = 2.10×10^{14} Bq

Converting Bq to Ci:

$$2.10 \times 10^{14}\ \frac{\text{decay}}{\text{s}} \times \frac{1\ \text{Ci}}{3.7 \times 10^{11}\ \text{decay/s}} = 5.7 \times 10^{2}\ \text{Ci}$$

LPT

Problem: Amount of Radiation

Tritium (H-3, $t^{1/2}$ = 12.32 y); atomic mass= 3.016 amu is used in a variety of self-illuminating devices; Beta particle from the radioactive decay strikes a phosphor that produces a glow. What ism the activity of a 1.00 mg sample?

Activity:

$$\lambda N = (\ln 2/ t^{1/2})\ N = (\ln 2/ 12.32\ y)\ 1.00\ mg \times \frac{1\ g}{1000\ mg} = 5.63 \times 10^{-5}\ g/y \text{ that decays}$$

Converting this activity to decays per second:

$$\frac{5.63 \times 10^{-5}\ g}{year} \times \frac{1\ yr}{365\ d} \times \frac{1\ d}{24\ hr} \times \frac{1\ hr}{3600\ s} \times \frac{1\ mol}{3.016\ g} \times \frac{6.02 \times 10^{23}\ atoms}{mol} \times \frac{1\ decay}{atom} = 3.56 \times 10^{11} \frac{decay}{s}$$

Since 1 decay/sec = 1 Bq, activity in Bq = 3.56×10^{11} Bq

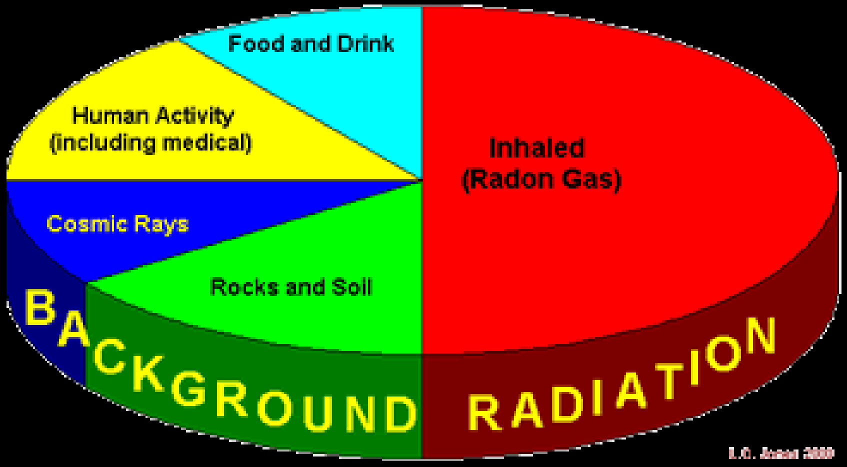
Converting Bq to Ci:

$$3.56 \times 10^{11} \frac{decay}{s} \times \frac{1\ Ci}{3.7 \times 10^{11}\ decay/s} = 0.952\ Ci$$

Long Term Exposure to Radiation

Radiation Effects on tissues depends upon:

- type of irradiation
- energy at impact
- internal vs. external
- location of source
- length of time of exposure



Sources:

- Background: cosmic rays, radon, radioactive minerals
- Medical: x-rays, CAT scans, tracer studies
- Therapy: radioactive therpay agents
- Cigarette Smoke
- Food
- Increased cosmic radiation at altitude (flying)

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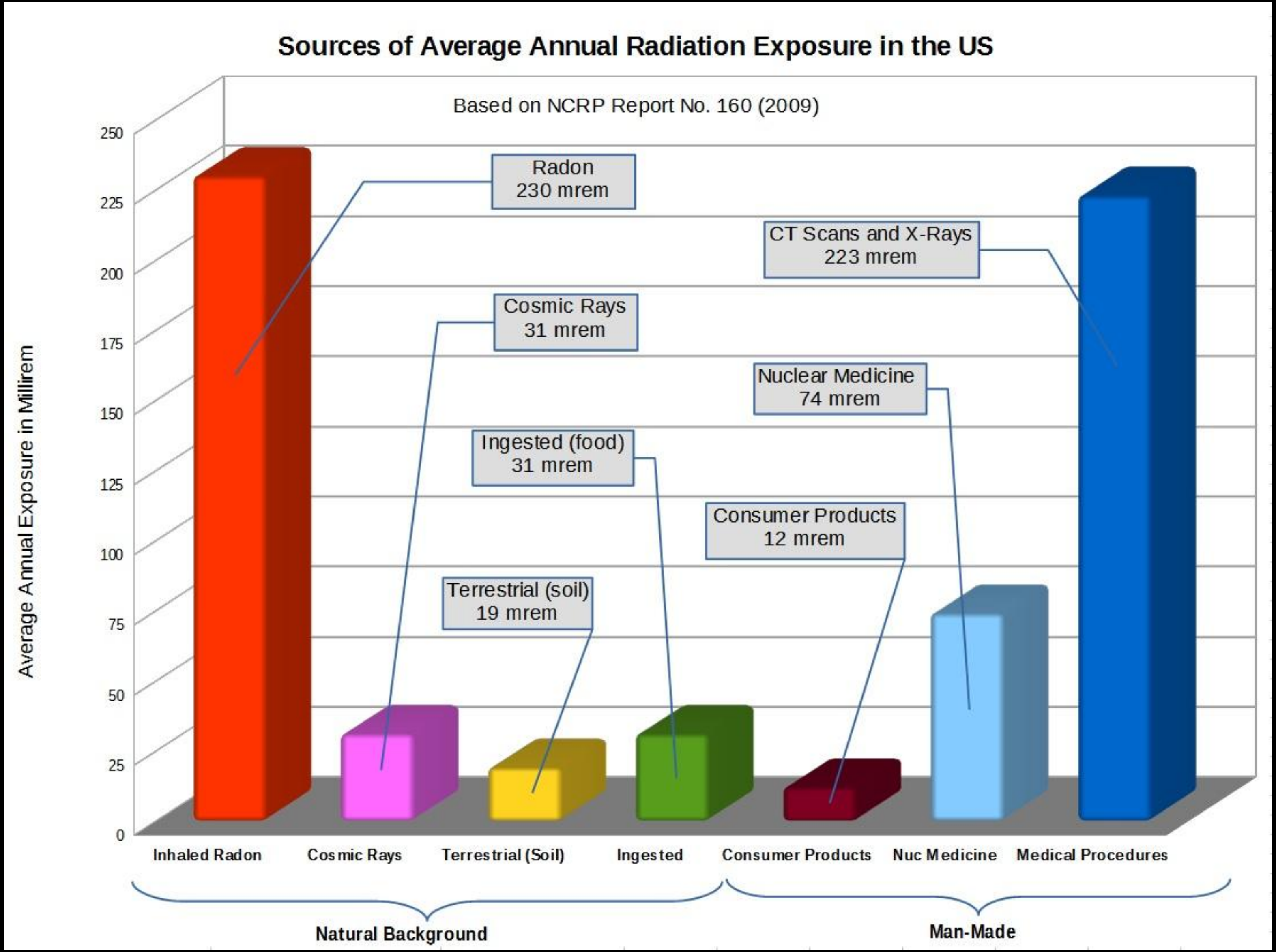
Long Term Exposure to Radiation



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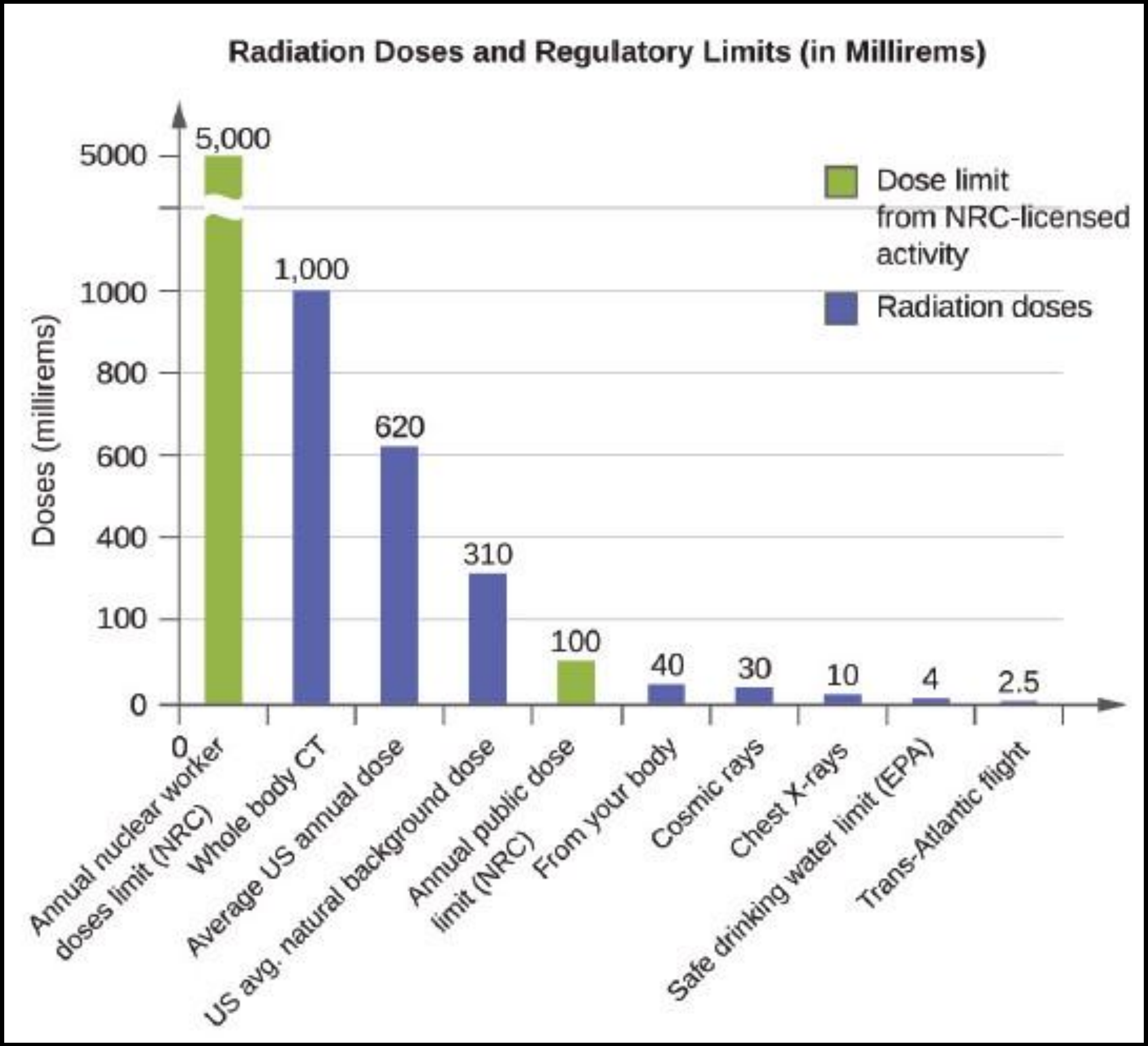
Long Term Exposure to Radiation



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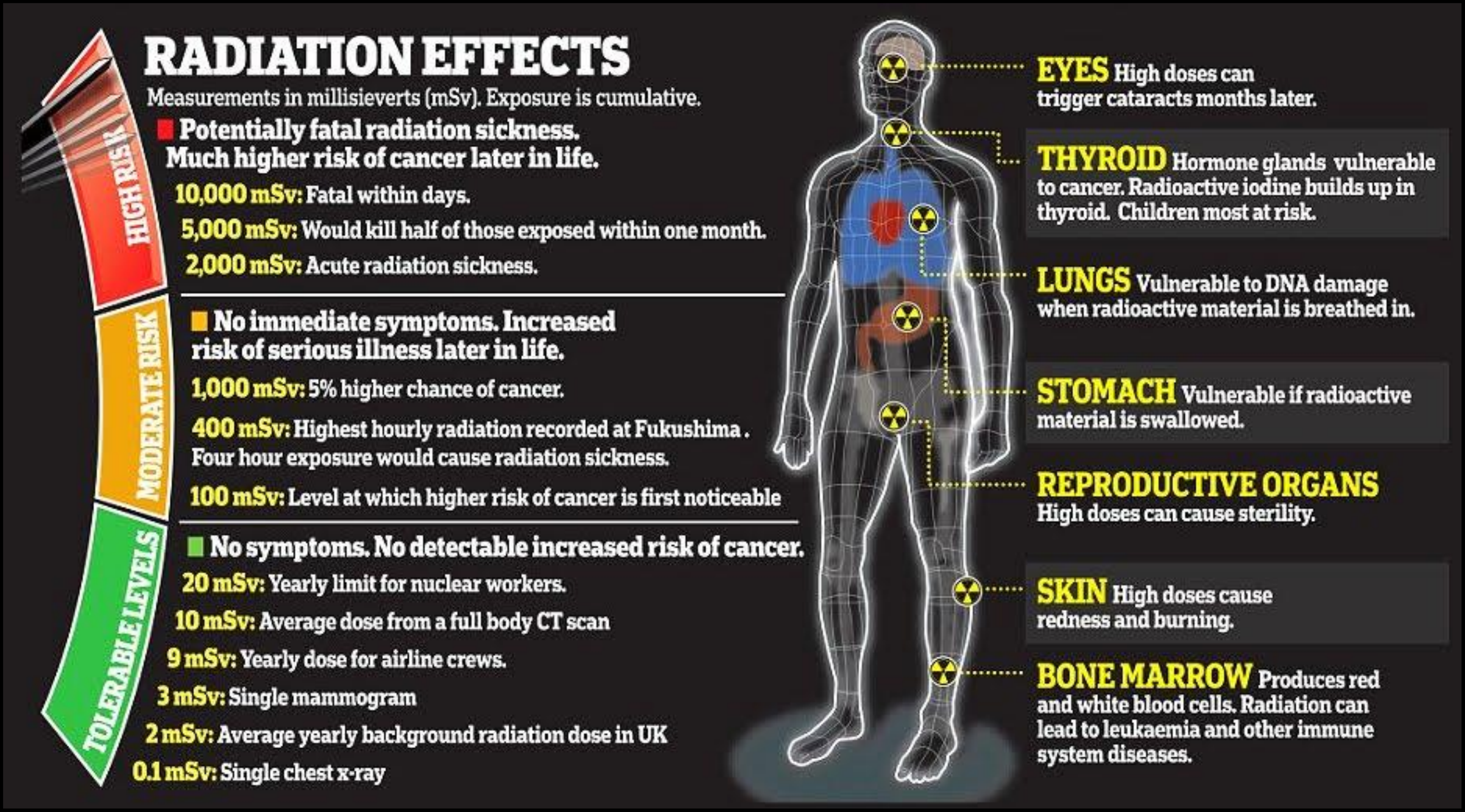
Long Term Exposure to Radiation



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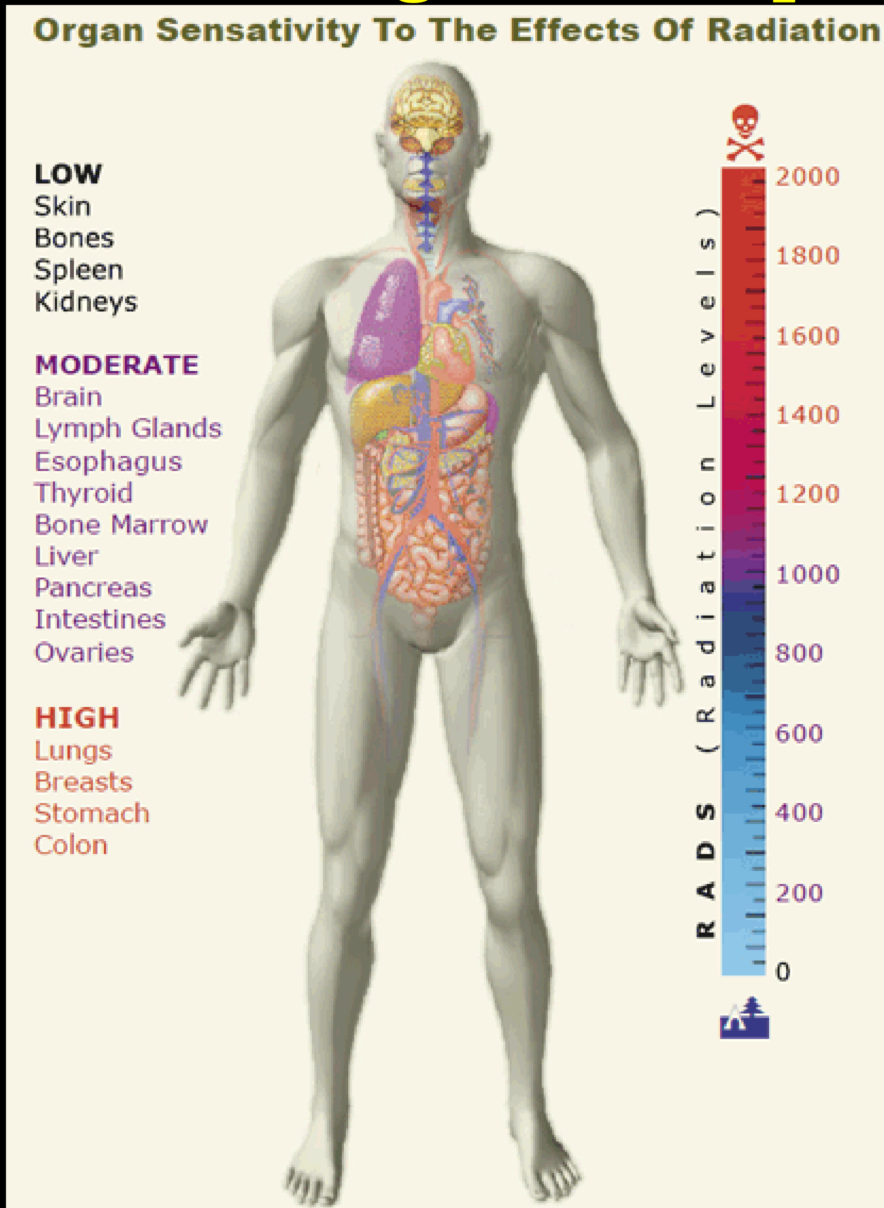
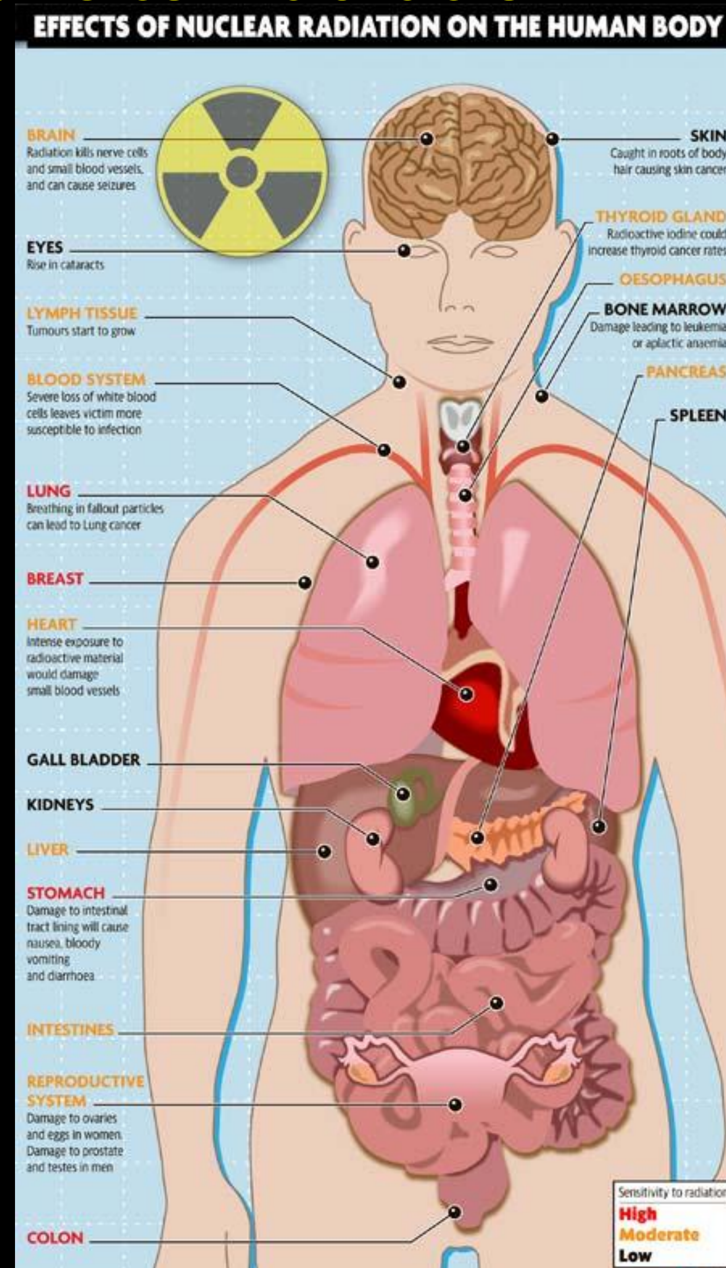
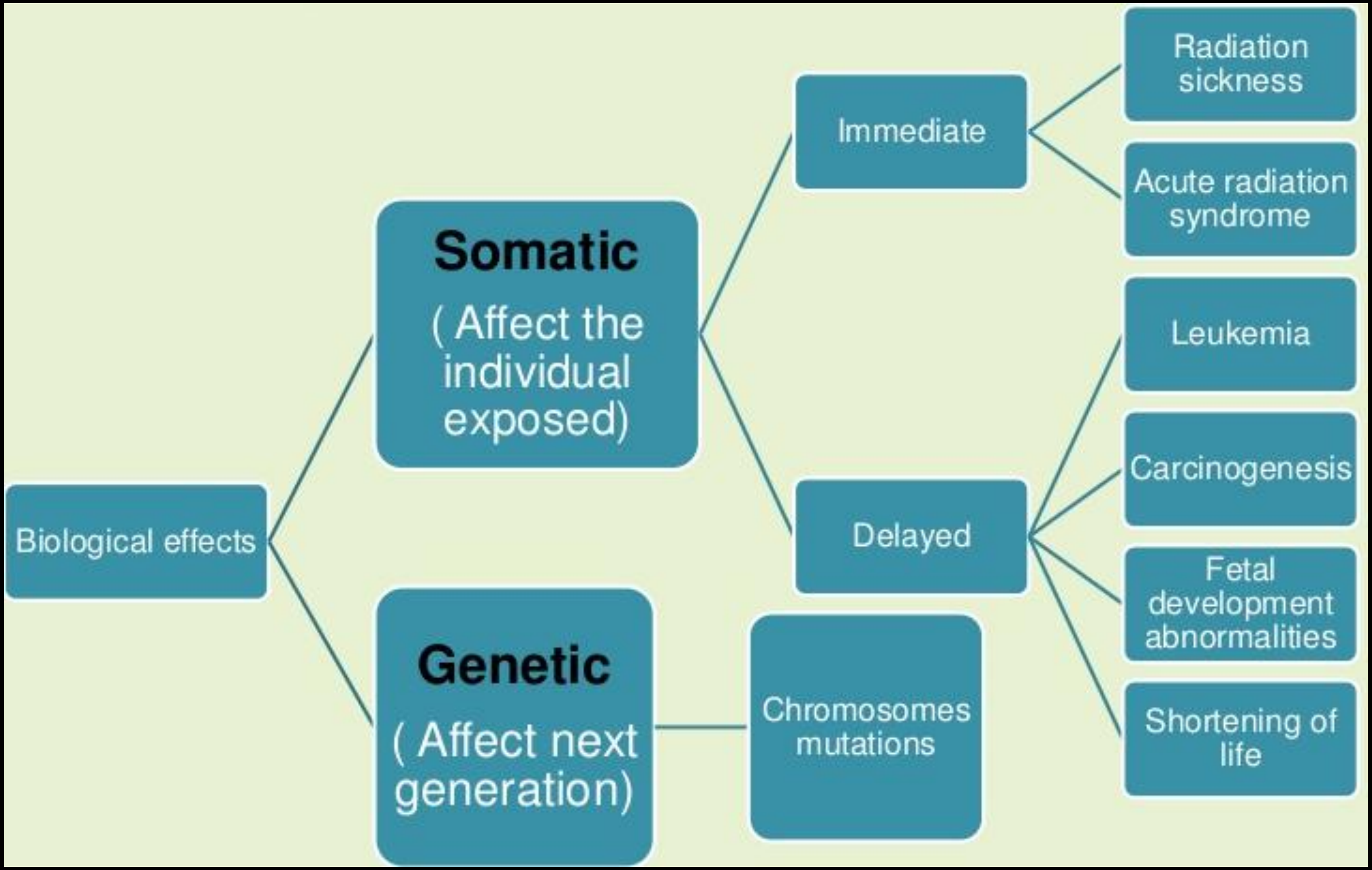
Long Term Exposure to Radiation





Biological Effects of Ionizing Radiation



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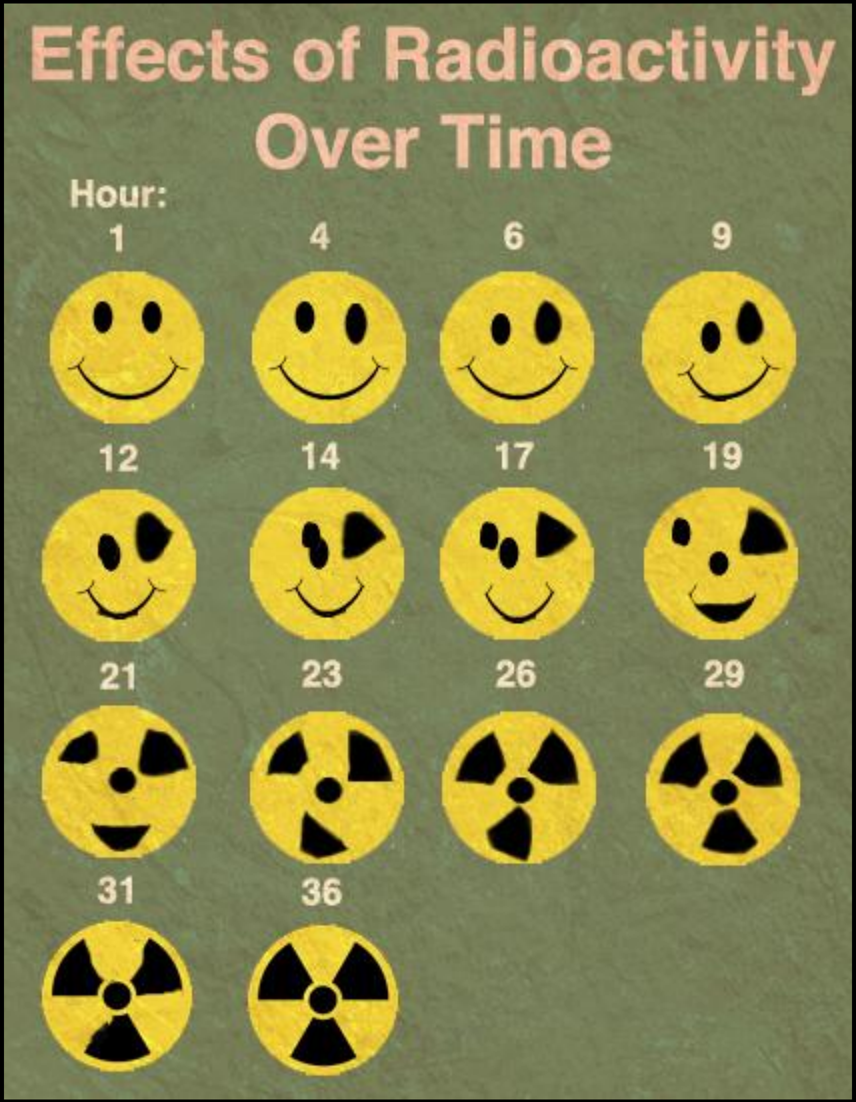
Effects of Radioactivity
Over Time
Hour:
1
4
6
9
12
14
17
19
21
23
26
29
31
36

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