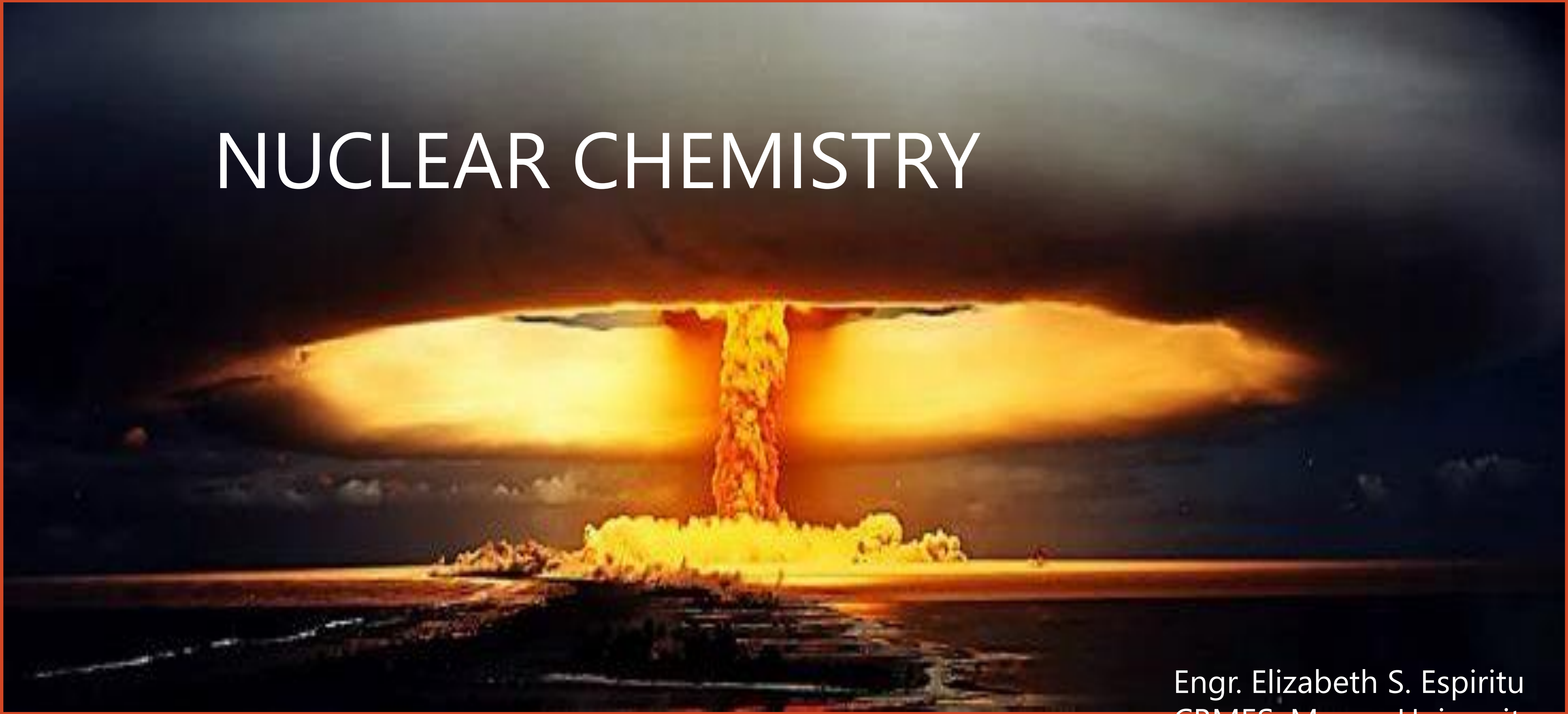
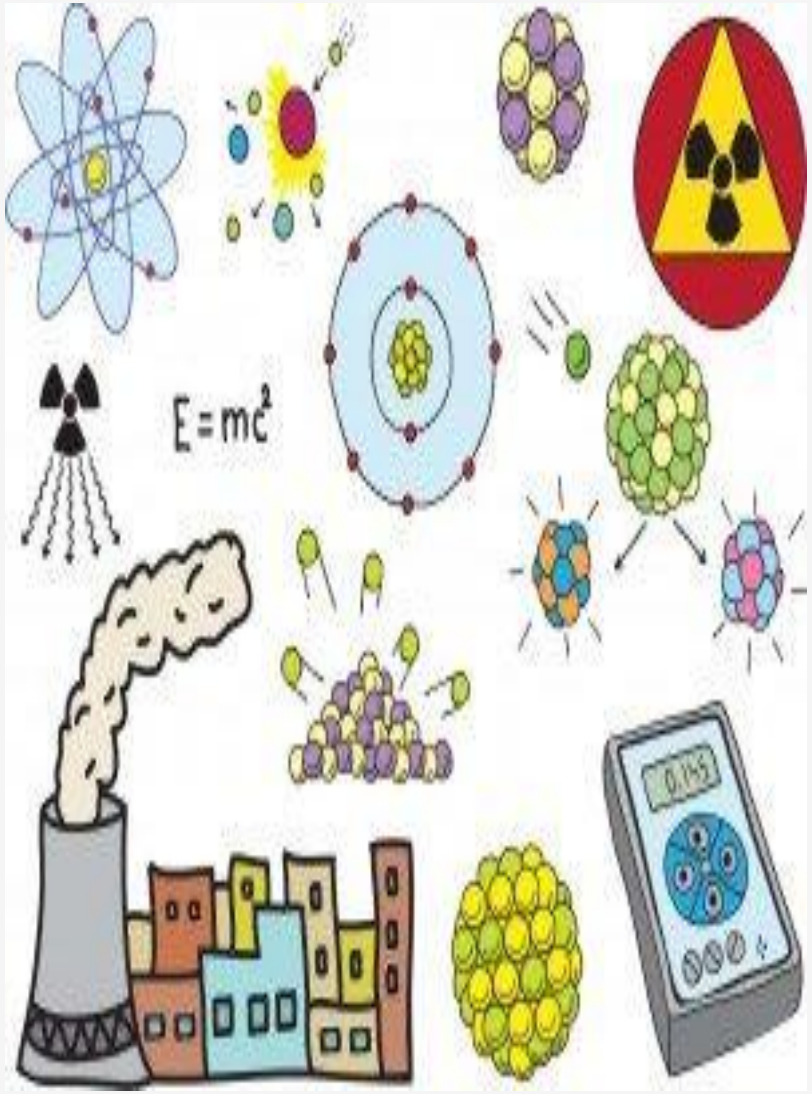


NUCLEAR CHEMISTRY

Engr. Elizabeth S. Espiritu
CBMES, Mapua University

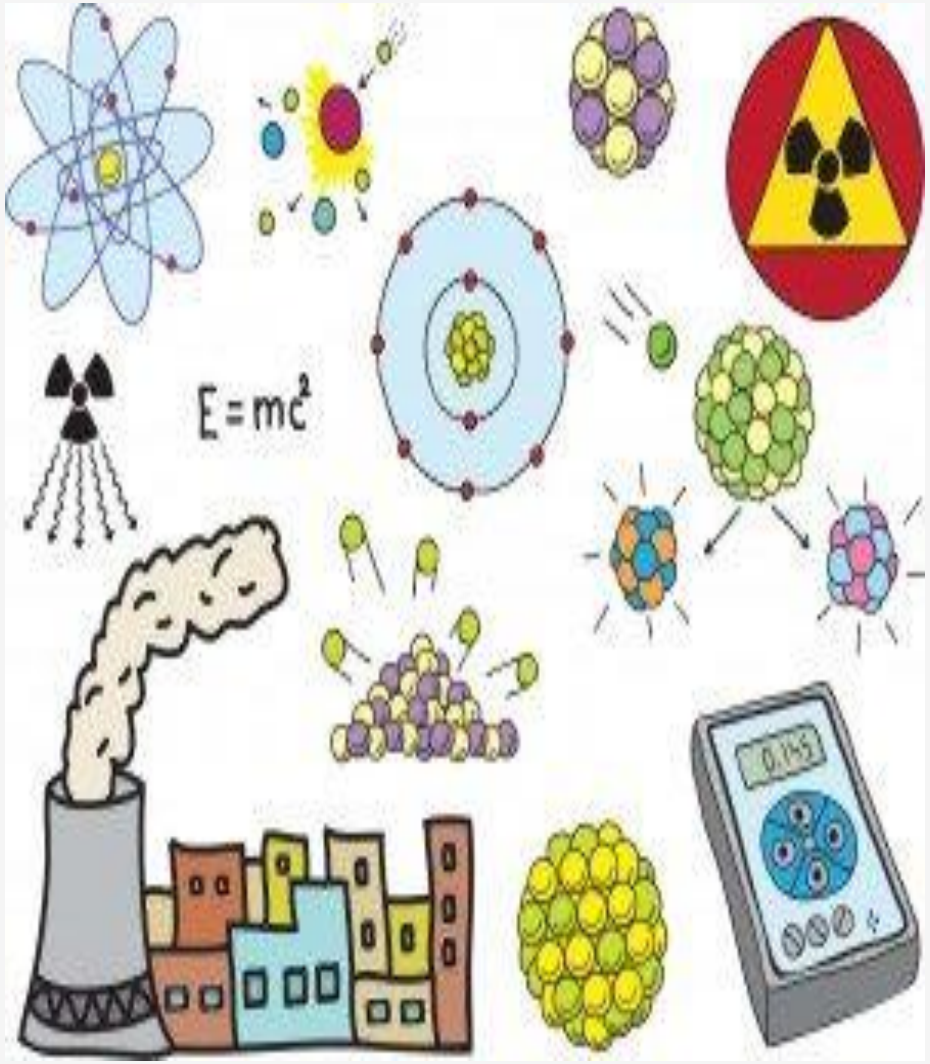
Objectives

- Describe the make up of the nucleus
- Describe the criteria for nuclear stability
- Calculate mass deficiency and nuclear binding energy
- Describe the common types of radiation emitted during radioactive decay
- Write and balance equations that describe nuclear reactions
- Predict the different kinds of nuclear reactions based on positions of the nuclei relative to the band of stability
- Describe methods of detecting radiation
- Understand half-lives of radioactive elements

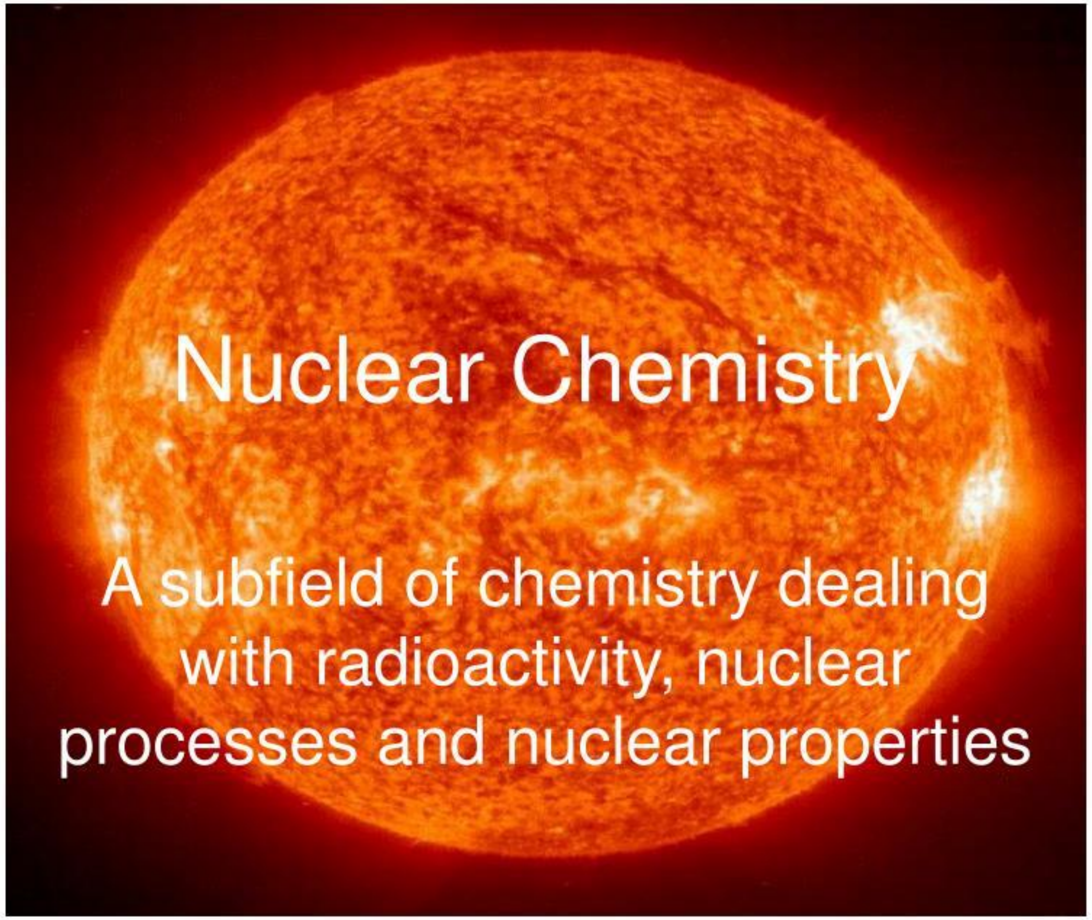


Objectives

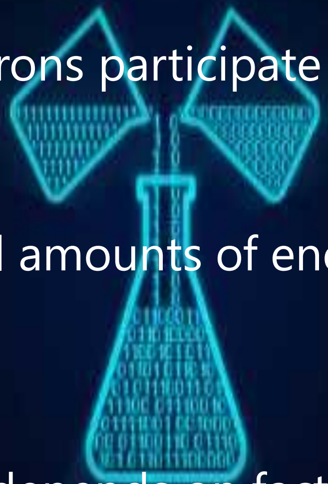
- Carry out calculations associated with radioactive decay
- Interpret decay series
- Tell about some uses of radionuclides in radiocarbon dating
- Describe some induced nuclear reactions
- Tell about nuclear fission and some of its applications
- Tell about nuclear fusion and some prospects for and barriers to its use for the production of energy.



Chemical vs Nuclear Reactions



Chemical Reactions vs Nuclear Reactions

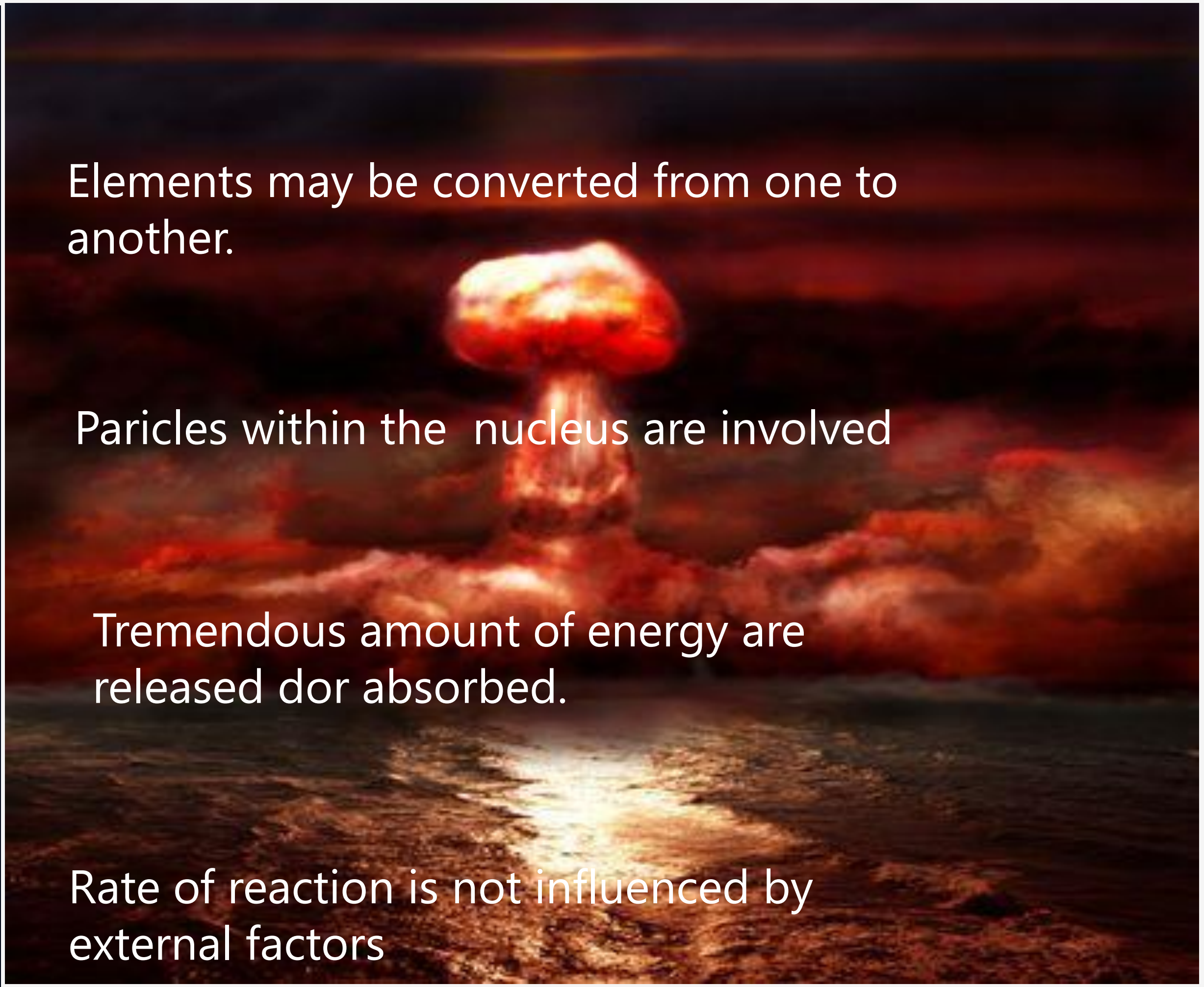


No new elements are formed

Only the electrons participate

Relatively small amounts of energy are released or absorbed

Rate of reaction depends on factors such as concentration, temperature, catalyst, and pressure



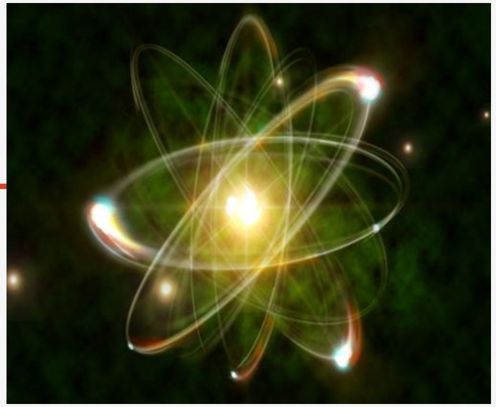
Elements may be converted from one to another.

Paricles within the nucleus are involved

Tremendous amount of energy are released dor absorbed.

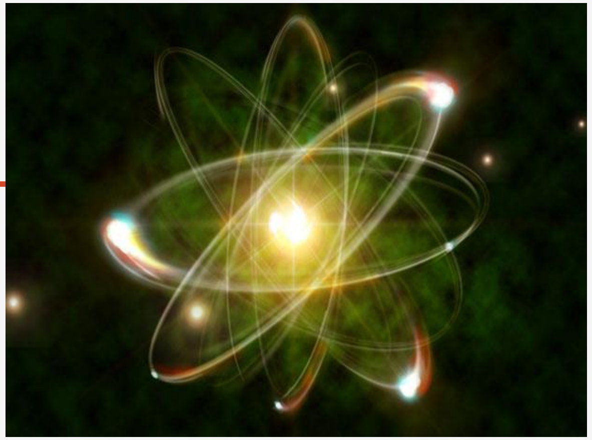
Rate of reaction is not influenced by external factors

What's in an atom?



Particle	Where it's found	What's its charge?	What's its mass?
Proton	In nucleus	+1	~ 1 amu
Neutron	In nucleus	0	~ 1 amu
Electron	Flying around nucleus	-1	~ 1/1840 amu

The Nucleus

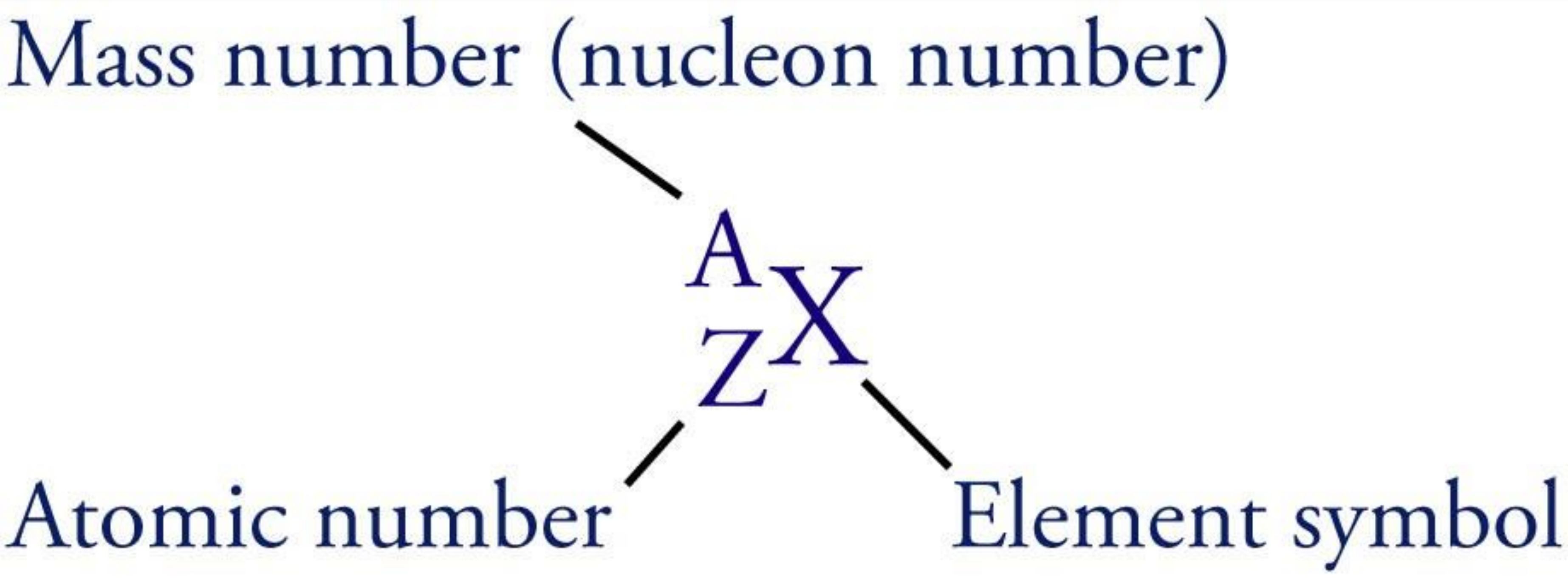


- The nucleus is composed of nucleons
  - –protons
  - –neutrons

- A nucleus is characterized by two numbers
  - –atomic mass number(A; total # of nucleons)
  - –atomic number (Z; number of protons)

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

Nuclide Symbol



Example

$${}_{13}^{27}Al$$

- total number of nucleons is 27
- total number of protons is 13
- the number of neutrons is 14

In the Nucleus

Contains most of the mass of the atom

VERY small volume

❖ radius ~ 10^{-15} m

Number of protons determines identity : (atomic number)

Number of neutrons in an element can vary

- Isotopes: atoms with equal number of protons but different numbers of neutrons
- *Average atomic mass = weighted average of the masses of all naturally-occurring isotopes.*

Average Atomic Mass

Boron contains ^{10}B and ^{11}B (10.0129; 11.0093 u). ^{10}B is 19.91% abundant. Calculate the atomic mass of B.

$$^{10}B \qquad \underbrace{\frac{19.91}{100}}_{\text{fraction}}\underbrace{(10.0129\ u)}_{\text{mass}} = 1.994\ u$$

Abundance of ^{11}B = 100% - 19.91% = 80.09%

$$^{11}B \qquad \underbrace{\frac{80.09}{100}}_{\text{fraction}}\underbrace{(11.0093\ u)}_{\text{mass}} = 8.817\ u$$

Atomic weight of B = 1.994 + 8.817 u

$$= \boxed{10.811\ u}$$

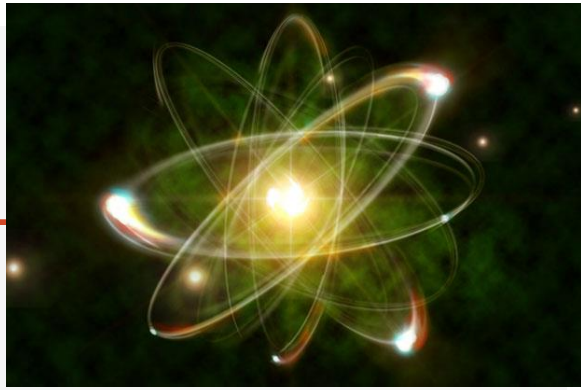
5

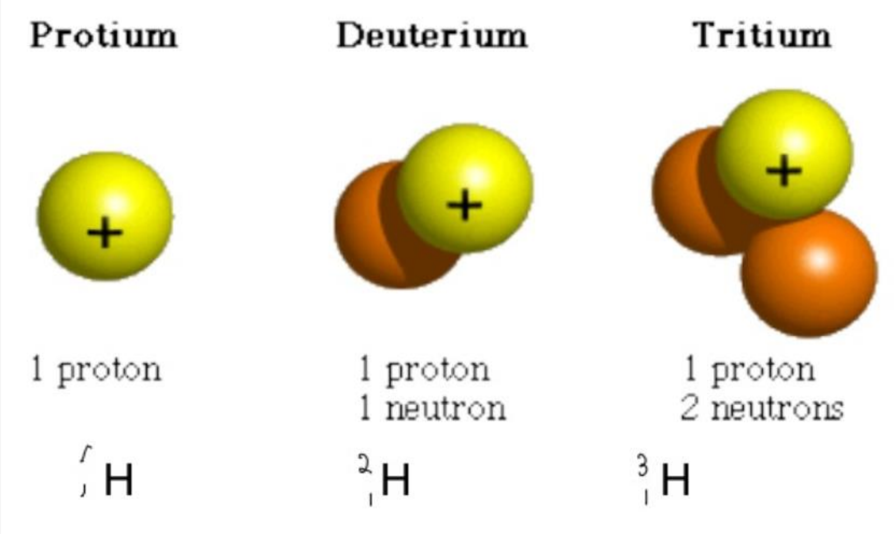
B

Boron

10.811

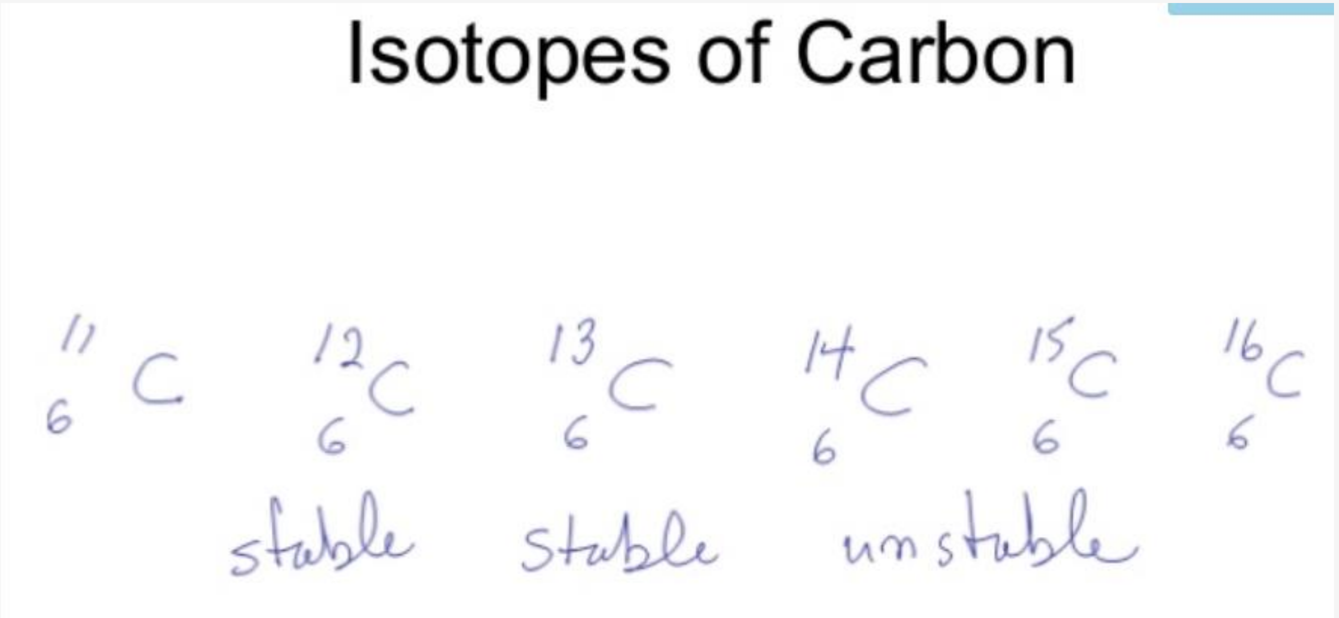
Isotopes





Stable stable unstable

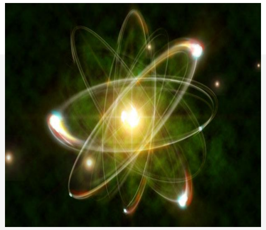
Isotopes of Hydrogen



In the Nucleus

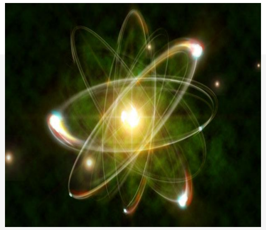
- **Electrostatic forces**: protons ***repel*** each other
- **"Strong" nuclear forces**: ***attract*** protons to neutrons
- The **balance** between these two forces determines whether or not a given nucleus will be **stable**.

Stability of Atoms

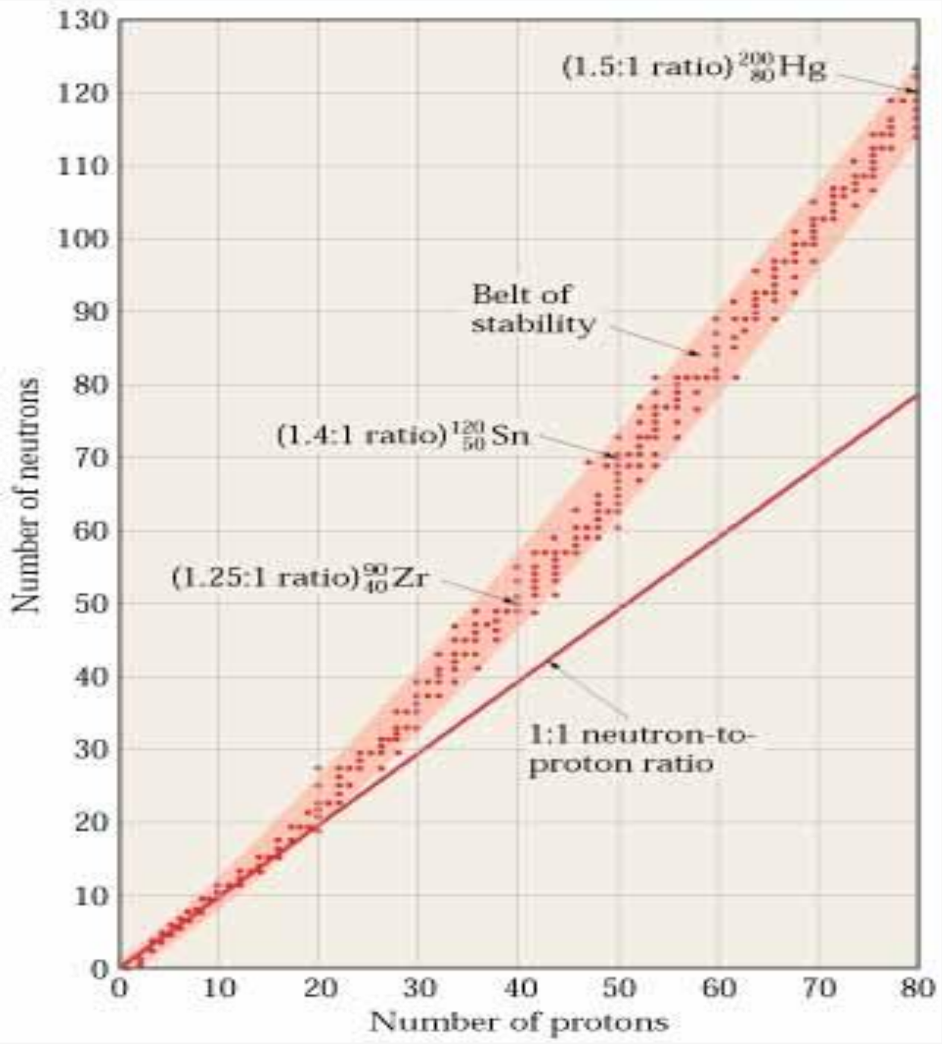


The two main factors that determine nuclear stability are the

- ✓ neutron/proton ratio and the
- ✓ **t**otal number of nucleons in the nucleus.



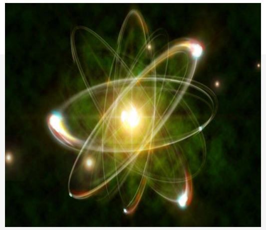
Neutron/Proton ratio

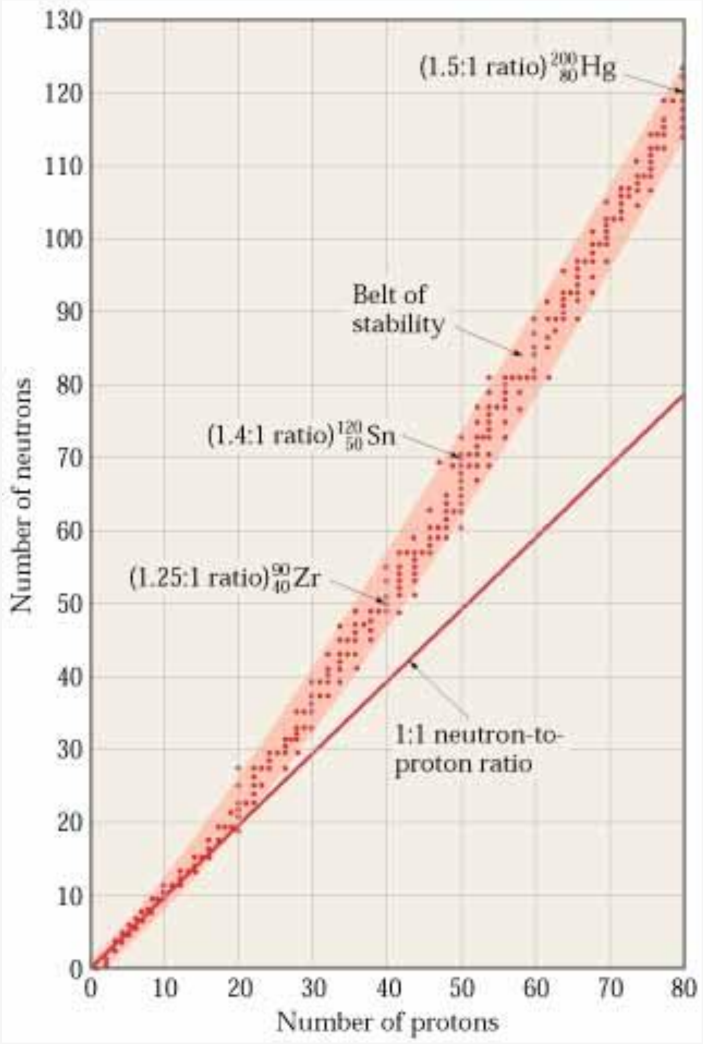


plot of the number of neutrons versus the number of protons

Above Z = 20, the number of neutrons always exceeds the number of protons in stable isotopes. The stable nuclei are located in the pink band known as the *belt of stability*. The belt of stability ends at lead-208.

Neutron/Proton ratio



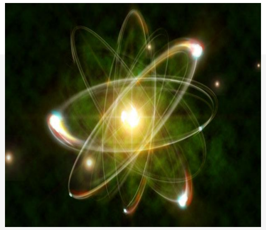


Stable nuclei have $N \geq Z$.

- Nuclei with $Z < 20$: $N / Z \approx 1$.
- Nuclei with $Z > 20$: N / Z gradually increases.
- ^{209}Bi ($Z = 83$) is the heaviest stable nucleus.
- Even-Z isotopes are more common than odd.
- When Z is odd, an even-N isotope is more stable.
  - 160 “even-even”
  - 110 “odd-even” or “even-odd”
  - Only 4 “odd-odd” isotopes known

plot of the number of neutrons versus the number of protons

Number of Nucleons



No nucleus higher than lead-208 is stable. That's because, although the nuclear strong force is about 100 times as strong as the electrostatic repulsions, it operates over only very short distances. When a nucleus reaches a certain size, the strong force is no longer able to hold the nucleus together.

Unstable Nuclei

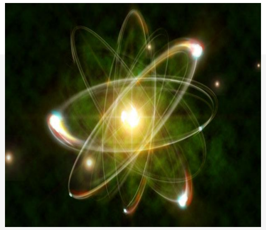
wrong Z/N balance, → ***radioactive decay***

- i.e. the atom will ***emit radiation***.

Radioactive nuclei ***spontaneously decay***

The degree of unbalance determines the ***type of decay***

Radioactive nuclei (**parent nuclei)** decay into **daughter nuclei**.



Types of Radiation

Alpha Radiation

a positive charged particle is released

a ***helium nucleus***

Beta Radiation

a negatively charged particle is released

an ***electron***

Gamma Radiation

no particle is released

high energy waves are released

Band of Stability & Type of Decay

Unstable isotopes decay so that the daughter enters the "peninsula of stability".

Elements with $Z > 83$

Most decay by alpha emission.

Elements with $Z < 83$

Use a periodic table to determine whether an isotope is too heavy or too light and hence its mode of decay.

The Nature of Radioactivity

Name	Symbol			Charge	Mass (g)	Pen. Power*
alpha	$^{4}_{2}He^{2+}$	$^{4}_{2}\alpha$	$^{4}_{2}He$	+2	6.65×10^{-24}	0.03 mm
beta	$^{0}_{-1}e$	$^{0}_{-1}\beta$		-1	9.11×10^{-28}	2 mm
gamma	$^{0}_{0}\gamma$	γ		0	0	100 mm

*Penetrating Power: Water layer to absorb 50 % of the radiation.

$m_\alpha \approx 10{,}000\ m_\beta$

Radiation Shielding

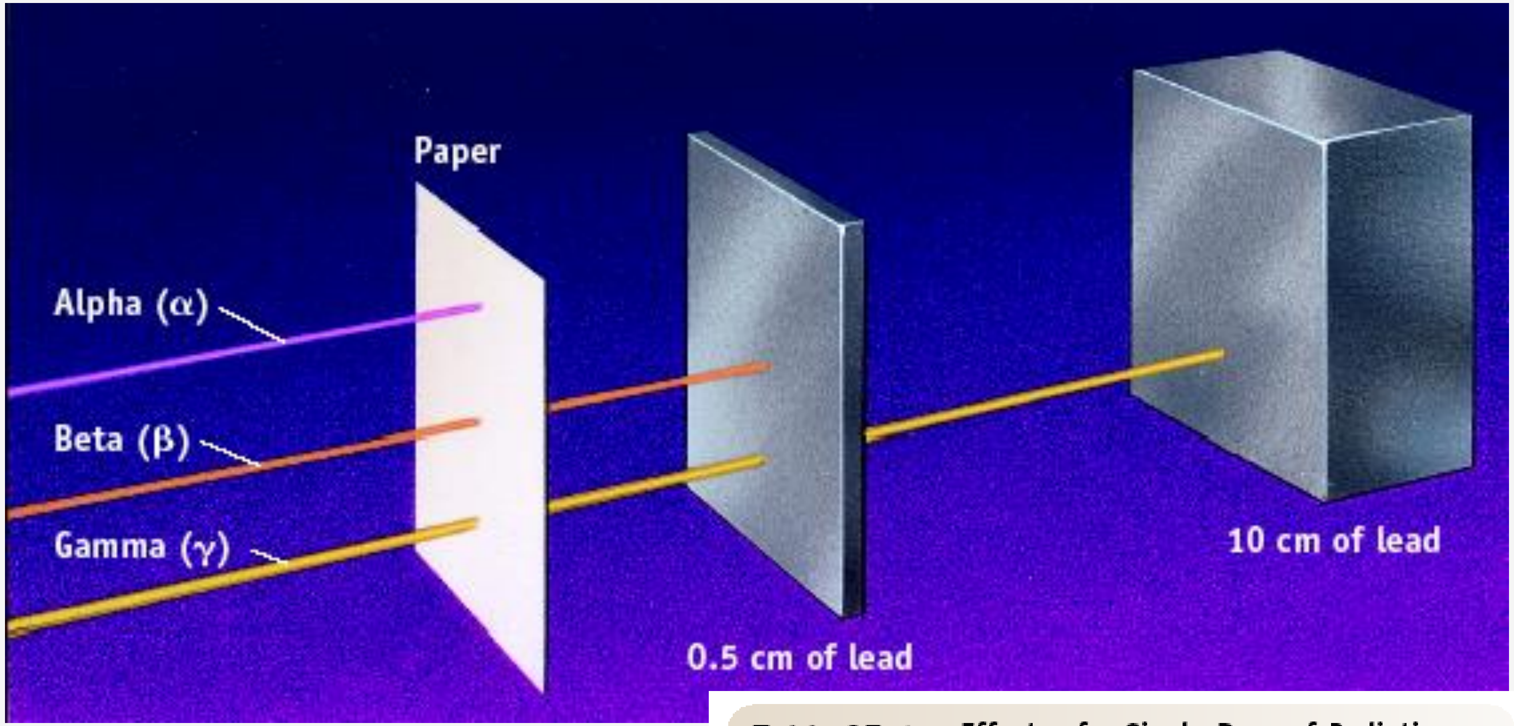


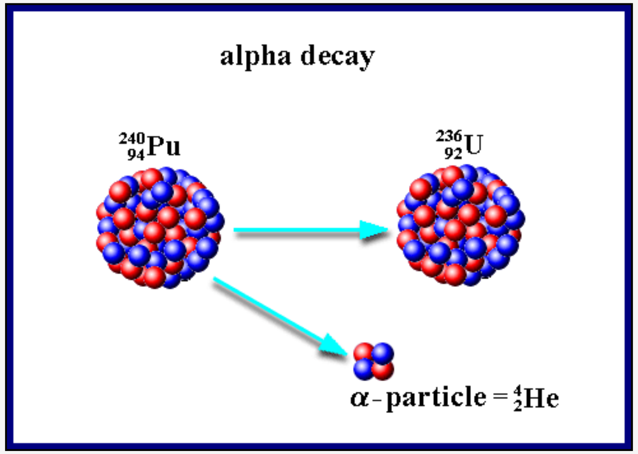
Table 23.4 • Effects of a Single Dose of Radiation

Dose (rem)	Effect
0–25	No effect observed
26–50	Small decrease in white blood cell count
51–100	Significant decrease in white blood cell count, lesions
101–200	Loss of hair, nausea
201–500	Hemorrhaging, ulcers, death in 50% of population
>500	Death

Alpha (α)Decay

The ***nucleus is too large*** for the **strong force** to hold it together,

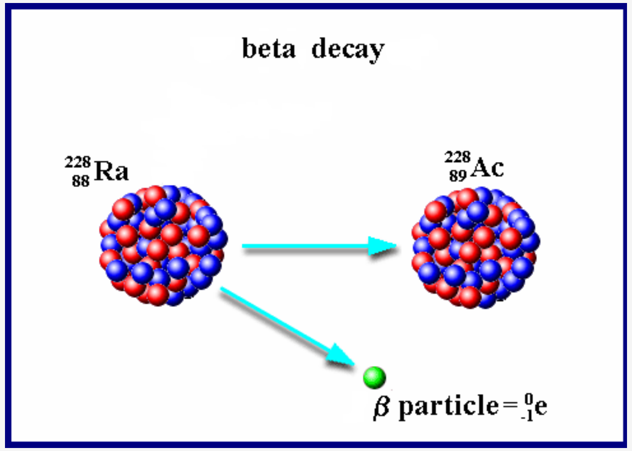
- an α-particle ($_2^4He$ nucleus) is emitted
- Daughter nucleus has *2 fewer protons* and *2 fewer neutrons* than parent.
- Alpha radiation is *too weak to penetrate paper or skin*
- Nuclear equation: $_{92}^{235}U \rightarrow {}_2^4He + {}_{90}^{231}Th$



Beta (β)Decay

When a ***nucleus has <u>too many neutrons</u>***,

- a β-particle ($_{-1}^{0}e$) is emitted, a neutron in the nucleus splits into a p^+ and an e^-
    - The p^+ stays in the nucleus.
    - The e^- is ejected and called a β-particle.
- Daughter nucleus has 1 more proton and 1 fewer neutron than parent.
- Nuclear equation:
    - $_{6}^{14}C \dashrightarrow _{7}^{14}N + _{-1}^{0}e$

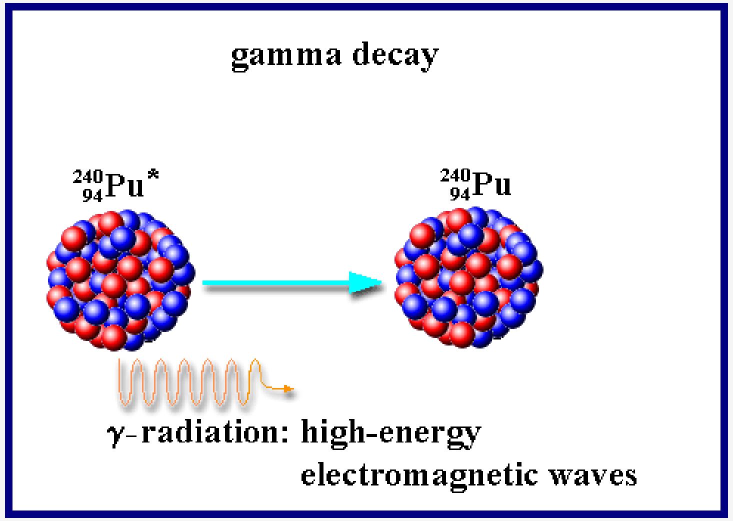


- Beta radiation is unable to penetrate aluminum foil or wood

Gamma (γ) Radiation

When a nucleus has too much energy, it can give off very high energy waves of light.

- the nucleus is unchanged - it still has the same # of p+ and # of n0.
- Nucleus goes from “excited state” to “ground state,” losing excess energy.



- Gamma rays are often given off with other types of radioactivity.
- Gamma radiation can pass through people

Electron Capture

When a ***nucleus has <u>too few neutrons</u>***,

- An electron falls into the nucleus
  - unites with a proton to form a neutron.
  - Electrons cascade in to fill in for the missing electron
  - Daughter nucleus has 1 more neutron and 1 fewer proton than parent.

- Nuclear equation:
  - ${}_{6}^{9}C + {}_{-1}^{0}e \dashrightarrow {}_{5}^{9}B$

Positron Emission

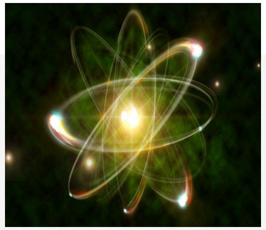
Positron emission or beta plus **decay** (β^+ **decay**) is a subtype of radioactive **decay** called beta **decay**, in which a proton inside a radionuclide nucleus is converted into a neutron while releasing a **positron** and an electron neutrino (v_e).

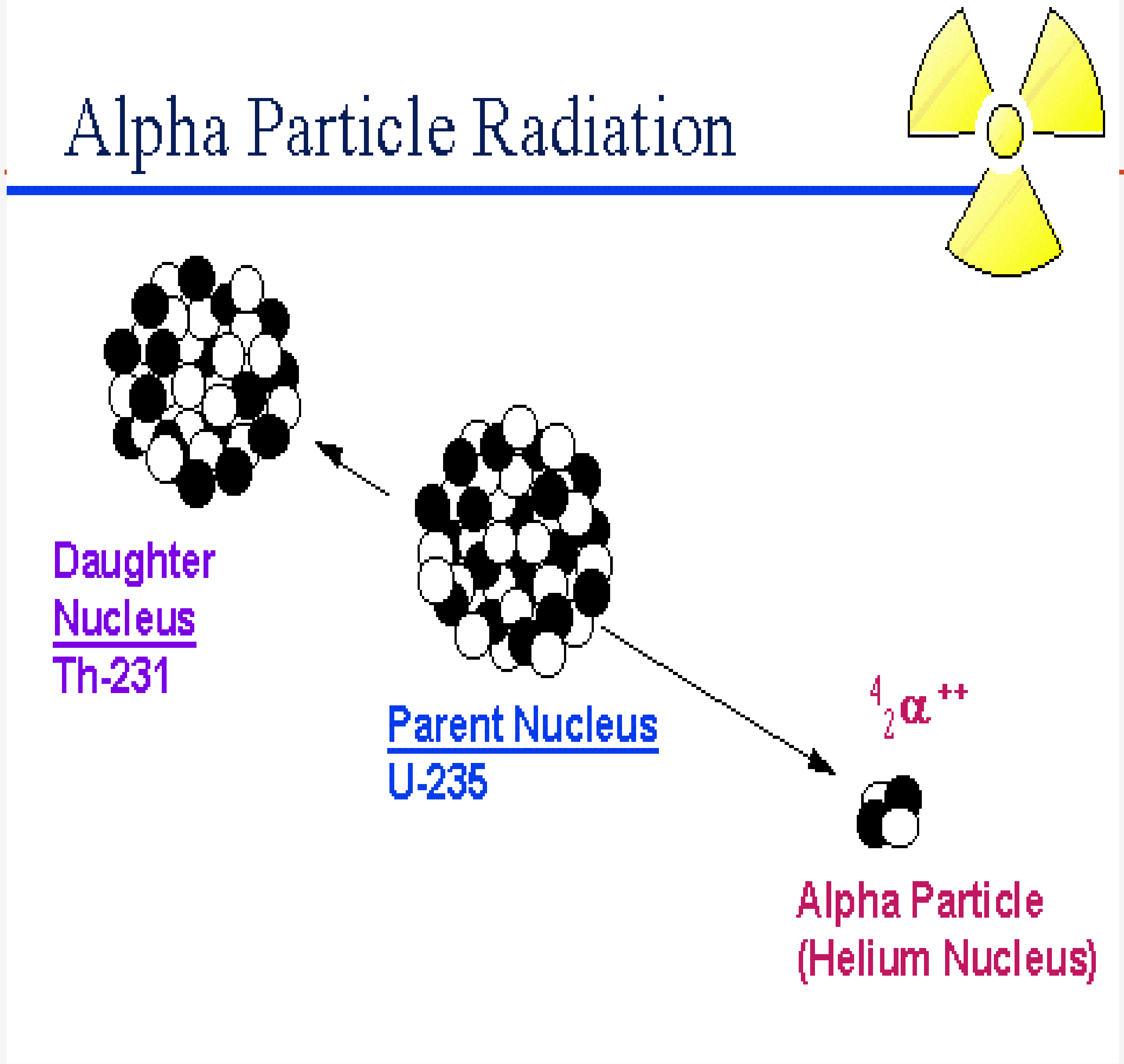
Radiation - Summary

Problem	Decay Type	Symbol	Resulting Daughter
Nucleus is too large	alpha	α or ${}_{2}{}^{4}He$	Atomic number -2 Mass number -4
Too many n^0 in nucleus	beta	β^- or ${}_{-1}{}^{0}e$	Atomic number +1 Mass number stays same
Too much energy	gamma emission	γ	Same nucleus, just lower energy

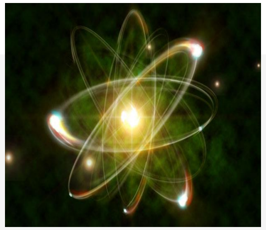
General Nuclear Equations

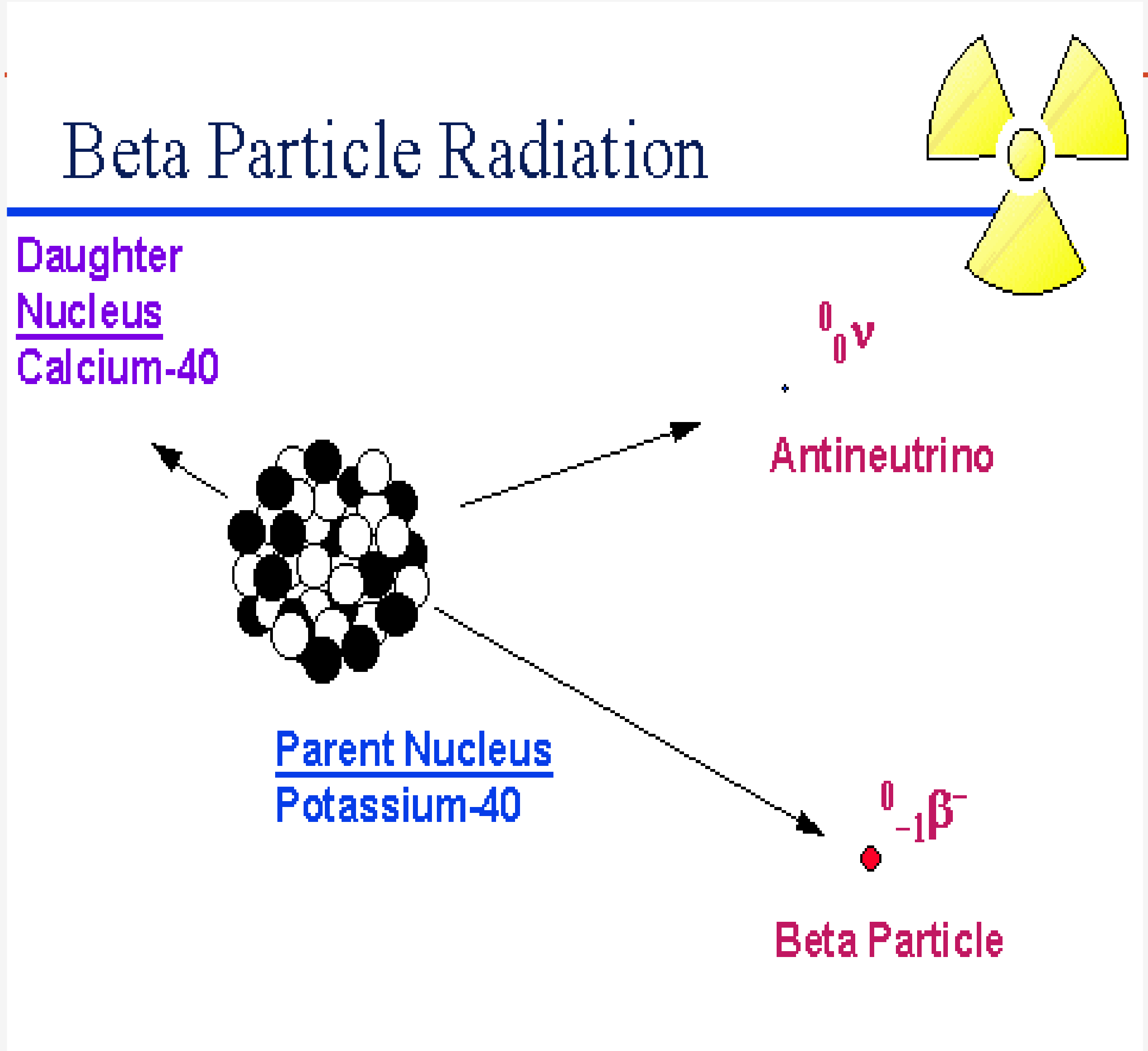
Alpha emission	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
Beta emission	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$
Positron emission	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$
Electron capture	${}^{0}_{-1}e + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y$





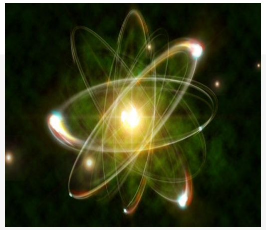
- $_{Z}^{A}X \longrightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}\alpha$
- Identity of the atom changes
- $_{92}^{235}U \longrightarrow {}_{90}^{231}Th + {}_{2}^{4}\alpha$
- Quick way for a large atom to lose a lot of nucleons

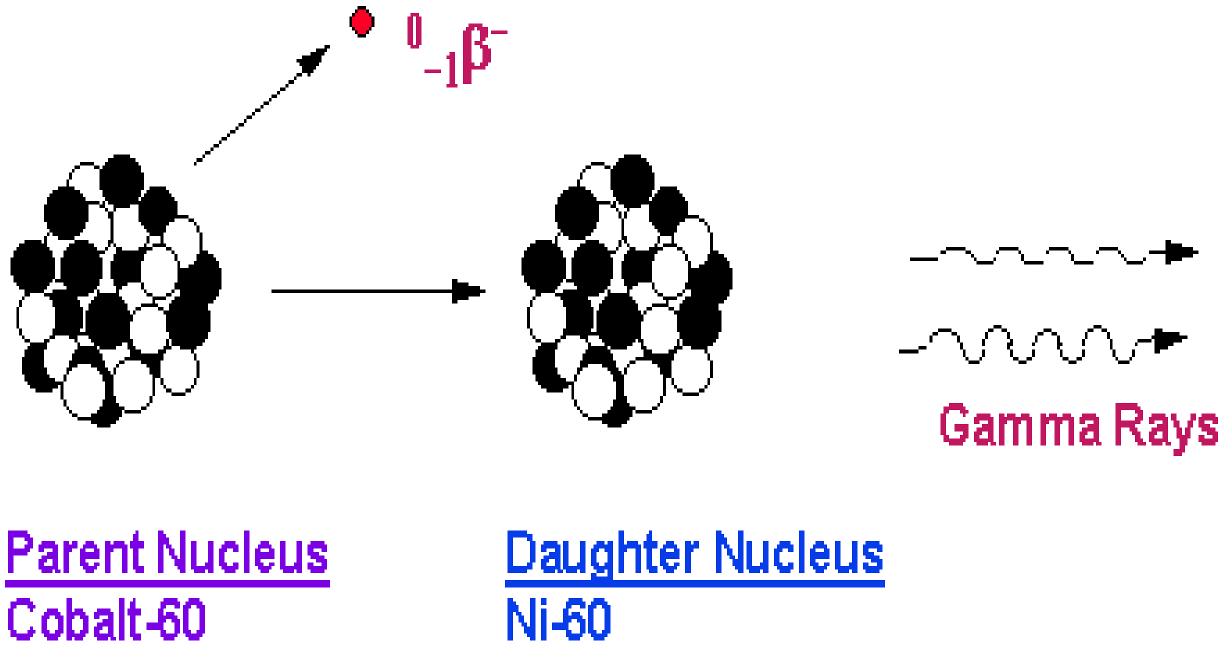




- Ejection of a high-speed electron from the nucleus
- ${}_{Z}^{A}X \longrightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}B$
- ${}_{19}^{40}K \longrightarrow {}_{20}^{40}Ca + {}_{-1}^{0}B$
- Identity of atom changes

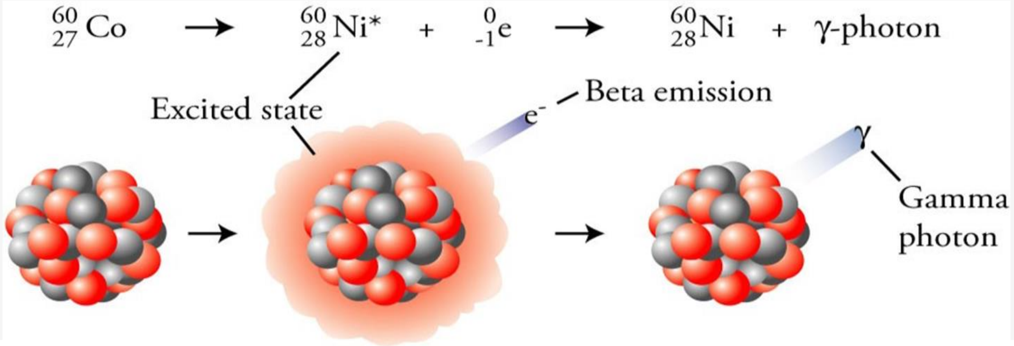
Gamma-Ray Radiation



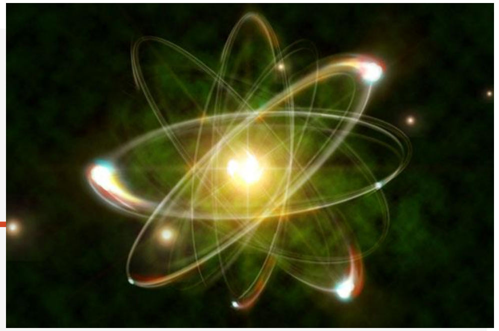


- Emission of high energy electromagnetic radiation
- Usually occurs after emission of a decay particle forms a metastable nucleus

Does not change the isotope or element

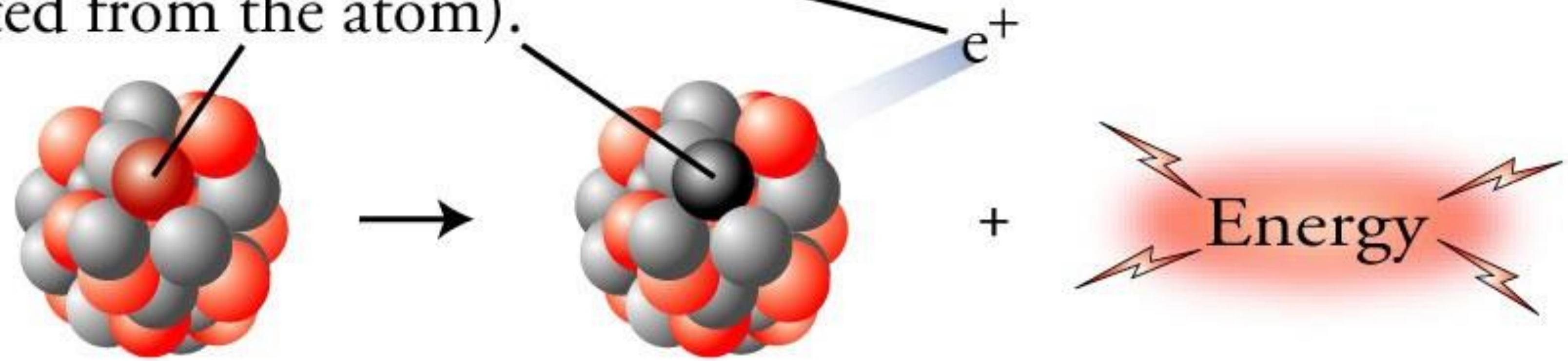


Positron Emission



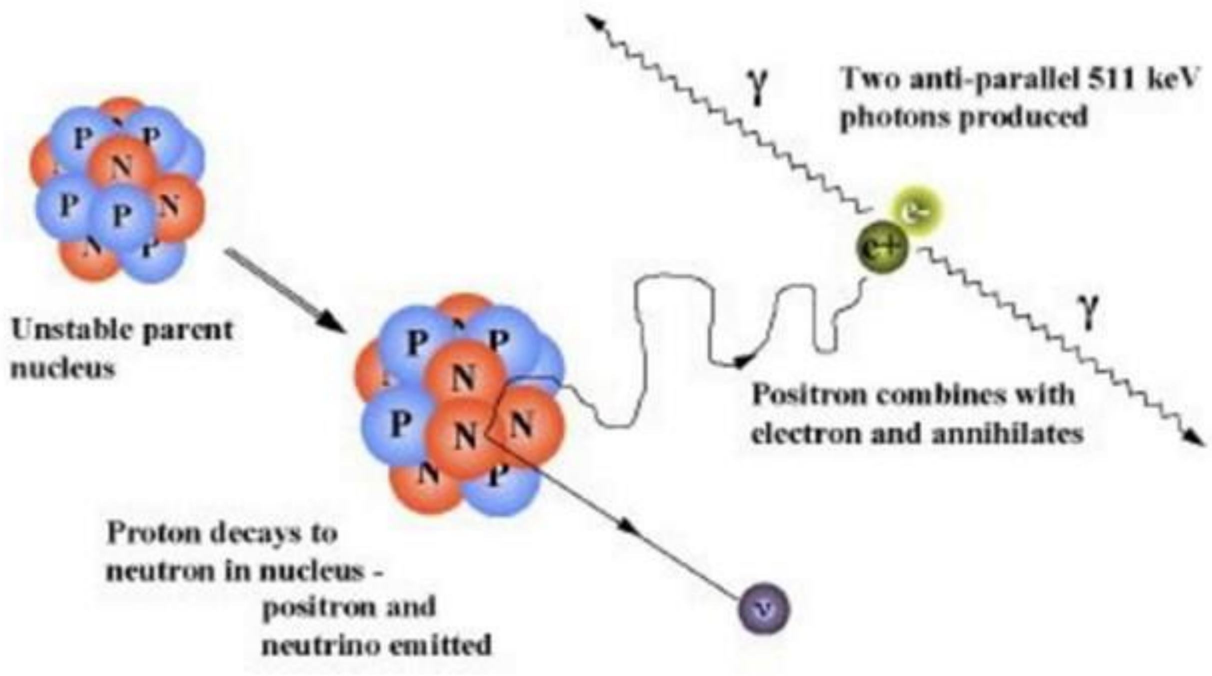
$${}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{18}\mathrm{Ar} + {}^{0}_{+1}\mathrm{e}$$

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



$${}^{X}_{Z}A \rightarrow {}^{0}_{1}e \; + \; {}_{Z-1}^{X}B$$

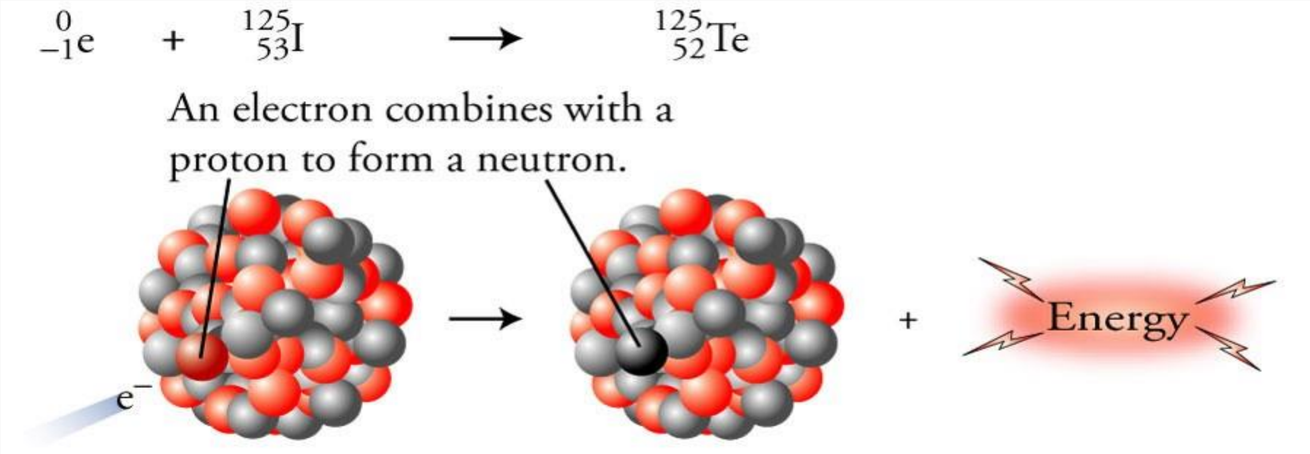
Positron Emission



Taken from: http://depts.washington.edu/nucmed/IRL/pet_intro/intro_src/fig1_small.JPG01-25-2017

Electron Capture

Electron capture is one process that unstable atoms can use to become more stable.
During **electron capture**, an **electron** in an atom's inner shell is drawn into the nucleus where it combines with a proton, forming a neutron and a neutrino. The neutrino is ejected from the atom's nucleus.



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

Neutrino

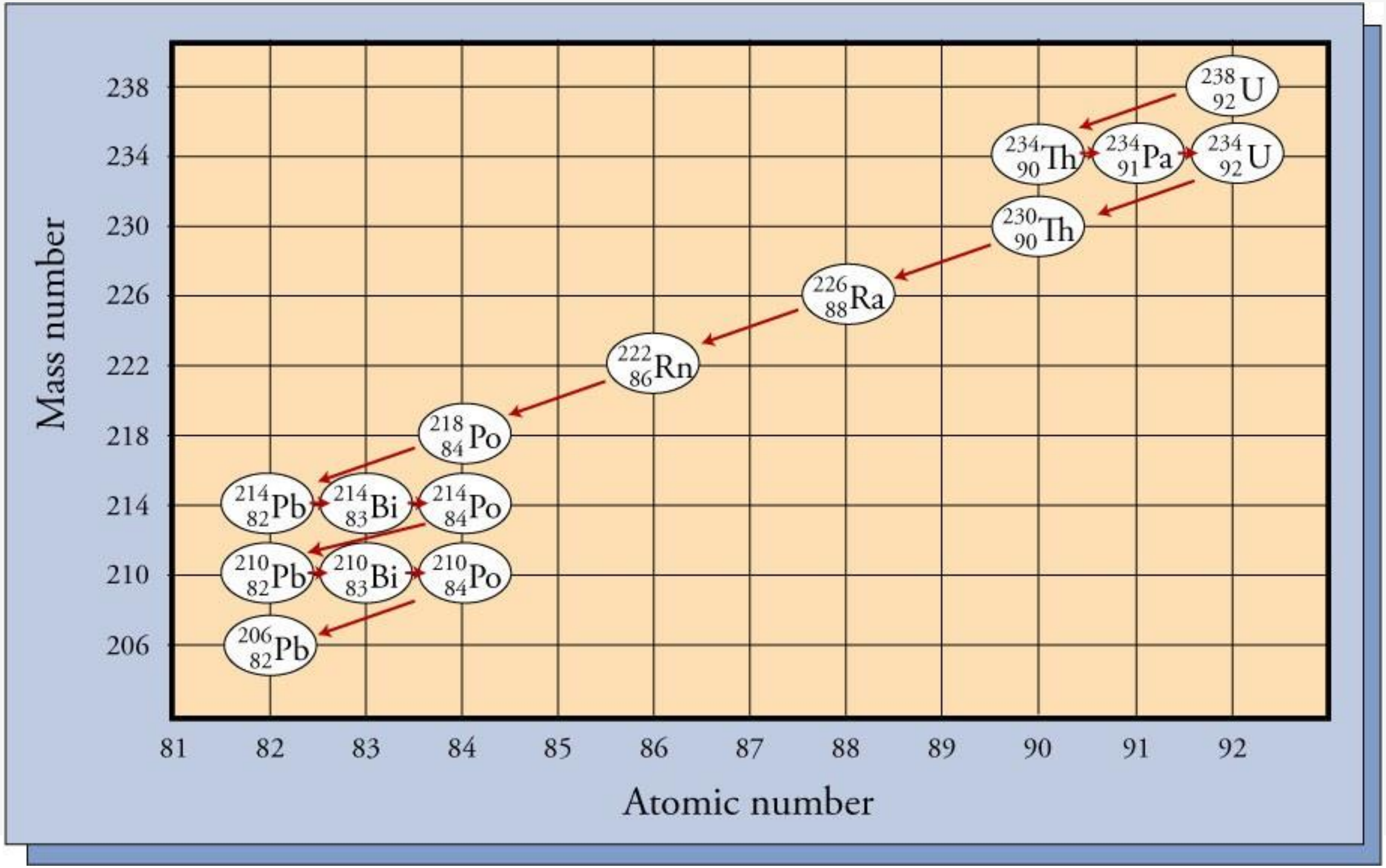
A neutrino is a subatomic particle that is very similar to an electron, but has no electrical charge and a very small mass, which might even be zero. Neutrinos are one of the most abundant particles in the universe. Because they have very little interaction with matter, however, they are incredibly difficult to detect.

It was first hypothesized by Wolfgang Pauli in 1930, to account for missing momentum and missing energy in beta decay,

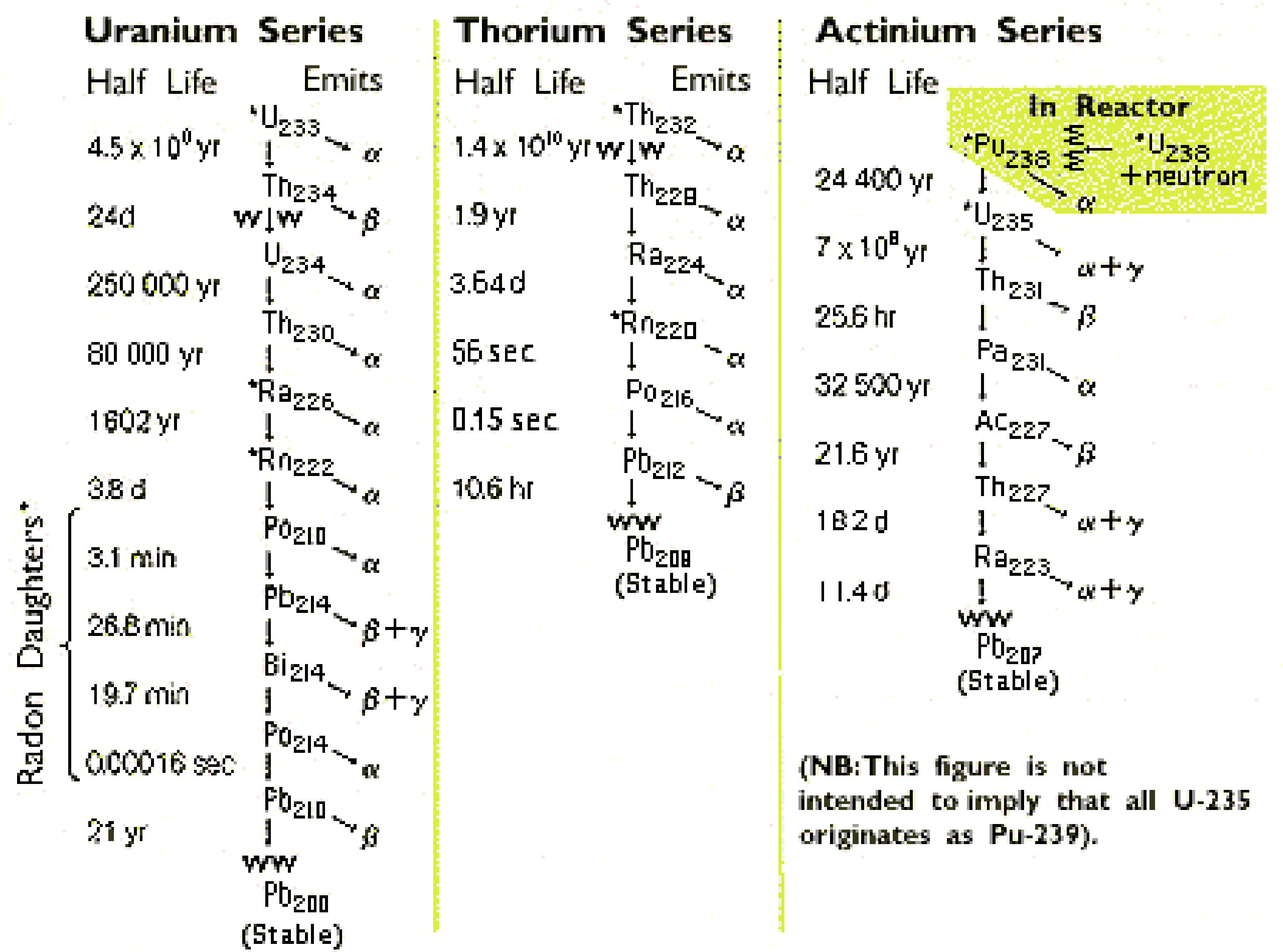
Decay Series

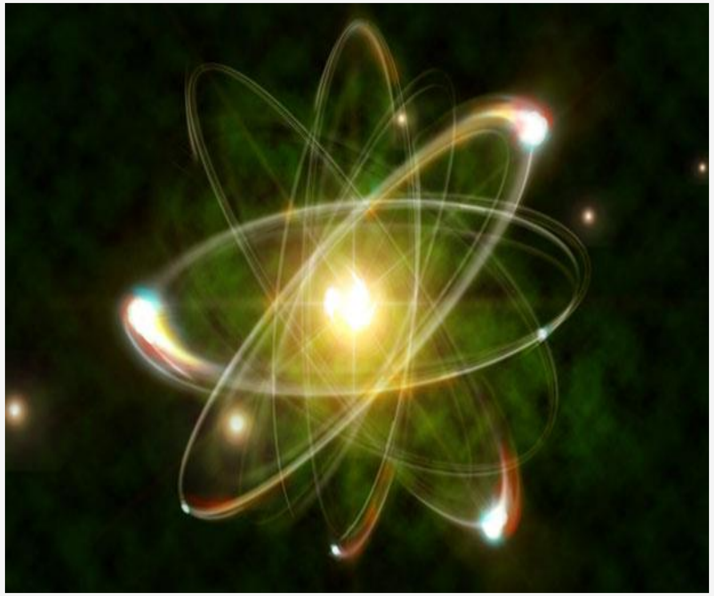
A series of elements produced from the successive emission of alpha & beta particles

Radioactive Decay Series



Decay Series





Nuclear Radiation: Effects & Units

rad radiation absorbed dose.

1 rad = 0.010 J absorbed/kg of material

gray (Gy) SI unit.

1 Gy = 1 J absorbed/kg of material

1 Gy = 100 rad

Roentgen (R) dosage of X-ray and γ-radiation.

1 R = 9.33 μJ deposited/g of tissue

Nuclear Radiation: Effects & Units

α, β, and γ have different biological effects, so…

rem

Roentgen equivalent in man.

dose in rem = (quality factor) x (dose in rads)

sievert (Sv)

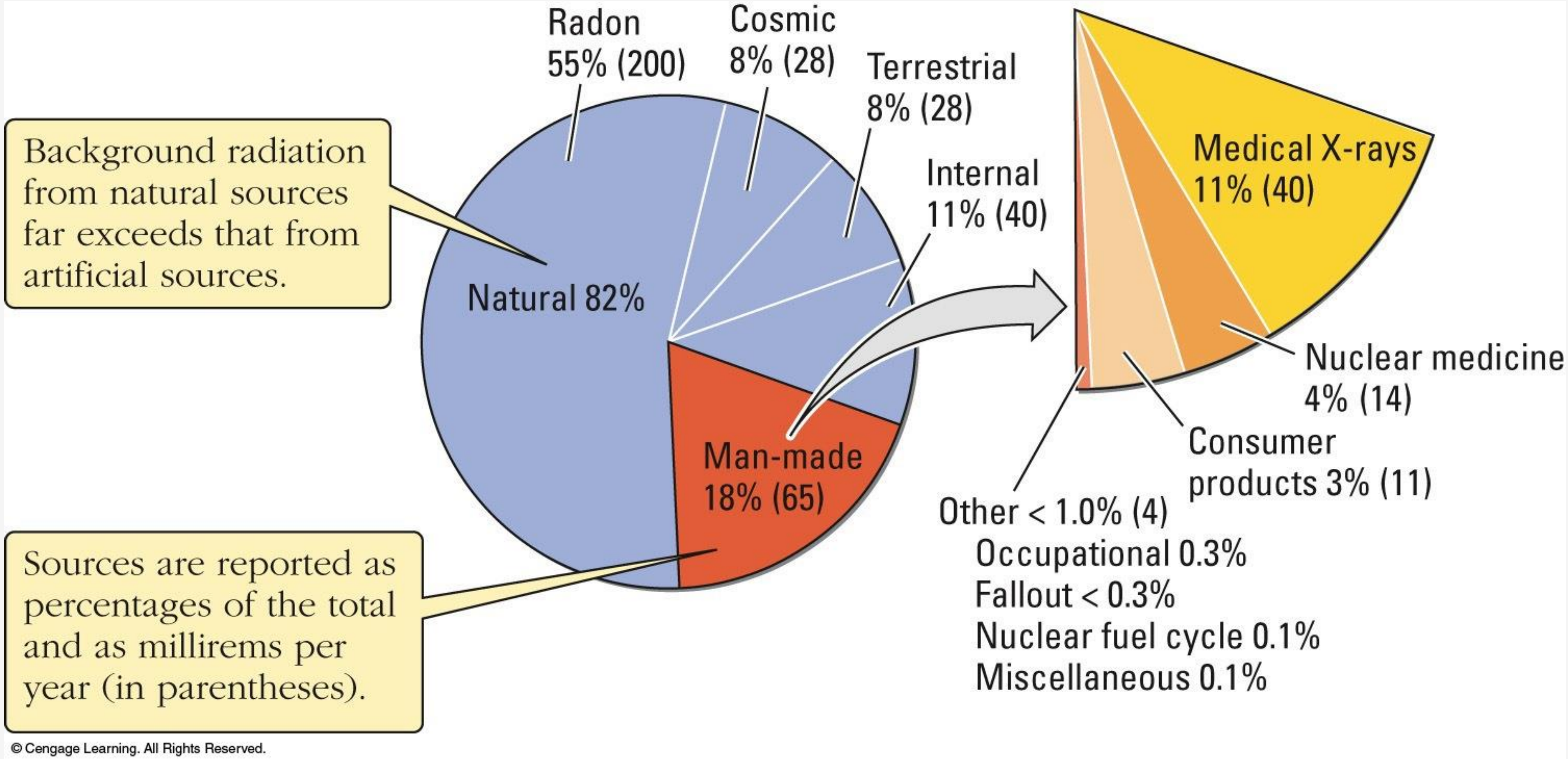
SI version. 1 Sv = 100 rem

Quality factors:

α = 10 - 20, β = 1, γ = 1

Film badge
(monitors radiation dose)

Background Radiation



Key: Source % of total (millirems/yr)

Applications of Radioactivity

Food Irradiation

- γ-rays kill bacteria, molds, spores…
- Food spoils much less rapidly.
- It does not make food radioactive.

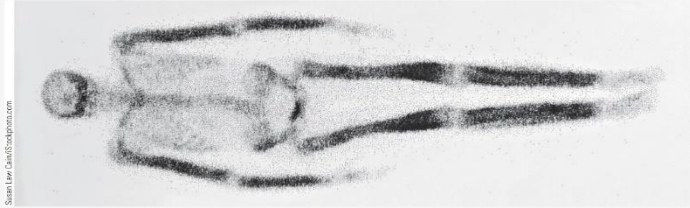
The radura
International symbol
for irradiated food

Tracers

- Chemicals made with radioactive atoms
- Introduced into plants, animals…
- Concentrate where used (rapid growth regions)
- Uptake can be monitored with a Geiger counter.

Applications of Radioactivity

Medical Imaging

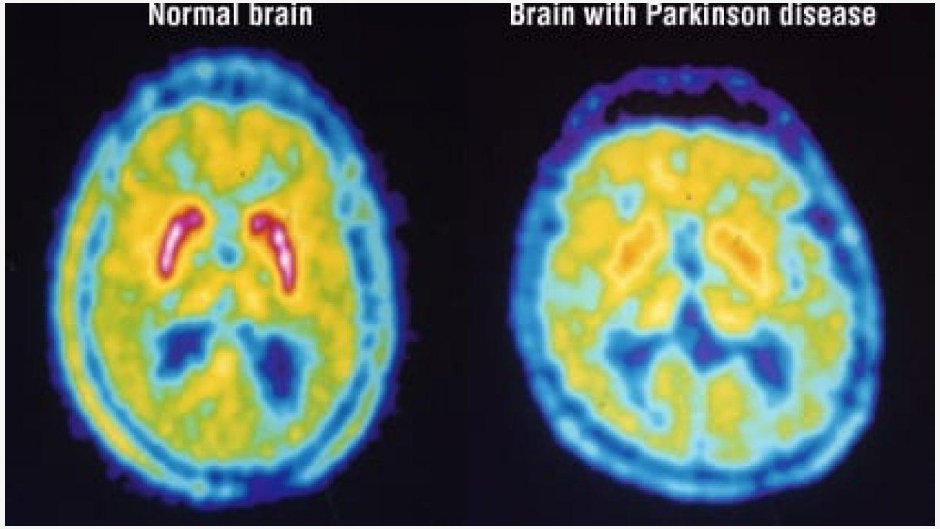


- γ-emitters are often used
- Gamma rays can exit the body
- Less damaging than α or β.
- Tracers are used by organs, bones…

- **X-rays** are a very energetic form of electromagnetic radiation that can be used to take images of the human body.
    - use ionizing radiation to generate images of the body. Ionizing radiation is a form of radiation that has enough energy to potentially cause damage to DNA and may elevate a person’s lifetime risk of developing cancer.

Applications of Radioactivity

Positron emission tomography (PET) is a type of nuclear medicine procedure that measures metabolic activity of the cells of body tissues. PET is actually a combination of nuclear medicine and biochemical analysis.



Applications of Radioactivity

- A **CT scan** shows detailed pictures of the organs and tissues inside your body.
  A **PET scan** can find abnormal activity and it can be more sensitive than other imaging tests. It may also show changes to your body sooner. Doctors use **PET-CT scans** to provide more information about the cancer.

- uses computer-processed combinations of many X-ray measurements taken from different angles to produce cross-sectional images of specific areas of a scanned object, allowing the user to see inside the object without cutting.

Applications of Radioactivity

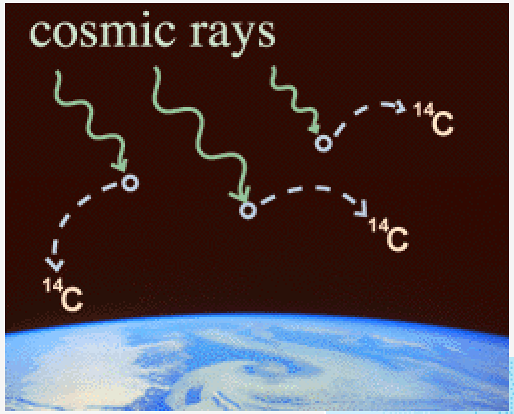
Radiation therapy (also called **radiotherapy**) is a **cancer treatment** that uses high doses of **radiation** to kill **cancer** cells and shrink tumors. Rapidly dividing cells are more susceptible to radiation than mature cells.

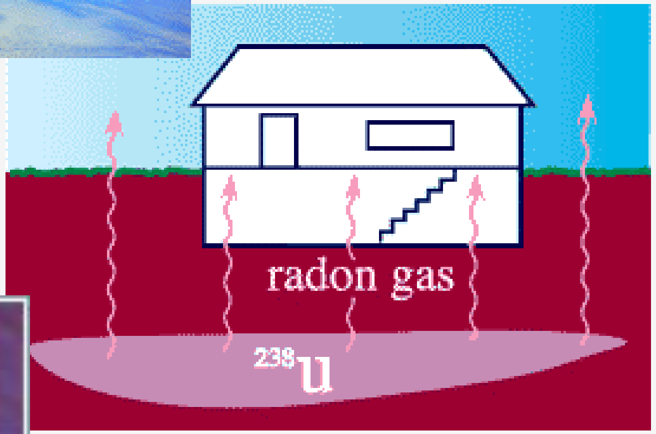
- Cancerous cells divide and grow more rapidly than normal cells.
  - hair follicles, bone marrow… also affected.
- Malignant cells are more likely to be killed than normal cells.

Chemotherapy is a drug treatment that uses powerful chemicals to kill fast-growing cells in your body.

Daily Exposure to Radiation

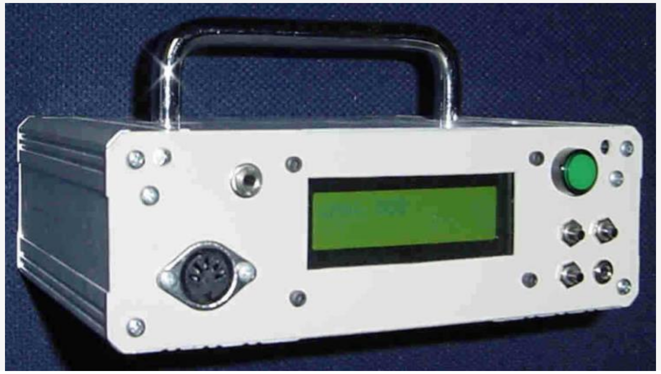
- Cosmic rays
- Radon gas
- Smoke detectors





Detecting Radiation

- Geiger Counters
  - (beta)
- Scintillation Counters
  - (alpha, beta and gamma)
- Film
  - (beta, gamma)



Energy in Radioactive Decay

Radioactive Decay generally gives off large amounts of energy.

Where does it come from?

The answer lies in something called “**mass defect**.”

Mass Defect

Law of Conservation of Mass

- **Mass cannot be created or destroyed.**

Law of Conservation of Energy

- **Energy cannot be created or destroyed.**

But, during nuclear reactions:

- **Mass can be converted into energy and energy can be converted into mass.**

Mass Defect

During nuclear reaction, some mass is either lost or gained. This change in mass is called the **mass defect (Δm).**

Δm = mass of products - mass of reactants

The relationship between the mass defect and the amount of energy given off or absorbed (ΔE) is

$$\Delta E = \Delta mc^2$$

where c = the speed of light = 3.0×10^8 m/s.

Subatomic Particles

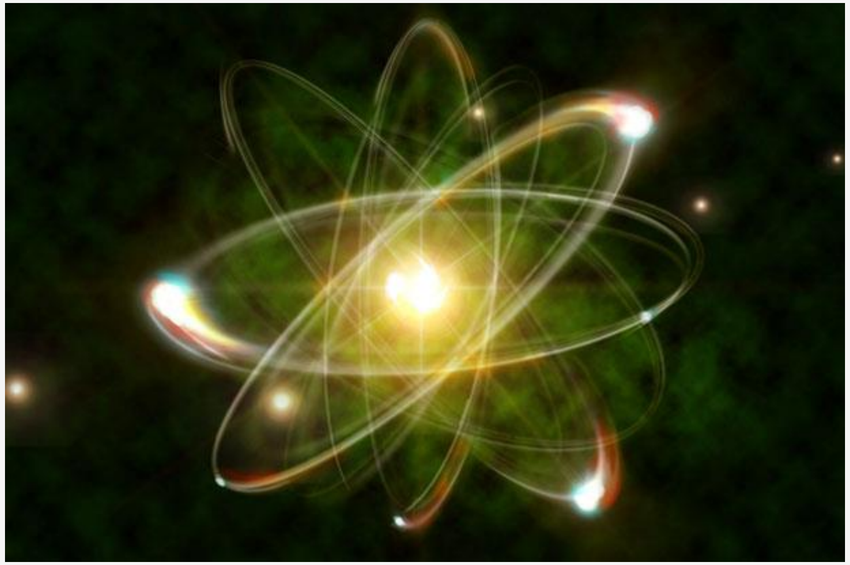
Particle	mass in kg	mass in u
electron	9.11×10^{-31} kg	5.485×10^{-4} u
proton	1.673×10^{-27} kg	1.0073 u
neutron	1.675×10^{-27} kg	1.0087 u

Mass Defect

- Carbon-12 has a mass of 12.000 u
- Its nucleus contains 12 nucleons (6 p & 6n)

- Each nucleon has a mass >1 u

- The mass of a nucleus is slightly less than the mass of the individual nucleons
- The missing mass is called the mass defect



- mass defect: Δm = mass nucleons - mass nucleus

Binding Energy

A measure of the force holding a nucleus together.

$$E_b = \Delta E_{\text{nucleus formation}}$$

Equals the energy needed to *separate* the component nucleons ($p^+ + n^0$) of an atom.

Component parts of a nucleus

Einstein (special relativity): $E = mc^2$

$$E_b = \Delta E = (\Delta m)c^2$$

with: Δm = (mass of $p^+ + n^0$) – (mass nucleus)

c = speed of light = $3.00 \times 10^8\ \text{ms}^{-1}$

Binding Energy

Determine the binding energy and binding energy per nucleon for ^{12}C. The mass of ^{12}C =12.00000 g/mol, m_n=1.00867 g/mol, and m_p=1.00783 g/mol.

$6\ n^0$:	6 x 1.00867	=	6.05202
$6\ p^+$:	6 x 1.00783	=	6.04698
Total mass nucleons		=	12.09900 g/mol

$$\Delta m = \text{sum of nucleons} - \text{mass of nucleus}$$
$$= 12.09900 - 12.00000 \text{ g/mol}$$
$$= 0.09900 \text{ g/mol}$$

Nuclear Binding Energy

Determine the binding energy and binding energy per nucleon for ^{12}C.

Δm = 0.09900 g/mol = 9.900×10^{-5} kg/mol

$\Delta E = 9.900 \times 10^{-5}\ \text{kg/mol}\ (3.00 \times 10^{8}\ \text{m/s})^2$

$\Delta E = 8.91 \times 10^{12}\ \text{kg m}^2\text{s}^{-2}\ \text{mol}^{-1}$

$E_b = 8.91 \times 10^{12}\ \text{J mol}^{-1}$ $(1\text{J} = 1\text{kg m}^2\ \text{s}^{-2})$

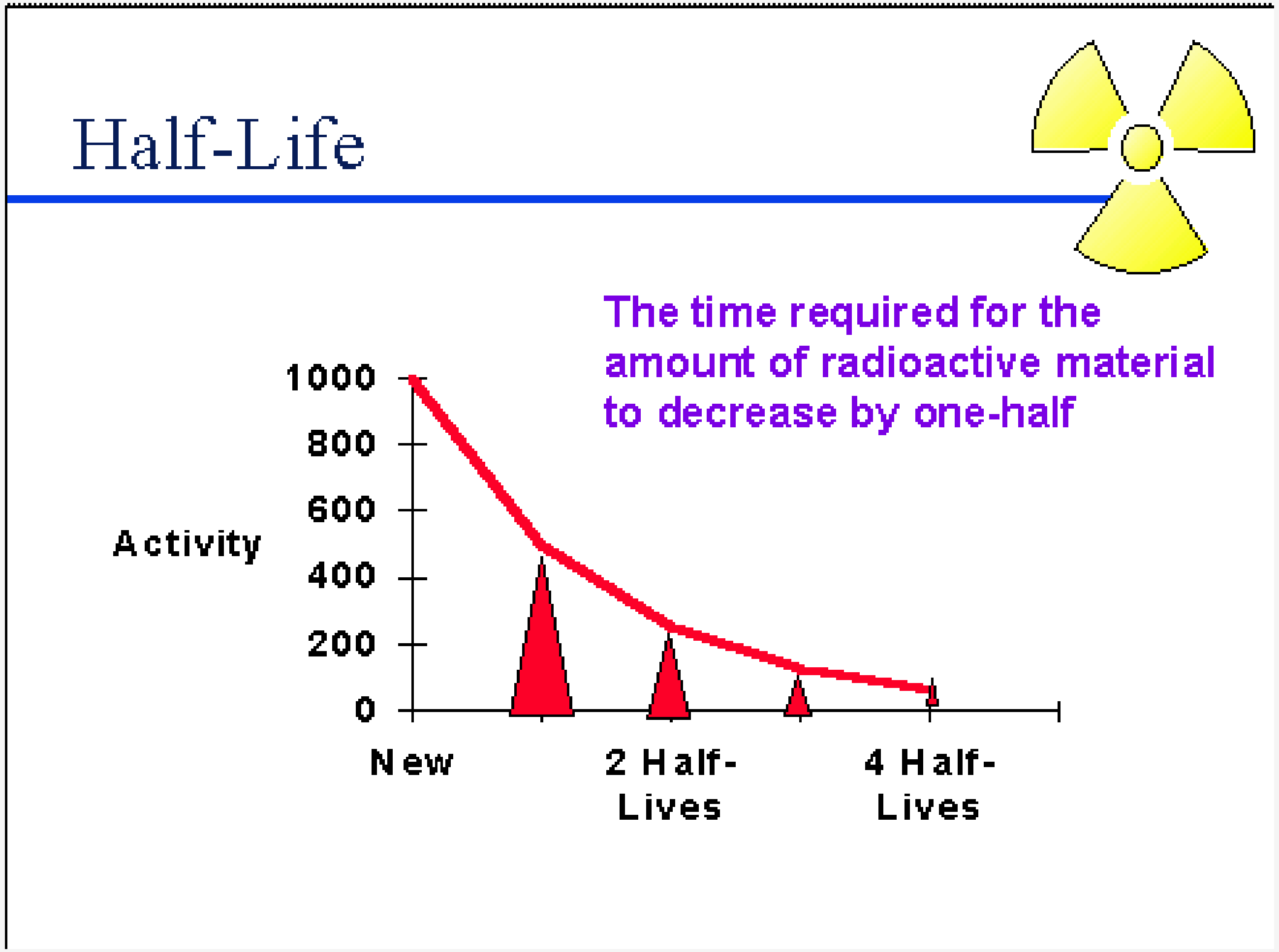
$\boxed{= 8.91 \times 10^{9}\ \text{kJ mol}^{-1}}$

Since ^{12}C has 12 nucleons:

$$E_b/\text{nucleon} = \frac{8.91 \times 10^{9}\ \text{kJ mol}^{-1}}{12} = \boxed{7.43 \times 10^{9}\ \text{kJ mol}^{-1}}$$

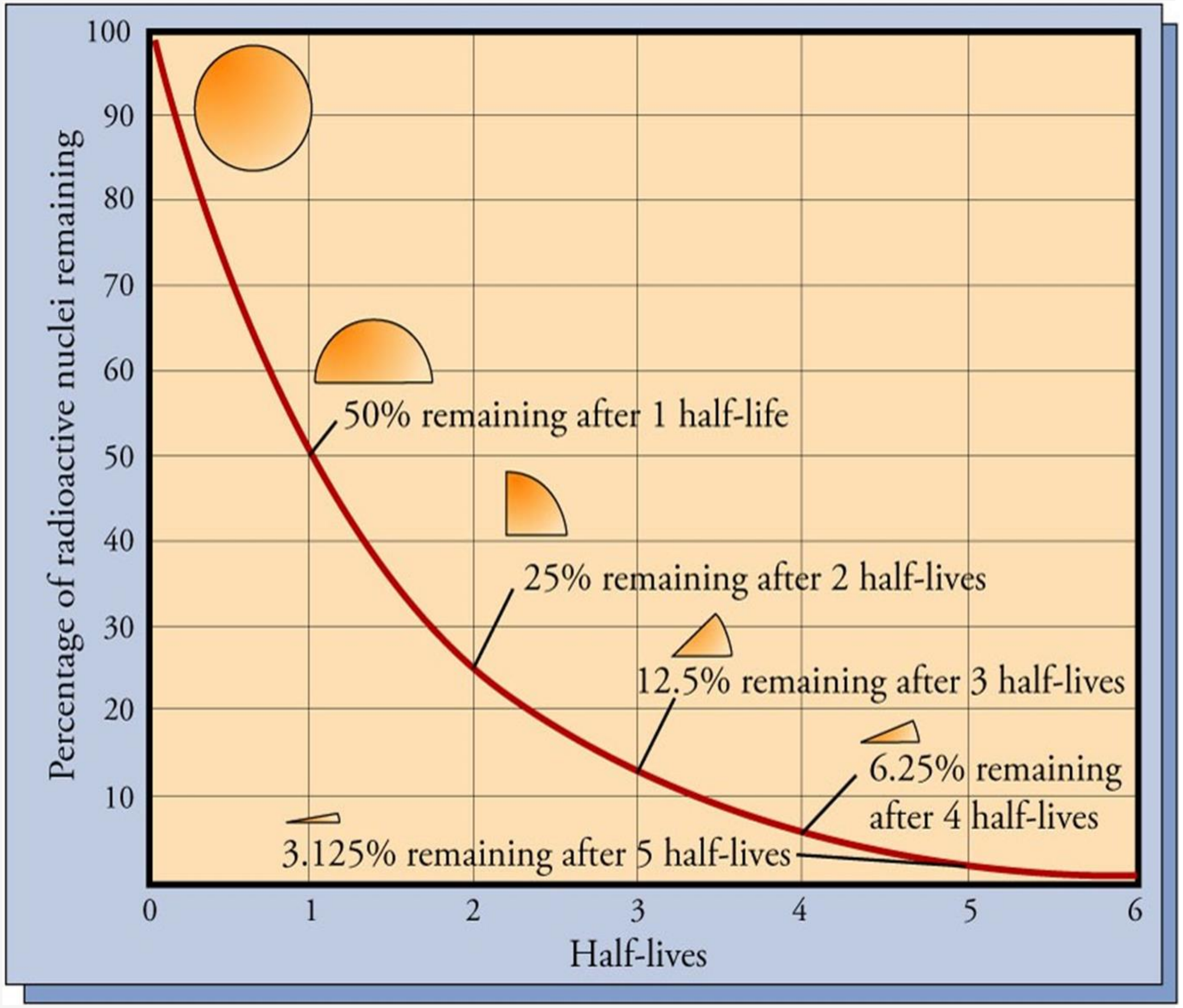
Half-Life

- amount of time it takes for half of a given sample to decay.
- Each half-life, half of the sample decays and half remains.
- Half lives vary from billionths of a second to billions of years.



Half-Life

- The level of radioactivity of an isotope is inversely proportional to its half-life.
- The shorter the half-life, more unstable the nucleus
- The half-life of a radionuclide is constant
- Rate of disintegration is independent of temperature or the number of radioactive nuclei present



Half-Life of some Isotopes

Isotope decay	Half-life
$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$	4.46×10^9 y
$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$	5730 y
$^{3}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{-1}e$	12.3 y
$^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e$	8.04 d
$^{123}_{53}I + ^{0}_{-1}e \rightarrow ^{123}_{52}Te$	13.2 h
$^{57}_{24}Cr \rightarrow ^{57}_{25}Mn + ^{0}_{-1}e$	21 s
$^{28}_{15}P \rightarrow ^{28}_{14}Si + ^{0}_{+1}e$	0.270 s
$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + \gamma$	6.0 h

"m" = "metastable" Decays to more stable version of the same isotope

Rates of Disintegration Reactions

Radioactive decay is 1st –order:

$$\ln\,[X]_t = -kt + \ln\,[X]_0$$

$[X]_0$ = initial concentration of isotope X

$[X]_t$ = concentration of X after time t

k = rate constant.

Half life: $t_{½} = \dfrac{\ln 2}{k} = \dfrac{0.693}{k}$

Half-Life

Americium-243 has a half-life of 7370 y. For a sample containing 10.0 µg of this isotope, calculate the mass (µg) of the isotope that remains after 22,110 years.

$$^{243}_{95}\text{Am} \longrightarrow \,^{239}_{93}\text{Np} + \,^{4}_{2}\text{He}$$

Find the number of half lives in 22,110 y:

$$\frac{22{,}110\text{ y}}{7{,}730\text{ y}} = 3.00$$

So sample reduces by ½ three times:

$$10.0\ \mu\text{g} \times \tfrac{1}{2} \times \tfrac{1}{2} \times \tfrac{1}{2} = 10.0\ \mu\text{g} \times \tfrac{1}{8} = \boxed{1.25\ \mu\text{g}}$$

Alternative solution:

Given: half-life, solve for k using

$$t_{½} = \frac{\ln 2}{k} = \frac{0.693}{k}$$

k= 0.692/7370 yrs

k = 9.40 x10^{-5} =

Given: t= 22,110 years, solve for $[X]t$ using

$$\ln [X]_t = -kt + \ln [X]_0$$

$$\ln [X]_t = -(9.40\text{-} \times 10^{-5} \times 22{,}110) + \ln 10.0$$

$$\ln [X]_t = -2.07834 + 2.3026$$

$$[X]_t = \boxed{1.25\ \mu g}$$

Rate of Radioactive Decay

The activity (*A*) of a sample of *N* atoms:

A = (disintegrations/time) observed.

A = *(constant)* N

constant = k if all decays are detected…

At t = 0 the activity $A_0 = (\text{constant})\ N_0$

At a later time, t $A = (\text{constant})\ N$

Then: $\dfrac{A}{A_0} = \dfrac{X}{X_0}$ = fraction of atoms remaining

Rate of Radioactive Decay

This is 1st order. The number atoms, *N*, will follow: (same as the previous formula but using other symbols such as A for activity or N for number of atoms)

$$\ln N_t = -kt + \ln N_0$$

or $\ln \frac{A}{A_0} = -kt$ or $\ln \frac{N}{N_0} = -kt$

As usual $t_{½} = \frac{\ln 2}{k} = \frac{0.693}{k}$

Half-Life

^{192}Ir decays with a rate constant of $9.3 \times 10^{-3}\ d^{-1}$

(a) What is $t_{1/2}$ for ^{192}Ir ? (b) What fraction of a ^{192}Ir sample would remain after 100 days?

(a) $t_{1/2} = (\ln 2)/\ k = (0.693)/(9.3 \times 10^{-3}\ d^{-1}) = 74.5\ d$

(b) $$\ln \frac{N}{N_0} = -kt = -(9.3 \times 10^{-3}\ d^{-1})(100\ d) = -0.930$$

$$\frac{N}{N_0} = e^{-0.930} = 0.394$$

$\boxed{39\%}$ of the original sample remains.

Carbon-14 Dating

High-energy cosmic rays eject n^0 from atoms in the upper atmosphere. ^{14}C is produced by collision:

$$ {}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{14}_{6}C + {}^{1}_{1}H $$

World-wide production of $^{14}C \approx 7.5$ kg/year. It is:

- Evenly distributed
- Converted into $^{14}CO_2$, then sugars (photosynthesis).

Mammals eat the plants…

Activity (living organisms) = 15.3 $min^{-1}\,g^{-1}$ of carbon.

Carbon-14 Dating

- After death the uptake stops. Stored ^{14}C decays.

$$t_{½}\ (^{14}C) = 5.73 \times 10^{3}\ y$$

- Used to measure up to ≈ 9 half-lives (≈ 50,000 years)

$A_0 = 15.3\ min^{-1}\ g^{-1}$ carbon

$A_{50,000y} = 0.030\ min^{-1}\ g^{-1}$ carbon

$\approx 2\ h^{-1}\ g^{-1}$ carbon

- Longer times are difficult to measure reliably.

Prehistoric cave painting

Carbon-14 Dating

Ancient charcoal was converted into 4.58 g of $CaCO_3$ with *total A* = 3.2 min^{-1}. Find the age of the charcoal.

For carbon-14: $t_{½}$ = 5730 y and A_0 = 15.3 min^{-1} g^{-1} carbon

$$g_{carbon} = 4.58\ g\ \frac{M_C}{M_{CaCO_3}} = 4.58\ g\ \frac{12.01\ g}{100.1\ g} = 0.550\ g$$

$$A = \frac{3.2\ min^{-1}}{0.550\ g} = 5.82\ min^{-1} g^{-1}_{carbon}$$

$$\ln\frac{A}{A_0} = -kt = -\frac{\ln 2}{t_{½}}\,t \qquad \text{or} \qquad t = \frac{-t_{½}}{\ln 2}\ln\frac{A}{A_0}$$

$$t = -8267 \ln\frac{5.82}{15.3} = \boxed{8.0 \times 10^3\ y}$$

Artificial Transmutations

Nuclear reactions can occur if a particle collides with a nucleus.

Rutherford produced the first transmutation:

$$^{4}_{2}\text{He} + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$$

An alpha particle converts one element (N)…

…into another element (O)

α particles are not ideal. Positive particles are hard to insert into a positive nucleus.

Artificial Transmutations

Neutrons work better:

- No repulsion
- Many elements are synthesized in this way.

$$ {}^{239}_{94}\mathrm{Pu} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{240}_{94}\mathrm{Pu} $$

$$ {}^{240}_{94}\mathrm{Pu} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{241}_{94}\mathrm{Pu} $$

$$ {}^{241}_{94}\mathrm{Pu} \longrightarrow {}^{241}_{95}\mathrm{Am} + \mathrm{e}^{0}_{-1} $$

Artificial Transmutations

- Technicium (Tc) and Promethium (Pm) are the only elements with $Z \leq 92$ which do not occur in nature.
- All transuranium elements ($Z > 92$) are synthetic.
- $Z \leq 101$ (Mendelevium; Md) elements are made by small particle bombardment (α, n) of light nuclei.
- $Z > 101$ are made by heavy-particle collision:

$$^{64}_{28}\mathrm{Ni} + ^{209}_{83}\mathrm{Bi} \longrightarrow ^{272}_{111}\mathrm{Rg} + ^{1}_{0}\mathrm{n}$$

Nickel nuclei fired at a bismuth-209 target

Roentgenium

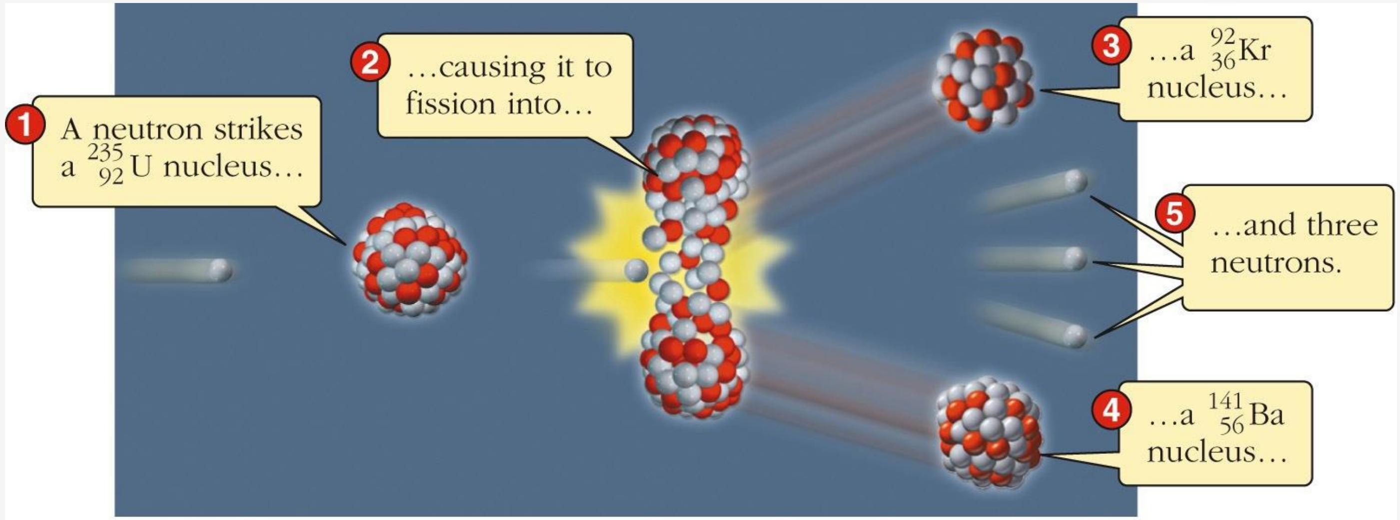
Nuclear Fission

Hahn and Strassman (1938) fired $^{1}_{0}n$ at ^{235}U. Ba was produced!

Nuclear fission had occurred.

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

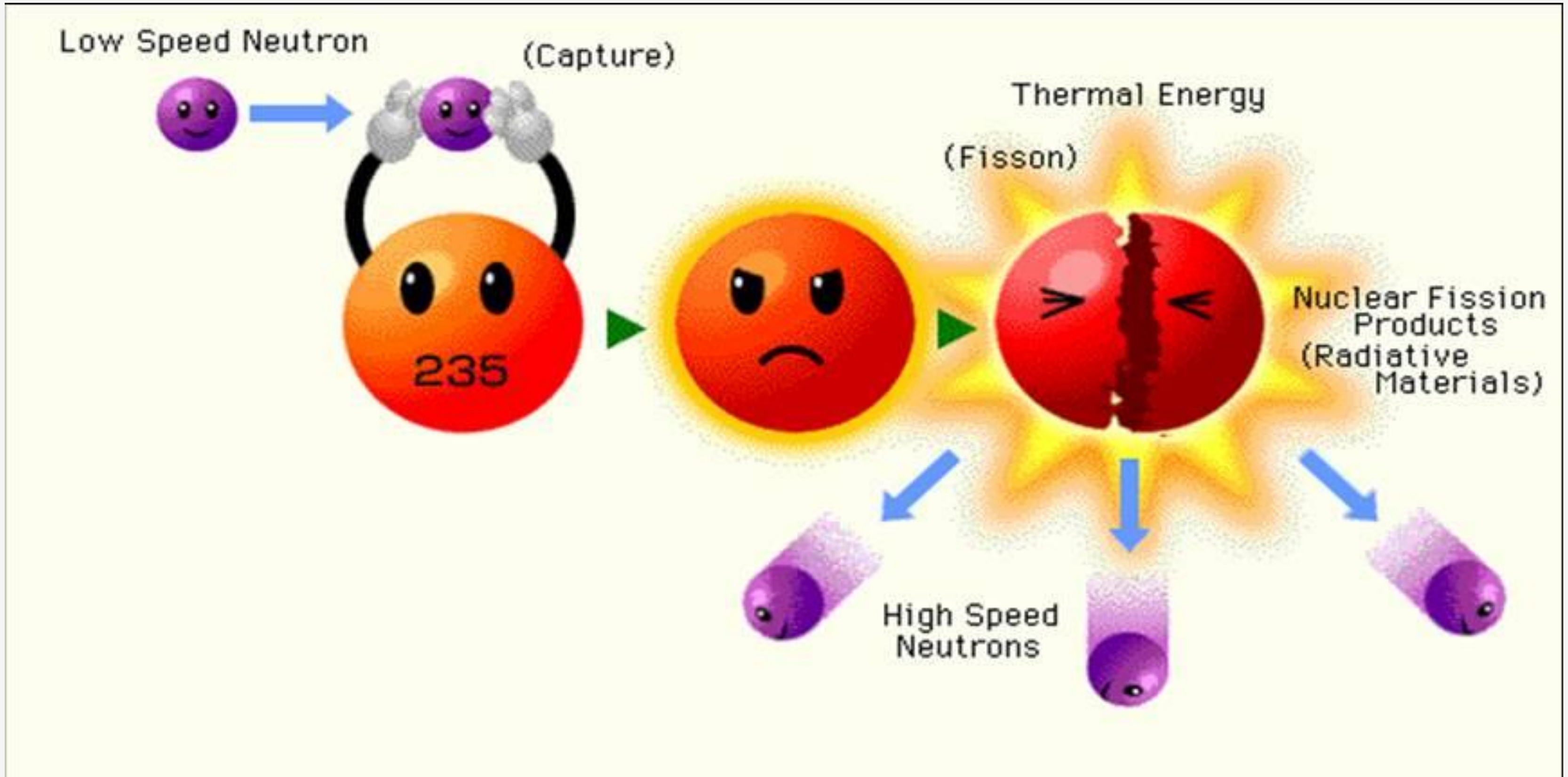
3 neutrons produced



Very exothermic

$\Delta H = -2 \times 10^{-10}$ kJ/mol

Nuclear Fission



Uranium 235 fisses, giving off energy, fission products, and high energy neutrons.

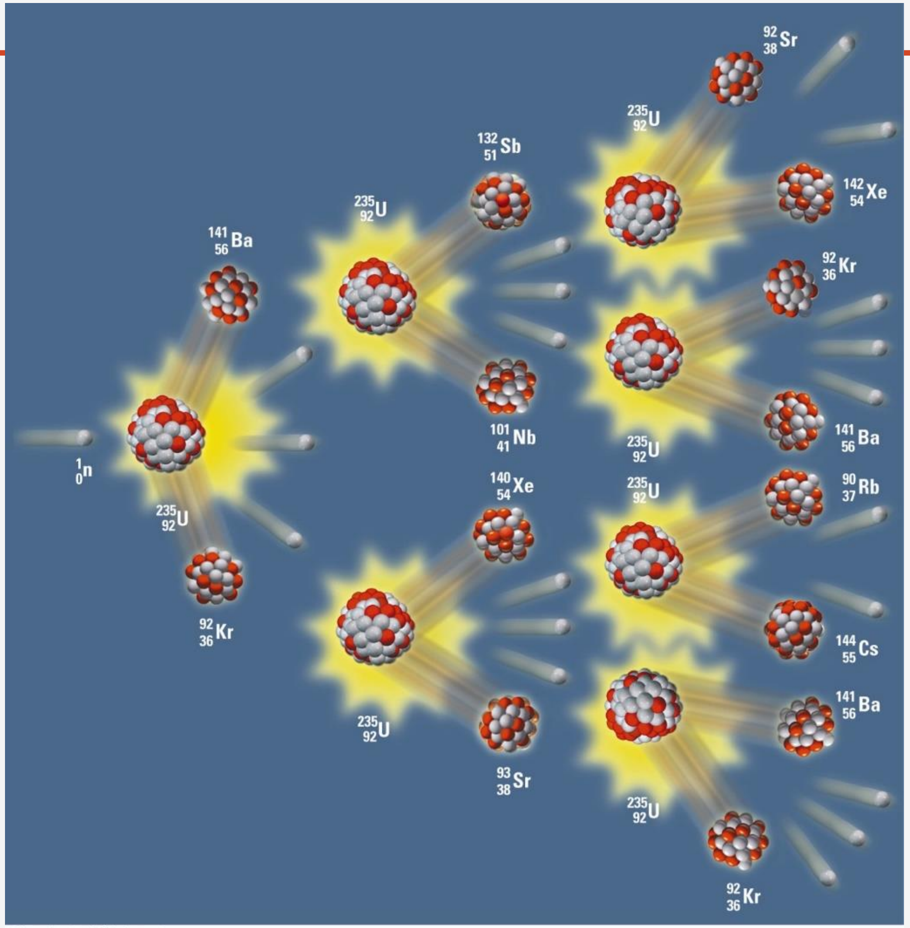
Nuclear Fission

Chain reactions are possible:

Small amounts of ^{235}U can't capture all the neutrons.

(stays under control).

Nuclear bombs exceed the critical mass; the chain reaction grows explosively.



$E_{fission}(^{235}U) = -2 \times 10^{13}$ J/mol.

1 kg of $^{235}U \approx 33$ kilotons of TNT.

Nuclear Reactors

Nuclear Reactors

Thermal energy from fission is used to generate power in a nuclear reactors.

- Control rods ($^{1}_{0}n$ absorbers: Cd, B…) keep it under control.
- UO_2 pellets are the "fuel"
- The chain reaction is started by a neutron source.

$$^{238}_{94}Pu \longrightarrow ^{234}_{92}U + ^{4}_{2}He$$

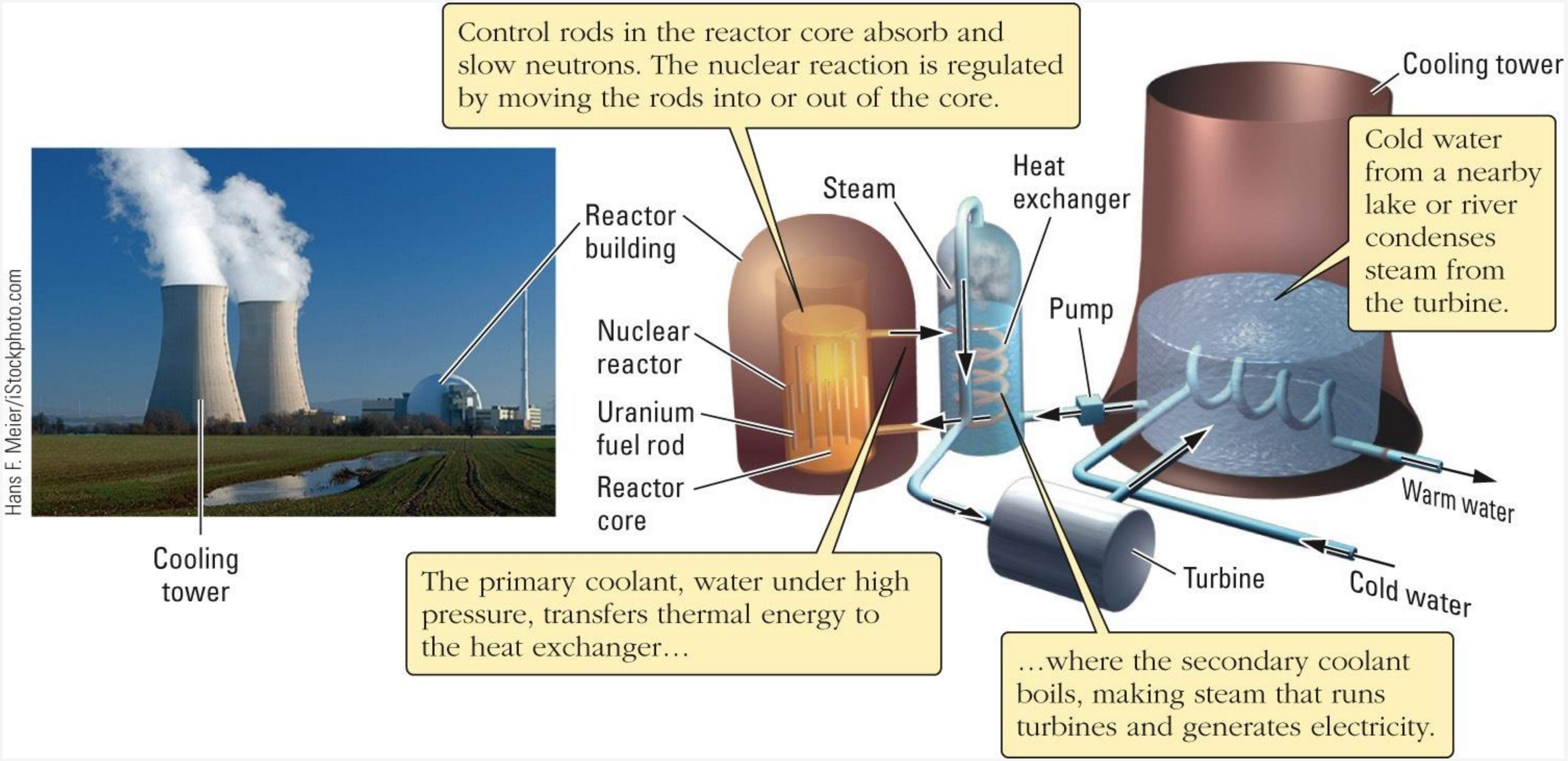
$$^{4}_{2}He + ^{9}_{4}Be \longrightarrow ^{12}_{6}C + n^{1}_{0}$$

Natural U is 99.3% ^{238}U (not fissile).

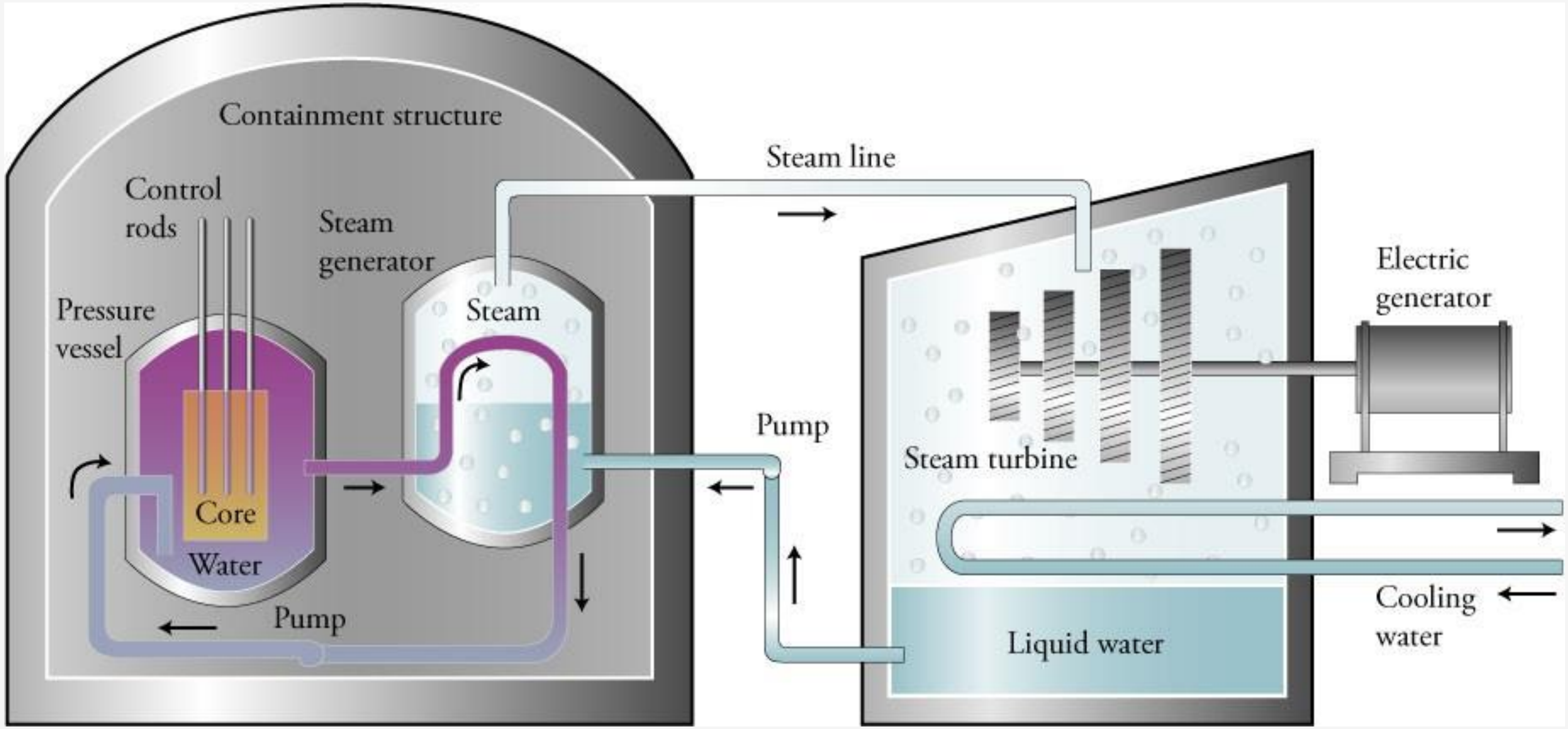
- Reactor fuel rods are enriched to 3% ^{235}U.
- Weapons-grade is > 90% ^{235}U.

UO_2 pellets

Nuclear Reactors
https://youtu.be/apODDbgFFPI



Nuclear Reactor



Nuclear Reactor Pros & Cons

Nuclear power-plants produce "clean" energy.

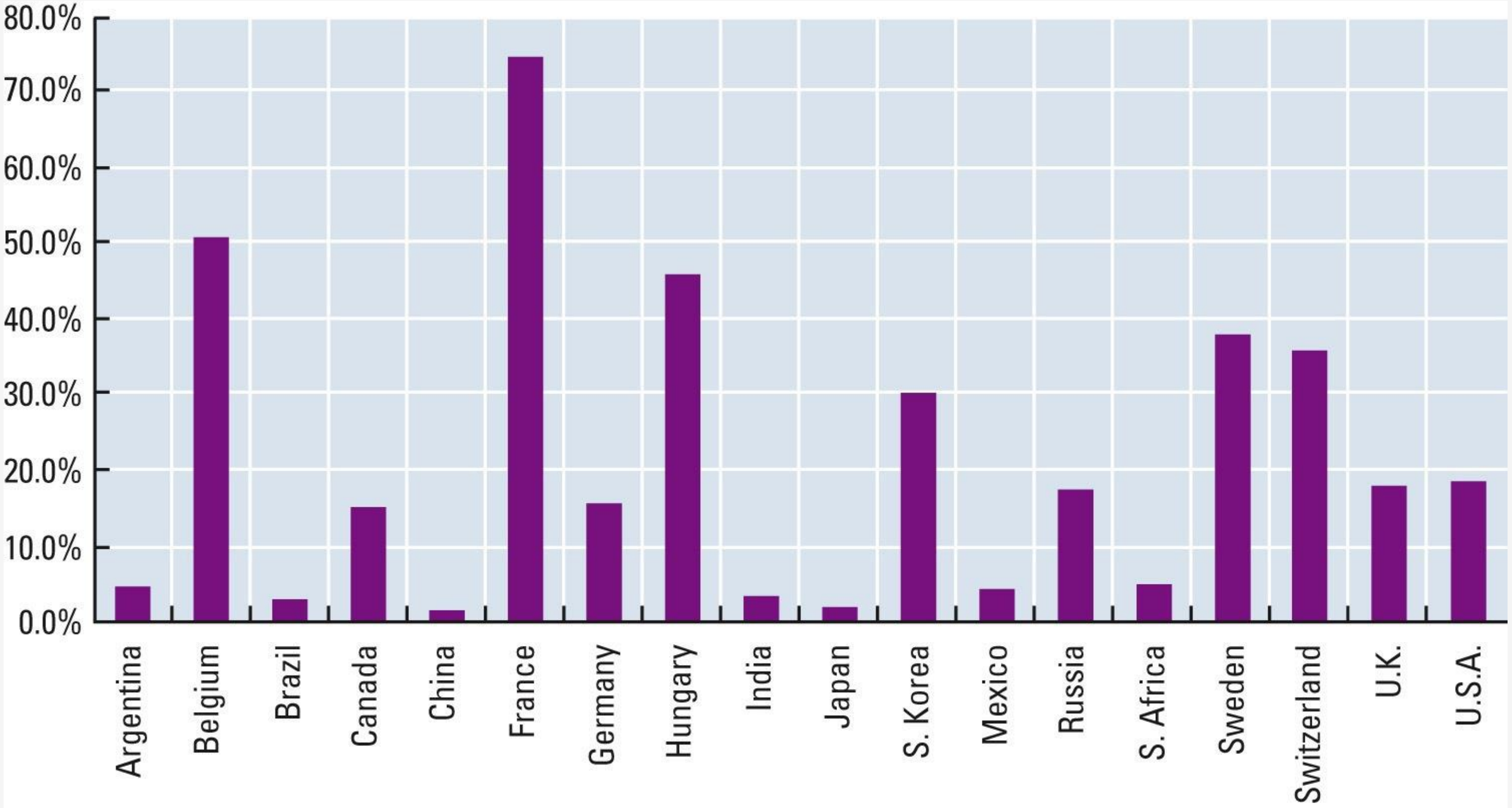
- No atmospheric pollution. No CO_2.

But… yield highly radioactive waste.

- Tens of thousands of tons in storage.
- Long half-lives (^{239}Pu, $t_{1/2}$ = 24,400 yr).
- Can be vitrified (encased in "glass").
- V_{waste} = 2 m^3/reactor/yr.
- No long-term storage site available in the U.S.

104 nuclear plants in the U.S. None built since 1979 (Three Mile Island).

Nuclear Reactors



The fraction of electricity generated by nuclear power in selected countries.

(http://www.world-nuclear.org/info/Facts-and-Figures/Nuclear-generation-by-country)

Nuclear Fusion

Light nuclei can be combined:

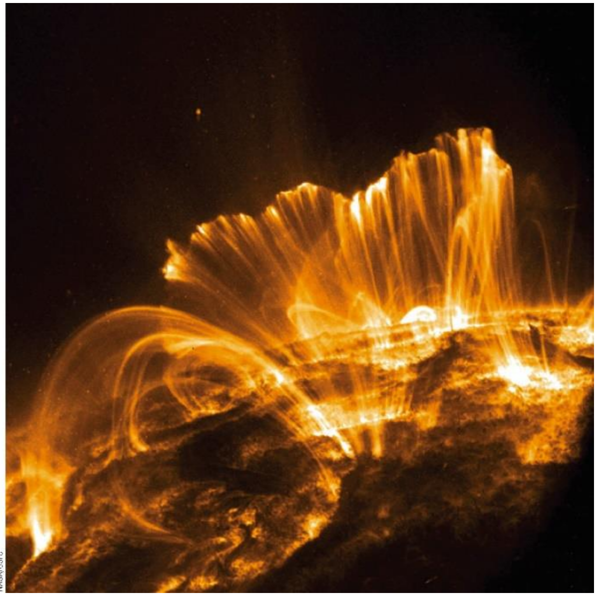
$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{+1}e$$

Nuclear fusion

- Very exothermic (ΔE = -2.5 x 10^9 kJ/mol).
- The energy source for stars.

An attractive power source:

- Hydrogen (the fuel) can be extracted from oceans.
- Waste products are short-lived, low-mass isotopes.



Fusion powers the sun

Nuclear Energy - Fusion

Release even more energy than fission.

emitted by stars (mostly hydrogen fusing to form helium).

no safe way yet to harness fusion

- takes too much energy to get started

Commercial fusion reactors are not very likely to occur in the near future.