PHYS 102- ATOMIC PHYSICS

Lesson Goals:

We've just discussed: Photons, Photo-Electric Effect and Momentum

Now, we will discuss the following:

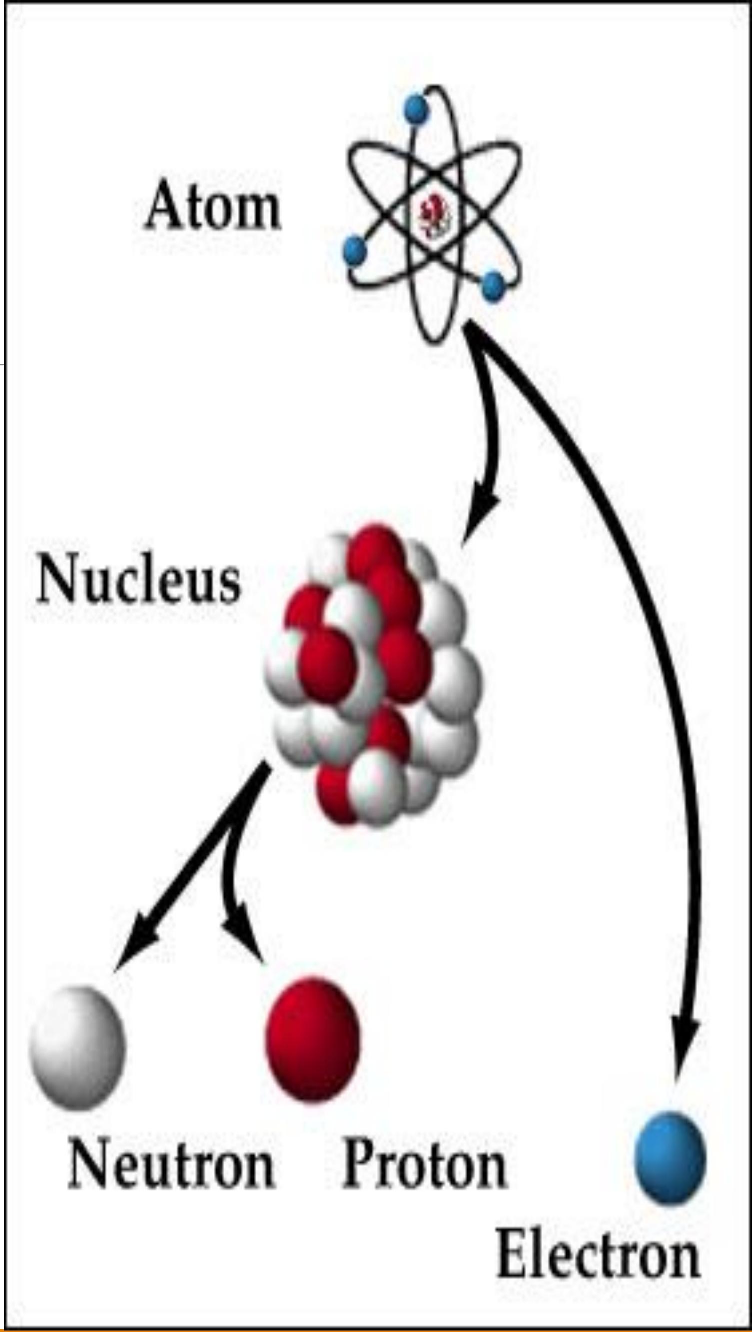
1) Radioactivity

2) The fundamental equation of radioactive decay

3) Half Life and Mean Life

4) Atomic Nucleus

5) Binding Energy



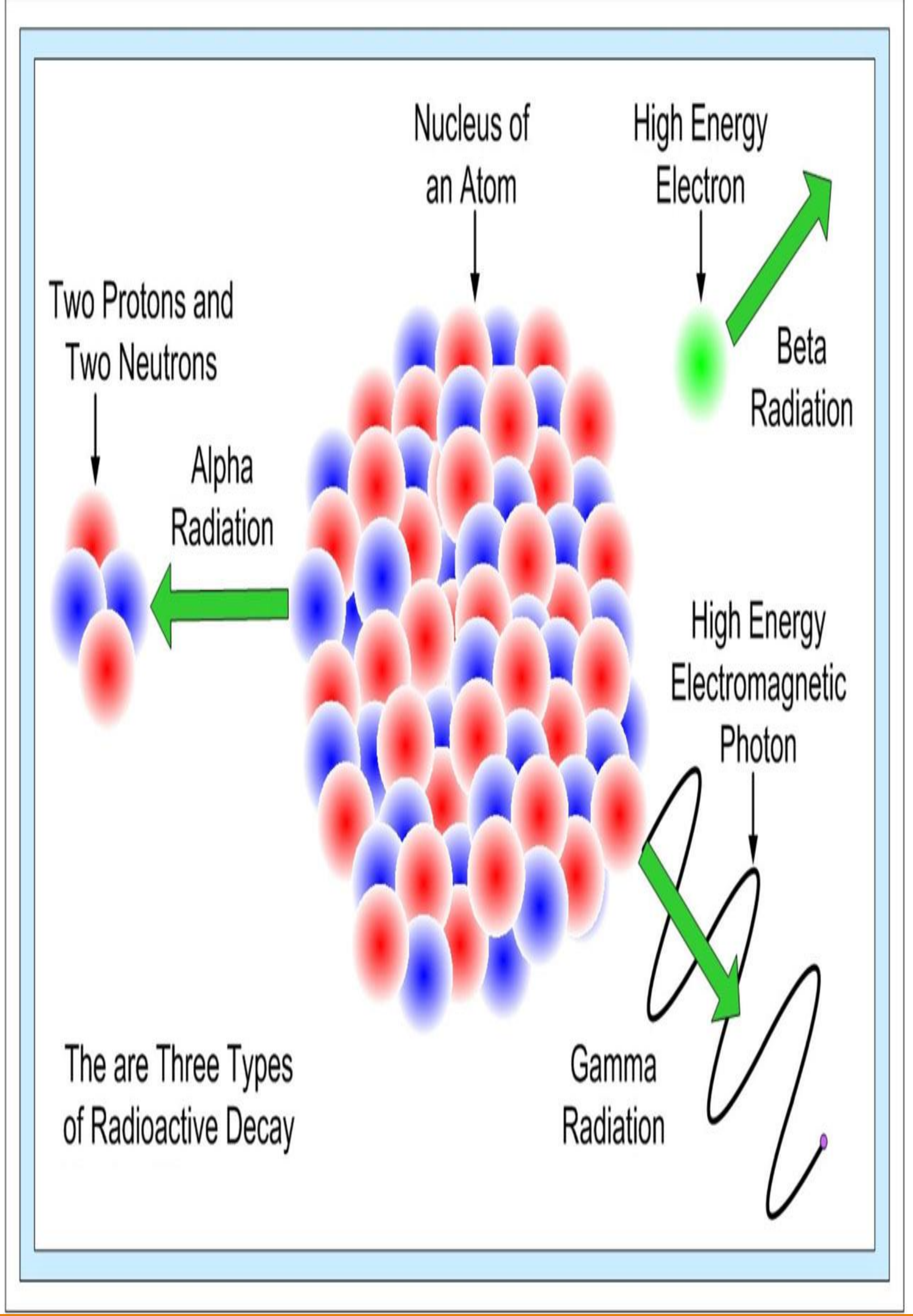
PHYSICS 102- RADIOACTIVITY

About 2500 known nuclides are available and fewer than 300 are stable elements.

Nuclides: atomic species characterized by the specific constituents of its nucleus i.e № of protons Z and № of neutrons N.

The rest (*2200*) are unstable because they decay to form other nuclides by emitting particles and electromagnetic radiation; a phenomenon called radioactivity.

Radioactivity: It is the spontaneous disintegration or breakdown of the nuclei of the atom of a natural occurring substance with emission of particles or radiation.



PHYSICS 102- RADIOACTIVITY

The radioactive atoms that emits the radiation are called **radioactive samples**.

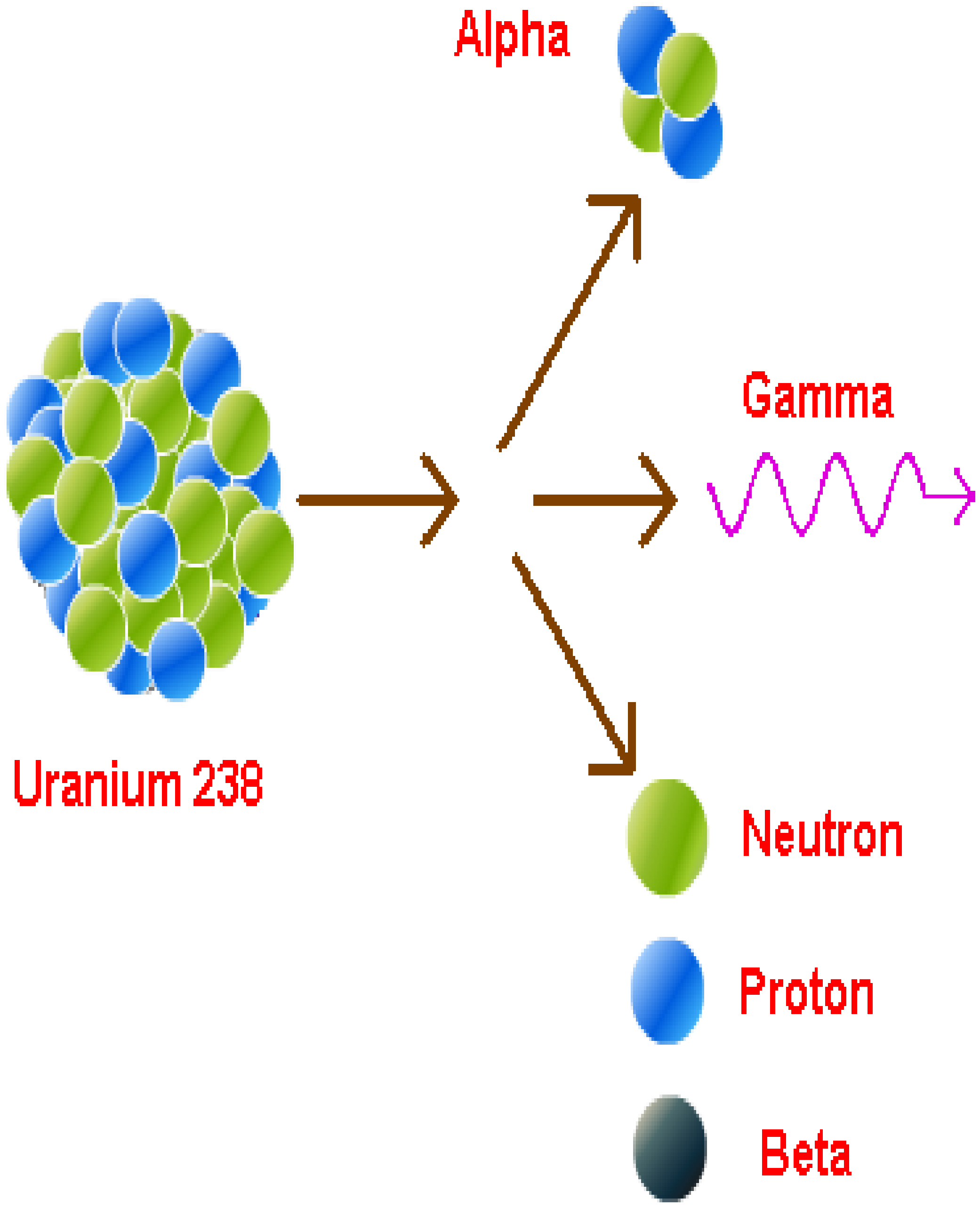
Examples of radioactive samples: Technetium, Radium, Uranium, Thorium, Cobalt e.t.c

The radiation that result from the nuclear disintegration are divided into three parts:

a) Alpha (α) particle

b) Beta (β) particle

c) Gamma (ɣ) ray

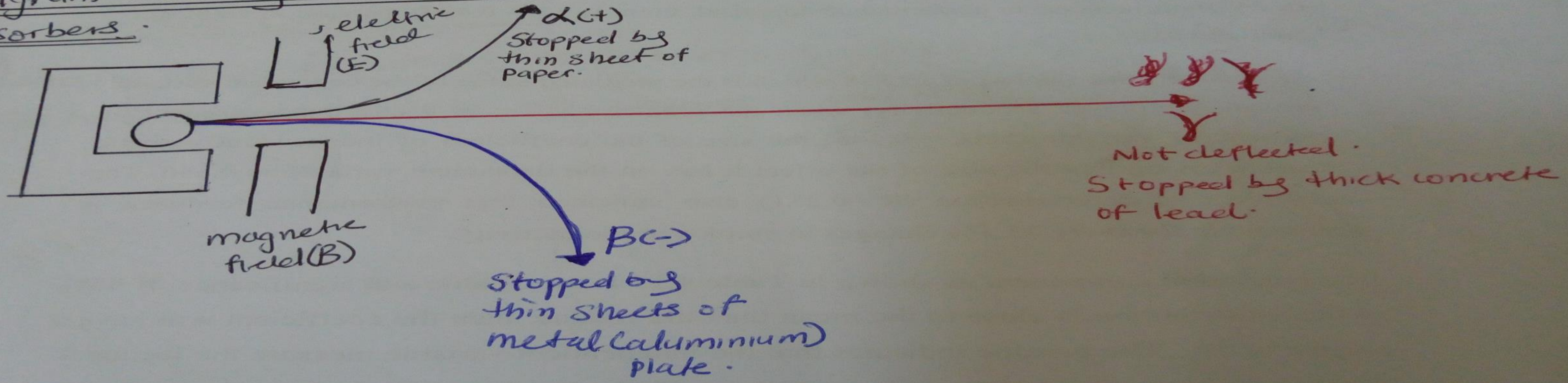


PHYSICS 102- RADIOACTIVITY

PHYSICS 102- RADIOACTIVITY

1) Alpha (α) particle.
2) Beta (β) particle.
3) Gamma (γ) ray.

Diagram showing radioactive samples with particle emission and their absorbers.



Quiz

Question 1: What symbol is this?

Ans: Radiation Symbol/ Radioactive sample

Question 2: The man is standing infront of…

Ans: Lead (Pb) Door

Question 3: The Pb door can stop which type of radiation…

Ans: Gamma Ray/X-ray or Photon Beams

PHYSICS 102-RADIOACTIVITY

1) **Alpha Particle**: radiation consists of a stream of positively-charged (α-particles). Each α-particle is a helium nucleus containing two protons and two neutrons. It is easily stopped by air or thin sheet of paper and it is deflected by electric and magnetic field.

Alpha (α) → ${}_{2}^{4}He$

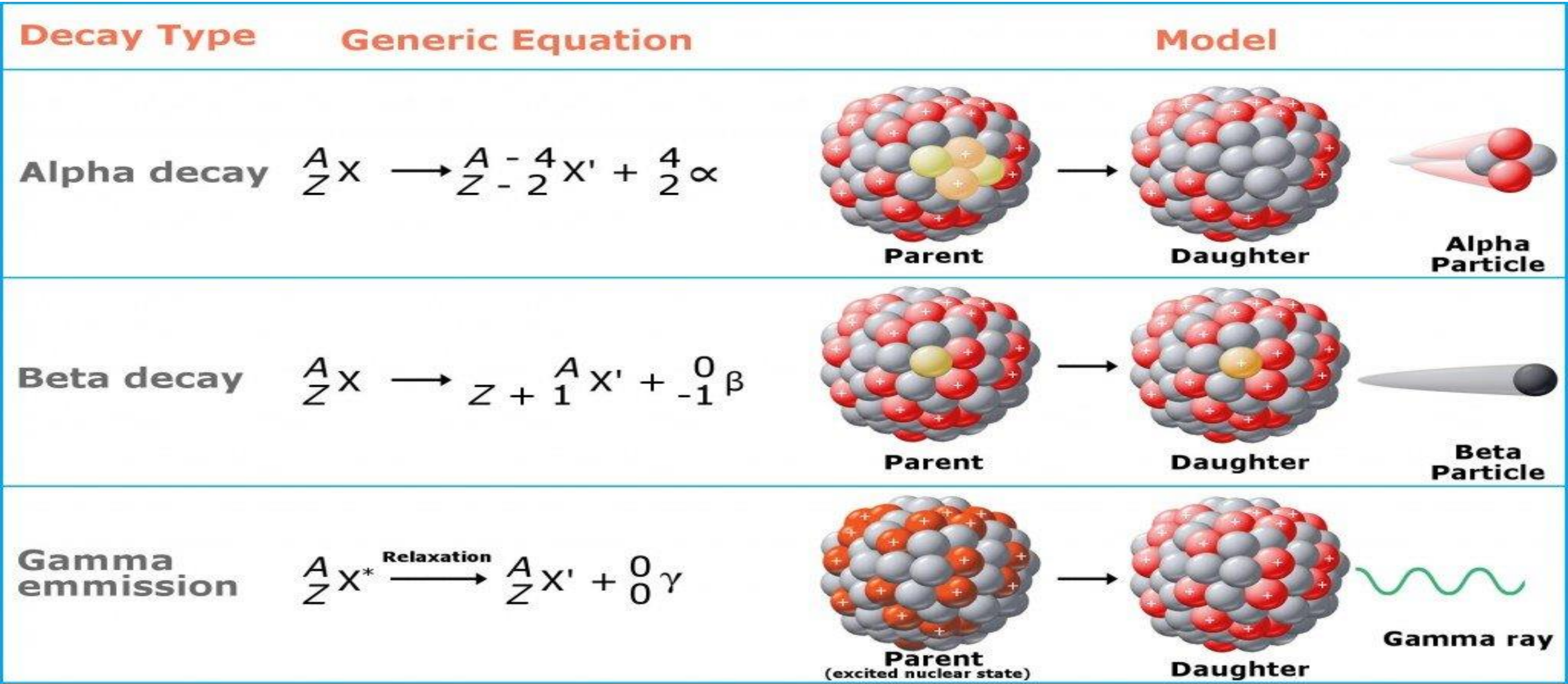
2) **Beta Particle**: radiation consists of fast moving electrons that are negatively charged (β-particles). They are easily deflected by electric and magnetic fields. They have a higher than α-particles and are absorbed by thin sheets of metal or aluminum plate.

Beta (β)→ ${}_{-1}^{0}e$

3) **Gamma Radiation**: radiation is a short wavelength electromagnetic wave ($\lambda = 10^{-14} m$). It is highly penetrating and un-deflected by both magnetic or electric fields and can be absorbed by a block of concrete lead.

Gamma (ɣ)→ ${}_{0}^{0}\gamma$

Radioactive Decay: Radioactive decay is the process by which the nucleus of a heavy radioactive nuclide disintegrates and emits α, β along with ɣ-ray



Decay Type	Generic Equation	Model
Alpha decay	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$	Parent → Daughter, Alpha Particle
Beta decay	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$	Parent → Daughter, Beta Particle
Gamma emmission	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	Parent (excited nuclear state) → Daughter, Gamma ray

The Fundamental Equation of Radioactive decay:

$N(t) \rightarrow$ large number of radioactive nuclei in a sample at time t.

$dN(t) \rightarrow$ change in the number of the radioactive nuclei during a short time interval (dt).

Hence the equation is expressed as:

$$\boldsymbol{N^{(t)} = N_0 \, e^{-\lambda t}}$$

$N^{(t)}$ = № of radioactive nuclei at time (t).

N_0 = № of radioactive nuclei at time (t=0).

λ = decay constant.

t = time.

$$\frac{dN}{N} = -\lambda dt$$

$$\int_{N_o}^{N} \frac{dN}{N} = -\int_{0}^{t} \lambda dt$$

$$\ln N \Big|_{N_o}^{N} = -\lambda(t-0)$$

$$\ln\left(\frac{N}{N_o}\right) = -\lambda t$$

$$e^{\ln\left(\frac{N}{N_o}\right)} = e^{-\lambda t}$$

$$\frac{N}{N_o} = e^{-\lambda t}$$

$$N = N_o e^{-\lambda t}$$

Half Life

*Every radioactive nuclide is characterized by the half-life and mean life.

Half-Life: It is the time required for the number of radioactive nuclei to decrease to one-half the original number №.

OR: time required for half of atoms of the radioactive nuclide to disintegrate.

Half-Life: $T_{1/2}$

From the equation of radioactive decay:

$$N^{(t)} = N_0\, e^{-\lambda t}$$

$$N = \frac{N_0}{2} \rightarrow \frac{N_0}{2} = N_0\, e^{-\lambda t}$$

Since $t = T_{1/2}$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

Divide both sides by N_0

$$\frac{1}{2} = e^{-\lambda T_{1/2}} \quad \text{(cross multiply, we have)}\ 1 = 2e^{-\lambda T_{1/2}}$$

Divide both sides by $e^{-\lambda T_{1/2}}$ *(we have)* $\frac{1}{e^{-\lambda T_{1/2}}} = 2$

Take Logarithms of both sides $\lambda T_{1/2} = \ln 2$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

$$T_{1/2} = \frac{0.693}{\lambda}$$

Mean Life

The mean life or mean life-time (T_{mean}) is the inverse of the disintegration (decay) constant.

Recall: $T_{1/2} = \frac{0.693}{\lambda}$

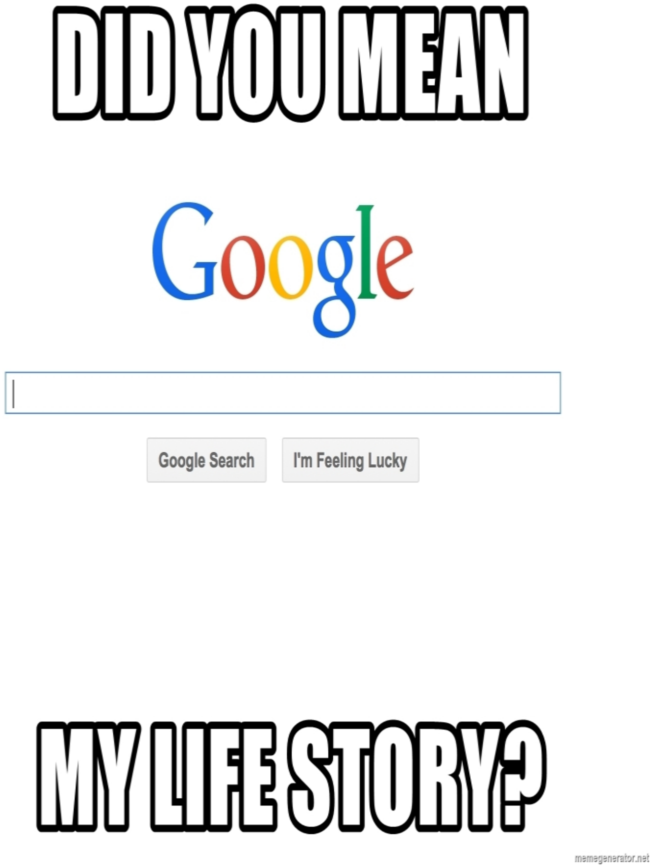
Where λ is the decay constant. *(make λ subject of formula).*

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

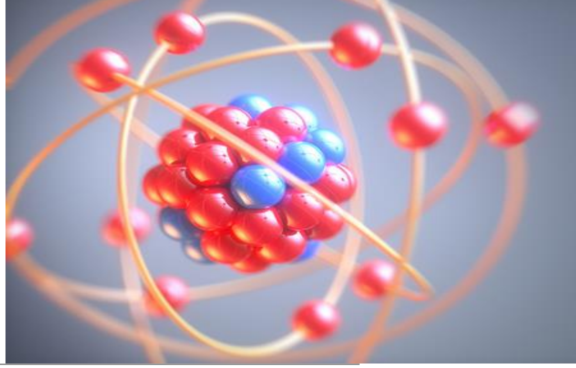
Recall that T_{mean} is the inverse of decay constant λ

$$T_{mean} = \frac{1}{\lambda}$$

$$T_{mean} = \frac{T_{1/2}}{\ln 2}$$



ATOMIC NUCLEUS AND RADIOACTIVITY



The atom is composed of an extremely dense positively charged **nucleus** containing **protons** and **neutrons**.

Also an extra-nuclear cloud of light negatively charged **electrons** orbit the **nucleus**.

In a non-ionized state, the atom is electrically neutral because the number of **protons** equals the number of **electrons**.

Protons are **positively** charged.

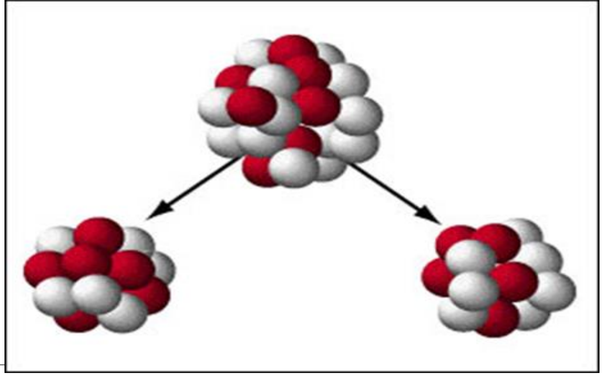
Electrons are **negatively** charged.

Neutrons have **no/neutral** charge.

Protons and neutrons form the nucleus and these particles are called **Nucleons**.

Nucleons = p + n.

ATOMIC NUCLEUS AND RADIOACTIVITY



The mathematical equation for the Nucleons is expressed as: **N = p + n**

The total number of protons is called **Atomic Number** and the atomic number is symbolized as **Z**.

The nuclide of an atom is always represented as $^{A}_{Z}X$.

Let's look at Carbon:

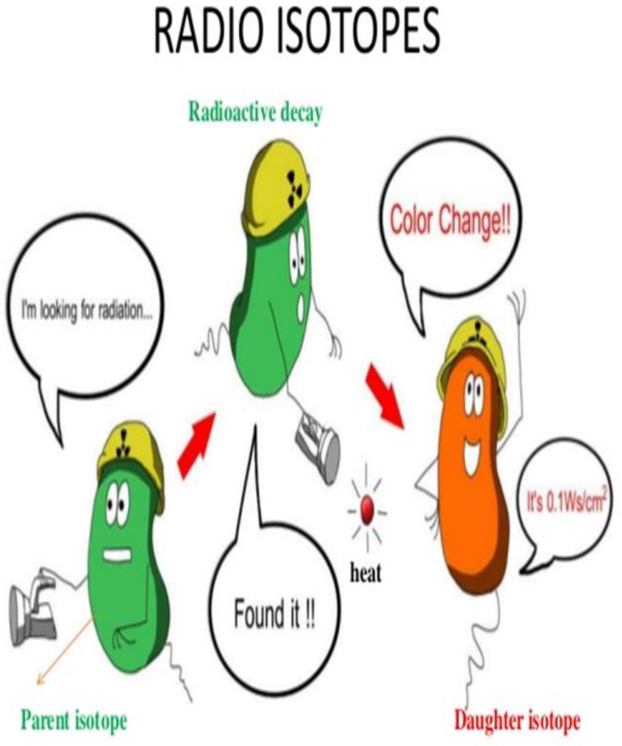
$^{A}_{Z}X$ nuclide for carbon is represented as: $^{14}_{6}C_{8}$

Mass Number

Neutron Number

Atomic Number

ATOMIC NUCLEUS AND RADIOACTIVITY



The atomic number is different from the atomic mass (amu).

Atomic Mass: It is the actual mass of the atom. Different element have their mass.

E.g: Oxygen atomic mass as: 15.9949 amu.

Where 1 atomic mass unit = $1.6606 \times 10^{-27} kg$

Let's look at classification of nuclides: What is a nuclide?

We have four different classifications:

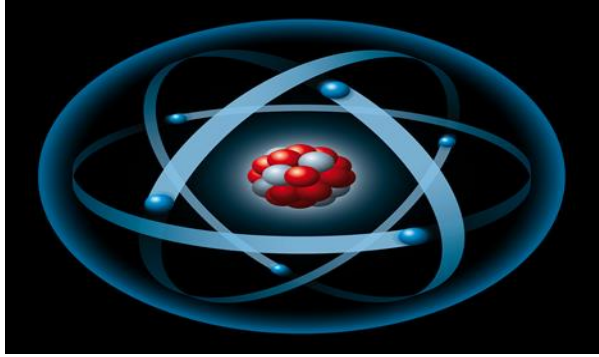
1) Isotopes

2) Isobars

3) Isotones

4) Isomers

ATOMIC NUCLEUS AND RADIOACTIVITY: Classification of Nucleus



1) Isoto**p**es: same number of protons or same atomic number but different mass number.

E.g: ${}^{35}_{17}CL$, ${}^{37}_{17}CL$, ${}^{1}_{1}H$, ${}^{2}_{1}H$, ${}^{3}_{1}H$, ${}^{12}_{6}C$ and ${}^{13}_{6}C$

Tritium

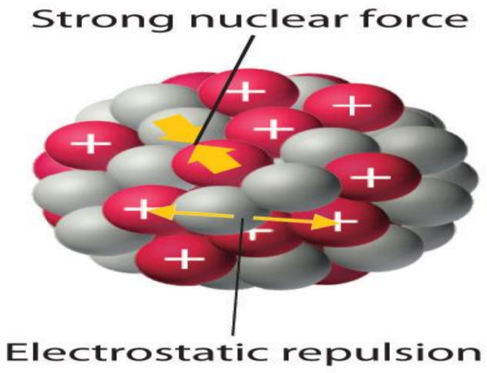
Deuterium

2) Isob**a**rs: atoms with the same atomic mass number.

3) Isoto**n**es: atoms with the same neutron number.

4) Isom**e**rs: atoms with the same nuclear energy states.

ATOMIC NUCLEUS AND RADIOACTIVITY: Properties of the Nuclei



Rutherford found out that the nucleus is tens of thousand times smaller in radius than the atom itself.

He found out that the radius of nucleus is dependent on the total number of nucleons (neutrons & protons) in the nucleus. Remember that the **nucleons** is also known as the mass number (A).

The radius of the atomic nucleus is expressed as:

$$R = R_0 A^{1/3}$$

Where R = radius of the atomic nucleus.

R_0 = experimentally determined constant = $1.2 \times 10^{-15} m \approx 1.2\, fm$

A = mass number // atomic mass number // nucleons

Work Problems

1) The nucleus of a certain iron has a mass number of 56. Find the radius, approximate mass and approximate density of the nucleus.

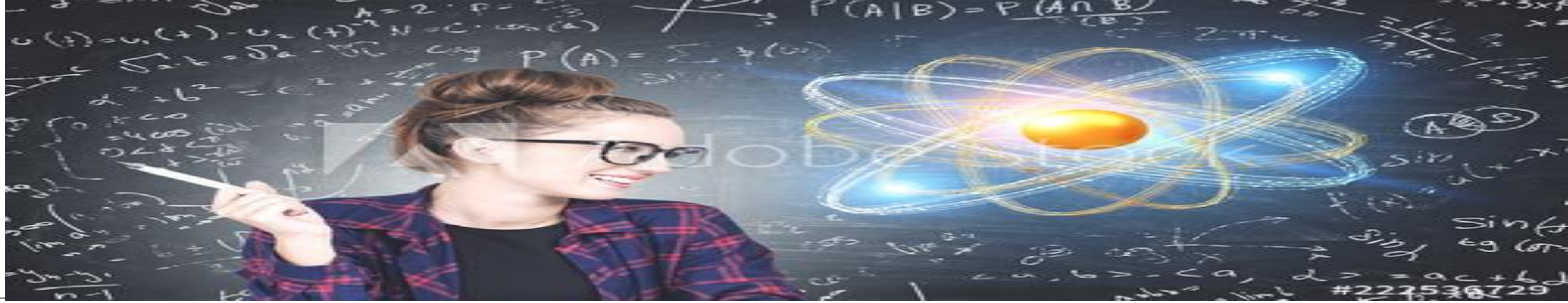
2) The radius of a carbon nucleus is about 3×10^{-15}m and its mass is 12u. a) Find the average density of the nuclear material. b) How many more times than water is this?

Answers:

1) **a) r = $\boldsymbol{4.6 fm}$ b) m = $\boldsymbol{9.3 \times 10^{-26}\,kg}$ c) $\boldsymbol{\rho = 2.3 \times 10^{17} kg/m^3}$**

2) **a) $\boldsymbol{\rho = 1.8 \times 10^{17} kg/m^3}$ b) $\boldsymbol{2 \times 10^{14}}$**

Work Problems



1) Iodine has a half-life of 8.05days. Calculate the decay constant.

2) A radium source has a disintegration constant of $1.36 \times 10^{-11}\, s^{-1}$. Calculate the half-life of radium in seconds and in years.

3) The half-life of tritium is 12.33 years. What is the number of tritium nuclei that will have an activity of $3.70 \times 10^{10}\, s^{-1}$?

ANSWER

1) $9.96 \times 10^{-7}\, s^{-1}$

2) a) $5.09 \times 10^{10}\, s^{-1}$ b) 1620 years

3) $2.07 \times 10^{19} nuclei$

[redacted] Compositions of Some Common Nuclides

Z = atomic number (number of protons)

N = neutron number

$A = Z + N$ = mass number (total number of nucleons)

Nucleus	Z	N	$A = Z + N$
${}^{1}_{1}\mathrm{H}$	1	0	1
${}^{2}_{1}\mathrm{H}$	1	1	2
${}^{4}_{2}\mathrm{He}$	2	2	4
${}^{6}_{3}\mathrm{Li}$	3	3	6
${}^{7}_{3}\mathrm{Li}$	3	4	7
${}^{9}_{4}\mathrm{Be}$	4	5	9
${}^{10}_{5}\mathrm{B}$	5	5	10
${}^{11}_{5}\mathrm{B}$	5	6	11
${}^{12}_{6}\mathrm{C}$	6	6	12
${}^{13}_{6}\mathrm{C}$	6	7	13
${}^{14}_{7}\mathrm{N}$	7	7	14
${}^{16}_{8}\mathrm{O}$	8	8	16
${}^{23}_{11}\mathrm{Na}$	11	12	23
${}^{65}_{29}\mathrm{Cu}$	29	36	65
${}^{200}_{80}\mathrm{Hg}$	80	120	200
${}^{235}_{92}\mathrm{U}$	92	143	235
${}^{238}_{92}\mathrm{U}$	92	146	238

Curled from University Physics with Modern Physics: Young & Freedman

[redacted] Neutral Atomic Masses for Some Light Nuclides

Element and Isotope	Atomic Number, Z	Neutron Number, N	Atomic Mass (u)	Mass Number, A
Hydrogen ($^{1}_{1}H$)	1	0	1.007825	1
Deuterium ($^{2}_{1}H$)	1	1	2.014102	2
Tritium ($^{3}_{1}H$)	1	2	3.016049	3
Helium ($^{3}_{2}He$)	2	1	3.016029	3
Helium ($^{4}_{2}He$)	2	2	4.002603	4
Lithium ($^{6}_{3}Li$)	3	3	6.015122	6
Lithium ($^{7}_{3}Li$)	3	4	7.016004	7
Beryllium ($^{9}_{4}Be$)	4	5	9.012182	9
Boron ($^{10}_{5}B$)	5	5	10.012937	10
Boron ($^{11}_{5}B$)	5	6	11.009305	11
Carbon ($^{12}_{6}C$)	6	6	12.000000	12
Carbon ($^{13}_{6}C$)	6	7	13.003355	13
Nitrogen ($^{14}_{7}N$)	7	7	14.003074	14
Nitrogen ($^{15}_{7}N$)	7	8	15.000109	15
Oxygen ($^{16}_{8}O$)	8	8	15.994915	16
Oxygen ($^{17}_{8}O$)	8	9	16.999132	17
Oxygen ($^{18}_{8}O$)	8	10	17.999160	18

Source: A. H. Wapstra and G. Audi, *Nuclear Physics* **A595,** 4 (1995).

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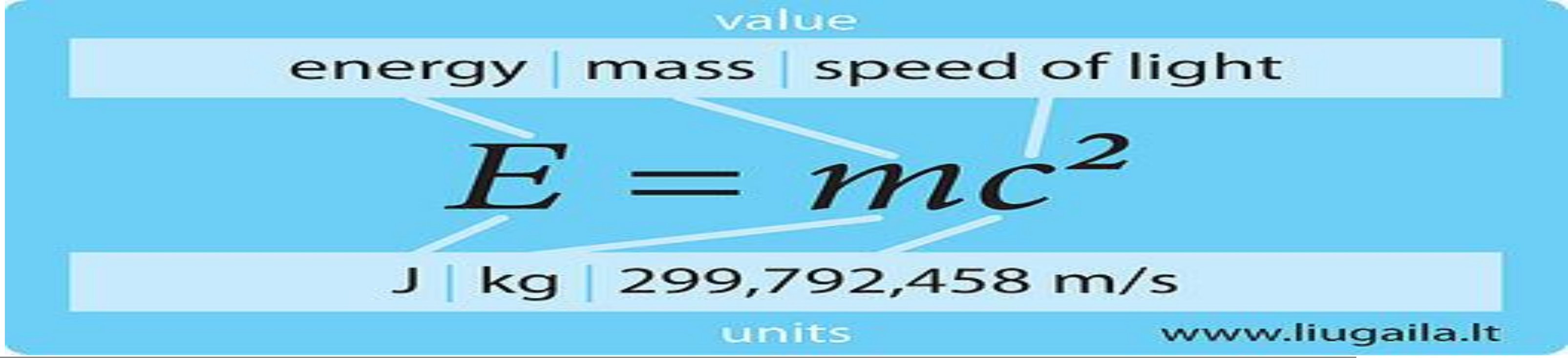
BINDING ENERGY



Recall:

From the Einstein's Theory of Relativity: He explains that mass is a form of energy and that a mass (m) equivalent to an amount of energy (E).

$E = mc^2$

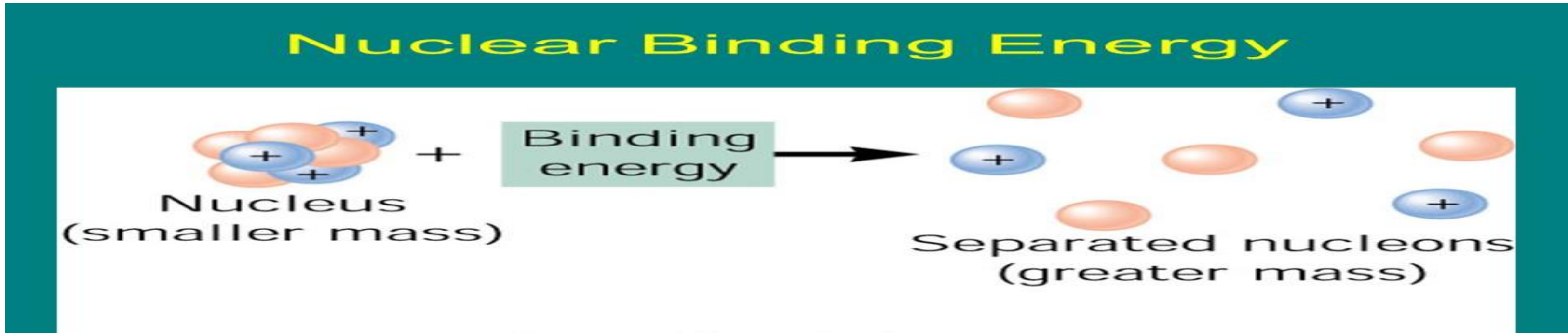
If the mass of an atom is slightly less than the sum of masses of its component particles, there is a difference between the two masses (Δm).

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

ΔE = binding energy (E_B).

Binding Energy (E_B) $=$ Energy that must be added to separate the nucleons.

BINDING ENERGY



When the nucleons are separated, the total rest energy (E_0) of the separated individual protons and neutrons is greater than the binding energy.

E_0 - E_B

E_0 = rest mass of the individual protons and neutrons.

$E_B = (ZM_H + NM_n - {}^{A}_{Z}M)\, c^2$

E_B = binding energy of a nucleus with Z protons and N neutrons.

Z = atomic number. N = neutron number M_H = mass of the hydrogen atom.

M_n = neutron mass ${}^{A}_{Z}M = mass\ of\ neutral\ atom\ containing\ the\ nucleus$.

c^2 = speed of light in vacuum $\approx 931.5\ MeV$/u

NUCLEAR FORCE

The force that binds protons and neutrons together in the nucleus, despite the electric repulsion of the protons is an example of a strong interaction.

In the context of the nuclear structure, this interaction is called the **nuclear force.**

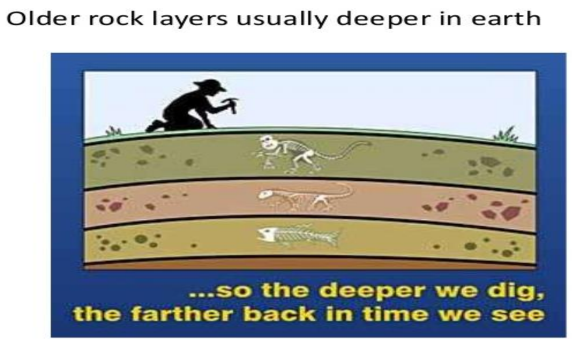
Characteristics of Nuclear Force:

1) It does not depend on the charge.

2) It has a short range, of the order of nuclear dimension $10^{-15}m$. ***But within this range, the nuclear force is much smaller than electric forces.***

3) The nearly constant density of nuclear matter and the nearly constant binding energy per nucleon of larger nuclides show that a particular nucleon cannot interact simultaneously with all the other nucleons in a nucleus, but only with those in its immediate vicinity.

RADIOACTIVE DATING



An important application of radioactivity is the dating of archaeological and geological specimens by measuring the concentration of radioactive isotopes.

The most familiar example is ___________ **Carbon dating**

During nuclear reaction in the atmosphere, an unstable isotope $^{14}C$is produced as a result of cosmic-ray bombardment.

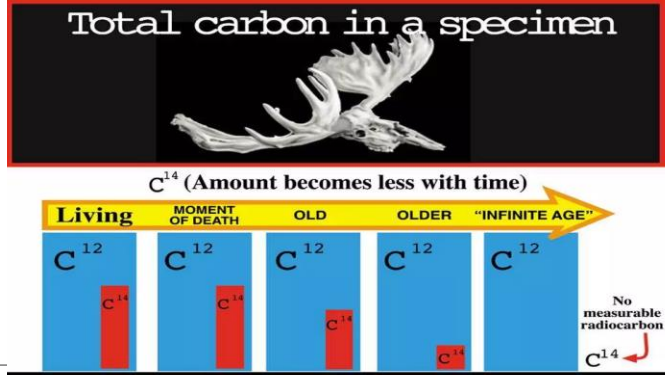
This gives a small proportion of ^{14}Cin the CO_2 in the atmosphere.

Plants that obtain their carbon from this source contain the same proportion of ^{14}C as the atmosphere.

When a plant dies, it stops taking in carbon, and its ^{14}C β-decay to ^{14}N with a half-life of 5730 years.

By measuring the proportion of ^{14}C in the remains, we can determine long ago, the organism died.

RADIOACTIVE DATING



The challenge with radiocarbon dating is that the ^{14}C concentration in the atmosphere changes over long time intervals.

Similar radioactive techniques are used with other isotopes for dating geological specimens.

Example: some rocks, contain unstable potassium isotope ^{40}K, a beta emitter that decays to the stable nuclide ^{40}Ar with half-life of $2\ \times 10^{8}$ y.

The age of the rock can be determined by comparing the concentrations of ^{40}K and ^{40}Ar.

NUCLEAR REACTIONS

When nuclear components are rearranged as a result of bombardment by a particle rather than a spontaneous natural process; nuclear reactions are created.

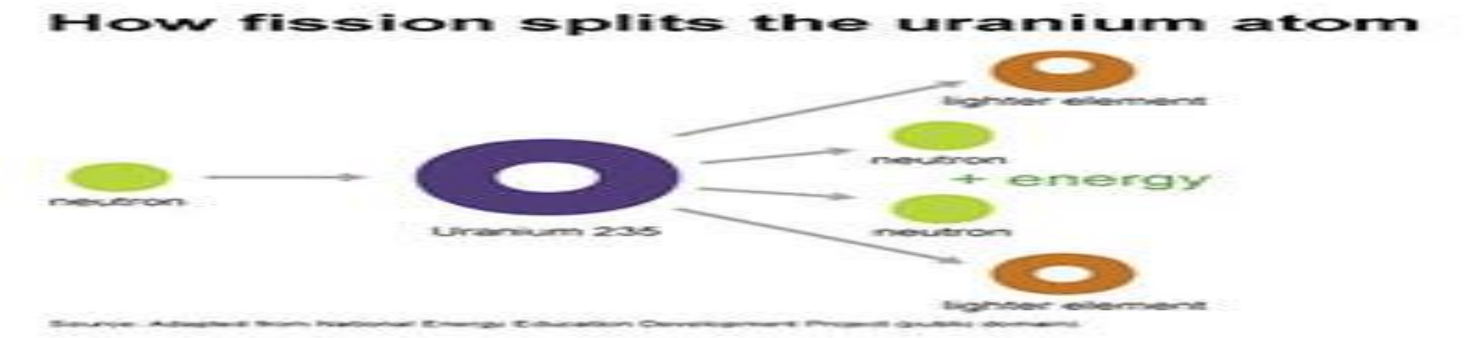
Rutherford suggested in 1919 that a massive particle with sufficient kinetic energy might be able to penetrate a nucleus.

He verified this when he bombarded nitrogen (^{14}N) with α-particles and obtained an oxygen (^{17}O) nucleus and a proton:

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

Nuclear reactions are subject to several conservation laws: principle for charge, momentum, angular momentum and energy are obeyed in all nuclear reactions.

NUCLEAR FISSION



Nuclear fission is a decay process in which an unstable nucleus splits into two fragments of comparable mass.

Fission was discovered in 1938 through the experiments of Otto Hahn and Fritz Strassman in Germany.

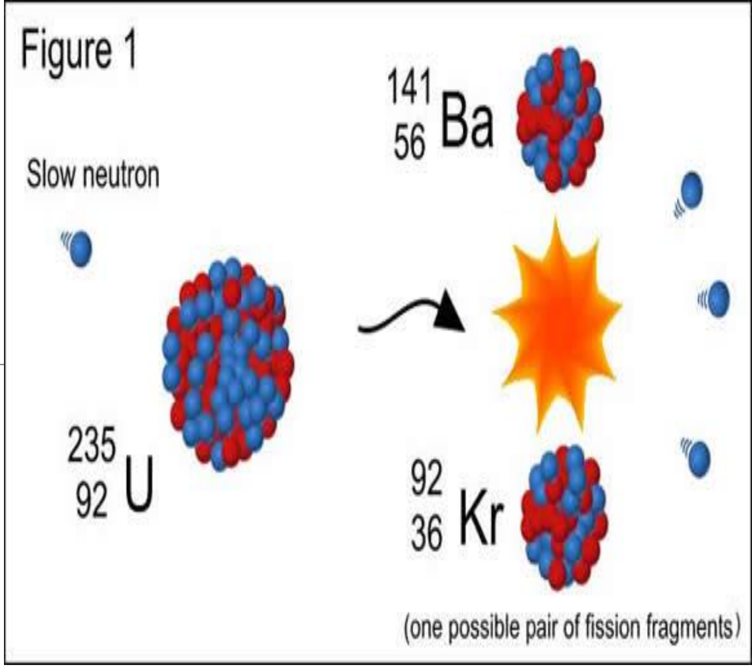
They pursued the work of Enrico Fermi and bombardment uranium (Z = 92) with neutrons.

From the experiments, they discovered radioactive isotope of barium (Z = 56) and radioactive krypton (Z = 36).

Also, two or three free neutrons usually appear along with the fission fragments and very occasionally, a light nuclide such as ^{3}H.

Over 100 different nuclides, representing more than 20 different elements have been found among the fission products.

NUCLEAR FISSION:
Fission Reactions



Example:

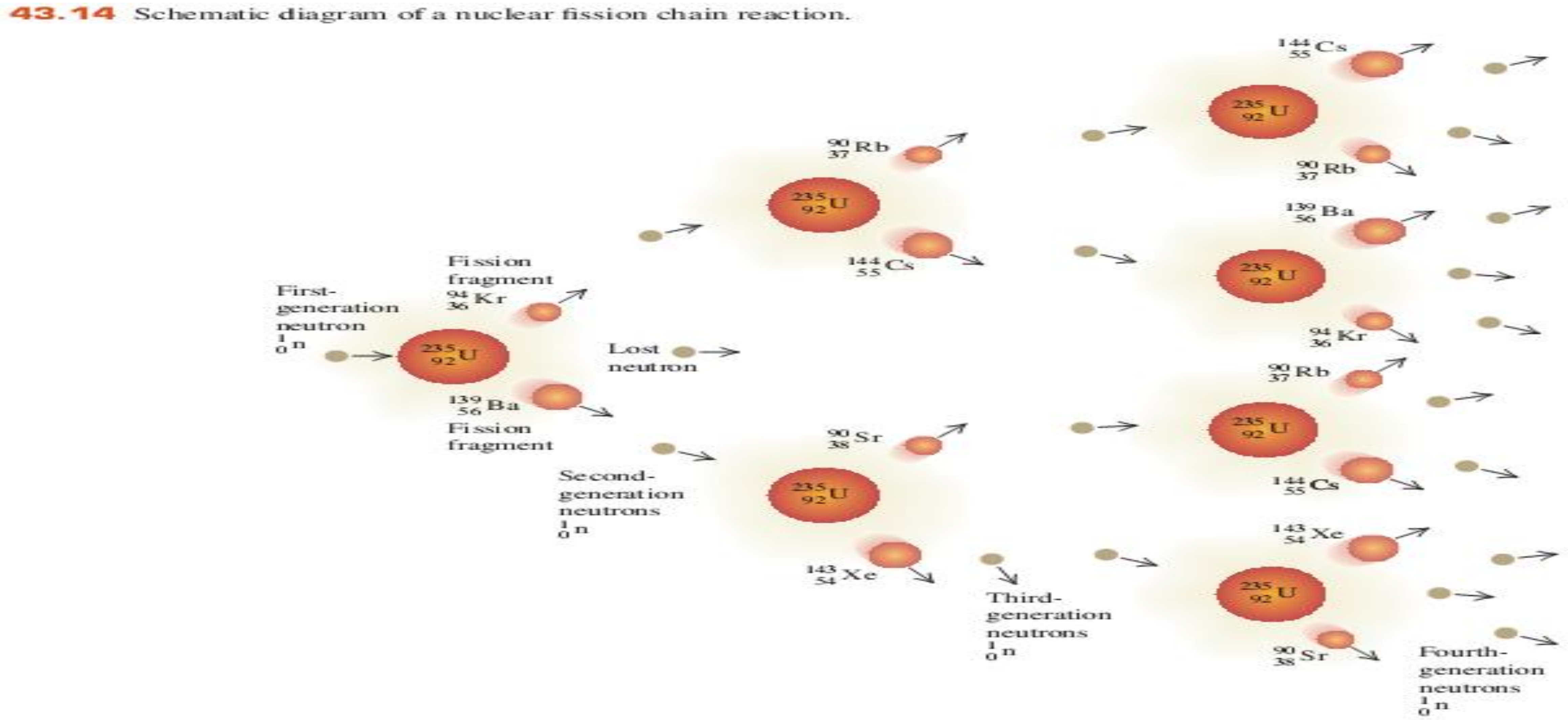
$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U^{*} \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3\,{}^{1}_{0}n$$

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U^{*} \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n$$

Note: Fission resulting from neutron absorption is called induced fission.

Some nuclides can also undergo spontaneous fission without neutron absorption, but this is quite rare.

NUCLEAR FISSION: Chain Reaction



NUCLEAR REACTOR

A nuclear reactor is a system in which a controlled nuclear chain reaction is used liberate energy.

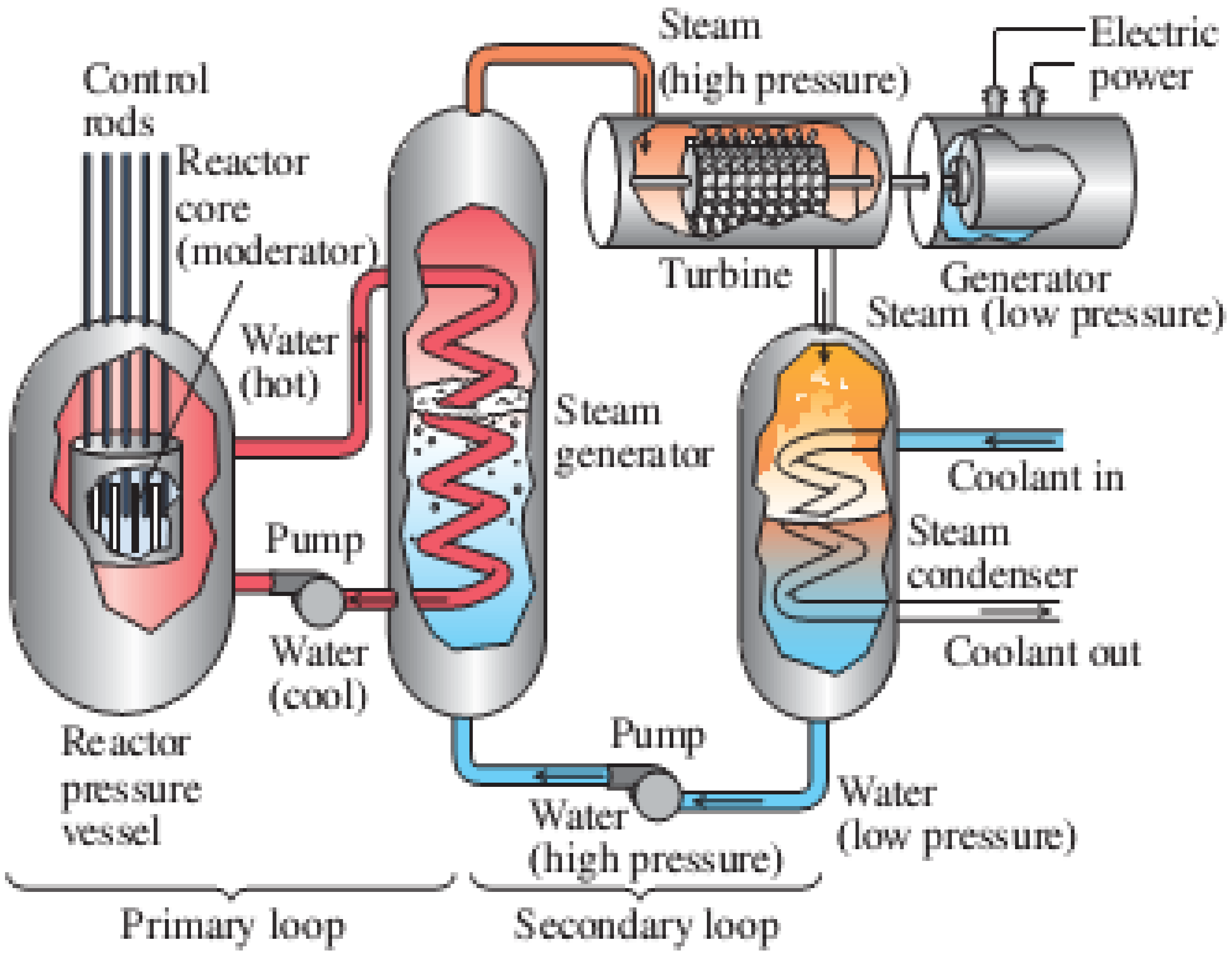
In a nuclear power plant, this energy is used to generate steam, which operates a turbine and turns an electrical generator.

On average, each fission of a ^{235}U nucleus produces about 2.5 free neutrons, so about 40% of the neutrons are needed to sustain a chain reaction.

NUCLEAR REACTOR:
Nuclear Power Plant

<u>Moderator:</u> houses the high energy neutrons and are slowed down by collisions with nuclei in the surrounding material. The moderator is often water, occasionally graphite

<u>Control Rods:</u> Rate of reaction is controlled by inserting or withdrawing the rods (boron or cadmium).



NUCLEAR FUSION

Nuclear Fusion is when two or more small light nuclei come together, or *fuse*, to form a larger nucleus.

Fusion reactions release energy for the same reaction as fission reactions.

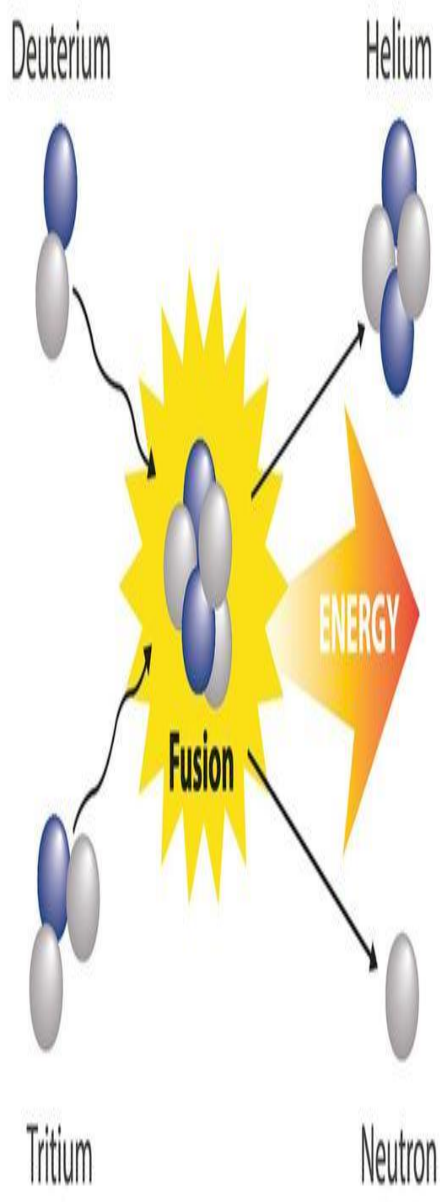
Here, the binding energy per nucleon after the reaction is greater than before.

Examples of energy-liberating fusion reactions:

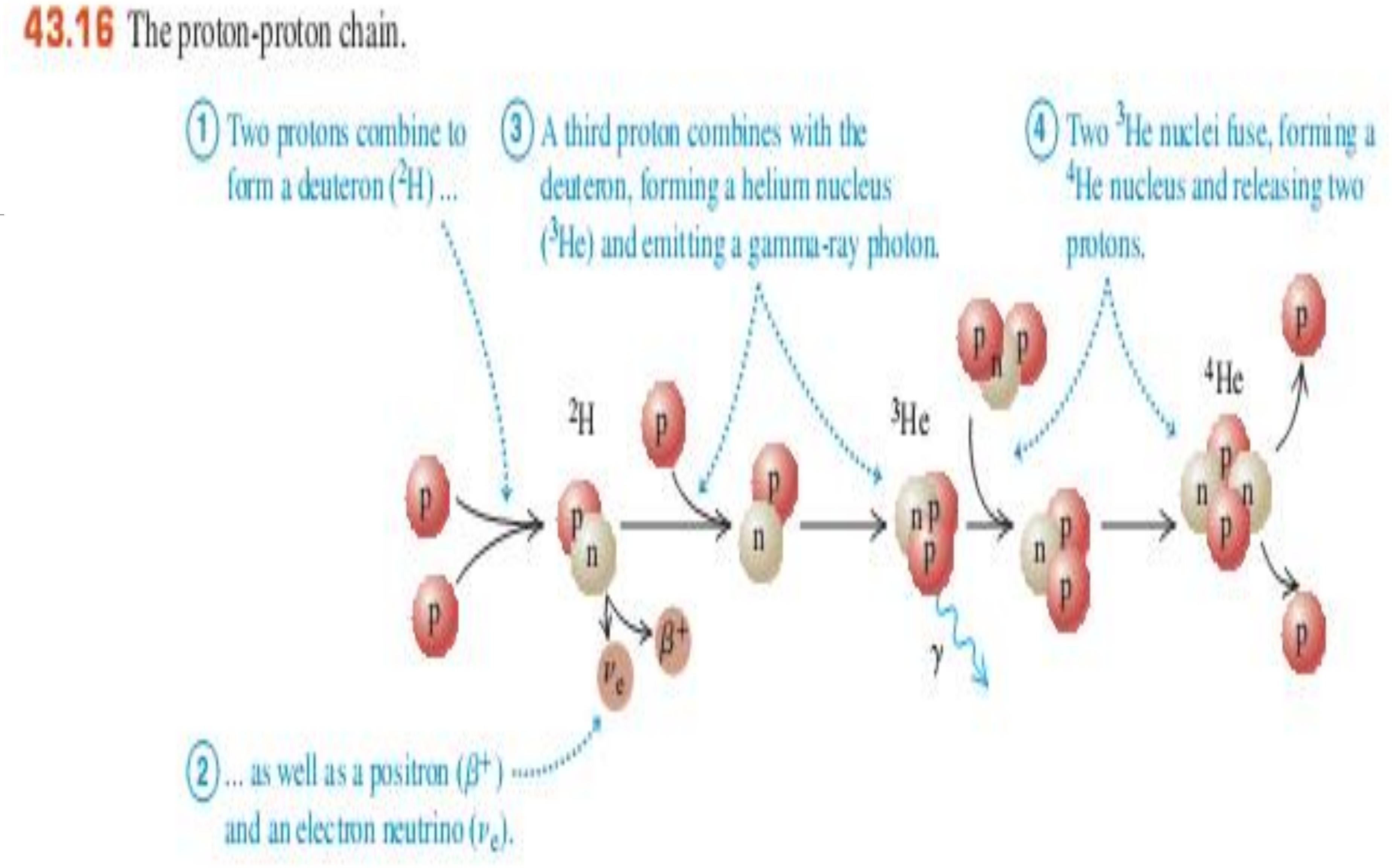
$${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + \beta^{+} + v_{e}$$

$${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma$$

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



NUCLEAR FUSION: Chain Reaction



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QUESTION TIME????????????????

About Lecturer:

Opadele A.E is a physics enthusiast with special interest in Medical Physics. He loves to present the complex theories in physics in seemingly simple approach for effectual understanding.

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