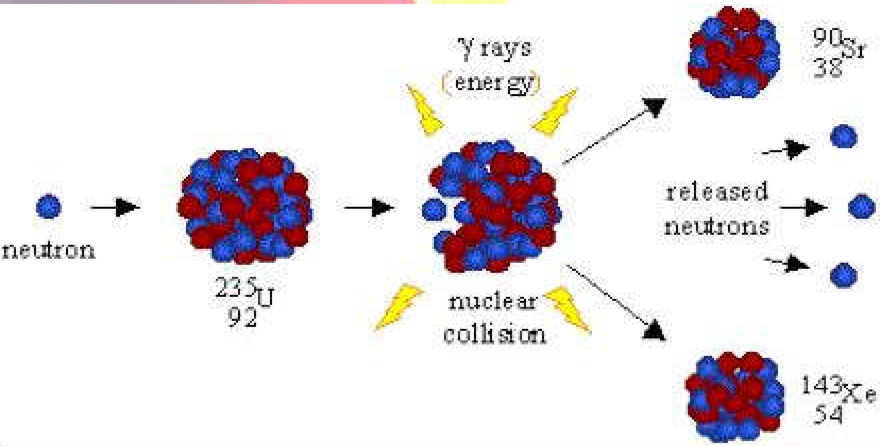
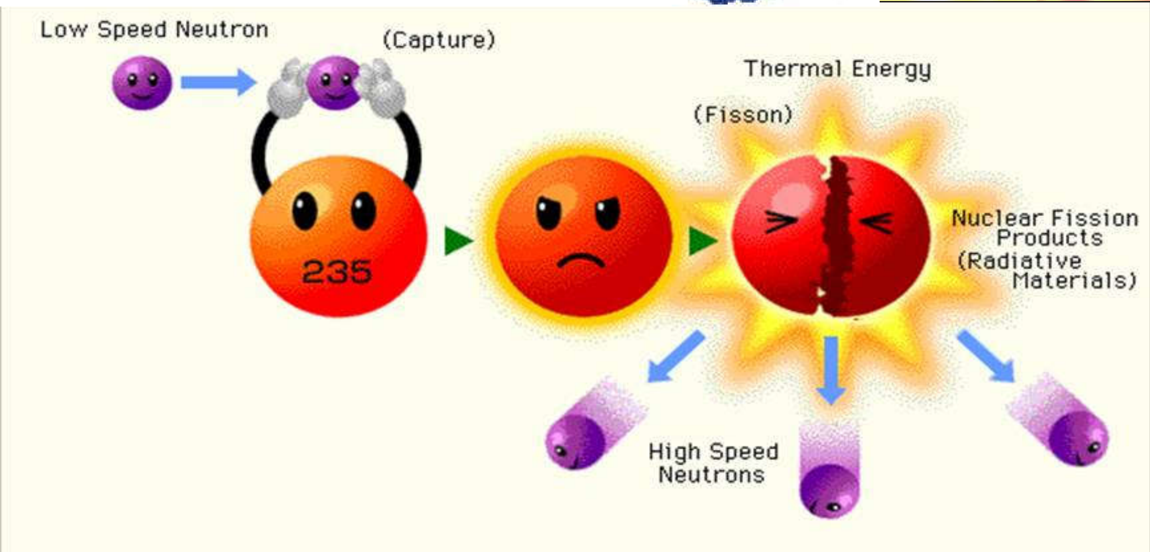
Nuclear Chemistry





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

NUCLEAR REACTIONS

Those reactions in which one or more nuclides are produced from the collisions between two atomic nuclei or one atomic nucleus and a subatomic particle are called nuclear reactions

TYPES OF NUCLEAR REACTION

Nuclear fission reaction
Nuclear fusion reaction
Nuclear Decay
NuclearTransmutation

Radioactivity

It is the spontaneous emission of radiation (in the form of particles or high energy photons) resulting from a nuclear reaction.

Marie Curie (1876-1934) and Pierre Curie successfully isolate radioactive radium salts from the mineral pitchblende in their laboratory (Paris). In 1898, the Curies discovered the elements radium & polonium in their research of pitchblende.

Nuclear Reactions vs. Normal Chemical Changes

- Nuclear reactions involve the nucleus
- The nucleus opens, and protons and neutrons are rearranged
- The opening of the nucleus releases a tremendous amount of energy that holds the nucleus together – called binding energy
- “Normal” Chemical Reactions involve electrons, not protons and neutrons

Nuclear reactions differ from ordinary chemical reactions

- Atomic numbers of nuclei may change (elements are converted to other elements or an element can be converted to an isotope of that element).
- Protons, neutrons, electrons and other elementary particles may be involved in a nuclear reaction.
- Reactions occur between particles in the nucleus.
- Matter is converted to energy & huge amounts of energy are released.
- Nuclear reactions involve a specific isotope of an element; different isotopes of an element may undergo different nuclear reactions.

Nuclear Stability & Magic Numbers

- Nuclei containing 2, 8, 20, 50, 82, or 126 protons or neutrons are generally more stable than nuclei that do not possess these magic numbers.
- As the atomic number increases, more neutrons are needed to help bind the nucleus together, so there is a high neutron:proton ratio.
- Nuclei of elements with > 83 protons are unstable due to the large no. of nucleons present in the tiny nucleus; by undergoing **radioactive decay unstable** nuclei can form more **stable** nuclei.
- Nuclei with both even numbers of both protons & neutrons are generally more stable than those with odd numbers:

Mass Defect

- **During nuclear reaction some of the mass can be converted into energy shown by a very famous Einstein's equation!**

$$E=mc^2$$

Energy

Mass

Speed of light

Types of Radiation

Alpha: These are fast moving helium atoms (**we usually ignore the charge because it involves electrons, not protons and neutrons)**

$${}^{4}_{2}He$$

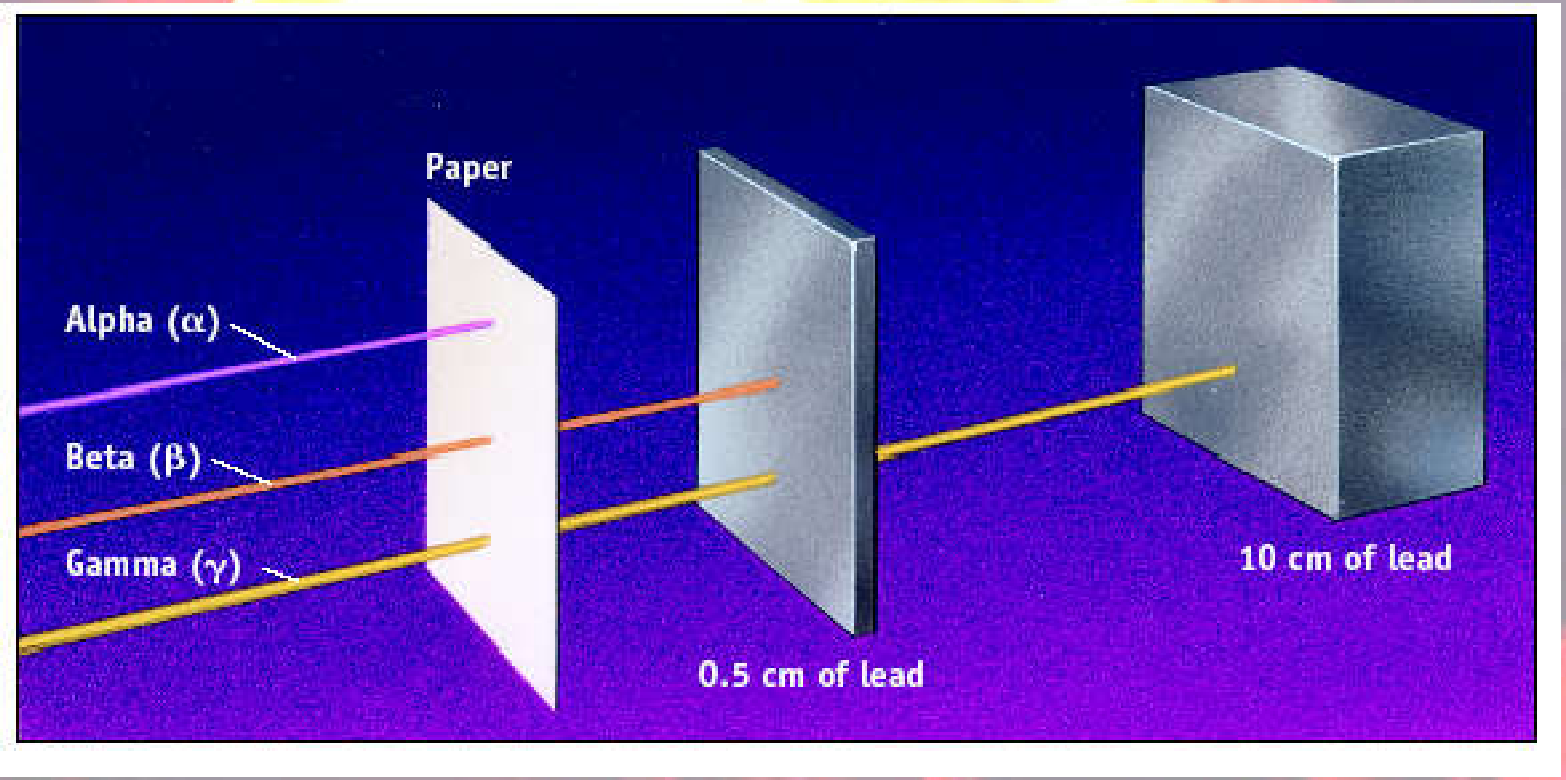
Beta: These are fast moving electrons.

$${}^{0}_{-1}e$$

Gamma: These are photons, just like light, except of much higher energy, typically from several keV to several MeV.

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

Penetrating Ability



Balancing Nuclear Reactions

In the reactants (starting materials – on the left side of an equation) and products (final products – on the right side of an equation)

Atomic numbers must balance

and

Mass numbers must balance

Use a particle or isotope to fill in the missing protons and neutrons

Nuclear Reactions

- **Alpha emission**

	$^{226}_{88}Ra$	$\longrightarrow$	$^{4}_{2}\alpha$	+	$^{222}_{86}Rn$
	radium-226	$\longrightarrow$	α particle	+	radon-222
Mass number: (protons + neutrons)	226	=	4	+	222
Atomic number: (protons)	88	=	2	+	86

Note that mass number (A) goes down by 4 and atomic number (Z) goes down by 2.

Nucleons (nuclear particles… protons and neutrons) are rearranged but conserved

Nuclear Reactions

- **Beta emission**

	$^{239}_{92}U$	$\longrightarrow$	$^{0}_{-1}\beta$	+	$^{239}_{93}Np$
	uranium-239	$\longrightarrow$	β particle	+	neptunium-239
Mass number: (protons + neutrons)	239	=	0	+	239
Atomic number: (protons)	92	=	−1	+	93

Note that mass number (A) is unchanged and atomic number (Z) goes up by 1.

Attempt these

What radioactive isotope is produced in the following bombardment of boron?

$$^{10}_{5}B + ^{4}_{2}He \longrightarrow ? + ^{1}_{0}n$$

Write the nuclear equation for the beta emitter Co-60.

Artificial Nuclear Reactions

New elements or new isotopes of known elements are produced by bombarding an atom with a subatomic particle such as a proton or neutron or even a much heavier particle such as ^{4}He and ^{11}B.

Reactions using neutrons are called **γ reactions** because a γ ray is usually emitted.

Radioisotopes used in medicine are often made by γ reactions.

Artificial Nuclear Reactions

Example of a g reaction is production of radioactive ^{31}P for use in studies of P uptake in the body.

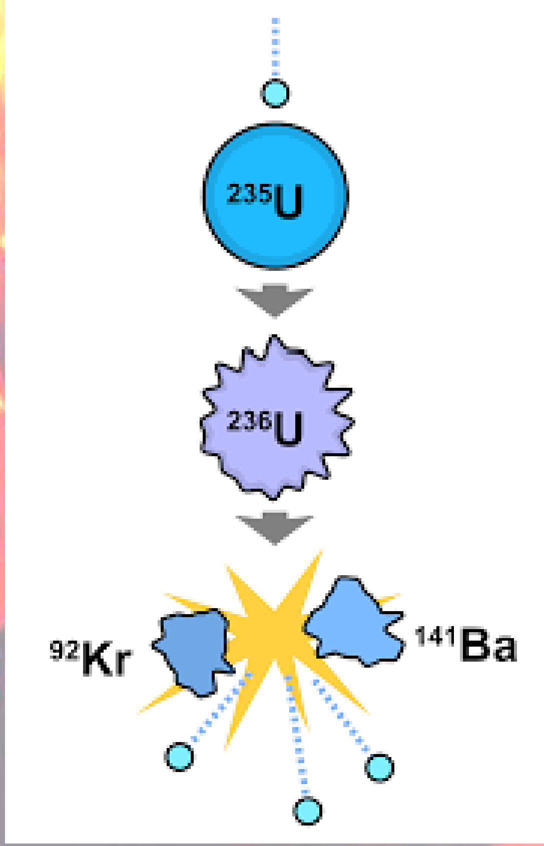
$${}^{31}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n} \text{ ---> } {}^{32}_{15}\mathrm{P} + \mathrm{g}$$

Nuclear Fission Reaction

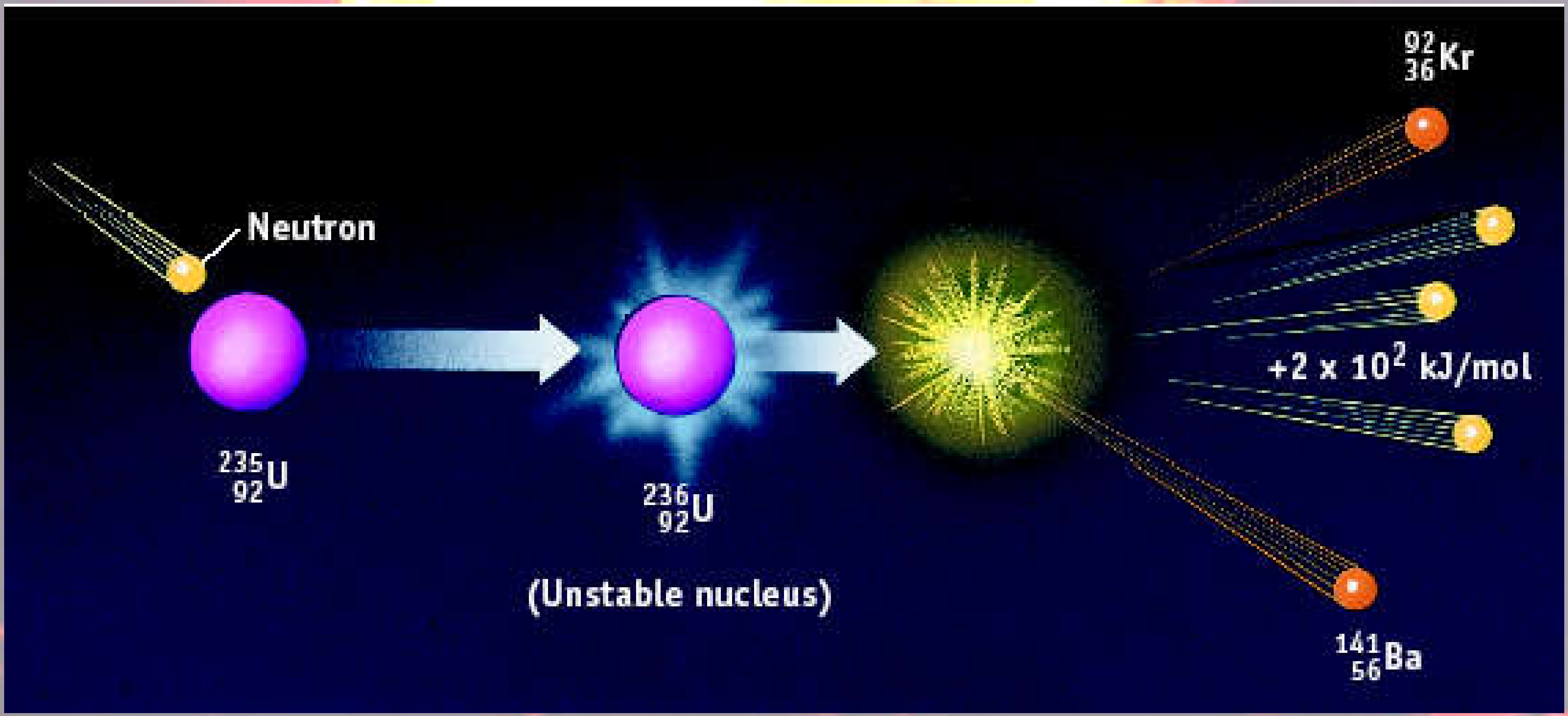
Nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei).

The fission process often produces free neutrons and gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.

Fission is a form of nuclear transmutation because the resulting fragments are not same element as the original atom.



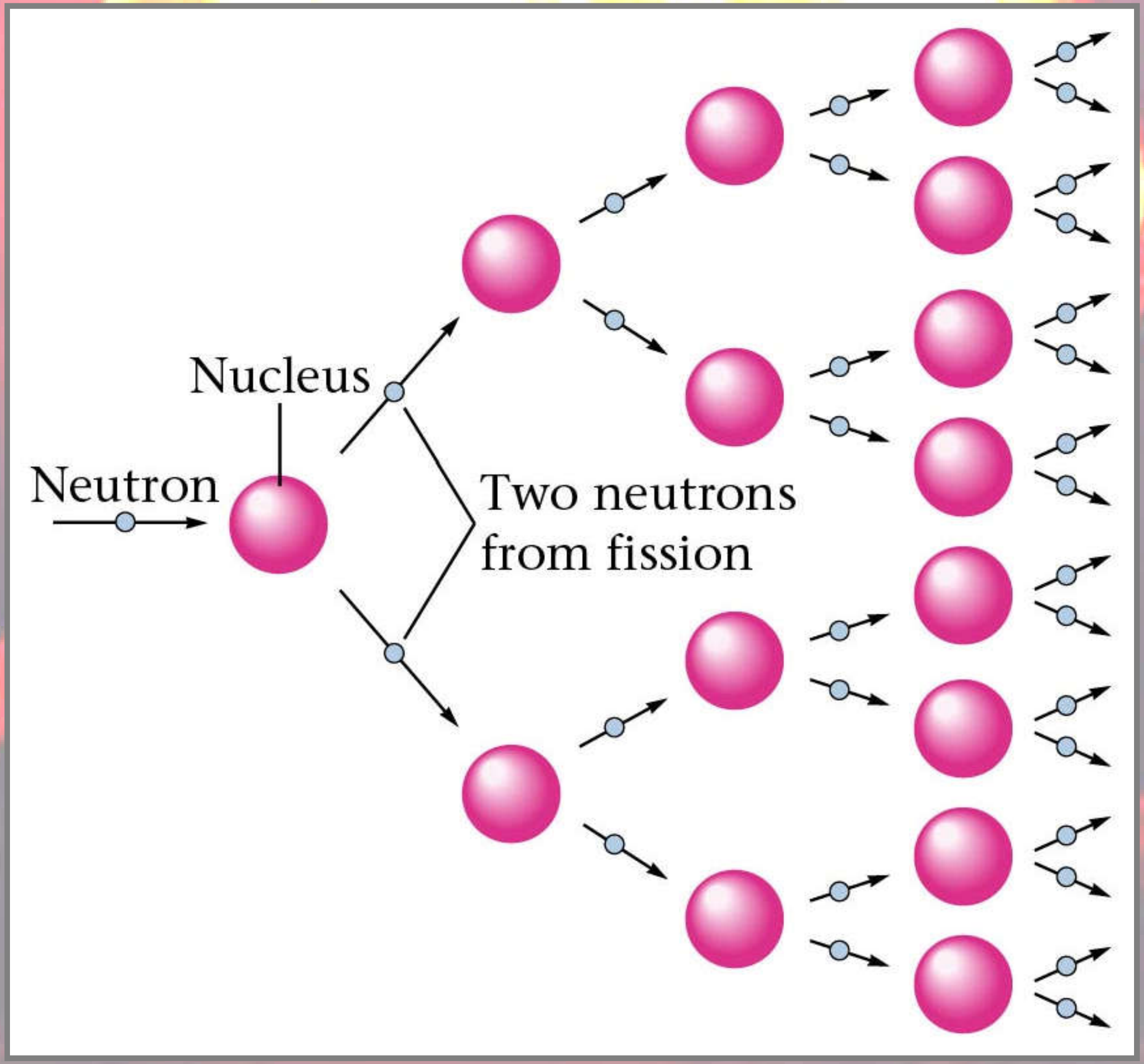
Nuclear Fission



CHAIN REACTION

- A chain reaction is a sequence of reactions where a reactive product or by-product causes additional reactions to take place.
 An atom of U^{235} to undergo fission by bombarding it with neutrons.
- Along with barium and krypton, three neutrons are released during the fission process. These neutrons can hit further U^{235} atoms and split them, releasing yet more neutrons. This is called a chain reaction.
- Although the half-life of U^{235} is a very long time, if we get enough of the atoms together in one place the chances that any one of them will undergo spontaneous fission is very, very high.
- Additional Neutrons create a chain reaction, which is controlled by the control rods.
- Newly created fission neutrons move at about 7% of the speed of light, and even moderated neutrons move at about 8 times the speed of sound.

Fission process



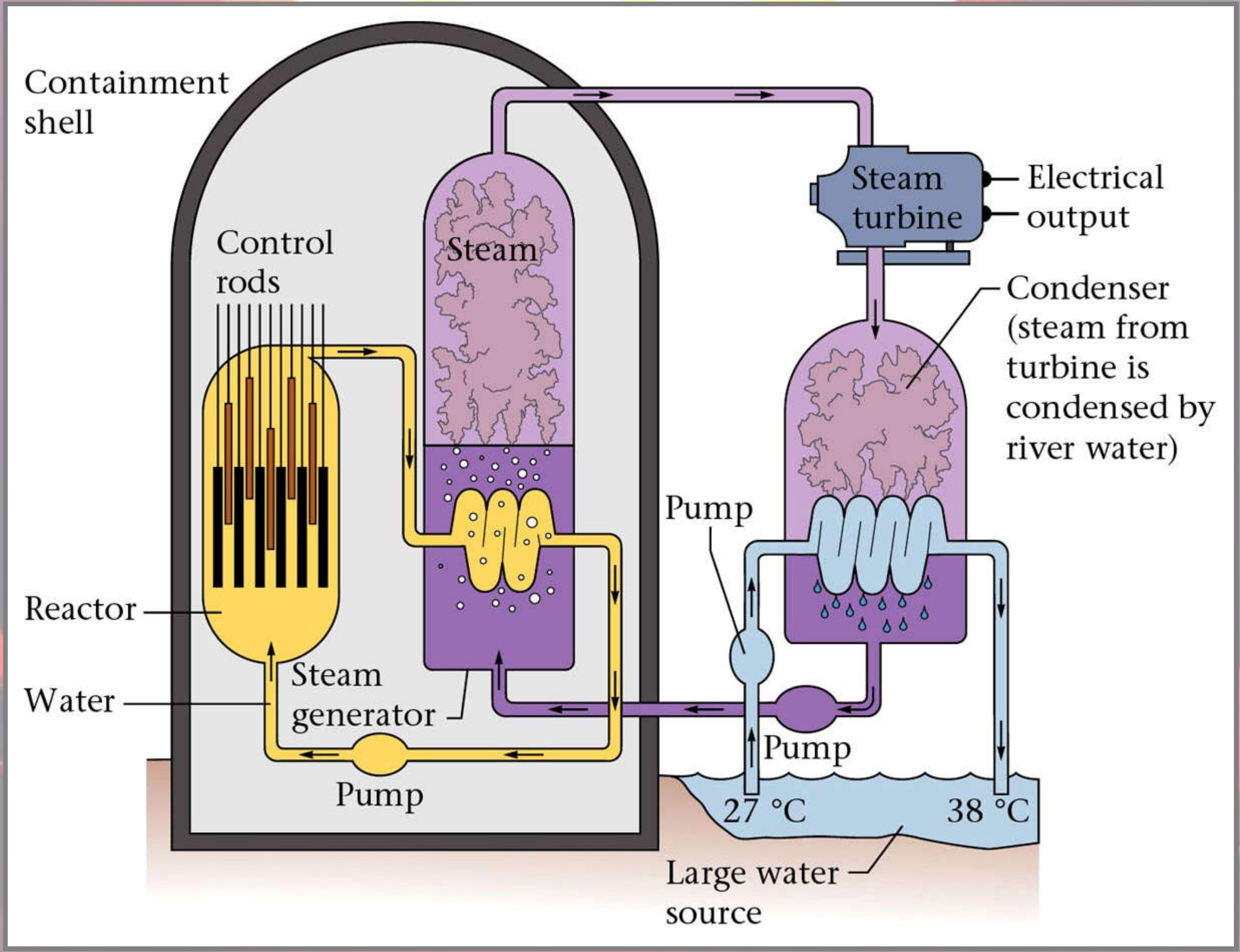
NUCLEAR REACTOR

- "The assembly which is used to convert heat generated in nuclear reaction into electrical energy is called Nuclear Reactor."

In a reactor fission reaction produces heat.

- When fission takes place in atom of uranium or any heavy atom, then energy at the rate of 200MeV per nucleus is produced in form of Kinetic energy of fission fragments.
- These fast moving fragments besides colliding with one another also collide to uranium atoms.
- Due to collisions kinetic energy gets transformed into heat energy.
- Heat produced is used to produce steam which in turn rotates the turbine.
- As a result, turbine rotates the generator which produces electricity

Figure 19.6: Diagram of a nuclear power plant.



WORKING OF REACTOR:

Reactor Core; cylindrical tubes in which fuel is kept. Uranium- ${}_{92}U^{235}$ is used as fuel. The quantity of ${}_{92}U^{235}$ in the naturally occurring Uranium is 0.7%.

Control rods are made of B or Cd; These rods absorb neutrons so the process doesn't accelerate too rapidly. Rods are raised/lowered to control the speed of the process.

Fuel rods; These are made of ${}^{235}U$. ${}^{238}U$ is the most abundant U isotope but is not fissionable so uranium must be enriched to increase the amount of ${}^{235}U$. Fuel rods are placed in substances of small atomic weight, such as water, heavy water, carbon etc called moderators.

Moderator - is used to slow down the speed of neutrons produced during the fission process to direct them towards the fuel. Water or other liquid coolant surround rods. The water serves to

1) slow down neutrons so they can collide with ^{235}U.
2) transfer heat to steam generator.

- Chain reaction takes place in the core and produces heat. Temperature rise about 500°C.
- Steam is produced from this heat and is transported with the help of water or heavy water.
- Temperature of steam coming out from turbine is about 300°C which is further cooled to produce water again.

Nuclear Fission & POWER

- Currently about 103 nuclear power plants in the U.S. and about 435 worldwide.
- 17% of the world's energy comes from nuclear.

Table 23.2 • Percent of Electricity Produced Using Nuclear Power Plants

Country (rank)	Total power from nuclear energy (%)
1. France	75.0
2. Lithuania	73.1
3. Belgium	57.7
4. Bulgaria	47.1
5. Slovak Republic	47.0
6. Sweden	46.8
. . .	
19. United States	19.9
20. Russia	14.4
21. Canada	12.7

Nuclear Fusion

small nuclei combine

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

Occurs in the sun and other stars

Fusion generates even more energy than fission and creates little radioactive waste, so it would provide a wonderful source of energy but, fusion requires very high temps (tens of millions of degrees Celsius) in order for nuclei to overcome strong repulsive forces. Attempts at “cold” fusion have FAILED. Magnetic fusion reactors are being designed and tested.

Half-Life

- **HALF-LIFE** **is the time that it takes for 1/2 a sample to decompose.**
- **The rate of a nuclear transformation depends only on the "reactant" concentration.**
- **Critical mass;** It is the minimum mass required to sustain a chain reaction.

Half-Life

Decay of 20.0 mg of ^{15}O. What remains after 3 half-lives? After 5 half-lives?

The half life of I-123 is 13 hr. How much of a 64 mg sample of I-123 is left after 39 hours?

Kinetics of Radioactive Decay

For each duration (half-life), one half of the substance decomposes.

For example: Ra-234 has a half-life of 3.6 days

If you start with 50 grams of Ra-234

After 3.6 days > 25 grams

After 7.2 days > 12.5 grams

After 10.8 days > 6.25 grams

Effects of Radiation

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

GeigerCounter is used to detect radioactive substance

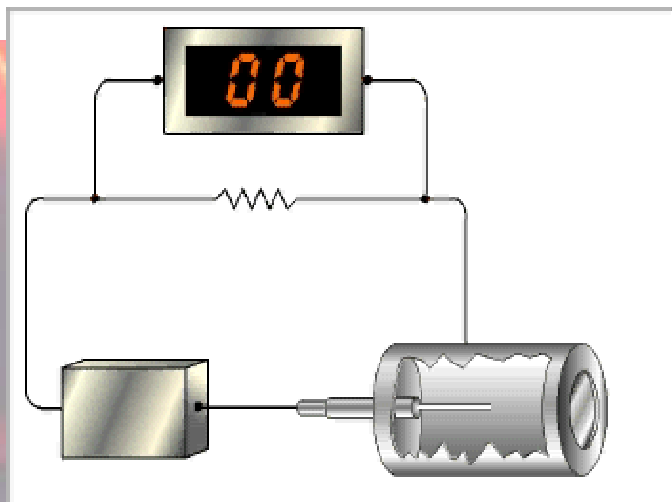


Table 23.3 • Radiation Exposure of an Individual for One Year from Natural and Artificial Sources

	Millirem/yr	Percentage
Natural Sources		
Cosmic radiation	50.0	25.8
The earth	47.0	24.2
Building materials	3.0	1.5
Inhaled from the air	5.0	2.6
Elements found naturally in human tissue	21.0	10.8
Subtotal	126.0	64.9
Medical Sources		
Diagnostic x-rays	50.0	25.8
Radiotherapy	10.0	5.2
Internal diagnosis	1.0	0.5
Subtotal	61.0	31.5
Other Artificial Sources		
Nuclear power industry	0.85	0.4
Luminous watch dials, TV tubes	2.0	1.0
Fallout from nuclear tests	4.0	2.1
Subtotal	6.9	3.5
Total	193.9	99.9

APPLICATIONS OF RADIOACTIVE ISOTOPES

- Nuclear power plants
- Medical diagnosis and treatment e.g. PET scan monitors glucose metabolism in brain using C-11 isotope; I-131 measures activity of thyroid
- Carbon dating (measure amount of C-14 remaining in a sample)
- Synthesis of new elements
- Irradiation of food - preserves food & destroys parasites
- Nuclear Weapons (Atomic bombs and H bombs)

Radiocarbon Dating

Radioactive C-14 is formed in the upper atmosphere by nuclear reactions initiated by neutrons in cosmic radiation

^{14}N + $^{1}_{o}n$ ---> ^{14}C + ^{1}H

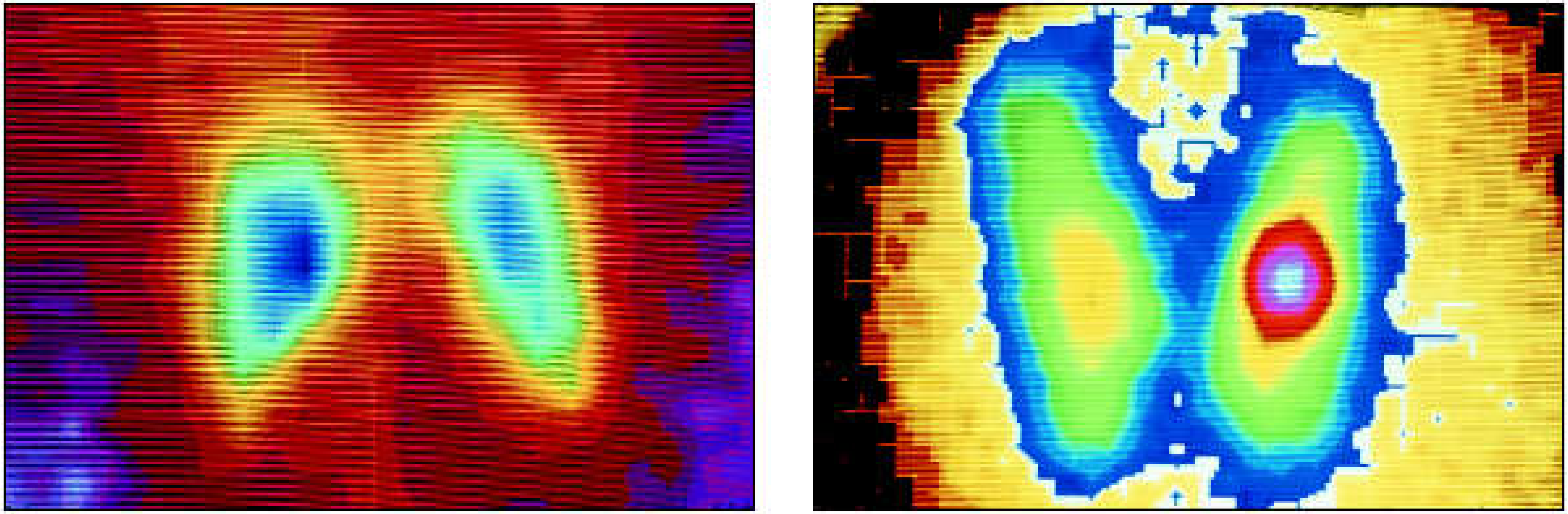
The C-14 is oxidized to CO_2, which circulates through the biosphere.

When a plant dies, the C-14 is not replenished.

But the C-14 continues to decay with $t_{1/2}$ = 5730 years.

Activity of a sample can be used to date the sample.

Nuclear Medicine: Imaging



(a) Healthy human thyroid gland.

(b) Thyroid gland showing effect of hyperthyroidism.

Thyroid imaging using Tc-99m

Food Irradiation

- Food can be irradiated with γ rays from ^{60}Co or ^{137}Cs.
- Irradiated milk has a shelf life of 3 mo. without refrigeration.
- USDA has approved irradiation of meats and eggs.