21. Nuclear Chemistry and Applications of Radioactivity

Learning outcomes

The students should be able to:

- ✓ Describe natural and artificial radioactivity.
- ✓ Give units of radioactivity.
- ✓ Explain nuclear reactions.
- ✓ Distinguish between nuclear fission and fusion reactions.
- ✓ Describe nuclear power and nuclear weapons.
- ✓ Explain industrial uses of radioactivity.
- ✓ State the medical uses of radioactivity.
- ✓ Explain radiocarbon dating.
- ✓ Describe the harmful effects of nuclear radiations

Nuclear chemistry is the branch of chemistry that deals with **changes of matter which are brought about by the nucleus of an atom rather than the electrons** in the valance shell.

Chemical reaction	Nuclear reaction
Element is neither created nor destroyed.	New elements are formed from the parent elements.
Mostly valance electrons are involved.	Mostly nuclei are involved.
The rate of reaction depends on temperature, pressure, catalyst etc.	Spontaneous, not affected by temperature, pressure, catalyst, etc.
Involve release or absorption of a small amount of energy.	Involve release or absorption of a huge amount of energy.

1. Give any two differences between nuclear reaction and chemical reaction. 2
2. Differentiate between chemical reactions and nuclear reactions. 2

Natural and artificial radioactivity

Artificial radioactivity	Natural radioactivity
The process of emission of radiation from the naturally occurring nuclei when they are bombarded with high-energy sub-atomic particles, X-rays or gamma rays.	The spontaneous emission of radiation from unstable nuclei is called natural radioactivity.
Artificial radioactive elements usually have short half-lifes.	The element which undergo natural radioactivity usually have long half-lives.
Artificial radioactivity can be induced even in elements with low atomic numbers.	Natural radioactive usually occurs in elements with atomic number greater than 83, which are naturally unstable.
$_{7}N^{14} + {}_{2}He^{4} \rightarrow {}_{9}F^{18} \rightarrow {}_{8}O^{17} + {}_{1}H^{1}$	$_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}He^{4}$

3. Distinguish between artificial and natural radioactivity. 2
4. How is natural radioactivity differed from artificial radioactivity?
5. What is meant by artificial radioactivity? Give an example of it. 2
6. Define the term natural radioactivity and give a suitable example of it.
7. What are nuclear isotopes? Write an example. 1+1
8. Give any two differences between α- particles and β- particles. 2

Units of radioactivity

The decay activity of radioactive elements is measured as the number of disintegration that the radioactive substance make at unit time from its unit mass. The unit of radioactivity is expressed in Curie (C*i*) scale.

1 Curie (***1Ci***) = Rate of disintegration of 1 gm of radium-226
= 3.7×10^{10} disintegrations per second by 1 gm of $^{226}_{88}Ra$

SI unit of radioactivity is Becquerel (Bq)

1 Becquerel (***1Bq***) = Activity of 1 disintegration per second

Therefore, ***1Ci*** = ***3.7 x 10^{10} Bq*** or 37 GBq

9. What is radioactivity? Give its unit. 2

Nuclear reactions

Nuclear reaction is a type of reaction in which one nuclei can be converted to another new nuclei. In a nuclear reaction, one element is converted into another element.

Nuclear fission and fusion reactions

Nuclear fission: A process in which the large nucleus splits into smaller nuclei is called nuclear fission.

e.g., $_{92}U^{235} + {}_{0}n^{1} \rightarrow [{}_{92}U^{236}] \rightarrow {}_{56}Ba^{144} + {}_{36}Kr^{90} + 2\ {}_{0}n^{1} + 200MeV$

The fission of uranium produces two energetic neutrons, which initiates the chain reaction and completes with a short span of time, releasing a large amount of energy. This increases the temperature of the surroundings by about million degrees. The energy thus produced is the nuclear energy. This tremendous amount of energy, if controlled by using a moderator, can be used for the commercial power generation. Otherwise, it is used as nuclear weapon.

10. What is meant by nuclear reaction? Write an example. 1+1
11. What is meant by nuclear fission reaction? Write an example. 1+1
12. Define nuclear fission reaction and write an example of it. 1+1
13. What is meant by controlled nuclear fission? Write an application of it.
14. What is meant by uncontrolled nuclear fission? Write an application of it.
15. Distinguish between controlled nuclear fission and uncontrolled nuclear fission reactions. 2
16. Give a use of controlled nuclear fission reaction. 1
17. Give a use of uncontrolled nuclear fission reaction. 1

Nuclear fusion: A nuclear reaction in which more than one lighter nuclei fuse together to form a heavier nucleus, is called nuclear fusion.

e.g., $4\ {}_1H^1 \rightarrow {}_2He^4 + 2\ {}_1e^0 + \text{Energy}$

Nuclear fusion is not an easy process because it requires extremely large amount of energy to fuse two lighter nuclei against the nuclear repulsion. The millions of degrees of temperature can only be acquired from nuclear fission. The explosion of hydrogen bomb is due to nuclear fusion reaction.

18. Define nuclear fusion reaction giving an example. 1+1
19. Write fission and fusion reaction giving one example of each. 2
20. What is meant by thermonuclear reaction? Write an example of it. 2
21. Nuclear fusion reaction is also called thermonuclear reaction. Why? 1

Nuclear power

- Nuclear power is the application of nuclear reactions for the generation of electricity.
- In a nuclear power plant, heat is generated from nuclear reactor, the heat is used to generate steam from water, which rotates steam turbine and generates electricity.
- It is estimated that nuclear power provides about 15% the world's electricity.

Advantages of nuclear power

- sustainable source of energy
- reduces carbon emission

Disadvantages

- Expensive to establish nuclear plant.
- high technology and qualified manpower are required to run it
- causes nuclear threat to people
- Disposal of radioactive waste is serious issue.

Nuclear weapons

- Devices designed to release energy in explosive manner via nuclear reaction (nuclear fusion or fission or both)
- Cause catastrophic effect by blast, fire and lethal ionizing radiation
- US detonated uranium fission bomb (64kg) named Little boy on 6th August 1945 in Hirosima and plutonium implosion type fission bomb named fat man in Nagasaki on 9th August, 1945. Nearly 200,000 people were killed.
- US, Russia, UK, France, China, India and North Korea have nuclear weapons.
- Fission type weapons commonly called **atomic bombs** e.g. Uranium-235, Plutonium-239 etc.- based on uncontrolled nuclear chain reactions.
- Fusion type weapons commonly called **thermonuclear bombs or hydrogen bombs-** mainly involve fusion reaction of isotopes of hydrogen(deuterium and tritium)

Industrial uses of radioactivity

- For materials thickness measurement
- For checking blocked water pipes and leakage of oil pipes
- Study of crack, wear and tear in machine
- For material sterilization
- For electricity generation

Radioactive isotopes are used to study the mechanism of many chemical reactions by trace labelling with the radioactive isotope. Let's consider the photosynthesis reaction;

$$6CO_{2(g)} + 6H_2O_{(l)} \longrightarrow C_6H_{12}O_{6(s)} + 6O_{2(g)}$$

To find out whether the O_2 produced in the reaction comes from CO_2 or H_2O, the O atoms of the CO_2 and H_2O are labelled with radioactive ^{18}O.

(i) When CO_2 is labelled with O-18 isotope, both the products glucose and O_2 are found to be contaminated with O-18 isotope.

$$6CO^*_2(g) + 6H_2O(l) \longrightarrow C_6H_{12}O^*_6(s) + 6O^*_2(g)$$

(ii) When H_2O is labelled with O-18 isotope, only the O_2 molecules are found to be contaminated with the O-18 isotope.

$$6CO_2(g) + 6H_2O^*(l) \longrightarrow C_6H_{12}O_6(s) + 6O^*_2(g)$$

Therefore, the O atoms from CO_2 go to form both glucose and molecular oxygen (O_2) while the O atoms from H_2O molecules only form molecular oxygen (O2).

- Some chemical synthesis can be carried out by γ radiation produced from radioactive isotope. When high intensity γ rays obtained from Co-60 isotope is irradiated on the mixture of ethane and hydrogen bromide gas at room temperature, bromoethane is formed.

$$H_2C{=}CH_2 + HBr \longrightarrow CH_3CH_2Br$$

- Radioactive isotope can also be used in agriculture. The fertilizers can be labelled with radioactive isotopes. Metabolism in plants can be studied through these labelled isotopes. Similarly, the metabolism in animals can also be studied.

Medical uses of radioactivity

- as diagnostic tracers. E.g., radioisotope Iodine-131 is used as tracer to locate malignant cells of thyroid gland
- Radio isotopes are also used for the treatment of diseases. E.g. Iodine-131, in addition of being a tumor marker, can also be used to destroy the malignant cells on the thyroid gland.
  Cobalt-60 is used in cancer therapy and also in food irradiation.

22. Write any two applications of isotopes: Cobalt-60 and Iodine-131. 2
23. What are radioisotopes? Write one use of such isotopes. 2
24. Write down any two uses of radioisotopes in the medical field. 2

Radiocarbon dating

Carbon dating is a technique to determine the age of archaeological materials like fossils, bone, wood, paper, leather etc. The following reaction occurs at the upper atmosphere as cosmic rays have neutrons which bombard on nitrogen;

C-14 is weakly radioactive decays continuously to produce N-14 by emitting **β rays**.

This ^{14}C although in small amount is absorbed by living plants as $^{14}CO_2$ during the process of photosynthesis and later enters into living animals. This ^{14}C has the same decay rate in all living plants and animals (15.3 β rays emitted per gram of natural carbon). When the plants and animals die the steady state ratio of carbon cycle is cut off but the ^{14}C keeps on decaying continuously by emitting β rays.

The rate of decay decreases continuously but slowly in dead plants or animals. By comparing the β ray activity of dead sample to that of living plants and animals the age of a given sample can be determined by using the following rate law equation**.**

$$t = \frac{2.303}{\lambda} log \frac{a}{(a-x)}$$

Let a = N_O = initial activity (living body)
and (a-x) = N = Activity left at time ***t*** which is directly proportional to the rate of ^{14}C decay in the dead sample.

$$t = \frac{2.303}{\lambda} log \frac{No}{N}$$

$$= \frac{0.693}{t1/2}$$

The $t_{1/2}$ for C is 5670 years

$$Therefore, \quad = \frac{0.693}{5670} \ year^{-1}$$

$$\boldsymbol{\lambda = 1.203 \times 10^{-4}/year}$$

25. The decay rate for ^{14}C of a sample is 10 disintegrations/min/gm of C and the same for the living sample is 15.3 disintegrations/min/gm of C. Determine the age of the givensample. ($t_{1/2}$ for ^{14}C = 5760 years) (Ans: t = 3535.69 years)

Harmful effects of nuclear radiations

- Common nuclear radiations (α, β, γ, n) have sufficient ionizing power to affect the atoms of living cells, leading to tissue damage and alteration in DNA genes.
- High levels of exposure may lead to cancer. But the requisite amount (γ rays from Co-60) also destroys cancerous cells.
- Exposure to high-level nuclear radiation may lead to radiation sickness (nausea, vomiting, or even death).
- Children and fetuses are more sensitive to the radiation exposures.
- Radiation can cause genetic effect which may not be visible instantly.
- Long-term or short-term exposure to radioactivity has harmful effects both on animals and vegetation.

26. Applied chemistry deals with the chemistry involved in the materials of daily use.
Explain the harms caused by nuclear radiation or radioactivity on human health. 2

1. Who discovered radioactivity?
   a. Madam Curie c. **Henry Becquerel**
   b. Neils Bohr d. J. J. Thompson
2. The unit of radioactivity is
   a. Plank b. Curie c. Joule d. Calorie
3. The SI unit of radioactivity is
   a. Curie b. Becquerel c. Rutherford d. Einstein
4. Atom bomb blast is based on
   a. Nuclear fusion reaction c. Nuclear fission reaction
   b. Radioactive decay reaction d. Chemical reaction
5. A hydrogen bomb is
   a. Bomb made by hydrogen gas under high pressure.
   b. Atom bomb c. Fission bomb d. Fusion bomb
6. Which of the following is used in dating archeological findings?
   a. $_{92}U^{238}$ b. $_{1}H^{3}$ c. $_{8}C^{18}$ d. $_{6}C^{14}$
7. Which radio-isotope is used to detect blood clot?
   a. Co-60 b. As-74 c. Na-24 d. I-131
8. Which of the following radioactive is used to test the functioning of the thyroid gland?
   a. Iodine b. phosphorus c. carbon d. sodium
9. Heavy water is
   a. Moderator b. Controller c. coolant d. both a and c
10. The ratio of the specific charge of a proton and an α-particle is
    a. 1:2 b. 2:1 c. 1:4 d. 1:1
11. $_{90}Th^{228} \rightarrow {}_{83}Bi^{212}$ by
    a. 4α, 1β b. 4α, 2β c. 5α, 1β d. 5α, 2β
12. Cathode rays are deflected by
    a. Both electric and magnetic field. C. An electric field only.
    b. Neither electric nor magnetic field. D. A magnetic field only.