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CHM 101: GENERAL CHEMISTRY 1: 3UNITS

RADIOACTIVITY

Radioactivity is the disintegration of radioactive elements. The phenomenon was first discovered in 1896 by Henri Bequerel. In 1990, the pair of Mme and Piere Curie further confirmed the existence of radiations from substances like $^{238}_{92}U$, $^{218}_{84}P_o$, $^{226}_{88}R_a$, $^{222}_{86}R_n$, $^{234}_{90}Th$ etc. These radiations were found to be alpha (α-), beta (β-) particles and gamma (γ-) rays

Transformation during emission of Alpha (α-), Beta (β-) particles and Gamma (γ-) rays

(a) Emission of Alpha (α-) Particles: When α- particles are emitted from an element, the mass number of the parent atom decreases by 4 units and the atomic number decreases by 2 units. This is illustrated as follows: $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

$$^{222}_{86}R_n \rightarrow ^{218}_{84}P_o + ^{4}_{2}He$$

(b) Emission of Beta (β-) Particles: When β- particles are emitted from an atom, the mass number remain unchanged while the atomic number increases by 1 unit. This is shown in the following equations: $^{214}_{82}Pb \rightarrow ^{214}_{83}P_o + ^{0}_{-1}e$

$$^{214}_{83}Bi \rightarrow ^{214}_{84}P_o + ^{0}_{-1}e$$

(c) Emission of Gamma (γ-) Rays: When γ- rays are emitted from an atom, both the mass and atomic numbers remain unchanged because it involves transition of energy from the excited state to the ground state. The following equations illustrate this type of emission:

$$^{99}_{43}Tc^* \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$$

$^{87}_{38}Sr^* \rightarrow ^{87}_{38}Sr + ^{0}_{0}\gamma$; where * shows the atom in an excited energy level.

Properties of Alpha (α-), Beta (β-) particles and Gamma (γ-) rays

	Alpha (α-) Particles	Beta (β-) particles	Gamma (γ-) rays
Nature	Helium atoms (^4_2He)	Stream of electrons $_{-1}^{0}e$	Electromagnetic waves
Charge	Positively charged (+)	Negatively charged (-)	Neutral (±)
Velocity	Travels with 1/20th that of speed of light	Travels 10 times faster than α- particles	Same as the speed of light
Ionization Power	Highest ionization power	Low ionization power	Least ionization power
Penetration Power	Least penetration power (can be stopped by sheets of paper)	Moderate penetration power (can be stopped by 1 cm of Al sheets)	Highest penetration power (can be stopped by several layers of lead)
Effect on Magnetic and Electric Fields	Slightly deflected to the positive (-) plate of the field	Strongly deflected to the positive (+) plate of the field	Remain undeflected

Detection and Measurement of Particles/Radiations

This is achieved through (i) Use of Cloud Chambers (ii) Ionization Chambers (or Dosimeter) (iii) Geiger – Muller counters (iv) Scintillation counters (v) Film badges.

Types of Radioactivity

There are two main types of radioactivity: Natural and Artificial radioactivity.

(i) **Natural Radioactivity**: This is the spontaneous disintegration of radioactive elements. Examples include: $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

$$^{222}_{86}R_n \rightarrow {}^{218}_{84}P_o + {}^{4}_{2}He$$

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}P_o + {}_{-1}^{0}e$$

$$^{214}_{83}Bi \rightarrow {}^{214}_{84}P_o + {}_{-1}^{0}e \text{ etc}$$

(ii) **Artificial/Induced Radioactivity**: This is the disintegration of radioactive elements by induction or bombardment with other particles. The following equations illustrate artificial radioactivity: $^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{94}Pu\ 2{}_{-1}^{0}e$

$$^{239}_{94}Pu + {}^{1}_{0}n \rightarrow {}^{90}_{38}Sr + {}^{147}_{56}Ba + 3\,{}^{1}_{0}n\ {}^{1}_{0}n$$

AE

$$^{40}_{18}Ar + ^{1}_{1}H \rightarrow ^{40}_{19}K + ^{1}_{0}n$$

$$^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{24}_{11}Na + ^{4}_{2}He \text{ etc}$$

Why Radioactive Nuclei are Unstable (Nuclear Stability)

There are three main reasons for the instability of radioactive nuclei. These are:

i) Neutron to Proton (n/p) Ratio

ii) Binding Energy per Nucleon and

iii) Nuclides with atomic numbers corresponding to Magic numbers.

Rate of Radioactive Decay

- The rate of radioactive decay is a characteristic of radioisotopes. It has been found to follow first order kinetics, The rate of decay is not dependent on external conditions like temperature, pressure etc. It depends only on the number of atoms present.

If No is the number of atoms at t = o and N is the amount of the isotope present at time = t

Then, $-{dN}/{dt} \propto N$ (the negative sign means that the isotope is decreasing)

or $-{dN}/{dt} = \lambda N$ (1)

where λ is the decay constant and ${dN}/{dt} = \lambda N$ is the activity (A) of the radioactive substance

ie $A = {dN}/{dt} = \lambda N$ (2)

The unit of activity is **Curie.** (Ci. **1 Ci = 3.7 x 10^{10}dps or Becquerel, Bq = 1dps)**

Half – life, $t_{1/2}$: This is the time (or period) taken for **half** of the radioisotope to decay. It varies from microseconds to millions of years.

Calculation of half – life, $t_{1/2}$: This is obtained from equation (1): $-{dN}/{N} = \lambda dt$.

On integration of equation (1), the following is obtained:

$$-\int {dN}/{N} = \lambda \int dt \text{ or } -\ln N = \lambda t + I \quad (3)$$

where I = the integration constant.

$-\ln N = \lambda t$

If No is the number of atoms at t = 0, I = = - In No. Substituting the value of I into equation (3) will give – In N = λt – In No

or In $\left(No/_N\right)$ = λt

or 2.303 log $\left(No/_N\right)$ = λt (4)

or log $\left(No/_N\right) = {\lambda t}/_{2.303}$

At half – life period ($t_{1/2}$), N = ½ No or 2.303 log $\left(No/_{½No}\right)$ = 2.303 log 2 = ($t_{1/2}$

or 0.693 = λ $t_{1/2}$

Therefore, $t_{1/2} = {0.693}/_{\lambda}$ **or** $\lambda = {0.693}/_{t_{1/2}}$

Worked Examples:

1. Calculate the decay constant of cobalt – 60 if its half – life is 5.2 years.

Solution: Let the decay constant be λ,

Recall that $t_{1/2} = {0.693}/_{\lambda}$ or $\lambda = {0.693}/_{t_{1/2}}$

$= {0.693}/_{5.2} = 0.13\ yr^{-1}$

2. Calculate the half - life of radium – 226 if 1.0g of it emits 3.70 x 10^{10} alpha particles per second.

Answer: Rate of decay = Rate of emission of α – particles.

${dN}/_{dt} = \lambda N = 3.70 \times 10^{10}$ per second (1)

Number of atoms in 1.0 g of Rn = $\frac{6.023\ x^{23}}{226}$

But $\lambda = {0.693}/_{t_{1/2}}$.

Substituting the values of λ and N into equation (1) will give

$${dN}/_{dt} = {0.693}/_{t_{1/2}} \times \frac{6.023\ x^{23}}{226} = 3.70 \times 10^{10}$$

$$\therefore t_{1/2} = \frac{0.693 \times 6.023 \times 10^{23}}{3.70 \times 10^{10} \times 226 \times 60 \times 60 \times 24 \times 365} = 1583 \text{ years}$$

3. Calculate the activity of radon – 222 if its half – life is 3.825 days.

Answer: dN = λN

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But $\lambda = {0.693}/{t_{\frac{1}{2}}} = \frac{0.693}{3.825 \times 24 \times 60 \times 60} = 2.096 \times 10^{-6}\ sec^{-1}$

$\therefore N = {dN}/{\lambda} = {3.70 \times 10^{10}}/{2.096 \times 10^{-6}} = 1.7653 \times 10^{16}$ atoms

Mass of 6.023×10^{23} atoms = 222 g

$\therefore$ Mass of 1.7653×10^{16} atoms = $\frac{222}{6.023 \times 10^{23}} \times 1.7653 \times 10^{16} = 6.51 \times 10^{-6}g$

$\therefore$ Activity of radon = $6.51 \times 10^{-6}g$

4. Cobalt – 60 disintegrate to give nickel – 60. Calculate the fraction and percentage of the sample that remains after 15 years if λ of Co - 60 is $0.13\ yr^{-1}$.

Solution: $\log ({No}/{N}) = {\lambda t}/{2.303}$

$= \frac{0.13\ yr^{-1} \times 15\ yrs}{2.303} = 0.847$

$\frac{No}{N}$ = Antilog of 0.847 = 7.031

Fraction of sample remaining is

$\frac{No}{N} = \frac{1}{7.031} = 0.14$

$\therefore$ % of sample that remains = 0.14 x 100 % = 14%.

5. What time will it take for a sample of cobalt – 60 to disintegrate to the extent that only 2.0 % remains if the decay constant of Co – 60 is $0.13\ yr^{-1}$?

Answer: Let the time = t years.

$\frac{No}{N} = \frac{2}{100} = 0.02$

or $\frac{No}{N} = \frac{1}{0.02} = 50$

But $\log ({No}/{N}) = {\lambda t}/{2.303}$

$\log 50 = \frac{(0.13\ yr^{-1}) \times t}{2.303}$

$\therefore t = \frac{2.303 \log 50}{0.13} = 30$ yrs

AD

The Group Displacement Law

The law states that when an ∝ - particle is emitted, the parent atom will be displaced two places to the left of the Periodic Table while the emission of a β – particle will displace the parent atom, one place to the right of the Periodic Table. The law was first stated by Fajans and Soddy in 1913.

IVB	VB	VIB
$\beta-$ Th ←	→ Pa α -	— U

Illustration of Group Displacement Law

Average – Life, τ: This is the statistical average of the lives of all atoms present at any time. It is denoted by tau, τ. Average – life, τ is the reciprocal of decay constant.

i.e $\tau = {}^{1}/_{\lambda}$

The average – life of a radioactive element is related to its half – life by the expression

Average – life = 1.44 x half – life

or $\tau = 1.44 \times t_{\frac{1}{2}}$

Nuclear Fission Reactions or Processes: In fission reactions, the parent atom disintegrates into daughter atom (s) after being bombarded by a particle (like $^{1}_{0}n$, $^{4}_{2}He$, $^{1}_{1}H$, $^{2}_{1}H$ etc). It is usually accompanied by a release of energy. All the positively charged particles are accelerated to high kinetic energies by a device like CYCLOTRON.

For example, $\xrightarrow[\ ^{4}_{2}He]{\propto\text{ - particle}} \ ^{14}_{7}N \longrightarrow \ ^{18}_{9}F \longrightarrow \ ^{17}_{8}O + \ ^{1}_{1}H$

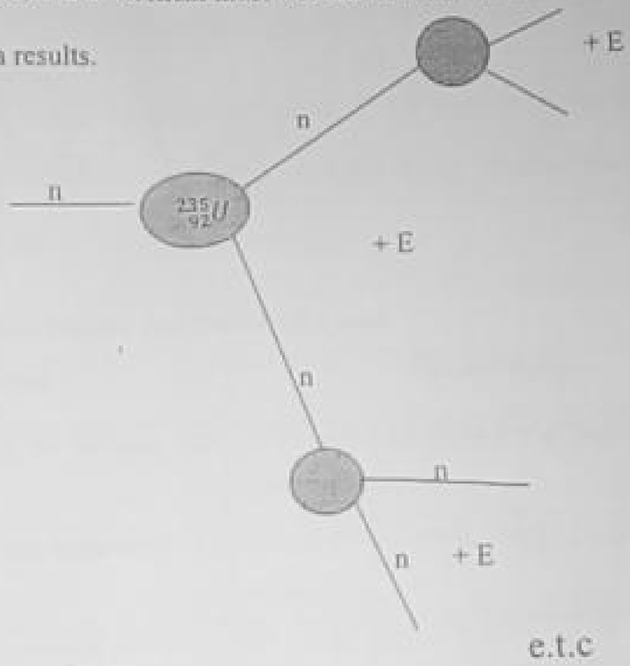
Unstable compound nucleus ($^{18}_{9}F$)

Nuclear fission involves the splitting of heavy nucleus into simpler ones after **bombardment**.

It was discovered in 1939 by Hahn and Stassmann.

E.g $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3^{1}_{0}n$

If the process is not controlled, and a **"critical mass"** of the fissionable material is exceeded, then a nuclear chain reaction results.



Chain Reaction

Fission process does not require high temperatures to occur. To control fission reactions, they are carried out in **Nuclear Piles or Reactors**. The energy is harnessed in this case for peaceful purposes. If fission reactions are not controlled, the energy released is destructively used.

<u>Nuclear Fusion Reactions (or Processes):</u> These involves combination of two or more light – weight nuclei to form heavier nucleus. The following equations are examples of nuclear fusion processes.

$2^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$ + Energy

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

Since fusion reactions take place at extremely high temperatures, they are called

Thermonuclear Reactions

In fusion reactions, the mass(es) of reacting nuclei is greater than those of nuclei formed. The difference in mass is accounted for by the energy released.

Fusion reactions require high activation energies to occur. The amount of energy produced in fusion is far greater than that obtain ed from fission reactions. These reactions form the basis of hydrogen and neutron bombs.

Differences Between Nuclear Fission and Nuclear Fusion

Nuclear Fission	Nuclear Fusion
- Involves splitting of heavier nucleus into smaller or lighter ones	Involves the combination of lighter nuclei to form heavier ones
- Does not require high temperature(s) to occur	Requires extremely high temperatures to occur
- If not controlled, a chain reaction sets in.	No chain reaction results.
- When controlled, the energy released can be used for peaceful purposes	Cannot be controlled, hence, the energy released cannot be properly be utilized.
- The products of fission reactions are radioactive in nature	The products of fusion reactions are non-radioactive in nature.
- Nuclear waste is left behind at the end of the reaction	No nuclear waste is left at the end of the reaction.

Writing Nuclear Equations

The following steps are/should be taken when writing nuclear equations:

- i) Write the symbols of the nuclei and particles including their mass numbers (as superscripts) and their atomic numbers (as subscripts) on the left (reactants) and right (products) of the arrow.

ii) Balance the equation by checking the mass and atomic numbers of the particles (including the unknown) on both sides of the equation ~~of the equation~~. Then find the mass and atomic numbers of the unknown atom, if any.

iii) Identify the unknown atom by looking at the Periodic Table.

Examples:

1) Disintegration of radium – 236 by alpha emission.

$^{226}_{88}Ra \rightarrow {}^{232}_{86}X + {}^{4}_{2}He$: X = Radon

2) Fission of argon – 40 by bombardment with a proton ($^{1}_{1}H$) .

$^{40}_{18}Ar + {}^{1}_{1}H \rightarrow {}^{40}_{19}K + {}^{1}_{0}n$

3) Disintegration of phosphorous – 32 by emission of beta ($^{0}_{-1}e$) particles.

$^{32}_{15}P \rightarrow {}^{-1}_{0}e + {}^{32}_{16}X$ (X = Sulphur)

4) Fission of uranium – 235 by absorption of a neutron ($^{1}_{0}n$)

$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{142}_{56}Ba + {}^{91}_{36}Kr + 3{}^{1}_{0}n$

5) Fusion of lithium – 7 and a proton ($^{1}_{1}H$)

$^{7}_{3}Li + {}^{1}_{1}H \rightarrow 2{}^{4}_{2}He$

Exercise:

1. Write the nuclear equation for the transformation that occurs in radium – 226 when it emits an alpha particle.

$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + ?$

$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{86}X$ where X = Radon.

2. Cobalt – 60 decays by beta emission. What is the mass number, atomic number and the name of the isotope formed?

$^{60}_{27}Co \rightarrow X + {}^{0}_{-1}e$

$^{60}_{27}Co \rightarrow {}^{60}_{28}X + {}^{0}_{-1}e$ Where X = Nickel (Ni).

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General Applications of Radioactivity and Radioisotopes:

Radioactivity/Radioisotopes are extremely useful in almost all spheres of life. The undermentioned examples illustrate some important applications of radioisotopes:

i) In Medicine: This application is termed radiotherapy. E.g $^{131}_{53}I$ is used in the detection and functioning of thyroid gland and to treat **hyperthyroidists**.

$^{131}_{53}I$ is mixed with organic dye and injected to detect the size and location of **brain tumour**.

- Radiophosphorous, $^{32}_{15}P$ is used to treat **leukaemia**. $^{60}_{27}Co$ is used to destroy cancer causing cells. $^{24}_{11}NaCl$ is injected in blood stream to trace the circulation of blood (i.e to find out the clotting of blood).

ii) In Agriculture iii) In the Industry iv) In Chemistry (i.e to study reaction pathways or mechanisms) e.g

$$\underset{\text{Benzamide}}{C_6H_5-CO-NH_2} + \underset{\text{Acetamide}}{CH_3-CO-N^*H_2} \rightarrow \underset{\text{Aniline}}{C_6H_5-NH_2} + 2KBr + K_2CO_3 + \underset{\text{Methyl amine}}{CH_3-N^*H_2} + 2KBr + K_2CO_3$$

v) Neutron Activation Analysis

vi) Discovery of New elements.

vii) Discovery of Alternative Source of Energy.

viii) In Biology – like in Photosynthesis

ix) In Geological or Carbon-dating (i.e predicting the age of the Earth and Rocks.

Hazards of Nuclear Radiations:

- **Genetic Damage** – caused by absorption of very high doses of radiations on chromosomes of the cellular nuclei and thus damaging the genes in the reproductive cells.

- **Pathological damage** – the extent of pathological damage depends on the doses of radiation. the smaller dose of radiations causes fatal diseases like cancer and leukaemia to develop while heavy doses of radiations cause immediate death.