Hydrogen Notes

❖ Position of Hydrogen in the Periodic Table

- Hydrogen is the **first element** of the periodic table.
- Its Electronic configuration: **$1s^1$**.
- It has similarities with **Group 1 (Alkali metals)** and **Group 17 (Halogens)**.

Similarities with Alkali Metals

- It Has **one electron** in the outermost shell (ns^1).
- It Loses only one electron to form **H^+**.
- It Forms **oxides, halides, and sulphides**.

Similarities with Halogens

- It Needs **one electron** to complete its shell.
- It Forms **H^- (hydride ion)**.
- It is Exists as a **diatomic molecule (H_2)**.
- Forms many **covalent compounds**.

Q1. Why Hydrogen is Unique?

Ans : Because

- It has High ionization enthalpy (**1312 kJ mol^{-1}**).
- It is Non-metal under normal conditions.
- **It has H^+ ion is extremely small** (~1.5×10^{-3} pm) and never exists freely.

Therefore, hydrogen is **placed separately** in the periodic table.

Dihydrogen (H_2)

- Elemental hydrogen exists as **H_2 (dihydrogen)**.
- It is **colourless, odourless, and diatomic**.
- It forms more compounds than any other element.
- It is considered a **future clean fuel** because it can be used as an energy source.

❖ Occurrence of Hydrogen

In the Universe

- It is Most abundant element.
- About **70% of the total mass** of the universe.
- it is Main element of the **Sun**.
- Jupiter and Saturn contain mostly hydrogen.

On Earth

- It is Only **0.15%** by mass in the atmosphere.
- About **15.4%** of the Earth's crust and oceans (in combined form).
- Found in: Water (H_2O) ,Plants and animals ,Carbohydrates ,Proteins ,Hydrocarbons ,Hydrides

❖ isotopes of Hydrogen

Hydrogen has **three isotopes**.

Isotope	Symbol	Protons	Neutrons	Nature
Protium	^1_1H	1	0	Stable
Deuterium (Heavy Hydrogen)	^2_1H or D	1	1	Stable
Tritium	^3_1H or T	1	2	Radioactive

Important notes :

- **Protium** is the most abundant isotope (**99.985%**).
- **Deuterium** abundance is **0.0156%**.
- **Tritium** is radioactive.
- Tritium emits **β^- (beta) particles**.
- Half-life of tritium = **12.33 years**.
- **Harold C. Urey** received the **1934 Nobel Prize** for discovering/separating deuterium

- Electronic configuration of H = **$1s^1$**
- Ionization enthalpy = **1312 kJ mol^{-1}**
- Electron gain enthalpy = **–73 kJ mol^{-1}**
- Covalent radius = **37 pm**
- Ionic radius (H^-) = **208 pm**

1. Why is hydrogen placed separately in the periodic table?

Ans : Hydrogen resembles both alkali metals and halogens, but it also differs from both. It has a high ionization enthalpy, is non-metallic, and its H^+ ion is extremely small and cannot exist freely. Therefore, hydrogen is placed separately in the periodic table.

2. Write the similarities of hydrogen with alkali metals.

Ans : Both have **one electron** in the outermost shell (ns^1).

- Both lose one electron to form **+1 ions** (H^+ and M^+).
- Both form **oxides, halides, and sulphides**.

3. Write the similarities of hydrogen with halogens.

Ans : Hydrogen needs **one electron** to complete its shell.

- It forms the **hydride ion (H^-)** like halogens form X^- ions.
- It exists as a **diatomic molecule (H_2)**.
- It forms many **covalent compounds**.

4. Why is H^+ not found freely?

Ans The **H^+ ion is extremely small** (about 1.5×10^{-3} pm) and has a very high charge density. Hence, it cannot exist freely and is always associated with other atoms or molecules.

5. What is dihydrogen?

Ans Dihydrogen (**H_2**) is the elemental form of hydrogen. It is a **colourless, odourless, diatomic gas** and is an important industrial chemical as well as a clean source of energy.

6. Describe the occurrence of hydrogen.

Ans Hydrogen is the **most abundant element in the universe**, making up about **70%** of its total mass.

- It is the principal element in the **Sun** and is abundant in **Jupiter and Saturn**.
- On Earth, it forms only about **0.15%** of the atmosphere by mass.
- In combined form, it makes up about **15.4%** of the Earth's crust and oceans.
- It occurs in **water, hydrocarbons, hydrides, carbohydrates, proteins, and living organisms**.

7. Name the three isotopes of hydrogen.

Ans The three isotopes of hydrogen are:

- **Protium (^1_1H)**
- **Deuterium (^2_1H or D)**
- **Tritium (^3_1H or T)**

8. Which isotope of hydrogen is radioactive?

Ans **Tritium (^3_1H or T)** is the radioactive isotope of hydrogen.

9. Who discovered deuterium?

Ans **Harold C. Urey** discovered (separated) deuterium and was awarded the **Nobel Prize in Chemistry in 1934**.

10. State the abundance of protium, deuterium, and tritium.

Ans **Protium: 99.985%**

- **Deuterium: 0.0156%**
- **Tritium:** About **1 atom per 10^{18} atoms of protium** (very rare).

❖ Preparation of Dihydrogen (H_2)

A. Laboratory Preparation

(i) Zinc + Dilute HCl

$$Zn + 2HCl \rightarrow ZnCl_2 + H_2 \uparrow$$

(ii) Zinc + NaOH

$$Zn + 2NaOH \rightarrow Na_2ZnO_2 + H_2 \uparrow$$

(Product: **Sodium zincate**)

2. Commercial Preparation

(i) Electrolysis of Water

$$2H_2O \rightarrow 2H_2 + O_2$$

Uses acid/base and Pt electrodes.

(ii) Electrolysis of $Ba(OH)_2$ Solution

Produces **99.95% pure hydrogen**.

(iii) Electrolysis of Brine

Anode

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

Cathode

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Products: Hydrogen , Chlorine ,Sodium hydroxide

(iv) Steam Reforming (Most Important)

$$CH_4 + H_2O \xrightarrow{Ni,1270K} CO + 3H_2$$

Mixture of **CO + H_2** is called

- **Water gas**
- **Synthesis gas (Syngas)**

➢ **Water Gas Shift Reaction**

$$CO + H_2O \xrightarrow{673K,FeCrO_4} CO_2 + H_2$$

Purpose: Increases hydrogen yield.

Industrial Sources

- **77%** Petrochemicals , **18%** Coal , **4%** Electrolysis , **1%** Others

Preparation of Dihydrogen (H_2)

Dihydrogen is prepared by several methods in the laboratory and industry.

1. Laboratory Preparation

Hydrogen is commonly prepared by the action of dilute acids on metals like zinc.

Reaction:

- $Zn + 2HCl \rightarrow ZnCl_2 + H_2\uparrow$
- $Zn + H_2SO_4$ (dil.) $\rightarrow ZnSO_4 + H_2\uparrow$

2. From Water

Highly reactive metals react with water to produce hydrogen.

Examples:

- $2Na + 2H_2O \rightarrow 2NaOH + H_2\uparrow$
- $Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2\uparrow$

3. Industrial Preparation

(a) Steam Reforming of Natural Gas

- $CH_4 + H_2O \rightarrow CO + 3H_2$
- $CO + H_2O \rightarrow CO_2 + H_2$

(b) Electrolysis of Water

- $2H_2O \rightarrow 2H_2 + O_2$ (using electricity)

➢ Properties of Dihydrogen (H_2)

Physical Properties

- Colourless, odourless, and tasteless gas.
- Lightest known gas.
- Sparingly soluble in water.
- Non-toxic and highly combustible.
- Burns with a pale blue flame.

➢ Chemical Properties

1. **Combustion**
   - $2H_2 + O_2 \rightarrow 2H_2O$ + Heat
2. **Reducing Nature**
   - Reduces metal oxides to metals.
   - Example:

- $CuO + H_2 \rightarrow Cu + H_2O$

3. **Reaction with Non-metals**
   - $H_2 + Cl_2 \rightarrow 2HCl$
   - $N_2 + 3H_2 \rightleftharpoons 2NH_3$ (Haber process)
4. **Reaction with Metals**

   It Forms metal hydrides.
   - Example: $2Na + H_2 \rightarrow 2NaH$

Uses of Dihydrogen

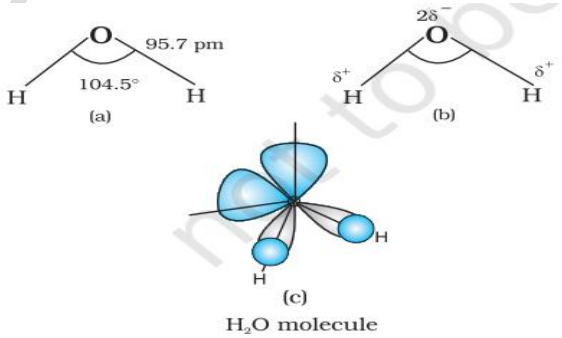
- Manufacture of ammonia (Haber process).
- Hydrogenation of vegetable oils.
- Fuel in rockets.
- Used in fuel cells for clean energy.
- Reducing agent in metallurgy.

❖ Physical Properties of Water (H_2O)

- Water is a **colourless, odourless, and tasteless** liquid.
- It has **high melting point (273 K)** and **high boiling point (373 K)** due to **strong hydrogen bonding**.
- It has **high heat of vaporisation** and **high heat of fusion**.
- Water has **high specific heat capacity**, so it absorbs a lot of heat without a large increase in temperature.
- It has **high surface tension** and **high thermal conductivity**.
- Water has a **high dielectric constant**, making it an excellent solvent for ionic compounds.
- It is called the **universal solvent** because it dissolves many ionic and polar substances.
- Polar covalent compounds such as **alcohols** and **carbohydrates** also dissolve in water because of hydrogen bonding.
- Water helps regulate **Earth's climate** and **body temperature** because of its high heat capacity and heat of vaporisation.

Structure of Water

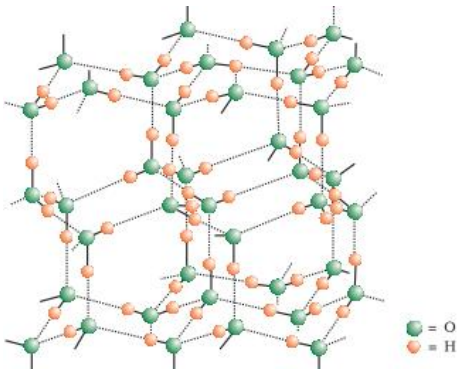
- Water is a **bent (V-shaped)** molecule.
- **H–O–H bond angle: 104.5°**
- **O–H bond length: 95.7 pm**
- Water is a **highly polar molecule** because oxygen is more electronegative than hydrogen.
- In the **liquid state**, water molecules are connected by **hydrogen bonds**, giving water its unusual properties.



H_2O molecule

Ice (Solid Water)

- Ice has a **hexagonal crystal structure** at normal atmospheric pressure.
- At very low temperatures, ice can exist in a **cubic form**.
- **Ice is less dense than liquid water**, so it **floats**.
- Floating ice forms an insulating layer on lakes during winter, allowing aquatic organisms to survive beneath it. This is **ecologically important**.



➢ Important Physical Properties of H_2O

Property	H_2O
Molecular mass	18.015 g mol^{-1}
Melting point	273 K
Boiling point	373 K
Density (298 K)	1.0 g cm^{-3}
Heat of vaporisation	40.66 kJ mol^{-1}

Property	H_2O
Heat of fusion	6.01 kJ mol^{-1}
Maximum density	277 K (≈ 4°C)

❖ Chemical Properties of Water (H_2O)

Water is a highly reactive substance and participates in many chemical reactions.

❖ Amphoteric Nature of Water

Water can act as both an **acid and a base**, so it is called an **amphoteric substance**.

(a) Water acts as a base (with acids):

$$H_2O + H_2S \rightleftharpoons H_3O^+ + HS^-$$

(b) Water acts as an acid (with bases):

$$H_2O + NH_3 \rightleftharpoons NH_4^+ + OH^-$$

Auto-protolysis (self-ionisation) of water:

$$H_2O + H_2O \rightleftharpoons H_3O^+ + OH^-$$

❖ Redox Reactions Involving Water

Water undergoes both **reduction and oxidation** reactions.

(a) Reduction of water by electropositive metals:

$$2Na + 2H_2O \rightarrow 2NaOH + H_2$$

Thus, water acts as a source of **dihydrogen (H_2)**.

(b) Oxidation of water during photosynthesis:

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

Water is oxidised to release oxygen.

(c) Reaction with fluorine:

$$2F_2 + 2H_2O \rightarrow 4H^+ + 4F^- + O_2$$

❖ Hydrolysis Reaction

Due to its **high dielectric constant** and strong hydrating ability, water dissolves many ionic compounds.

Some covalent compounds undergo hydrolysis:

Phosphorus pentoxide:

$$P_4O_{10} + 6H_2O \rightarrow 4H_3PO_4$$

Silicon tetrachloride:

$$SiCl_4 + 2H_2O \rightarrow SiO_2 + 4HCl$$

Nitrogen nitride:

$$Mg_3N_2 + 6H_2O \rightarrow 3Mg(OH)_2 + 2NH_3$$

❖ Hydrates Formation

Many salts crystallise from aqueous solutions with water molecules attached. These are called **hydrated salts**.

Types of water present in hydrates:

1. **Coordinated water**
   - Water molecules directly bonded to metal ions.
   - Example:

$$[Cr(H_2O)_6]Cl_3$$

2. **Interstitial water**
   - Water molecules occupy spaces in crystal lattice.
   - Example:

$$BaCl_2 \cdot 2H_2O$$

3. **Hydrogen-bonded water**
   - Water molecules attached through hydrogen bonding.
   - Example:

$$CuSO_4 \cdot 5H_2O$$

In **$CuSO_4 \cdot 5H_2O$**, only **one water molecule** is hydrogen-bonded; the other four are coordinated.

❖ Hard and Soft Water

Hard Water

Water containing dissolved salts of **calcium (Ca^{2+})** and **magnesium (Mg^{2+})** is called hard water.

- Does not form lather easily with soap.
- Forms scum due to insoluble calcium/magnesium stearates.
- Causes scale formation in boilers.

Soap reaction:

$$2C_{17}H_{35}COONa + Ca^{2+} \rightarrow (C_{17}H_{35}COO)_2Ca \downarrow + 2Na^+$$

Soft Water

Water free from calcium and magnesium salts is called soft water.

- Forms lather easily with soap.

❖ Types of Hardness of Water

1. Temporary Hardness

Cause: Presence of calcium and magnesium bicarbonates.

Examples:

- $Ca(HCO_3)_2$
- $Mg(HCO_3)_2$

Removal Methods:

(a) Boiling

$$Mg(HCO_3)_2 \xrightarrow{heat} Mg(OH)_2 \downarrow + 2CO_2$$
$$Ca(HCO_3)_2 \xrightarrow{heat} CaCO_3 \downarrow + H_2O + CO_2$$

The precipitates are removed by filtration.

(b) Clark's Method

Calculated amount of lime, $Ca(OH)_2$, is added.

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3 \downarrow + 2H_2O$$
$$Mg(HCO_3)_2 + 2Ca(OH)_2 \rightarrow Mg(OH)_2 \downarrow + 2CaCO_3 \downarrow + 2H_2O$$

❖ Permanent Hardness

Cause: Presence of calcium and magnesium chlorides and sulphates.

It cannot be removed by boiling.

Removal Methods:

(a) Washing Soda Method

Sodium carbonate reacts with calcium and magnesium salts.

$$CaCl_2 + Na_2CO_3 \rightarrow CaCO_3 \downarrow + 2NaCl$$
$$MgSO_4 + Na_2CO_3 \rightarrow MgCO_3 \downarrow + Na_2SO_4$$

(b) Calgon Method

Calgon is **sodium hexametaphosphate ($Na_6P_6O_{18}$)**.

It forms soluble complexes with Ca^{2+} and Mg^{2+} ions, preventing hardness.

(c) Zeolite/Permutit Method

Zeolite (sodium aluminium silicate) exchanges Na^+ ions with Ca^{2+} and Mg^{2+} ions.

$$2NaZ + Ca^{2+} \rightarrow CaZ_2 + 2Na^+$$

Regeneration:

$$CaZ_2 + 2NaCl \rightarrow 2NaZ + CaCl_2$$

(d) Synthetic Resin Method

Synthetic cation exchange resins replace Ca^{2+} and Mg^{2+} ions with Na^+ ions.

$$2RNa + Ca^{2+} \rightarrow R_2Ca + 2Na^+$$

For complete demineralisation:

- Cation exchange resin removes positive ions.
- Anion exchange resin removes negative ions.

Hydrogen ions and hydroxide ions combine:

$$H^+ + OH^- \rightarrow H_2O$$

This produces **pure de-ionised water**.

Hydrogen Peroxide (H_2O_2)

❖ Structure of Hydrogen Peroxide

- Hydrogen peroxide has a **non-planar structure**.
- The two O–H bonds and the O–O bond are not present in the same plane.
- The molecule has a **skew (open book) conformation** due to rotation around the O–O bond.

Structure in Different States:

- **Gas phase:**
  - Dihedral angle = **111.5°**
- **Solid phase (at 110 K):**
  - Dihedral angle = **90.2°**

❖ Chemical Properties of Hydrogen Peroxide

Hydrogen peroxide acts as both an **oxidising agent** and a **reducing agent** in acidic as well as alkaline media.

(i) Oxidising Action in Acidic Medium

Hydrogen peroxide oxidises substances by accepting electrons.

Oxidation of Fe^{2+} ions:

$$2Fe^{2+} + 2H^+ + H_2O_2 \rightarrow 2Fe^{3+} + 2H_2O$$

Oxidation of Lead sulphide:

$$PbS + 4H_2O_2 \rightarrow PbSO_4 + 4H_2O$$

(ii) Reducing Action in Acidic Medium

Hydrogen peroxide reduces strong oxidising agents.

Reduction of permanganate ions:

$$2MnO_4^- + 6H^+ + 5H_2O_2 \rightarrow 2Mn^{2+} + 8H_2O + 5O_2$$

Reduction of hypochlorous acid:

$$HOCl + H_2O_2 \rightarrow H_2O + Cl^- + H^+ + O_2$$

(iii) Oxidising Action in Basic Medium

Hydrogen peroxide oxidises metal ions.

Examples:

$$2Fe^{2+} + H_2O_2 \rightarrow 2Fe^{3+} + 2OH^-$$
$$Mn^{2+} + H_2O_2 \rightarrow MnO_2 + 2OH^-$$

(iv) Reducing Action in Basic Medium

Hydrogen peroxide reduces oxidising ions.

Reduction of iodine:

$$I_2 + H_2O_2 + 2OH^- \rightarrow 2I^- + 2H_2O + O_2$$

Reduction of permanganate:

$$2MnO_4^- + 3H_2O_2 \rightarrow 2MnO_2 + 3O_2 + 2OH^- + 2H_2O$$

❖ *Storage of Hydrogen Peroxide*

Hydrogen peroxide slowly decomposes in the presence of light:

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

- *Metal surfaces and traces of alkali accelerate this decomposition.*
- *It is stored in:*
  - ***Wax-lined glass containers***
  - ***Plastic containers***
  - ***Dark conditions***
- ***Urea** may be added as a stabiliser.*
- *Dust should be avoided because it can cause explosive decomposition.*

❖ Uses of Hydrogen Peroxide

- *Used as a **hair bleach** and mild disinfectant.*
- *Used as an antiseptic (commercially sold as **perhydrol**).*
- *Used in manufacturing:*
  - *Sodium perborate*
  - *Sodium percarbonate (used in detergents)*
- *Used in synthesis of:*
  - *Hydroquinone*
  - *Tartaric acid*
  - *Pharmaceuticals*
- *Used as a bleaching agent for:*
  - *Textiles*
  - *Paper pulp*
  - *Leather*
  - *Oils and fats*
- *Used in **green chemistry** for:*
  - *Treatment of industrial and domestic effluents*
  - *Oxidation of cyanides*
  - *Restoration of aerobic conditions in sewage waste*

❖ Heavy Water (D_2O)

- *Heavy water is water in which hydrogen atoms are replaced by **deuterium (D)**.*
- *It is widely used:*
  - *As a **moderator in nuclear reactors***
  - *In studying reaction mechanisms through exchange reactions*

Preparation:

- *Prepared by **exhaustive electrolysis of water**.*
- *Obtained as a by-product in some fertiliser industries.*

Uses:

- *Preparation of deuterium compounds.*

Examples:

$$CaC_2 + 2D_2O \rightarrow C_2D_2 + Ca(OD)_2$$
$$Al_4C_3 + 12D_2O \rightarrow 3CD_4 + 4Al(OD)_3$$

➢ Dihydrogen as a Fuel

Hydrogen is considered an important future fuel because:

- *It releases a **large amount of energy on combustion**.*
- *It produces mainly **water as a product**, causing less pollution than fossil fuels.*

Advantages of Hydrogen Fuel

- *On a mass basis, hydrogen releases about **three times more energy than petrol**.*
- *Combustion produces fewer pollutants.*
- *Used in:*
  - *Fuel cells*
  - *Rockets*

- *Hydrogen-powered vehicles*

Limitations

- *Storage of hydrogen is difficult.*
- *Compressed hydrogen cylinders are heavy.*
- *Liquid hydrogen requires cooling to **20 K**, requiring expensive insulated tanks.*
- *Special storage materials are used, such as:*
  - *$NaNi_5$*
  - *$Ti–TiH_2$*
  - *$Mg–MgH_2$*

Hydrogen Economy

*The **hydrogen economy** involves storing and transporting energy in the form of hydrogen rather than electricity.*

Advantages:

- *Hydrogen can act as a clean energy carrier.*
- *Reduces dependence on fossil fuels.*
- *Used in fuel cells to generate electricity.*

Hydrogen in Vehicles:

- *A pilot project in India began in **2005**, where **5% hydrogen was mixed with CNG** for four-wheeler vehicles.*
- *The proportion was planned to increase gradually.*