9. CHEMISTRY OF NON-METALS

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Learning outcomes

By the end of this chapter, Students should be able to:

9.1 Explain and compare the chemistry of atomic and nascent hydrogen.
9.2 Describe isotopes of hydrogen and their uses,
- Discuss the application of hydrogen as fuel, heavy water, and its applications.
9.3 Explain types of oxides (acidic, basic, neutral, amphoteric, peroxide, and mixed).
9.4 Recognise applications of hydrogen peroxide.
9.5 State medical and industrial applications of oxygen.
9.6 Describe the occurrence, preparation (from oxygen), structure, and test of ozone.
9.7 Describe ozone layer depletion (causes, effects, and control measures) and uses of ozone.

9.1 Hydrogen

- The simplest and lightest element in the periodic table.
- The most abundant element in the known universe.
- Discovered by Henry Cavendish (1776) by passing steam through iron.
- Named inflammable air, then.
- Later, Lavoisier named it hydrogen as it produced water when burnt.
- Exists as a diatomic molecule (H_2) under standard conditions.

Symbol: H	Molecular formula: H_2
Atomic number: 1	Atomic mass: 1.008 amu
Atomic radius: 0.37 Å	Ionic radius (H^-): 2.1 Å
($1\ A^0 = 10^{-10}$ m)	
Ionisation energy: 1310 KJ mol^{-1}	Electronegativity: 2.1

9.1.1 Chemistry of atomic and nascent hydrogen

Atomic hydrogen

- Consists of individual hydrogen atoms (H)
- Generally **produced by passing molecular hydrogen through an electric arc between two tungsten electrodes at about 3000 °C**.
- **Exceptionally strong reducing agent, more powerful than nascent hydrogen**; can reduce oxides and chlorides of metals like silver, mercury, copper, and lead.

$$AgCl + H \longrightarrow Ag + HCl$$

$$HgCl_2 + H \longrightarrow HgCl + HCl$$

$$CuO + 2\,H \longrightarrow Cu + H_2O$$

It can reduce $BaSO_4$ to BaS and CO to formaldehyde (Methanal).

$$BaSO_4 + 8\,H \longrightarrow BaS + 4\,H_2O$$

$$CO + 2\,H \longrightarrow HCHO$$

Uses of atomic hydrogen:

- As a reducing agent
- In an atomic hydrogen torch for welding metals of very high melting points (refractory metals, e.g., tungsten, molybdenum).

Nascent Hydrogen

- Nascent hydrogen refers to **freshly generated hydrogen at the moment of formation.**
- Ordinary molecular hydrogen gas, when passed through acidified $KMnO_4$, $K_2Cr_2O_7$ & $FeCl_3$ solutions separately, doesn't reduce them.
- But nascent hydrogen produced *in situ*, in the medium itself containing the oxidising agents, reduces them. This shows nascent hydrogen is a more powerful reducing agent than ordinary hydrogen gas.

i $KMnO_4 + H_2SO_4 + H_2 \longrightarrow$ no reaction

$$\underset{\text{Pink}}{2\,KMnO_4} + 2\,H_2SO_4 + 4\,[H] \longrightarrow \underset{\text{Colourless}}{K_2SO_4 + 2\,MnSO_4} + 4\,H_2O$$

ii $K_2Cr_2O_7 + H_2SO_4 + H_2 \longrightarrow$ no reaction

$$K_2Cr_2O_7 + 4\,H_2SO_4 + 6\,[H] \longrightarrow K_2SO_4 + Cr_2(SO_4)_3 + 7\,H_2O$$

iii $FeCl_3 + H_2 \longrightarrow$ no reaction

$$FeCl_3 + [H] \longrightarrow FeCl_2 + HCl$$

- Earlier assumed that nascent hydrogen is atomic hydrogen.
- But at present, it is thought that a part of the heat change of the chemical reaction is imparted to the hydrogen in situ, making it more energetic.
- The internal pressure of the tiny bubbles formed in the solution also contributes to its higher reactivity.

Uses of nascent hydrogen:

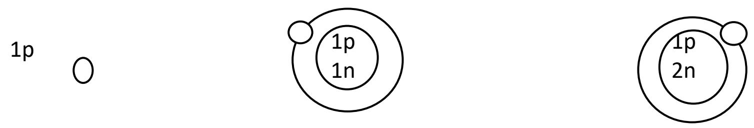
- As a reducing agent.

1. Distinguish between nascent and atomic hydrogen. **2**

Nascent Hydrogen	Atomic Hydrogen
Freshly formed hydrogen	Individual hydrogen atoms
Can be produced at ordinary temperature by reaction between acid, alkali, alcohols, or water with reactive metals.	Can be produced only at high temperatures (about 3000 °C) by the dissociation of H_2 molecules at low pressure.
Couldn't be isolated.	Could be isolated.
Relatively less powerful reducing agent.	More powerful reducing agent.

9.1.2 Isotopes of hydrogen and their uses

There are three isotopes of hydrogen, viz. Protium, Deuterium, and Tritium.



Protium, $_1H^1$, Deuterium, $_1H^2$, D, Tritium, $_1H^3$, T

These isomers differ from one another in the number of neutrons in the nucleus, as shown above. Protium does not have any neutrons. Deuterium has 1 neutron, and tritium has 2 neutrons in the nucleus. Their mass numbers are 1, 2, and 3, respectively.

The three isotopes have the **same atomic number and electronic configuration**. Hence, they have the **same chemical properties**.

Due to different atomic masses, their physical properties and rate of reactions differ.

The relative abundances of protium, deuterium, and tritium are 99.985 %, 0.015 %, and 10^{-15} %, respectively.

Uses of Hydrogen (or Protium)

- In the industrial synthesis of ammonia by Haber's process.
- In the hydrogenation of vegetable oil into vegetable ghee (margarine).
- In rockets and missiles as a fuel.
- In metallurgical processes as a reducing agent.
  - Promising **future clean fuel**: produces only water on combustion, with zero carbon emissions, if water could be decomposed economically by using solar or other renewable energy.
- In filling balloons and airships

Uses of *Heavy hydrogen* (deuterium)

- As a tracer in the study of the reaction mechanism.
- In the transformation of elements (i.e., nuclear reactions)

Uses of Tritium (Radioactive isotope)

- As a radioactive tracer in biology, chemistry, medicine, etc.
- In nuclear reactions to produce energy.
- In exit signs in dark halls.

9.1.3 Application of hydrogen as fuel

Because of its high inflammability, pollution-free combustion, and high enthalpy of combustion, hydrogen is used as a fuel and considered a very promising future fuel. It can be used in fuel cells and internal combustion engines.

$$2\ H_2\ (g) + O_2\ (g) \longrightarrow 2\ H_2O\ (g) + \text{energy}$$

A wide variety of research is currently being conducted on this topic.

Hydrogen is currently used as fuel in rockets and missiles.

It could be used as our future fuel without polluting the environment if water could be decomposed economically using solar or other renewable energy.

Advantages of hydrogen as a fuel:

- **High energy efficiency**
- **Mitigation of greenhouse gases (green fuel)**
- **Reduction of petroleum use**
- **Reduction of air pollution**
- **Zero carbon emissions**

Challenges in the use of hydrogen as a fuel

- High cost of hydrogen, its storage, transportation, and distribution technology.
- Takes up more space to store in the fuel tank
- Difficult to store in a high-pressure tank or cryogenic tank.

9.1.4 Heavy water and its applications

Deuterated water (D_2O or $_1H^2{}_2O$) or deuterium oxide is called heavy water. It is obtained in residual water after electrolysis of a large amount of water. This is employed

- As a moderator in nuclear reactors to slow down the neutrons, as well as a coolant at the same time.
- In the preparation of heavy hydrogen (deuterium, D_2) and other deuterated compounds.
- In scientific research involving isotopic labeling.

9.2 Oxygen

- Discovered by Joseph Priestley in 1772 and by Scheele in 1773.
- Named by Antoine Lavoisier after its detailed study.
- 3rd most abundant element in the Earth's crust & the human body.

  Atomic number: 8 Atomic mass: 15.999amu

  Molecular mass (O_2): 32 Valency: 2

  Oxidation number: -2 (-1 in peroxide and -1/2 in superoxide)

  Electronegativity: 3.5 (2nd most electronegative element after F)

  Ionisation energy or IP: 1317KJ/mol
- Oxygen has 3 isotopes $_8O^{16}$, $_8O^{17}$, $_8O^{18}$, their relative abundances are 99.76%, 0.03% and 0.204% respectively.

9.2 Allotropes of Oxygen

The property by virtue of which an element exists in different forms with different physical properties and the same chemical properties is called **allotropy**. Such different forms of the same element are called allotropes.

Oxygen shows allotropy. Oxygen (O_2) and ozone (O_3) are allotropes.

9.2.2 Types of oxides

Binary compounds of other elements with oxygen are called oxides. These can be classified on a different basis as discussed below.

- Classification based on acidic or basic behaviour

a) Basic oxides

The oxides that form a base in combination with water are called basic oxides. Generally, **metal oxides** are basic. e.g.

$$Na_2O + H_2O \longrightarrow 2\,NaOH$$

$$CaO + H_2O \longrightarrow Ca(OH)_2$$

Basic oxide + water $\longrightarrow$ Base

The basic oxides react with an acid to form a salt and water.

$BaO + HCl \longrightarrow BaCl_2 + H_2O$

b) Acidic oxides

The oxides that form acids in combination with water are called acidic oxides. Generally, oxides of **non-metals** are acidic. E.g.

$CO_2 + H_2O \longrightarrow H_2CO_3$

$SO_3 + H_2O \longrightarrow H_2SO_4$

$I_2O_5 + H_2O \longrightarrow$ 2 HIO_3 (Iodic acid)

$N_2O_5 + H_2O \longrightarrow$ 2 HNO_3 (Nitric acid)

$N_2O_3 + H_2O \longrightarrow$ 2 HNO_2 (Nitrous acid)

Acidic oxide + water $\longrightarrow$ acid

Acidic oxides react with bases to form salt and water.

$SO_2 + 2\ KOH \longrightarrow K_2SO_3 + H_2O$

c) Neutral oxides

Neutral oxides do not react with an acid or a base to form salt, e.g., **NO, CO, H_2O, N_2O,** etc.

d) Amphoteric oxides

These are oxides that react with acids as well as bases to form salts. Oxides of **Al, Zn, Sn, and Pb** are amphoteric oxides.

$Al_2O_3 + 6\ HCl \longrightarrow 2\ AlCl_3 + 3\ H_2O$

$Al_2O_3 + 2\ NaOH \longrightarrow 2\ NaAlO_2 + H_2O$

$ZnO + H_2SO_4 \longrightarrow ZnSO_4 + H_2O$

$ZnO + 2\ NaOH \longrightarrow Na_2ZnO_2 + H_2O7$

Periodic Trend in Oxide Behaviour

Moving across Period 3 from left to right, the oxide character changes progressively from **strongly basic → amphoteric → acidic → strongly acidic**:

Na_2O →	MgO →	Al_2O_3 →	SiO_2 →	P_2O_5 →	SO_3 →	Cl_2O_7
basic	basic	amphoteric	weakly acidic	acidic	acidic	strongly acidic

- Classification of oxides based on structure

a) Peroxides

These oxides contain the group **$(-O-O-)^{2-}$**, in which the oxidation number of oxygen is **-1**. E.g., H_2O_2, Na_2O_2, BaO_2, R-O-O-R (ROOR), etc.

b) Mixed oxides

These oxides behave as if they were the mixtures of two simpler oxides of the same element.

e.g. Fe_3O_4 ($FeO + Fe_2O_3$) - ferroso ferric oxide, Pb_3O_4 ($PbO+PbO_2$)

Summary Table: Types of Oxides

Type	Examples	Reaction with Water	Additional Notes
Basic Oxide	Na_2O, CaO, MgO	Forms a base (alkali)	Metal oxides; react with acids
Acidic Oxide	CO_2, SO_3, N_2O_5	Forms an acid	Non-metal oxides; react with bases

Neutral Oxide	NO, CO, H_2O, N_2O	No reaction	Neither acidic nor basic
Amphoteric Oxide	Al_2O_3, ZnO, SnO	Reacts with both acids and bases	Show dual behaviour
Peroxide	H_2O_2, Na_2O_2, BaO_2	Releases H_2O_2 or O_2^-	O.N. of oxygen = −1
Mixed Oxide	Fe_3O_4, Pb_3O_4	No simple reaction	Act as mixtures of two oxides

9.2.3 Applications of hydrogen peroxide

- H_2O_2 is an important peroxide with strong oxidising properties.
- Pale blue liquid that decomposes readily into water and oxygen.

Applications

- As a bleaching agent for wool, pulp, paper, silk, cotton, wool, etc.
- To produce different chemicals by oxidation reaction (as an oxidising agent).
- As an antiseptic, to clean wounds & in some sanitisers also
- To prepare mouthwash (for dental hygiene - due to antiseptic properties)
- To produce organic peroxides (ROOR), some of which are explosives too
- As a propellant in rockets

9.2.4 Medical and industrial applications of oxygen

It is the most essential element for life on Earth. Apart from being used in respiration and combustion. It is used in

1. In the Manufacture of steel
2. As an oxidising and bleaching agent in different chemical industries
3. Oxy-hydrogen and oxy-acetylene flames in the cutting and welding of metals.
4. **Artificial respiration** in hospitals
   All living cells need a constant supply of oxygen for aerobic respiration. It is used by the cells to oxidise the food to produce energy.
   $$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$$
   Lack of oxygen for a few minutes leads to cell death. Therefore, in a wide variety of medical conditions (hypoxemia, chronic obstructive pulmonary disease, pneumonia, heart attack, **respiratory diseases**, during surgeries, etc.), oxygen should be given to the patients.
5. Mountaineering, diving, and space travelling.
6. Fuel for rockets and missiles.

Ozone

9.3.1 Occurrence

The ozone layer lies in the stratosphere, 12 to 24 km above the Earth's surface. Ozone is naturally formed in the stratosphere as O_2 molecules absorb the high-energy ultraviolet rays of the sun. UV radiation splits O_2 molecules into oxygen atoms that combine with oxygen molecules to form ozone.

$$O_2 \xrightarrow{h\nu} O + O$$
$$[\, O + O_2 \longrightarrow O_3 \,] \times 2$$

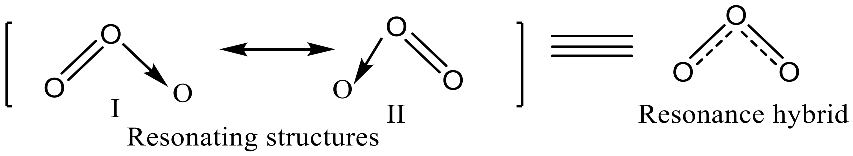
9.3.2 Preparation of ozone from oxygen

It is prepared in the laboratory by passing silent electric discharge (i.e., without any spark) or ultraviolet radiation in a spherically designed instrument called an ozonizer. It is an endothermic reaction.

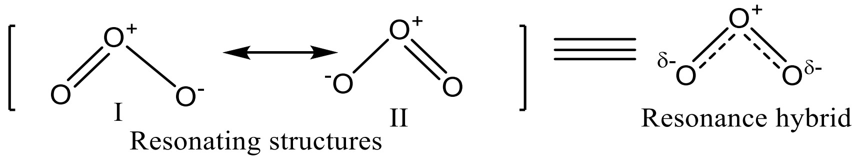
$$3\,O_2\,(g) \rightleftharpoons 2O_3\,(g)\ -142 KJmol^{-1}$$

9.3.3 Structure of ozone

The ozone molecule has an **angular (bent) shape** with a bond angle of approximately **116.8°**.
The two O–O bond lengths are equal (1.28 Å), intermediate between an O–O single bond and an O=O double bond. This is because ozone is best described as a **resonance hybrid** of two equivalent Lewis structures:



But it is found to have a dipole moment of 0.53D. Hence, its structure may be represented as:



2. Give the resonance structure of ozone. 2

9.3.4 Test for ozone

The test of ozone may be based on one of its following properties.

1. It is a pale blue gas with a distinctively pungent fishy smell.
2. When ozone is passed into a mixture of KI solution and starch solution, blue colouration appears. The involved reaction may be shown as;

$$O_3 \longrightarrow O_2 + O$$
$$2\,KI + O \longrightarrow K_2O + I_2$$
$$K_2O + H_2O \longrightarrow 2\,KOH$$
$$\overline{2\,KI + H_2O + O_3 \longrightarrow 2\,KOH + O_2 + I_2}$$
$$I_2 + \text{starch} \longrightarrow \text{Blue coloration}$$

3. Tailing of mercury test: Mercury does not stick to the glass surface. However, when exposed to the atmosphere of ozone, it loses its meniscus and sticks to the glass surface. This is due to the formation of mercurous oxide as shown below.

$$2\,Hg + O_3 \longrightarrow Hg_2O + O_2$$

9.3.5 Ozone layer depletion (causes, effects, and control measures)

🌍 **The Ozone Layer: Our Planetary Shield**

🔹 **1. Understanding the Stratospheric Guard**

The ozone layer is a region within the **stratosphere** (approximately 15–35 km above Earth) with a relatively high concentration of ozone (O_3).

- **The Function:** It absorbs ~98% of high-frequency **Ultraviolet-B (UV-B)** radiation.
- **The Natural Balance:** In a healthy atmosphere, ozone is constantly formed and destroyed in a balanced cycle.

🔹 **2. The Chemistry of Depletion (The "Villains")**

Ozone depletion is the accelerated breakdown of O_3 caused by **Ozone-Depleting Substances.**

A. Chlorofluorocarbons (CFCs)

CFCs are chemically inert in the troposphere, but when they drift into the stratosphere, UV radiation causes **photodissociation**:

$CF_2Cl_2 + UV \rightarrow CF_2Cl + Cl\bullet$

B. The Catalytic Destruction Cycle

This is a "chain reaction" where a single Chlorine radical acts as a catalyst:

- $Cl\bullet + O_3 \rightarrow ClO\bullet + O_2$
- $ClO\bullet + O \rightarrow Cl\bullet + O_2$

- **Net Reaction:** $O_3 + O \rightarrow 2O_2$
- **Crucial Fact:** Because the Cl• radical is regenerated, **one single chlorine atom can destroy over 100,000 ozone molecules** before it is removed by other reactions.

C. Other ODS to Remember

- **Halons:** Contain Bromine (Br•), which is even more effective at destroying ozone than Chlorine.
- **Nitrogen Oxides (NO_x):** Released by supersonic jets flying in the stratosphere.
- **Carbon Tetrachloride (CCl_4):** Formerly used in industrial solvents.

🔹 **3. Consequences: Why It Matters**

Impact Area	Specific Effects
Human Health	Increased DNA mutations leading to **Basal Cell Carcinoma** (skin cancer), cataracts, and suppression of the immune response.
Marine Life	UV-B penetrates deep into clear water, killing **phytoplankton**, the foundation of the aquatic food web.
Agriculture	Inhibits photosynthesis and reduces crop yields in sensitive plants like rice,

Impact Area	Specific Effects
	wheat, and corn.
Materials	Accelerated "weathering" and degradation of polymers (plastics) and wood.

◆ **4. Global Action & Recovery**

- **The Montreal Protocol (1987):** Widely considered the most successful environmental treaty. It mandated the phase-out of CFCs.
- **Modern Alternatives:** Transitioning from CFCs to **HCFCs** (temporary) and finally **HFCs** (which do not deplete ozone but are strong greenhouse gases).
- **Recovery:** Scientific observations show that the "Ozone Hole" is slowly healing, with full recovery expected by mid-century if regulations are followed.

9.3.6 Uses of Ozone

1. As a germicide and as a disinfectant for sterilising water.
2. To improve the atmosphere of crowded places.
3. As an oxidising agent in different chemical industries.
4. In food processing and cold store sanitation.
5. For bleaching oils, ivory articles, and other soft materials.
6. In the ozonolysis of unsaturated hydrocarbons.

Chapter Summary

Key Points to Remember

- **Atomic hydrogen** is produced at ~3000°C and is the most powerful reducing form of hydrogen; used in high-temperature welding.
- **Nascent hydrogen** is freshly generated hydrogen in solution; more reactive than ordinary H_2 but less so than atomic hydrogen.
- Hydrogen has three isotopes: **protium** (^1H), **deuterium** (^2H), and **tritium** (^3H). Chemical properties are identical; physical properties differ.
- **Heavy water (D_2O)** is used as a neutron moderator and coolant in nuclear reactors.
- **Oxides** are classified as basic, acidic, neutral, amphoteric, peroxide, or mixed based on their behaviour.
- **Hydrogen peroxide (H_2O_2)** is a powerful oxidising/bleaching/antiseptic agent.
- **Oxygen** is essential for respiration, combustion, steelmaking, and medicine.
- **Ozone (O_3)** is an angular molecule; it absorbs ~98% of UV-B radiation in the stratosphere.
- **CFCs** catalytically destroy ozone; one Cl• radical can destroy 100,000 O_3 molecules.
- The **Montreal Protocol (1987)** successfully regulated ODS; the ozone layer is gradually recovering.

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