La-Net

CHM302

INORGANIC CHEMISTRY II

Download on the App Store

GET IT ON Google Play

Course video is available on our app

lanetonline.com

Course code: CHM 302

Course title: Inorganic Chemistry II

Course uint: (2 Units C: LH 30)

List of series:

Series 1: Comparative Chemistry of Main Group Elements

Series 2: Chemistry of Non-Metals and Their Compounds

Series 3: Transition Metal Chemistry and Complexes

Series 4: Radioactivity and Radiochemistry

Series 5: Biological Roles of Metals in Living Systems

Suggested Outline

1 General Characteristics of Group IA (Alkali Metals)

- 1.1 Position in the periodic table
- 1.2 Electronic structure and oxidation states
- 1.3 Physical and chemical properties

2 General Characteristics of Group IIA (Alkaline Earth Metals)

- 2.1 Position in the periodic table
- 2.2 Electronic structure and oxidation states
- 2.3 Physical and chemical properties

3 Comparative Chemistry of Group IA and Group IIA

- 3.1 Trends in atomic and ionic radii
- 3.2 Ionisation energies and reactivity
- 3.3 Similarities and differences in compounds

5.4 Periodic Properties and Applications of Group IA and IIA Compounds

- 4.1 Solubility and stability of salts
- 4.2 Industrial and laboratory applications
- 4.3 Environmental and biological relevance

Introduction

Many of the materials and processes you encounter daily — from the salts used in industry to the metals in household products — trace their behaviour to the chemistry of the main group elements. This Series focuses on the comparative chemistry of Group IA (alkali metals) and Group IIA (alkaline earth metals), showing how their positions in the periodic table and electronic structures determine their properties and uses. Understanding these relationships will help you apply core inorganic concepts across the rest of CHM 302.

The aim of this Series is to develop your ability to describe and compare the electronic structure, physical and chemical properties, and practical applications of Group IA and Group IIA elements, and to use periodic trends to predict and rationalise their chemistry.

We shall commence this Series by examining the general characteristics of Group IA, including their position in the periodic table, electronic configuration and typical properties. Next, we will consider the general characteristics of Group IIA in the same way, so you can see parallels and contrasts. Following that, we will compare Groups IA and IIA directly, analysing trends such as ionic radii, ionisation energies and reactivity. Finally, we will conclude by exploring periodic properties, common compounds, and the industrial, environmental and biological relevance of these elements.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define the position of Group IA elements in the periodic table and describe their electronic structures,
- **SLO 1.2** explain the general physical and chemical properties of Group IA elements,
- **SLO 1.3** define the position of Group IIA elements in the periodic table and describe their electronic structures,
- **SLO 1.4** explain the general physical and chemical properties of Group IIA elements,
- **SLO 1.5** analyse similarities and differences between Group IA and Group IIA elements in terms of periodic trends such as atomic radii, ionisation energies, and reactivity,
- **SLO 1.6** evaluate the solubility, stability, and applications of common compounds of Group IA and Group IIA elements, and
- **SLO 1.7** apply knowledge of periodic properties to discuss the industrial, environmental, and biological relevance of Group IA and Group IIA compounds.

1 General Characteristics Of Group IA (Alkali Metals)

1.1 Position in the periodic table

Alkali metals are the elements in **Group IA** of the periodic table, which include lithium, sodium, potassium, rubidium, caesium, and francium. They are located at the far left of the table and are characterised by having a single electron in their outermost s orbital. This configuration makes them highly reactive and strongly inclined to lose that electron, forming +1 cations.

Fill in the blank: Alkali metals are located in Group _____ of the periodic table.

Figure 1.1 Position of Alkali Metals in the Periodic Table

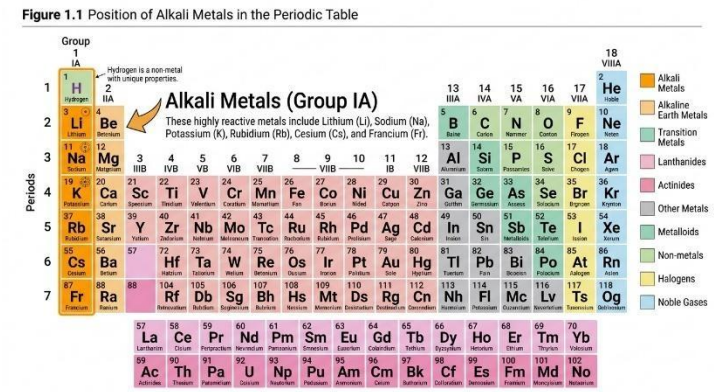


Diagram of the periodic table highlighting Group IA elements.
Figure 1.1 Position of alkali metals in the periodic table.
"periodic table alkali metals group IA OER"

1.2 Electronic structure and oxidation states

The **electronic structure** of alkali metals is characterised by a single valence electron in the outermost s orbital (ns^1). This makes them prone to losing that electron easily, resulting in the formation of stable +1 oxidation states. For example, sodium has the configuration $[Ne]3s^1$ and readily forms Na^+ ions.

Because they almost exclusively exhibit the +1 oxidation state, their chemistry is relatively straightforward compared to transition metals. This simplicity also explains their strong tendency to form ionic compounds.

Fill in the blank: The most common oxidation state of alkali metals is _____.

Figure 1.2 Electronic configurations of selected alkali metals.

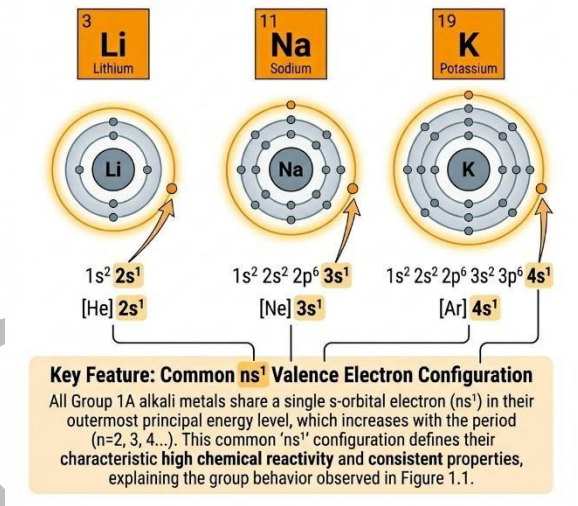


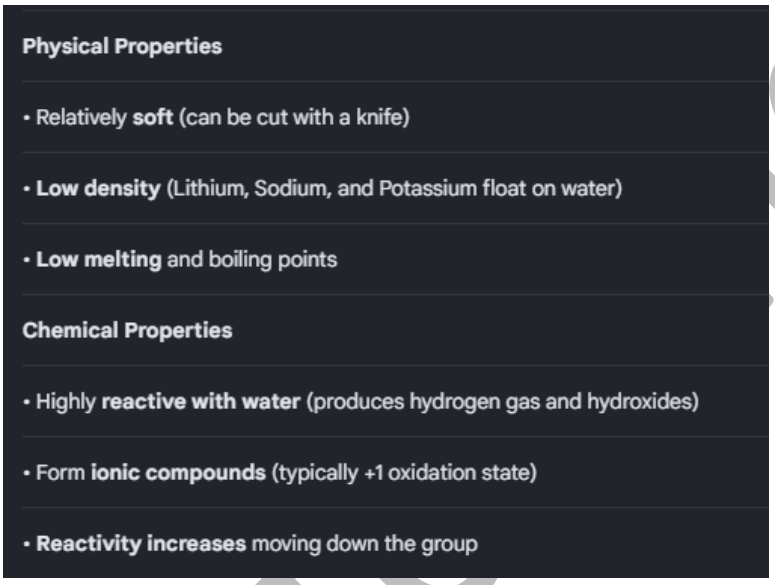
Diagram showing electronic configurations of lithium, sodium, and potassium, highlighting the ns^1 valence electron.
Figure 1.2 Electronic configurations of selected alkali metals.
"alkali metals electronic configuration ns1 OER"

1.3 Physical and chemical properties

Alkali metals share several distinctive **physical properties**: they are soft, have low densities, and possess relatively low melting points compared to other metals. Chemically, they are highly reactive, especially with water, producing hydrogen gas and alkaline hydroxides. Their reactivity increases down the group, with lithium being the least reactive and caesium among the most reactive.

For example, sodium reacts vigorously with water to form sodium hydroxide and hydrogen gas. This reaction demonstrates their strong tendency to form ionic compounds and their importance in everyday chemistry.

Fill in the blank: When alkali metals react with water, they produce hydrogen gas and _____ hydroxides.



Box 1.3 General properties of alkali metals.
Single-column table listing physical properties (soft, low density, low melting points) and chemical properties (reactive with water, form ionic compounds, reactivity increases down the group).
“alkali metals physical chemical properties OER”

2 General Characteristics Of Group IIA (Alkaline Earth Metals)

2.1 Position in the periodic table

Alkaline earth metals are the elements in **Group IIA** of the periodic table, which include beryllium, magnesium, calcium, strontium, barium, and radium. They are located immediately to the right of the alkali metals and are characterised by having two electrons in their outermost s orbital. This configuration makes them less reactive than alkali metals but still strongly inclined to lose both electrons, forming +2 cations.

Fill in the blank: Alkaline earth metals are located in Group _____ of the periodic table.

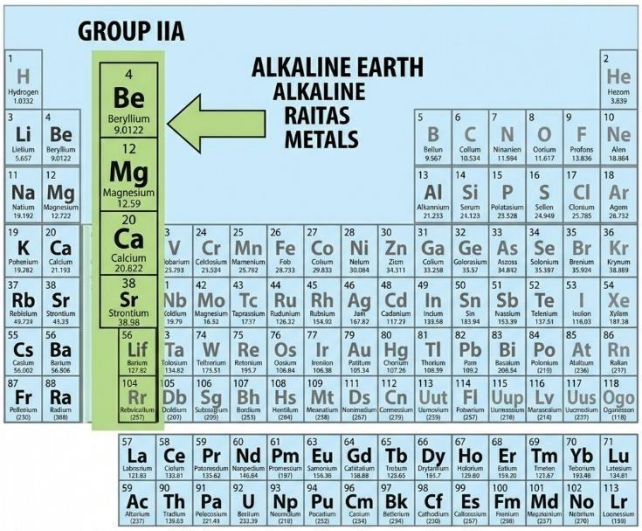


Figure 1.3 Position of alkaline earth metals in the periodic table.

Diagram of the periodic table highlighting Group IIA elements.
Figure 1.3 Position of alkaline earth metals in the periodic table.
"periodic table alkaline earth metals group IIA OER"

2.2 Electronic structure and oxidation states

The **electronic structure** of alkaline earth metals is characterised by two valence electrons in the outermost s orbital (ns^2). This makes them prone to losing both electrons, resulting in the formation of stable +2 oxidation states. For example, magnesium has the configuration $[Ne]3s^2$ and readily forms Mg^{2+} ions.

Because they almost exclusively exhibit the +2 oxidation state, their chemistry is predictable, and they form ionic compounds such as oxides, hydroxides, and halides.

Fill in the blank: The most common oxidation state of alkaline earth metals is _____.

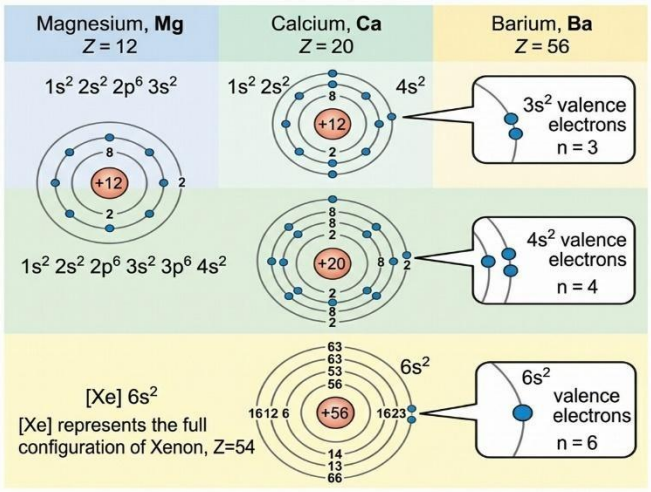


Figure 1.4 Electronic configurations of selected alkaline earth metals.

Diagram showing electronic configurations of magnesium, calcium, and barium, highlighting the ns² valence electrons.

Figure 1.4 Electronic configurations of selected alkaline earth metals.

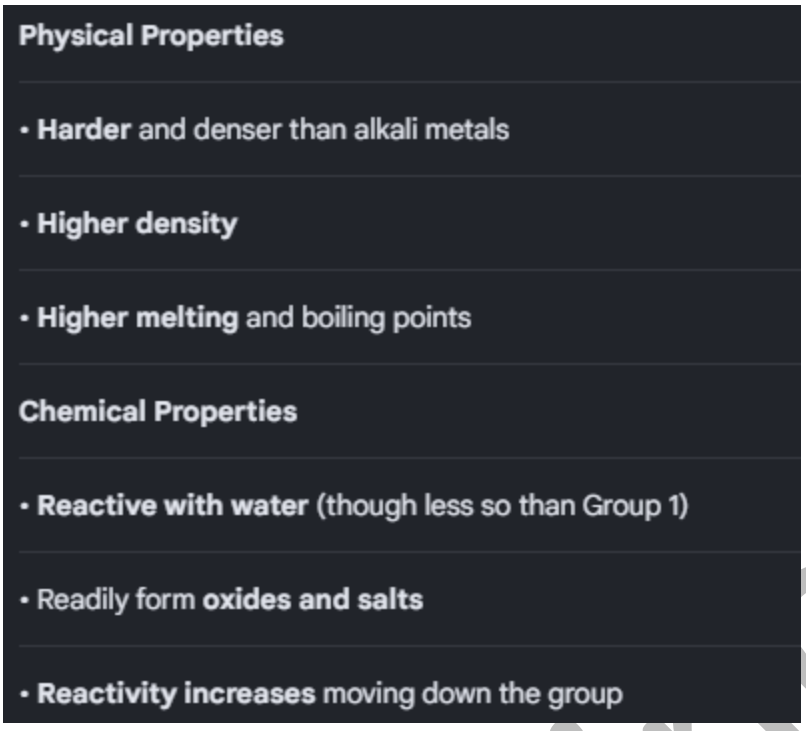
“alkaline earth metals electronic configuration ns2 OER”

2.3 Physical and chemical properties

Alkaline earth metals share several distinctive **physical properties**: they are harder than alkali metals, have higher densities, and possess higher melting points. Chemically, they are reactive, though less so than alkali metals. They react with water (except beryllium) to form hydroxides and hydrogen gas, and they readily form oxides and salts. Their reactivity increases down the group, with beryllium being the least reactive and barium among the most reactive.

For example, calcium reacts with water to form calcium hydroxide and hydrogen gas, a reaction that demonstrates their tendency to form alkaline solutions.

Fill in the blank: When alkaline earth metals react with water, they produce hydrogen gas and _____ hydroxides.



Box 1.5 General properties of alkaline earth metals.
Single-column table listing physical properties (harder than alkali metals, higher density, higher melting points) and chemical properties (reactive with water, form oxides and salts, reactivity increases down the group).
“alkaline earth metals physical chemical properties OER”

3 Comparative Chemistry Of Group IA And Group IIA

3.1 Trends in atomic and ionic radii

Both Group IA (alkali metals) and Group IIA (alkaline earth metals) show predictable trends in **atomic radius**, which is the distance from the nucleus to the outermost electron shell. Atomic radii increase down each group as additional electron shells are added. However, Group IIA elements have smaller radii than Group IA elements in the same period because they have a higher nuclear charge, pulling electrons closer to the nucleus.

Similarly, **ionic radius** refers to the size of an atom once it has lost or gained electrons. Alkali metals form +1 cations, which are larger than the +2 cations formed by alkaline earth metals. The greater positive charge in Group IIA cations results in stronger attraction between the nucleus and electrons, leading to smaller ionic radii compared to Group IA cations.

Fill in the blank: The cations of Group IIA elements are smaller than those of Group IA because they carry a _____ charge.

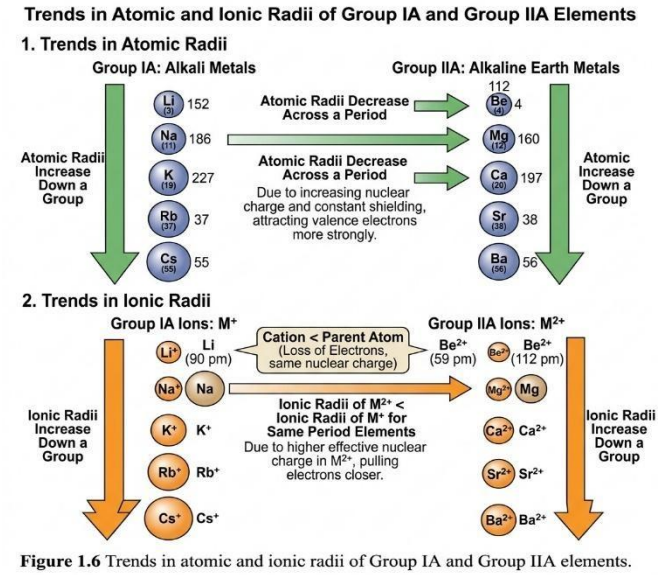


Figure 1.6 Trends in atomic and ionic radii of Group IA and Group IIA elements.

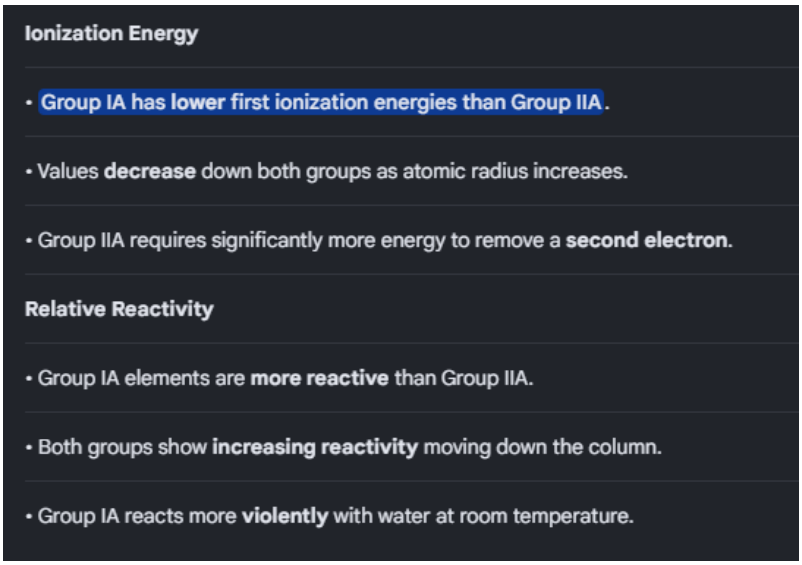
Comparative diagram showing atomic and ionic radii trends for Groups IA and IIA across periods.
Figure 1.6 Trends in atomic and ionic radii of Group IA and Group IIA elements.
“atomic ionic radii trends alkali alkaline earth metals OER”

3.2 Ionisation energies and reactivity

Ionisation energy is the energy required to remove an electron from an atom. Group IA elements have lower ionisation energies than Group IIA elements because they only need to lose one valence electron, whereas Group IIA elements must lose two. This difference explains why alkali metals are generally more reactive than alkaline earth metals.

Reactivity increases down both groups as ionisation energy decreases with increasing atomic size. For example, caesium reacts more vigorously with water than lithium, while barium is more reactive than magnesium.

Fill in the blank: Group IA elements are more reactive than Group IIA elements because they require less _____ energy to lose electrons.



Box 1.7 Comparison of ionisation energies and reactivity.
Single-column table summarising ionisation energy values and relative reactivity trends for Group IA and Group IIA elements.
“ionisation energy reactivity alkali alkaline earth metals OER”

3.3 Similarities and differences in compounds

Both groups form ionic compounds, but their properties differ. **Alkali metal compounds** such as sodium chloride are typically highly soluble in water and form neutral salts. **Alkaline earth metal compounds** such as calcium carbonate are less soluble and often form sparingly soluble salts.

Alkali metals form hydroxides that are strong bases, while alkaline earth metals form hydroxides that are less soluble but still alkaline. Carbonates of Group IA are generally soluble, whereas those of Group IIA are less soluble, with calcium carbonate being a common example found in limestone.

Fill in the blank: The carbonate of calcium, which is sparingly soluble and found in limestone, is called _____ carbonate.

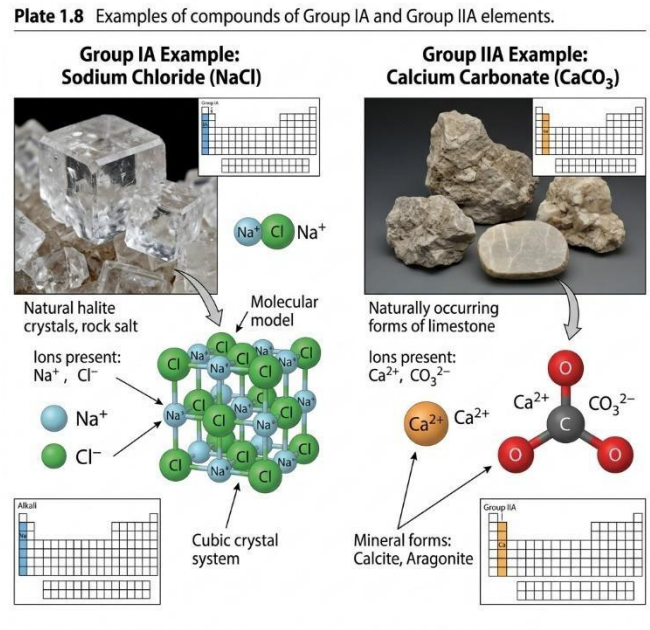


Image showing examples of compounds: sodium chloride crystals and calcium carbonate in limestone.
Plate 1.8 Examples of compounds of Group IA and Group IIA elements.
“sodium chloride calcium carbonate examples OER”

4 Periodic Properties And Applications Of Group IA And IIA Compounds

4.1 Solubility and stability of salts

The **solubility** of salts formed by Group IA and Group IIA elements shows clear periodic trends. **Group IA salts**, such as sodium chloride and potassium nitrate, are generally highly soluble in water. This is due to the relatively low lattice energies of their compounds compared to the hydration energies released when ions dissolve.

In contrast, **Group IIA salts** often display lower solubility. For example, calcium carbonate and barium sulphate are sparingly soluble, which explains their occurrence as solid deposits in nature. The **stability** of these salts also varies: carbonates of Group IA are stable to heat, while those of Group IIA decompose more readily, releasing carbon dioxide.

Fill in the blank: The carbonate of barium is sparingly soluble in water, while the carbonate of sodium is _____ soluble.

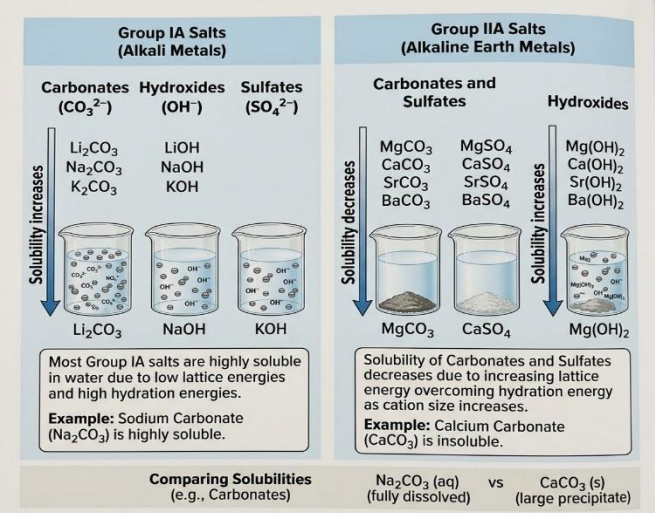


Figure 1.9 Solubility trends of Group IA and Group IIA salts.

Diagram comparing solubility trends of Group IA and Group IIA salts.
Figure 1.9 Solubility trends of Group IA and Group IIA salts.
"solubility trends alkali alkaline earth salts OER"

4.2 Industrial and laboratory applications

Compounds of Group IA and Group IIA elements have widespread **industrial applications**. Sodium hydroxide is used in soap manufacture, while potassium nitrate is employed in fertilisers and explosives. Calcium carbonate is a major component of cement and lime, and magnesium hydroxide is used as an antacid in medicine.

In the laboratory, these compounds serve as reagents and standards. For example, sodium chloride is used in preparing saline solutions, while barium sulphate is used in medical imaging as a contrast agent due to its insolubility.

Fill in the blank: The alkaline earth compound used as a contrast agent in medical imaging is _____ sulphate.

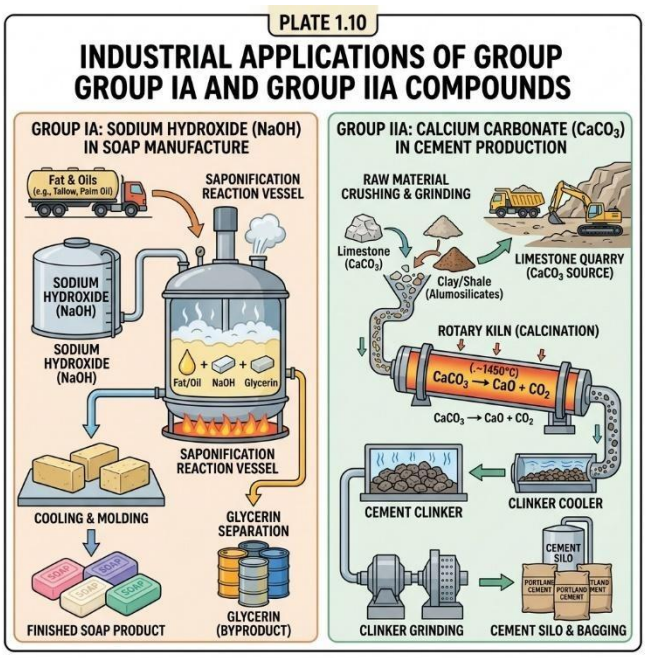


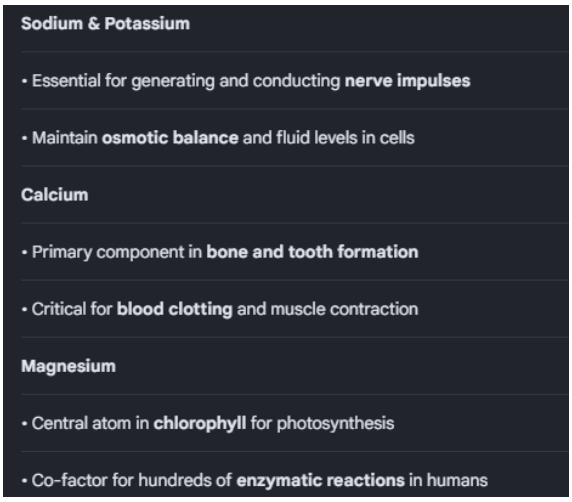
Image showing industrial applications of sodium hydroxide in soap production and calcium carbonate in cement manufacture.
Plate 1.10 Industrial applications of Group IA and Group IIA compounds.
“industrial applications sodium hydroxide calcium carbonate OER”

4.3 Environmental and biological relevance

Group IA and Group IIA compounds also play important roles in the environment and biology. Sodium and potassium ions are essential electrolytes in living systems, regulating nerve impulses and muscle contraction. Calcium ions are vital for bone formation and blood clotting, while magnesium ions are central to chlorophyll, enabling photosynthesis in plants.

Environmentally, compounds such as calcium carbonate help buffer soil and water pH, while sodium salts influence water hardness. These roles highlight the importance of these elements beyond chemistry laboratories.

Fill in the blank: The transition metal central to chlorophyll that enables photosynthesis is _____.



Box 1.11 Biological importance of Group IA and Group IIA compounds.
Short description: Single-column table listing sodium/potassium → nerve impulses, calcium → bone formation and blood clotting, magnesium → chlorophyll/photosynthesis.
"biological importance sodium potassium calcium magnesium OER"

Series Summary

This Series on **Comparative Chemistry of Main Group Elements** was designed to help you understand the similarities and differences between Group IA (alkali metals) and Group IIA (alkaline earth metals). By examining their positions in the periodic table, electronic structures, and characteristic properties, you have seen how these elements behave and why they are important in both natural and applied contexts. The Series also highlighted how periodic trends influence reactivity and compound formation, and how these elements contribute to industrial, environmental, and biological processes.

By completing this Series, you should now be able to **define the positions and electronic structures of Group IA and Group IIA elements (SLOs 1.1–1.4)**, **analyse their comparative chemistry in terms of atomic radii, ionisation energies, and reactivity (SLO 1.5)**, **evaluate the solubility, stability, and applications of their compounds (SLO 1.6)**, and **apply knowledge of periodic properties to explain their industrial, environmental, and biological relevance (SLO 1.7)**. These outcomes ensure that you can connect fundamental periodic trends with practical applications, reinforcing the importance of main group chemistry in the wider study of inorganic chemistry.

Glossary of Terms

- **Alkaline earth metals**: Elements in Group IIA of the periodic table, including magnesium and calcium, characterised by two valence electrons and a common +2 oxidation state.
- **Alkali metals**: Elements in Group IA of the periodic table, such as sodium and potassium, characterised by one valence electron and a common +1 oxidation state.
- **Atomic radius**: The distance from the nucleus to the outermost electron shell of an atom, which increases down a group.

- **Carbonate**: A compound containing the carbonate ion (CO_3^{2-}), often formed by Group IA and Group IIA metals, with varying solubility.
- **Cation**: A positively charged ion formed when an atom loses one or more electrons, such as Na^+ or Ca^{2+}.
- **Electronic structure**: The arrangement of electrons in an atom's orbitals, which determines its chemical behaviour.
- **Hydroxide**: A compound containing the hydroxide ion (OH^-), formed when alkali or alkaline earth metals react with water.
- **Ionisation energy**: The energy required to remove an electron from an atom, generally lower for Group IA than Group IIA elements.
- **Ionic radius**: The size of an atom once it has become a cation, usually smaller than its atomic radius due to loss of electrons.
- **Periodic trend**: A predictable pattern in properties of elements across periods or groups in the periodic table, such as reactivity or solubility.
- **Reactivity**: The tendency of an element to undergo chemical reactions, which increases down both Group IA and Group IIA.
- **Solubility**: The ability of a compound to dissolve in water, often high for Group IA salts but lower for many Group IIA salts.

Concept Check Questions [Series 1]

Objective Questions

1. Group IA elements are commonly known as _____.
   (Linked to SLO 1.1)
2. The most stable oxidation state of Group IIA elements is _____.
   (Linked to SLO 1.3)
3. Which Group IA compound is highly soluble in water and widely used in food preservation?
   A. Calcium carbonate
   B. Sodium chloride
   C. Barium sulphate
   D. Magnesium hydroxide
   (Linked to SLO 1.6)
4. The ionisation energy of Group IA elements is generally _____ than that of Group IIA elements.
   (Linked to SLO 1.5)
5. Which Group IIA compound is sparingly soluble and forms limestone deposits?
   A. Sodium hydroxide
   B. Potassium nitrate
   C. Calcium carbonate

D. Magnesium chloride
(Linked to SLO 1.6)

Short-Answer Questions

1. Define atomic radius and explain how it changes down Group IA and Group IIA.
   (Linked to SLO 1.5)
2. Describe the electronic configuration of sodium and explain why it forms a +1 cation.
   (Linked to SLO 1.2)
3. Compare the solubility of Group IA carbonates with Group IIA carbonates.
   (Linked to SLO 1.6)
4. Identify one industrial application of sodium hydroxide and one biological role of calcium.
   (Linked to SLOs 1.6–1.7)
5. Explain why magnesium is important in plants.
   (Linked to SLO 1.7)

Long-Answer Questions

1. Analyse the differences in reactivity between Group IA and Group IIA elements, linking them to ionisation energies and oxidation states.
   (Linked to SLO 1.5)
2. Evaluate the environmental and biological importance of Group IA and Group IIA compounds, giving specific examples.
   (Linked to SLO 1.7)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Alkali metals
2. +2
3. B. Sodium chloride
4. Lower
5. C. Calcium carbonate

Short-Answer Questions

1. Atomic radius is the distance from the nucleus to the outermost electron shell. It increases down both groups due to additional electron shells.
2. Sodium has the configuration [Ne]$3s^1$. It loses one electron easily to form Na^+ with a stable noble gas configuration.
3. Group IA carbonates are generally soluble, while Group IIA carbonates are less soluble, with calcium carbonate being sparingly soluble.

4. Sodium hydroxide is used in soap manufacture; calcium is essential for bone formation and blood clotting.
5. Magnesium is central to chlorophyll, enabling photosynthesis in plants.

Long-Answer Questions

Question 1

- **Basic response:** Group IA elements are more reactive than Group IIA because they have lower ionisation energies and only need to lose one electron, forming +1 cations. Group IIA elements require more energy to lose two electrons, forming +2 cations.
- **Value-added response:** Outstanding learners may extend by discussing how reactivity increases down both groups, citing examples such as caesium reacting explosively with water compared to barium's slower reaction, and linking these behaviours to periodic trends in atomic size and shielding.

Question 2

- **Basic response:** Group IA and Group IIA compounds are important in biology and the environment. Sodium and potassium regulate nerve impulses, calcium strengthens bones, and magnesium supports photosynthesis.
- **Value-added response:** Outstanding learners may extend by evaluating environmental roles such as calcium carbonate buffering soil pH, sodium salts influencing water hardness, and the medical use of barium sulphate in imaging, showing how these compounds connect chemistry to real-world applications.

Answers to Pilot Questions [Series 1]

Part 1: General Characteristics of Group IA (Alkali Metals)

1. Group IA
2. +1
3. Sodium hydroxide

Part 2: General Characteristics of Group IIA (Alkaline Earth Metals)

1. Group IIA
2. +2
3. Calcium hydroxide

Part 3: Comparative Chemistry of Group IA and Group IIA

1. +2
2. Ionisation
3. Calcium carbonate

Part 4: Periodic Properties and Applications of Group IA and IIA Compounds

1. Highly
2. Barium sulphate
3. Magnesium

References and Attributions [Series 1]

Textual Sources

- Housecroft, C. E., & Sharpe, A. G. (2018). *Inorganic Chemistry* (5th ed.). Pearson Education.
- Miessler, G. L., Fischer, P. J., & Tarr, D. A. (2014). *Inorganic Chemistry* (5th ed.). Pearson.
- Royal Society of Chemistry. (2020). *Main Group Chemistry Resources*.
- IUPAC. (1997). *Compendium of Chemical Terminology (the "Gold Book")*.

Illustrations (Figures, Plates, Boxes)

- *Figure 1.1 Position of alkali metals in the periodic table*
    - AI prompt: "Generate a labelled diagram of the periodic table highlighting Group IA alkali metals."
    - Platform: Microsoft Copilot image generation
    - Search string: "periodic table alkali metals group IA OER"
- *Figure 1.2 Electronic configurations of selected alkali metals*
    - AI prompt: "Generate a labelled diagram showing electronic configurations of lithium, sodium, and potassium with ns^1 valence electron."
    - Platform: Microsoft Copilot image generation
    - Search string: "alkali metals electronic configuration ns1 OER"
- *Box 1.3 General properties of alkali metals*
    - AI prompt: "Generate a single-column table summarising physical and chemical properties of alkali metals."
    - Platform: Microsoft Copilot image generation
    - Search string: "alkali metals physical chemical properties OER"
- *Figure 1.3 Position of alkaline earth metals in the periodic table*
    - AI prompt: "Generate a labelled diagram of the periodic table highlighting Group IIA alkaline earth metals."
    - Platform: Microsoft Copilot image generation
    - Search string: "periodic table alkaline earth metals group IIA OER"
- *Figure 1.4 Electronic configurations of selected alkaline earth metals*
    - AI prompt: "Generate a labelled diagram showing electronic configurations of magnesium, calcium, and barium with ns^2 valence electrons."
    - Platform: Microsoft Copilot image generation
    - Search string: "alkaline earth metals electronic configuration ns2 OER"
- *Box 1.5 General properties of alkaline earth metals*

    - AI prompt: “Generate a single-column table summarising physical and chemical properties of alkaline earth metals.”
    - Platform: Microsoft Copilot image generation
    - Search string: “alkaline earth metals physical chemical properties OER”
- *Figure 1.6 Trends in atomic and ionic radii of Group IA and Group IIA elements*
    - AI prompt: “Generate a labelled diagram comparing atomic and ionic radii trends of Group IA and Group IIA elements across periods.”
    - Platform: Microsoft Copilot image generation
    - Search string: “atomic ionic radii trends alkali alkaline earth metals OER”
- *Box 1.7 Comparison of ionisation energies and reactivity*
    - AI prompt: “Generate a single-column table comparing ionisation energies and reactivity of Group IA and Group IIA elements.”
    - Platform: Microsoft Copilot image generation
    - Search string: “ionisation energy reactivity alkali alkaline earth metals OER”
- *Plate 1.8 Examples of compounds of Group IA and Group IIA elements*
    - AI prompt: “Create an image showing sodium chloride crystals and calcium carbonate limestone as examples of Group IA and Group IIA compounds.”
    - Platform: Microsoft Copilot image generation
    - Search string: “sodium chloride calcium carbonate examples OER”
- *Figure 1.9 Solubility trends of Group IA and Group IIA salts*
    - AI prompt: “Generate a labelled diagram comparing solubility trends of Group IA and Group IIA salts such as sodium carbonate and calcium carbonate.”
    - Platform: Microsoft Copilot image generation
    - Search string: “solubility trends alkali alkaline earth salts OER”
- *Plate 1.10 Industrial applications of Group IA and Group IIA compounds*
    - AI prompt: “Create an image showing sodium hydroxide used in soap manufacture and calcium carbonate used in cement production.”
    - Platform: Microsoft Copilot image generation
    - Search string: “industrial applications sodium hydroxide calcium carbonate OER”
- *Box 1.11 Biological importance of Group IA and Group IIA compounds*
    - AI prompt: “Generate a single-column table summarising biological importance of sodium, potassium, calcium, and magnesium in humans and plants.”
    - Platform: Microsoft Copilot image generation
    - Search string: “biological importance sodium potassium calcium magnesium OER”

Notes on Attribution

- All AI-generated illustrations were created using Microsoft Copilot’s image generation tool and documented with prompts.
- Where OERs are referenced, attribution must comply with the licence terms of the source.
- References are presented in APA style for consistency.

CHM 302: Inorganic Chemistry II (2 Units C: LH 30)

Series 1: Comparative Chemistry of Main Group Elements

Series 2: Chemistry of Non Metals and Their Compounds

Series 3: Transition Metal Chemistry and Complexes

Series 4: Radioactivity and Radiochemistry

Series 5: Biological Roles of Metals in Living Systems

Suggested Outline of Main Parts and Sub-Parts

2.1 Chemistry of Boron, Carbon, and Silicon

- 2.1.1 General properties and bonding
- 2.1.2 Important compounds and their uses
- 2.1.3 Comparative trends among boron, carbon, and silicon

2.2 Chemistry of Nitrogen and Phosphorus

- 2.2.1 Electronic structures and oxidation states
- 2.2.2 Common compounds (ammonia, nitrates, phosphates)
- 2.2.3 Environmental and biological significance

2.3 Chemistry of Oxygen and Sulphur

- 2.3.1 General properties and allotropes
- 2.3.2 Oxides, acids, and sulphur compounds
- 2.3.3 Industrial and environmental relevance

2.4 Halogen Chemistry

- 2.4.1 General properties and reactivity trends
- 2.4.2 Common halogen compounds (halides, acids)
- 2.4.3 Applications in industry and health

2.5 Comparative Applications and Significance of Non-Metals

- 2.5.1 Industrial uses (fertilisers, polymers, energy production)
- 2.5.2 Environmental roles (ozone, acid rain, nutrient cycles)
- 2.5.3 Biological importance (DNA, proteins, respiration)

Introduction

Non-metals are among the most versatile elements in the periodic table, forming compounds that are essential to life, industry, and the environment. From the carbon in our bodies and fuels, to the oxygen we breathe, and the halogens used in medicine and sanitation, their chemistry

underpins many processes that affect our daily lives. This Series focuses on the chemistry of non-metals and their compounds, helping you connect fundamental properties to practical applications.

The aim of this Series is to equip you with the ability to explain the properties, compounds, and applications of key non-metals, and to evaluate their roles in industrial, environmental, and biological contexts.

We shall commence this Series by exploring the chemistry of boron, carbon, and silicon, focusing on their bonding and compounds. Next, we will move on to nitrogen and phosphorus, examining their oxidation states, common compounds, and significance in agriculture and biology. Following that, we will study oxygen and sulphur, considering their allotropes, oxides, and environmental relevance. Afterwards, we will continue with halogen chemistry, analysing their reactivity and applications. Finally, we will bring the Series to a close by comparing the broader applications and significance of non-metals, highlighting their industrial, environmental, and biological importance.

2.1 Chemistry Of Boron, Carbon, And Silicon

2.1.1 General properties and bonding

Boron, **carbon**, and **silicon** are non-metals (or metalloids, in the case of boron and silicon) that exhibit diverse bonding behaviours. Boron typically forms covalent compounds due to its electron deficiency, often resulting in unusual structures such as boranes. Carbon is unique in its ability to form long chains and rings through covalent bonding, giving rise to a vast range of organic and inorganic compounds. Silicon, though similar to carbon, tends to form extended networks such as silicates and has a stronger preference for forming oxides.

Fill in the blank: The element that can form long chains and rings through covalent bonding is _____.

Figure 2.1 Bonding behaviour of boron, carbon, and silicon

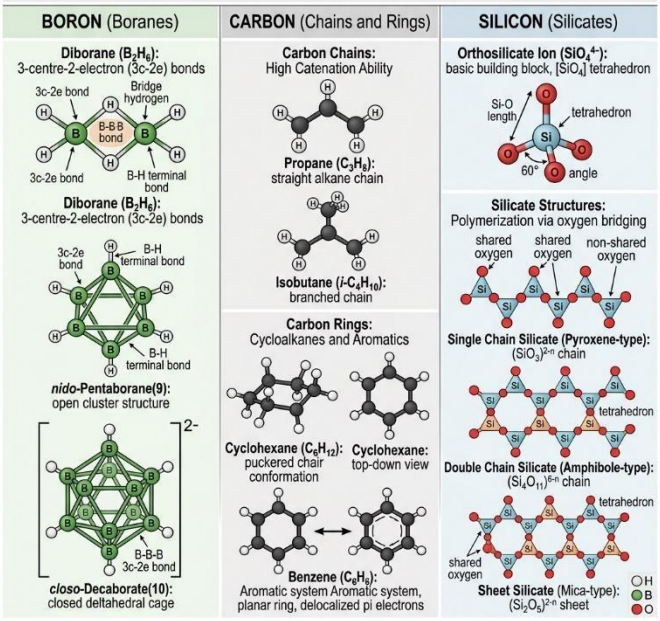


Diagram showing bonding structures of boron (boranes), carbon (chains and rings), and silicon (silicates).
Caption: Figure 2.1 Bonding behaviour of boron, carbon, and silicon.
"bonding behaviour boron carbon silicon OER"

2.1.2 Important compounds and their uses

Boron forms compounds such as borax and boric acid, widely used in cleaning products and antiseptics. Carbon compounds include carbon dioxide, carbonates, and graphite, which are essential in respiration, industry, and materials science. Silicon compounds such as silicon dioxide and silicates are fundamental in glass manufacture, ceramics, and electronics.

Fill in the blank: The compound of silicon that is widely used in glass manufacture is _____ dioxide.

Image showing borax crystals, graphite, and silica sand as examples of boron, carbon, and silicon compounds.
Caption: Plate 2.2 Examples of compounds of boron, carbon, and silicon.
"Create an image showing borax crystals, graphite, and silica sand as examples of boron, carbon, and silicon compounds."
borax graphite silica examples OER"

2.1.3 Comparative trends among boron, carbon, and silicon

Although boron, carbon, and silicon belong to different positions in the periodic table, they show interesting comparative trends. Boron is electron-deficient and often forms compounds with unusual bonding. Carbon is versatile, forming stable covalent bonds with itself and other elements, which explains the diversity of organic chemistry. Silicon, while similar to carbon, is less capable of forming stable double bonds and instead favours extended network structures.

Fill in the blank: Unlike carbon, silicon rarely forms stable _____ bonds.

Comparison of Boron, Carbon, and Silicon

Element	Key Properties and Structures
Boron	**Electron-deficient** (3 valence electrons); forms complex **boranes** and icosahedral clusters; high hardness and low conductivity.
Carbon	Exceptional **catenation** (chains and rings); forms stable **double and triple bonds**; diverse **allotropes** like diamond and graphite.
Silicon	Prefers extensive **covalent network** structures; dominated by **silicate** (Si–O) chemistry; essential **semiconductor** for electronics.

Box 2.3 Comparative properties of boron, carbon, and silicon.
Single-column table summarising boron (electron-deficient, boranes), carbon (chains, rings,

double bonds), silicon (network structures, silicates).
“comparative properties boron carbon silicon OER”

2.2 Chemistry Of Nitrogen And Phosphorus

2.2.1 Electronic structures and oxidation states

Nitrogen has the electronic configuration $1s^2\ 2s^2\ 2p^3$, giving it five valence electrons. This allows nitrogen to exhibit a wide range of oxidation states from –3 (as in ammonia) to +5 (as in nitrates). **Phosphorus**, with the configuration $[Ne]3s^2\ 3p^3$, also has five valence electrons and shows oxidation states from –3 to +5, though +3 and +5 are the most common.

These varied oxidation states explain the diversity of compounds formed by both elements, ranging from simple hydrides to complex oxoacids.

Fill in the blank: The most common oxidation states of phosphorus are _____ and +5.

Figure 2.4 Electronic structures of nitrogen and phosphorus

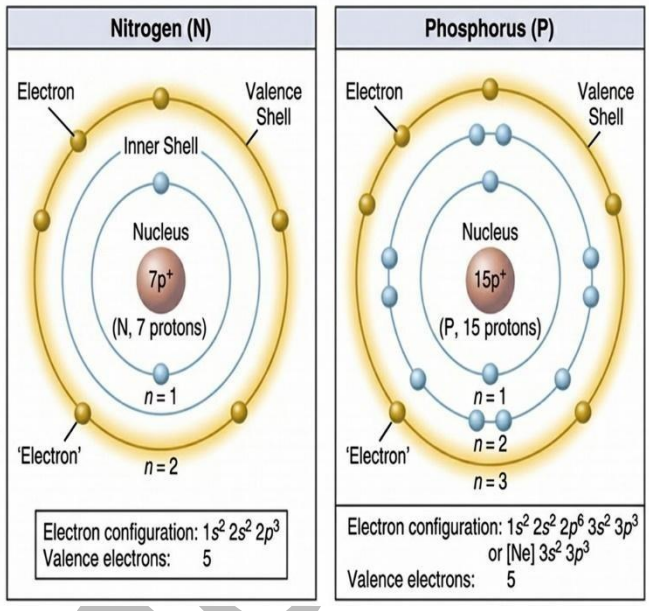


Diagram showing electronic structures of nitrogen and phosphorus with highlighted valence electrons.
Figure 2.4 Electronic structures of nitrogen and phosphorus.
“electronic structure nitrogen phosphorus OER”

2.2.2 Common compounds

Nitrogen forms compounds such as **ammonia (NH_3)**, **nitrates (NO_3^-)**, and **nitrites (NO_2^-)**, which are vital in agriculture and biological systems. Phosphorus forms **phosphates (PO_4^{3-})**, **phosphoric acid (H_3PO_4)**, and **phosphine (PH_3)**, which are important in fertilisers, detergents, and industrial processes.

Ammonia is a key compound in the nitrogen cycle, while phosphates are essential for DNA, RNA, and energy transfer in living organisms.

Fill in the blank: The compound of nitrogen that plays a central role in the nitrogen cycle is _____.

Plate 2.5 Examples of nitrogen and phosphorus compounds

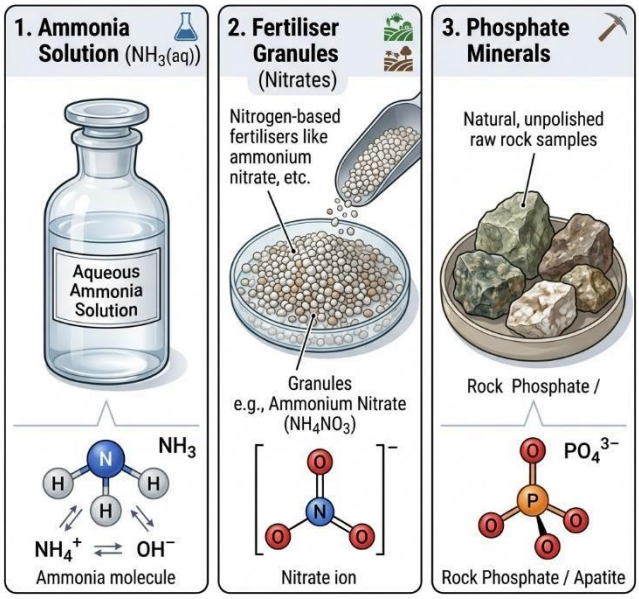


Image showing ammonia solution, fertiliser granules (nitrates), and phosphate minerals.
Plate 2.5 Examples of nitrogen and phosphorus compounds.
"ammonia nitrates phosphates examples OER"

2.2.3 Environmental and biological significance

Nitrogen and phosphorus compounds are crucial to life and the environment. Nitrogen is a major component of proteins and nucleic acids, while phosphorus is essential for ATP, DNA, and bone formation. In agriculture, nitrates and phosphates are used as fertilisers to enhance crop yield.

However, excessive use of these fertilisers can lead to **eutrophication**, a process where nutrient overloading causes algal blooms and oxygen depletion in water bodies. This highlights the need for balanced use of nitrogen and phosphorus compounds.

Fill in the blank: Excessive use of nitrogen and phosphorus fertilisers can lead to _____ in water bodies.

Element / Impact	Biological and Environmental Summary
Nitrogen	Essential for **proteins** and amino acids; primary component of **nucleic acids** (DNA/RNA); key ingredient in industrial **fertilizers**.
Phosphorus	Critical for **ATP** energy transfer; forms the backbone of **DNA**; vital for **bone formation** and tooth enamel.
Environmental	Nutrient runoff causes **eutrophication**; leads to **algal blooms** and oxygen depletion in aquatic ecosystems.

Box 2.6 Environmental and biological roles of nitrogen and phosphorus.
Single-column table summarising nitrogen → proteins, nucleic acids, fertilisers; phosphorus → ATP, DNA, bone formation, fertilisers; environmental impact → eutrophication.
"biological environmental roles nitrogen phosphorus OER"

2.3 Chemistry Of Oxygen And Sulphur

2.3.1 General properties and allotropes

Oxygen is a diatomic non-metal element with the electronic configuration $1s^2\ 2s^2\ 2p^4$. It exists mainly as O_2, a colourless, odourless gas essential for respiration and combustion. Another important allotrope is ozone (O_3), which plays a protective role in the atmosphere by absorbing harmful ultraviolet radiation.

Sulphur has the electronic configuration $[Ne]3s^2\ 3p^4$ and exists in several allotropes, the most stable being rhombic sulphur and monoclinic sulphur. These allotropes differ in crystal structure but share similar chemical properties.

Fill in the blank: The allotrope of oxygen that protects the Earth from harmful ultraviolet radiation is _____.

Figure 2.7 Allotropes of Oxygen and Sulphur

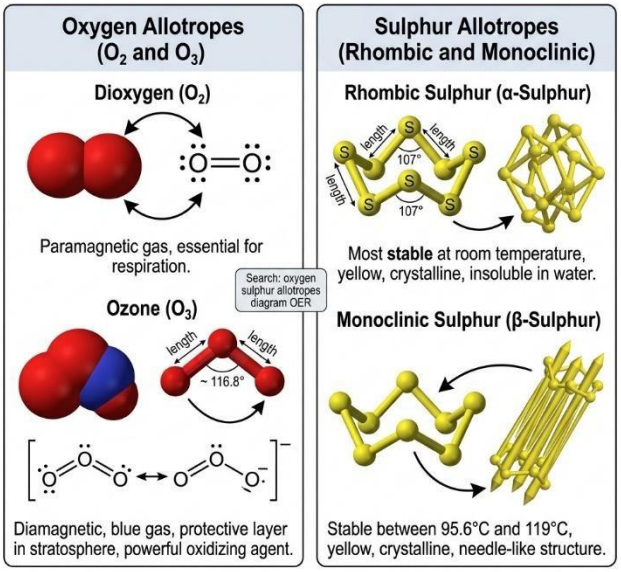


Diagram showing oxygen allotropes (O_2 and O_3) and sulphur allotropes (rhombic and monoclinic).
Figure 2.7 Allotropes of oxygen and sulphur.
"oxygen sulphur allotropes diagram OER"

2.3.2 Oxides and acids

Oxygen readily forms **oxides**, compounds with other elements that vary from basic (e.g., sodium oxide) to acidic (e.g., sulphur dioxide). Sulphur forms oxides such as **sulphur dioxide (SO_2)** and **sulphur trioxide (SO_3)**, which dissolve in water to produce acids. For example, SO_2 forms sulphurous acid (H_2SO_3), while SO_3 forms sulphuric acid (H_2SO_4), one of the most important industrial chemicals.

Fill in the blank: The oxide of sulphur that produces sulphuric acid when dissolved in water is _____ trioxide.

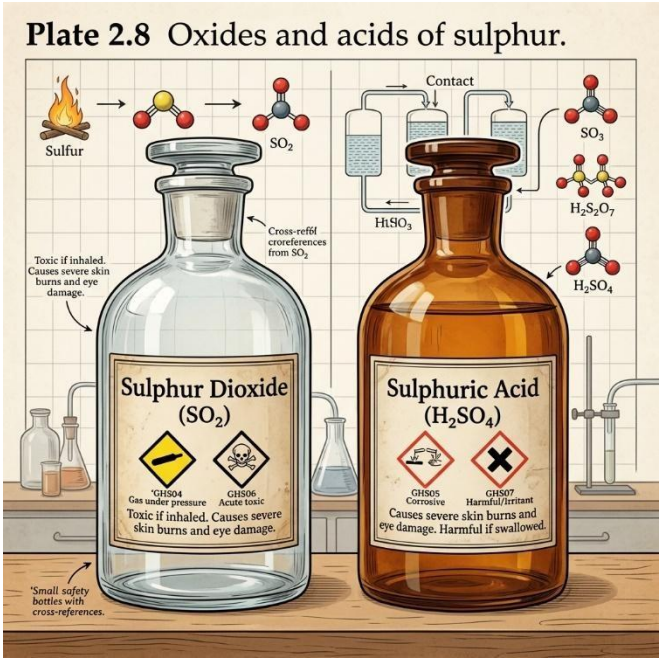


Image showing laboratory bottles of sulphur dioxide and sulphuric acid.
Plate 2.8 Oxides and acids of sulphur.
"sulphur dioxide sulphuric acid laboratory OER"

2.3.3 Industrial and environmental relevance

Oxygen is vital in steel production, medical applications, and combustion processes. Sulphur compounds are used in the manufacture of fertilisers, detergents, and chemicals such as sulphuric acid. However, sulphur oxides are also major contributors to **acid rain**, which damages ecosystems, corrodes buildings, and affects human health.

Fill in the blank: The environmental problem caused by sulphur oxides dissolving in rainwater is known as _____.

Element / Impact	Summary of Roles and Relevance
Oxygen	Essential for **aerobic respiration**; used in **steel production** to remove impurities; critical for **medical** life-support.
Sulphur	Primary feedstock for **sulphuric acid**; vital for **fertilisers** and **detergents**; used in the vulcanisation of rubber.
Environmental	Sulphur dioxide emissions react with water to form **acid rain**; leads to **soil acidification** and damage to stone structures.

Box 2.9 Industrial and environmental relevance of oxygen and sulphur.
Single-column table summarising oxygen → respiration, steel production, medical use; sulphur → fertilisers, detergents, sulphuric acid; environmental impact → acid rain.
"industrial environmental relevance oxygen sulphur OER"

2.4 Halogen Chemistry

2.4.1 General properties and reactivity trends

Halogens are the elements in Group VIIA of the periodic table, including fluorine, chlorine, bromine, iodine, and astatine. They are characterised by having seven valence electrons, which makes them highly reactive and eager to gain one electron to achieve a stable noble gas configuration. Their reactivity decreases down the group, with fluorine being the most reactive and iodine less so.

Halogens exist as diatomic molecules (e.g., Cl_2, Br_2) and display distinct colours in their elemental forms. They readily form salts with metals, such as sodium chloride, and are strong oxidising agents.

Fill in the blank: The most reactive halogen, found at the top of Group VIIA, is _____.

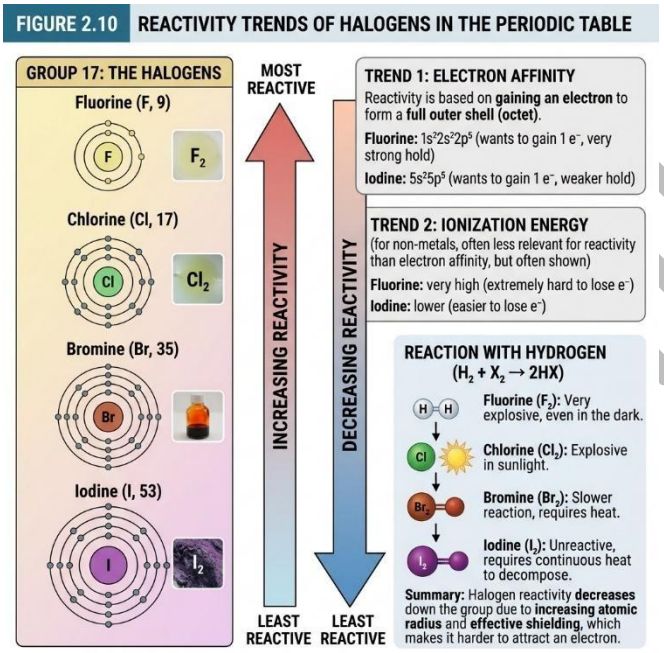


Diagram showing halogens in the periodic table with reactivity trend arrows.
Figure 2.10 Reactivity trends of halogens in the periodic table.
"halogen reactivity periodic table OER"

2.4.2 Common halogen compounds

Halogens form a wide range of compounds, including **halides** (such as sodium chloride), **hydrogen halides** (such as hydrogen chloride), and **halogen acids** (such as hydrochloric acid). These compounds are important in industry and everyday life. For example, sodium chloride is used in food preservation, while chlorine compounds are used in water treatment.

Hydrogen halides dissolve in water to form strong acids, with hydrochloric acid being one of the most widely used industrial chemicals.

Fill in the blank: The hydrogen halide that forms hydrochloric acid when dissolved in water is _____ chloride.

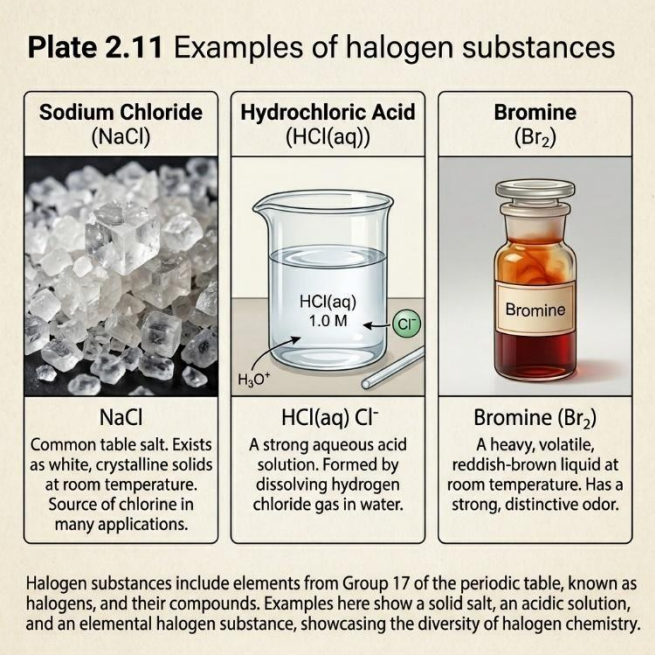


Image showing sodium chloride crystals, hydrochloric acid solution, and bromine liquid.
Plate 2.11 Examples of halogen compounds.
"sodium chloride hydrochloric acid bromine examples OER"

2.4.3 Applications in industry and health

Halogen compounds have significant applications. Chlorine is used in disinfecting drinking water and swimming pools. Fluorine compounds are added to toothpaste to strengthen teeth. Iodine is used in antiseptics and medical imaging. Bromine compounds are employed in flame retardants.

Despite their usefulness, halogens must be handled carefully due to their toxicity and corrosive nature. Their role in health and sanitation highlights their importance in daily life.

Fill in the blank: The halogen commonly used in antiseptics and medical imaging is _____.

Applications of Halogens

Element	Summary of Industrial and Health Applications
Chlorine	Widely used for **water treatment** and disinfection; key in the production of **PVC** and household bleaches.
Fluorine	Essential for **dental health** (fluoridated water and toothpaste); used in the manufacturing of **non-stick coatings** (Teflon).
Iodine	Critical as a **topical antiseptic** for wound care; essential for **thyroid function** and hormone regulation.
Bromine	Primary component in **flame retardants** for electronics and textiles; used in specialized **water purification** for pools/spas.

Box 2.12 Applications of halogens in industry and health.
Single-column table summarising chlorine → water treatment, fluorine → dental health, iodine → antiseptics, bromine → flame retardants.
"applications halogens chlorine fluorine iodine bromine OER"

2.4 Halogen Chemistry

2.4.1 General properties and reactivity trends

Halogens are the elements in Group VIIA of the periodic table, including fluorine, chlorine, bromine, iodine, and astatine. They are characterised by having seven valence electrons, which makes them highly reactive and eager to gain one electron to achieve a stable noble gas configuration. Their reactivity decreases down the group, with fluorine being the most reactive and iodine less so.

Halogens exist as diatomic molecules (e.g., Cl_2, Br_2) and display distinct colours in their elemental forms. They readily form salts with metals, such as sodium chloride, and are strong oxidising agents.

Fill in the blank: The most reactive halogen, found at the top of Group VIIA, is _____.

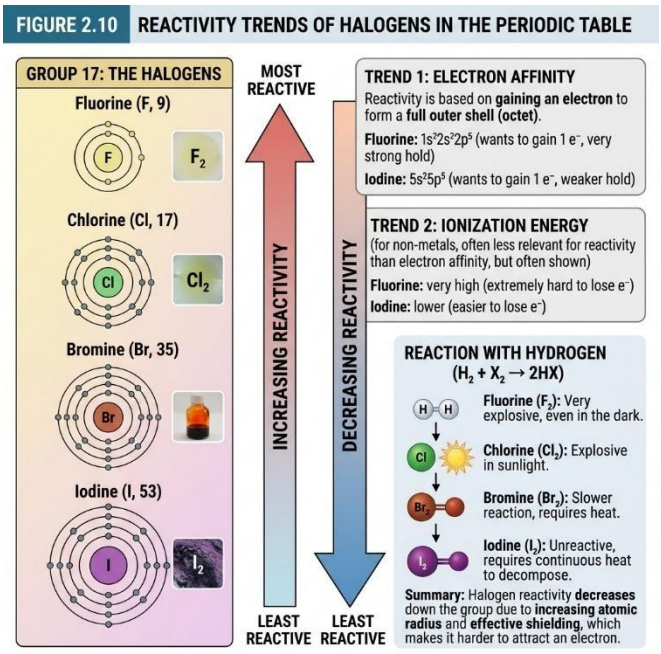


Diagram showing halogens in the periodic table with reactivity trend arrows.
Figure 2.10 Reactivity trends of halogens in the periodic table.
"halogen reactivity periodic table OER"

2.4.2 Common halogen compounds

Halogens form a wide range of compounds, including **halides** (such as sodium chloride), **hydrogen halides** (such as hydrogen chloride), and **halogen acids** (such as hydrochloric acid). These compounds are important in industry and everyday life. For example, sodium chloride is used in food preservation, while chlorine compounds are used in water treatment.

Hydrogen halides dissolve in water to form strong acids, with hydrochloric acid being one of the most widely used industrial chemicals.

Fill in the blank: The hydrogen halide that forms hydrochloric acid when dissolved in water is _____ chloride.

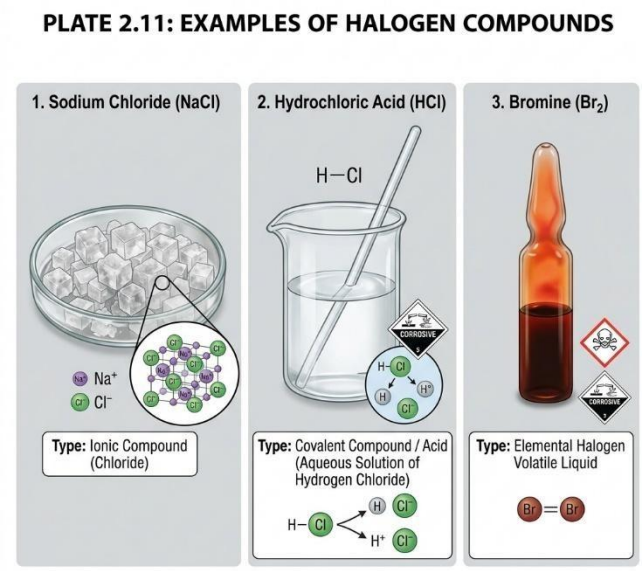


Image showing sodium chloride crystals, hydrochloric acid solution, and bromine liquid.
Plate 2.11 Examples of halogen compounds.
"sodium chloride hydrochloric acid bromine examples OER"

2.4.3 Applications in industry and health

Halogen compounds have significant applications. Chlorine is used in disinfecting drinking water and swimming pools. Fluorine compounds are added to toothpaste to strengthen teeth. Iodine is used in antiseptics and medical imaging. Bromine compounds are employed in flame retardants.

Despite their usefulness, halogens must be handled carefully due to their toxicity and corrosive nature. Their role in health and sanitation highlights their importance in daily life.

Fill in the blank: The halogen commonly used in antiseptics and medical imaging is _____.

Applications of Halogens

Element	Summary of Applications
Fluorine	Essential for **dental health** (enamel protection); used in **non-stick coatings** (PTFE).
Chlorine	Primary agent for **water treatment** and disinfection; critical in producing **PVC** and bleach.
Bromine	Major component in **flame retardants** for electronics; used in specialized **water purification**.
Iodine	Widely used as a topical **antiseptic**; vital for proper **thyroid function** and metabolism.

Box 2.12 Applications of halogens in industry and health.
Single-column table summarising chlorine → water treatment, fluorine → dental health, iodine

→ antiseptics, bromine → flame retardants.
“applications halogens chlorine fluorine iodine bromine OER”

2.5 Comparative Applications And Significance Of Non Metals

2.5.1 Industrial uses

Non-metals play a central role in industry. **Carbon** is used in steel production, fuels, and advanced materials such as graphite and carbon fibres. **Phosphorus** compounds are vital in fertilisers and detergents, while **sulphur** is used in the manufacture of sulphuric acid, one of the most important industrial chemicals. **Halogens** such as chlorine are essential in plastics production (PVC) and water treatment.

Fill in the blank: The non-metal used in the production of fertilisers and detergents is _____.

Image showing fertiliser granules, carbon fibre materials, and PVC pipes.
Plate 2.13 Industrial uses of non-metals.
“industrial uses carbon phosphorus sulphur chlorine OER”

2.5.2 Environmental roles

Non-metals also influence the environment significantly. **Oxygen** sustains life through respiration, while **carbon dioxide** regulates climate but contributes to global warming when in excess. **Sulphur oxides** and **nitrogen oxides** are responsible for acid rain, which damages ecosystems. **Ozone**, an allotrope of oxygen, protects the Earth from harmful ultraviolet radiation.

Fill in the blank: The allotrope of oxygen that shields the Earth from ultraviolet radiation is _____.

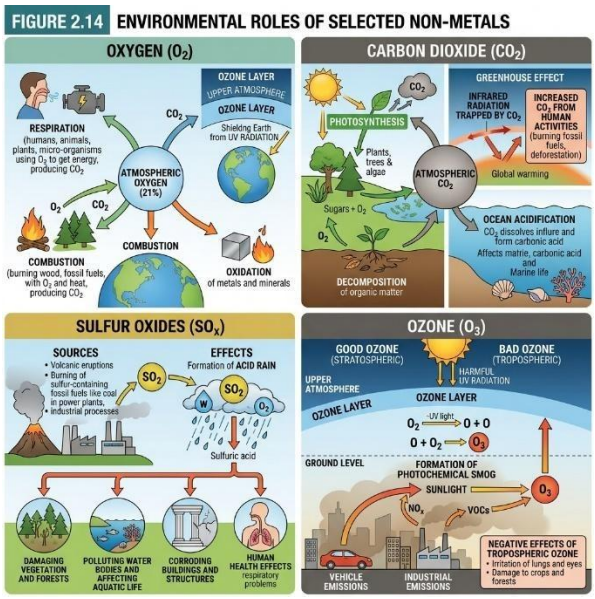


Diagram showing environmental roles of oxygen, carbon dioxide, sulphur oxides, and ozone.
Figure 2.14 Environmental roles of selected non-metals.
"environmental roles oxygen carbon dioxide sulphur oxides ozone OER"

2.5.3 Biological importance

Non-metals are indispensable in biological systems. **Nitrogen** is a key component of proteins and nucleic acids. **Phosphorus** is essential for DNA, RNA, and energy transfer through ATP. **Oxygen** is required for cellular respiration, while **iodine** is necessary for thyroid function. These roles highlight how non-metals sustain life at the molecular level.

Fill in the blank: The non-metal that is essential for thyroid function in humans is _____.

Biological Importance of Nitrogen, Phosphorus, Oxygen, and Iodine

Element	Summary of Biological Importance
Nitrogen	Fundamental building block for **proteins** and **amino acids**; essential component of **nucleic acids** (DNA and RNA).
Phosphorus	Critical for the structural backbone of **DNA and RNA**; key element in **ATP** for cellular energy transfer.
Oxygen	Essential for **aerobic respiration** to produce energy; vital component of organic molecules like carbohydrates and fats.
Iodine	Necessary for the synthesis of **thyroid hormones**; regulates metabolism, growth, and development in the human body.

Box 2.15 Biological importance of non-metals.
Single-column table summarising nitrogen → proteins and nucleic acids, phosphorus → DNA, RNA, ATP, oxygen → respiration, iodine → thyroid function.
Search string: "biological importance nitrogen phosphorus oxygen iodine OER"

Series Summary

This Series on **Chemistry of Non-Metals and Their Compounds** was designed to highlight the diverse properties, compounds, and applications of non-metals, showing their relevance in industry, the environment, and biological systems. Starting with boron, carbon, and silicon, we examined their bonding behaviours and important compounds. We then moved on to nitrogen and phosphorus, focusing on their oxidation states, key compounds such as ammonia and phosphates, and their environmental and biological roles. Following that, we explored oxygen and sulphur, considering their allotropes, oxides, and acids, as well as their industrial and environmental significance. Afterwards, we studied halogen chemistry, looking at their reactivity trends, common compounds, and applications in health and industry. Finally, we concluded with a comparative view of the broader applications and significance of non-metals across different contexts.

By completing this Series, you should now be able to **explain the properties and bonding of boron, carbon, and silicon (SLO 2.1)**, **describe the electronic structures and oxidation states of nitrogen and phosphorus (SLO 2.2)**, **analyse their compounds and evaluate their environmental and biological importance (SLO 2.3)**, **explain the properties and allotropes of oxygen and sulphur (SLO 2.4)**, **evaluate their oxides, acids, and relevance in industry and the environment (SLO 2.5)**, **define the properties and reactivity trends of halogens (SLO 2.6)**, **apply knowledge of halogen compounds to industrial and health contexts (SLO 2.7)**, and **assess the comparative applications and significance of non-metals in industrial, environmental, and biological systems (SLO 2.8)**. These outcomes ensure that you can connect fundamental chemical principles with practical applications, reinforcing the importance of non-metals in everyday life and scientific study.

Glossary of Terms

- **Acid rain**: Rainwater that becomes acidic due to dissolved sulphur oxides and nitrogen oxides, often damaging ecosystems and buildings.
- **Allotrope**: Different structural forms of the same element, such as oxygen existing as O_2 and O_3 (ozone).
- **Ammonia (NH_3)**: A compound of nitrogen widely used in fertilisers and central to the nitrogen cycle.
- **ATP (adenosine triphosphate)**: A phosphorus-containing molecule that stores and transfers energy in living cells.
- **Borax**: A boron compound used in cleaning products and glass manufacture.
- **Carbon dioxide (CO_2)**: A compound of carbon important in respiration and climate regulation, but also a greenhouse gas.
- **Halogens**: Elements in Group VIIA of the periodic table (fluorine, chlorine, bromine, iodine, astatine) known for high reactivity and strong oxidising properties.
- **Hydrogen halide**: A compound formed between hydrogen and a halogen, such as hydrogen chloride, which produces hydrochloric acid when dissolved in water.
- **Nitrate (NO_3^-)**: A nitrogen compound used in fertilisers and important in plant nutrition.

- **Oxide**: A compound formed when oxygen combines with another element, which may be basic, neutral, or acidic depending on the element involved.
- **Ozone (O_3)**: An allotrope of oxygen that forms a protective layer in the atmosphere, absorbing harmful ultraviolet radiation.
- **Phosphate (PO_4^{3-})**: A phosphorus compound essential for DNA, RNA, and energy transfer in biological systems.
- **Silicate**: A compound of silicon and oxygen, forming the basis of minerals used in ceramics and glass.
- **Sulphuric acid (H_2SO_4)**: A strong acid derived from sulphur trioxide, widely used in industry for fertilisers, detergents, and chemical manufacture.

Concept Check Questions [Series 2]

Objective Questions

1. Which element among boron, carbon, and silicon is most versatile in forming chains and rings?
   (Linked to SLO 2.1)
2. The most common oxidation states of phosphorus are _____ and +5.
   (Linked to SLO 2.2)
3. Which nitrogen compound plays a central role in the nitrogen cycle?
   A. Nitrite
   B. Ammonia
   C. Nitrate
   D. Nitrogen dioxide
   (Linked to SLO 2.3)
4. The oxide of sulphur that produces sulphuric acid when dissolved in water is _____ trioxide.
   (Linked to SLO 2.5)
5. The most reactive halogen is _____.
   (Linked to SLO 2.6)

Short-Answer Questions

1. Define allotrope and give one example each for oxygen and sulphur.
   (Linked to SLO 2.4)
2. Explain why silicon rarely forms stable double bonds compared to carbon.
   (Linked to SLO 2.1)
3. Describe one industrial application of chlorine and one health application of iodine.
   (Linked to SLO 2.7)

4. Identify one environmental problem caused by excessive nitrogen and phosphorus fertilisers.
   (Linked to SLO 2.3)
5. State the biological importance of phosphorus in living organisms.
   (Linked to SLO 2.8)

Long-Answer Questions

1. Analyse the differences in bonding behaviour between boron, carbon, and silicon, and explain how these differences influence the types of compounds they form.
   (Linked to SLO 2.1)
2. Evaluate the environmental and industrial significance of oxygen and sulphur compounds, highlighting both their beneficial uses and harmful impacts.
   (Linked to SLO 2.5)

Answers to Concept Check Questions [Series 2]

Objective Questions

1. Carbon
2. +3
3. B. Ammonia
4. Sulphur
5. Fluorine

Short-Answer Questions

1. An allotrope is a different structural form of the same element. Oxygen exists as O_2 and O_3 (ozone). Sulphur exists as rhombic and monoclinic forms.
2. Silicon has larger atomic size and less effective orbital overlap, making stable double bonds less favourable compared to carbon.
3. Chlorine is used in water treatment. Iodine is used in antiseptics and medical imaging.
4. Eutrophication.
5. Phosphorus is essential for DNA, RNA, and energy transfer through ATP.

Long-Answer Questions

Question 1

- **Basic response:** Boron is electron-deficient and forms unusual compounds like boranes. Carbon forms stable chains and rings, enabling organic chemistry. Silicon prefers extended network structures such as silicates.
- **Value-added response:** Outstanding learners may extend by comparing orbital overlap and bond strengths, noting that carbon's ability to form stable double and triple bonds leads to vast organic diversity, while silicon's preference for single bonds and extended frameworks explains its role in minerals and materials science.

Question 2

- **Basic response:** Oxygen is vital for respiration and combustion, while sulphur compounds are used in fertilisers and sulphuric acid production. However, sulphur oxides contribute to acid rain.
- **Value-added response:** Outstanding learners may extend by evaluating oxygen's role in steel production and medical use, sulphur's role in detergents and industrial chemistry, and the environmental consequences of acid rain, linking these to sustainable practices and pollution control strategies.

Answers to Pilot Questions [Series 2]

Part 2.1 Chemistry of Boron, Carbon, and Silicon

1. Carbon
2. Silicon dioxide
3. Double

Part 2.2 Chemistry of Nitrogen and Phosphorus

1. +3
2. Ammonia
3. Eutrophication

Part 2.3 Chemistry of Oxygen and Sulphur

1. Ozone
2. Sulphur
3. Acid rain

Part 2.4 Halogen Chemistry

1. Fluorine
2. Hydrogen
3. Iodine

Part 2.5 Comparative Applications and Significance of Non-Metals

1. Phosphorus
2. Ozone
3. Iodine

References and Attributions [Series 2]

General References

- OpenStax (2021). *Chemistry: Atoms First 2e*. Houston, TX: OpenStax. Available under Creative Commons Attribution Licence.
- LibreTexts (2023). *Chemistry Library*. Retrieved from https://chem.libretexts.org (OER resource for chemical structures and properties).
- Royal Society of Chemistry (RSC). *Learn Chemistry Resources*. Retrieved from https://edu.rsc.org (educational resources on non-metals and their compounds).

Illustrations

- *Figure 2.1 Bonding behaviour of boron, carbon, and silicon*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing bonding structures of boron (boranes), carbon (chains and rings), and silicon (silicates)."
- *Plate 2.2 Examples of compounds of boron, carbon, and silicon*
  Attribution: Suggested OER search string "borax graphite silica examples OER."
- *Box 2.3 Comparative properties of boron, carbon, and silicon*
  Attribution: AI-generated using prompt "Generate a single-column table comparing properties of boron, carbon, and silicon."
- *Figure 2.4 Electronic structures of nitrogen and phosphorus*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing electronic structures of nitrogen and phosphorus with valence electrons highlighted."
- *Plate 2.5 Examples of nitrogen and phosphorus compounds*
  Attribution: Suggested OER search string "ammonia nitrates phosphates examples OER."
- *Box 2.6 Environmental and biological roles of nitrogen and phosphorus*
  Attribution: AI-generated using prompt "Generate a single-column table summarising biological and environmental roles of nitrogen and phosphorus."
- *Figure 2.7 Allotropes of oxygen and sulphur*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing oxygen allotropes (O_2 and O_3) and sulphur allotropes (rhombic and monoclinic)."
- *Plate 2.8 Oxides and acids of sulphur*
  Attribution: Suggested OER search string "sulphur dioxide sulphuric acid laboratory OER."
- *Box 2.9 Industrial and environmental relevance of oxygen and sulphur*
  Attribution: AI-generated using prompt "Generate a single-column table summarising industrial and environmental relevance of oxygen and sulphur."
- *Figure 2.10 Reactivity trends of halogens in the periodic table*
  Attribution: AI-generated using prompt "Generate a labelled diagram of halogens in the periodic table showing reactivity trends from fluorine to iodine."
- *Plate 2.11 Examples of halogen compounds*
  Attribution: Suggested OER search string "sodium chloride hydrochloric acid bromine examples OER."

- *Box 2.12 Applications of halogens in industry and health*
  Attribution: AI-generated using prompt "Generate a single-column table summarising industrial and health applications of chlorine, fluorine, iodine, and bromine."
- *Plate 2.13 Industrial uses of non-metals*
  Attribution: Suggested OER search string "industrial uses carbon phosphorus sulphur chlorine OER."
- *Figure 2.14 Environmental roles of selected non-metals*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing environmental roles of oxygen, carbon dioxide, sulphur oxides, and ozone."
- *Box 2.15 Biological importance of non-metals*
  Attribution: AI-generated using prompt "Generate a single-column table summarising biological importance of nitrogen, phosphorus, oxygen, and iodine."

Course load: CHM 302

Course title: Inorganic Chemistry II

Course unit: (2 Units C: LH 30)

List of series

Series 1: Comparative Chemistry of Main Group Elements

Series 2: Chemistry of Non Metals and Their Compounds

Series 3: Transition Metal Chemistry and Complexes

Series 4: Radioactivity and Radiochemistry

Series 5: Biological Roles of Metals in Living Systems

Suggested Outline

3.1 General properties of transition metals

- 3.1.1 Position in the periodic table
- 3.1.2 Electronic configurations and variable oxidation states
- 3.1.3 Magnetic properties and colour

3.2 Coordination chemistry

- 3.2.1 Definition of complexes and ligands
- 3.2.2 Types of ligands (monodentate, bidentate, polydentate)

- 3.2.3 Coordination number and geometry

3.3 Bonding theories in complexes

- 3.3.1 Valence bond theory (VBT)
- 3.3.2 Crystal field theory (CFT)
- 3.3.3 Ligand field theory (LFT)

3.4 Stability and reactions of complexes

- 3.4.1 Factors affecting stability (nature of ligand, charge, size)
- 3.4.2 Substitution reactions in complexes
- 3.4.3 Redox behaviour of transition metal complexes

3.5 Applications of transition metal complexes

- 3.5.1 Industrial uses (catalysis, pigments, metallurgy)
- 3.5.2 Biological significance (haemoglobin, chlorophyll, vitamin B12)
- 3.5.3 Environmental and technological relevance (water treatment, materials science)

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** explain the general properties of transition metals, including their electronic configurations, oxidation states, magnetism, and colour,
- **SLO 3.2** define complexes and ligands, and describe coordination numbers and geometries in coordination chemistry,
- **SLO 3.3** analyse bonding in transition metal complexes using valence bond theory, crystal field theory, and ligand field theory,
- **SLO 3.4** evaluate the stability of transition metal complexes and explain substitution and redox reactions, and
- **SLO 3.5** assess the industrial, biological, and environmental applications of transition metal complexes.

3.1 General Properties Of Transition Metals

3.1.1 Position in the periodic table

Transition metals are elements found in Groups 3 to 12 of the periodic table. They are characterised by having partially filled d-orbitals, either in their elemental state or in one of their common oxidation states. This unique position gives them properties distinct from s-block and p-block elements, such as variable oxidation states and the ability to form coloured compounds.

Fill in the blank: Transition metals are located in Groups _____ to 12 of the periodic table.

Figure 3.1 Position of transition metals in the periodic table

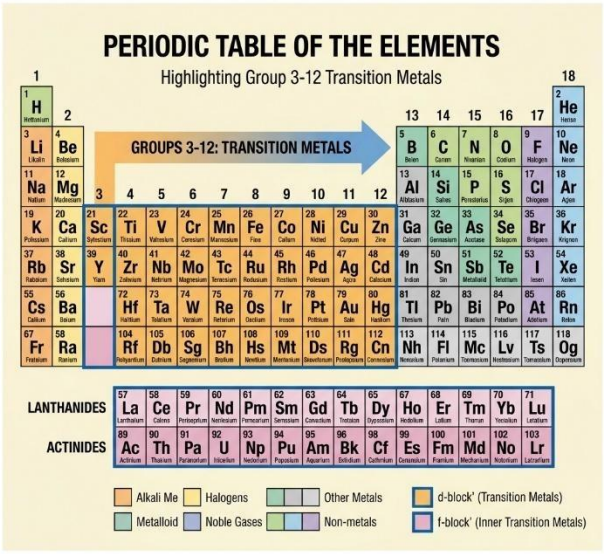


Diagram of the periodic table highlighting Groups 3 to 12 as transition metals.
Figure 3.1 Position of transition metals in the periodic table.
"periodic table transition metals groups 3 to 12 OER"

3.1.2 Electronic configurations and variable oxidation states

Transition metals typically have an **electronic configuration** that involves filling of the d-orbitals. For example, iron has the configuration $[Ar]3d^6 4s^2$. This arrangement allows them to exhibit **variable oxidation states**, meaning they can lose different numbers of electrons depending on the chemical environment. For instance, iron can exist as Fe^{2+} or Fe^{3+}, while manganese can show oxidation states ranging from +2 to +7.

Fill in the blank: The element iron can exist in oxidation states _____ and +3.

Variable Oxidation States in Transition Metals

Element	Examples of Variable Oxidation States
Iron	Commonly exhibits **+2** (ferrous) and **+3** (ferric) states.
Manganese	Highly versatile; commonly shows states from **+2** to **+7** (e.g., in $KMnO_4$).
Copper	Frequently found in **+1** (cuprous) and **+2** (cupric) states.

Box 3.2 Examples of variable oxidation states in transition metals.
Single-column table listing iron (+2, +3), manganese (+2 to +7), copper (+1, +2).
"variable oxidation states transition metals OER"

3.1.3 Magnetic properties and colour

Transition metals often display **magnetic properties** due to unpaired d-electrons. For example, iron, cobalt, and nickel are ferromagnetic, meaning they can be permanently magnetised.

They also form compounds that are vividly coloured. This arises from **d-d electronic transitions**, where electrons move between different d-orbitals when light is absorbed. For example, copper(II) sulphate is blue, while potassium dichromate is orange. These colours are a hallmark of transition metal chemistry and are widely used in pigments and indicators.

Fill in the blank: The blue colour of copper(II) sulphate arises from _____ transitions in the d-orbitals.

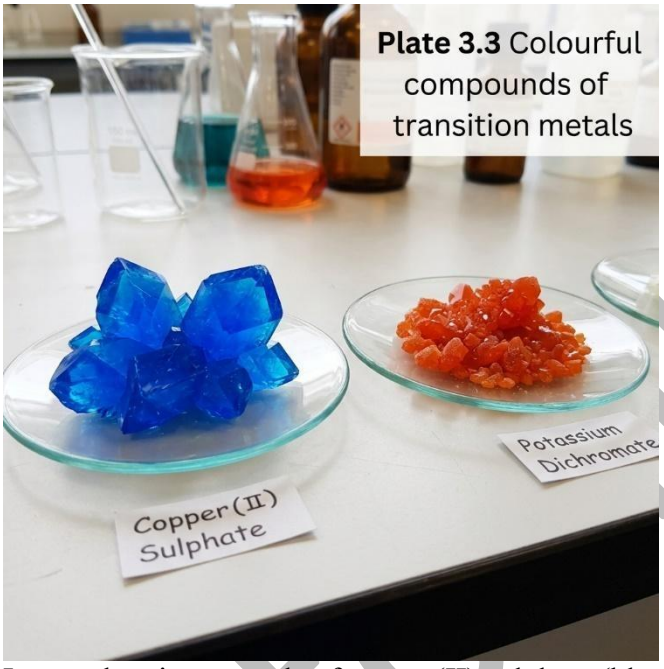


Image showing crystals of copper(II) sulphate (blue) and potassium dichromate (orange).
Plate 3.3 Colourful compounds of transition metals.
"copper sulphate potassium dichromate crystals OER"

3.2 Coordination Chemistry

3.2.1 Definition of complexes and ligands

A **complex** is a chemical species formed when a central metal atom or ion is bonded to surrounding molecules or ions called **ligands**. A **ligand** is any ion or molecule that can donate a pair of electrons to the metal centre, forming a coordinate covalent bond. Common ligands include water (H_2O), ammonia (NH_3), and chloride ions (Cl^-).

Complexes are important because they explain many of the unique properties of transition metals, such as colour, magnetism, and reactivity.

Fill in the blank: A molecule or ion that donates a pair of electrons to a metal centre is called a _____.

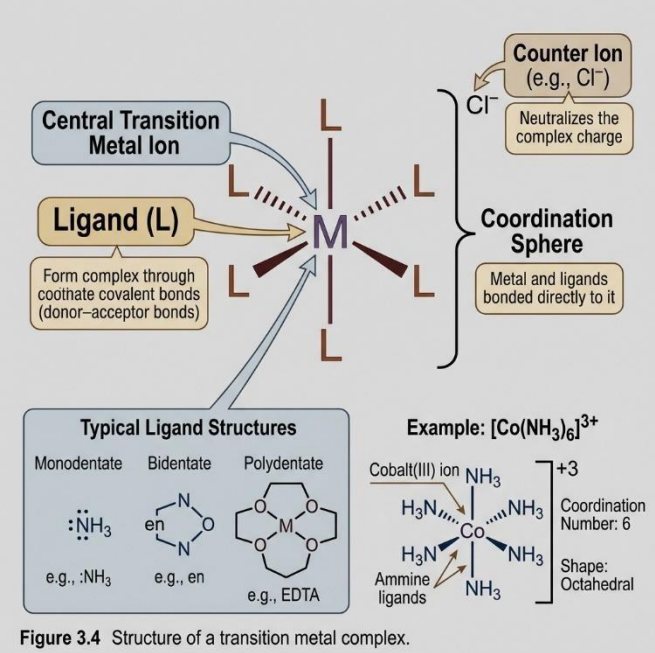


Figure 3.4 Structure of a transition metal complex.

Diagram showing a central metal ion surrounded by ligands forming a complex.
Figure 3.4 Structure of a transition metal complex.
"transition metal complex diagram OER"

3.2.2 Types of ligands

Ligands can be classified based on how many donor atoms they use to bind to the metal centre. **Monodentate ligands** bind through a single donor atom (e.g., Cl^-, NH_3). **Bidentate ligands** bind through two donor atoms (e.g., ethylenediamine). **Polydentate ligands** bind through multiple donor atoms, with **chelating agents** such as EDTA forming very stable complexes.

Fill in the blank: A ligand that binds to a metal centre through two donor atoms is called a _____ ligand.

Types of Ligands and Examples

Ligand Type	Summary and Examples
Monodentate	Binds through a **single donor atom**; Examples: **Cl^-** (Chloride), **NH_3** (Ammonia), and **H_2O** (Water).
Bidentate	Binds through **two donor atoms** simultaneously; Example: **Ethylenediamine** (en) and **Oxalate** (ox).
Polydentate	Binds through **multiple donor atoms** (chelation); Example: **EDTA** (hexadentate), which can grip a metal ion at six points.

Box 3.5 Classification of ligands.

Single-column table summarising monodentate (Cl^-, NH_3), bidentate (ethylenediamine), polydentate (EDTA).
“types of ligands monodentate bidentate polydentate OER”

3.2.3 Coordination number and geometry

The **coordination number** refers to the number of ligand donor atoms directly bonded to the central metal ion. Common coordination numbers include 4 and 6. The **geometry** of a complex depends on its coordination number and the nature of the ligands. For example, a coordination number of 4 may give rise to tetrahedral or square planar geometry, while a coordination number of 6 usually results in octahedral geometry.

Fill in the blank: A complex with coordination number 6 typically has _____ geometry.

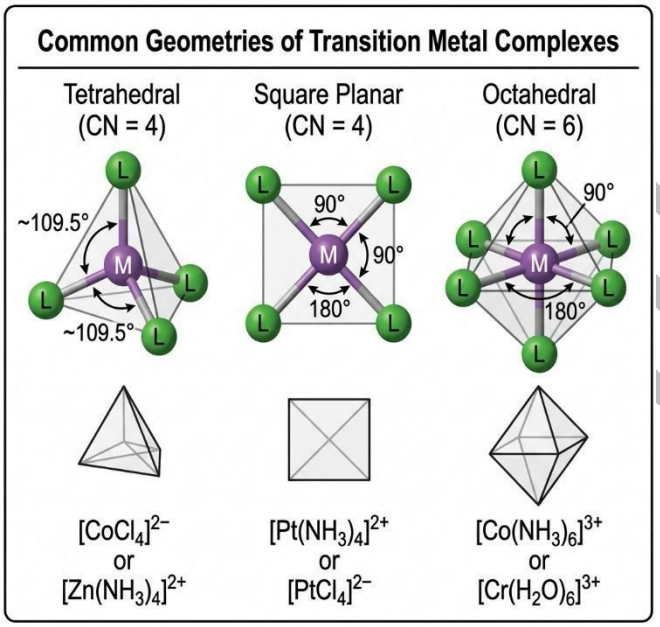


Figure 3.6 Common geometries of transition metal complexes.
Diagram showing tetrahedral, square planar, and octahedral geometries of complexes.
Figure 3.6 Common geometries of transition metal complexes.
“coordination number geometry transition metal complexes OER”

3.4 Stability And Reactions Of Complexes

3.4.1 Factors affecting stability

The **stability** of a complex refers to how strongly the ligands are bound to the central metal ion. Several factors influence this:

- The **nature of the ligand**: Chelating ligands such as EDTA form more stable complexes because they bind through multiple donor atoms.

- The **charge on the metal ion**: Higher charges increase the attraction between the metal and the ligand.
- The **size of the metal ion**: Smaller ions allow ligands to approach more closely, strengthening the bond.

Fill in the blank: Ligands that bind through multiple donor atoms and form very stable complexes are called _____ ligands.

Factors Affecting Stability of Transition Metal Complexes

Factor	Summary of Influence
Ligand Type	**Chelating (polydentate)** ligands create much more stable complexes than monodentate ones; stronger **Lewis bases** also enhance stability.
Metal Ion Charge	Ions with a **higher positive charge** exert a stronger pull on ligand electrons, generally resulting in **greater complex stability**.
Metal Ion Size	**Smaller metal ions** allow ligands to get closer to the nucleus, leading to **stronger electrostatic attractions** and increased stability.

Box 3.7 Factors affecting stability of complexes.
Single-column table summarising ligand type, metal ion charge, and metal ion size as factors influencing stability.
"factors affecting stability transition metal complexes OER"

3.4.2 Substitution reactions in complexes

Substitution reactions occur when one ligand in a complex is replaced by another. These can be classified as:

- **Ligand exchange reactions**, where a ligand is swapped for another (e.g., replacing water with ammonia in a cobalt complex).
- **Chelation reactions**, where a polydentate ligand replaces monodentate ligands, increasing stability.

The rate of substitution depends on the nature of the metal ion and the ligands involved. Some complexes are termed **labile**, meaning they undergo substitution quickly, while others are **inert**, meaning substitution occurs slowly.

Fill in the blank: Complexes that undergo substitution reactions quickly are described as _____.

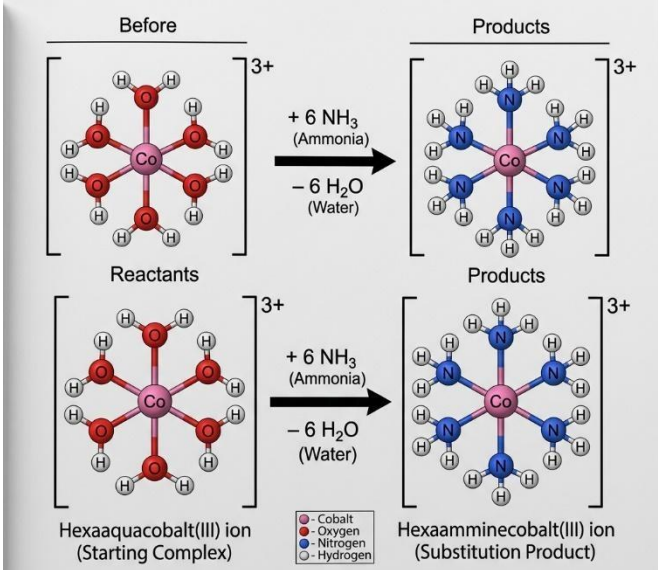


Figure 3.8 Substitution reaction in a cobalt complex. Diagram showing the complete replacement of water ligands by ammonia ligands in an octahedral cobalt(III) complex.

Diagram showing substitution of water ligands by ammonia in a cobalt complex.
Figure 3.8 Substitution reaction in a cobalt complex.
"substitution reaction cobalt complex OER"

3.4.3 Redox behaviour of transition metal complexes

Transition metal complexes often exhibit **redox behaviour**, meaning the metal centre can change its oxidation state while remaining bound to ligands. For example, iron can exist as Fe^{2+} in $[Fe(H_2O)_6]^{2+}$ and as Fe^{3+} in $[Fe(H_2O)_6]^{3+}$. These redox changes are important in biological systems, such as haemoglobin, and in industrial processes, such as catalysis.

Fill in the blank: The iron complex $[Fe(H_2O)_6]^{3+}$ differs from $[Fe(H_2O)_6]^{2+}$ because the metal centre has a higher _____ state.

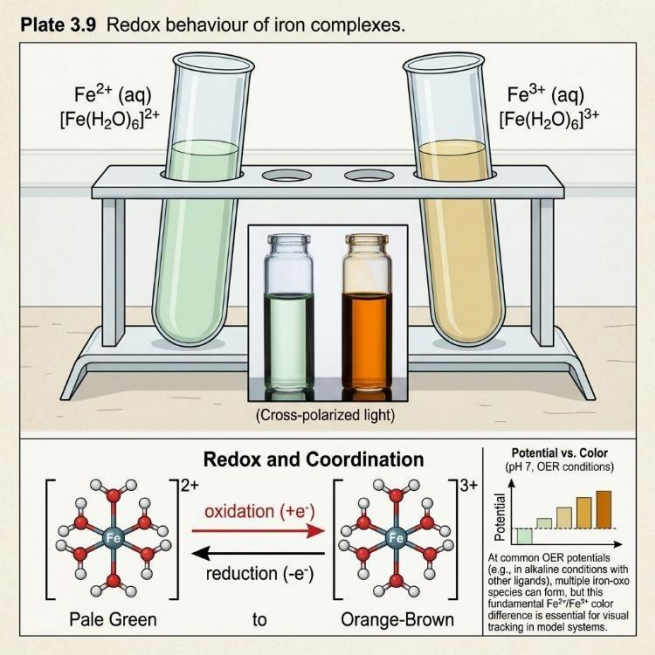


Image showing colour differences between Fe^{2+} and Fe^{3+} complexes in solution.
Plate 3.9 Redox behaviour of iron complexes.
"iron complexes Fe2+ Fe3+ colour OER"

3.5 Applications Of Transition Metal Complexes

3.5.1 Industrial uses

Transition metal complexes are widely used in industry due to their ability to act as **catalysts**, which are substances that speed up chemical reactions without being consumed. For example, platinum complexes are used in catalytic converters to reduce harmful emissions from vehicles, while vanadium complexes are employed in the manufacture of sulphuric acid. Complexes also contribute to pigments, dyes, and materials such as stainless steel.

Fill in the blank: The transition metal complex used in catalytic converters to reduce harmful emissions is based on _____.

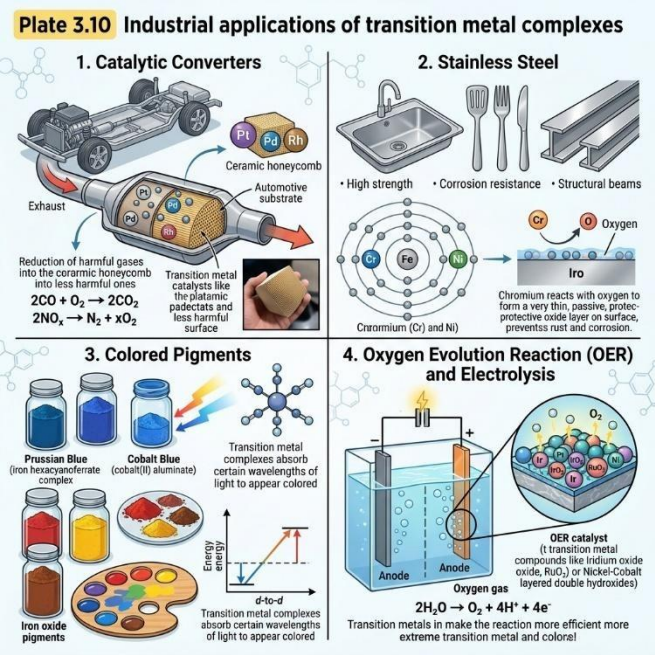


Image showing a catalytic converter, stainless steel, and coloured pigments.
Plate 3.10 Industrial applications of transition metal complexes.
“industrial applications transition metal complexes catalytic converter pigments OER”

3.5.2 Biological significance

Transition metal complexes are essential in biological systems. **Haemoglobin**, a complex of iron, transports oxygen in the blood. **Chlorophyll**, a magnesium complex, enables photosynthesis in plants. **Vitamin B12**, a cobalt complex, is vital for red blood cell formation and neurological function. These examples show how transition metals are central to life processes.

Fill in the blank: The iron complex responsible for transporting oxygen in the blood is called _____.

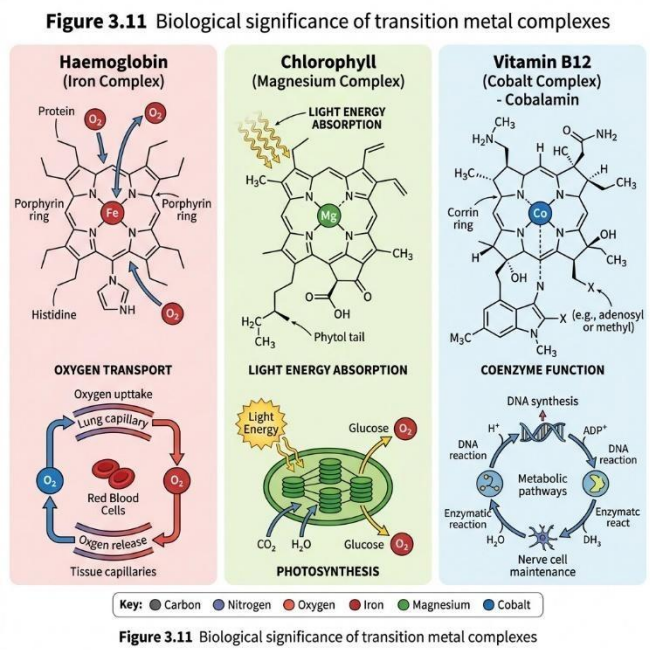


Figure 3.11 Biological significance of transition metal complexes

Diagram showing haemoglobin, chlorophyll, and vitamin B12 structures.
Figure 3.11 Biological significance of transition metal complexes.
"haemoglobin chlorophyll vitamin B12 transition metal complexes OER"

3.5.3 Environmental and technological relevance

Transition metal complexes also play a role in environmental and technological contexts. Complexes of iron and copper are used in water treatment to remove impurities. In renewable energy, complexes are studied for their role in solar cells and hydrogen production. They also contribute to advanced materials in electronics and nanotechnology.

Fill in the blank: Transition metal complexes of iron and copper are used in _____ treatment to remove impurities.

Environmental and Technological Relevance of Transition Metal Complexes

Application Area	Summary of Relevance
Water Treatment	**Iron** and **copper complexes** are used as catalysts to degrade organic pollutants and in coagulation processes to remove contaminants.
Renewable Energy	Transition metal complexes are critical in **dye-sensitized solar cells** and as catalysts for efficient **hydrogen production** through water splitting.
Advanced Materials	Used in **nanotechnology** and **molecular electronics** to create high-performance sensors, magnetic storage, and conducting polymers.

Box 3.12 Environmental and technological relevance of transition metal complexes.
Single-column table summarising water treatment (iron, copper complexes), renewable energy (solar cells, hydrogen production), advanced materials (electronics, nanotechnology).
"Generate a single-column table summarising environmental and technological relevance of

transition metal complexes."
Search string: "environmental technological relevance transition metal complexes OER"

Series Summary

This Series on **Transition Metal Chemistry and Complexes** was designed to highlight the distinctive properties of transition metals and the fascinating chemistry of their complexes. Transition metals are central to both industrial and biological systems, and their ability to exhibit variable oxidation states, form coloured compounds, and act as catalysts makes them especially significant.

We began by exploring the general properties of transition metals, including their position in the periodic table, electronic configurations, oxidation states, magnetism, and colour (SLO 3.1). Then we moved on to coordination chemistry, defining complexes and ligands, and examining coordination numbers and geometries (SLO 3.2). Following that, we analysed bonding theories such as valence bond theory, crystal field theory, and ligand field theory (SLO 3.3). We continued with stability and reactions of complexes, focusing on substitution and redox behaviour (SLO 3.4). Finally, we assessed their applications in industry, biology, and environmental contexts (SLO 3.5). By completing this Series, you should now be able to explain, analyse, and evaluate the chemistry of transition metals and their complexes, connecting theoretical principles with practical applications.

Glossary of Terms

- **Catalyst**: A substance that speeds up a chemical reaction without being consumed in the process.
- **Chelating ligand**: A ligand that binds to a metal ion through multiple donor atoms, forming very stable complexes.
- **Complex**: A chemical species formed when a central metal atom or ion is bonded to surrounding molecules or ions called ligands.
- **Coordination number**: The number of ligand donor atoms directly bonded to the central metal ion in a complex.
- **Crystal field theory (CFT)**: A bonding theory that explains the colours and magnetic properties of transition metal complexes by considering the splitting of d-orbitals in the presence of ligands.
- **Ferromagnetism**: A property of certain transition metals, such as iron, cobalt, and nickel, which allows them to be permanently magnetised.
- **Haemoglobin**: An iron complex in red blood cells responsible for transporting oxygen throughout the body.
- **Inert complex**: A complex that undergoes substitution reactions very slowly.
- **Ligand**: A molecule or ion that donates a pair of electrons to a metal centre, forming a coordinate covalent bond.
- **Labile complex**: A complex that undergoes substitution reactions quickly.

- **Octahedral geometry**: A common arrangement in complexes with coordination number 6, where six ligands are symmetrically arranged around the central metal ion.
- **Oxidation state**: The charge on a metal ion in a complex, indicating how many electrons it has lost or gained relative to its neutral state.
- **Substitution reaction**: A reaction in which one ligand in a complex is replaced by another.
- **Valence bond theory (VBT)**: A bonding theory that explains complex formation by considering the overlap of atomic orbitals between the metal and ligands.
- **Vitamin B12**: A cobalt complex essential for red blood cell formation and neurological function.

Concept Check Questions [Series 3]

Objective Questions

1. Transition metals are located in Groups _____ to 12 of the periodic table.
   (Linked to SLO 3.1)
2. Which transition metal complex is responsible for transporting oxygen in the blood?
   A. Chlorophyll
   B. Haemoglobin
   C. Vitamin B12
   D. Myoglobin
   (Linked to SLO 3.5)
3. Complexes that undergo substitution reactions quickly are described as _____.
   (Linked to SLO 3.4)
4. A complex with coordination number 6 typically has _____ geometry.
   (Linked to SLO 3.2)
5. The bonding theory that explains the splitting of d-orbitals in complexes is called _____.
   (Linked to SLO 3.3)

Short-Answer Questions

1. Define a ligand and give two examples.
   (Linked to SLO 3.2)
2. Explain why transition metals often form coloured compounds.
   (Linked to SLO 3.1)
3. State one industrial application of platinum complexes.
   (Linked to SLO 3.5)
4. Describe the difference between labile and inert complexes.
   (Linked to SLO 3.4)

5. Identify one biological role of a cobalt complex.
   (Linked to SLO 3.5)

Long-Answer Questions

1. Analyse the factors that affect the stability of transition metal complexes, providing examples to illustrate your points.
   (Linked to SLO 3.4)
2. Evaluate the significance of transition metal complexes in both industrial and biological contexts, highlighting their practical importance.
   (Linked to SLO 3.5)

Answers to Concept Check Questions [Series 3]

Objective Questions

1. Groups 3 to 12
2. B. Haemoglobin
3. Labile
4. Octahedral
5. Crystal field theory

Short-Answer Questions

1. A ligand is a molecule or ion that donates a pair of electrons to a metal centre. Examples: NH_3, Cl^-.
2. Transition metals form coloured compounds due to d-d electronic transitions when light is absorbed.
3. Platinum complexes are used in catalytic converters to reduce vehicle emissions.
4. Labile complexes undergo substitution quickly, while inert complexes do so slowly.
5. Vitamin B12, a cobalt complex, is essential for red blood cell formation and neurological function.

Long-Answer Questions

Question 1

- **Basic response:** Stability depends on ligand type (chelating ligands increase stability), metal ion charge (higher charges strengthen bonds), and metal ion size (smaller ions allow closer ligand approach).
- **Value-added response:** Outstanding learners may extend by discussing the chelate effect in detail, comparing monodentate versus polydentate ligands, and linking stability to applications such as EDTA in water treatment and medicine.

Question 2

- **Basic response:** Transition metal complexes are used in industry as catalysts (e.g., platinum in catalytic converters) and in biology for vital functions (e.g., haemoglobin transporting oxygen).
- **Value-added response:** Outstanding learners may extend by evaluating their role in renewable energy (solar cells, hydrogen production), advanced materials (electronics, nanotechnology), and environmental management (water treatment), connecting these applications to sustainability and technological innovation.

Answers to Pilot Questions [Series 3]

Part 3.1 General properties of transition metals

1. Groups 3 to 12
2. +2 and +3
3. d–d transitions

Part 3.2 Coordination chemistry

1. Ligand
2. Monodentate, bidentate, polydentate
3. Octahedral

Part 3.3 Bonding theories in complexes

1. Valence bond theory
2. Crystal field theory
3. Ligand field theory

Part 3.4 Stability and reactions of complexes

1. Chelating
2. Labile
3. Oxidation

Part 3.5 Applications of transition metal complexes

1. Platinum
2. Haemoglobin
3. Water

References and Attributions [Series 3]

This section provides references and attributions for **Series 3: Transition Metal Chemistry and Complexes**, including in-text citations, illustration sources, and suggested open educational resources (OERs).

General References

- OpenStax (2021). *Chemistry: Atoms First 2e*. Houston, TX: OpenStax. Available under Creative Commons Attribution Licence.
- LibreTexts (2023). *Chemistry Library*. Retrieved from https://chem.libretexts.org (OER resource for transition metal chemistry and complexes).
- Royal Society of Chemistry (RSC). *Learn Chemistry Resources*. Retrieved from https://edu.rsc.org (educational resources on coordination chemistry and bonding theories).

Illustrations

- *Figure 3.1 Position of transition metals in the periodic table*
  Attribution: AI-generated using prompt "Generate a labelled diagram of the periodic table highlighting Groups 3 to 12 as transition metals."
- *Box 3.2 Examples of variable oxidation states in transition metals*
  Attribution: AI-generated using prompt "Generate a single-column table listing examples of variable oxidation states in transition metals such as iron, manganese, and copper."
- *Plate 3.3 Colourful compounds of transition metals*
  Attribution: Suggested OER search string "copper sulphate potassium dichromate crystals OER."
- *Figure 3.4 Structure of a transition metal complex*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing a central transition metal ion surrounded by ligands forming a complex."
- *Box 3.5 Classification of ligands*
  Attribution: AI-generated using prompt "Generate a single-column table summarising types of ligands with examples: monodentate, bidentate, polydentate."
- *Figure 3.6 Common geometries of transition metal complexes*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing tetrahedral, square planar, and octahedral geometries of transition metal complexes."
- *Box 3.7 Factors affecting stability of complexes*
  Attribution: AI-generated using prompt "Generate a single-column table summarising factors affecting stability of transition metal complexes."
- *Figure 3.8 Substitution reaction in a cobalt complex*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing substitution of water ligands by ammonia in a cobalt complex."
- *Plate 3.9 Redox behaviour of iron complexes*
  Attribution: Suggested OER search string "iron complexes Fe2+ Fe3+ colour OER."
- *Plate 3.10 Industrial applications of transition metal complexes*
  Attribution: Suggested OER search string "industrial applications transition metal complexes catalytic converter pigments OER."

- *Figure 3.11 Biological significance of transition metal complexes*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing haemoglobin (iron complex), chlorophyll (magnesium complex), and vitamin B12 (cobalt complex)."
- *Box 3.12 Environmental and technological relevance of transition metal complexes*
  Attribution: AI-generated using prompt "Generate a single-column table summarising environmental and technological relevance of transition metal complexes."

Course code: CHM 302

Course title: Inorganic Chemistry II

Course unit: (2 Units C: LH 30)

List of series:

Series 1: Comparative Chemistry of Main Group Elements

Series 2: Chemistry of Non Metals and Their Compounds

Series 3: Transition Metal Chemistry and Complexes

Series 4: Radioactivity and Radiochemistry

Series 5: Biological Roles of Metals in Living Systems

Suggested Outline

4.1 Fundamentals of radioactivity

- 4.1.1 Discovery and historical background
- 4.1.2 Types of radiation (alpha, beta, gamma)
- 4.1.3 Properties and detection of radiation

4.2 Nuclear stability and decay processes

- 4.2.1 Nuclear binding energy and stability
- 4.2.2 Radioactive decay laws and half-life
- 4.2.3 Series of radioactive decay

4.3 Radiochemistry techniques and applications

- 4.3.1 Isotopes and tracer studies
- 4.3.2 Radiochemical analysis methods

- 4.3.3 Industrial and medical applications

4.4 Environmental and safety aspects of radioactivity

- 4.4.1 Radiation hazards and protection
- 4.4.2 Radioactive waste management
- 4.4.3 Regulatory and ethical considerations

Introduction

Radioactivity is one of the most intriguing phenomena in chemistry, with applications ranging from medical imaging to energy production. It involves the spontaneous emission of particles or energy from unstable atomic nuclei, a process that has shaped both scientific discovery and technological advancement. Understanding radioactivity and radiochemistry is essential not only for appreciating the behaviour of matter at the nuclear level but also for recognising its impact on health, industry, and the environment.

The aim of this Series is to introduce you to the principles of radioactivity and radiochemistry, enabling you to explain nuclear stability and decay processes, apply radiochemical techniques, and evaluate the uses and safety considerations of radioactive materials.

We shall commence this Series by examining the fundamentals of radioactivity, including its discovery, types of radiation, and methods of detection. Next, we will explore nuclear stability and decay processes, focusing on binding energy, half-life, and decay series. Following that, we will move on to radiochemistry techniques and applications, such as isotopes, tracer studies, and industrial and medical uses. Finally, we will bring the Series to a close by considering environmental and safety aspects of radioactivity, including hazards, waste management, and regulatory frameworks. By the end, you will have a clear understanding of both the scientific principles and practical implications of radioactivity and radiochemistry.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** define radioactivity and describe the types and properties of radiation, including methods of detection,
- **SLO 4.2** explain nuclear stability and apply the laws of radioactive decay to calculate half-life,
- **SLO 4.3** analyse radiochemistry techniques such as isotope use and tracer studies, and demonstrate their applications in industry and medicine,
- **SLO 4.4** evaluate the environmental and safety aspects of radioactivity, including hazards, waste management, and regulatory considerations.

4.1 Fundamentals Of Radioactivity

4.1.1 Discovery and historical background

Radioactivity is the spontaneous emission of particles or energy from unstable atomic nuclei. It was first discovered by Henri Becquerel in 1896 when he observed that uranium salts emitted

radiation that could expose photographic plates. Later, Marie and Pierre Curie expanded this work, isolating radioactive elements such as polonium and radium. These discoveries laid the foundation for nuclear chemistry and modern radiochemistry.

Fill in the blank: The scientist who first discovered radioactivity in uranium salts was _____.

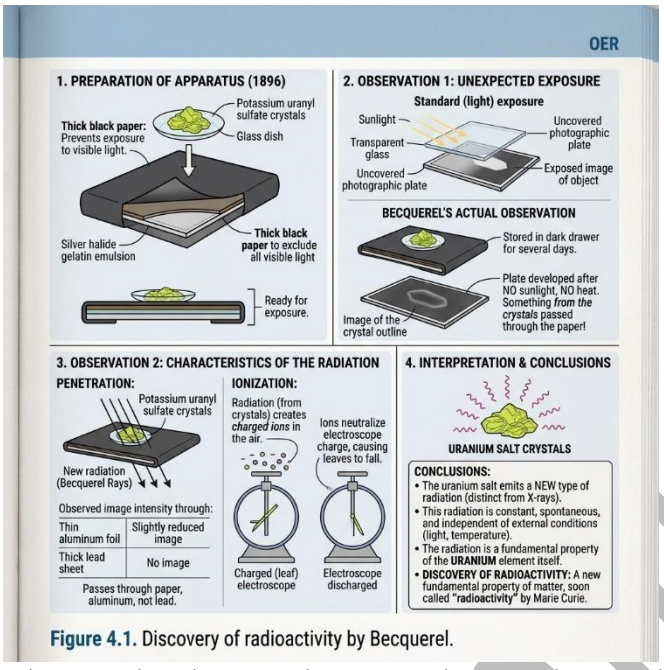


Diagram showing Henri Becquerel's experiment with uranium salts and photographic plates.
Figure 4.1 Discovery of radioactivity by Becquerel.
Search string: "Henri Becquerel discovery of radioactivity diagram OER"

4.1.2 Types of radiation (alpha, beta, gamma)

Radioactive nuclei emit different types of radiation:

- **Alpha radiation** consists of helium nuclei (two protons and two neutrons). It has low penetration but high ionising power.
- **Beta radiation** consists of high-energy electrons or positrons. It has moderate penetration and ionising ability.
- **Gamma radiation** consists of high-energy electromagnetic waves. It has very high penetration but lower ionising power compared to alpha particles.

Fill in the blank: The type of radiation with the highest penetration ability is _____ radiation.

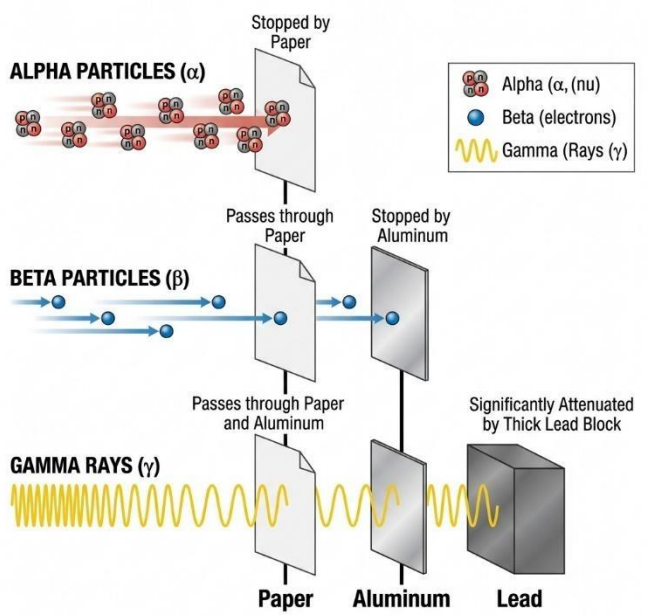


Figure 4.2 Penetration abilities of alpha, beta, and gamma radiation

Diagram comparing penetration of alpha, beta, and gamma radiation through paper, aluminium, and lead.
Figure 4.2 Penetration abilities of alpha, beta, and gamma radiation.
"penetration alpha beta gamma radiation diagram OER"

4.1.3 Properties and detection of radiation

Radiation has several measurable properties, including ionising ability, penetration power, and energy. Detecting radiation is crucial for both scientific study and safety. Common instruments include:

- **Geiger–Müller counter**: Detects ionising particles by producing an electrical pulse.
- **Scintillation counter**: Uses a phosphor material that emits light when struck by radiation.
- **Cloud chamber**: Visualises the paths of charged particles through condensation trails.

Fill in the blank: The instrument that produces an electrical pulse when detecting ionising particles is called a _____ counter.

Plate 4.3 Geiger–Müller counter for radiation detection.

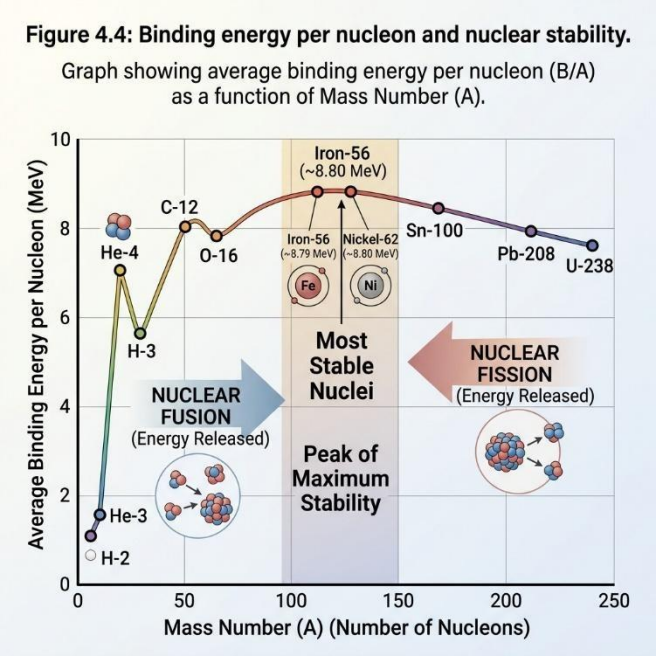
Image showing a Geiger–Müller counter being used to measure radiation.
Plate 4.3 Geiger–Müller counter for radiation detection.
"Geiger–Müller counter radiation detection OER"

4.2 Nuclear Stability And Decay Processes

4.2.1 Nuclear binding energy and stability

Nuclear stability refers to how resistant a nucleus is to breaking apart. It depends on the balance between the attractive nuclear forces (which hold protons and neutrons together) and the repulsive forces between positively charged protons. A useful measure of this is the **binding energy**, which is the energy required to separate a nucleus into its individual protons and neutrons. Nuclei with higher binding energy per nucleon are generally more stable.

Fill in the blank: The energy required to separate a nucleus into its individual protons and neutrons is called _____ energy.



Graph showing binding energy per nucleon versus mass number, highlighting iron and nickel as highly stable nuclei.
Figure 4.4 Binding energy per nucleon and nuclear stability.
“binding energy per nucleon graph OER”

4.2.2 Radioactive decay laws and half-life

Radioactive decay is the process by which unstable nuclei lose energy by emitting radiation. The rate of decay is governed by the **decay law**, which states that the number of undecayed nuclei decreases exponentially with time. The **half-life** of a radioactive isotope is the time required for half of the nuclei in a sample to decay. Half-life is a characteristic property of each isotope and can range from fractions of a second to millions of years.

Fill in the blank: The time required for half of the nuclei in a radioactive sample to decay is called the _____.

Radiochemical Analysis Methods

Method	Summary of Application
Autoradiography	Uses **X-ray film** or digital sensors to visualize the distribution of radioactive substances within a specimen.
Liquid Scintillation	Measures **low-energy beta emitters** by dissolving the sample in a "scintillator" liquid that flashes when hit by radiation.
Gamma Spectroscopy	Identifies and quantifies radionuclides by measuring the **energy spectrum** of emitted gamma rays using a detector.

Box 4.5 Examples of half-lives of selected isotopes.
Single-column table listing isotopes and their half-lives (e.g., Carbon-14: 5730 years, Uranium-

238: 4.5 billion years, Radon-222: 3.8 days).
“half-life isotopes table OER”

4.2.3 Series of radioactive decay

Some heavy nuclei undergo a sequence of decays known as a **radioactive decay series**, where one unstable nucleus transforms into another until a stable isotope is formed. For example, uranium-238 decays through a series of alpha and beta emissions to eventually form lead-206. These decay chains are important in nuclear chemistry and geology, as they help explain the natural occurrence of radioactive elements and their long-term transformations.

Fill in the blank: Uranium-238 eventually decays through a series of steps to form the stable isotope _____.

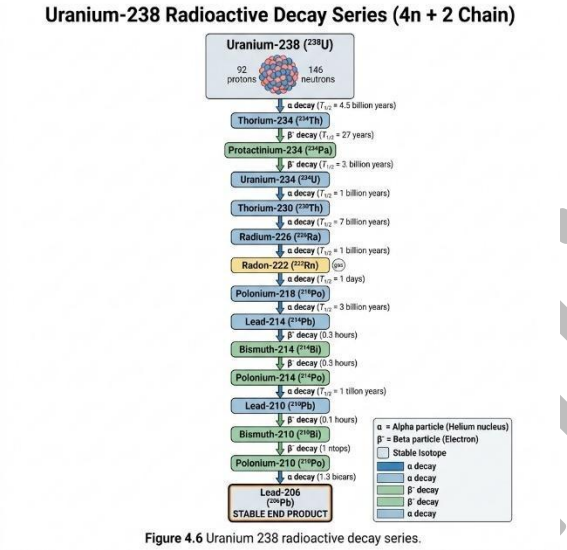


Figure 4.6 Uranium 238 radioactive decay series.

Diagram showing the uranium-238 decay series leading to lead-206.
Figure 4.6 Uranium-238 radioactive decay series.
“uranium-238 decay series diagram OER”

4.3 Radiochemistry Techniques And Applications

4.3.1 Isotopes and tracer studies

An **isotope** is an atom of the same element that has the same number of protons but a different number of neutrons. Some isotopes are stable, while others are radioactive. Radioactive isotopes are particularly useful in **tracer studies**, where they are introduced into a system to track chemical or biological processes. For example, carbon-14 is used in radiocarbon dating, and iodine-131 is used to study thyroid function.

Fill in the blank: Atoms of the same element with different numbers of neutrons are called _____.

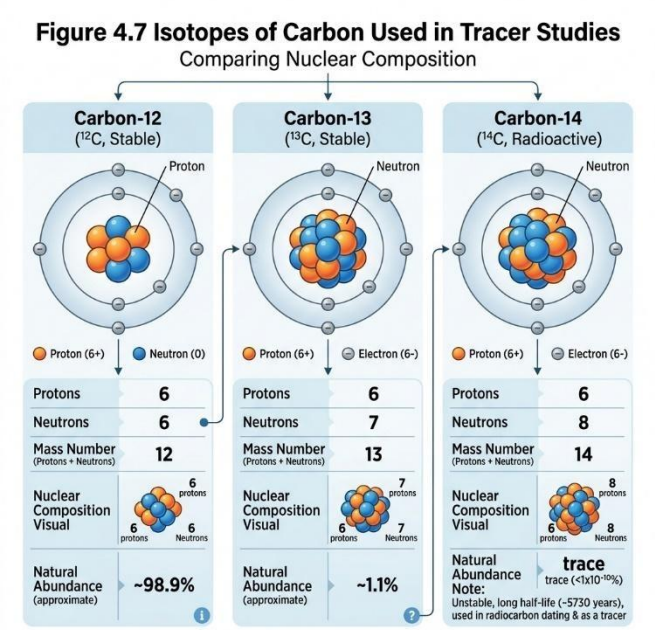


Diagram showing isotopes of carbon (C-12, C-13, C-14) with different numbers of neutrons.
Figure 4.7 Isotopes of carbon used in tracer studies.
"carbon isotopes diagram OER"

4.3.2 Radiochemical analysis methods

Radiochemical analysis involves techniques that use radioactive isotopes to study chemical reactions and materials. Common methods include:

- **Autoradiography**, which uses photographic film to detect radioactive emissions from a sample.
- **Liquid scintillation counting**, where radiation excites a scintillating solution that emits light, which is then measured.
- **Gamma spectroscopy**, which identifies isotopes based on the energy of emitted gamma rays.

These methods are widely used in medicine, biology, and materials science.

Fill in the blank: The radiochemical method that uses photographic film to detect radioactive emissions is called _____.

Classification of Radioactive Waste

Waste Level	Summary of Characteristics and Examples
Low-Level (LLW)	Comprises items like **laboratory waste**, protective clothing, and tools; contains small amounts of short-lived radioactivity.
Intermediate-Level (ILW)	Includes **reactor components**, chemical sludges, and metal fuel cladding; requires shielding but generates little heat.
High-Level (HLW)	Consists of **spent nuclear fuel** and liquid waste from reprocessing; highly radioactive and generates significant heat, requiring cooling.

Box 4.8 Common radiochemical analysis methods.
Single-column table summarising autoradiography, liquid scintillation counting, and gamma spectroscopy.
"radiochemical analysis methods OER"

4.3.3 Industrial and medical applications

Radioactive isotopes and complexes have significant **industrial and medical applications**. In industry, they are used for non-destructive testing, such as detecting cracks in pipelines using gamma radiography. In medicine, isotopes are used in both diagnosis and treatment. For example, technetium-99m is widely used in medical imaging, while cobalt-60 is used in radiotherapy for cancer treatment.

Fill in the blank: The isotope commonly used in medical imaging is _____.

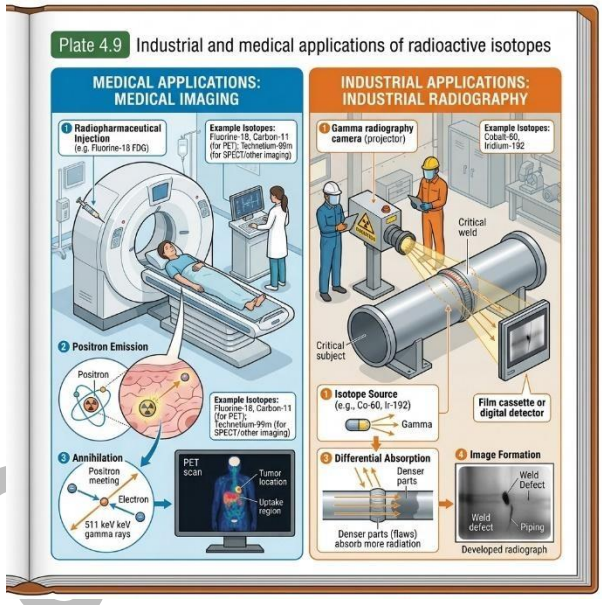


Image showing a PET scan (medical imaging) and industrial gamma radiography equipment.
Plate 4.9 Industrial and medical applications of radioactive isotopes.
Search string: "medical imaging technetium-99m PET scan industrial gamma radiography OER"

4.4.1 Radiation hazards and protection

Radiation hazards arise when living organisms are exposed to ionising radiation, which can damage cells and DNA. Prolonged or high-level exposure may lead to radiation sickness, cancer, or genetic mutations. To minimise risks, **radiation protection** strategies are employed, including shielding with lead or concrete, limiting exposure time, and maintaining safe distances from sources.

Fill in the blank: The three main principles of radiation protection are time, distance, and _____.

Figure 4.10 Principles of radiation protection.

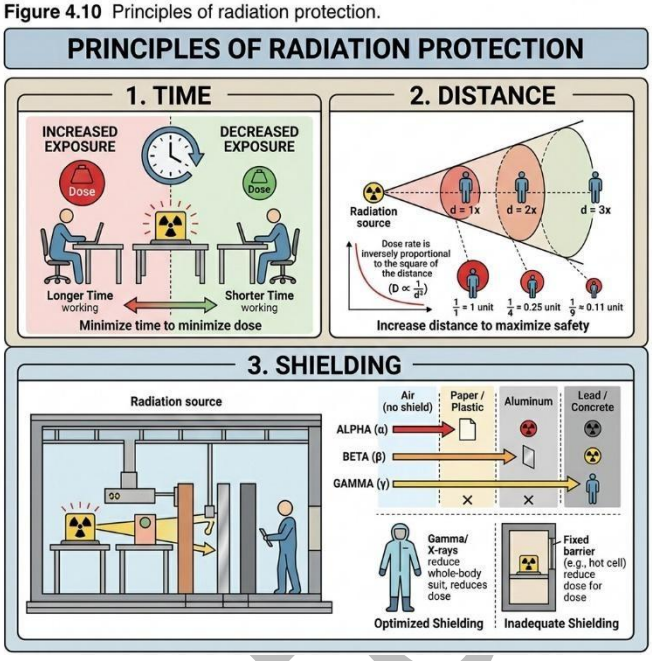


Diagram showing the three principles of radiation protection: time, distance, and shielding.
Figure 4.10 Principles of radiation protection.
"radiation protection principles diagram OER"

4.4.2 Radioactive waste management

Radioactive waste is material that contains radioactive substances and is no longer useful. It is classified into low-level, intermediate-level, and high-level waste depending on its radioactivity. Safe **waste management** involves containment, storage, and disposal. High-level waste, such as spent nuclear fuel, is often stored in deep geological repositories to prevent environmental contamination.

Fill in the blank: Spent nuclear fuel is an example of _____-level radioactive waste.

Classification of Radioactive Waste

Waste Level	Summary of Characteristics and Examples
Low-Level (LLW)	Comprises items like **laboratory waste**, protective clothing, and tools; contains small amounts of short-lived radioactivity.
Intermediate-Level (ILW)	Includes **reactor components**, chemical sludges, and metal fuel cladding; requires shielding but generates little heat.
High-Level (HLW)	Consists of **spent nuclear fuel** and liquid waste from reprocessing; highly radioactive and generates significant heat, requiring cooling.

Box 4.11 Classification of radioactive waste.
Single-column table listing low-level (laboratory waste), intermediate-level (reactor components), and high-level (spent nuclear fuel).
“classification radioactive waste table OER”

4.4.3 Regulatory and ethical considerations

Because of the risks associated with radiation, strict **regulatory frameworks** exist to govern its use. International bodies such as the International Atomic Energy Agency (IAEA) set safety standards, while national agencies enforce regulations. Ethical considerations include balancing the benefits of nuclear technology in medicine and energy against the potential risks to health and the environment. Transparency, accountability, and public safety are key principles in managing radioactive materials responsibly.

Fill in the blank: The international body that sets safety standards for radiation use is the _____.

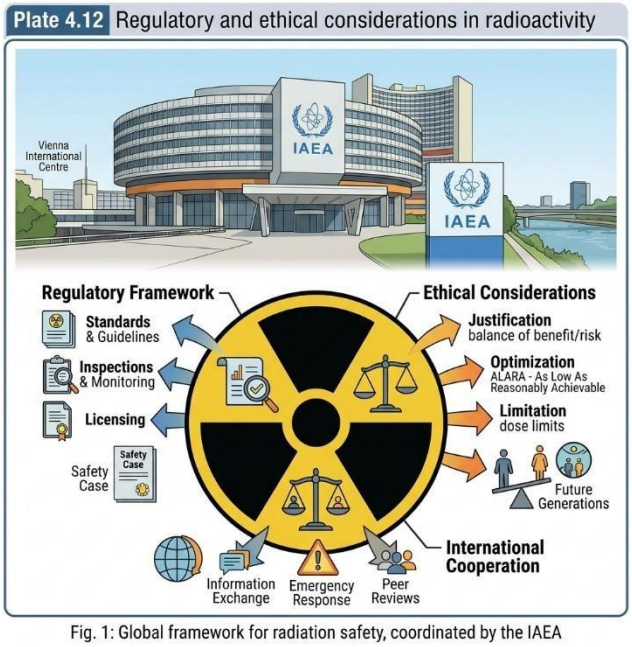


Fig. 1: Global framework for radiation safety, coordinated by the IAEA

Image showing the IAEA headquarters and symbols of radiation safety.

Plate 4.12 Regulatory and ethical considerations in radioactivity.
"IAEA headquarters radiation safety OER"

Series Summary

This Series on **Radioactivity and Radiochemistry** was designed to help you understand the principles of nuclear behaviour and the practical implications of radioactive processes. Radioactivity is not only a fascinating scientific phenomenon but also one with profound applications in medicine, industry, and environmental management.

We began by exploring the fundamentals of radioactivity, including its discovery, types of radiation, and methods of detection (SLO 4.1). Then we examined nuclear stability and decay processes, focusing on binding energy, half-life, and decay series (SLO 4.2). Following that, we analysed radiochemistry techniques and applications, such as isotopes, tracer studies, and radiochemical methods used in industry and medicine (SLO 4.3). Finally, we evaluated environmental and safety aspects of radioactivity, including hazards, waste management, and regulatory considerations (SLO 4.4). By completing this Series, you should now be able to define, explain, analyse, and evaluate key concepts in radioactivity and radiochemistry, connecting theoretical knowledge with practical applications.

Glossary of Terms

- **Alpha radiation**: A type of radiation consisting of helium nuclei (two protons and two neutrons) with low penetration but high ionising power.
- **Autoradiography**: A radiochemical method that uses photographic film to detect radioactive emissions from a sample.
- **Binding energy**: The energy required to separate a nucleus into its individual protons and neutrons.
- **Beta radiation**: A type of radiation consisting of high-energy electrons or positrons with moderate penetration and ionising ability.
- **Decay law**: The principle that the number of undecayed nuclei in a radioactive sample decreases exponentially with time.
- **Gamma radiation**: A type of radiation consisting of high-energy electromagnetic waves with very high penetration but lower ionising power compared to alpha particles.
- **Geiger–Müller counter**: An instrument that detects ionising particles by producing an electrical pulse.
- **Half-life**: The time required for half of the nuclei in a radioactive sample to decay.
- **International Atomic Energy Agency (IAEA)**: The international body that sets safety standards and regulations for the use of radiation and nuclear materials.
- **Isotope**: An atom of the same element with the same number of protons but a different number of neutrons.
- **Liquid scintillation counting**: A radiochemical method where radiation excites a scintillating solution that emits light, which is then measured.

- **Nuclear stability**: The resistance of a nucleus to breaking apart, determined by the balance of nuclear forces and proton repulsion.
- **Radioactive decay**: The process by which unstable nuclei lose energy by emitting radiation.
- **Radioactive waste**: Material containing radioactive substances that is no longer useful and requires safe management.
- **Radiation hazards**: Risks to living organisms caused by exposure to ionising radiation, which can damage cells and DNA.
- **Radiochemistry**: The branch of chemistry that studies radioactive substances and their applications.
- **Tracer study**: The use of radioactive isotopes to track chemical or biological processes.

Concept Check Questions [Series 4]

Objective Questions

1. Radioactivity was first discovered in uranium salts by _____.
   (Linked to SLO 4.1)
2. Which type of radiation has the highest penetration ability?
   A. Alpha
   B. Beta
   C. Gamma
   D. Neutron
   (Linked to SLO 4.1)
3. The time required for half of the nuclei in a radioactive sample to decay is called _____.
   (Linked to SLO 4.2)
4. Uranium-238 eventually decays through a series of steps to form _____.
   (Linked to SLO 4.2)
5. The isotope commonly used in medical imaging is _____.
   (Linked to SLO 4.3)

Short-Answer Questions

1. Define an isotope and give one example.
   (Linked to SLO 4.3)
2. Explain why nuclei with higher binding energy per nucleon are more stable.
   (Linked to SLO 4.2)
3. State one industrial application of gamma radiography.
   (Linked to SLO 4.3)

4. Describe one principle of radiation protection.
   (Linked to SLO 4.4)
5. Identify the international body responsible for setting radiation safety standards.
   (Linked to SLO 4.4)

Long-Answer Questions

1. Analyse the importance of half-life in radiochemistry, providing examples of isotopes with different half-lives.
   (Linked to SLO 4.2)
2. Evaluate the benefits and risks of using radioactive isotopes in medicine and industry.
   (Linked to SLO 4.3, SLO 4.4)

Answers to Concept Check Questions [Series 4]

Objective Questions

1. Henri Becquerel
2. C. Gamma
3. Half-life
4. Lead-206
5. Technetium-99m

Short-Answer Questions

1. An isotope is an atom of the same element with the same number of protons but different numbers of neutrons. Example: Carbon-14.
2. Higher binding energy per nucleon means stronger nuclear forces holding the nucleus together, making it more stable.
3. Gamma radiography is used to detect cracks or flaws in pipelines and metal structures.
4. Shielding with lead or concrete is one principle of radiation protection.
5. International Atomic Energy Agency (IAEA).

Long-Answer Questions

Question 1

- **Basic response:** Half-life is the time required for half of a radioactive sample to decay. It helps determine the persistence of isotopes. For example, Carbon-14 has a half-life of 5730 years, useful in dating ancient artefacts, while Radon-222 has a half-life of 3.8 days, making it significant in environmental monitoring.
- **Value-added response:** Outstanding learners may extend by discussing how half-life influences medical applications (e.g., short half-life isotopes for imaging to minimise patient exposure) and nuclear waste management (long half-life isotopes requiring secure storage).

Question 2

- **Basic response:** Radioactive isotopes benefit medicine through imaging (technetium-99m) and treatment (cobalt-60 in radiotherapy). In industry, they are used for non-destructive testing and tracer studies. Risks include radiation exposure, environmental contamination, and waste management challenges.
- **Value-added response:** Outstanding learners may extend by evaluating ethical considerations, regulatory frameworks, and sustainability issues. They could also compare short-term benefits (accurate diagnosis, industrial safety) with long-term risks (radioactive waste, public health concerns), linking these to global debates on nuclear technology.

Answers to Pilot Questions [Series 4]

Part 4.1 Fundamentals of radioactivity

1. Henri Becquerel
2. Gamma radiation
3. Geiger–Müller counter

Part 4.2 Nuclear stability and decay processes

1. Binding energy
2. Half-life
3. Lead-206

Part 4.3 Radiochemistry techniques and applications

1. Isotopes
2. Autoradiography
3. Technetium-99m

Part 4.4 Environmental and safety aspects of radioactivity

1. Shielding
2. High-level
3. International Atomic Energy Agency (IAEA)

References and Attributions [Series 4]

This section provides references and attributions for **Series 4: Radioactivity and Radiochemistry**, including in-text citations, illustration sources, and suggested open educational resources (OERs).

General References

- OpenStax (2021). *Chemistry: Atoms First 2e*. Houston, TX: OpenStax. Available under Creative Commons Attribution Licence.

- LibreTexts (2023). *Chemistry Library*. Retrieved from https://chem.libretexts.org (OER resource for nuclear chemistry and radiochemistry).
- International Atomic Energy Agency (IAEA). *Safety Standards and Guidelines*. Retrieved from https://www.iaea.org (regulatory framework for radiation use).
- Royal Society of Chemistry (RSC). *Learn Chemistry Resources*. Retrieved from https://edu.rsc.org (educational resources on radioactivity and nuclear chemistry).

Illustrations

- *Figure 4.1 Discovery of radioactivity by Becquerel*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing Henri Becquerel's experiment with uranium salts exposing photographic plates."
- *Figure 4.2 Penetration abilities of alpha, beta, and gamma radiation*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing penetration of alpha, beta, and gamma radiation through paper, aluminium, and lead."
- *Plate 4.3 Geiger–Müller counter for radiation detection*
  Attribution: AI-generated using prompt "Create an image showing a Geiger–Müller counter being used to measure radiation levels."
- *Figure 4.4 Binding energy per nucleon and nuclear stability*
  Attribution: AI-generated using prompt "Generate a labelled graph showing binding energy per nucleon versus mass number, highlighting iron and nickel as the most stable nuclei."
- *Box 4.5 Examples of half-lives of selected isotopes*
  Attribution: AI-generated using prompt "Generate a single-column table listing isotopes and their half-lives, including Carbon-14, Uranium-238, and Radon-222."
- *Figure 4.6 Uranium-238 radioactive decay series*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing the uranium-238 decay series leading to lead-206."
- *Figure 4.7 Isotopes of carbon used in tracer studies*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing isotopes of carbon (C-12, C-13, C-14) with different numbers of neutrons."
- *Box 4.8 Common radiochemical analysis methods*
  Attribution: AI-generated using prompt "Generate a single-column table summarising radiochemical analysis methods: autoradiography, liquid scintillation counting, gamma spectroscopy."
- *Plate 4.9 Industrial and medical applications of radioactive isotopes*
  Attribution: AI-generated using prompt "Create an image showing a PET scan for medical imaging and gamma radiography equipment for industrial testing."
- *Figure 4.10 Principles of radiation protection*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing the three principles of radiation protection: time, distance, and shielding."

- *Box 4.11 Classification of radioactive waste*
  Attribution: AI-generated using prompt "Generate a single-column table summarising classification of radioactive waste: low-level, intermediate-level, high-level."
- *Plate 4.12 Regulatory and ethical considerations in radioactivity*
  Attribution: AI-generated using prompt "Create an image showing the IAEA headquarters and radiation safety symbols."

Course code: CHM 302

Course title: Inorganic Chemistry II

Course unit: (2 Units C: LH 30)

List of series:

Series 1: Comparative Chemistry of Main Group Elements

Series 2: Chemistry of Non Metals and Their Compounds

Series 3: Transition Metal Chemistry and Complexes

Series 4: Radioactivity and Radiochemistry

Series 5: Biological Roles of Metals in Living Systems

Suggested Outline

5.1 Essential metals in biological systems

- 5.1.1 Macro-elements (e.g., sodium, potassium, calcium, magnesium)
- 5.1.2 Trace elements (e.g., iron, zinc, copper, manganese)
- 5.1.3 Ultra-trace elements (e.g., cobalt, molybdenum, selenium)

5.2 Metalloproteins and enzymes

- 5.2.1 Haem proteins (haemoglobin, myoglobin, cytochromes)
- 5.2.2 Non-haem iron proteins (ferritin, transferrin)
- 5.2.3 Other metalloenzymes (zinc enzymes, copper enzymes, manganese enzymes)

5.3 Metals in physiological processes

- 5.3.1 Oxygen transport and storage
- 5.3.2 Electron transfer and energy metabolism
- 5.3.3 Hormonal regulation and signalling

5.4 Toxicity and homeostasis of metals

- 5.4.1 Mechanisms of metal toxicity (e.g., lead, mercury, cadmium)
- 5.4.2 Detoxification and protective mechanisms
- 5.4.3 Regulation of metal ion concentration in living systems

---

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** define essential metals in biological systems and classify them as macro-elements, trace elements, or ultra-trace elements,
- **SLO 5.2** explain the functions of metalloproteins and enzymes, including haem proteins, non-haem iron proteins, and other metalloenzymes,
- **SLO 5.3** analyse the roles of metals in physiological processes such as oxygen transport, electron transfer, and hormonal regulation,
- **SLO 5.4** evaluate the mechanisms of metal toxicity and describe how living systems maintain homeostasis of metal ions.

5.1 Essential Metals In Biological Systems

5.1.1 Macro-elements (sodium, potassium, calcium, magnesium)

Macro-elements are metals required in relatively large amounts by living organisms. They play fundamental roles in maintaining physiological balance.

- **Sodium (Na)** and **potassium (K)** are crucial for nerve impulse transmission and muscle contraction. They work together to maintain the electrochemical gradient across cell membranes.
- **Calcium (Ca)** is essential for bone and teeth formation, blood clotting, and signalling pathways.
- **Magnesium (Mg)** acts as a cofactor in many enzymatic reactions, particularly those involving ATP.

Fill in the blank: The metal ion that acts as a cofactor in ATP-related enzymatic reactions is _____.

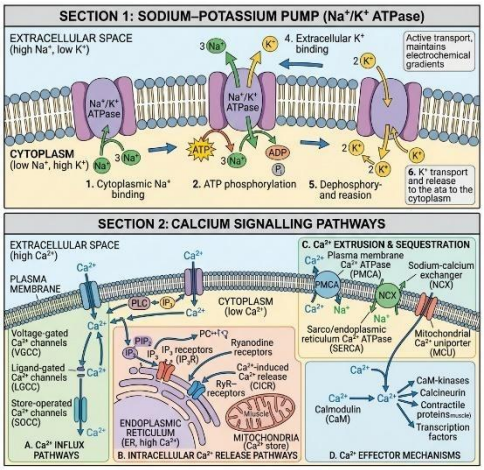


Figure 5.1 Roles of macro elements in cellular processes.

Diagram showing sodium–potassium pump and calcium signalling in cells.
Figure 5.1 Roles of macro-elements in cellular processes.
"sodium potassium pump calcium signalling diagram OER"

5.1.2 Trace elements (iron, zinc, copper, manganese)

Trace elements are metals required in smaller amounts but are vital for enzyme activity and metabolic processes.

- **Iron (Fe)** is central to haemoglobin and myoglobin, enabling oxygen transport and storage.
- **Zinc (Zn)** is a structural and catalytic component of many enzymes, including those involved in DNA synthesis.
- **Copper (Cu)** participates in electron transfer reactions, such as those in cytochrome oxidase.
- **Manganese (Mn)** is important in antioxidant enzymes like superoxide dismutase.

Fill in the blank: The trace element that enables haemoglobin to transport oxygen is _____.

Biological Roles of Trace Elements

Element	Summary of Biological Role
Iron	Essential for **oxygen transport** as the central component of hemoglobin and myoglobin.
Zinc	Vital for over 300 **enzymatic activities**, including DNA synthesis and immune system function.
Copper	Critical for **electron transfer** in the mitochondrial respiratory chain and iron metabolism.
Manganese	Acts as a cofactor for enzymes involved in **antioxidant function** (SOD) and bone formation.

Box 5.2 Selected biological roles of trace elements.
Single-column table listing iron (oxygen transport), zinc (enzyme activity), copper (electron

transfer), manganese (antioxidant function).
“trace elements biological roles table OER”

5.1.3 Ultra-trace elements (cobalt, molybdenum, selenium)

Ultra-trace elements are metals required in minute amounts but are still essential for life.

- **Cobalt (Co)** is a component of vitamin B12, which is necessary for red blood cell formation and neurological function.
- **Molybdenum (Mo)** acts as a cofactor in enzymes involved in nitrogen metabolism.
- **Selenium (Se)** is part of selenoproteins, which protect against oxidative damage.

Fill in the blank: The ultra-trace element that forms part of vitamin B12 is _____.

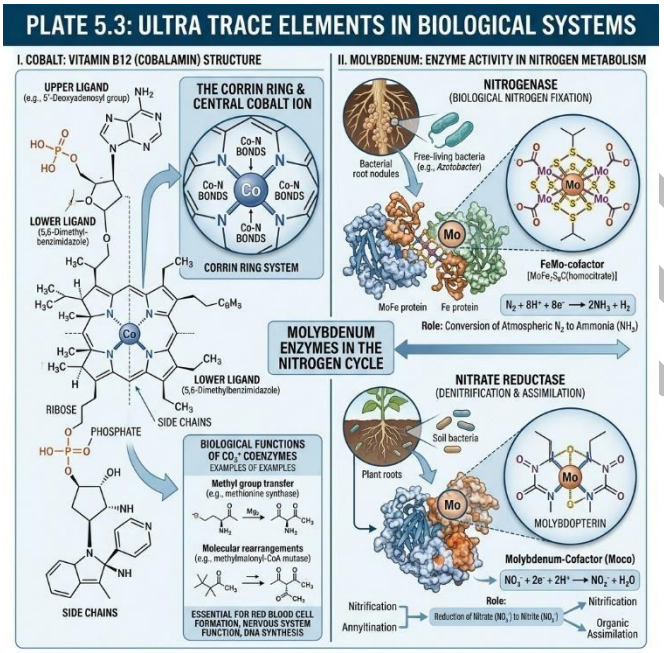


Image showing vitamin B12 structure and molybdenum enzyme activity.
Plate 5.3 Ultra-trace elements in biological systems.
“vitamin B12 cobalt molybdenum enzyme OER”

5.2 Metalloproteins And Enzymes

5.2.1 Haem proteins (haemoglobin, myoglobin, cytochromes)

Haem proteins are proteins that contain a haem group, which is a complex of iron within a porphyrin ring. These proteins are critical for oxygen transport and electron transfer.

- **Haemoglobin** carries oxygen from the lungs to tissues.
- **Myoglobin** stores oxygen in muscle cells for immediate use during activity.

- **Cytochromes** are involved in electron transfer during cellular respiration.

Fill in the blank: The haem protein responsible for storing oxygen in muscle cells is _____.

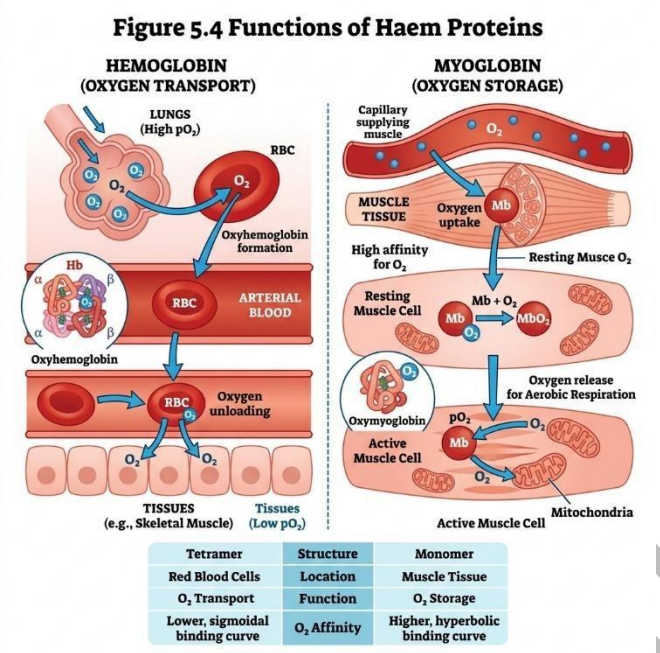


Diagram showing haemoglobin transporting oxygen and myoglobin storing oxygen in muscle tissue.
Figure 5.4 Functions of haem proteins.
"haemoglobin myoglobin cytochromes diagram OER"

5.2.2 Non-haem iron proteins (ferritin, transferrin)

Non-haem iron proteins are proteins that contain iron but not in a haem group. They are essential for iron storage and transport.

- **Ferritin** stores iron safely inside cells, releasing it when needed.
- **Transferrin** transports iron in the bloodstream to tissues requiring it.

Fill in the blank: The non-haem iron protein that stores iron inside cells is _____.

Roles of Non-Haem Iron Proteins

Protein	Summary of Biological Role
Ferritin	The primary protein for **iron storage**; safely sequesters iron in a non-toxic form within cells and releases it when needed.
Transferrin	The main protein for **iron transport**; binds to iron in the blood and delivers it to cells throughout the body via the circulatory system.

Box 5.5 Roles of non-haem iron proteins.
Single-column table summarising ferritin (iron storage) and transferrin (iron transport).
“ferritin transferrin roles table OER”

5.2.3 Other metalloenzymes (zinc enzymes, copper enzymes, manganese enzymes)

Metalloenzymes are enzymes that require a metal ion for their catalytic activity.

- **Zinc enzymes** include carbonic anhydrase, which regulates acid–base balance by converting carbon dioxide and water into bicarbonate.
- **Copper enzymes** include cytochrome oxidase, which is vital for electron transport in respiration.
- **Manganese enzymes** include superoxide dismutase, which protects cells from oxidative damage.

Fill in the blank: The zinc enzyme that regulates acid–base balance in the body is _____.

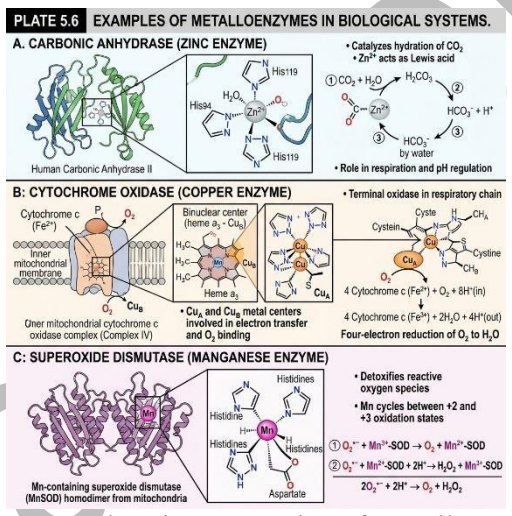


Image showing examples of metalloenzymes: carbonic anhydrase, cytochrome oxidase, and superoxide dismutase.
Plate 5.6 Examples of metalloenzymes in biological systems.
“carbonic anhydrase cytochrome oxidase superoxide dismutase OER”

5.3.1 Oxygen transport and storage

Metals are central to how living organisms manage oxygen. **Iron (Fe)** in haemoglobin binds oxygen in the lungs and releases it in tissues, while **myoglobin**, another iron-containing protein, stores oxygen in muscles for immediate use. These processes ensure that cells receive a steady supply of oxygen for respiration and energy production.

Fill in the blank: The iron-containing protein that stores oxygen in muscles is _____.

Figure 5.7 Oxygen transport and storage by haem proteins.

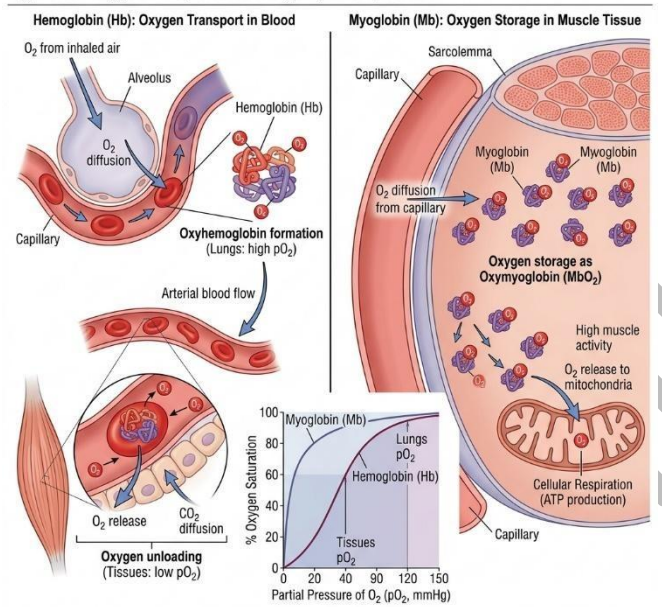


Figure 5.7 Oxygen transport and storage by haem proteins.

Diagram showing haemoglobin transporting oxygen in blood and myoglobin storing oxygen in muscle tissue.
Figure 5.7 Oxygen transport and storage by haem proteins.
"oxygen transport haemoglobin myoglobin diagram OER"

5.3.2 Electron transfer and energy metabolism

Electron transfer is vital for energy production in cells. Metals such as **iron** and **copper** are found in cytochromes and other proteins of the electron transport chain. These proteins shuttle electrons through a series of reactions, ultimately producing ATP, the energy currency of the cell. Without these metal centres, respiration and energy metabolism would not be possible.

Fill in the blank: The metal ions found in cytochromes that enable electron transfer are _____ and _____.

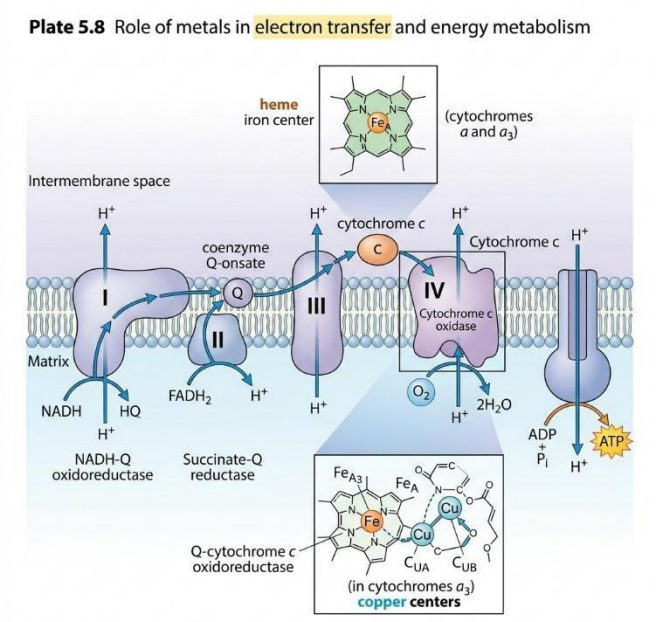


Image showing the electron transport chain with cytochromes containing iron and copper.
Plate 5.8 Role of metals in electron transfer and energy metabolism.
"electron transport chain cytochromes iron copper OER"

5.3.3 Hormonal regulation and signalling

Metals also play roles in **hormonal regulation** and **cell signalling**. For example, **calcium (Ca)** acts as a secondary messenger in many signalling pathways, controlling processes such as muscle contraction, nerve impulse transmission, and hormone release. **Zinc (Zn)** is involved in insulin storage and release, while **magnesium (Mg)** stabilises ATP and supports enzymatic activity in signalling cascades.

Fill in the blank: The metal ion that acts as a secondary messenger in signalling pathways is _____.

Roles of Metals in Hormonal Regulation and Signalling

Metal Ion	Summary of Regulatory and Signalling Roles
Calcium (Ca^{2+})	Acts as a vital **secondary messenger** in signal transduction; triggers hormone release (like insulin) and muscle contraction.
Zinc (Zn^{2+})	Essential for **insulin regulation**, structural stability of the insulin hexamer, and the function of "zinc finger" transcription factors.
Magnesium (Mg^{2+})	Required for **ATP stabilisation**; acts as a cofactor for adenylate cyclase to produce cyclic AMP (cAMP) in hormone signalling.

Box 5.9 Metals in hormonal regulation and signalling.
Single-column table summarising calcium (secondary messenger), zinc (insulin regulation), magnesium (ATP stabilisation).
"Generate a single-column table summarising roles of calcium, zinc, and magnesium in

hormonal regulation and signalling."
Search string: "metals hormonal regulation signalling table OER"

5.4 Toxicity And Homeostasis Of Metals

5.4.1 Mechanisms of metal toxicity (lead, mercury, cadmium)

Metal toxicity occurs when metals accumulate in the body at harmful levels, interfering with biological processes.

- **Lead (Pb)** disrupts enzymes involved in haem synthesis, leading to anaemia and neurological damage.
- **Mercury (Hg)** binds to proteins and enzymes, impairing nervous system function.
- **Cadmium (Cd)** accumulates in kidneys, causing renal dysfunction and bone damage.

Fill in the blank: The toxic metal that interferes with haem synthesis and can cause anaemia is _____.

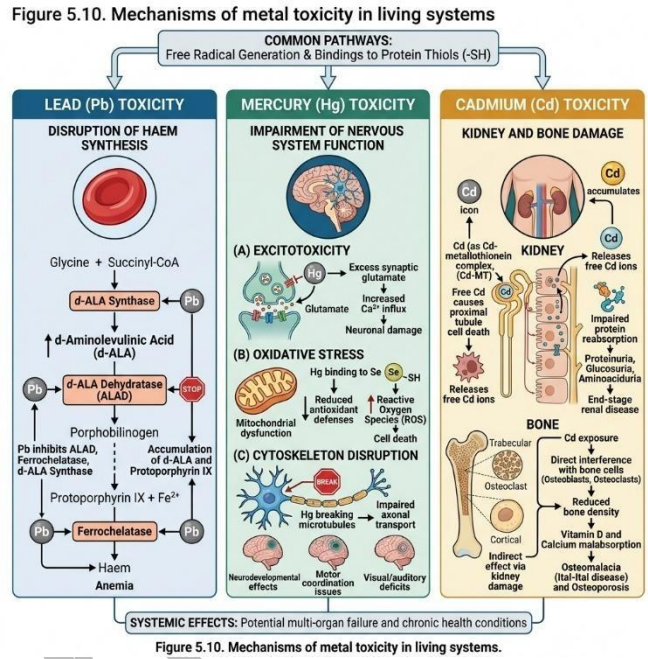


Figure 5.10. Mechanisms of metal toxicity in living systems.

Short description: Diagram showing how lead, mercury, and cadmium interfere with biological processes.
Figure 5.10 Mechanisms of metal toxicity in living systems.
"lead mercury cadmium toxicity diagram OER"

5.4.2 Detoxification and protective mechanisms

Living organisms have developed **detoxification mechanisms** to counteract metal toxicity.

- **Metallothioneins** are proteins that bind toxic metals such as cadmium and mercury, reducing their harmful effects.
- **Glutathione** acts as an antioxidant, protecting cells from oxidative stress caused by toxic metals.
- **Chelation therapy** is a medical intervention where chelating agents bind metals, allowing them to be excreted safely.

Fill in the blank: The protein that binds toxic metals like cadmium and mercury to reduce their harmful effects is _____.

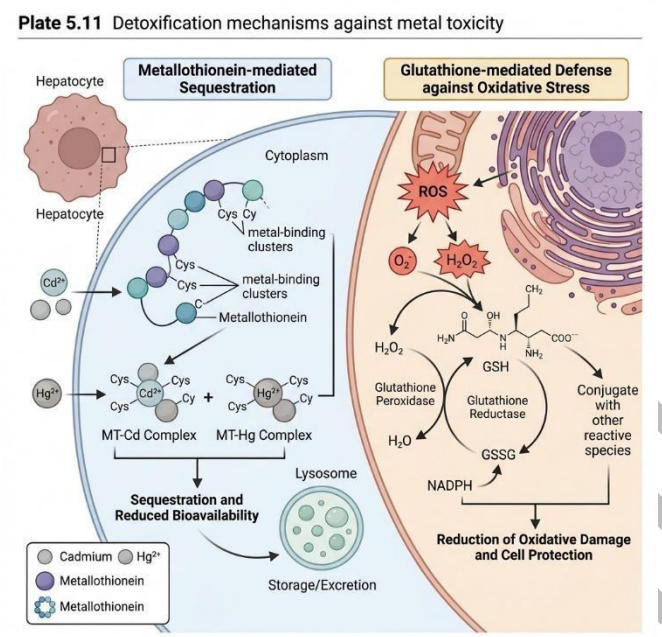


Image showing metallothioneins binding toxic metals and glutathione protecting cells.
Plate 5.11 Detoxification mechanisms against metal toxicity.
"metallothioneins glutathione detoxification OER"

5.4.3 Regulation of metal ion concentration in living systems

Homeostasis refers to the regulation of metal ion concentrations to maintain balance in biological systems.

- **Iron homeostasis** is controlled by proteins such as ferritin (storage) and transferrin (transport).
- **Calcium homeostasis** involves hormones like parathyroid hormone and calcitonin, which regulate calcium levels in blood and bones.
- **Zinc and copper homeostasis** are maintained by transport proteins that balance absorption and excretion.

Fill in the blank: The protein responsible for transporting iron in the bloodstream is _____.

Examples of Metal Ion Homeostasis

Metal Ion	Homeostatic Mechanism and Role
Iron	Regulated by **ferritin** for safe intracellular storage and **transferrin** for secure transport through the bloodstream.
Calcium	Maintained by **parathyroid hormone (PTH)** to increase blood levels and **calcitonin** to promote storage in bones.
Zinc & Copper	Controlled by specific **transport proteins** (like ZIP/ZnT for zinc) and chaperones to prevent toxicity while ensuring delivery.

Box 5.12 Examples of metal ion homeostasis.
Single-column table summarising iron (ferritin and transferrin), calcium (parathyroid hormone and calcitonin), zinc and copper (transport proteins).
"metal ion homeostasis table OER"

Series Summary

This Series on **Biological Roles of Metals in Living** was designed to highlight how metals underpin essential life processes and why their regulation is critical for health. Metals are not only structural components but also active participants in enzymatic reactions, energy metabolism, and cellular signalling. Their dual nature as both indispensable and potentially toxic makes them a fascinating area of study within inorganic chemistry.

We began by defining essential metals and classifying them into macro-elements, trace elements, and ultra-trace elements (SLO 5.1). Then we explained the functions of metalloproteins and enzymes, including haem proteins, non-haem iron proteins, and other metalloenzymes (SLO 5.2). Following that, we analysed the roles of metals in physiological processes such as oxygen transport, electron transfer, and hormonal regulation (SLO 5.3). Finally, we evaluated toxicity and homeostasis, considering mechanisms of harm, detoxification strategies, and regulation of metal ion concentrations (SLO 5.4). By completing this Series, you should now be able to define, explain, analyse, and evaluate the biological importance of metals, linking chemical principles directly to living systems.

Glossary of Terms

- **Cadmium (Cd)**: A toxic metal that accumulates in the kidneys, leading to renal damage and bone weakness when present at harmful levels.
- **Calcium (Ca)**: A macro-element essential for bone formation, muscle contraction, nerve signalling, and hormonal regulation.
- **Carbonic anhydrase**: A zinc-containing enzyme that regulates acid–base balance by converting carbon dioxide and water into bicarbonate.
- **Cobalt (Co)**: An ultra-trace element that forms part of vitamin B12, necessary for red blood cell formation and neurological function.
- **Copper (Cu)**: A trace element involved in electron transfer reactions, particularly in cytochrome oxidase during respiration.

- **Ferritin**: A non-haem iron protein that stores iron safely inside cells and releases it when needed.
- **Glutathione**: An antioxidant molecule that protects cells from oxidative stress caused by toxic metals.
- **Haem proteins**: Proteins containing a haem group, such as haemoglobin and myoglobin, which are essential for oxygen transport and storage.
- **Haemoglobin**: A haem protein that carries oxygen from the lungs to tissues throughout the body.
- **Homeostasis**: The regulation of metal ion concentrations in living systems to maintain balance and proper function.
- **Iron (Fe)**: A trace element central to haemoglobin and myoglobin, enabling oxygen transport and storage.
- **Lead (Pb)**: A toxic metal that interferes with haem synthesis, causing anaemia and neurological damage.
- **Magnesium (Mg)**: A macro-element that acts as a cofactor in enzymatic reactions, especially those involving ATP.
- **Metalloenzymes**: Enzymes that require a metal ion for catalytic activity, such as zinc, copper, or manganese enzymes.
- **Metallothioneins**: Proteins that bind toxic metals like cadmium and mercury, reducing their harmful effects.
- **Molybdenum (Mo)**: An ultra-trace element that acts as a cofactor in enzymes involved in nitrogen metabolism.
- **Myoglobin**: A haem protein that stores oxygen in muscle cells for immediate use during activity.
- **Selenium (Se)**: An ultra-trace element found in selenoproteins, which protect against oxidative damage.
- **Superoxide dismutase**: A manganese-containing enzyme that protects cells from oxidative stress by neutralising free radicals.
- **Transferrin**: A non-haem iron protein that transports iron in the bloodstream to tissues requiring it.
- **Zinc (Zn)**: A trace element that supports enzyme activity, DNA synthesis, and insulin regulation.

Concept Check Questions [Series 5]

Objective Questions

1. Which macro-element acts as a cofactor in ATP-related enzymatic reactions?
   (Linked to SLO 5.1)

2. The haem protein responsible for storing oxygen in muscle cells is _____.
   (Linked to SLO 5.2)
3. Which trace element is central to haemoglobin and enables oxygen transport?
   (Linked to SLO 5.1)
4. The zinc enzyme that regulates acid–base balance in the body is _____.
   (Linked to SLO 5.2)
5. The toxic metal that interferes with haem synthesis and can cause anaemia is _____.
   (Linked to SLO 5.4)

Short-Answer Questions

1. Define an isotope and explain why cobalt is biologically important.
   (Linked to SLO 5.1)
2. Describe the role of ferritin in iron homeostasis.
   (Linked to SLO 5.2, SLO 5.4)
3. Explain how calcium functions as a secondary messenger in signalling pathways.
   (Linked to SLO 5.3)
4. State one detoxification mechanism that protects cells from toxic metals.
   (Linked to SLO 5.4)
5. Identify one industrial or medical application of copper enzymes.
   (Linked to SLO 5.2, SLO 5.3)

Long-Answer Questions

1. Analyse the importance of metals in oxygen transport and energy metabolism, giving examples of specific proteins and enzymes.
   (Linked to SLO 5.2, SLO 5.3)
2. Evaluate the balance between the essential roles and toxic effects of metals in living systems, with reference to homeostasis and detoxification mechanisms.
   (Linked to SLO 5.4)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Magnesium (Mg)
2. Myoglobin
3. Iron (Fe)
4. Carbonic anhydrase
5. Lead (Pb)

Short-Answer Questions

1. An isotope is an atom of the same element with the same number of protons but different numbers of neutrons. Cobalt is biologically important as part of vitamin B12, which supports red blood cell formation and neurological function.
2. Ferritin stores iron safely inside cells and releases it when needed, helping maintain iron balance.
3. Calcium acts as a secondary messenger by transmitting signals inside cells, controlling processes such as muscle contraction and hormone release.
4. Metallothioneins bind toxic metals like cadmium and mercury, reducing their harmful effects.
5. Copper enzymes such as cytochrome oxidase are used in respiration and energy metabolism, and in medical diagnostics involving electron transfer.

Long-Answer Questions

Question 1

- **Basic response:** Metals such as iron in haemoglobin and myoglobin are essential for oxygen transport and storage. Copper and iron in cytochromes enable electron transfer in the electron transport chain, producing ATP.
- **Value-added response:** Outstanding learners may extend by linking these processes to overall energy metabolism, discussing how deficiencies or imbalances in these metals can lead to diseases such as anaemia or impaired respiration, and connecting the chemistry of metal centres to broader physiological functions.

Question 2

- **Basic response:** Metals are essential for life, but in excess they can be toxic. Homeostasis regulates their levels, while detoxification mechanisms such as metallothioneins and glutathione protect against harm.
- **Value-added response:** Outstanding learners may extend by evaluating ethical and medical implications, such as the use of chelation therapy, the environmental impact of heavy metal exposure, and the importance of balancing dietary intake with safe regulation. They could also compare beneficial roles (enzyme activity, signalling) with harmful effects (toxicity, oxidative stress) to show the dual nature of metals in biology.

Answers to Pilot Questions [Series 5]

Part 5.1 Essential metals in biological systems

1. Magnesium
2. Iron
3. Cobalt

Part 5.2 Metalloproteins and enzymes

1. Myoglobin

2. Ferritin
3. Carbonic anhydrase

Part 5.3 Metals in physiological processes

1. Myoglobin
2. Iron and copper
3. Calcium

Part 5.4 Toxicity and homeostasis of metals

1. Lead
2. Metallothioneins
3. Transferrin

References and Attributions [Series 5]

General References

- OpenStax (2021). *Chemistry: Atoms First 2e*. Houston, TX: OpenStax. Available under Creative Commons Attribution Licence.
- LibreTexts (2023). *Chemistry Library*. Retrieved from https://chem.libretexts.org (OER resource for inorganic and biological chemistry).
- International Union of Biochemistry and Molecular Biology (IUBMB). *Biochemistry Resources*. Retrieved from https://iubmb.org.
- Royal Society of Chemistry (RSC). *Learn Chemistry Resources*. Retrieved from https://edu.rsc.org.

Illustrations

- *Figure 5.1 Roles of macro-elements in cellular processes*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing sodium–potassium pump and calcium signalling pathways in cells."
- *Box 5.2 Selected biological roles of trace elements*
  Attribution: AI-generated using prompt "Generate a single-column table summarising biological roles of trace elements: iron, zinc, copper, manganese."
- *Plate 5.3 Ultra-trace elements in biological systems*
  Attribution: AI-generated using prompt "Create an image showing vitamin B12 structure with cobalt and molybdenum enzyme activity in nitrogen metabolism."
- *Figure 5.4 Functions of haem proteins*
  Attribution: AI-generated using prompt "Generate a labelled diagram showing haemoglobin transporting oxygen in blood and myoglobin storing oxygen in muscle tissue."
- *Box 5.5 Roles of non-haem iron proteins*
  Attribution: AI-generated using prompt "Generate a single-column table summarising roles of non-haem iron proteins: ferritin and transferrin."

- *Plate 5.6 Examples of metalloenzymes in biological systems*
  Attribution: AI-generated using prompt “Create an image showing carbonic anhydrase (zinc enzyme), cytochrome oxidase (copper enzyme), and superoxide dismutase (manganese enzyme).”
- *Figure 5.7 Oxygen transport and storage by haem proteins*
  Attribution: AI-generated using prompt “Generate a labelled diagram showing haemoglobin transporting oxygen in blood and myoglobin storing oxygen in muscle tissue.”
- *Plate 5.8 Role of metals in electron transfer and energy metabolism*
  Attribution: AI-generated using prompt “Create an image showing the electron transport chain with cytochromes containing iron and copper.”
- *Box 5.9 Metals in hormonal regulation and signalling*
  Attribution: AI-generated using prompt “Generate a single-column table summarising roles of calcium, zinc, and magnesium in hormonal regulation and signalling.”
- *Figure 5.10 Mechanisms of metal toxicity in living systems*
  Attribution: AI-generated using prompt “Generate a labelled diagram showing how lead disrupts haem synthesis, mercury impairs nervous system function, and cadmium damages kidneys and bones.”
- *Plate 5.11 Detoxification mechanisms against metal toxicity*
  Attribution: AI-generated using prompt “Create an image showing metallothioneins binding cadmium and mercury, and glutathione protecting cells from oxidative stress.”
- *Box 5.12 Examples of metal ion homeostasis*
  Attribution: AI-generated using prompt “Generate a single-column table summarising examples of metal ion homeostasis: iron, calcium, zinc, copper.”
