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Prelims Paper-I

Basics of
Material Science
and
Engineering

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PREFACE

Materials are the spinal cord of technology. Material Science is the scientific study of materials and their properties for resulting engineering design and improvement. An engineer must have a sound understanding of the basic concepts of Material Science.

This understanding of materials enables the engineers to select the most appropriate materials and use them with greatest efficiency whilst causing minimum pollution in their extraction, refinement and manufacturing.

This book has been written after intensive study of the probable topics in Material Science from where questions are expected. Based on the pattern and trend of questions asked in UPSC examinations, all the necessary concepts and information have been compiled in a simple and lucid form.

This revised and updated edition (**9th edition**) is primarily aimed at explaining the basic concepts of Material Science for students preparing for ESE. The treatment of each chapter is such as to start from the fundamentals and build up to the level of ESE.

This book is divided into **12 chapters** plus **one Annexure**. The Annexure given at the end of this book serves as a ready reckoner, covering short and brief description of properties of various important materials in the periodic table and short notes on metallurgical extraction, for a hassle-free learning.

This book has many student-friendly features. Important points, which are vital from examination point of view, are highlighted in the chapters, and at the end of each chapter these are given under 'Points to be Remembered'. A good number of practice questions are provided at the end of every chapter. So, as a topic is finished, students test their understanding in the language asked in the UPSC exam. The spin given to the concepts, tests the ability of the students to derive the correct answer, which facilitates the students to acquire necessary confidence. Students may generally not require any additional study and may be reasonably confident that all the probable questions and topics are covered in this book. Apart from the foresaid, UPSC sample papers and questions asked in **ESE 2017-24** are discussed after the completion of relevant topics.

All care has been taken to make the understanding of this subject more clear and interesting. The credit goes to the entire IES Master team for its continuous support in bringing out this book. Hope this will suffice the need of students who are preparing for Engineering Services Examination. All comments and suggestions for further improvement of the book are welcome, and will be appreciated.

Bipin Thakur
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CONTENTS

1 Atomic Structure and Radioactivity

1.1 INTRODUCTION

All substances contain matter which can exist in three states; solid, liquid or gas. The constituent particles are held in different ways in these states of matter and they exhibit their characteristic properties. Matter can also be classified into elements, compounds or mixtures. An element contains particles of only one type which may be atoms or molecules. The compounds are formed where atoms of two or more elements combine in a fixed ratio to each other. Mixtures occur widely and many of the substances present around us are mixtures.

This chapter consider several fundamental and important concept namely atomic structure and it's related theory, electron configuration, periodic table, types of bonds that hold together the atoms comprising a solid and finally radioactivity at the end.

1.2 ATOMIC MODEL

The concept of atom was given by early Greek philosophers. In Greek the word atom means indivisible. In 1804, Dalton put forward his atomic theory, thereafter in 1815. Prout found that atomic weights of most elements were simple multiple of atomic weight of hydrogen atom but with time this has been discarded because it was found that certain elements have fraction atomic weights. According to modern concept, an atom is composed of a nucleus which is surrounded by electrons.

1.2.1 Dalton's Atomic Theory

The **Dalton's atomic theory** states that atoms are building blocks of matter.

According to Dalton's atomic theory:

- Matter consists of indivisible atoms
- All the atoms of a given element have identical properties including identical mass. Atoms of different elements differ in mass.
- Compounds are formed when atoms of different elements combine in a fixed ratio.

1 part by weight of hydrogen is actually the reference weight.

$$\underset{2g}{H_2} + \underset{(35.5\times2)g}{Cl_2} \rightarrow \underset{2\times36.5g}{2HCl}$$

2g hydrogen is equivalent $(\equiv)$ to 71g chlorine (Cl_2) thus, 1g hydrogen is equivalent to $(\equiv)$ 35.5g Cl_2. Thus, equivalent weight of Cl_2 = 35.5g equivalent^{-1} and also equivalent weight of HCl = 36.5g equivalent^{-1}.

Isotopes, Isobars and Isotones

All atoms having same atomic number (Z) but having different atomic weight (A) are termed as **isotopes**. **For example:** $_{17}Cl^{35}$ *and* $_{17}Cl^{37}$.

Atoms having same atomic weight (A) but different atomic number (Z) i.e. different number of protons are called isobars. **For example:** $_{18}Ar^{40}$ *and* $_{20}Ca^{40}$.

Atoms having same number of neutrons but different atomic number (Z) and atomic weight (A) are called **isotones**. **For example:** $_{6}C^{13}$ *and* $_{7}N^{14}$.

Mole

A mole is the amount of matter that has a mass in grams equal to the atomic mass in amu of the atoms. Thus, a mole of oxygen has a mass of 32 grams.

1 mole = 6.022×10^{23} atoms

32 g oxygen = 1 mole of oxygen gas

= 6.022×10^{23} oxygen molecules

= $2 \times 6.022 \times 10^{23}$ oxygen atoms

Avogadro's number (N_{av})

The number of atoms in a mole is called avogadro number. The numerical value of avogadro's number is

$$N_{av} = 6.023 \times 10^{23}$$

1.4 FUNDAMENTAL COMPONENTS OF ATOM

Matter is composed of tiny particles called **atoms**. These particles can be divided in three groups as stable, unstable and composite particles. The different tiny particles are given in Table 1.2

Table 1.2

Particle	State	Charge	Remarks
Electron	Stable	–e where, $e = 1.602 \times 10^{-19}$ C	Carrier of electric current Rest mass $m_o = 9.1 \times 10^{-31}$ kg
Proton	Stable	+e	Mass of proton m = 1.672×10^{-27} kg The protons and the neutron are considered to be two different charge states of the same particle which is called a nucleon.
Neutron	Stable	0	A neutral nuclear particle. Slightly heavier than proton. Mass = 1.675×10^{-27} kg.
Positron	Unstable	+e	Positive counter part of electron. Electron and positron mutually annihilate each other.
Neutrino & antineutrino	Unstable	0	Produced during radio active decay of electrons and positron.
Meson	Unstable	+e	Mass of meson is in between electron and proton. Two types - (i) π-meson, which is heavier (ii) μ-meson, which is light
Deutron	Composite	+e	Heavy isotope of hydrogen with mass about double that of ordinary hydrogen. Useful as bombarding agent.
Alpha (α) Particle	Composite	+2e	Doubly charged helium nucleus.

1.5 THE ENERGY-BAND THEORY

The **electronic band structure** of a ***solid*** describes the range of energies that an ***electron*** within the solid may have (called energy *bands*) and ranges of energy that it may not have (called ***band gaps*** or *forbidden bands*).

Band theory derives these bands and band gaps by examining the allowed quantum mechanical ***wave functions*** for an electron in a large, periodic lattice of atoms or molecules. Band theory has been successfully used to explain various physical properties of solids, such as ***electrical resistivity*** and ***optical absorption,***

1.6.2 Modern Periodic Table

Mendeleev's Periodic Law was modified and known as the Modern Periodic Law and can be stated as:

The physical and chemical properties of the elements are periodic functions of their atomic numbers.

Features of Modern Period Table

Table consists of 7-horizontal rows known as periods and 18-vertical columns known as **groups**. It is divided in four blocks- s,p,d and f. In s,p, d and f-block elements, the valence electrons lies in s, p, d and f-subshells respectively. All the elements in d-block are called **transition elements**.

The s-block and the p-block are numbered as groups I to VII and 0 (zero), depending on number of electrons in the outer shell of the atoms, and the transition elements are dealt with as triads of elements and named as the top element in each group of three.

The IUPAC has recommended that the main groups and the transition metals should be numbered from 1 to 18. This system has gained acceptance, and has now been adopted everywhere.

Further note that in periodic table most of the elements come under metal classification. These are some times electropositive elements, means capable of giving up valence electron to become positively charged ion.

From examination point of view properties of various important material in period table are exclipictly mentioned in Annexure-I of this book.

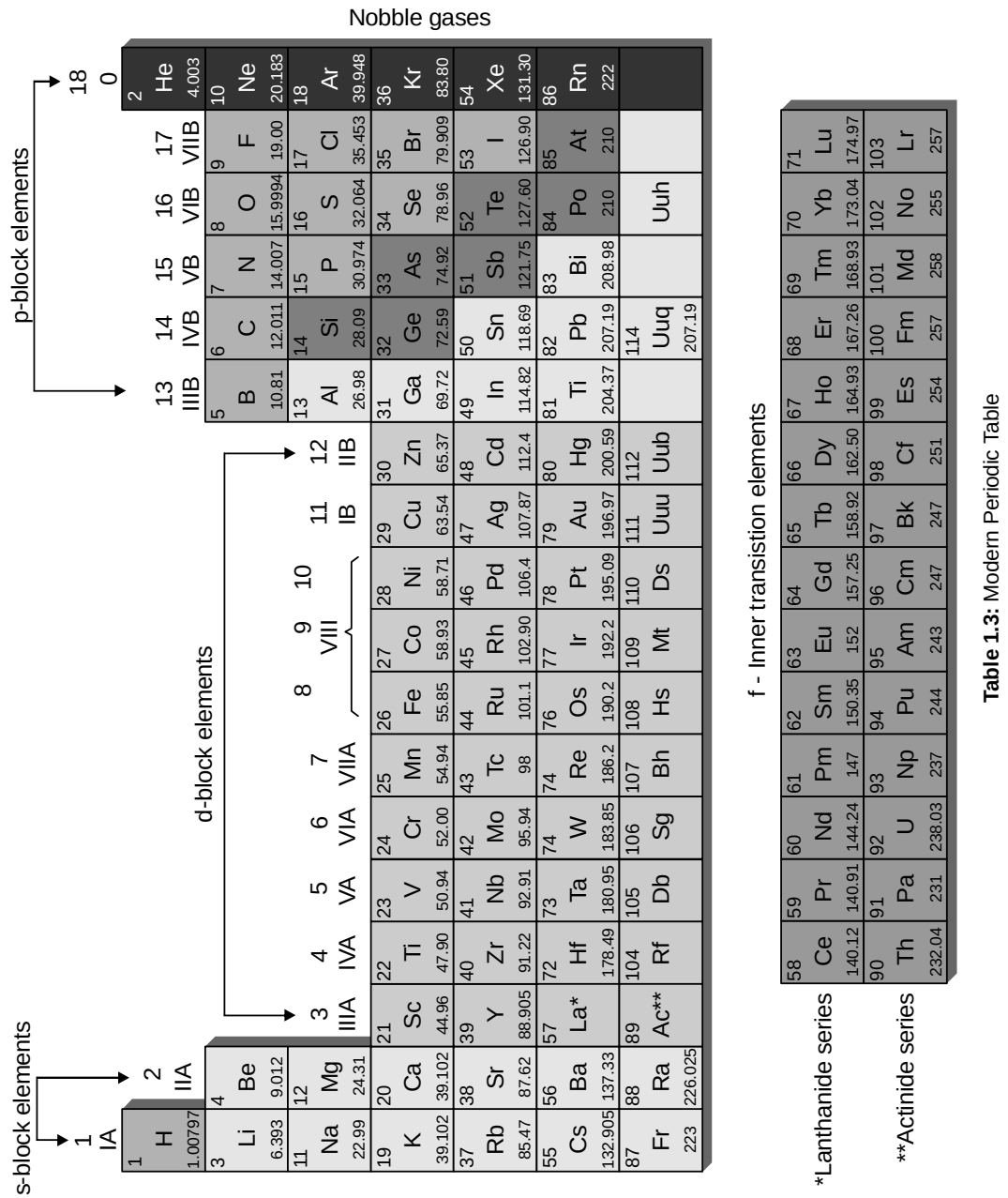

Table 1.3: Modern Periodic Table

Ionic Packing Theory

This theory deals with the packing of both anion and cation in formed molecule. Also, tells us that whether the formed ionic molecule is stable or not.

For stable configuration of ionic crystal the following conditions are to be satisfied simultaneously.

(i) An anion and a cation assumed to be hard sphere always touch each other.

(ii) Anions generally will not touch each other but may be close enough to be in contact with one another in a limiting situation.

(iii) As many anions as possible is permitted by geometry to surround the cation for maximum reduction in electrostatic energy.

Ionic packing theory also deals with radius ratio rule by which we can determined the shape of ionic crystal. For detail of it, refer ionic crystal mentioned in chapter-2 of this book.

Example 1.4

Consider the following assumptions made while developing the ionic packing theory :

1. Cations and anions are spherical but these spheres are not hard
2. Cations are always smaller than anions
3. Each cation would tend to be surrounded by the maximum number of anions permitted by geometry
4. Cations and anions do not touch each other

Which of the above assumptions are correct?

(a) 1 and 3 (b) 1 and 4
(c) 2 and 4 (d) 2 and 3

[ESE–2017]

Ans: (d)

3. Metallic Bond

Metallic bond is a characteristic of elements having small valence electrons. These electrons are loosely held and can be easily removed to the common pool. *e.g., Molecules of Al, Mg, Cu etc.*

Metallic bonding is found not only in metals and alloys but also in several other compounds as in –

(i) Interstitial bodies, carbides, nitrides and hydrides formed by transition elements.

(ii) Metal cluster compounds of transition metals and cluster compounds of boron.

(iii) A group of compound including metal carbonyl which contain a metal-metal bond.

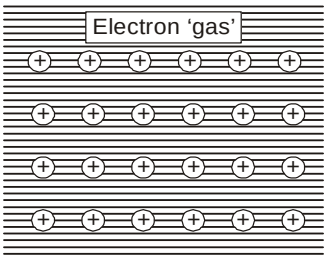

Fig. 1.4: A metallic crystal, pictured as a lattice of positive ions embedded in a 'sea' of electrons. The charge distribution of electrons is here shown uniform, although in practice it is not quite so. This is electron sea model to explain metallic bonding.

(iv) Metallic bond is similar to covalent bond in respect of sharing of electrons. The difference in between these two are metallic bond sharing electrons belong to metal as a whole rather than any particular atom.

(v) These material have 1, 2 or atmost 3 valence electrons.

(vi) In this bond free electrons act as a glue to hold the ion core together. In periodic table group IA & IIA and infacts all metal are formed this bond.

(vii) Bonding may be weak or strong. Energies range from 68 kJ/mol for Hg to 850 kJ/mol for tungsten (W).

Example 1.5

In which one of the following types of bonds, the bond formation is by free moving electrons in an array of positive ions?

(a) Homopolar bond (b) Electrostatic bond
(c) Metallic bond (d) Covalent bond

[ESE–2020]

Ans: (c)

Secondary Bonds

1. Hydrogen Bond

Hydrogen bond is a dipole-dipole attraction bond, in which a hydrogen atom serves as a bridge between two electronegative atoms holding one by a covalent bond and the other by purely electrostatic force. This bond is sufficiently strong.

When hydrogen is attached to a highly electronegative atom, the electron cloud is greatly distorted toward the electronegative atom, exposing the hydrogen nucleus. The strong positive charge of the thinly shielded hydrogen nucleus is strongly attracted by the negative charge of the electronegative atom of a second molecule.

Questions

1. According to Thomson's plum pudding model, an atom consists of

(a) A nucleus of negative charge with protons around

(b) A sphere of negative charge seasoned with enough number of proton plums.

(c) A heavy sphere of positive charge seasoned with enough number of electron plums to make it electrically neutral

(d) None of these

2. When an electron 'jumps' from an energy level to a lower one, the energy released is usually

(a) absorbed by the nucleus

(b) emitted as a photon

(c) emitted as light

(d) emitted as a continuous electromagnetic wave

3. The radiation emitted by a heated gas of hydrogen atoms contains

(a) all wavelengths

(b) one specific wavelength

(c) a set of discrete values of wavelength

(d) None of the above

4. The emission of radiation from a gas of atoms occurs when

(a) an electron is spiralling towards the nucleus

(b) an electron jumps between two energy levels

(c) the wavelength of an electron changes

(d) None of the above

5. The principal quantum number n may have only the values

(a) 0, 1, 2,...

(b) $0, \pm 1, \pm 2, \pm 3,...$

(c) 1, 2, 3,...

(d) None of the above

6. The angular momentum quantum number *l* may take only the values

(a) 0, 1, 2,...(n – 1) (b) 0, 1, 2, 3,...n

(c) 1, 2, 3,...n (d) 1, 2, 3,...(n – 1)

7. The magnetic quantum number m may have only the values

(a) $0, \pm 1, \pm 2,... \pm l$

(b) $0, \pm 1, \pm 2,... \pm n$

(c) $0, \pm 1, \pm 2,... \pm (l - 1)$

(d) $0, \pm 1, \pm 2,... \pm (n - 1)$

8. How many quantum numbers are needed to define the wave function of an electron moving in two dimensions (excluding spin)?

(a) one (b) two

(c) three (d) four

9. Pauli's exclusion principle states that, within one atom

(a) no more than two electrons may have the same energy

(b) the spins of the electrons interact so as to become parallel if possible

(c) no two electrons may have the same four quantum numbers

(d) there are only two values for the quantum number m_s

10. The maximum number of electrons in the L shell (n = 2) is

(a) 4 (b) 6

(c) 8 (d) 14

11. The maximum number of electrons allowed in the 4d subshell is

(a) 14 (b) 10

(c) 8 (d) 4

12. The lithium atom, which contains three electrons, has the strcuture

(a) $1s^2 2s^1$ (b) $1s^2 2p^1$

(c) $1s^1 2p^2$ (d) $2s^2 2p^1$

13. The atomic number of the element whose outermost electron fills the 3s subshell exactly is

(a) 13 (b) 8

(c) 10 (d) 12

14. Equal moles of the substance are present in

(1) 1.6g CH_4 (2) 1.7g NH_3

(3) 1.8g H_2O (4) 1.2g Mg

(a) 1, 2 (b) 2, 3

(c) 1, 2 and 3 (d) 1, 2, 3 and 4

15. The difference between A and Z is a result of the presence in the nucleus of

(a) electrons (b) protons

(c) photons (d) neutrons