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Brief and Intensive Notes

Multiple Choice Questions

Based On NEP 2020

SOLID STATE & NUCLEAR PHYSICS

B.Sc. VI SEM

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Syllabus

Subject: **Physics**	
Year: First	Semester: **VIth**
Course Code: **B010601T**	Course Title: **Solid State & Nuclear Physics**

Unit	Topics
	PART A **Introduction to Solid State Physics**
I	**Crystal Structure** Lattice, Basis & Crystal structure. Lattice translation vectors, Primitive & non-primitive cells. Symmetry operations, Point group & Space group. 2D & 3D Bravais lattice. Parameters of cubic lattices. Lattice planes and Miller indices. Simple crystal structures - HCP & FCC, Diamond, Cubic Zinc Sulphide, Sodium Chloride, Cesium Chloride and Glasses.
II	**Crystal Diffraction** X-ray diffraction and Bragg's law. Experimental diffraction methods - Laue, Rotating crystal and Powder methods. Derivation of scattered wave amplitude. Reciprocal lattice, Reciprocal lattice vectors and relation between Direct & Reciprocal lattice. Diffraction conditions, Ewald's method and Brillouin zones. Reciprocal lattice to SC, BCC & FCC lattices. Atomic Form factor and Crystal Structure factor.
III	**Crystal Bindings** Classification of Crystals on the Basis of Bonding - Ionic, Covalent, Metallic, van der Waals (Molecular) and Hydrogen bonded. Crystals of inert gases, Attractive interaction (van der Waals- London) & Repulsive interaction, Equilibrium lattice constant, Cohesive energy and Compressibility & Bulk modulus. Ionic crystals, Cohesive energy, Madelung energy and evaluation of Madelung constant.
IV	**Lattice Vibrations** Lattice Vibrations: Lattice vibrations for linear mono & di atomic chains, Dispersion relations and Acoustical & Optical branches (qualitative treatment). Qualitative description of Phonons in solids. Lattice heat capacity, Dulong-Petit's law and Einstein's theory of lattice heat capacity. Free Electron Theory: Fermi energy, Density of states, Heat capacity of conduction electrons, Paramagnetic susceptibility of conduction electrons and Hall effect in metals. Band Theory: Origin of band theory, Qualitative idea of Bloch theorem, Kronig-Penney model, Effective mass of an electron & Concept of Holes & Classification of solids on the basis of band theory.

PART B **Introduction to Nuclear Physics**	
V	**Nuclear Forces & Radioactive Decays** General Properties of Nucleus: Mass, binding energy, radii, density, angular momentum, magnetic dipole moment vector and electric quadrupole moment tensor. Nuclear Forces: General characteristic of nuclear force and Deuteron ground state properties. Radioactive Decays: Nuclear stability, basic ideas about beta minus decay, beta plus decay, alpha decay, gamma decay & electron capture, fundamental laws of radioactive disintegration and radioactive series.
VI	**Nuclear Models & Nuclear Reactions** Nuclear Models: Liquid drop model and Bethe-Weizsacker mass formula. Single particle shell model (the level scheme in the context of reproduction of magic numbers included). Nuclear Reactions: Bethe's notation, types of nuclear reaction, Conservation laws, Cross-section of nuclear reaction, Theory of nuclear fission (qualitative), Nuclear reactors and Nuclear fusion.
VII	**Accelerators & Detectors** Accelerators: Theory, working and applications of Van de Graff accelerator, Cyclotron and Synchrotron. Detectors: Theory, working and applications of GM counter, Semiconductor detector, Scintillation counter and Wilson cloud chamber.
VIII	**Elementary Particles** Fundamental interactions & their mediating quanta. Concept of antiparticles. Classification of elementary particles based on intrinsic-spin, mass, interaction & lifetime. Families of Leptons, Mesons, Baryons & Baryon Resonances. Conservation laws for mass-energy, linear momentum, angular momentum, electric charge, baryonic charge, leptonic charge, isospin & strangeness. Concept of Quark model.

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Unit - I

Unit I

(Crystal Structure)

Summary

Crystal Lattice

Solids are characterized by incompressibility, rigidity and mechanical strength. This indicates that the molecules, atoms or ions that make up as solid is closely packed. Thus in solids we will have a well ordered molecular, atomic or ionic arrangement [1].
In general solids can be classified into:

- Crystalline-particles are orderly arranged (long range order).
- Amorphous-particles are randomly oriented.
- If the atoms or molecules are uniquely arranged in crystalline solid or liquid we call it as a crystal structure.
- A crystal possess long range order and symmetry. The main property of crystal structure is its periodicity. This periodicity is due to the arrangement of atoms/molecules in the lattice points.
- A crystal structure is formed only when the group of atoms is arranged identically at the lattice point. The group of atoms or molecules is called a basis. Lattice point is actually an imaginary concept [2-3].
  In other way, we can say that, Lattice + Basis=crystal structure [4]
- Line joining any two points is a translation in lattice. Two non-collinear translation leads to a plane lattice and three non-coplanar translation leads to a space lattice.

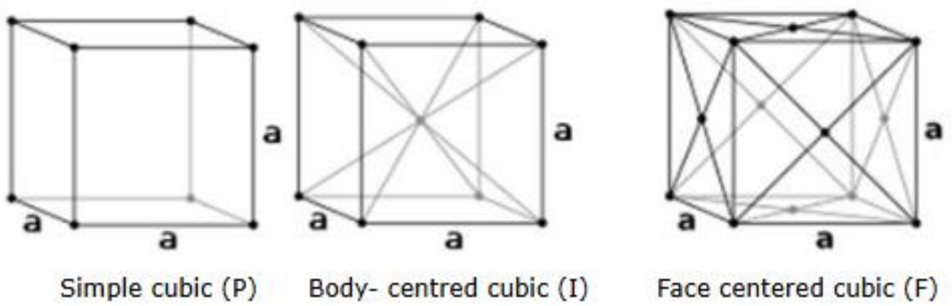


Fig. 1.1 SC, BCC and FCC unit cell [4]

Unit Cell:

- Unit cell can be considered as the building block of a crystal.
- It has the same symmetry as the entire crystal. When we arrange the unit cell in 3D, we get the bulk crystal.
- In other words it can be described as the smallest volume which when repeated in all direction gives the crystal.
- The crystal structure as a whole can be considered as the repetition of unit cell. For a given crystal structure the shape of unit cell is same but varies from crystal to crystal.
- Unit cell can be of primitive as well as non-primitive type.

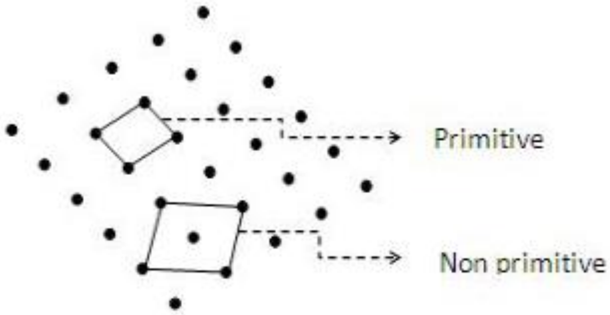


Fig. 1.2. Primitive and Non-primitive cell [5]

A primitive cell is a minimum volume unit cell and has only one lattice point in it and the latter contains more than one. e.g. Simple cubic is primitive, BCC and FCC is non-primitive cell.

- A crystal lattice is an array of points related by the lattice translation operator $T = aU_1 + bU_2 + cU_3$ where a, b, c are the integers and U_1, U_2, and U_3 are called the translation vectors.
- The set of points defined by all integral linear combination of primitive translation vectors is called a Bravais lattice. There are 5 Bravais lattices in two-dimension and 14 in three dimensions.

Miller indices, Coordination Number, lattice point and Packing fraction

- Miller indices of a plane are given by the reciprocal of its three numerical parameters expressed as whole numbers.
- A direction in the crystal is denoted by [u v w] and a plane in the crystal is denoted by the indices (h k l) [5].
- Number of atoms surrounding the particular atom.
  C.No. for SC = 6, BCC = 8, FCC and HCP = 12
- Number of atoms per unit cell
  For SC = 1, BCC = 2, FCC = 4
- Atomic packing fraction mainly gives us an idea about the arrangement of atoms/ions in solids. It will give the efficiency with which the available space is being filled by atoms.
- Packing fraction is defined as the ratio of volume of atoms occupying the unit cell to the volume of unit cell.Packing Factor for SC = 0.52, BCC = 0.68, FCC = 0.74, Diamond = 0.34

- Relation between the **density** (*d*) of crystal material and lattice constant (*Z*) in a cubic lattice

$$d = \frac{MZ}{a^3 N_A}$$

- Important simple crystal structure include the BCC, FCC, HCP, diamond, NaCl, CsCl, and ZnS structure.
- The collection of symmetry operations excluding translation which leave a body invariant is called a point group.

- In two dimension these include rotation and rotation reflections making a total of 10 point group.
- In three dimension these include rotations, rotation-reflection, and rotation-inversion making a total of 32 point group [1-2].

Multiple Choice Questions and Answers

1. The smallest portion of the lattice is called
   a) Lattice point
   b) Lattice structure
   c) Unit cell
   d) Bravais crystal
   Ans. c) Unit cell

2. Coordination number of a FCC is?
   a) 6
   b) 8
   c) 10
   d) 12
   Ans. d) 12

3. Which of the following unit cell has all the angles at 90^0 but sides are of unequal length?
   a) Triclinic
   b) Monoclinic
   c) Orthorhombic
   d) Hexclinic
   Ans. c) Orthorhombic

4. Packing fraction of diamond structure is
   a) 0.74
   b) 0.68
   c) 0.54
   d) 0.34
   Ans. d) 0.34

5. The axial relationship of a Triclinic crystal system is given as [1]
   a) a = b = c
   b) a ≠ b = c
   c) a = b ≠ c
   d) a ≠ b ≠ c
   Ans. d) a ≠ b ≠ c

6. Which of the following rotation symmetry operation <u>not</u> possible in the crystal?
   a) 2-fold

b) 3-fold
c) 4-fold
d) 5-fold
Ans. d) 5-fold

7. Crystal is equal
a) Lattice + Basis
b) Unit cell + Basis
c) Lattice + Unit cell
d) Basis + Unit cell
Ans. a) Lattice + Basis

8. Find out the miller indices of the set of parallel plane makes intercept in the ratio 2a:5b on the X and Y axis and are parallel to Z axis.
a) [5, 2, 0]
b) [2, 5, 0]
c) [0, 5, 2]
d) [0, 2, 5]
Ans. a) [5, 2, 0]

9. Direction and orientation of planes in the crystal are denoted as
a) Unit cell
b) Miller indices
c) Lattice point
d) None of these
Ans. b) Miller indices

10. The number of Bravais lattice for 2D and 3D crystal system are respectively:
a) 4, 12
b) 8, 16
c) 5, 14
d) 7, 14
Ans. c) 5, 14

11. The reciprocal lattice to a BCC lattice is a
a) SC lattice
b) BCC lattice
c) FCC lattice
d) None of these
Ans. c) FCC lattice

12. Which of the two crystal structure have the same atomic packing factor among SC, BCC, HCP and FCC?
a) FCC and HCP
b) BCC and FCC
c) SC and HCP

d) SC and BCC
Ans. a) FCC and HCP

13. The crystal structure having an axial ratio (c/a) of 1.63 is:
a) Diamond structure
b) Hexagonal close packed structure
c) Zinc blende structure
d) Body centered cubic structure
Ans. c) Hexagonal close packed structure

14. Germanium and silicon have diamond structure for which the molecules per unit cell are equal to
a) 1
b) 2
c) 4
d) 8
Ans. d) 8

15. The Miller indices of two plane are (2,1,1) and (4, 2, 2), then they are**:**
a) Parallel
b) Perpendicular
c) at an angle of 45^0
d) None of these
Ans. a) Parallel

16. The translation vectors of a space lattice given:

$$\vec{a} = \frac{\hat{x}}{2} + \frac{\sqrt{3}}{2}\hat{y}; \vec{b} = -\frac{\hat{x}}{2} + \frac{\sqrt{3}}{2}\hat{y}; \vec{c} = \hat{z}$$

The volume of the cell is-
a) $\frac{\sqrt{3}}{2}$
b) $\frac{2}{\sqrt{3}}$
c) $2\sqrt{3}$
d) $3\sqrt{2}$
Ans. a) $\frac{\sqrt{3}}{2}$

17. Ice (H_2O) is an example of -
a) Triclinic system
b) Hexagonal system
c) Orthorhombic system
d) Monoclinic system
Ans. b) Hexagonal system

18. Classify the unit cell given by the following parameters into proper system-
    a = 11.20 Å, b = 8.63 Å, c = 6.19 Å
    $\alpha = 47^o$, $\beta = 81^o$, $\gamma = 95^o$
    a) Monoclinic
    b) Triclinic
    c) Hexagonal
    d) Tetragonal
    Ans. b) Triclinic
    Hint: since $a \neq b \neq c$, $\alpha \neq \beta \neq \gamma$ therefore Triclinic system

19. A cubic crystal can have -
    a) Only primitive Bravais lattices
    b) Any one of primitive, body centered and face centered Bravais lattices
    c) All of primitive, body centered and face centered Bravais lattices
    d) All of primitive, base centered and face centered Bravais lattices
    Ans. c) All of primitive, body centered and face centered Bravais lattices

20. The number of sulphide atoms in the unit cell of Zinc sulphide crystal is -
    a) 2
    b) 3
    c) 4
    d) 6
    Ans. c) 4

21. In a simple cubic lattice the ratio $d_{100} : d_{110} : d_{111}$ is
    a) 6 : 3 : 2
    b) $6 : 3 : \sqrt{2}$
    c) $\sqrt{6} : \sqrt{3} : \sqrt{2}$
    d) $\sqrt{6} : \sqrt{3} : \sqrt{4}$
    Ans. c) $\sqrt{6} : \sqrt{3} : \sqrt{2}$

22. Which of the following is **NOT** true?
    a) All unit cell are primitive.
    b) FCC structure is a close packed structure.
    c) A unit cell is primitive if it contains lattice points only at its corners
    d) A lattice doesnot contain any atom or molecule.
    Ans. a) All unit cell are primitive.

23. The $\frac{c}{a}$ ratio for an ideal hexagonal closed packed structured is - [5]
    a) $\frac{2}{\sqrt{3}}$
    b) $\sqrt{8}$

c) $\sqrt{\frac{8}{3}}$

d) $\sqrt{5}$

Ans. c) $\sqrt{\frac{8}{3}}$

24. Which one of the following statements is NOT correct about the Brillouin Zones (BZ) of as square lattice with lattice constant a?
    a) The first BZ is a square of side ($2\pi/a$) in k_x and k_y plane
    b) The areas of the first BZ and third BZ are the same
    c) The k-points are equidistant in k_x as well as in k_y directions
    d) The area of second BZ is twice that of the first BZ
    Ans. d) The area of second BZ is twice that of the first BZ

25. The atomic radius of BCC lattice is
    a) $\frac{a}{2}$
    b) $\frac{\sqrt{3}a}{4}$
    c) $\frac{\sqrt{3}a}{2}$
    d) $\frac{a}{2\sqrt{2}}$
    Ans. b) $\frac{\sqrt{3}a}{4}$

26. Atomic packing factor is
    a) Distance between two adjacent atoms
    b) Projected area fraction of atoms on a plane
    c) Volume fraction of atoms in cell
    d) None of these
    Ans. c) Volume fraction of atoms in cell

27. A family of directions is represented by- [5]
    a) (hkl)
    b) <hkl>
    c) {hkl}
    d) [hkl]
    Ans. b) <hkl>

28. The unit cells
    a) contain the smallest number of atoms which when taken together have all the properties of the crystals of the particular metal

b) may be defined as the smallest parallelopiped which could be transposed in three coordinate directions to build up the space lattice
c) have the same orientation and their similar faces are parallel
d) All of these
Ans. d) All of these

29. The ratio of the volume occupied by the atoms to the total volume of the unit cell is called
a) Coordination number
b) Packing fraction
c) Density of crystal
d) None of these
Ans. b) Packing fraction

30. Which of the following arrangements of particles does a simple cubic lattice follow?
a) ABAB
b) ABCABC
c) AABB
d) AAA
Ans. d) AAA

31. A compound is formed by atoms of elements **A** occupying the corners of the unit cell and an atom of element **B** present at the center of the unit cell. Deduce the formula of the compound?
a) AB_2
b) AB_3
c) AB_4
d) AB
Ans. d) AB
Hint: The description is of a BCC. For BCC, each atom at the corner is shared by 8 unit cells. One atom at the center wholly belongs to the corresponding unit cell.
Therefore, total number of atoms of A present = (1/8) x 8=1
Total number of atoms of B present=1
Therefore, A:B=1:1 implying the formula of the compound is AB. [1]

32. Metallic iron changes from bcc structure to fcc structure at 910°C with an increase in the atomic radii. The density of iron in this structural change -
a) decreases
b) increases
c) remains constant
d) becomes zero
Ans. b) increases
Hint: atomic radius and density of unit cell relation

33. Gold (at. Mass 197 g mol^{-1}) crystallises in cubic closest packed structures (the face-centred cubic) and has a density of 19.3 g/cm^3. Atomic radius is

a) 144.17 nm
b) 407.8 nm
c) 128.32 nm
d) 203.4 nm
Ans. b) 144.17 nm

Hint: Use density relation, $d = \dfrac{MZ}{a^3 N_A}$ and radius, $r = \dfrac{a}{2\sqrt{2}}$

34. Match A with B with correct options. [7]

A	B
(a) Triclinic	**(p)** a ≠ b ≠ c, α = γ = 90°, β ≠ 120°
(b) Hexagonal	**(q)** a = b ≠ c, α = β = γ = 90°
(c) Monoclinic	**(r)** a = b ≠ c, α = β = 90°, γ = 120°
(d) Tetragonal	**(s)** a ≠ b ≠ c, α ≠ β ≠ γ ≠ 90°

a) (a) → (s), (b) → (r), (c) → (p), (d) → (q)
b) (a) → (r), (b) → (s), (c) → (q), (d) → (p)
c) (a) → (p), (b) → (q), (c) → (r), (d) → (s)
d) (a) → (q), (b) → (p), (c) → (s), (d) → (r)
Ans. a) (a) → (s), (b) → (r), (c) → (p), (d) → (q)

35. The amorphous solids atoms are arranged in
a) long range
b) short range
c) both (a) and (b)
d) None of these
Ans. b) short range

36. The translation operation in crystal is defined as-
a) $T = aU_1 + bU_2 + cU_3$
b) $T = aU_1 - bU_2 - cU_3$
c) $T = -aU_1 - bU_2 - cU_3$
d) $T = -aU_1 - bU_2 + cU_3$
Ans. a) $T = aU_1 + bU_2 + cU_3$

37. The relation between interplaner spacing (d_{hkl}) and lattice points of crystal (a, b, c) is

a) $d_{hkl} = \dfrac{1}{\sqrt{\dfrac{h^2}{a^2} + \dfrac{k^2}{b^2} + \dfrac{l^2}{c^2}}}$

b) $d_{hkl} = \dfrac{a}{\sqrt{\dfrac{1}{h^2} + \dfrac{1}{k^2} + \dfrac{1}{l^2}}}$

c) $d_{hkl} = \dfrac{a}{\sqrt{h^2 + k^2 + l^2}}$

d) None of these

Ans. a) $d_{hkl} = \dfrac{1}{\sqrt{\dfrac{h^2}{a^2} + \dfrac{k^2}{b^2} + \dfrac{l^2}{c^2}}}$

38. What type of crystal is CsCl?
   a) FCC
   b) SC
   c) BCC
   d) None of these
   Ans. c) BCC

39. Point group symmetry does not consider-
   a) rotation
   b) translation
   c) mirror plane
   d) rotary inversion
   Ans. c) translation

40. The volume of primitive cell for reciprocal lattice of simple cubic structure having lattice parameter 'a' is
   a) a^3
   b) $1/a^3$
   c) $2\pi/a^3$
   d) $(2\pi/a)^3$
   Ans. d) $(2\pi/a)^3$
   Hint: use Volume of reciprocal lattice, $V_r = (2\pi)^3/V_d$ where V_d = volume of direct lattice = a^3

41. Space groups are -
   a) Collection of lattice points
   b) Collection of basis
   c) Collection of symmetry
   d) None of these
   Ans. c) Collection of symmetry

42. Which of the following is true?
   a) The diamond and zinc blende structures are both tetrahedral.
   b) diamond consists of a single atom (carbon) while zinc blende (ZnS) consists of two elements (zinc and sulfur) in a unit cell.

c) ZnS is a semiconductor and diamond is insulator.
d) All of these
Ans. d) All of these

43. Sodium metal crystallizes in body centered cubic lattice with cell edge 4.29 Å. The radius of the sodium atom is
a) 1.76 Å
b) 1.86 Å
c) 0.76 Å
d) 0.86 Å
Ans. b) 1.86 Å
Hint: For BCC, $r = \frac{\sqrt{3}}{4}a$

44. Na and Mg crystallize in BCC and FCC type crystals respectively. Then the number of atoms of Na and Mg present in the unit cell of their respective crystal is
a) 4 and 2
b) 2 and 4
c) 1 and 4
d) 9 and 14
Ans. b) 2 and 4
Hint: No. of lattice point of BCC and FCC is 2 and 4.

45. Which of the following has least packing factor?
a) SC
b) FCC
c) BCC
d) Diamond
Ans. d) Diamond

46. If the coordination number of an element in its crystal lattice is 8 then the packing is
a) FCC
b) BCC
c) HCP
d) None of these
Ans. b) BCC
Hint: Coordination number SC = 6, BCC = 8, FCC = 12, HCP = 12

47. Volume of primitive cell of BCC structure having conventional lattice parameter 'a' is
a) a^3
b) $2a^3$
c) $a^3/4$
d) $a^3/2$
Ans. d) $a^3/2$
Hint: For BCC translation vector,

$$\vec{a} = \frac{a}{2}(\hat{i} + \hat{j} - \hat{k}),\ \vec{b} = \frac{a}{2}(\hat{i} - \hat{j} + \hat{k}),\ \vec{c} = \frac{a}{2}(-\hat{i} + \hat{j} + \hat{k})$$ Therefore

Volume of primitive cell, $V_P = \vec{a}.\vec{b}\times\vec{c}$

In general formula $V_P = V_c$/(No. of lattice point)

Where $V_c = a^3$ and lattice point = 1, 2 and 4 for SC, BCC and FCC respectively

48. The density of Cu is 8.980 kg/m^3 and edge length 3.61 Å. Find out the interplanar spacing of [110] plane
a) 2.56 Å
b) 2.08 Å
c) 3.61 Å
d) 1.81 Å
Ans. a) 2.56 Å

49. A metal crystallizes in FCC structure with a unit cell side of 500 pm. If the density of the crystal is 1.33 g/cc, the molar mass of the metal is close to
a) 23
b) 24
c) 25
d) 26
Ans. c) 25
Hint: Use $\rho = \frac{ZM}{N_A V}$

50. The value of d_{111} in a cubic crystal is 325.6 pm. The value of d_{333} is
a) 325.6 pm
b) 108.5 pm
c) 625.6 pm
d) 976.8 pm
Ans. a) 108.5 pm

Unit - II

Unit II

(Crystal Diffraction)

Summary

X-ray diffraction and Bragg's law

- The phenomena by which X-rays are reflected from the atoms in a crystalline solid is called diffraction. The diffracted X-rays generate a pattern that reveals structural orientation of each atom in a given compound.
- XRD finds the geometry or shape of a molecule using X-rays. This technique is based on the elastic scattering of X-rays from structures that have long range order (crystalline solids).
- When the X-ray beam encounters the regular three-dimensional arrangements of atoms in a crystal, most of the X-rays will destructively interfere with each-other and cancel each-other out, but in some specific directions the X-ray beams interfere constructively and reinforce one another. It is these reinforced diffracted X-rays that produce the characteristic X-ray diffraction pattern that is used for crystal structure determination.

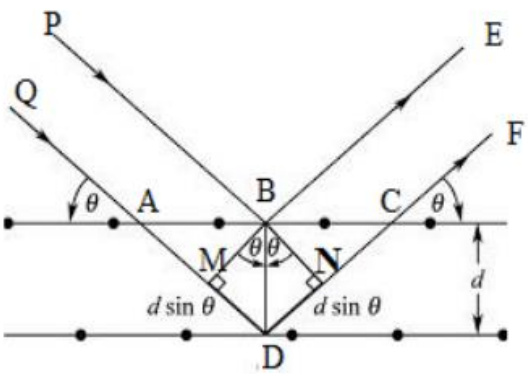


Fig. 2.1 Bragg's diffraction by crystal planes [5]

- These reflections occur only under certain conditions which satisfy the equation:

$$n\lambda = 2d\sin\theta$$

- The above equation is also known as Bragg's equation. Here *n* is an integer (1,2,3,...n), λ is the wavelength, *d* is the distance between the atomic planes, and theta is the angle of incidence of the X-ray beams.
- By analyzing the diffraction patterns we can find out the lattice parameters, size, shape, orientation of crystal, inter planner distance etc.
- Wavelengths of X-rays are of the order of 10^{-8} to 10^{-9} cm and spacing between the layers of these atoms in a crystal is in order of 10^{-8} cm, which are of the same order.

Diffraction methods

- The diffraction occurs whenever the Bragg's condition is satisfied.
- In general when monochromatic x ray beam falls on a single crystal, for arbitrary setting x rays will not produce any diffraction pattern.

- But some way if we continuously vary wavelength (λ) or diffraction angle (θ) then at a particular setting of single crystal, the Bragg's condition satisfies, and diffraction occurs.
- The ways, in which these quantities vary, there are three diffraction method as given below:

Method	Wavelength	Angle	Specimen type
Laue Method	Variable	Fixed	Single crystal
Rotating crystal method	Fixed	Varying	Single crystal
Powder method	Fixed	Variable	powder

Reciprocal lattice System

- When we observe diffraction patterns, the diffraction spot form a picture of crystal lattice. This periodic structure like lattice is not direct picture of crystal but image of actual crystal. This is called reciprocal lattice.
- Reciprocal lattice points are inverse of actual lattice points. Thus the distance in reciprocal lattice system is 1/ distance corresponding to actual distance d in actual crystal lattice [1].
- All the periodic points of reciprocal lattice form a reciprocal lattice system. Such space is called reciprocal space or Fourier space.
- Reciprocal lattice vector is defined as the vector has magnitude $1/d_{hkl}$ and direction perpendicular to the plane (hkl). Generally reciprocal lattice vector is denoted by

$$G_{hkl} = 1/d_{hkl}$$

Brillouin Zones:

- The concept of a Brillouin zone was developed by Leon Brillouin (1889–1969), a French physicist.

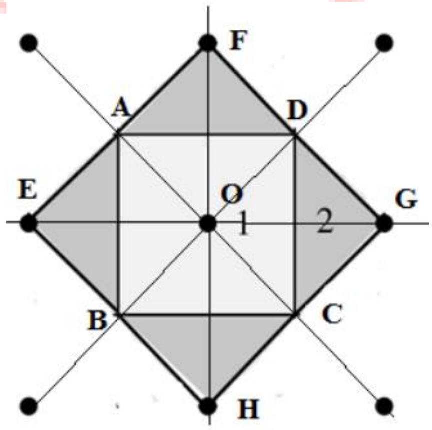


Fig 2.2 First and IInd Brillouin Zone in 2D space [3]

- In direct lattice system we defined Wigner Seitz cell which is nothing but a type of unit cell constructed by the area enclosed by perpendicular bisectors of nearest neighbours.
- If we construct a unit cell by area enclosed by perpendicular bisectors of nearest neighbours reciprocal lattice points that is called Brilloun zone.
- In three dimensional space, Brillouin zone is the minimum volume under perpendicular bisectors of Bragg planes in reciprocal lattice space.
- Brillouin zone can also be understood by Ewald construction. According to Ewald construction, Bragg diffraction occurs for all possible value of wave vector K for which condition satisfies.
- A Brillouin zone is the locus of all such values of K in reciprocal lattice system for which Bragg diffraction occurs.

Ewald Sphere

- The Ewald sphere is a pictorial way to show the diffraction condition. We construct a sphere which is known as the Ewald constructions as shown in Fig. 2.3.

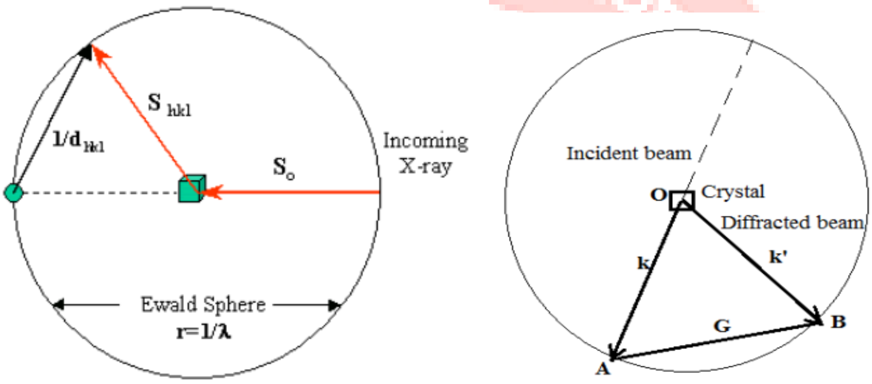


Fig. 2.3 Ewald Construction and diffraction in reciprocal lattice system [5]

- Ewald sphere is a virtual or imaginary sphere, that sphere whose radius is 1/λ.
- The geometrical construction of Eward sphere provides the relationship between the orientations of a crystal and the directions of the beams diffracted by it.
- If the origin of reciprocal space is placed at the tip of incident beam then diffractions will occur only for those reciprocal lattice points that lie on the surface of the Ewald sphere.
- $K + G = K'$ and $K - K' = G$ or $\mathbf{G^2 + 2KG = 0}$
  This is diffraction condition in reciprocal lattice system.

Atomic form factor (f)

- The condition for diffraction from point scattering centres in space lattice is given by Bragg or Laue's equations.
- It is the ratio of the amplitude of the radiation scattered from the atom to the amplitude of radiation scattered from a single electron [2].

Multiple Choice Questions and Answers

1. The crystal lattice is a lattice in a real ordinary space but the reciprocal lattice is a lattice in
   a) Gaussian space
   b) Laplacian space
   c) Hypothetical space
   d) Fourier space
   Ans. d) Fourier space

2. The reciprocal lattice to an BCC lattice is
   a) FCC lattice
   b) a SC lattice
   c) a BCC lattice
   d) None of these
   Ans. a) FCC lattice

3. For Characterization of crystal_____ are used.
   a) Visible rays
   b) Infra-red rays
   c) X-rays
   d) Gamma rays
   Ans. c) X-rays

4. In diffraction of crystal, diffracted beams are found only when reflected waves from various plane of atoms-
   a) Interfere constructively
   b) Interfere destructively
   c) Do not interfere
   d) None of these
   Ans. a) Interfere constructively

5. In Bragg's law ($2d\sin\theta = n\lambda$) if $n = 0$, then
   a) Diffraction occur
   b) No diffraction
   c) May or may not diffraction
   d) None of these
   Ans. b) No diffraction

6. One of the widely used target material for generation of X-ray spectral line is
   a) Zinc
   b) Molybdenum
   c) Xenon
   d) Manganese
   Ans. b) Molybdenum

7. The X-ray diffraction is based on
   a) Boltzmann equation
   b) Bragg's equation
   c) Moseley equation
   d) None of these
   Ans. b) Bragg's equation

8. Which one of the following statements about X-rays is not true?
   a) They have wavelength about 1 Å
   b) These can be generated by bombarding of high energy electron on the metal target.
   c) Due to their wavelength being shorter used for radar system
   d) None of these
   Ans. c) Due to their wavelength being shorter used for radar system

9. Bragg's law of X-ray diffraction is
   a) $2d\sin\theta = n\lambda$
   b) $2d\cos\theta = n\lambda$
   c) $nd\sin\theta = 2\lambda$
   d) $2\lambda\cos\theta = n\lambda$
   Ans. a) $2d\sin\theta = n\lambda$

10. The Bragg's law have no solution if
    a) $\lambda < 2d$
    b) $\lambda > 2d$
    c) $\lambda < d$
    d) $\lambda > d$
    Ans. b) $\lambda > 2d$

11. What type of material Rotating crystal method is used for determining the crystal structure?
    a) Single crystal
    b) Polycrystalline
    c) Fine grain polycrystalline
    d) none of these
    Ans. b) Polycrystalline

12. In Lau's method, the glancing angle θ is
    a) Fixed
    b) Becomes zero
    c) May or may not change
    d) Changes to infinity
    Ans. a) fixed

13. In X-ray powder method, the detector used is
    a) Photomultiplier tube
    b) Photographic film

c) Thermistor
d) Bolometer
Ans. b) Photographic film

14. Which method is used to determine the imperfection in the crystal?
a) Rotating crystal method
b) Powder method
c) Lau's method
d) Bragg's law
Ans. a) Lau's method

15. The diffraction takes place from those plane which satisfy
a) Boltzmann's law
b) Hook's law
c) Bragg's law
d) None of the above
Ans. c) Bragg's law

16. Which statement is Correct for reciprocal lattice?
a) Reciprocal lattice has unit which is inverse of the wavelength
b) Reciprocal space is representation in real space.
c) Reciprocal lattice have units of length.
d) All of these
Ans. a) Reciprocal lattice has unit which is inverse of the wavelength

17. What is crystal structure of Copper in real space and its representation in reciprocal space?
a) SC, FCC
b) BCC, FCC
c) FCC, BCC
d) FCC, SC
Ans. c) FCC, BCC

18. In cubic crystal the (1 1 1) and (2 2 2) reflections are observed but not the (0 0 1) reflection. The Bravais lattice is
a) FCC
b) BCC
c) SC
d) None of these
Ans. a) FCC
Hint: In SC all the plane allowed, In BCC sum of h, k, l = even allowed but odd are not allowed where as in FCC all h, k, l are odd or even allowed rest are not.

19. Powder method for crystal method was suggested by
a) Bragg
b) Debye & Scherrer

c) Lau
d) None of the above
Ans. b) Debye & Scherrer

20. X-ray used in Lau's method is
a) monochromatic
b) continuous beam
c) both (a) and (b)
d) none of these
Ans. b) continuous beam

21. If $\vec{a}$, $\vec{b}$, $\vec{c}$ are translational vectors of crystal lattice and $\vec{A}, \vec{B}, \vec{C}$ are vectors in reciprocal lattice, then
a) $\vec{a}.\vec{A} = 0$
b) $\vec{a}.\vec{A} = 2\pi$
c) $\vec{a}.\vec{A} = 1$
d) $\vec{a}.\vec{A} = \vec{a}.\vec{B}$
Ans. b) $\vec{a}.\vec{A} = 2\pi$

22. In terms of (h, k, l) the reciprocal lattice vector $\vec{G}$ is [2]
a) $h\vec{A} + k\vec{B} + l\vec{C}$
b) $2\vec{K}.\vec{G} + G^2$
c) $h\vec{A} + l\vec{B} + k\vec{C}$
d) None of these
Ans. a) $h\vec{A} + k\vec{B} + l\vec{C}$

23. The Laue method of X-ray diffraction by a crystal is suitable for determination of crystal orientation and also for studying-
a) Crystal Imperfection
b) Surface structure
c) Magnetic moment
d) Scattering from neighbouring elements in periodic table
Ans. a) Crystal Imperfection

24. The white X-rays as used in Laue diffraction method as source means-
a) X-rays beam of continuous range of wavelength
b) X-ray beam of discrete values of wavelength
c) X-rays may be both of continuous and discrete values of wavelength depending on the material of the target
d) None of these

Ans. a) X-rays beam of continuous range of wavelength

25. The Bragg's angle for first order reflection from (1, 1, 1) planes in a crystal is 30^o when X-rays of wavelength 1.75 Å are used, the interatomic spacing -
a) 3.13 Å
b) 3.31 Å
c) 3.03 Å
d) 3.33 Å
Ans. c) 3.03 Å

26. A crystal is held together entirely by-
a) Gravitational force
b) Electrostatic force
c) Magnetic force
d) Nuclear force
Ans. b) Electrostatic force

27. Reciprocal lattice develop by-
a) Ewald
b) Bragg
c) Von Laue
d) Davison
Ans. a) Ewald

28. If direct lattice is Hexagonal closed pack structure then its reciprocal lattice is -
a) SC
b) HCP
c) FCC
d) Diamond
Ans. b) HCP

29. The maximum wavelength of X-rays which can be diffracted by a crystal of spacing d = 2.5 Å is
a) 2.5 Å
b) 1.25 Å
c) 5 Å
d) 10 Å
Ans. c) 5 Å

30. X-ray of wavelength λ= a reflected from the (1 1 1) plane of a simple cubic lattice. If the lattice constant a then the corresponding Bragg angle is
a) π/6
b) π/4
c) π/3
d) π/8
Ans. c) π/3

31. A metal with body centred cubic structure shows the first diffraction peak at a Bragg's angle of 30^0 and the wavelength used is 2.1 Å. The volume of the primitive unit cell of the metal is
a) 4.6 $(Å)^3$
b) 9.3 $(Å)^3$
c) 13.2 $(Å)^3$
d) 26.2 $(Å)^3$
Ans. c) 13.2 $(Å)^3$
Hint: use $2d\sin\theta = n\lambda$, and Volume of primitive cell = (volume of nomal cell)/N_{eff}

32. Using powder diffraction, ______of a crystal can be determined.
a) the interatomic spacing
b) the interplanar spacing
c) both (a) and (b)
d) None of these
Ans. b) the interplanar spacing

33. Bragg's law is used in which process
a) X-ray production
b) Gamma ray production
c) X-ray crystallography
d) X-ray scan
Ans. c) X-ray crystallography

34. X-ray diffraction patterns are used for studying crystal structure of solids because
a)They have very high energy, hence they can penetrate through solids
b) They are electromagnetic radiation, hence do not interact with matter
c) Their wavelength are comparable to inter-atomic distances
d) Their high frequency enables rapid analyses
Ans. c) Their wavelength are comparable to inter-atomic distances

35. The utilized reflecting plane of a sodium fluoride (NaF) analysing crystal has a interplanar distance of 1.5 Å. Calculate the wavelength of the 2nd order diffracted line which has a glancing angle of 45^0
a) 1.02 Å
b) 2.16 Å
c) 1.2 Å
d) 3.21 Å
Ans. b) 2.16 Å

36. In Diffractometer, the identification of a component of the sample from its powder diffraction pattern is based upon the ______of lines and their relative____.
a) Number, length
b) Number, intensity
c) Position, length
d) Position, intensity

Ans. d) Position, intensity

37. In powder diffractometer, the sharpness of the lines is greatly determined by which of the following?
a) Quality of the sample, size of the slit
b) Quality of the slit, size of the sample
c) Thickness of the slit, amount of the sample
d) Number of slits, composition of the sample
Ans. b)

38. The Miller indices of set of parallel planes which makes equal intercept on three axes are
a) (1 2 1)
b) (1 1 1)
c) (1 0 0)
d) (1 0 1)
Ans. b) (1 1 1)

39. Ewald construction is ______ interpretation of Bragg's law. [1]
a) Theoretical
b) Geometrical
c) Mathematical
d) None of these
Ans. b) Geometrical

40. Brillouin zone is defined as
a) Regular arrangements of atoms in space
b) Weigner-Seitz primitive cell in the reciprocal lattice
c) Smallest volume enclosed by parallel planes in crystal lattice
d) None of these
Ans. c) Weigner-Seitz primitive cell in the reciprocal lattice

41. The boundaries of Brillouin zone shows
a) order of reflection in reflecting planes
b) type of the space lattice
c) both (a) and (b)
d) none of these
Ans. a) order of reflection in reflecting planes

42. In reciprocal lattice, lattice points are defined by -
a) Interplanar space
b) Lattice constant
c) Miller indices
d) None of these
Ans. c) Miller indices

43. The shape Ewald construction is-

a) Square
b) Sphere
c) Rectangle
d) Cube
Ans. b) Sphere

44. If $K^{'}$ = scattered wave vector, G = reciprocal lattice vector, K = incident lattice vector
Then the relation between $K^{'}$, G and K is-
a) $K^{'} = K - G$
b) $K^{'} = K.G$
c) $K^{'} = G/K$
d) $K^{'} = K + G$
Ans. b) $K^{'} = K + G$

45. In Ewald's method, the radius drawn of the Ewald sphere is :
a) λ
b) $\frac{1}{\lambda}$
c) $\sqrt{\lambda}$
b) λ^2
Ans. a) $\frac{1}{\lambda}$

46. In Ewald construction, if sphere passes through reciprocal lattice vector the-
a) Diffraction occurs
a) Interference occurs
b) Polarisation occurs
d) No diffraction occurs
Ans. b) Diffraction occurs

47. The reciprocal lattice have the dimension of :
a) [L]
b) $[L^{-1}]$
c) $[L^{-1/2}]$
d) $[L^{1/2}]$
Ans. b) $[L^{-1}]$

48. What is K-point in Brillouin zone?
a) Wave function
b) Space point
c) Wavelength
d) Wave vector
Ans. d) Wave vector

49. What is Structure factor?
a) Structure factor are used to describe the scattering of X-rays by atoms in a crystal

b) Structure factor are used to describe the scattering by the unit cell
c) Both (a) and (b)
d) None of these
Ans. b) Structure factor are used to describe the scattering by the unit cell

50. Correct position for calculating structure factor in body centred orthorhombic? [1]
a) Atom of (0, 0, 0) and equivalent positions
b) Atom of (0, 0, 0) and (½, ½, ½) and equivalent positions
c) Atom of (0, 0, 0) and (½, ½, 0) and equivalent positions
d) None of these
Ans. c) Atom of (0, 0, 0) and (½, ½, ½) and equivalent positions

Unit - III

Unit III

(Crystal Bindings)

Summary

Bonding of Common Crystal Structure

- The energy of the crystal is lower than that of the free atoms by an amount equal to the energy required to pull the crystal apart into a set of free atoms and this is called binding energy (also known as **cohesive energy of the crystal**).
- The forces berween atoms are of two kinds' attractive forces and repulsive forces. Attractive forces keep the atoms together and repulsive forces come into play when the solid is compressed [1].
- Bonding force F, between atom may be expressed as

$$F(r) = \frac{A}{r^M} - \frac{B}{r^N} \quad \text{with N > M, r} \rightarrow \text{centre to centre spacing}$$

A, B, M and N are constants characteristics of the molecule

- Spacing $r_0 = \left(\frac{B}{A}\right)^{\frac{1}{N-M}}$
- Cohesive energy $U(r) = \frac{a}{r^m} + \frac{b}{r^n}$

U(r) exhibit minimum at r = r_0, when

$$\left[\frac{dU}{dr}\right]_{r=r_0} = 0$$

Types of Crystal bonding

(i) Ionic bonding

- Formed due to electrostatic attraction between two stable atoms which becomes positive and negative ions because of complete transfer of electrons between them.

- Very strong bonding, high metting point, close packed structure, good ionic conductors but poor conductors of heat and electricity, transparent over wide range of electromagnetic spectrum.
- Example: NaCl, CsCl etc.
- Lattice energy of ionic crystal is defined as the energy released when the constituents ions placed in their respective positions in the crystal lattice.
- The total energy due to all the ions in the linese array is

$$\frac{-e^2}{4\pi\varepsilon_0 r_0}[2\log_e 2]$$

Where $2\log_e 2$ is Madelung constant per molecule of ionic solid [2].

(ii) **Covalent bonding**

- Covalent bonds are formed between two atoms when they share one or more pair of electrons between them.
- mutual sharing of valence electrons between atoms.
- Strongly bound, hard, high melting point, semiconductors, transparent in infrared region, opaque at higher frequencies.
- Example: Diamond, Ge, Si etc.

(ii) **Metallic bonding**

- Metallic bonds results from the sharing of variable number of electrons by a variable number of atoms.
- Metallic bond is the attraction between the lattice of ion cores and the free electron.
- Moderate to strong binding. Close-packed structure, low melting points very good conductors of heat and electricity, ductile, good reflectors and opaque to electromagnetic radiation.
- Example: Na, Al etc.

(iv) **Molecular bonding**

- Molecular bonds are formed by weak Van der Waals forces which exist between two atoms.
- Molecular solids may be crystalline or non-crystalline, have low melting points, are insulators, transparent to light and are easily soluble.
- Weak-binding, transparent, soft, lowest melting points, closed-packed structures, low electrical and thermal conductivities
- Example: Ne, N_2 (solid) etc.

(v) **Hydrogen bonding**

- Hydrogen bond is lowering of K.E. by atomic arrangement (eg, in H_2O).
- Moderately weak binding, loose H_2O. structures, low electrical and thermal conductivities, transparent, peculiar dielectric properties.
- Example: Ice (H_2O)

Some More Important Facts [1]

- Crystals of inert gas atoms are bound by the Van der Waals interaction (induced dipole-dipole interaction) and this varies with distance as $1/R^6$.
- The repulsive interaction between atoms arises generally from the electrostatic repulsion of overlapping charge distributions and the Pauli's principle which compels overlapping electrons of parallel spin to enter orbits of higher energy.
- lonic crystals ace bound by the electrostatic attraction of charged tons of opposite sign The electrostatic energy of a structure of 2N ion of charge q is

$$U = -N\alpha \frac{q^2}{R}$$

- Metals are bound by the reduction in kinetic energy of the valence electrons in the metal as compared with the free atom.

- A covalent bond is characterized by the overlap of charge distributions of antiparallel electron spin. The Pauli contribution to the repulsion is reduced for antiparallel spins. and this makes possible a greater degree of overlap. The overlapping electrons bind their associated ton cores by electrostatic attraction.
- Bulk modulus of solids at T=0K is given by

$$K = -\frac{dP}{(dV/V)}$$

Compressibility, C = 1/K

Multiple Choice Questions and Answers

1. KBr is ____ crystal.
a) Covalent
b) Ionic
c) Metallic
d) Hydrogen bonded
Ans. b) Ionic

2. Example of ionic bond
a) NaCl
b) LiF
c) CaO
d) All of these
Ans. d) All of these

3. Cohesive energy of inert gas crystals is proportional to
a) r^3
b) r^{-3}
c) r^6
d) r^{-6}
Ans. d) r^{-6}

4. On the basis of bonding, how many types of crystals are:
a) 4
b) 5
c) 8
d) 10
Ans. b) 5

5. The radius of an atom is ________ than nuclear radius
a) smaller
b) greater
c) equal to

d) None of these
Ans. b) greater

6. For visible light spectrum, ionic crystals are
a) opaque
b) transparent
c) depends on crystal
d) None of these
Ans. a) opaque

7. The attractive potential energy of inert gas molecule proportional to -
a) r^5
b) r^6
c) r^{-12}
d) r^{-6}
Ans. b) r^{-6}

8. The energy that must be added to the crystal to separate its component into neutral free atoms is called -
a) binding energy
b) electrostatic energy
c) cohesive energy
d) None of these
Ans. c) cohesive energy
9. Bulk modulus of solids at T = 0K is - [2]
a) $K = -\frac{dV/V}{dP}$
b) $K = -\frac{dV}{-(P/dP)}$
c) $K = -\frac{dP}{(dV/V)}$
d) None of these
Answer: c) $K = -\frac{dP}{(dV/V)}$

10. The reciprocal of bulk modulus is -
a) Lattice constant
b) Compressibility
c) Cohesive energy
d) Madelung constant
Ans. b) Compressibility

11. Which of the following is **NOT** a characteristic of ionic crystals?

a) High melting points
b) Poor electrical conductivity in solid state
c) Malleability
d) Solubility in polar solvents
Ans. c) Malleability

12. The lattice energy of an ionic crystal is directly proportional to:
a) Ionic radii
b) Charges of the ions
c) Crystal structure
d) Solvent polarity
Ans. b) Charges of the ions

13. The Madelung constant for ZnS (zinc blende) is: [2]
a) 1.763
b) 1.638
c) 1.747
d) 1.471
Ans. b) 1.638

14. Diamond is very hard because:
a) large cohesive energy
b) high melting point
c) amorphous solid
d) It has a covalent bond
Ans. a) large cohesive energy

15. ZnS have
a) Ionic bonding
b) Covalent bonding
c) Mixture of ionic and covalent bonding
d) None of these
Ans. a) Ionic bonding

16. The amount of energy with two atoms bond together and the same amount of energy required to separate them is called
a) Bonding energy
b) Dissociation energy
c) Cohesive energy
d) All of these
Ans. c) Cohesive energy

17. The main attractive interaction in crystals of inert gases is known as:
a) Vander waal's interaction

b) Induced dipole-dipole interaction
c) London interaction
d) All of these
Ans. d) All of these

18. Which of the following is **NOT** the property of the ionic bond?
a) Electron loss
b) Electron gain
c) Electron sharing
d) Electron transfer
Ans. c) Electron sharing

19. The total energy of an ionic solid is given by –

$$U = -\frac{\alpha e^2}{4\pi\varepsilon_0 r} + \frac{B}{r^9}$$

Where α is Madelung constant, r is the distance between the nearest neighbour in the crystal. If r_0 is the equilibrium separation then the constant B is given by-

a) $\frac{\alpha e^2 r_0^{\ 8}}{36\pi\varepsilon_0}$

b) $\frac{2\alpha e^2 r_0^{\ 8}}{9\pi\varepsilon_0}$

c) $\frac{\alpha e^2 r_0^{\ 10}}{36\pi\varepsilon_0}$

d) $\frac{-\alpha e^2 r_0^{\ 10}}{36\pi\varepsilon_0}$

Ans. a) $\frac{\alpha e^2 r_0^{\ 8}}{36\pi\varepsilon_0}$

Hint: Use at equilibrium, $\frac{dU}{dr} = 0$ [1]

20. The nature of bonding for a crystal with alternate and evenly spaced positive and negative ions is –
a) Dipole
b) Ionic
c) Covalent
d) Metallic
Ans. b) Ionic

21. A covalently bonded crystal is -
a) Aluminium
b) Germanium
c) Lead

d) Sodium chloride
Ans. b) Germanium

22. The bond energy of NaCl molecule is given by the relation-

a) $V = \frac{e^2}{4\pi\varepsilon_0 r_0}$

b) $V = \frac{-e^2}{4\pi\varepsilon_0 r_0}$

c) $V = \frac{e}{4\pi\varepsilon_0 {r_0}^2}$

d) $V = \frac{-e}{4\pi\varepsilon_0 {r_0}^2}$

Ans. b) $V = \frac{-e^2}{4\pi\varepsilon_0 r_0}$

Hint: For NaCl the two ion of charges separated by a distance r_0 and the energy will be attractive.

23. In NaCl, the Na ions are positively charged and chloride ions are negatively charged. Inspite of coulomb attraction between them, the two ions do not collapse -
a) Because of the presence of free electrons
b) Because of its low melting point
c) Because of its high specific heat
d) Because of short range repulsive forces
Ans. d) Because of short range repulsive forces

24. The unit of Madelung Constant is
a) J
b) J-m/^{o}C
c) J-m/^{o}C^2
d) None of these
Ans. d) None of these

25. In a Crystal, covalent molecules held together by
a) Dipole-dipole interaction
b) Hydrogen bonds
c) Vander waals interaction
d) Electrostatic interaction
Ans. c) Vander waals interaction

26. Metallic bonds do not have
a) delocalised electrons

b) highly directed bonds
c) mobile valence electrons
d) overlapping valence orbitals
Ans. b) highly directed bonds

27. Which type of crystalline solids is also called giant molecules?
a) Ionic solids
b) Covalent solids
c) Metallic solids
d) Polar molecular solids
Ans. b) Covalent solids

28. The relation gives the potential energy of a diatomic molecule -
a) $-\frac{a}{r^m}+\frac{b}{r^n}$
b) ar^m+br^n
c) $\frac{a}{r^m}-\frac{b}{r^n}$
d) ar^m-br^n
Ans. a) $-\frac{a}{r^m}+\frac{b}{r^n}$

29. Lithium and Sodium are chemically similar because -
a) Both have same number of electrons
b) Both are adjacent elements in the atomic table
c) Both have one electron in the outermost incomplete shell
d) Both are alkali metals
Ans. c) Both have one electron in the outermost incomplete shell

30. In the crystal structure of Si we have
a) Electrovalent bonding
b) Covalent bonding
c) Co-ordinate bonding
d) Mixture of covalent and electrovalent bonding
Ans. b) Covalent bonding

31. When irradiated with visible light, which of the following type of solids are always opaque?
a) Ionic crystal
b) Covalent solids
c) Metallic solids
d) None of these
Ans. a) Metallic solids

32. Which type of crystals are generally good optical reflectors?
a) Metals
b) Ionic crystals
c) Covalent crystals
d) All of these
Ans. a) Metals

33. Ionic crystals are very good insulators at room temperature conducting at higher temperature. This is due to -
a) Thermal expansion of the ionic solids
b) Generation of more free electrons
c) Transition of large number of electrons from valence band
d) Movement of large number of ions in vacancies
Ans. b) Generation of more free electrons

34. The nature of bonding in solid Argon is -
a) Vander Waal's force of attraction
b) Metallic
c) Ionic
d) Covalent
Ans. a) Vander Waal's force of attraction

35. HF crystal is -
a) Hydrogen bonded crystal
b) Vander Waal crystal
c) Metallic crystal
d) Ionic crystal
Ans. a) Hydrogen bonded crystal

36. The degree of ionization is maximum of -
a) Ionic crystal
b) Covalent crystal
c) Metallic
d) Hydrogen bonded crystal
Ans. a) Ionic crystal

37. The Vander Waal crystal is
a) Ice
b) Rock salt
c) Copper
d) Argon
Ans. d) Argon

38. Metallic bonds are developed in the lattice between
a) the positive ions and the electron gas
b) the negative ions and the electron gas
c) the positive ions and atoms
d) the negative ions and atoms
Ans. a) the positive ions and the electron gas

39. Nature of bonding in Cu is -
a) Vander Waal's forces
b) Metallic
c) Ionic
d) Covalent
Ans. b) Metallic

40. The Born-Haber cycle is used to calculate:
a) Polarizability
b) Lattice energy
c) Bond energy
d) Electronegativity
Ans. b) Lattice energy

41. The Madelung constant depends on:
a) Atomic number
b) Crystal structure
c) Atomic weight
d) Dipole moment
Ans. b) Crystal structure

42. For which of the following structure is the Madelung constant highest?
a) NaCl
b) CsCl
c) ZnS
d) CaF_2
Ans. d) CaF_2

43. The crystal of inert gas have
a) low melting point
b) transparent
c) large binding energy
d) Both (a) and (b)
Ans. d) Both (a) and (b)

44. For which of the following structure is the Madelung constant lowest?
a) NaCl

b) CsCl
c) ZnS
d) MgO
Ans. c) ZnS

45. Inert gas crystal are soft due to
a) Strong forces
b) Weak forces
c) Constant forces
d) None of these
Ans. b) Weak forces

46. The value of Madelung constant for one dimensional crystal lattice is -
a) $2\log_e 2$
b) $2\log_e 3$
c) $3\log_e 2$
d) $3\log_e 3$
Ans. a) $2\log_e 2$

47. The potential energy of Na^+ and $6Cl^-$ ion is -
a) $\frac{6e^2}{4\pi\varepsilon_0 r_0}$
b) $-\frac{6e^2}{4\pi\varepsilon_0 r_0}$
c) $\frac{e^2}{4\pi\varepsilon_0 r_0}$
d) $-\frac{e^2}{4\pi\varepsilon_0 r_0}$
Ans. b) $-\frac{6e^2}{4\pi\varepsilon_0 r_0}$

48. Two crystalline state of carbon is
a) CO_2 and diamond
b) CH_4 and diamond
c) CH_4 and graphite
d) Diamond and graphite
Ans. d) Diamond and graphite

49. The atomic radius of chemical element is a measure of -
a) Bulk modulus

b) Compressibility
c) Lattice parameter
d) Size of atom
Ans. b) Compressibility

50. The value of Madelung constant is of central importance in the theory of -
a) an inert gas crystals
b) hydrogen bonded crystals
c) covalent crystals
d) ionic crystals
Ans. d) ionic crystals

Unit - IV

Unit IV

(Lattice Vibrations)

Summary

Lattice vibrations

- The study of lattice vibrations is important for how energy is absorbed in solids.
- At low temperature, most of the energy that is absorbed is two types: lattice energy and electronic energy-the heat can go to the electrons, or to vibrations of the positive charges in the lattice.
- For metal, Heat capacity can be represented as, $C = aT + bT^3$, where first term is electronic contribution and second is lattice term.
- A solid body oscillating freely in its normal modes and under the influence of dynamic external forces will give rise to the acoustical and optical properties of solids.
- Lattice vibrations: acoustic and optical branches In three-dimensional lattice with p atoms per unit cell there are 3P phonon branches: 3 acoustic, 3P - 3 optical branch.

- **Model of lattice vibrations**
  1) One-dimensional lattice: linear chain of atoms

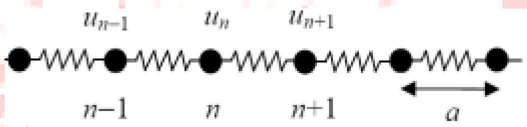


Fig. 4.1 atomic arrangement 1D monoatomic lattice [5]

- Dispersion relation: The angular frequency (ω) for elastic wave propagating in monoatomic linear lattice is

$$\omega = \pm\sqrt{\frac{4\beta}{m}}\sin\left(\frac{ka}{2}\right)$$

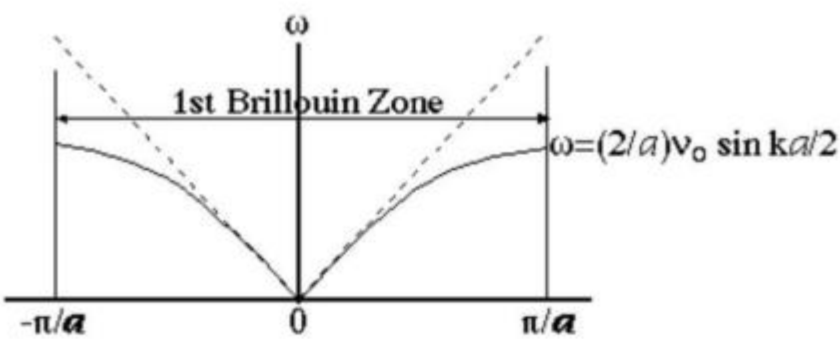


Fig. 4.2 1[st] brillouin zone representation of dispersion curve [5]

2) Diatomic lattice: One-dimensional linear chain, atoms of two types: m and M

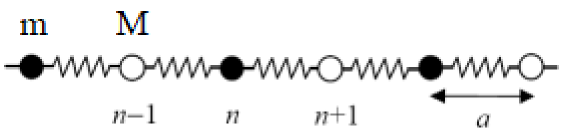


Fig. 4.3 atomic arrangement 1D diatomic lattice m and M [5]

- Dispersion relation:

$$\omega^2 = \beta\left(\frac{1}{m}+\frac{1}{M}\right) \pm \beta\sqrt{\left(\frac{1}{m}+\frac{1}{M}\right)^2 - \frac{4\sin^2 ka}{Mm}}$$

- Depending on sign in this formula there are two different solutions corresponding to two different dispersion curves: the first Brillouin zone is now from -π/2a to +π/2a

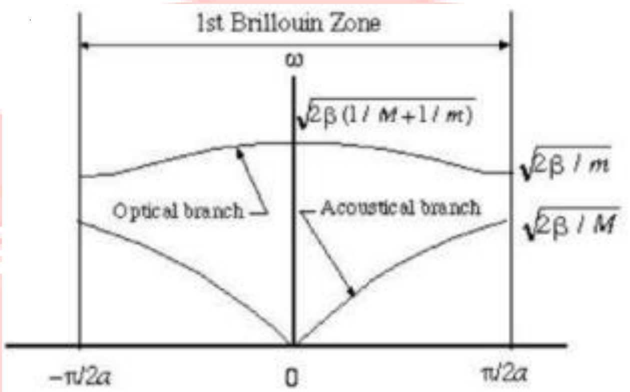


Fig. 4.4 1st brillouin zone representation of dispersion curve consists of optical and acoustical branch. [6]

- The lower curve - acoustic branch, the upper curve - optical branch.
- The character of the acoustic branch is similar to that of the monoatomic case while the optical branch is essentially flat throughout the k-space.
- Frequency gap between the two branches and thus this lattice act as the band pass filter

- **Phonon** - the quantum of lattice vibration. Energy ħω; momentum ħk
- Optical phonon are quantized modes of lattice vibrations when two or more charged particles in a primitive cell move in opposite directions with the center of mass at rest. This mode has highest energy for wavelength infinity or k=0, when the two lattices move in opposing direction of each other. It turns out that the large wavelength (small k i.e. wavenumber) optical phonons have energies similar to infrared radiation, so they can absorb light. I.e. light can excite optical phonons.
- Acoustic phonons are a type of phonon, representing the collective, in-phase motion of atoms in a crystal lattice, and correspond to sound waves in the material. They have low frequencies and are responsible for heat conduction in solids.

- All elastic waves can be described by wave vectors that lie within the first Brillouin zone in reciprocal space.

- When a phonon of wave vector & is created by inelastic scattering of a photon or neutron from wave vector & to k, the wave vector selection rule that governs the process is k = k' + K + G
  Where G is a reciprocal lattice
- If there are p atoms in the primitive cell, the phonon dispersion relation will have 3 acoustical phonon branches and optical phonon branches 3p – 3.

Lattice heat capacity

- The atoms in the lattice are arranged like a harmonic oscillators and their energy as the average energy of these oscillations.
- **According to Classical theory**, the average energy for one dimensional oscillator is kT, total thermal energy per mole 3NkT and the molar specific heat is given by

$$C_v = \frac{\partial U}{\partial T} = 3Nk = 3R$$

  This result is known as **Dulong and Petit's law** and asserts that C_v is constant and independent of temperature. However, this law found to be valid only at high temperature. At low temperature, the specific heat decreases and then vanishes at T = 0 K [1].

- **Einstein** rectified the discrepancy by treating the independent atomic oscillator quantum mechanically. The average thermal energy for the oscillator is given by

$$\bar{\varepsilon} = \frac{\hbar\omega}{e^{\hbar\omega/kT} - 1}$$ Which approaches to the classical value kT only at high temperature.
- At low temperatures, the quantum mechanical energy decreases rapidly because of freezing motion.
- Treating the atoms as independent oscillators vibrating with common frequency, Einstein found that the specific heat is [5]

$$C_v = 3R\left(\frac{\theta_E}{T}\right)^2 \frac{e^{\theta_E/T}}{\left(e^{\theta_E/T} - 1\right)^2}$$

  Specific heat approaches classical value 3R at high temperatures vanishes at T→0 K.

- Careful measurement show that the decrease in C_v near absolute zero is slower than by Einstein. **Debye** explained this by treating the atoms not as independent oscillators but as **coupled oscillators** vibrating collectively as sound waves.
- Making the long wavelength approximation, the specific heat is given by:

$$C_v = 9R\left(\frac{T}{\theta_D}\right)^2 \int_0^{\theta_D/T} \frac{x^3 e^x}{\left(e^x - 1\right)^2} dx$$ Where $x = \hbar\omega/k_B T$

  At high temperature $C_v \sim 3R$ (Dulong and Petit's law)
  At lower temperature $C_v \sim T^3$ (Debye T^3 law)

Free electron theory [4]

- A solid metal is composed of atoms and the atoms have nucleus, around which there are revolving electrons. In a metal the valance electrons of atoms are free to move throughout the volume of the metal like gas molecules of a perfect gas in a container.
- In solids, electrons in outer most orbits of atoms determine its electrical properties. Electron theory is applicable to all solids, both metals and non-metals. In addition, it explains the electrical, thermal and magnetic properties of solids. The structure and properties of solids are explained employing their electronic structure by the electron theory of solids. It has been developed in three main stages.

  (i) Classical free electron theory: The first theory was developed by Drude and Lorentz in 1900. According to this theory, metal contains free electrons which are responsible for the electrical conductivity and electrons obey the laws of classical mechanics.

  Failure of classical free electron theory:

  1. The phenomena such as photo electric effect, Compton Effect and black body radiation could not be explained by classical free electron theory.

  2. According to classical theory the value of specific heat of metals is given by 4.5R (R =Universal gas constant) where as the experimental value is nearly 3R (Dulang Petit law)

  3. Electrical conductivity of semiconductor or insulator could not be explained by using this model.

  4. According to classical free electron model ($K/\sigma T$) is constant. (Widemann-franz law) as this not constant at low temperature

  5. Ferromagnetism could not be explained by this theory.

  (ii). Quantum Free Electron Theory: In 1928 Sommerfeld applied quantum mechanics to explain conductivity phenomenon in metals. He has improved the Drude-Lorentz theory by quantizing the free electron energy and retaining the classical concept of force motion of electrons at random.

  1. The electrons are free to move within the metal like gaseous molecules. They are confined to the metal due to surface potential.

  2. The velocities of electrons obey Fermi-Dirac distribution because electrons are spin – half particles.

  3. The electrons would go into different energy levels and obey Pauli's exclusion principle.

  5. The electrons cannot have all energies but will have discrete energies according to the equation $E = \frac{n^2h^2}{8mL^2}$ where L is the dimension of the metals.

  However, this theory fails to explain the metallic properties exhibited by certain crystals. This theory also fails to distinguish between metal, semiconductor and Insulator. It also unable to explain the positive value of Hall coefficient.

(iii) Band Theory: Bloch introduced the band theory in 1928. According to this theory, free electrons move in a periodic potential provided by the lattice. It gives complete informational study of electrons.

- This theory is based on wave nature of electrons.
- Electrons exhibit wave character as they move between atoms in a solid.
- It is also assumed that potential varies in a periodic manner in the solid. Electrons move in a periodic potential provided by lattice.
- This theory successfully explained the classification of solids into three groups such as conductors, insulators and semiconductors.

KRONIG-PENNEY MODEL:

The free electrons in a metal move under a periodic potential due to regularly arranged positive ions. The nature of the energies of the electron is determined by solving Schrödinger wave equation. For simplicity, the periodic potential is taken in the form of regular one dimensional array of square well potentials [5].

Formation of bands in solids

A single isolated atom has discrete energy levels.

- When two identical atoms are considered to be far apart, the electron energy levels in an individual atom are not affected by the presence of the other.
- As long as the atoms are widely separated, they have identical energy levels; electrons fill the levels in each atom independently.
- But when the atoms are brought closer, they begin to interact strongly and as a result, each isolated energy level will be transformed into two energy levels of similar energies.

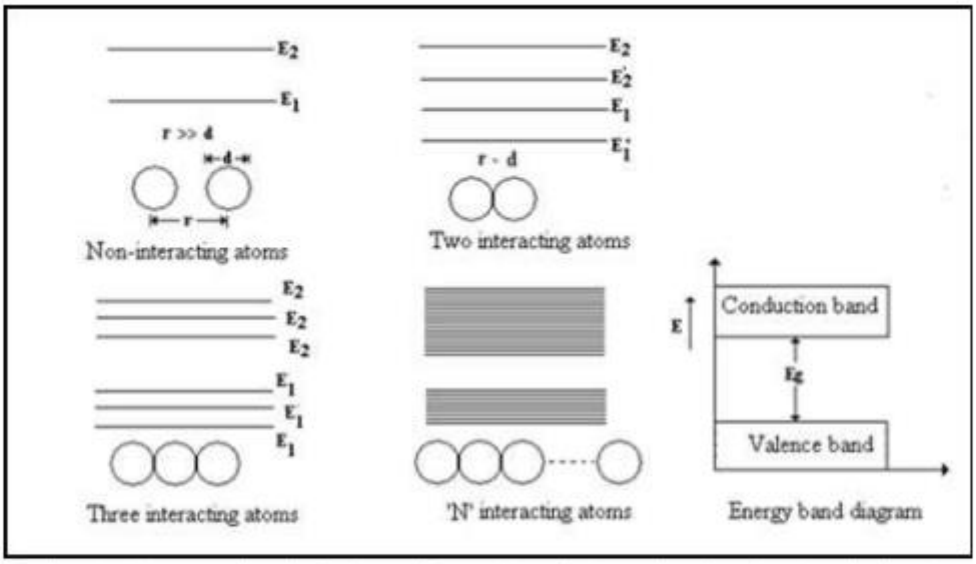


Fig. 4.5 Energy level splitting and formation of valence band and conduction band

- A single isolated atom has discrete energy levels.
- When two identical atoms are considered to be far apart, the electron energy levels in an individual atom are not affected by the presence of the other.

- As long as the atoms are widely separated, they have identical energy levels; electrons fill the levels in each atom independently.
- But when the atoms are brought closer, they begin to interact strongly and as a result, each isolated energy level will be transformed into two energy levels of similar energies.
- Therefore, when atoms are brought together to form a solid, their energy levels split up and form a group of closely spaced allowed energy levels of same energy value. This group of closely spaced energy levels of same energy is called Energy band.

CLASSIFICATION OF SOLIDS BASED ON BAND THEORY

• Solids can be classified into conductors, semiconductors or insulators depending upon width of Energy gap.

• Completely filled bands contain large number of electrons but do not contribute to the conductivity of the material.

• Partially filled bands are necessary for electrical conduction.

• The energy band diagram of conductors, semiconductors or insulators is shown in figure 1.5.

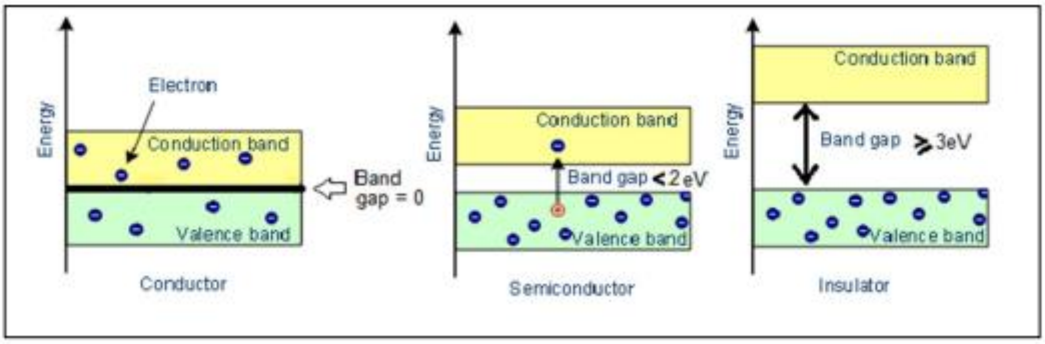


Fig. 4.6 Energy band diagram of Conductor, Semiconductor and Insulator

Conductors:

• The solids in which conduction and valence band overlap each other are called conductors. Therefore, the energy gap between valence band and conduction band is zero.

• Electrons can easily jump from lower energy band to higher one and become available for conduction.

• An application of a small amount of voltage leads to generation of large amount of current. Hence these solids are good electrical conductors. For e.g., Lithium, Beryllium and sodium.

Semiconductors:

• The solids in which the conduction and valence bands are separated by a small energy gap of less than 2eV are called semiconductors. For e.g. Semiconductors like Silicon has Bandgap of 1.12 eV and Germanium has bandgap of 0.72 eV.

• A small energy gap means that a small amount of energy is required to free the electrons and move them from the valence band to the conduction band.

Insulators:

• The solids in which the conduction band and valence bands are separated by a large energy gap of ≥ 3 eV are called insulators.

• At room temperature, the valence electrons do not have enough energy to jump into the conduction band, therefore insulator do not conduct current. Thus, insulators have very high resistivity and extremely low conductivity at room temperatures. For e.g. Diamond and glass.

FERMI DIRAC DISTRIBUTION FUNCTION F(E)

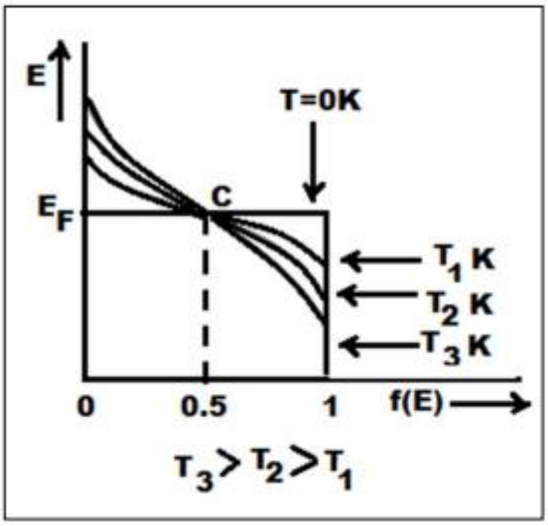


Fig.4.7 Fermi function **with variation of temperature [5]**

- Fermi Dirac distribution function gives the probability that any energy level 'E' at given temperature T is occupied or not.

$$f(E) = \frac{1}{1 + \exp\left[\frac{(E-E_F)}{kT}\right]}$$

- This expression governs the distribution of electrons among the energy levels as a function of temperature.
  E – Energy level for which occupancy is to be determined.
  E_F – Fermi level.
  k – Boltzmann constant.
  T – Temperature at which occupancy is to be determined.
- When f (E) = 0; it indicates that energy level E is completely empty.
- When f (E) = 1; it indicates that energy level E is completely filled.

CONCEPT OF EFFECTIVE MASS

- Experimentally it is observed that mass of electrons in some solids are less and, in some solids, larger than the mass of free electron.

- The experimentally determined electron mass in solids is called effective mass.
- It is denoted by m*.
- Change in the mass of electron in solids is due to interaction between atoms of solids and drifting of electrons.

- Expression of effective mass, $m^* = \frac{\hbar^2}{\frac{d^2E}{dK^2}}$

- Special cases:

  (1). If $\frac{d^2E}{dK^2}$ is positive then the effective mass is positive

  (2) If $\frac{d^2E}{dK^2}$ is negative then the effective mass is negative.

  (3) If $\frac{d^2E}{dK^2}$ =0 then the effective mass becomes ∞

Concept of hole

- When a small amount of external energy is applied to a semiconductor, the electrons in a valence band move to the conduction band leaving a vacancy behind in the valence band. This vacancy is called as hole.
- The electric charge of hole is same as that of electron but has opposite polarity.
- When a covalent bond somewhere in the solid breaks, this vacancy gets filled by electron and a hole is created at another place.
- In this way, position of vacancy changes within the crystal.
- In other words, the 'hole' moves from one place to other within the crystal lattice.
- The movement of hole causes electrical current.
- The current in a semiconductor is due to movement of electrons in conduction band and holes in valence bands.

Hall Effect: The principle of the Hall Effect states that when a current-carrying conductor or a semiconductor is introduced to a perpendicular magnetic field, a voltage can be measured at the right angle to the current path. This effect of obtaining a measurable voltage is known as the Hall Effect.

- The Hall coefficient R_H is mathematically expressed as

$$R_H = \frac{E_H}{jB}$$

  Where E_H is the Hall electric field, which is the electric field perpendicular to the current density and the magnetic field strength.
  j is the current density, which is the current per unit area of cross-section of the conductor.
  B is the magnetic field strength

- The Hall coefficient is positive for semiconductors with majority hole carriers, and negative for semiconductors with majority electron carriers.

- It can help us in determining the sign of the current carriers in metals and semiconductors.
- Using the principles of the Hall Effect, we can investigate whether the conductivity of the material is due to the motion of electrons (it is negative) or due to holes (it is positive).
- It helps in the determination of Hall Voltage, Hall current, Hall coefficient, hall angle, etc.
- It helps us in the measurements of the strength of magnetic field [3].

Multiple Choice Questions and Answers

1. The upper branch of frequency range in 1D diatomic lattice called
(a) Optical branch
(b) Acoustical branch
(c) Either acoustical or optical branch
(d) None of these
Ans. (a) Optical branch

2. In lattice atoms are connected by:
a) elastic spring
b) Inelastic spring
c) spring of constant length
d) None of these
Ans. a) elastic spring

3. The angular frequency (ω) for elastic wave propagating in monoatomic linear lattice is

a) $\omega = \pm\sqrt{\frac{4f}{m}}\sin\left(\frac{ka}{2}\right)$

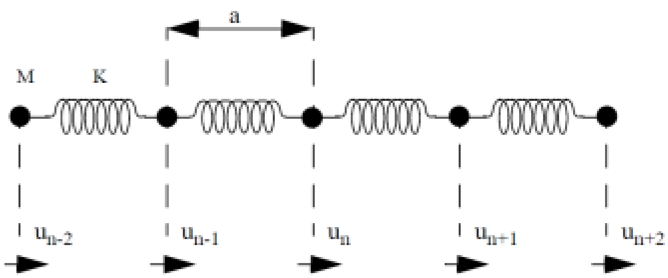
b) $\omega = \sin\left(\frac{ka}{2}\right)$

c) $\omega = \cos\left(\frac{ka}{2}\right)$

d) $\omega = \pm\sqrt{\frac{m}{4f}}\sin\left(\frac{ka}{2}\right)$

Ans. a) $\omega = \pm\sqrt{\frac{4f}{m}}\sin\left(\frac{ka}{2}\right)$

4. Consider the 1-dimensional linear chain in the figure below with N atoms in the chain. How many vibrational branches will be in the dispersion relation (k)?



a) 1 branch
b) 3 branch
c) 3N branch
d) 3N-3 branch
Ans. a) 1 branch

5. Consider a one-dimensional solid with a lattice spacing of 0.32 nm. What is the value for the wave vector *k* at the zone boundary of the first Brillouin zone?
a) 8.17 nm^{-1}
b) 9.82 nm^{-1}
c) 10.43 nm^{-1}
d) 21.63 nm^{-1}
Ans. b) 9.82 nm^{-1}

6. Which statement is correct? Phonons are:
a) Bosons
b) Fermions
c) Anions
d) they can be both Fermions or Bosons depending on the nuclear spina
Ans. a) Bosons

7. A phonon is emitted or absorbed in
a) Inelastic scattering of a photon by a crystal
b) Elastic scattering of a photon by a crystal
c) Both the elastic and inelastic scattering of a photon by a crystal
d) None of these
Ans. a) Inelastic scattering of a photon by a crystal

8. The knowledge of lattice vibrations is useful for providing information about
a) thermal conductivity
b) specific heat
c) thermal expansion
d) All of these
Ans. b) specific heat

9. For a linear diatomic chain, the long wavelength satisfy the condition:
a) k→0

b) Phase velocity $\upsilon_p \to \infty$
c) Group velocity $\upsilon_{g \to 0}$
d) All of these
Ans. d) All of these

10. In optical branch:
a) two consecutive atoms displace in same direction
b) two consecutive atoms displace in opposite direction
c) all the particles at rest
d) None of these
Ans. b) two consecutive atoms displace in opposite direction

11. Electronic contribution of specific heat of metal at low temperature is
a) A linear function of T
b) Zero
c) An exponential function of T
d) None of these
Ans. a) A linear function of T

12. According to Free electron theory Sommerfeld's model, the energy can have discrete values given by-
a) $E = \frac{n^2 h^2}{8mL^2}$
b) $E = \frac{mh^2}{8nL^2}$
c) $E = \frac{Lh^2}{8mn}$
d) $E = \frac{8n^2 h^2}{mL^2}$
Ans. a) $E = \frac{n^2 h^2}{8mL^2}$

13. The Fermi energy (E_f) of metal at 0K related to number density (n) of electron as
a) $n^{1/3}$
b) $n^{3/2}$
c) $n^{2/3}$
d) n^2
Ans. c) $n^{2/3}$

14. If the Fermi energy of a metal is 1.4 eV, the Fermi temperature of the metal is approximately:
a) 1.6×10^3 K
b) 1.6×10^4 K

c) 1.6×10^5 K
d) 1.6×10^6 K
Hint: Use formula $E_f = K_B T_f$, Where $K_B = 1.38 \times 10^{-23}$ J/K
Ans. b) 1.6×10^4 K

15. Einstein's theory concludes that at lower temperature the specific heat:
a) drops linearly with increase of temperature
b) drops linearly with decrease of temperature
c) drops exponentially with decrease of temperature
d) remains constant
Ans. c) drops exponentially with decrease of temperature

16. At lower temperature the lattice specific heat varies as
a) T
b) T^2
c) T^3
d) 1/T
Ans. c) T^3

17. Dulong and Petit's law obeys at room temperature for many metals while it fails for light elements such as boron beryllium because:
a) The Debye's temperature of these elements is very high
b) Their Debye's temperature is about 300K
c) The Debye's temperature of these element is low
d) None of these
Ans. a) The Debye's temperature of these elements is very high

18. The form of the graph between energy E and wave vector k for an electron in periodic lattice is:
a) Linear
b) Parabolic
c) Linear at lower k value and parabolic at higher k value.
d) Parabolic at lower k value and linear at higher k value.
Ans. b) Parabolic

19. The Fermi level of an intrinsic semiconductor lies near the middle of the forbidden gap but for an n-type semiconductor it is nearer the:
a) Conduction band
b) Valence band
c) Middle of the energy gap
d) Merges with the conduction band
Ans. a) Conduction band

20. A ferromagnetic material has a Curie temperature 100 K. Then

a) its suscebtibility is doubled when it is cooled from 300K to 200K.
b) All the atomic magnets in it get oriented in the same direction above 100K
c) The plot of inverse susceptibility versus temperature is linear with a slope T_c
d) The plot of its susceptibility versus temperature is linear with an intercept T_c
Ans. a) its suscebtibility is doubled when it is cooled from 300K to 200K.

21. The crystal structure is NOT studied through the diffraction of:
a) electron
b) proton
c) neutron
d) X-rays
Ans. b) proton

22. The ratio of the thermal to the electrical conductivity is constant for all metals at the same temperature and this ratio is proportional to the absolute temperature.
a) Meissener effect
b) Weissman-Franz law
c) Mathiessen rule
d) Curie law
Ans. b) Weissman-Franz law

23. The energy of a spin wave is quantized and the unit of energy is called a:
a) Phonon
b) Magnon
c) Polaron
d) Exciton
Ans. d) Phonon

24. In a non-dispersive medium, the angular frequency ω and wave vector k are related to the wave velocity υ as
a) $\omega = \upsilon k$
b) $\omega = \frac{\upsilon}{k}$
c) $\omega = \frac{2\upsilon}{a}\sin(\frac{ka}{2})$
d) $\omega = \frac{\upsilon}{a}$
Ans. a) $\omega = \upsilon k$

25. The quanta of energy in elastic wave is called a :
a) Photon
b) Phonon
c) Hyperon

d) Nucleon
Ans. b) Phonon|

26. The energy of a phonon is
a) $\hbar\omega$
b) $\hbar k$
c) $\hbar\nu$
d) Infinite
Ans. a) $\hbar\omega$

27. k values lies in the region $-\pi/a<k<\pi/a$ is known as [5]
(a) First Brillouin zone
(b) Second Brillouin zone
(c) Third Brillouin zone
(d) Fourth Brillouin zone
Ans. (a) First Brillouin zone

28. The specific heat at constant volume (C_v) for metals varies with temperature as
(a) $a + bT^3$
(b) $a + bT$
(c) $aT + bT^2$
(d) $aT + bT^3$
Ans. (d) $aT + bT^3$

29. Madelung constant depends upon
(a) Nature of bond
(b) Lattice type
(c) Crystal structure
(d) Type of ions
Ans. (c) Crystal structure

30. According to Classical theory, specific heat of solids fails to explain at
(a) High temperature
(b) Low temperature
(c) Both at low and high temperature
(d) None of these
Ans. (b) Low temperature

31. According to Einstein theory of specific heat, solids consists of atoms as [2]
(a) quantum oscillators vibrate with same natural frequency
(b) quantum oscillators vibrate with different natural frequency
(c) classical oscillators vibrate with same natural frequency
(d) None of these

Ans. (a) quantum oscillators vibrate with same natural frequency

32. According to Debye theory of specific heat, the specific heat at low temperature varies as
(a) T^2
(b) T^3
(c) $e^{-a/T}$
(d) $(a/T)^2$
Ans. (b) T^3

33. In Hall effect, if $R_H = -\frac{1}{ne}$, it represents charge carrier is
(a) Holes
(b) Electrons
(c) R_H does not explain type of charge carrier
(d) None of these
Ans. (b) Electrons

34 By using the Hall effect in semiconductor material, we can find [4]
(a) Carrier concentration
(b) Mobility of charge carriers
(c) Type of semiconductor (n or p type)
(d) All of these
Ans. (d) All of these

35. If the electron concentration in an n-type semiconductor material is 10^{16} cm^{-3} then Hall coefficient (in unit m^3 per coulomb) is
(a) 6.25×10^{-4}
(b) -6.25×10^{-4}
(c) 6.25×10^{-2}
(d) -6.25×10^{-2}
Ans. (b) -6.25×10^{-4}

36. According to Bloch theorem, the Bloch function $\Psi(x)$ can be written as product of
(a) e^{ikx} and $u_k(x)$
(b) $\sin(kx)$ and $u_k(x)$
(c) e^{-ikx} and $u_k(x)$
(d) $\cos(kx)$ and $u_k(x)$
Ans. (a) e^{ikx} and $u_k(x)$

37. Which one of the following is semiconductor material?
(a) Silicon
(b) Diamond
(c) Sodium
(d) All of these
Ans. (a) Silicon

38. An electron is moving under influence of uniform potential, its effective mass is equal to
(a) zero
(b) negative
(c) infinite
(d) its rest mass
Ans. (d) its rest mass

39. According to Debye's model, a system of coupled harmonic oscillators have:
a) single frequency
b) range of frequency
c) zero frequency
d) None of these
Ans. b) range of frequency

40. According to Dulong and Petit's law, the average energy of an atom of a solid at temperature T is
a) (1/2)kT
b) kT
c) 2kT
d) 3kT
Ans. b) kT

41. A crystal lattice behaves like an elastic continuum for the wave propagation. It refers to
a) Debye theory of specific heat
b) Einstein theory of specific heat
c) Dulong and Petit's law
d) None of these
Ans. a) Debye theory of specific heat

42. A dispersion relation links angular frequency ω with
a) wavelength
b) velocity
c) refractive index
d) wave number
Ans. d) wave number

43. In a debye model for a 3D crystal the internal energy U at low temperature is given by
a) $U \propto T$
b) $U \propto T^2$
c) $U \propto T^3$
d) $U \propto T^4$
Ans. d) $U \propto T^4$

44. Phonons are quantized form of ________motion. [3]
a) Rotatory
b) Linear
c) Oscillatory
d) None of these
Ans. c) Oscillatory

45. If the velocity of a moving wave is not dependent on the frequency, the solid is known as
a) Crystalline
b) Non-crystalline
c) Dispersive
d) Non dispersive
Ans. d) Non dispersive

46. The particles responsible for the interaction of solids with light because they have higher frequencies are called
a) Photon
b) Phonon
c) Acoustical phonon
d) Optical phonon
Ans. d) Optical phonon

47. Monoatomic linear lattice works as
a) low pass filter
b) high pass filter
c) both (a) and (b)
d) None of these
Ans. a) low pass filter

48. The potential energy of free electron in metal is
a) constant
b) periodic
c) sine curve
d) none of these
Ans. a) constant

49. The fermi energy of metals depends on
a) number of free electrons in metals
b) density of free electrons
c) shape of metal
d) volume of metal
Ans. b) density of free electrons

50. Kronig-Penny model gives motion of electron in [5]
a) periodic potential
b) regular potential well
c) both (a) and (b)
d) None of these
Ans. a) periodic potential

Unit - V

Unit V
(Nuclear Forces & Radioactive Decays)

Summary

According to proton-neutron theory of nuclear constitution: [1]

- The number of protons give the atomic number Z.
- The number of protons and neutrons together gives atomic mass numbers A.
- The number of neutron is A-Z.
- The n/p ratio increases with increases mass number of atoms in order to ensure nuclear stability.
- The nuclei have different shape, some are spherical while others are distorted. Radius of different nuclei is different. From experiments, it has been found that

  Volume of the nucleus $\propto$ mass number

  $$\frac{4}{3}\pi R^3 \propto A$$

  $$R \propto A^{1/3}$$

  $$R = R_0 A^{1/3},$$

  where R_0 is constant whose values varies from 1.2 to 1.4 $\times 10^{-15}$ m
- **Nuclear density** is constant for all nuclei and is same throughout the nucleus except near the surface.

  Nuclear density = Mass/Volume

  $$= \frac{A \times 1.6 \times 10^{-27}}{\frac{4}{3}\pi R_0^{\,3} A}$$

  $$= 2.4 \times 10^{17}\, kg/m^3$$

  This clearly shows that the nuclear density is very high and independent of the atomic mass number.
- **Nuclear spin or the angular momentum of nuclei:** Pauli suggested that just like the electrons, nuclei of atoms also possess the orbital and spin angular momentum. Thus likewise spin and orbital magnetic moment associated with them. The interaction between them give rise to the splitting of the energy level known as hyperfine structure. The nuclear spin of nuclei is given by

  $$\left|\vec{I}\right| = \sqrt{I(I+1)}\hbar$$ Where I is half integral for nuclei with odd mass number and integeral value for even mass number nuclei. If both Z and A are even the value of I is zero.
- **The nuclear magnetic moment** is given by-

  $$\mu_I = g\frac{e\hbar}{2M_p} = g\mu_n$$

  Whereas the magnetic moment of electron is $\frac{e\hbar}{2m_e} = 9.27 \times 10^{-27}\, Amp.m^2$

The nuclear magneton, $\mu_n = \dfrac{e\hbar}{2m_p} = 4.63\times10^{-27}\,Amp.m^2$ [7]

Thus nuclear magnetic moment less than electron magnetic moment.

- The experimental evidence suggest that nuclei do not possess electric dipole moment but the **electric quadrupole moment** have been observed in some nuclei. It is a measure of the departure of nucleus from spherical symmetry. Electrical quadrupole moment may be either positive or negative.

Mass defect, Binding energy and Packing fraction

- The difference between the mass of the nucleus and the sum of the mass of the constituent particles is termed as the **mass defect** (Δm).

$$\Delta m = (M - A)$$

Where M is the measured mass and the mass no. of atom.

- **Binding energy** of nucleus is defined as the energy required to decompose a nucleus into its constituent particles.

$$B.E. = \Delta E = (\Delta m)c^2$$
$$= 931\times\Delta m\ \text{MeV}$$

- The binding energy per nucleon is

$$\frac{\Delta E}{A} = 931\times\frac{\Delta m}{A}\,MeV$$

The other expression for true mass defect and binding energy is given by

$$\Delta m = ZM_H + (A-Z)M_n - M$$

Where M_H = Mass of one hydrogen atom, M_n = Mass of one neutron

$$\Delta E = 931[ZM_H + (A-Z)M_n - M]MeV$$

If the binding energy per nucleon ($\dfrac{\Delta E}{A}$) is plotted against A, we get a B.E. curve shown in Fig. 5.1.

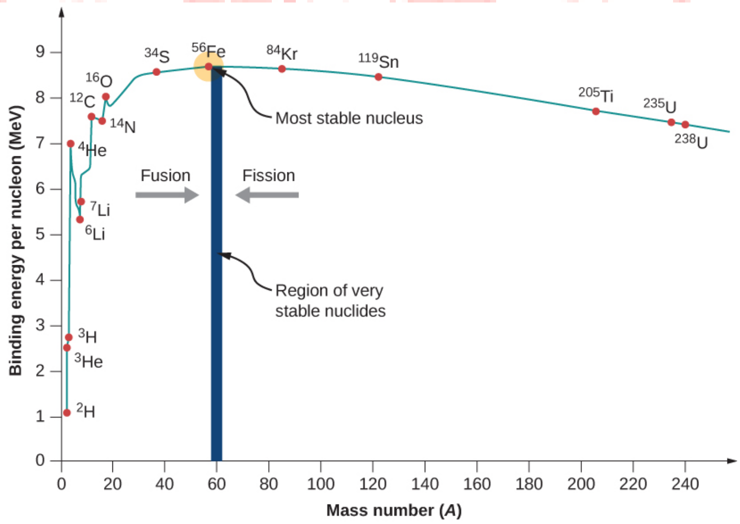


Fig. 5.1 Binding energy curve [6]

- ΔE is almost constant between A=30 and A=100 and decreases both for smaller and larger values of A.

- The decrease in ΔE for large A is due to the coulomb repulsion between the protons. This makes the nuclei less stable.
- In light nuclei, the individual nucleons are attracted by only a few other nucleons and hence their distances of separations are largers. This again reduces the stability and the decrease of binding energy for small A is a surface effect.
- Nuclides with an even number of neutrons and protons have higher binding energies than the neighbouring odd mass nuclides.

Packing fraction: The divergence of the masses of the nuclide from whole number can be expressed in terms of packing fraction is given by

$$P = \frac{M - A}{A} = \frac{\Delta m}{A}$$

Nuclear Force

Existance of long range coulomb force between the protons inside the nucleus, there also exist short range attractive nuclear forces which keep various nucleons bound together in a nucleus. These forces are considered to arise from continuous and rapid jumping back and forth pions between the two nucleons.

- Properties of Nuclear Forces: These are
  1. strong atrractive forces.
  2. short range forces.
  3. charge independent.
  4. non-central forces.
  5. saturated forces.
  6. About 10^{33} times greater than electromagnetic forces and 10^{35} times as the gravitational force between the two nucleus.
- By comparing the nuclear size with the debroglie wavelength of nucleon of energy about 10 MeV, we find that both are of almost same order and hence quantum mechanical consideration are relevant to the study of nuclei.

The Deuteron:

The deuteron consists of a neuteron and a proton. It possess some measurable properties whch accounts the nature of nuclear interaction.

These properties-

- The reduced mass of the system is

$$\mu = \frac{m_n m_p}{m_n + m_p} = \frac{m}{2} \quad (m = \text{average mass of nucleon})$$

- Binding energy is small 2.25 MeV which is loosely bound.
- Angular momentum or nuclear spin in ground state is 1. Spins are parallel.
- Parity is even.
- The magnetic dipole moment is 0.85735 nuclear magneton.
- The quadrupole moment 0.00282 barn which shows it is not a purely spherically symmetric state.

- The force between neutron and proton is nuclear, attractive and along the line joining the two particles.
- Deuteron doesnot possess any excited state.
- The explanation of the nuclear forces can be made by Meson theory.

Radioactivity:

The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called radioactivity.

- Radioactive radiations consists of α-rays, β-rays and γ-rays.
- The two laws of radioactive disintegration are:
  1. Atoms of all radioactive elements undergo spontaneous disintegration to form fresh radioactive products with the emission of α-rays, β-rays and γ-rays.
  2. The rate of radioactive disintegration is not affected by environmental factors but depends on the number of the atoms of the original kind at any time.
- The radioactive decay is given by

$$N = N_0 e^{-\lambda t}$$

  The decay constant λ may be defined as the reciprocal of the time during which the number of atoms of a radioactive substance falls to 37 percent of its original value.
- Half-life (T) of a radioactive element is equal to the time during which a given amount of that element is reduced by disintegration to half its initial amount.

$$T = \frac{0.693}{\lambda}$$

- The average life expectancy of radioactive atoms is equal to the reciprocal of the decay constant.

$$T_{avg} = \frac{1}{\lambda} = \frac{T}{0.693} = 1.44T$$

- The rate of disintegration or activity of radioactive material is given by:

$$\frac{dN}{dt} = -\lambda t$$

- **Unit of Radioactivity:** Curie (c) is the unit of activity i.e., rate of disintegration. 1 curie = 3.7×10^{10} disintegrations per second. Rutherford (rd) is also the unit of activity and is equal to 10^6 disintegration per second.
- To determine the age of the rocks, earth and history of planets and the solar system by radioactivity is called the **radioactive dating** [2]

Artificial Radioactivity:

- It was discovered by Curie-Joliots when they bombarded aluminium with α-partcles from polonium.
- Radioisotopes have used as
  (i) tracer elements.
  (ii) diagnosis of diseases.
  (iii) research and industry.
  (iv) dating purposes in geology.

Multiple Choice Questions and Answer

1. The density of the nucleus is of the order of
a) 10^6 Kg/m^3
b) 10^{17} Kg/m^3
c) 10^{24} Kg/m^3
d) 10^3 Kg/m^3
Ans. b) 10^{17} Kg/m^3

2. The radius of nucleus depends on mass number (A) as
a) A
b) $A^{2/3}$
c) $A^{1/3}$
d) $A^{-1/3}$
Ans. c) $A^{1/3}$

3. In the formula, $R = R_0A^{1/3}$ the value of R_0 is
a) 1.2 to 1.4 Fermi
b) 1.2 to 1.4 Angstorm
c) 1.2 to 1.4 nm
d) 1.2 to 1.4 m
Ans. a) 1.2 to 1.4 Fermi

4. Which of the following is correct about the nucleus?
a) Chadwick discovered the existence of neutrons inside the nucleus
b) Density of all the nuclei is independent of the mass number
c) Radius of the nuclei depends on the mass number (A)
d) All of these are correct
Ans. d) All of these are correct

5. Hyperfine structure of atomic lines due to [1]
a) Coupling between the spin and orbital angular momentum of atomic electrons
b) Coupling between the spin and orbital angular momentum of atomic nuclei
c) Coupling between spin of nuclei with the orbital angular momentum of atomic electrons
d) None of these
Ans. b) Coupling between the spin and orbital angular momentum of atomic nuclei

6. If nuclear radius of $_8O^{16}$ is 3 Fermi. What is the nuclear radius of $_{52}Te^{128}$?
a) 12 Fermi
b) 6 Fermi
c) 0.6 Fermi
d) 1.2 Fermi
Ans. b) 6 Fermi

7. The quantity describe the departure of nucleus from the spherical symmetry is
a) Electric dipole moment
b) Electric quadrupole moment
c) Magnetic moment
d) None of the above
Ans. b) Electric quadrupole moment.

8. The nuclear forces are
a) short range
b) long range
c) electromagnetic forces
d) None of these
Ans. a) short range

9. Nuclei obey Fermi-Dirac statistics having mass number (A)
a) Even
b) Zero
c) Odd
d) None of these
Ans. c) Odd

10. The neutrons and protons with in the nucleus are held together by
a) Strong attractive forces
b) Weak attractive forces
c) Electromagnetic forces
d) Gravitational force
Ans. a) Strong attractive forces

11. The binding energy of nucleus is a measure of its
a) momentum
b) charge
c) mass
d) Stability
Ans. d) Stability

12 The binding energy per nucleon is maximum for the nucleus
a) ^{56}Fe
b) ^{4}He
c) ^{208}Pb
d) ^{101}Mo
Ans. a) ^{56}Fe

13. The ratio of the sizes of $_{82}Pb^{208}$ and $_{12}Mg^{24}$ nuclei is approximately

a) 2
b) 4
c) 8
d) 16
Ans. a) 2

14. The volume of a nucleus in an atom is proportional to the
a) Mass number
b) Proton number
c) Neutron number
d) electron number
Ans. a) Mass number

15. Which of these statement is **NOT** correct with reference to nuclear forces. Nuclear forces are
a) short range
b) charge independent
c) spin independent
d) non-central
Ans. c) spin independent

16. A nuclide having atomic mass equal to its mass number (A). The value of packing fraction is
a)Positive
b)zero
c)negative
d) none of these
Ans. b) zero

17. Which of the following quantity is constant for all the nuclei.
a) size
b) volume
c) density
d) All of these
Ans. c) density

18. The binding energy per nucleon of nucleus A is greater than nucleus B. Then
a) A is more stable than B
b) B is more stable than A
c) Both are equally stable
d) Stability does not depends on binding energy
Ans. a) A is more stable than B

19. Deuteron consists of

a) one proton and one neutron
b) Two protons and one electron
c) Two neutrons and one positrons
d) None of these
Ans. a) one proton and one neutron

20. The order of magnitude of the binding energy per nucleon in a nucleus is
a) 10^{-5} MeV
b) 10 MeV
c) 0.1 MeV
d) 10 MeV
Ans. d) 10 MeV

21. “Nucleon” name used for
a) All light nuclei
b) Hydrogen nuclei only
c) both protons and neutrons
d) neutrons only
Ans. (c) both protons and neutrons

22. The Packing fraction is zero for the nuclei
a) O^{16}
b) C^{12}
c) C^{11}
d) N^{15}
Ans. b) C^{12}

23. India has the world largest reserve of which of the following radioactive metals?
a) Uranium
b) Radium
c) Thorium
d) Bismuth
Ans c) Thorium

24. The half-life of a radioactive substance depends on
a) temperature
b) pressure
c) nature of the substance
d) None of these
Ans. c) nature of the substance

25. The correct order of ionising power of radioactive rays:
a) $\alpha > \beta > \gamma$
b) $\alpha < \beta < \gamma$

c) $\alpha = \beta = \gamma$
d) $\alpha > \beta < \gamma$
Ans. a) $\alpha > \beta > \gamma$

26. The size of the nucleus is estimated to be of the order of
a) femtometer (10^{-15} m)
b) nanometer (10^{-9} m)
c) micrometer (10^{-6} m)
d) Angstorm (10^{-10} m)
Ans. a) femtometer (10^{-15} m)

27. Which one has the highest penetrating power?
a) β-rays
b) γ-rays
c) α-rays
d) All have same
Ans. b) γ-rays

28. A nucleus X emits an α particle followed by two β particles. The final nucleus will be
a) an Isotone of the original X
b) an isotope of the original X
c) an isobar of the original X
d) None of these
Ans. b) an isotope of the original X

29. Two radioactive substance X and Y have decay constant 10λ and λ respectively. If initially they have same number of nuclei, then the ratio of number of nuclei of X to that of Y will be $1/e^2$ after a time is
a) 2/9λ
b) 2/10λ
c) 1/11λ
d) 22/10λ
Ans. a) 2/9λ

30. Radioactivity is dependent on the law of conservation of
a) Energy
b) Charge
c) Angular momentum
d) Linear momentum
Ans. b) Charge

31. In equation

$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + X$; Where X is [2]

a) $^{1}_{0}n$

b) 3H

c) 3 $^{1}_{0}n$

d) None of these

Ans. c) 3 $^{1}_{0}n$

32. Which one is correct with respect to barn

(a) It is unit of area of cross section of nuclei

(b) One barn is equal to 10^{-28} m^2

(c) Both are correct

(d) None of these

Ans. (c) Both are correct

33. Which one of the following statement is correct?

(a) mass of the nucleus must be greater than the sum of the masses of the constituent neutrons and protons

(b) The mass of the nucleus must be equal to mass of the constituents nucleons.

(c) mass of the nucleus must be less than the sum of the mass of constituent nucleons

(d) None of these

Ans. (c) mass of the nucleus must be less than the sum of the mass of constituent nucleons

34. The atomic number is not changed by which type of radioactive decay?

a) β

b) γ

c) α

d) None of these

Ans. b) γ

35. According to the meson theory of nuclear forces

a) A neutron emits a (π^-) meson and converted into a proton

b) A neutron emits a (π^0) meson and converted into a proton

c) A neutron emits a (π^+) meson and converted into a proton

d) A neutron cannot be converted into a proton.

Ans. a) A neutron emits a (π^-) meson and converted into a proton

36. According to Yukawa theory, the nuclear forces between the nucleus act through the exchange of

a) μ-meson

b) positron

c) π-meson

d) α-particle

Ans. c) π-meson

37. "Nuclear forces are charge independent". This statement explains through
a) Mirror nuclei
b) Meson theory
c) Binding energy
d) None of these
Ans. a) Mirror nuclei

38. Which of the following are not Mirror nuclei?
a) $_1H^3$, $_2He^3$
b) $_5B^{11}$, $_6C^{11}$
c) $_3Li^7$, $_4Be^7$
d) $_6C^{13}$, $_7N^{14}$
Ans. d) $_6C^{13}$, $_7N^{14}$

39. In radioactive decay which of the following quantity depends on the number of atoms
a) Half life
b) Mean life
c) Rate of decay
d) Rate of decay and mean life
Ans. c) Rate of decay

40. The spontaneous emission of highly penetrating radiations from heavy elements is called
a) Radioactivity
b) Fluorescence
c) Photoluminescence
d) Laser
Ans. a) Radioactivity

41. Radioactivity was discovered by
a) Madame Curie
b) Rutherford
c) Becquerel
d) Roentgen
Ans c) Becquerel

42. Radioactivity is affected by change of
a) Temperature
b) Pressure
c) Electric and Magnetic field
d) None of these
Ans. d) None of these

43. Which of the following statement is/are correct ?
a) Radioactivity discovered by Henry Becquerel in 1896.
b) Radioactive radiation consists of α-rays, β-rays and γ-rays.
c) Radioactivity is unaffected by change of temperature and pressure.
d) All of these
Ans. d) All of these

44. A radioactive nuclei X having mass number A and atomic number Z disintegrates to Y with emitting an α particle and two β particle. The resulting nuclei Y has mass number and atomic number respectively.
a) A-4 and Z-2
b) A+4 and Z-2
c) A-4 and Z-1
d) A-4 and Z
Ans. d) A-4 and Z

45. Find out the number of α and β particles respectively when nuclei $_{92}U^{238}$ decay into final nuclei $_{82}Pb^{206}$.
a) 8, 6
b) 8, 8
c) 32, 12
d) 6, 8
Ans. a) 8, 6

46. Which one of the following radioactive rays behave as the nature of electromagnetic waves like photons.
a) α-rays
b) β-rays
c) γ-rays
d) None of these
Ans. c) γ-rays

47. The correct equation for the radioactive decay is
a) $N = N_0 e^{-\lambda t}$
b) $N = N_0 e^{\lambda t}$
c) $N = N_0 \lambda t$
d) $N = N_0 Sin(\lambda t)$
Ans. a) $N = N_0 e^{-\lambda t}$

48. The relation between half-life (T) and decay constant (λ) of a radioactive substance is
a) $T = \frac{\log_e 2}{\lambda}$

b) $T = \frac{\log_{10} 2}{\lambda}$

c) $T = \frac{\log_e 10}{\lambda}$

d) $T = \frac{\log_{10} e}{\lambda}$

Ans. a) $T = \frac{\log_e 2}{\lambda}$

49. Half-life of Radium is 1600 years. If the initial mass is 10 Kg, then find out the amount of radium left after 4800 years.
a) 5 Kg
b) 2.5 Kg
c) 1.25 Kg
d) zero
Ans. c) 1.25 Kg

50. If the mean life of the radioactive element is 50 days, then the half life of the element will be
a) 100 days
b) 72 days
c) 34.65 days
d) 50 days
Ans. c) 34.65 days

Hint: Use $T_{1/2} = \frac{\log_e 2}{\lambda}$ and $T_{avg} = \frac{1}{\lambda}$

Unit - VI

Unit VI
(Nuclear Models & Nuclear Reactions)

Summary

Nuclear Models

The results obtained from the study of two body system cannot be easily applied to the many body system. To account for the complex inter relationship between nucleons a number of nuclear models have been developed on the basis of which the nuclear properties are studied [9].

Liquid Drop Model:

- In this model, a nucleus resembles a liquid drop in many respects. The short range nuclear forces play the part of surface tension and keep the nucleus in a spherical shape. The electrostatic repulsive forces play the role of disruptive forces which tend to push the nucleon apart. The nuclear stability is determined by the balance of these two forces.
- It also explains the phenomena of artificial radioactivity and the nuclear fission. However, this model fails to explain the spin and magnetic moment of nuclei.

Nuclear Shell Model:

- This model considers the various nucleons to lead independent existence and move about in quantum shells just as do the extra nuclear electrons. Nuclear stability is due to complete and filled nuclear shells.
- This model predicts that the nucleons move nearly independently in a common static spherical potential that follows the nuclear density distribution. There are number of evidences that prove that the nuclei with either N or Z equal to one of the magic numbers (2, 8, 20, 28, 50, 82, 126) are stable likewise in the case of atoms shell having electrons 2, 8, 18… are most stable thus supporting this model.

Collective Model:

- The shell model has been successful in explaining a number of nuclear properties but it fails to explain.
    1. The large electric quadrupole moments and spherical shapes which many nuclei possess.
    2. The ground states of the odd nuclei in the range $150 \leq A \leq 190$ and at $A \geq 220$.
    3. The existence of large electric quadrupole moments for certain nuclei is a clear indication that the nuclear surface is no longer spherical but deformed.
- This model combines the best features of the liquid drop and the shell model.
- In this model the nucleus is regarded to be having a shell structure capable of performing rotational and vibrational motion as a whole. Therefore predict the fine structure of nuclear level spectrum.
- According to this model all even- even nuclei will have spherical shape and zero electric quadrupole moment, while the even odd, odd – even or odd-odd nuclei have non-spherical shapes and finite electric quadrupole moment [10].

SEMIEMPIRICAL (WEIZSACKER'S) MASS FORMULA:

- The semi-empirical (Bethe-Weizsacker) mass formula is a nuclear model that produces approximate values for the nuclear binding energy B(A,Z), as a function of the number of nucleons A and the number of protons Z.
- This model used to approximate the binding energy of an atomic nucleus, considering factors like volume, surface, Coulomb, asymmetry, and pairing terms.
- The general form of the SEMF for binding energy (B(Z, A)) is:

  $$B(Z, A) = a_v A - a_s A^{2/3} - a_c Z(Z-1)/A^{1/3} - a_a (A-2Z)^2/A + \delta(A,Z) \quad [1]$$

  Where:

  A = mass number (total number of nucleons)

  Z = atomic number (number of protons)

  a_v, a_s, a_c, a_a = empirical coefficients, representing the strength of the volume, surface, Coulomb, and asymmetry terms, respectively.

  $\delta(A,Z)$ = pairing term, which depends on whether the number of neutrons and protons are even or odd.

  Limitations:

- The SEMF provides a good approximation of binding energies, but it has limitations, such as failing to accurately predict the existence of "magic numbers" (specific numbers of protons or neutrons that lead to enhanced stability).
- It also doesn't capture the finer details of nuclear structure.

Stability: the N-Z curve

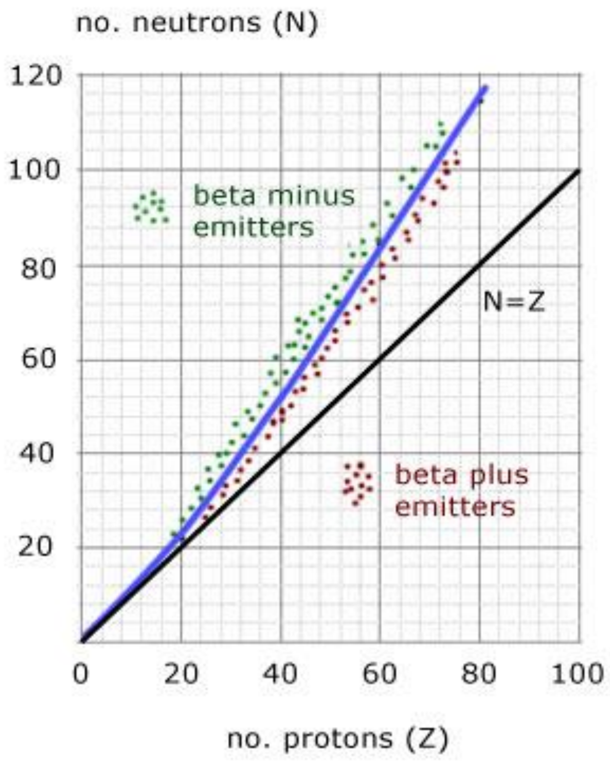


Fig.6.1 neutron-proton stability curve [10]

- The N-Z curve is a plot of the number of neutrons (N) against the number of protons(Z).
- For proton numbers (Z) up to 20, N=Z is a straight line.
- For all nuclei with Z>20, stable nuclei have more neutrons than protons, the line curves upwards.
- Unstable nuclei above the stability curve are called neutron-rich.
- Unstable nuclei below the stability curve are called neutron-poor.
- Regions:
  (i) the 'stability' line - a gentle curve starting from the origin and of increasing gradient
  (ii) beta minus (electron) particle emitters
  (iii) beta plus (positron) particle emitters
- Unstable neutron-rich nuclei can become more stable by losing neutrons. They do this by '**beta decay**'.
- Unstable neutron-poor nuclei can become more stable by gaining neutrons. They do this by '**positron decay**'.

Nuclear Reactions

The study of nuclear reactions involved the measurement of the following quantities:

(i) Intensity, energy and identity of the incident beam of particles.

(ii) The number of particles which are emitted from the target per unit time.

(iii) The energy and identity of the emitted particles and of the nucleus.

- The overall energy liberated or absorbed in a nuclear disintegration is called nuclear reaction energy Q.
- Those nuclear reactions in which energy is liberated or absorbed are called exothermic or endothermic. They have positive Q or negative Q value.
- In general a nuclear reaction may be expressed as

$$a + X \rightarrow Y + b$$

Where a is energetic incident particle, X is target nucleus, Y is residual nucleus and b is outgoing particle.

- In compact form the nuclear reaction may be expressed as

$$X\,(a, b)\,Y$$

Thus nuclear reaction is the process of strong interaction of an atomic nucleus with an elementary particle, resulting in the formation of a new nucleus and one or more new particles.

Nuclear Fission and Fusion:

- **Nuclear fusion** means fusing of two lighter nuclei into one stable and heavier nuclide. The energy released is called fusion energy and its value is nearly 6.7 MeV/nucleon.
- The division of a nuclide into two approximately equal parts when hit by neutron is called **nuclear fission**.
- The fission fragments are initially radioactive and ultimately become stable after emitting a few β particles.

Nuclear Cross-section (σ): [2]

- It gives an idea of the probability that bombarding particle will interact with the target nucleus. This probability may be visualised in terms of area presented by the nucleus to the incident particle.
- The magnitude of nuclear cross-section depends upon (i) kinetic energy and nature of incident particle and (ii) nature of target nucleus.
- The unit of nuclear reaction cross-section is barn. One barn = 10^{-28} m^2

Nuclear Reactor:

A nuclear reactor is a system in which a self-sustaining fission chain reaction occurs in a controlled manner.

- The nuclear reactor have been built for research, electricity generation, isotope production etc.
- It consists of the following parts:
  (i) Fuel: Fissionable material are U^{233}, U^{235}, Pu^{239}
  (ii) Moderator: slow down the fast neutrons produced in fission. Example Heavy water (D_2O) and carbon (graphite) are best choice.
  (iii) Reflector: Graphite is frequently used as reflector.
  (iv) Controller: control rods are made of cadmium or boron steel.
  (v) Coolant: Reactor generates a large amount of heat due to fission reactions. Coolant fluid have low neutron capture cross-section and large thermal capacity. Commonly used coolants are air, CO_2, light and heavy water and a liquid sodium/potassium alloy.
  (vi) Biological shield: Reactor core surrounded by reactor shield made of concrete with a high water content or concrete containing barium compound to stop γ-radiations.

<u>Multiple Choice Questions and Answers</u>

1. Which of the statement is not correct with reference to Liquid drop model
a) it consider a nucleus to be identical to a liquid drop
b) The short range nuclear force play like the surface tension in liquid drop and keep the nucleus in spherical shape.
c) The model explains the nuclear fission same way as liquid drop break into multiple droplets.
d) It also explain the spin and magnetic moments of nuclei.
Ans d) It also explain the spin and magnetic moments of nuclei.

2. According to the shell model of the nucleus, which of the following statement is correct?
a) nucleus interact with the nearest neighbours only
b) magic number nucleons are more stable.
c) large electronic quadrupole moment exist for certain nuclei.
d) All are correct.
Ans. b) magic number nucleons are more stable.

3. Which one is not a magic number?
a) 126

b) 82
c) 50
d) 58
Ans. d) 58

4. The contribution of coulomb energy in the semi-empirical mass formula of a nucleus of mass number (A) and atomic number (Z) is of the form:
a) $\frac{Z(Z-1)}{A^{1/3}}$
b) $\frac{Z(Z+1)}{A}$
c) $\frac{Z}{A^{2/3}}$
d) $ZA^{2/3}$
Ans. a) $\frac{Z(Z-1)}{A^{1/3}}$

5. The surface energy term appears in semi-empirical mass formula as a result of
a) intrinsic nuclear spin
b) exces no. of neutrons in the nucleus
c) repulsion between the protons in the nucleus
d) reduction of total binding energy due to nucleons on the surface of the nucleus
Ans. d) reduction of total binding energy due to nucleons on the surface of the nucleus

6. The asymmetry term in the semi-empirical mass formula is due to [10]
a) non-spherical shape of the nucleus
b) odd no. of protons inside the nucleus
c) non-zero spin of the nucleus
d) Unequal number of protons and neutrons in the nucleus
Ans. d) Unequal number of protons and neutrons in the nucleus

7. According to Collective model, which one of the following nuclei have spherical shape and zero electric quadrupole moment.
a) $_{20}Ca^{40}$
b) $_{7}N^{14}$
c) $_{6}C^{11}$
d) $_{3}Li^{7}$
Ans. a) $_{20}Ca^{40}$

8. The liquid drop model successfully explain
a) nucleus has spherical shape and uniform density
b) excited state of nuclei
c) spin

d) magnetic moment of nuclei
Ans. a) nucleus has spherical shape and uniform density

9. The liquid drop model was proposed by
a) Bohr
b) Rutherford
c) Thomson
d) Chadwick
Ans. a) Bohr

10. Which phenomenon is best explained by liquid drop model?
a) Nuclear fission
b) Nuclear fusion
c) Both (a) and (b)
d) None of these
Ans. a) Nuclear fission

11. The number can be explained in terms of the shell model of the nucleus:
a) Atomic number
b) Group number
c) Magic number
d) None of these
Ans. c) Magic number

12. Which of the following model also called independent particle model?
a) liquid drop model
b) Shell model
c) Fermi gas model
d) None of these
Ans. b) Shell model

13. The semiempirical formula for binding energy of nucleus contains a surface correction term. This term depends upon the mass number A of nucleus as:
a) $A^{1/3}$
b) $A^{-1/3}$
c) $A^{2/3}$
d) $A^{-2/3}$
Ans. c) $A^{2/3}$

14. The deviation of the charge distribution of a nucleus from spherical symmetry can be estimated by measuring its
a) electric charge
b) electric dipole moment
c) electric quadrupole moment
d) magnetic dipole moment

Ans. c) electric quadrupole moment

15. Q value is exactly a:
a) momentum
b) mass
c) energy
d) binding
Ans. c) energy

16. Nuclear model that best describe the coherent behaviour of all nucleons is
a) Liquid drop model
b) Shell model
c) Collective model
d) All of these
Ans. b) Collective model

17. In 1919 first artificial transmutation made by
a) Bohr
b) Chadwick
c) Rutherford
d) Newton
Ans. c) Rutherford

18. Which nuclear model is similar to atomic model?
a) Collective model
b) Liquid drop model
c) both (a) and (b)
d) Shell model
Ans. d) Shell model

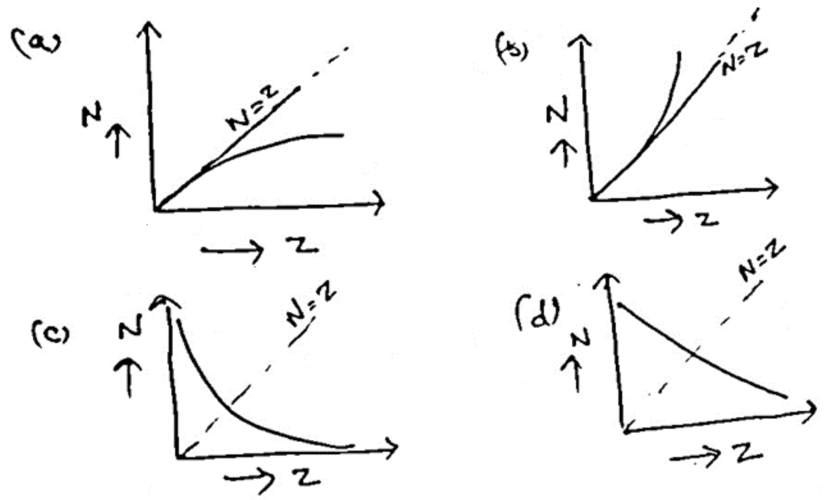
19. The light energy emitted by a star is due to
a) joining of nuclei
b) burning of nuclei
c) breaking of nuclei
d) reflection of solar light
Ans. a) joining of nuclei

20. The stable nucleus that has a radius half that of Fe^{56} is :
a) Ca^{40}
b) Na^{21}
c) S^{32}
d) Li^{7}
Ans. d) Li^{7}

21. Ne^{22} nucleus after absorbing energy, decays into two α-particles and an unknown nucleus. The unknown nucleus is

a) Nitrogen
b) Oxygen
c) Boron
d) Carbon
Ans. a) Nitrogen

22. The correct graph for the stability curve [1]



Ans. b)

23. For most stable nuclei, neutron number (N) and Proton number (Z) has the relation
a) N = Z
b) N≥ Z
c) N < Z
d) N > Z
Ans. b) N≥ Z

24. In lighter nuclei Z<20, the ratio of number of neutron to proton in stability curve is
a) More than 1
b) Less than 1
c) Much greater than 1
d) Nearly equal to 1
Ans. d) Nearly equal to 1

25. According to Shell model, which of the following is NOT the magic number
a) 126
b) 82
c) 50
d) 58
Ans. d) 58

26. The process in which incident particle changes the internal structure of target nucleus and itself changed into other particle called as

a) Elastic scattering
b) Inelastic scattering
c) Nuclear reaction
d) None of these
Ans. c) Nuclear reaction

27. In general, Nuclear reaction expressed as X (a, b) Y is
a) $a + X \rightarrow Y + b$
b) $a + Y \rightarrow X + b$
c) $a + b + X \rightarrow Y$
d) $X \rightarrow a + b + Y$
Ans. a) $a + X \rightarrow Y + b$

28. Which one is correct for the nuclear reaction?
a) Strong interaction of nucleus with the elementary particle
b) Formation of new nuclide
c) Kinetic energy is not conserved in the process
d) All of these
Ans. d) All of these

29. Which of the following is not conserved during Nuclear reactions?
a) Total energy
b) Momentum
c) Charge
d) Kinetic energy
Ans. d) Kinetic energy

30. In the nuclear reaction

$$a + X \rightarrow Y + b + Q$$

The Q value expressed as change in
a) Total energy
b) Kinetic energy
c) Rest mass energy
d) Both (b) and (c)
Ans. d) Both (b) and (c)

31. In the nuclear reaction given by [2]

$${}_{2}^{4}He + {}_{7}^{14}N \rightarrow {}_{Z}^{A}X + {}_{1}^{1}H$$; Where the nuclide X is

a) Nitrogen of mass number 16
b) Nitrogen of mass number 17
c) Oxygen of mass number 16
d) Oxygen of mass number 17
Ans. d) Oxygen of mass number 17

32. Which statement is not correct for Nuclear reaction Cross-section?
(a) It depends upon kinetic energy and nature of interaction process.

(b) It is a probabilistic approach.
(c) Its unit is barn.
(d) Larger the value of cross-section than smaller be the probability of nuclear reaction to take place.
Ans. (d) Larger the value of cross-section than smaller be the probability of nuclear reaction to take place.

33. The nuclear reaction

$$4\ {}_{1}H^{1} \rightarrow {}_{2}He^{4} + 2\ {}_{-1}e^{0} + 26\ MeV$$

represents:
(a) Fusion
(b) Fission
(c) β-decay
(d) γ-decay
Ans. (a) Fusion

34. The probability of electron being captured by the nucleus-
a) K- shell electrons
b) L-shell electrons
c) M-shell electrons
d) Electrons in the outermost orbit
Ans. a) K- shell electrons

35. Nuclear fusion required the high temperature because -
a) All nuclear reactions absorbs heat
b) The binding energy must be supplied from external source
c) The particles cannot come closer unless they are moving rapidly
d) The mass-deficit must be supplied.
Ans. c) The particles cannot come closer unless they are moving rapidly.

36. Typical energies released in nuclear fission and a nuclear fusion reaction are respectively-
a) 50 MeV and 1000 MeV
b) 200 MeV and 1000 MeV
c) 1000 MeV and 50 MeV
d) 200 MeV and 10 MeV
Ans. d) 200 MeV and 10 MeV

37. The Sun release energy by-
a) Nuclear fission
b) Nuclear fusion
c) Hydro-thermal process
d) Spontaneous combustion
Ans. b) Nuclear fusion

38. The atoms ${}_{92}U^{238}$ and ${}_{92}U^{234}$ are
a) Isotopes

b) Isobars
c) Isomers
d) Isotones
Ans. a) Isotopes

39. Nuclear reactor is based on the process:
a) Photoelectric effect
b) Nuclear fusion
c) Nuclear fission
d) Thermionic emission
Ans. c) Nuclear fission

40. U^{238} Nuclei can be fissioned by
a) Slow neutrons
b) Fast neutrons
c) Protons
d) X-rays
Ans. b) Fast neutrons

41. Artificial Nuclear Transmutation was discovered by-
a) Thomson
b) Rutherford
c) Chadwick
d) Bohr
Ans. b) Rutherford

42. During an atomic explosion, the energy released is due to conversion of
a) mass into energy
b) protons to neutrons
c) mechanical energy into nuclear energy
d) chemical energy into heat energy
Ans. a) mass into energy

43. The fuel mainly used in nuclear fission reactors are:
a) U^{235}
b) U^{239}
c) U^{233}
d) U^{238}
Ans. a) U^{235}

44. The "magic numbers" for atoms are
a) number of electrons that confer atomic stability
b) number of protons and/or neutrons that confer nuclear stability
c) n/p ratio that confer nuclear stability
d) atomic masses that indicate fissile isotopes
Ans. b) number of protons and/or neutrons that confer nuclear stability

45. Emission of which one of the following leaves both atomic number and mass number unchanged?
a) β particle
b) neutron
c) α particle
d) γ radiation
Ans. d) γ radiation

46. Which of the following is NOT used as a moderator in a nuclear reactor?
(a) H_2O
(b) D_2O
(c) C
(d) Al
Ans. (d) Al

47. In nuclear reactor, the controller rods are made of
(a) Cadmium
(b) Uranium
(c) Graphite
(d) None of these
Ans. a) Cadmium

48. The stability of the nucleus can be predicted by which of the following?
a) electron to neutron ratio
b) neutron to proton ratio
c) neutron to electron ratio
d) proton to electron ratio
Ans. b) neutron to proton ratio

49. The *Q* value of any nuclear reaction can be calculated by the following formula
a) $Q = (m_1 + m_2)c^2$
b) $Q = (m_1 m_2)c^2$
c) $Q = (m_1 - m_2)c^2 = \Delta mc^2$
d) $Q = (m_1/m_2)c^2$
Ans. c) $Q = (m_1 - m_2)c^2 = \Delta mc^2$

50. ${}_3Li^7$ and ${}_4Be^7$ example of
a) Magic nuclei
b) Mirror nuclei
c) Both (a) and (b)
d) None of these
Ans. b) Mirror nuclei

Unit – VII

By Dr. Kaleem Ahmed

Unit VII

(Accelerators & Detectors)

Summary

Accelerators:

A very high energy particles are required for transmutation or initiate nuclear disintegration of one element into other by artificial means. This can be achieved with the help of mechanical devices called particle accelerators.

- Particle accelerator is a machine for increasing the kinetic energy of electrically charged particles.
- These accelerators used electric fields or varying magnetic fields to accelerate the charged particles.

Van De Graff generator

- Designed by American scientist Robert Van de Graff which can give large current at very high voltages of the order of ten million volts.

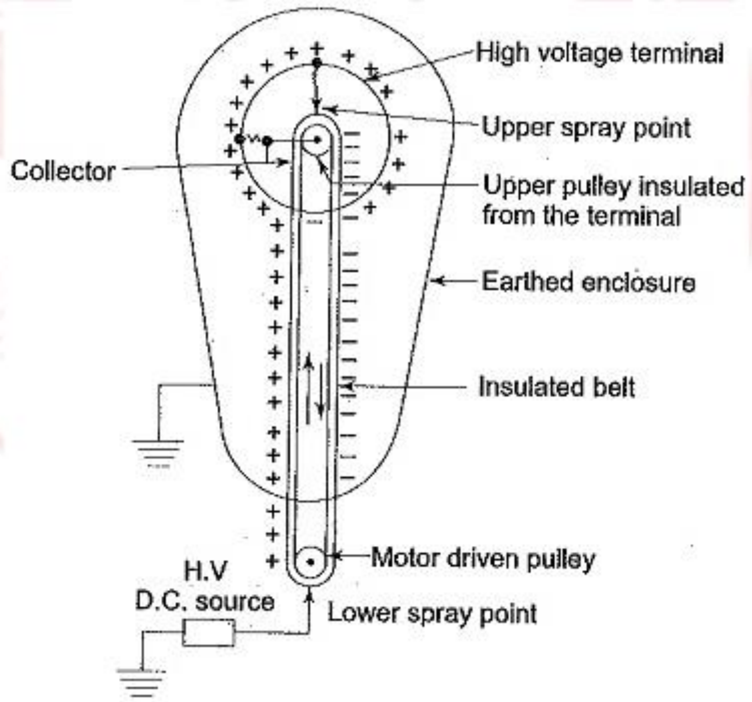


Fig. 7.1 Van de Graffe generator [10]

- Based on the two principle
  (i) There is no electric field inside a charged conducting sphere.
  (ii) Discharge of electricity occurs readily at pointed objects (Corona discharge).

Cyclotron

- The cyclotron devised by Lawrence and Livingston.
- It is used for accelerating ions to high speed by the application of accelerating potential.
- In a cyclotron, charged particles accelerate outwards from the centre along a spiral path.
- A cyclotron accelerates a charged particle beam using a high frequency alternating voltage which is applied between two hollow "D"-shaped sheet metal electrodes known as the "dees" inside a vacuum chamber.
- The magnetic field causes the path of the particle to bend in a circle due to the Lorentz force perpendicular to their direction of motion.
- An alternating voltage of several thousand volts is applied between the dees. The voltage creates an oscillating electric field in the gap between the dees that accelerates the particles.
- Cyclotrons can be used in particle therapy to treat cancer, using the ion beams from cyclotrons to penetrate the body and kill tumours by radiation damage [1].

The centripetal force required to keep the particles in a curved path is given by the formula:

$$F_c = \frac{m\upsilon^2}{r}$$

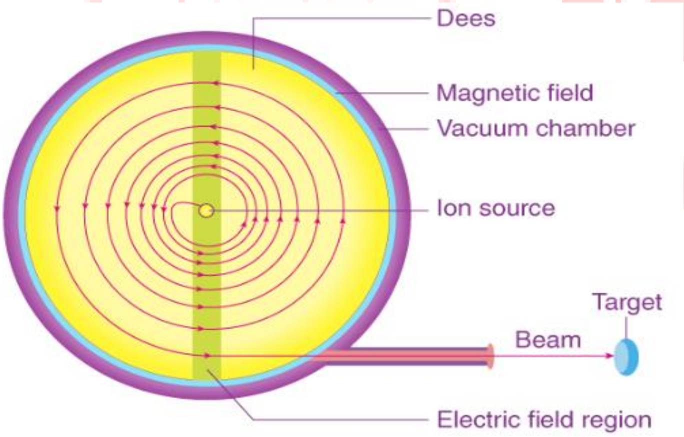


Fig. 7.2 Cyclotron diagram [7]

The force is provided by the Lorentz's force F_B on the magnetic field B

$$F_B = q\upsilon B$$

Equating these equations, we get

$$\upsilon = \frac{qBr}{m}$$

Hence, the output energy of the particles is given by the expression

$$E = \frac{q^2B^2r^2}{2m}$$

Limitations:

- Cyclotrons cannot accelerate electrons because electrons are of very small mass.
- A cyclotron cannot be used to accelerate neutral particles.
- It cannot accelerate positively charged particles with large mass due to the relativistic effect.

Detectors

When charged particles like α-particles, β-particles, protons and deuterons pass through matter, they collide with the molecules of the materials and lose energy. They produce ions by collisions. This ionisation is the basis of many detecting instruments such as electroscope, ionization chamber, Geiger-Muller counter, cloud chamber.

Geiger-Muller Counter:

- Geiger counter is a device which is used to detect and measure particles in ionized gases. It is widely used in applications like radiological protection, radiation dosimetry, and experimental physics.
- It is made up of a metallic tube, filled with gas such as helium, neon, or argon at the pressure being the lowest and a high voltage range of multiples of 100V is applied to this gas. It detects alpha, beta, and gamma particles.
- There would be the conduction of the electrical charge on the tube when a particle or photon of incident radiation would turn the gas conductive by the means of ionization.

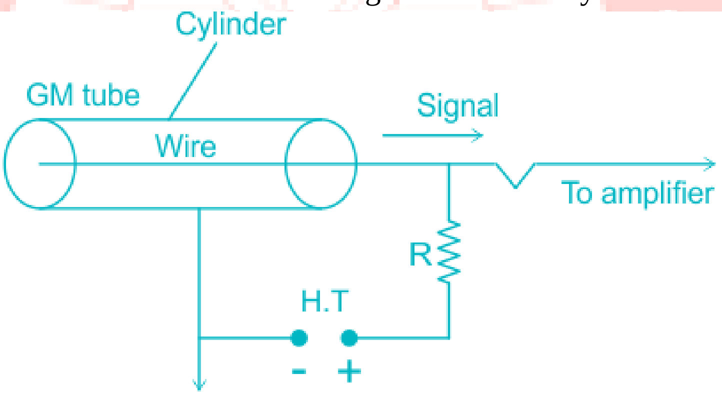


Fig. 7.3 GM Counter [8]

- A high-energy particle coming via the mica window will ionize one or more argon atoms. In a cascade effect, the argon electrons and ions created force more argon atoms to ionize.
- As the electron accelerates towards the central wire, it knocks additional electrons off Argon atoms, resulting in a cascade.
- The current flowing through resistance (R) generates a voltage spike of the magnitude of 10V.
- An electron pulse amplifier receives low-voltage pulses and amplifies them to 5 to 50 volts.After that, the amplified output is transferred to a counter.

Disadvantages of Geiger Counter

- Due to a lack of distinguishing skills, GM counters are unable to measure energy.

- Neutrons and other uncharged particles cannot be detected.
- Due to their long paralysis time restrictions and high dead-time, GM countermeasures are less efficient.
- Quenching chemicals used in GM counters frequently disintegrate, resulting in a loss in lifespan.

Scintillation Detector

A scintillation counter is a device for detecting and measuring ionizing radiation by detecting light pulses produced by the excitation effect of incident radiation on a scintillator material.

- A scintillator is a device that detects and measures the intensity of high levels of radiation. It is made up of a phosphor with which particles collide, resulting in light flashes and are detected by a photomultiplier and transformed into electric current pulses that are counted for individual ionizing events.

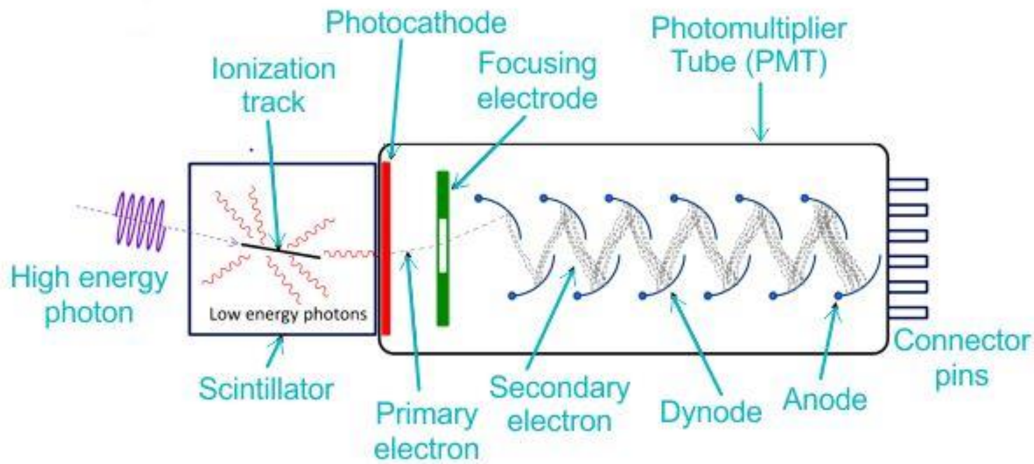


Fig. 7.4 Scintillation Detector [7]

- Atoms are ionised along a track when an ionising particle passes through the scintillator material. For charged particles, the track is the particle's own path. The energy of uncharged gamma rays is converted to an energetic electron via the photoelectric effect, Compton scattering, or pair production.

- **Types of Scintillation Counter**

  In nuclear and particle physics, there are two types of scintillators. Plastic or organic scintillators as well as crystalline or inorganic scintillators are the two types.

  (i) Organic Scintillators

  Organic scintillators are organic materials that emit photons in the visible spectrum when a charged particle passes through them. Its mechanism differs from that of inorganic material. The transition of energy levels of a single molecule causes fluorescence or scintillation through organic materials.

  (ii) Inorganic Scintillators

  Crystals manufactured in high-temperature furnaces are inorganic scintillators. Lithium iodide (LiI), cesium iodide (CsI), sodium iodide (NaI), zinc sulphide (ZnS) and NaI(TI) (thallium-doped sodium iodide) are among them.

Multiple Choice Questions and Answers

1. A particle accelerator used to increase very high speed of
   (a) uncharged particles
   (b) charged particles
   (c) both charged and uncharged particles
   (d) None of these
   Ans: (b) charged particles

2. Which of the following is/are NOT accelerated by Cyclotron?
   (a) Protons
   (b) Electrons
   (c) α-particles
   (d) both (a) and (c)
   Ans: (b) Electrons

3. A Vande Graff generator produces
   (a) Large current and less voltage
   (b) Large voltage and less current
   (c) Large resistance and less voltage
   Ans: (b) Large voltage and less current

4. Vande Graff generator produce the potential difference of the order of
   (a) Hundreds volts
   (b) Tens of volts
   (c) Million of volts
   (d) None of these
   Ans: (c) Million of volts

5. In Cyclotron, the frequency of revolution of a charged particle is independent of
   (a) Mass of the particle
   (b) Magnetic field
   (c) Charge of the particle
   (d) Speed of the particle
   Hint: Cyclotron frequency, $\nu = \frac{qB}{2\pi m}$
   Ans: (d) Speed of the particle

6. Calculate the speed of an electron if it travels in a circular path of radius 50 cm in a magnetic field of 5×10^{-3} T.
   (a) 0.4×10^{7} m/s
   (b) 4×10^{7} m/s

(c) 44×10^{7} m/s
(d) 440×10^{7} m/s
Hint: equate the Lorentz magnetic force with centripetal force of electron,

$$\upsilon = \frac{qBr}{m}$$

Ans: (c) 44×10^{7} m/s

7. To compensate the relativistic variation of mass at high speed of charge in Cyclotron. Adjustment can be made as:
(a) Frequency of A.C. is decreased
(b) Magnetic field is increased
(c) Both (a) and (b)
(d) None of these
Ans: (c) Both (a) and (b)

8. The maximum kinetic energy of the positive ion in the Cyclotron is
(a) $\frac{qBR^2}{2m}$
(b) $\frac{q^2B^2R^2}{2m}$
(c) $\frac{qBR}{2m}$
(d) $\frac{q^2B^2R^2}{m}$
Ans: (b) $\frac{q^2B^2R^2}{2m}$

9. A Cyclotron can accelerate
(a) β-particles
(b) α-particles
(c) γ rays
(d) X-rays
Ans: (b) α-particles

10. An electron is accelerated by an electric field of 200 volt/cm acting for 10 cm and then enters a uniform magnetic of 10000 Gauss in a plane perpendicular to the field. The radius of the circular orbit of the electron is -
(a) 1.8×10^{-4} m
(b) 1.5×10^{-4} m
(c) 1.8×10^{-5} m
(d) 1.5×10^{-3} m

Hint: use $r = \dfrac{m\upsilon}{qB}$

Ans: (b) 1.5×10^{-4} m

11. GM Counter detects

(a) Photons

(b) Neutrons

(c) α-particles

(d) All of the above

Ans: (c) α-particles

12. When the charged particles pass through matter, the energy loss of the particles per unit length of the medium called as

(a) Stopping power

(b) Reflecting power

(c) Stopping potential

(d) None of the above

Ans: (a) Stopping power

13. When the particles pass through the matter, its intensity decreases and given by the equation

(a) $I = I_0 e^{-\mu x}$

(b) $I = I_0 e^{\mu x}$

(c) $I = \dfrac{I_0}{x}$

(d) $I = I_0 x$

Ans: (a) $I = I_0 e^{-\mu x}$

14. When the nuclear radiation pass through the gas, ionization is produced. This is the principle of which of the following detectors?

(a) Proportional Counter

(b) Flow Counter

(c) GM Counter

(d) Scintillation Counter

Hint: Think about the type of charge carriers involved in the base current.

Ans: (c) GM Counter

15. What is a Geiger Muller counter used to measure

(a) Water flow

(b) Pressure

(c) Temperature

(d) Radioactivity

Ans: (d) Radioactivity

16. When γ rays interact with matter, which of the following process takes place ?
   (a) Photoelectric absorption
   (b) Compton scattering
   (c) elecrtron-positron pair production
   (d) All of these
   Ans: (d) All of these

17. The rest energy of electron and positron is 0.51 MeV. For pair production, the energy of photon (E) must be in (MeV)
   (a) $E \geq 1.02$ MeV
   (b) $E < 0.51$ MeV
   (c) $1.02 > E > 0.51$
   (d) any value

Ans: (a) $E \geq 1.02$ MeV

18. In case of photoelectric absorption, W is the binding energy of the shell, the Kinetic energy of ejected photoelectron (T) is given by
   (a) $h\nu + W$
   (b) $h\nu - W$
   (c) $W - h\nu$
   (d) $W/h\nu$
   Ans: (b) $h\nu - W$

19. At very low energy of γ rays photon, which process becomes dominant
   (a) Photoelectric absorption
   (b) Pair production
   (c) Compton scattering
   (d) All of these
   Ans: (a) Photoelectric absorption

20. Which of the maximum penetrating power?
   (a) Radiowaves
   (b) Microwaves
   (c) Ultraviolet
   (d) Gamma rays
   Ans: (b) Gamma rays

21. Quenching gas in GM counter is
   (a) Argon
   (b) Alcohol
   (c) Hydrogen
   (d) Oxygen

Ans: (b) Alcohol

22. Which of the following act as ionising gas in GM counter?
   (a) Argon
   (b) Alcohol
   (c) Hydrogen
   (d) Krypton
   Ans: (a) Argon

23. A GM counter wire collects 10^8 electrons per discharge. Calculate the average current in the circuit, when counting rate is 500 counts/min.
   (a) 1.33×10^{-10} A
   (b) 1.33×10^{-6} A
   (c) 1.33×10^{-8} A
   (d) 1.33×10^{-12} A
   Hint: use $q = ne$ and $I = q/t$ where $n = 500\times10^8$
   Ans: (a) 1.33×10^{-10} A

24. The period during which the ionisation remains suspended and the GM counter becomes inoperative is called
   (a) Recovery time
   (b) Dead time
   (c) Reset
   (d) none of these
   Ans: (b) Dead time

25. In GM counter, the dead time is about [2]
   (a) 100 s
   (b) 200 μs
   (c) 300 μs
   (d) 400 μs
   Ans: (b) 200 μs

26. In GM tube, bromine is use as ____ gas
   (a) quenching
   (b) cleaning
   (c) working
   (d) both working and quenching
   Ans: (a) quenching

27. Scintillation counter detects
   (a) α particles only
   (b) β particles only
   (c) α and β particles only

(d) α, β and γ particles
Ans: (d) α, β and γ particles

28. In GM counter, the central electrode wire is kept at the potential which is _____
(a) positive
(b) negative
(c) zero
(d) of any kind and value
Ans: (a) positive

29. In Scintillation counter, the phosphor converts energy of the incoming particles into _____
(a) photoelectric current
(b) magnetic field
(c) light
(d) heat
Ans: (c) light

30. GM counter works on the principle of _____
(a) Ion chamber
(b) Nuclear emulsion formation
(c) Light sensing
(d) Photoelectric method
Ans: (a) Ion chamber

31. In ionization chamber, gas amplification is _____
(a) ~ 10^8
(b) ~ 10^3
(c) equal to unity
(d) less than unity
Ans: (a) ~ 10^8

32. The electron multiplication is achieved in
(a) GM counter
(b) Photomultiplier tube
(c) Scintillation detector
(d) Cerenkov detector
Ans: (b) Photomultiplier tube

33. Heart of a Scintillation counter is
(a) MgO coating
(b) Photomultiplier tube
(c) Phosphor
(d) light guide
Ans: (b) Photomultiplier tube

34. What type of voltage is applied to the D-shaped disc of the Cyclotron?
(a) Low frequency alternating voltage
(b) High frequency alternating voltage
(c) Low current direct voltage
(d) High current direct voltage
Ans: (b) High frequency alternating voltage

35. A cyclotron accelerates particles of mass m and charge q. The kinetic energy of the particle is proportional to
(a) q^2
(b) q
(c) q^3
(d) 1/q
Ans: (a) q^2

36. Scintillation detector is a large flat crystal of which of the following materials [2]
(a) Sodium chloride
(b) Sodium Iodide
(c) Sodium sulphate
(d) Sodium Carbonate
Ans: (b) Sodium Iodide

37. Scintillation counter based on the phenomenon of
(a) Photoelectric effect
(b) Pair production
(c) compton effect
(d) fluoroscence
Ans: (d) fluoroscence

38. Which of the following is/are used as scintillators
(a) ZnS
(b) Phosphor
(c) Sodium Iodide
(d) All of these
Ans: (d) All of these

39. In a scintillation counter, the magnitude of the output pulse from the photomultiplier
(a) remains constant
(b) increases with increase of energy of incident particle
(c) decreases with increase of energy of incident particle
(d) first increases and then decreases
Ans: (b) increases with increase of energy of incident particle

40. Lab coats and gloves provide shielding from
   (a) α-rays
   (b) α and β rays
   (c) α, β and γ rays
   (d) γ radiation
   Ans: (b) α and β rays

41. Which of the following is not a type of radiation detectors?
   (a) GM counter
   (b) Semiconductor detector
   (c) Scintillation counter
   (d) Flame emission detector
   Ans: (d) Flame emission detector

42. Which of the following is the main disadvantage of solid state semiconductor detector?
   (a) Low accuracy
   (b) Low sensitivity
   (c) Maintained at low temperature
   (d) None of these
   Ans: (c) Maintained at low temperature

43. Both proton and deuteron are accelerated by the cyclotron with the same accelerating potential follow circular path. If radius of circular path for proton is 15 cm than for deuteron find out the radius of circular path.
   (a) 30 cm
   (b) 21.15 cm
   (c) 15 cm
   (d) 17.32 cm
   Ans: (b) 21.15 cm
   Hint: As potential same therefore K.E. is same. Than find v_p and v_d, given $m_d = 2m_p$ after that equate force and find out the radius.

44. The function of the Scintillation crystal with in the Scintillation detector is to convert
   (a) X-rays into electrons
   (b) electrons into more electrons
   (c) X-rays into light
   (d) none of the above
   Ans: (a) X-rays into electrons

45. A relativistic particle having same rest mass and charge equal to electron moving with velocity 2.7×10^8 m/s in a direction perpendicular to magnetic field 0.02 T. Find the radius of curvature of the path.
   (a) 12.66 cm
   (b) 17.66 cm

(c) 7.68 cm
(d) 10.66 cm
Hint: Think about the relativistic mass formula and use r = (mv/qB).
Ans: (b) 17.66 cm

46. A cyclotron has dee radius 50 cm and frequency of 12 MHz. Calculate the magnetic field required to accelerate particle of mass 3.3×10^{-27} and charge 1.6×10^{-19} C.
(a) 1.56 T
(b) 7.56 T
(c) 25.6 T
(d) 75.5 T
Ans: (a) 1.56 T

47. The Cerenkov radiation is an electromagnetic radiation that lies in
(a) Infra-red region
(b) Visible region
(c) U.V. region
(d) None of these
Ans: (b) Visible region

48. The saturation current in the graph between voltage and current is called
(a) Ionization region
(b) Proportional region
(c) Plateau region
(d) None of these
Ans: (c) Plateau region

49. In Nuclear disintegration:
(a) the incident and ejected particle are always same
(b) the incident particle is always light ion
(c) the incident and ejected particles are always different
(d) None of these
Ans: (c) the incident and ejected particles are always different

50. In fission reactor, the moderators are
(a) used to capture the neutrons and stop the chain reaction
(b) materials of low mass number having small absorption cross-section and large slowing power for fast neutrons
(c) materials of high mass number material and have high neutron absorption cross -section
(d) generally fertile material
Ans: (b) materials of low mass number having small absorption cross-section and large slowing power for fast neutrons

Unit – VIII

Unit VIII

(Elementary Particles)

Summary

Fundamental or elementary particles are subatomic particles that are not composed of other particles. Thus, they cannot be subdivided into smaller components. They have no known internal structure.

- The Standard Model of particle physics is the best current theory explaining the fundamental particles (the most basic building blocks of the universe) and the fundamental forces that govern their interactions, except for gravity. It explains how particles called quarks (which make up protons and neutrons) and leptons (which include electrons) make up all known matter.
- The Standard Model of Particle Physics consists of 17 fundamental particles. Based on their spin, they are divided into two main types: fermions and bosons. They are the smallest and basic building blocks of matter and energy [1].

Fermions:

- Fermions include Leptons and Quarks. They are fundamental particles which make up matter in the universe. They have odd half-integer spins (1/2, 3/2, and 5/2, but not 2/2 or 6/2).
- Fermions obey the Pauli exclusion principle, which states that no two or more identical fermions can occupy the same quantum state simultaneously. Due to this, fermions are solitary in nature.

Leptons:

- Leptons are fundamental particles that do not experience a strong nuclear force.
- There are six leptons: electron, muon, tau, and their corresponding neutrinos.

Electron

- Electrons are negatively charged particles orbiting the nucleus of an atom.
- Electron is the lightest stable subatomic particle known and is the most well-known lepton.

Muon

- A muon is an elementary particle similar to an electron but with much greater mass.
- Muons are negatively charged. They are unstable and decay into other particles within microseconds.

Tau

- The tau particle is the heaviest of the three charged leptons (electron, muon, tau).
- Like muons, negatively charged tau particles are unstable and decay rapidly into other particles within 290 femtoseconds.

Neutrino

- Neutrinos are tiny particles with no electric charge (neutral) and very little mass. They are the lightest of all the subatomic particles that have mass. They are the most abundant particles in the universe [2].

- They are called "ghost particles" due to their extremely weak interactions with matter, making them hard to detect (elusive). They interact only via the weak nuclear force and gravity.
- Neutrinos are formed through various processes, such as nuclear fission in nuclear reactors, fusion reactions inside the sun, radioactive decay, cosmic rays, supernova explosions, and particle accelerators. Even bananas emit neutrinos due to the natural radioactivity of potassium.
- Neutrinos come in three types called flavours: electron neutrino, muon neutrino, and tau neutrino.

Quarks

- Quarks combine to form composite subatomic particles called hadrons.
- Quarks carry a type of charge known as "colour charge," which is related to the strong nuclear force that the quarks experience. There are three types of colour charges (red, green, and blue), and quarks combine to form colour-neutral particles.
- Due to the strong force, quarks are always confined within hadrons; they cannot exist independently.
- In terms of electric charge, they can be positively and negatively charged.
- There are six types (flavours) of quarks based on charge: up (lightest of all quarks), down, charm, strange, top (heaviest of all quarks and the most massive subatomic particle known), and bottom [1].

Hadron

- Hadrons are composite particles made of quarks held together by the strong nuclear force, mediated by gluons. They are divided into two main groups:
- Baryons: comprises three quarks (e.g., protons and neutrons, the components of atomic nuclei).
- Mesons: comprises a quark-antiquark pair (e.g., pions).

Bosons:

- Bosons are fundamental particles that mediate forces between other particles. They are energy and force carriers throughout the universe.
- Bosons do not follow the Pauli exclusion principle so that multiple bosons can occupy the same quantum state. This allows them to form a Bose-Einstein condensate, a state of matter where extremely cold atoms act as a single entity.
- They have integer spin values (0, 1, 2, etc.).
- They fall into two categories: gauge bosons and scalar bosons.

Gauge Bosons

- Gauge bosons are particles with a spin of 1. They include:
    1. **Photons**: They are the constituent particles of light & the mediators of the electromagnetic force.
    2. **Gluons:** They mediate the strong nuclear force and bind quarks together to form composite particles like protons and neutrons, holding the nucleus together.
    3. **W and Z Bosons:** They mediate the weak nuclear force and help in radioactive decay.

Scalar Bosons

- Scalar bosons are particles with a spin of 0 (unique particles).
- The Higgs boson is the only known fundamental scalar boson.

Higgs Boson

- Nobel prize-winning physicist Peter Higgs, who recently passed away, proposed the existence of the Higgs Boson in 1964. The Higgs Boson could lead to discoveries of new particles or reveal connections between forces we never knew existed.
- Scientists confirmed the existence of Higgs Boson in 2012 through experiments at the Large Hadron Collider (LHC — produces collisions with high energies to replicate conditions similar to the Big Bang) at CERN in Switzerland. This discovery led to the 2013 Nobel Prize in Physics awarded to Higgs and Englert.
- The Higgs Boson, also called the God particle, is the fundamental force-carrying particle of the Higgs field (a scalar field that permeates all of space). It is responsible for granting other particles, such as electrons and quarks, their mass.

Isospin quantum number:

- Neutron and proton has got almost the same mass, same intrinsic spin, also that nuclear forces are charge independent which inferences that the two particles are different charge manifestation of the same entity the nucleon. Thus the particles are grouped like isotopic grouping of the elements. The charge is treated as variable for different state of nucleon known as Isotopic quantum number. Since neutron and protons are not isotopes, is-spin quantum number is used [11].
- I_3 = ½ for the proton state and -1/2 for the neutron state
- I_3 = +1 for the π^+ state, 0 for π^0 state and -1 for π^- state

Strangeness

- Introduced by Gellmann and Nishijima for observing the strange behaviour of k-mesons and hyperons known as a strange particles.
- S = -1 for $\Lambda^0 and \Sigma$
- S = -2 for $\Xi doublet$
- S = -3 for Ω^-
- The charge of the particle is

$$Q = I_3 + \frac{1}{2}(B + S)$$

Multiple Choice Questions and Answers

1. Neutron was discovered by:
   (a) Thomson
   (b) Rutherford
   (c) Chadwick
   (d) Anderson
   Ans: (c) Chadwick

2. A particle having no charge and almost no mass is
(a) electron
(b) neutron
(c) positron
(d) neutrino
Ans: (d) neutrino

3. For pair production, the minimum energy of gamma photon must be [2]
(a) 0.51 MeV
(b) 1.02 MeV
(c) 5.04 MeV
(d) 13.6 MeV
Ans: (b) 1.02 MeV

4. In the nuclear reaction which of the following is conserved?
(a) Momentum
(b) Charge
(c) Mass and energy
(d) All of these
Ans: (d) All of these

5. Who postulated that "every particle has an antiparticle?"
(a) Dirac
(b) Rutherford
(c) Pauli
(d) Thomson
Ans: (a) Dirac

6. The field particle in electromagnetic force is:
(a) muon
(b) pion
(c) photon
(d) hyperon
Ans: (c) photon

7. Leptons responds to
(a) strong interaction
(b) weak interaction
(c) weak and electromagnetic interaction
(d) strong and weak interaction
Ans: (d)

8. If an elementary particle $\sum^+$ made up of quarks composition u+u+s. What is the charge of $\sum^+$?
(a) 0
(b) 1e
(c) 2e
(d) 3e
Hint: we know charge for u = (2/3)e, d = (1/3)e and s = (-1/3)e use this to get the answer.
Ans: (b) 1e

9. In the process of fusion, the binding energy per nucleon ___________
(a) increases
(b) decreases
(c) remains same
(d) energy is absorbed
Ans: (a) increases

10. In the quark model, the proton is made up of three u quarks, while the neutron is made up of two u quarks one d quarks. This statement is
(a) True
(b) False
(c) Partially true
(d) None of these
Ans: (b) False

11. Which one of the following particle does not have spin 1/2?
(a) proton
(b) neutron
(c) photon
(d) neutrino
Ans: (c) photon

12. Which of these is not made from quarks?
(a) proton
(b) neutron
(c) lepton
(d) meson
Ans: (c) lepton

13. Which of the following reaction violates lepton number conservation? [1]
(a) $e^+ + e^- \rightarrow \nu + \bar{\nu}$
(b) $e^+ + p \rightarrow \nu + n$
(c) $e^+ + n \rightarrow p + \nu$
(d) $\mu^- \rightarrow e^- + \nu + \bar{\nu}$

Ans: (c) $e^{+} + n \rightarrow p + \nu$

14. As per the standard model, how many elementary particles are seen?
   (a) 91
   (b) 71
   (c) 61
   (d) 81
   Ans: (c) 61

15. Which of the following functions describe the nature of interaction potential V(r) between two quarks inside a nucleon? (r is the distance between the quarks and a and b are positive constants)
   (a) $V(r) = \frac{a}{r} + br$
   (b) $V(r) = -\frac{a}{r} - br$
   (c) $V(r) = -\frac{a}{r} + br$
   (d) $V(r) = \frac{a}{r} - br$
   Ans: (c) $V(r) = -\frac{a}{r} + br$

16. The baryon number of proton, the lepton number of proton, lepton number of electron and the baryon number of electron are respectively:
   (a) 0, 0, 1, 0
   (b) 1, 0, 1, 0
   (c) 1, 1, 0, 0
   (d) 0, 1, 1, 0
   Ans: (b) 1, 0, 1, 0

17. The decay of a free neutron, $n \rightarrow p + e^{-} + \overline{\nu_e}$ [1]
   (a) does not occur because of energy conservation
   (b) does not occur because of strangeness conservation
   (c) violate baryon number conservation
   (d) occurs in nature with half life of about 10^3 seconds.
   Ans: (d) occurs in nature with half life of about 10^3 seconds.

18. The nucleus of the atom $^{9}Be_4$ consists of up and down quarks respectively:
   (a) 13, 13
   (b) 14, 13
   (c) 13, 14
   (d) 14, 14

Ans: (c) 13, 14

Hint: For $^9Be_4$, number of proton = 4, therefore charge = 4e

For up quark, charge = (2/3)e

Down quark charge = (-1/3)e,

check all the option to get the charge 4e and find out the correct option.

19. Spin of electron is
(a) 1/2
(b) 1/3
(c) 1/4
(d) 1/8
Ans: (a) 1/2

20. Suppose that a neutron is at rest in free space decays into a proton and an electron. This process would violate:
(a) Conservation of charge
(b) Conservation of energy
(c) Conservation of linear momentum
(d) Conservation of angular momentum
Ans: (d) Conservation of angular momentum

21. Which of the following elementary particle is a lepton?
(a) Photon
(b) μ-meson
(c) π-meson
(d) Proton
Ans: (b) μ-meson

22. The method of carbon dating works because
(a) C^{14} has a higher atomic weight than C^{12}.
(b) C^{14} is a stable isotope.
(c) C^{14} content of the dead body increases with time because of cosmic ray bombardment.
(d) none of the above
Ans: (b) C^{14} is a stable isotope.

23. The quarks are supposed to be exist in following number of flavours:
(a) 2
(b) 3
(c) 4
(d) 6
Ans: (d) 6

24. Which one of the following statement regarding neutrino is wrong?
(a) Neutrino has spin (½)

(b) Neutrino has zero rest mass
(c) Neutrino does not interact with matter
(d) Neutrino has charge equal to electron.
Hint: Neutrino are massless and chargeless particle.
Ans: (d) Neutrino has charge equal to electron.

25. The energy of the electron emitted from the light sensitive surface will increase when the incident light
(a) increase in intensity
(b) decrease in wavelength
(c) increase in wavelength
(d) decrease in frequency
Ans: (b) decrease in wavelength

26. When an electron and positron annihilate:
(a) one photon created
(b) two photon are created
(c) two neutrons are created
(d) Nothing is created
Ans: (b) two photon are created

27. The atoms ${}_{92}U^{238}$ and ${}_{92}U^{234}$ are [2]
(a) Isotopes
(b) Isobars
(c) Isotones
(d) Isomers
Ans: (a) Isotopes

28. Spins of boson is equal to
(a) A positive integer
(b) Integer
(c) Positive integral multiple of 1/2
(d) Any fraction
Ans: (a) A positive integer

29. The annihilation energy for 1 a.m.u (atomic mass unit) is given below. Choose the correct answer
(a) 931 x 10^6 V
(b) 931 million electron volt
(c) 931 MeV
(d) All of these
Ans: (d) All of these

30. The minimum energy that a photon must have in order to produce an e^+ and e^- pair in a collision with an electron at rest is (m =mass of electron)

$$\gamma + e^- \rightarrow e^- + e^+ + e^-$$

(a) mc^2
(b) $2mc^2$
(c) $3mc^2$
(d) $4mc^2$
Ans: (d) $4mc^2$

31. The measure of the strength of strong nuclear force holding the nucleus together is called
(a) Kinetic energy
(b) Potential energy
(c) Nuclear energy
(d) Binding energy
Ans: (d) Binding energy

32. The exchange particle in electromagnetic force has mass and spin as follows. Find the correct answer?
(a) 0, 1
(b) 1, 0
(c) 0, ½
(d) ½, 0
Ans: (a) 0, 1

33. The law of conservation of parity is valid only for the following interaction. Choose the correct answer.
(a) Strong
(b) Electromagnetic
(c) Weak
(d) Strong and electromagnetic
Ans: (d) Strong and electromagnetic

34. The law of conservation of isospin is valid only for
(a) Strong interaction
(b) Electromagnetic interaction
(c) Weak interaction
(d) Gravitational interaction
Ans: (a) Strong interaction

35. The proton, neutron, electron and photon are called the :
(a) Secondary particles
(b) Fundamental particles

(c) Basic particles
(d) Initial particles
Ans: (b) Fundamental particles

36. Particles that interact by the strong force are called
(a) leptons
(b) hadrons
(c) muons
(d) electrons
Ans: (b) hadrons

37. Which elementary particle is associated with the weak nuclear force?
(a) Higgs boson
(b) Gluon
(c) W boson
(d) Quark
Ans: (c) W boson

38. What is the main goal of particle accelerator like "The large Hadron Collider (LHC)"?
(a) To generate electricity
(b) To produce antimatter
(c) To artificial elements
(d) To uncover new particles and study fundamental forces
Ans: (d) To uncover new particles and study fundamental forces

39. The relative magnitudes of gravitational, weak, electromagnetic and strong interactions are in the ratio
(a) 10^{-39}: 10^{-13}:10^{-3}:1
(b) 1 : 10^{-3} :10^{-13} : 10^{-39}
(c) 1000 : 100 : 10 : 1
(d) 1 : 10 : 100 : 1000
Ans: (a) 10^{-39}: 10^{-13}: 10^{-3}: 1

40. The particles carrying the strong forces are
(a) W or Z bosons
(b) Photons
(c) Gluons
(d) None of these
Ans: (c) Gluons

41. The quark structure of proton and neutron is respectively: [1]
(a) uss, uus
(b) uus, uss
(c) udd, uud

(d) uud, udd
Ans: (d) uud, udd

42. Gell-Mann–Nishijima formula is [2]

(a) $Q = I_3 + \frac{3}{2}(B+S)$

(b) $Q = I_3 + \frac{1}{2}(B+S)$

(c) $Q = (B+S)$

(d) $Q = I_3 + (B+S)$

Ans: (b) $Q = I_3 + \frac{1}{2}(B+S)$

43. Hypercharge of the particles is
(a) $Y = 2Q - I_3$
(b) $Y = 2Q - 2I_3$
(c) $Y = Q - I_3$
(d) $Y = 2Q$
Ans: (b) $Y = 2Q - 2I_3$

44. Concept of Isospin is not applied to the from the following elementary paticles :
(a) Mesons
(b) Leptons
(c) Nucleons
(d) Hyperons
Ans: (b) Leptons

45. In elementary particle physics, the mirror symmetry is called as:
(a) Strangeness
(b) Isomerism
(c) Parity
(d) Charge independence
Ans: (c) Parity

46. The strangeness for Ω^- is
(a) 0
(b) -1
(c) -3
(d) -2
Ans: (c) -3

47. The sum of strangeness quantum number (S) and baryon number (Y) is called

(a) Isospin
(b) Intrinsic spin
(c) Hypercharge
(d) None of these
Ans: (c) Hypercharge

48. A particle moves in such a way that its kinetic energy just equal to its rest energy. The velocity of the particle is:
(a) 0.866c
(b) 0.25c
(c) 0.707c
(d) 0.5c
Ans: (a) 0.866c

49. A baryon is made up of
(a) A quark-antiquark pair
(b) Three quark
(c) Three antiquark
(d) An electron positron gamma state
Ans: (b) Three quark

50. Graviton have spin:
(a) 0
(b) 1
(c) 2
(d) 3
Ans: (c) 2

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