

MODULE 3

QUANTUM MECHANICS

Up to 19th century, the old classical mechanics proposed by Newton was enough to explain all motion of bodies . In 1900 Max plank explained black body spectrum .In order to understand the world of atomic or subatomic scale, a new branch in physics is necessary.Quantum mechanics is the science of microscopic world

COMPARISON BETWEEN NEWTONIAN MECHANICS & QUANTUM MECHANICS

NEWTONIAN MECHANICS

1. Related to macroscopic universe
2. Deals with motion under applied forces
3. Predicted values agrees with the observed values
4. Gives the correct behavior of moving bodies
5. Based on Newton's laws

QUANTUM MECHANICS

1. Related to microscopic universe
2. Based on uncertainty principle
3. Gives the relation between predicted value and observed value
4. Gives the probable value.
5. Schrodinger equation is the fundamental of Q.M

MATTER WAVES OR DE BROGLIE WAVES

Louis de Broglie introduced the concepts of matter waves.De Broglie argued that nature was symmetrical,then the fundamental quantities matter and energy should display symmetrical characters. If light shows dual nature then matter also shows particle nature and wave nature.

De Broglie hypothesis says that every moving matter exhibit wave like properties. The wave associated with a moving particle is called matter wave .

DE BROGLIE WAVELENGTH

Let c be the velocity of light. consider a photon of momentum p and frequency ϑ

$$mc^2 = h\vartheta$$

The momentum of the photon, $p = mc = h\vartheta/c$

$$\frac{\vartheta}{c} = \frac{1}{\lambda}$$

$$p = \frac{h}{\lambda} \quad \text{ie} \quad \lambda = \frac{h}{p}$$

If m is the mass and v is the velocity of the particle, then

De Broglie wavelength is

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

This is known as de Broglie wave equation.

DE BROGLIE WAVELENGTH FOR ELECTRONS

Consider an electron of mass m and charge e subjected to a potential difference of V volts. If v is the velocity acquired by the electron, then

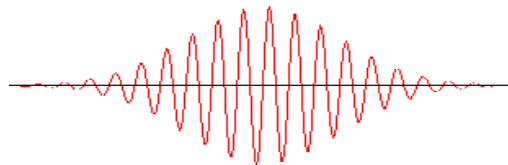
$$\frac{1}{2}mv^2 = eV$$

then wavelength

$$\lambda = \frac{h}{\sqrt{2meV}} = \sqrt{\frac{150}{V}} \text{Å} = \frac{12.3}{\sqrt{V}} \text{Å}$$

The wavelength of electron is inversely proportional to the square root of accelerating potential.

A WAVE PACKET



According to De Broglie hypothesis a wave is associated with a moving particle. Hence a particle can be represented by a wave confined in space.

A wave that is confined to a small region of space in the vicinity of the particle is called a wave packet. It is the envelope of number of waves superimposed. In Quantum mechanics a *particle can be represented by a wave packet*. They are not electromagnetic waves. The velocity of matter waves is not constant and it is always greater than the velocity of light.

WAVE PACKET, PHASE VELOCITY AND GROUP VELOCITY

The velocities of the individual waves which superimpose to produce the wave packet representing the particle are different - the wave packet as a whole has a different velocity from the waves that comprise it

Phase velocity, v : The velocity of individual waves that forming a wave packet.

Group velocity, u : The velocity with which wave packet moves .

$$U = \frac{c^2}{v}$$

WAVE FUNCTION

$$\Psi(r, t)$$

- I. Gives character about matter waves.
- II. Gives the probability of finding the particle at particular point and time

PHYSICAL CONCEPT (significance) OF WAVE FUNCTION

The quantity whose variation makes up the matter waves is called the wave function Ψ . The quantity that undergoes periodic changes of a body is Ψ .

$$\Psi = Ae^{i(kx - \omega t)}$$

Ψ is a complex valued function and itself has no physical meaning. The square of the absolute magnitude/ $|\Psi|^2$ or $\Psi \Psi^* dx dy dz$ gives the probability of finding the particle in the volume element $dx dy dz$. We can obtain the physical properties of the system if we know the wave function.

Since $\Psi \Psi^* dx dy dz$ is proportional to the probability of finding the particle with in the volume element, the integral $\int \Psi \Psi^* dx dy dz$ must be finite if the particle is somewhere there. If $\int \Psi \Psi^* dx dy dz$ is zero, the particle doesn't exist and if it is infinity, the particle is everywhere simultaneously.

Since the probability of finding the particle in the volume element is a surety, then

$$\int \Psi \Psi^* dx dy dz = 1$$

The wave function which obeys this condition is called normalized wave function.

REQUIREMENTS OF WAVE FUNCTION

1. Ψ must be finite, single valued and continuous.
2. $\partial \Psi / \partial x$, $\partial \Psi / \partial y$, $\partial \Psi / \partial z$ must also be continuous and single valued everywhere.
3. Ψ can be normalized

HEISENBERG'S UNCERTAINTY PRINCIPLE

According to the classical mechanics the position and momentum of a particle can be determined simultaneously with accuracy. In Newtonian mechanics every particle has a fixed position in space and has a definite momentum at any time. But the concept of dual nature, particle and wave, inspired Heisenberg to state the principle of uncertainty.

According to this principle it is impossible to have an accurate measurement of the position and momentum of particles simultaneously.

or

The Uncertainty Principle states that the simultaneous determination of the exact position and momentum of a moving particle is impossible

The product of uncertainty (error) in the measurement of position of the particle (Δx) and the uncertainty in the momentum (ΔP_x) of the particle is of the order of Planks constant.

$$\Delta x \cdot \Delta P_x = \hbar \quad (\hbar = h/2\pi)$$

$$\Delta y \cdot \Delta P_y = \hbar$$

$$\Delta z \cdot \Delta P_z = \hbar$$

If Δx is small, ΔP_x will be large and vice versa. If one quantity is measured accurately, the other quantity become less accurate. If $\Delta x = 0$, $\Delta P_x = \text{infinity}$; that is if we know the exact position of a particle we shall never know its momentum with certainty. If $\Delta P_x = 0$, $\Delta x = \text{infinity}$; that is if we know the momentum of particle, its position is not known.

Position & momentum

$$\Delta x \Delta p_x = \frac{h}{2\pi}$$

Similarly in the simultaneous measurement of energy and time, if ΔE and Δt are the uncertainties we have $\Delta E \Delta t = \hbar$

Energy & time

$$\Delta E \Delta t = \frac{h}{2\pi}$$

Angular position and angular momentum

$$\Delta J \Delta \theta = \frac{h}{2\pi}$$

APPLICATIONS OF UNCERTAINTY PRINCIPLE

1. Uncertainty in frequency of light emitted by an atom

An electron exists in an excited state only for a short interval of time. Thus Δt is small, then ΔE must be large

$$\Delta t = 10^{-8} \text{ s}$$

$$\Delta E \Delta t = \hbar$$

The uncertainty in energy, $\Delta E = \hbar / 10^{-8}$

$$E = h \nu$$

$$\Delta E = h \Delta \nu$$

$$\Delta \nu = \Delta E / h$$

$$\Delta \nu = \left[\frac{\frac{h}{2\pi}}{10^{-8}} \right] * \frac{1}{h} = 1.67 * 10^7 \text{ Hz}$$

2. Non existence of electron in the nucleus

The nuclear diameter is of the order of 10^{-15} m . If an electron exists in the nucleus, the maximum uncertainty, Δx , in position is of the order of the diameter.

So the uncertainty in the momentum,

$$\begin{aligned} \Delta p &= \frac{\hbar}{\Delta x} = \frac{6.626 \times 10^{-34}}{2 \times 3.14 \times 10^{-15}} \\ &= 1.055 \times 10^{-19} \text{ kg m/s} \end{aligned}$$

The energy of electron is given by

$$\begin{aligned}
 E &= pc = 1.055 \times 10^{-19} \times 3 \times 10^8 \\
 &= 3.165 \times 10^{-11} \text{ J} \\
 &= 3.165 \times 10^{-11} / 1.6 \times 10^{-19} \text{ eV} \\
 &= 1.98 \times 10^8 \text{ eV} \\
 &= 198 \text{ MeV}
 \end{aligned}$$

For an electron to exist in the nucleus, it should have an energy of this order. Energy of an electron is of the order of only a few MeV. So it is not possible for electron to exist inside nucleus

3. Natural line broadening

The average time period that takes between the excitation of an atom and the time it radiates is 10^{-8} . Thus the photon energy is uncertain by the amount

$$\begin{aligned}
 \Delta E &= \hbar / \Delta t \\
 &= 1.055 \times 10^{-26} \text{ J}
 \end{aligned}$$

It means that the excited energy levels have a finite energy spread. Thus the energy levels of the atom must have a finite width or in other words the spectral lines can never be sharp but have some broadening in frequency, called natural line broadening.

OPERATORS

An operator transforms one function to another function. If the operator A transforms $f(x)$ into the function $g(x)$, then we can write

$$g(x) = A f(x)$$

In Q.M each dynamic variable is represented by an operator which acts on a wave function to give a new wave function.

The operators associated with some of the dynamical variables is given below

Dynamical Variable	Quantum Mechanical operator
time t	t
Position Co-ordinates x, y, z	x, y, z
Momentum co-ordinates p_x, p_y, p_z	$-i\hbar \frac{\partial}{\partial x}, -i\hbar \frac{\partial}{\partial y}, -i\hbar \frac{\partial}{\partial z}$
Momentum p	$-i\hbar \nabla$
Energy E	$i\hbar \frac{\partial}{\partial t}$

TIME DEPENDENT SCHRÖDINGER EQUATION FOR A FREE PARTICLE

Schrodinger's equation is the basic expression in quantum mechanics. We can derive it by considering the plane wave equation and combining with Einstein's eqn for quantum energy and de Broglie expression for wavelength.

A particle in motion is associated with a wave function that contains the information about the motion.

A plane wave that propagates along x- direction is given by

$$\Psi = Ae^{i(kx - \omega t)}$$

where k is the wave vector, $k = 2\pi/\lambda$

ω is the angular frequency, $\omega = 2\pi\nu$

Einstein's formula for photon energy is

$$E = h\nu = \frac{h\omega}{2\pi} = \hbar\omega; \text{ where } \hbar = \frac{h}{2\pi}$$

de-Broglie's expression for matter wavelength is $\lambda = \frac{h}{p}$

$$\therefore p = \frac{h}{\lambda} = \frac{h}{2\pi} \cdot \frac{2\pi}{\lambda} = \hbar k$$

Using the above expression, equation (1) becomes

$$\Psi = Ae^{\frac{i}{\hbar}(\hbar kx - \hbar\omega t)}$$

$$\text{ie } \Psi = Ae^{\frac{i}{\hbar}(px - Et)}$$

On partial differentiation of Ψ with respect to x, twice, we get

$$\frac{\partial^2 \Psi}{\partial x^2} = \frac{-p^2}{\hbar^2} \Psi \dots\dots\dots(2) \quad \text{and}$$

Differentiating with respect to time,

$$\frac{\partial \Psi}{\partial t} = \frac{-iE}{\hbar} \Psi \dots\dots\dots(3)$$

$$p^2 \Psi = -\hbar^2 \frac{\partial^2 \Psi}{\partial x^2} \dots\dots\dots(4)$$

$$= -i\hbar \frac{\partial}{\partial x} \left(-i\hbar \frac{\partial}{\partial x} \right) \Psi \dots\dots\dots(4a)$$

From 3 and 4, $p = -i\hbar \frac{\partial}{\partial x}$

This is called momentum operator:

$$E \Psi = i\hbar \frac{\partial \Psi}{\partial t} \dots\dots\dots(5)$$

$$\therefore E = i\hbar \frac{\partial}{\partial t} \dots\dots\dots(5a)$$

This is called Energy operator.

For a free particle total energy is given by

$$E = \frac{p^2}{2m}, \text{ since } V = 0$$

$$\text{ie } E \Psi = \frac{p^2}{2m} \Psi \dots\dots\dots(6)$$

Using equation (4) and (5), Equation (6) becomes

$$\frac{-\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} = i\hbar \frac{\partial \Psi}{\partial t} \dots\dots\dots(7)$$

This is Schrodinger's equation for a free particle in one dimension.

In three dimension it becomes for a free particle,

$$\frac{-\hbar^2}{2m} \nabla^2 \Psi = i\hbar \frac{\partial \Psi}{\partial t} \dots\dots\dots(8)$$

$$\text{where } \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

is called *Laplacian operator*

If the particle is moving under a potential $V(r,t)$ then equation (8) becomes

$$\left[\frac{-\hbar^2}{2m} \nabla^2 + V_{(r,t)} \right] \Psi = i\hbar \frac{\partial \Psi}{\partial t}$$

This is Schrodinger's time dependent equation

TIME INDEPENDENT SCHRÖDINGER EQUATION (STEADY STATE EQUATION)

According to Schrodinger, de- Broglie's wavelength holds good for any particle moving in any field of force with potential energy V.

Then total energy $E = \text{Kinetic energy} + \text{Potential Energy}$

$$E = \frac{1}{2} m v^2 + V$$

$$= \frac{p^2}{2m} + V$$

$$\text{ie } p^2 = 2m(E - V)$$

$$\text{or } p = [2m(E - V)]^{1/2}$$

The wave equation in Cartesian co-ordinate system can be written as

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} = \frac{1}{u^2} \frac{\partial^2 \Psi}{\partial t^2} \dots\dots\dots(9)$$

$$\text{where } \Psi = \Psi_0 e^{-i\omega t} \dots\dots\dots(10)$$

'u' is the velocity of motion of wave and $\Psi(x, y, z, t)$ represents the amplitude of the wave associated with the particle

From (10), we get

$$\frac{\partial^2 \Psi}{\partial t^2} = -\omega^2 \Psi$$

So Equation (9) becomes

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} = \frac{-\omega^2}{u^2} \Psi \dots\dots\dots(11)$$

$$\frac{\omega^2}{u^2} = \frac{(2\pi\nu)^2}{(\nu\lambda)^2} = \frac{4\pi^2}{\lambda^2}$$

So we have

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} = \frac{-4\pi^2}{\lambda^2} \Psi \quad \text{or}$$

$$\nabla^2 \Psi + \frac{4\pi^2}{\lambda^2} \Psi = 0 \dots\dots\dots(12)$$

Equation (12) is a general equation which is independent of time.

Let us now introduce the concept of de-Broglie wavelength.

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m(E - V)}}$$

$$\lambda^2 = \frac{h^2}{2m(E - V)}$$

Substituting the wavelength in eqn (12)

$$\nabla^2 \Psi + \frac{4\pi^2}{h^2} [2m(E - V)] \Psi = 0$$

or

$$\nabla^2 \Psi + \frac{8\pi^2 m}{h^2} (E - V) \Psi = 0$$

or

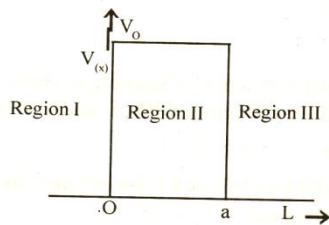
$$\nabla^2 \Psi + \frac{2m}{\hbar^2} (E - V) \Psi = 0 \dots \dots \dots (13)$$

This represents Schrodinger's time - independent wave equation.

For the case of a free particle ($V=0$), the Schrodinger equation becomes

$$\nabla^2 \Psi + \frac{2mE}{\hbar^2} \Psi = 0$$

QUANTUM MECHANICAL TUNELLING



Consider particle of mass m incident on the barrier from left

Classically

If $E < V_0$ all the particle will be reflected at the barrier

If $E > V_0$ all will be transmitted in to the region III

Quantum mechanically

If $E < V_0$ there will be a finite probability for the particle to be transmitted in to the region III

This phenomenon of tunnelling through the barrier is known as quantum mechanical tunnelling or barrier penetration . The solution of the schrodinger equation for the particle gives the wave function for the three region

Region I

wave function corresponds to two wave - one wave for the incident particle & other is for the reflected particle by the barrier

Region II

two solution are possible – an exponentially increasing function & an exponentially decreasing function

Region III

wave travelling from left to right

The concept is used to explain a number of phenomena in physics

1. The emission of α particles from the radioactive nuclei
2. Barrier penetration in tunnel diode and Josephson junction
3. Electron tunnelling in scanning tunnelling microscope

ONE DIMENSIONAL INFINITE SQUARE WELL POTENTIAL

Consider the motion of a particle of mass m confined to move in a one dimensional square well of infinite depth.

Since there is no interaction between the particle and wall, the potential energy of the particle is taken to be zero. It is very clear that potential energy does not depend on time and we are considering only time independent Schrodinger equation for the solution. The problem is one dimensional and the Schrodinger equation is

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} (E - V) \psi = 0$$

since $V = 0$, the equation becomes

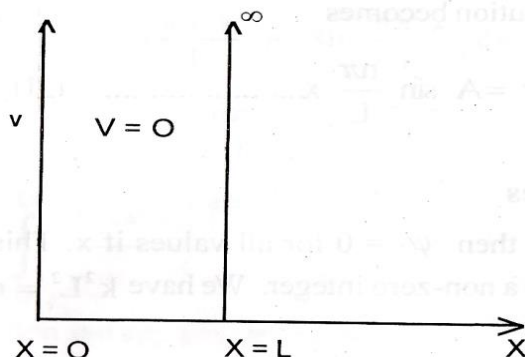
$$\frac{d^2\psi}{dx^2} + \frac{2mE}{\hbar^2} \psi = 0 \quad \text{or}$$

$$\frac{d^2\psi}{dx^2} + k^2 \psi = 0 \quad \text{where } k^2 = \frac{2mE}{\hbar^2} \dots\dots\dots(17)$$

The solution of the above differential equation is of the form

$$\psi = A \sin kx + B \cos kx \dots\dots\dots(18)$$

The solution has to be well behaved wave function. Since the particle is inside a square well of infinite depth, it is impossible to find the particle outside. i.e. ψ must be zero for all points outside the square well.



$$\psi = 0 \text{ for } x < 0 \text{ and}$$

$$\psi = 0 \text{ for } x > L$$

This is possible only if $\psi = 0$ at $x = 0$ and $x = L$ as demanded by continuity condition.

Applying first condition on equation 18, we get

$$0 = A \sin 0 + B \cos 0$$

$$\text{ie } B = 0$$

So solution reduces to

$$\psi = A \sin kx \dots \dots \dots (19)$$

Using the next condition $\psi = 0$ at $x = L$, we get

$$0 = A \sin kL$$

There are two possibilities. Either $A = 0$ or $\sin kL = 0$

A cannot be zero, since the wavefunction cannot exist. So we have the other possibility

$$\sin kL = 0$$

$$\text{ie } kL = n\pi \dots \dots \dots (20)$$

where n is an integer.

So the solution becomes

$$\psi = A \sin \frac{n\pi}{L} x \dots \dots \dots (21)$$

Eigen Values

If $n = 0$, then $\psi = 0$ for all values of x . This is ruled out.

Therefore n is a non-zero integer. We have $k^2 L^2 = n^2 \pi^2$ on using equation (17)

$$k^2 = 2mE/\hbar^2$$

$$\frac{2mE}{\hbar^2} L^2 = n^2 \pi^2$$

$$E = \frac{n^2 \pi^2 \hbar^2}{2mL^2} \quad \text{or}$$

$$E_n = \frac{n^2 \pi^2 \hbar^2}{2mL^2} \quad \text{ie} \quad E_n = \frac{n^2 h^2}{8mL^2}$$

E_n as the energy corresponding to n . The quantity n is called quantum number. The different values of energy for n are called **Eigen values**. Since n is restricted, the particle cannot have any value of energy but will be restricted to certain values.

Eigen wave functions

The wave functions associated with different Eigen values of energy are called **Eigen Functions**.

By applying the normalization condition,

$$\int \psi^* \psi dx dy dz = 1$$

So we have $\int_0^L A \sin \frac{n\pi x}{L} A \sin \frac{n\pi x}{L} dx = 1$

$$A^2 \int_0^L \sin^2 \frac{n\pi x}{L} dx = 1$$

$$A^2 \int_0^L \frac{1 - \cos 2 \left(\frac{n\pi x}{L} \right)}{2} dx = 1.$$

On integration and applying limits we get

$$A^2 \frac{L}{2} = 1 \quad \text{or } A = \sqrt{\frac{2}{L}}$$

So the normalised wave function is

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right) \quad \text{where } n = 1, 2, 3, \dots \quad (22)$$

For the ground state $n=1$, the wave function is given by

$$\psi_1 = \sqrt{\frac{2}{L}} \sin \frac{\pi x}{L}$$

Similarly the wave function for the first two excited states are given by

$$\psi_2 = \sqrt{\frac{2}{L}} \sin \frac{2\pi x}{L} \quad \psi_3 = \sqrt{\frac{2}{L}} \sin \frac{3\pi x}{L}$$

These wave functions associated with different energy are called Eigen wave functions.

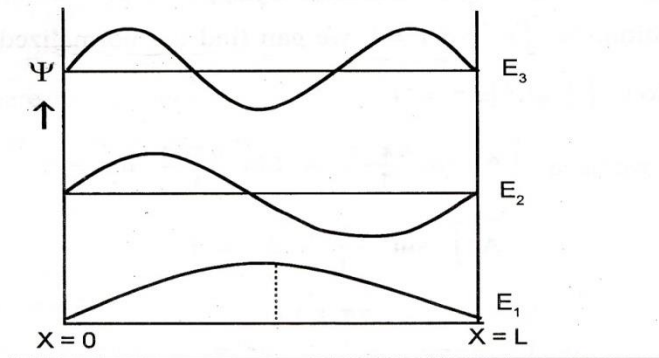
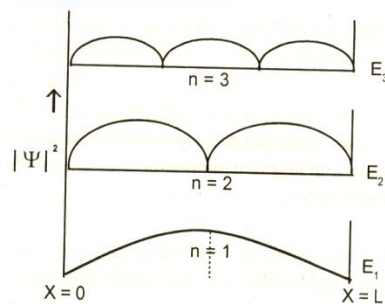


Fig. 2 wave function of first three energy levels



NANOTECHNOLOGY

Study of matter at atomic level is Nano technology . One nanometer(nm) 10^{-9} (or one billionth) of a meter. Generally nanotechnology deals with structures of size 100 nm or smaller.

Nanofabrication

Nanofabrication involves 2 ways

- **'Top-down' fabrication:** Starting with a chunk of materials and cutting it to nano scale.
- **'Bottom-up' fabrication:** Starting with individual atoms and building up to nanostructure.

The theoretical predictions of the present Nanotechnology were made by Richard Feynman in 1959. In a talk entitled “there is plenty of room at the bottom” . Molecular self assembly is the science of automatically arranging molecules themselves into some useful structures through a “bottom up “ approach. The ability of one molecule to attract and bind to another is referred to as molecular recognition

Increase in surface to volume ratio

Nano material have a relatively larger surface area to volume ratio when compared to bulk solids. Consider a sphere of radius ‘r’ .

The surface area $= 4\pi r^2$

Its volume $= \frac{4}{3} \pi r^3$

$$\text{Ratio} = \frac{\text{surface area}}{\text{volume}} = \frac{3}{r}$$

Thus when the radius of the sphere decreases, its surface area to volume ratio increases. Hence as the particle size decreases a greater number of atoms are found at the surface compared to those inside. Thus nano material have more surface area per given volume compared with larger particles. It makes material more chemically reactive as chemical reaction occurs at surfaces.

When the size of the bodies decrease, physical properties of the bodies change. A number of physical properties(mechanical, electrical, optical) change like this.

Examples of physical change at nanosize

- When nano scale is reached, the colour of gold changes, its melting point and chemical properties changes.
- Nano gold does not act like bulk gold
- Copper which is opaque become transparent.

- Stable materials like aluminium turn combustible.
- Solids turn into liquid at room temperature(gold)
- Insulators become conductors (silicon)
- Chemically inert materials like gold become good catalyst (reactive) at nano scales.

SIGINIFICANCE OF NANO SCALE

The important factors that cause significant change in the properties of nano materials are

- Increased surface to volume ratio
- Quantum confinement effects

Quantum Confinement Effects

When electron gets excited in a semi conductor due to thermal excitation, an electron-hole pair is created. The electron in the conduction band and hole in the valence band can be bound when the, approach each other at a finite distance. This bound pair is called EXCITON. Bulk material have continuous energy levels. In the case of nano range, the energy level become discrete. As the size reduces energy level changes from continuous to discontinuous. This increases the band gap energy. Motion of the electron become restricted. the band gap and wavelength are inversely related to each other. Wavelength decrease with the decrease in size and proof is the emission of blue radiation

To understand this effect we break the word like quantum and confinement. The word confinement means to confine the motion of randomly moving electron to restrict its motion in specific energy levels. Quantum reflects the atomic domain of particles. The quantum confinement effects is observed when the size of the particle is too small to be comparable to the de-broglie wavelength of the electron

Quantum confinement is the restricted motion of randomly moving electron in specific energy levels when the dimensions of a material approach the de Broglie wavelength of electron

When the material size is sufficiently small(10nm or less) the electrons and holes are squeezed into a dimension that approaches a quantum measurement called "Exciton Bohr Radius". When the particle size approaches the Bohr exciton radius, the quantum confinement effect increases .

Nanostructured materials

The material which have at least one dimension in the order of nanometer are called nanostructured materials

Based on number of dimensions that are confined, nano structure is classified in to 4 categories

1. Zero dimensional (0D) nano structured material:- If all the three dimensions become nanometer range, we obtain a Zero dimensional nano structure called nano particles
2. One dimensional (1D) nano structured material:- If two dimensions are restricted and one dimension remains large, then the resulting structure is one dimensional nano structure called nano wires, nano rods and nano tube
3. Two dimensional (2D) nano structured material:- If one dimension is reduced to the nano range while the other two dimensions remain large, then a two dimensional nano structured material are obtained (nano sheet)
4. Three dimensional (3D) nano material:- all the 3 dimensions become large (bundles of nano wires)
 - Zero dimensional (0D) nano structured material - 3 D confinement
 - One dimensional (1D) nano structured material - 2 D confinement
 - Two dimensional (2D) nano structured material - 1 D confinement
 - Three dimensional (3D) nano material – 0 D confinement

Quantum sheets

Quantum sheets are two dimensional structure in which quantum confinement act only in one direction. Quantum confinement act along the thickness of the film. Electrons are free to move in xy plane of the film. So quantum confinement is in one dimension and are free to move in 2 dimensions. They are now used to make semiconductor lasers, LEDs and solar cell .

Quantum wires

A nano wire or quantum wire is a wire of dimensions of the order of nanometers. Quantum wire is a one dimensional structure. Quantum wires are formed when 2 dimensions of the system are confined ie by making a thin wire of semiconductor. Two direction have quantum confinement. It is only free to move along one dimension that is along the wire. A quantum wire is an electrically conducting wire in which quantum effects influence the transport properties. Such effects appear in the dimension of Nano meters. So they are called Nano wires. Electrical conductance of wire is found to be quantized in multiples of $2e^2/h$. quantum wires can be used as an electron wave guide. It is used to make high speed lasers.

Quantum dots

Quantum dots are zero dimensional structure in which the electron is confined in all three dimensions. Their energy states are quantized in all three directions. consider a tiny dot

of semi conductor material then we have a 3D quantum confinement of charge carriers. That is there are no freely moving electrons or holes in any direction. This is called “quantum dot”. Although this quantum dot consists of thousands of atoms it behaves like a single atom with discrete energy levels rather than many atoms. When the size of the crystal become so small that it approaches the size of exciton bohr radius, then the electron energy levels will change from continuous to discrete values. That is there is a finite separation between energy levels. The energy gap increases with the decreases in the diameter of the dot. So quantum dot can emit any colour from blue to red depending on the size of the dot.

Variation of properties of nano materials

1. Physical properties
2. Chemical properties
3. Electrical properties
4. Optical properties
5. Magnetic properties
6. Mechanical properties

Electrical properties

- Ionization potential at nano sizes are higher than that at bulk solids.
- The change in electrical properties is not the same in all nano materials.
- In nano ceramics the electrical conductivity increases with the decrease in particle size.
- But in metals it decreases.
- In the case of bulk metals the energy level of electron is continuous where as in nano sized metals the energy levels are discrete.

Optical properties

- Depending on the particle size, same substance shows different colours.
- Gold spheres of 100 nm size appears orange while that of 50 nm size appears green

The particles can be made to emit or absorb specific wavelength of light by varying its size

Mechanical properties

- Nano crystalline nickel is as strong as hardened steel. Because of nano size many mechanical properties such as hardness, elastic modulus, fracture toughness, scratch resistance and fatigue strength are modified
- 30-50 % lower elastic moduli than conventional materials
- 2-7 times higher hardness
- Super plastic behaviour in brittle ceramics

NANOCLUSTERS

Their size is in between bulk materials and their atoms or molecules. Their properties are fundamentally different from those of discrete molecules and bulk solids

Fullerenes

They are spheroidal in structure. They are the largest molecules formed by the same atoms. A carbon molecule with chemical formula C_{60} containing 60 carbon atoms in the shape of a soccer ball. A mass number of 720 consisting of 60 carbon atoms, each of mass 12 was seen. Named after the architect buckminster fuller. Solid state: FCC structure.

CARBON NANOTUBE

When a single sheet of sp^2 hybridized graphite (graphene) is curled in the form of a cylinder, carbon nanotubes are formed

Applications of Nanotechnology

Nanomedicine

- Cell imaging
- Treating cancer
- For diagnostic purposes
- The drug consumption and side effects can be reduced significantly by targeted medicine.
- This is done depositing the medicine in the affected region only and in the correct dose
- NT helps to reproduce or repair damaged tissue.

In Energy

Applications in the field of energy are

1. By reducing energy consumption
by designing LEDs or Quantum Caged Atoms(QCAs) etc.
2. By increasing energy production efficiency
by designing specific catalysts to improve the combustion efficiency in IC engines
3. By using more environmentally friendly energy systems
such as fuel cells powered by hydrogen
4. By recycling batteries
rechargeable batteries using nanomaterials

chemistry and Environment

- Chemical catalysts from nanoparticles are highly useful
- Filtration : Nanofiltration helps

1. Waste water management
2. Air purification
3. Energy storage devices

Information and communication

- Memory storage devices such as Nano-RAM is developed using nanotubes
- **Food**
- There are more than thousand nanoproducts in the market.
- Eg. of food products are canola cooking oil, nanotea etc.

Textiles

- Clothes made of nanofibers are stain-repellent and wrinkle-free
- These textiles can be washed less frequently

Implication of Nanotechnology

- Nano Pollution
- Lack of Privacy
- Nano Weapons