APPLIED PHYSICS 2

2nd Semester | Diploma / Polytechnic

UNIT – 7

MODERN PHYSICS

Bohr's Atomic Model • X-Rays • Laser • Fiber Optics • Nanotechnology

Unit – 7: Modern Physics

Modern Physics deals with the behaviour of matter and energy at atomic and subatomic scales. It emerged in the early 20th century and forms the foundation of technologies such as lasers, X-ray machines, optical fibres, and nanotechnology. This unit covers atomic structure, electromagnetic radiation, quantum phenomena, and their engineering applications.

1. Bohr's Atomic Model

In 1913, Danish physicist Niels Bohr proposed a modified atomic model to explain the stability of the atom and the line spectrum of hydrogen. He combined classical mechanics with quantum ideas to describe electron motion.

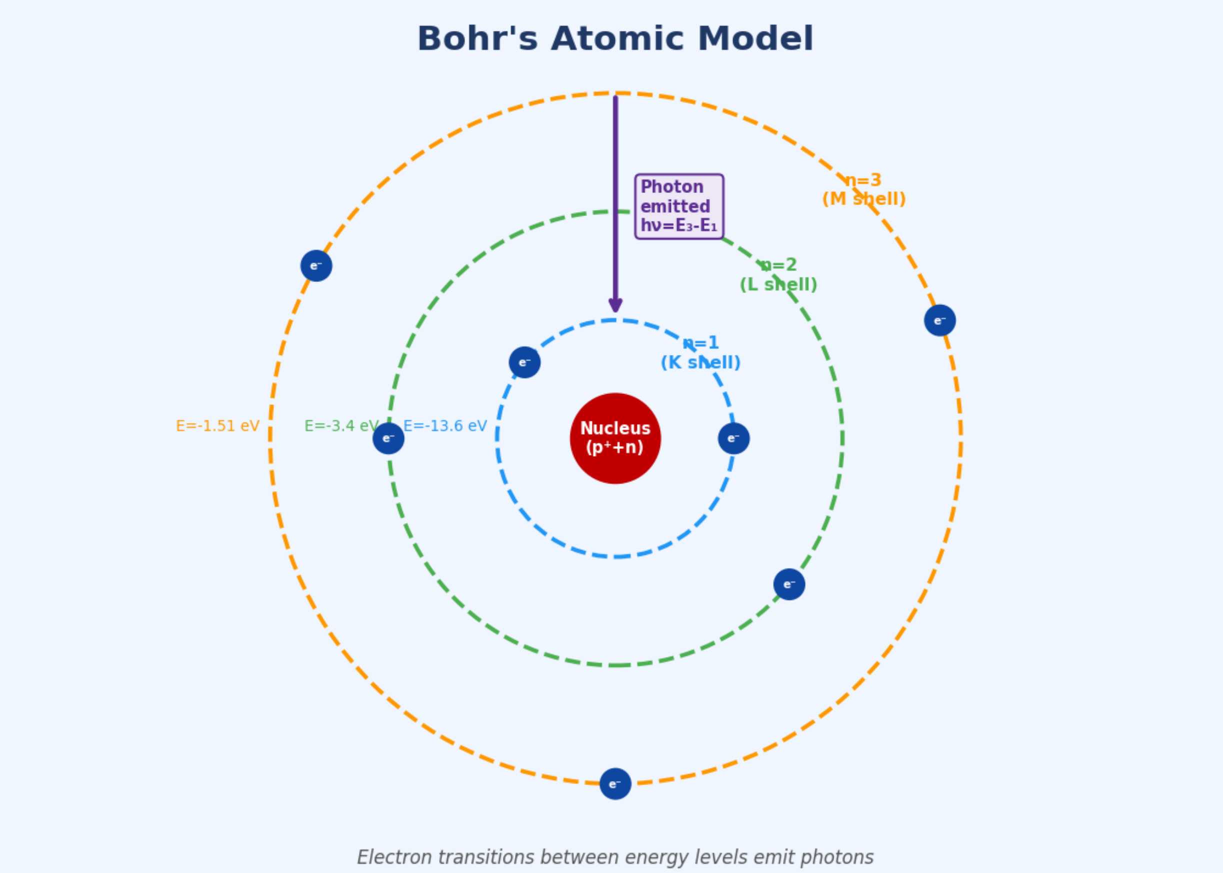

Fig. 1 – Bohr's Atomic Model: Electrons in fixed orbits (K, L, M shells) around the nucleus; arrow shows electron transition emitting a photon

1.1 Postulates of Bohr's Atomic Model

- Electrons revolve around the nucleus in fixed circular orbits called stationary orbits or energy levels. As long as an electron stays in its orbit, it neither emits nor absorbs energy.
- Only those orbits are allowed in which the angular momentum of the electron is an integral multiple of $h/2\pi$ (quantisation of angular momentum): $mvr = nh/2\pi$
- When an electron jumps from a higher energy level (E_2) to a lower level (E_1), it emits a photon of energy: $hv = E_2 - E_1$. Absorption of a photon causes upward jump.
- The energy of an electron in the nth orbit (hydrogen): $E_n = -13.6/n^2$ eV

1.2 Energy Levels

Each orbit corresponds to a fixed energy value. The innermost orbit (n=1) has the lowest energy — the ground state. When electrons are excited, they move to higher levels. When they fall back, they emit photons of specific frequencies, producing atomic spectra.

Key Formulas

- Angular momentum: $mvr = nh/2\pi$
- Energy of nth orbit (Hydrogen): $E_n = -13.6/n^2$ eV
- Energy of emitted photon: $E = hv = E_2 - E_1$
- Radius of nth orbit: $r_n = 0.53 \times n^2$ Å

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2. Ionisation and Excitation Potential

2.1 Excitation Potential

Definition: The minimum energy (in eV) required to raise an electron from its ground state to a higher energy level (excited state) is called excitation potential.

The atom is then in an ‘excited state’, which is unstable. The electron quickly falls back to a lower level, emitting a photon.

2.2 Ionisation Potential

Definition: The minimum energy required to completely remove an electron from the atom is called ionisation potential. For hydrogen, ionisation energy from ground state = 13.6 eV.

Key Difference: Excitation vs Ionisation

- Excitation: Electron moves to a higher orbit but stays within the atom.
- Ionisation: Electron is completely removed from the atom.
- Excitation energy < Ionisation energy always.
- Both are measured in electron volts (eV).

3. X-Rays

X-rays were discovered by Wilhelm Röntgen in 1895. They are electromagnetic radiation with very short wavelengths (0.01–10 nm) and high energy, capable of penetrating matter.

3.1 Nature and Properties

- Electromagnetic waves of very short wavelength (0.01–10 nm).
- Travel in straight lines at the speed of light (3×10^8 m/s).
- Not deflected by electric or magnetic fields.
- Can ionise gases and cause fluorescence in certain materials.
- Penetrate through soft tissues and thin metals.
- Affect photographic plates; can cause biological damage at high doses.
- Exhibit wave properties: diffraction, interference, and polarisation.

3.2 Production of X-Rays – Coolidge Tube

The Coolidge tube is the standard X-ray production device. High-speed electrons, when suddenly decelerated by striking a metal target, produce X-rays.

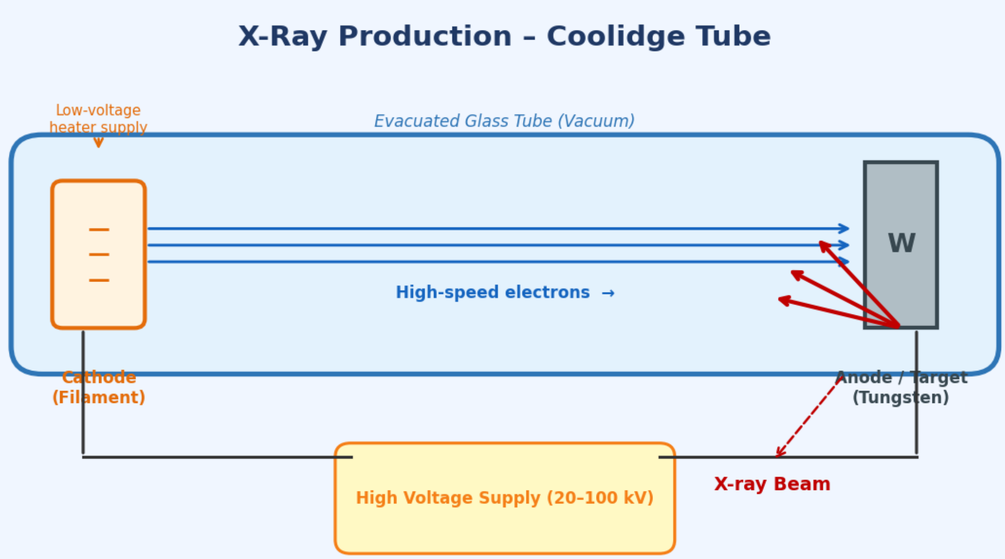

Fig. 2 – Coolidge X-Ray Tube: Heated cathode emits electrons; HV supply accelerates them toward tungsten anode; sudden deceleration produces X-rays

- The cathode is a heated tungsten filament (thermionic emission of electrons).
- High voltage (20–100 kV) accelerates electrons toward the tungsten anode (target).
- Sudden deceleration of electrons at the target produces X-rays.

- Intensity is controlled by heater current; hardness is controlled by applied voltage.

3.3 X-Ray Spectrum

The X-ray spectrum has two components: continuous (Bremsstrahlung) X-rays formed over a range of wavelengths, and sharp characteristic X-ray peaks specific to the target material.

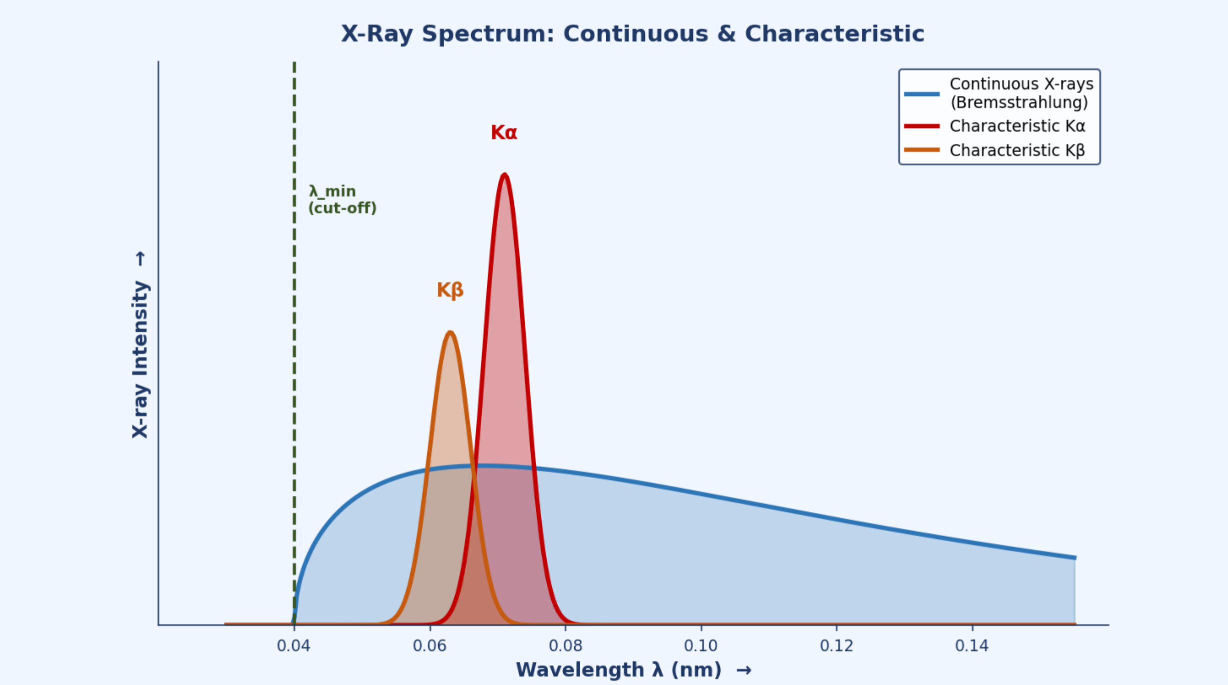

Fig. 3 – X-Ray Spectrum: Smooth continuous curve (Bremsstrahlung) with sharp Kα and Kβ characteristic peaks; λ_{min} marks the minimum wavelength cut-off

Continuous X-rays (Bremsstrahlung): Electrons lose varying amounts of energy as they are deflected near nuclei, producing X-rays across a range of wavelengths.

Characteristic X-rays: When incident electrons knock out inner-shell (K/L) electrons, outer-shell electrons fill the vacancy, emitting X-rays at fixed, element-specific wavelengths (Kα, Kβ peaks).

3.4 Soft vs Hard X-Rays

Property	Soft X-Rays	Hard X-Rays
Wavelength	Longer (~1–10 nm)	Shorter (~0.01–0.1 nm)
Energy	Lower energy	Higher energy
Penetrating Power	Less – absorbed easily	More – penetrates deeply
Voltage Used	Low (~20 kV)	High (~100 kV+)
Application	Crystallography, surface imaging	Medical diagnosis, therapy

3.5 Uses of X-Rays

- Medical diagnosis – detecting fractures, tumors, lung diseases.
- Cancer treatment (radiotherapy) – hard X-rays destroy cancerous cells.
- Industrial inspection – detecting internal cracks in metal castings.
- Security scanning – baggage X-ray screening at airports.
- Crystal structure analysis – X-ray diffraction for molecular structure.

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4. Laser

LASER = Light Amplification by Stimulated Emission of Radiation. A laser produces an intense, highly directional, monochromatic, and coherent beam of light.

4.1 Spontaneous Emission

An excited atom randomly returns to ground state after $\sim 10^{-8}$ s by releasing a photon of random direction and phase. This is spontaneous emission — responsible for ordinary light sources (bulbs, LEDs).

4.2 Stimulated Emission

When an excited atom is struck by a photon of exactly the right energy ($E_2 - E_1$), it is triggered to emit a second photon identical to the incident one in energy, direction, phase, and polarisation. This is stimulated emission — the basis of laser action.

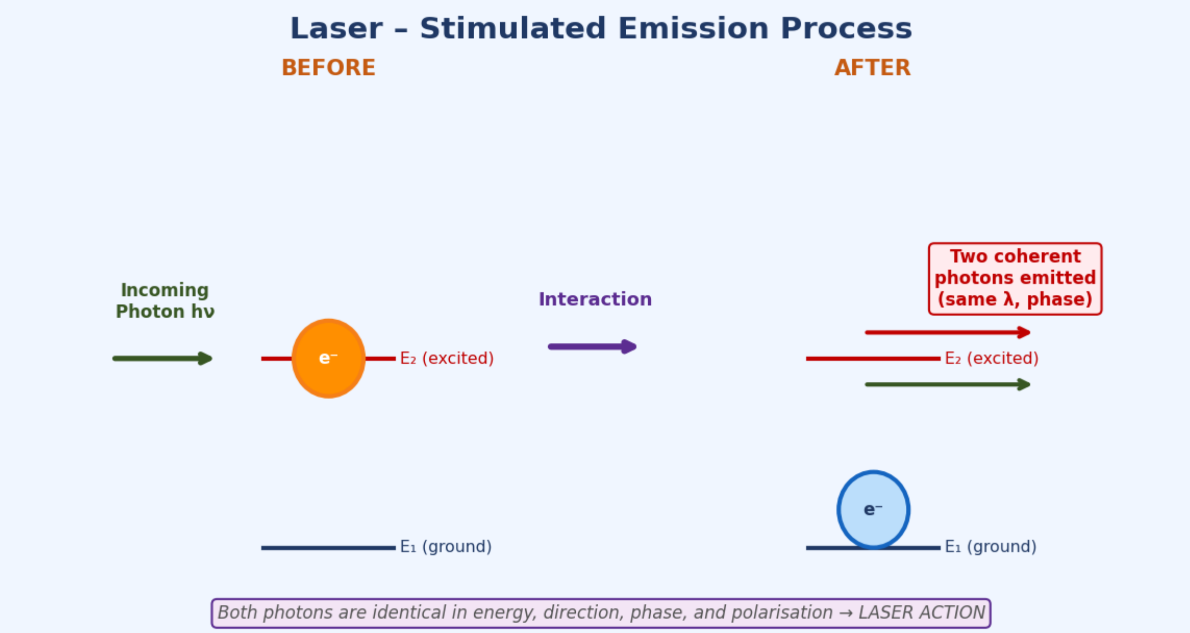

Fig. 4 – Stimulated Emission: Incoming photon triggers excited atom to emit a second identical photon; both are coherent, same direction and phase

Population Inversion: For laser action, more atoms must be in the excited state than in the ground state. This is called population inversion and is created by a pumping mechanism (optical, electrical, or chemical).

4.3 Characteristics of Laser Light

- Monochromaticity: Single, very precise wavelength.
- Coherence: All photons in the same phase and frequency.
- Directionality: Extremely narrow beam with very little divergence.
- High Intensity: Energy concentrated in a tiny area; very intense beam.

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5. He-Ne Laser

The Helium-Neon (He-Ne) laser is the most widely used gas laser, producing a visible red beam at 632.8 nm. It was the first continuous-wave laser (1960).

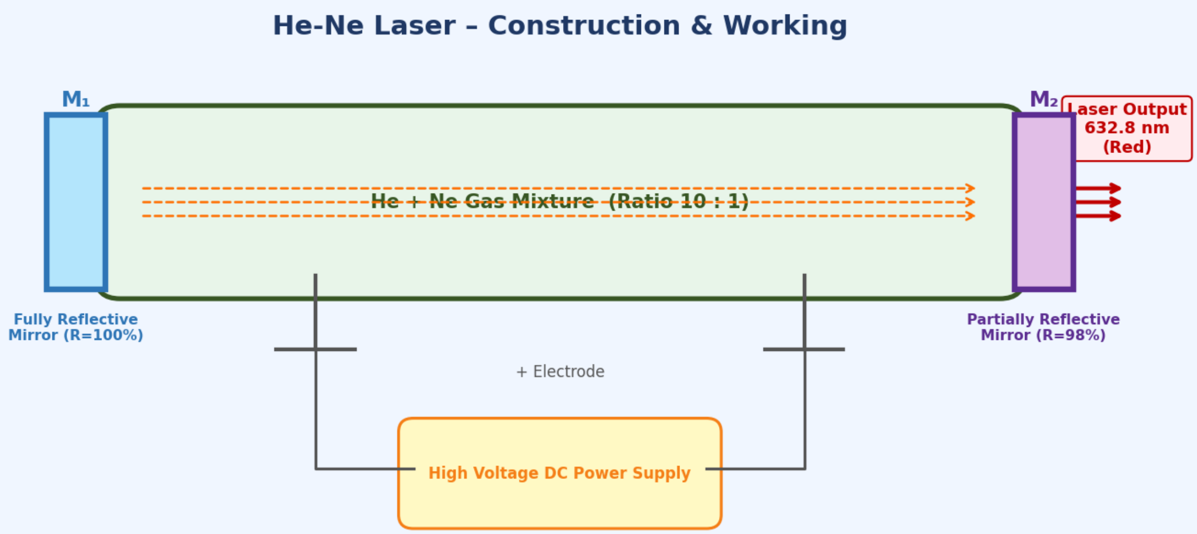

Fig. 5 – He-Ne Laser Setup: He+Ne gas tube between two mirrors (M_1 100% reflective, M_2 98% reflective); electrons excite He atoms which transfer energy to Ne; laser output exits through M_2

5.1 Construction

- Long narrow glass discharge tube filled with He+Ne gas mixture (ratio 10:1) at low pressure.
- Two electrodes connected to a high-voltage DC supply for electrical discharge (pumping).
- Two mirrors: fully reflective (M_1, 100%) and partially reflective (M_2, ~98%) forming an optical resonator.

5.2 Working Principle

- Electrical discharge: electrons collide with He atoms, exciting them to He*.
- He* atoms collide with Ne atoms, transferring energy — creating population inversion in Ne.
- Excited Ne atoms undergo stimulated emission, emitting photons of 632.8 nm.
- Photons bounce between mirrors, amplifying the beam by stimulating more Ne atoms.
- The output laser beam exits through the partially reflective mirror (M_2).

5.3 Characteristics

- Wavelength: 632.8 nm (visible red light)
- Continuous wave (CW) operation – operates continuously, not in pulses.
- Low power output (1–50 mW), highly coherent and directional.
- Gas laser – stable, precise, and widely used in labs and instruments.

6. Applications of Laser

Lasers are used across fields due to their unique properties of high intensity, coherence, and monochromaticity.

- **Medical:** Laser surgery (LASIK eye surgery), cutting and sealing tissues, dermatology, dentistry, and cancer treatment (photodynamic therapy).
- **Industrial:** Laser cutting, welding, drilling, and surface hardening of metals with high precision.
- **Communication:** Transmitting data as light pulses through fibre optic cables over long distances.
- **Defence:** Laser rangefinders, target designators, and laser-guided missiles.
- **Scientific Research:** Spectroscopy, holography, nuclear fusion research, and atomic physics.
- **Barcode Scanners:** Reading barcodes instantly in supermarkets and warehouses.
- **Optical Storage:** CD, DVD, and Blu-ray discs use lasers to read and write data.
- **Printing:** Laser printers use a focused beam to produce high-quality text and images.

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7. Fiber Optics

Fibre optics is the technology of transmitting light through thin, transparent glass or plastic fibres. It has revolutionised communication, allowing data to be sent at the speed of light over very long distances.

7.1 Introduction

An optical fibre is a thin, flexible strand (~125 µm diameter) of transparent material that guides light from one end to the other with virtually no loss. A fibre optic cable contains hundreds or thousands of such fibres.

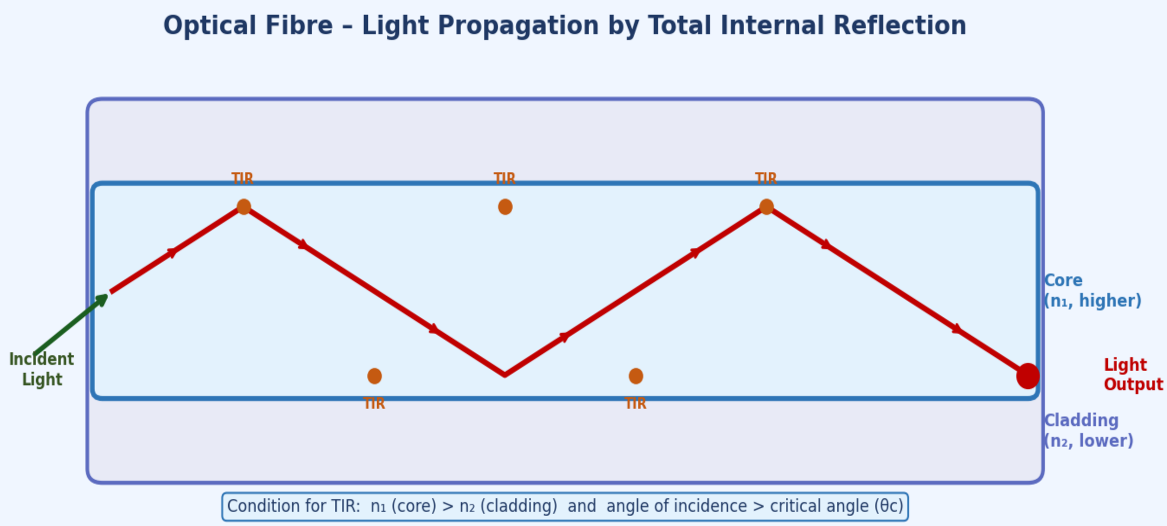

Fig. 6 – Optical Fibre: Light ray bouncing inside the core by Total Internal Reflection (TIR); Core (n_1, higher) surrounded by Cladding (n_2, lower); condition $n_1 > n_2$

7.2 Total Internal Reflection (TIR)

When light travels from a denser medium (higher refractive index n_1) to a rarer medium (lower n_2), and if the angle of incidence exceeds the critical angle, light is completely reflected back — this is Total Internal Reflection. Optical fibres exploit this to keep light confined within the core.

- Core: Central part (high n_1) where light travels.
- Cladding: Surrounding layer (lower n_2) that causes TIR, keeping light in the core.
- Buffer coating: Protective plastic layer around the cladding.

Key Formulas

- Condition for TIR: $n_1 > n_2$ and angle of incidence > critical angle θc
- Critical angle: $\sin(\theta c) = n_2 / n_1$
- Numerical Aperture: $NA = \sqrt{(n_1^2 – n_2^2)}$

7.3 Applications

- Telecommunication: Transmitting telephone, internet, and TV signals at high speed over long distances.
- Medical Endoscopy: Viewing internal organs using fibre optic endoscopes without surgery.
- Industrial Inspection: Examining inaccessible areas in engines, pipelines, and machinery.
- Sensors: Measuring temperature, pressure, and strain in harsh environments.
- Networking: Backbone of high-speed computer networks (LAN, WAN).

8. Nanoscience and Nanotechnology

Nanoscience is the study of materials and phenomena at the nanometre scale (1–100 nm). Nanotechnology applies this to design materials, devices, and systems at this scale. 1 nm = 10^{-9} m.

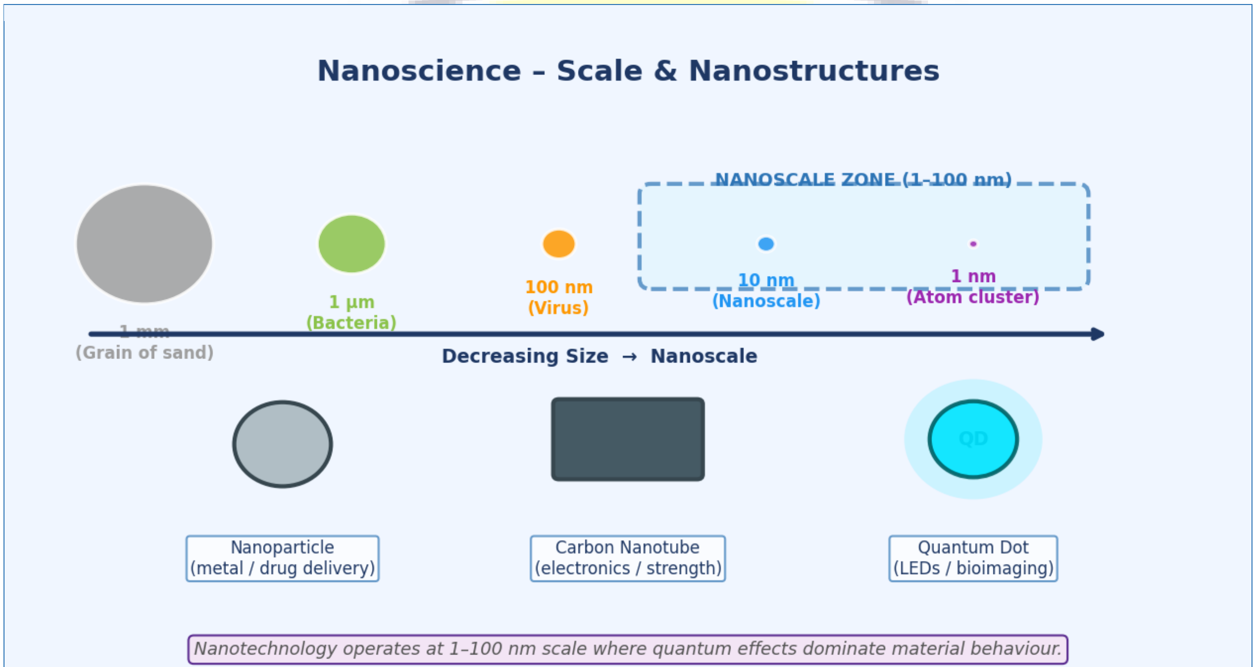

Fig. 7 – Nanoscale: Scale comparison from 1 mm (sand) down to 1 nm (atoms); Nanostructures: Nanoparticle (Au), Carbon Nanotube (CNT), Quantum Dot (QD)

8.1 Importance

- At the nanoscale, materials show different optical, electrical, magnetic, and chemical properties than their bulk form. E.g., gold nanoparticles appear red/purple instead of gold.
- Large surface area-to-volume ratio makes nanoparticles highly reactive and useful in catalysis.
- Quantum mechanical effects dominate, enabling novel electronic and optical behaviours.

8.2 Applications

- **Medicine:** Targeted drug delivery to cancer cells, nanoscale biosensors, diagnostic imaging using quantum dots, and antibacterial nano-coatings.
- **Electronics:** Nano-transistors, carbon nanotube electronics, and nano-memory for faster, smaller computers.

- **Energy:** Nanostructured solar cells, fuel cells, and high-capacity batteries.
- **Materials Science:** Nanocomposites with superior strength and lightweight properties for aerospace and automobiles.
- **Environment:** Nano-catalysts for water purification and air filtration.
- **Textiles:** Stain-resistant and antibacterial clothing using silver nanoparticles.

⭑ IMPORTANT FOR EXAM

- State and explain all 4 postulates of Bohr's atomic model.
- Difference between excitation potential and ionisation potential.
- Explain X-ray production using Coolidge tube with labelled diagram.
- Distinguish between continuous and characteristic X-rays.
- Soft X-rays vs Hard X-rays – comparison table.
- Explain spontaneous emission and stimulated emission with diagram.
- State and explain 4 characteristics of laser light.
- Explain construction and working of He-Ne laser with diagram.
- Explain Total Internal Reflection and its use in optical fibre with diagram.
- List 5 applications each of: Laser, X-rays, Optical Fibre, Nanotechnology.

COMMON VIVA QUESTIONS

- Q: What does LASER stand for? Ans: Light Amplification by Stimulated Emission of Radiation.
- Q: What is population inversion? Ans: More atoms in excited state than ground state – needed for laser action.
- Q: What type of mirrors are used in He-Ne laser? Ans: One fully reflective (100%) and one partially reflective (~98%).
- Q: Why is tungsten used as the X-ray target? Ans: High atomic number + high melting point.
- Q: What is the wavelength of He-Ne laser? Ans: 632.8 nm (red visible light).
- Q: What is TIR? Ans: Total Internal Reflection – light completely reflected inside denser medium when incidence angle > critical angle.
- Q: What is 1 nanometre? Ans: 1 nm = 10^{-9} m.
- Q: What is Bremsstrahlung? Ans: 'Braking radiation' – continuous X-rays from deceleration of electrons at the anode.
- Q: What is numerical aperture? Ans: Light-gathering ability of fibre: NA = $\sqrt{n_1^2 - n_2^2}$.
- Q: State the condition for TIR. Ans: $n_1 > n_2$ and angle of incidence > critical angle θ_c.

KEY POINT SUMMARY

- Bohr's model: Electrons in fixed orbits; energy quantised; angular momentum = $nh/2\pi$.
- Excitation: Electron moves to higher orbit. Ionisation: Electron removed from atom.
- X-rays produced by sudden deceleration of fast electrons on metal target (Coolidge tube).
- Continuous X-rays → Bremsstrahlung. Characteristic X-rays → element-specific sharp peaks.
- Hard X-rays: shorter λ, higher penetration. Soft X-rays: longer λ, less penetration.
- Laser = stimulated emission + population inversion + optical resonator (cavity).
- He-Ne laser: 632.8 nm red, gas laser, continuous wave, low power, highly coherent.
- Optical fibre guides light via TIR; core (n_1) > cladding (n_2).
- Nanotechnology: 1–100 nm scale; quantum effects dominate; applications everywhere.
- $NA = \sqrt{n_1^2 - n_2^2}$ | $E_n = -13.6/n^2$ eV | $h\nu = E_2 - E_1$.

——— *End of Unit 7: Modern Physics* ———