PH 107: Quantum Physics and applications

Introduction to Quantum Theory

Sunita.srivsatava@phy.iitb.ac.in

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Learning Objectives

- Historical developments in science that lead to the need of Quantum Theory

You already know…

Class 12 Physics Book Part-1
Chapter 1 – Electric Charges and Fields
Chapter 2- Electrostatic Potential and Capacitance
Chapter 3- Current Electricity
Chapter 4- Moving Charges and Magnetism
Chapter 5- Magnetism and Matter
Chapter 6- Electromagnetic Induction
Chapter 7- Alternating Current
Chapter 8- Electromagnetic Waves
Class 12 Physics Book Part 2
Chapter 9- Ray Optics and Optical Instruments
Chapter 10- Wave Optics
Chapter 11- Dual Nature of Radiation and Matter
Chapter 12- Atoms
Chapter 13- Nuclei
Chapter 14- Semiconductor Electronics: Materials, Devices and Simple Circuits

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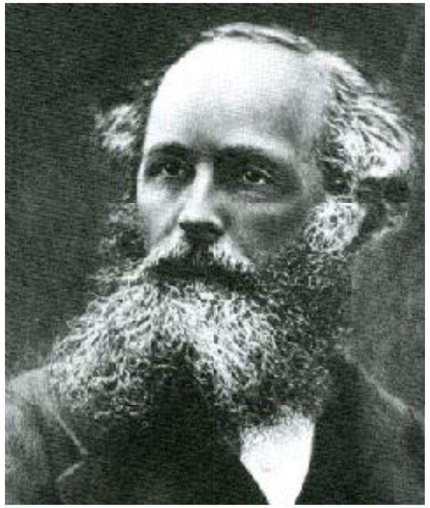
PH107

Classical Physics 1890s

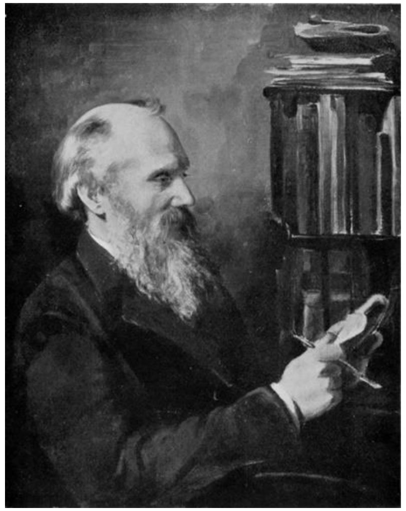
Classical Theories

Mechanics **Electrodynamics** **Thermodynamics** **Statistical Mechanics**

Isaac Newton



James Clerk Maxwell



Lord Kelvin

Classical Physics 1890s

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote… Our future discoveries must be looked for in the sixth place of decimals. - Albert A. Michelson, 1894

There is nothing new to be discovered in physics now*. All that remains is more and more precise measurement.* - Lord Kelvin, 1900

Mechanics achieved maturity with Isaac Newton

Newton's first law (*Law of inertia*):
An object with a constant velocity will continue in motion unless acted upon by some net external force

Newton's second law: Introduces force (F) as responsible for the change in linear momentum ($p = m\mathrm{v}$)

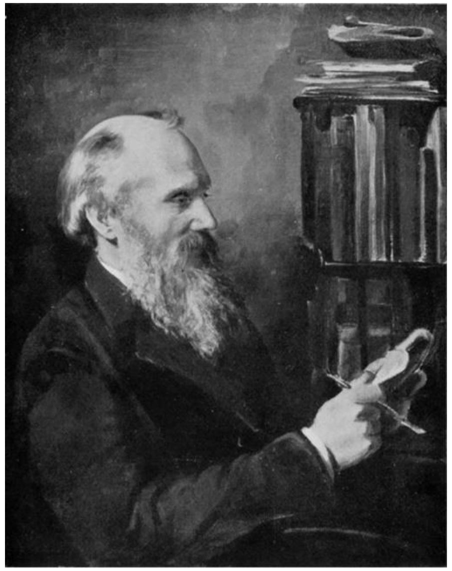
$$\vec{F} = m\vec{a} \quad \text{or} \quad \vec{F} = \frac{d\vec{p}}{dt}$$

Newton's third law (*Law of action and reaction*): The force exerted by body 1 on body 2 is equal in magnitude and opposite in direction to the force that body 2 exerts on body 1

$$\vec{F}_{21} = -\vec{F}_{12}$$

Isaac Newton

The four laws of thermodynamics



Lord Kelvin

First law: The change in the internal energy ΔU of a system is equal to the heat Q added to a system plus the work W done by the system: $\Delta U = \Delta\, Q + W$

Second law: It's impossible to convert heat completely into work without some other change taking place.

Added later:

The "zeroth" law: Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.

Third law: It's impossible to achieve absolute zero temperature.

Electromagnetism culminated with Maxwell's Equations

Gauss's law:

(definition of electric field)

$$\vec{\nabla} \cdot \vec{E} = \rho / \varepsilon_0$$

Gauss's law:

(definition of magnetic field)

$$\vec{\nabla} \cdot \vec{B} = 0$$

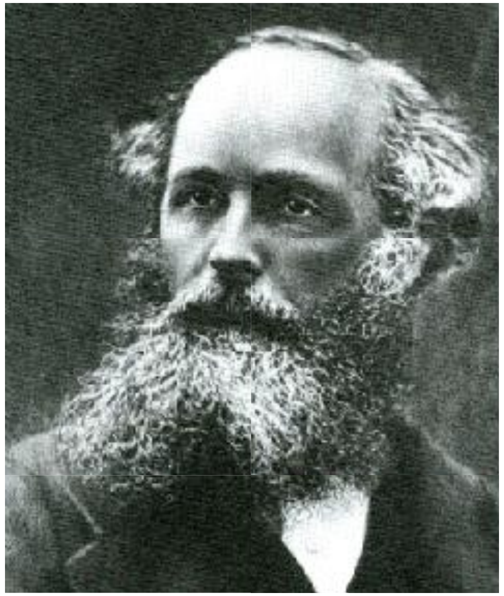
Faraday's law:

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Ampère's law:

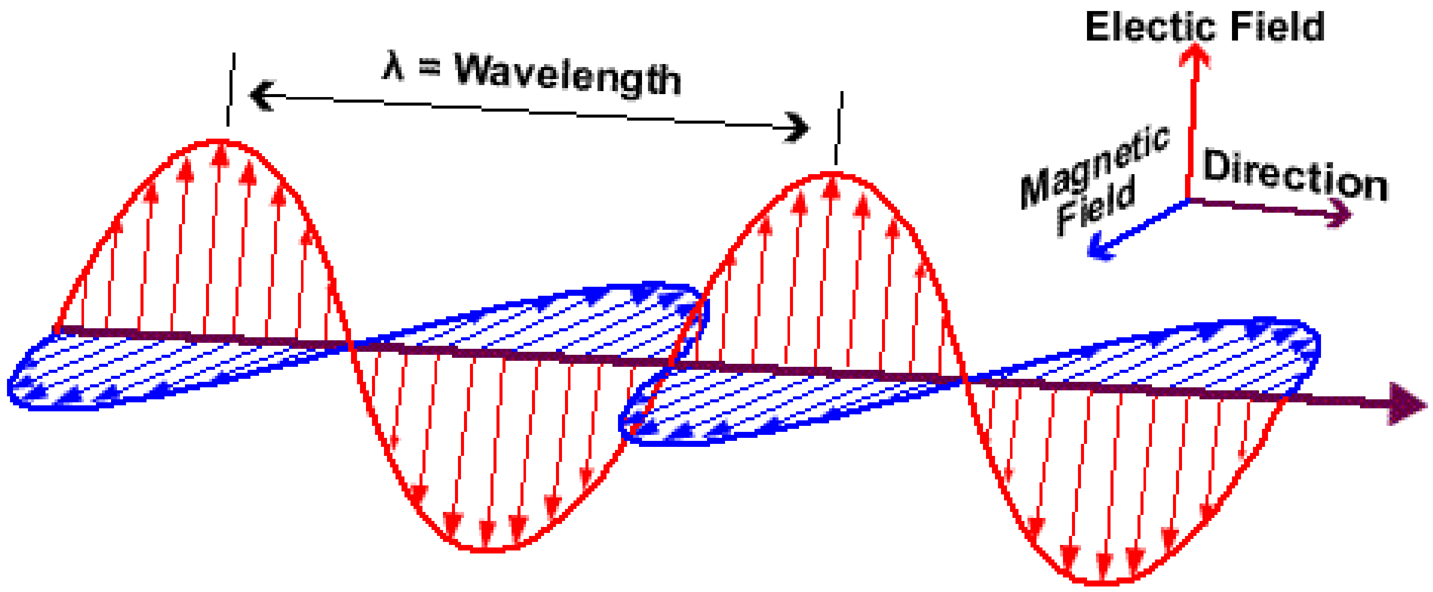
$$\vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

in the presence of only stationary charges



James Clerk Maxwell

Outcome of Maxwell’s Equations (1860)



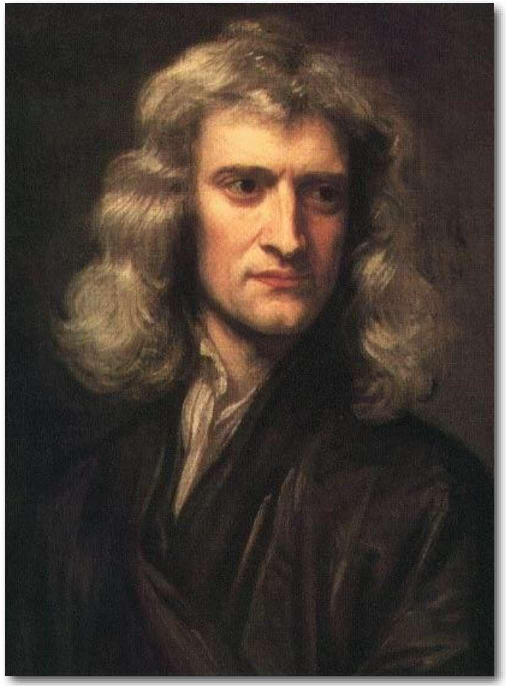
Electromagnetic (EM) waves travelling with speed $c = 1/\sqrt{\epsilon_0 \mu_0} = 3 \times 10^8\ ms^{-1}$ (same speed as that of light)

Understanding of Light before Maxwell

Christiaan Huygens 1629-1695
light consists of waves (1678)

Huygens' principle gave explanations of reflection and refraction, being based solely on the so-called of secondary wave fronts.

Sir Isaac Newton (1643 - 1727)
light consists of particles



light consists of material corpuscles in motion

Understanding of Light before Maxwell

Christiaan Huygens 1629-1695
light consists of waves (1678)

Explain:
Reflection
Refraction
Diffraction
Interference

Cannot Explain:
Polarization

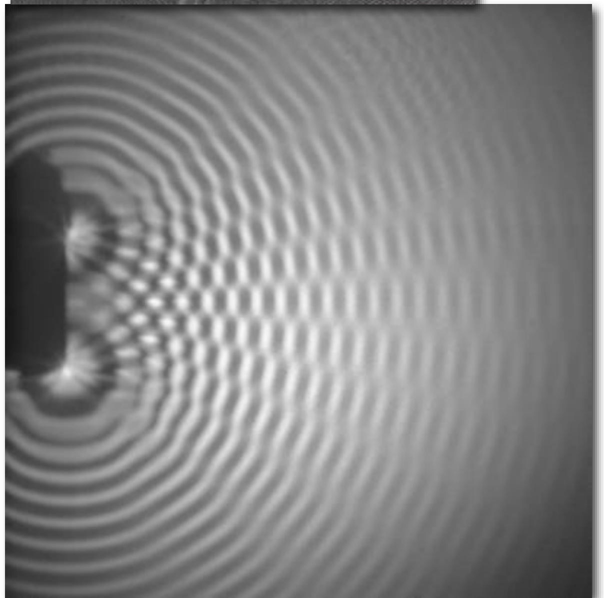
Sir Isaac Newton (1643 - 1727)
light consists of particles

Explain:
Reflection
Refraction

Cannot Explain:
Diffraction
Interference
Polarization

What is light?

Thomas Young's double slit experiment (1803)

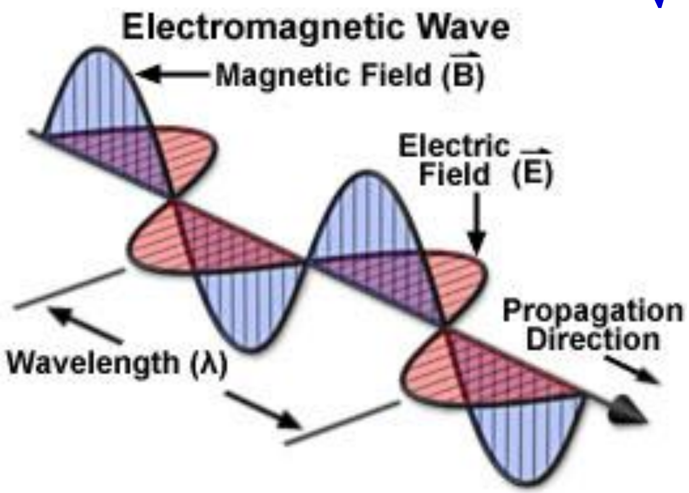


James Maxwell

Maxwell's Equations (1860)

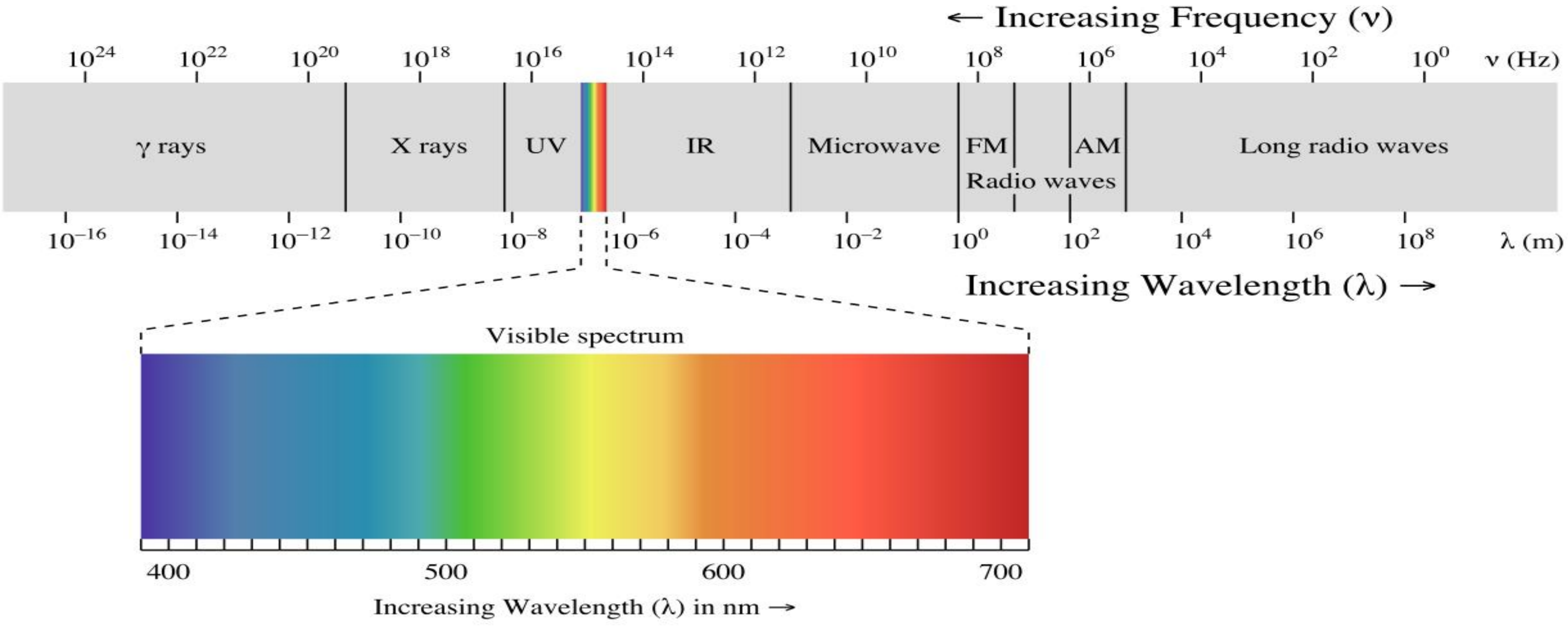
Electromagnetic wave

$$v = c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$



Light is a electromagnetic wave (1860)

EM waves can be reflected, refracted, and diffracted and they obey the **principle of superposition**



Why Quantum Theory ?

By 1900, some discoveries were NOT explained by the "Classical Theory" of Light

- **Black-body radiation (**1860-**1901)**
- **Photoelectric Effect (**1887-**1905)**
- **Hydrogen Spectra (**1888-1913**)**

Birth of Quantum Physics (Quantum Mechanics)

Theory which questions the "Wave ONLY" nature of light (electromagnetic wave)

Black body radiation: Recap from XI class

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CHAPTER ELEVEN

THERMAL PROPERTIES OF MATTER

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11.9.3 Radiation

11.9.4 Blackbody Radiation

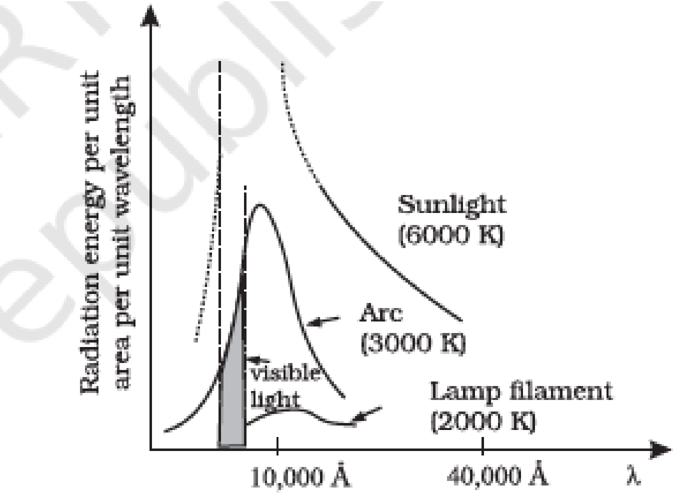


Fig. 11.18: *Energy emitted versus wavelength for a blackbody at different temperatures*

Gustav Kirchhoff (1824-1887)

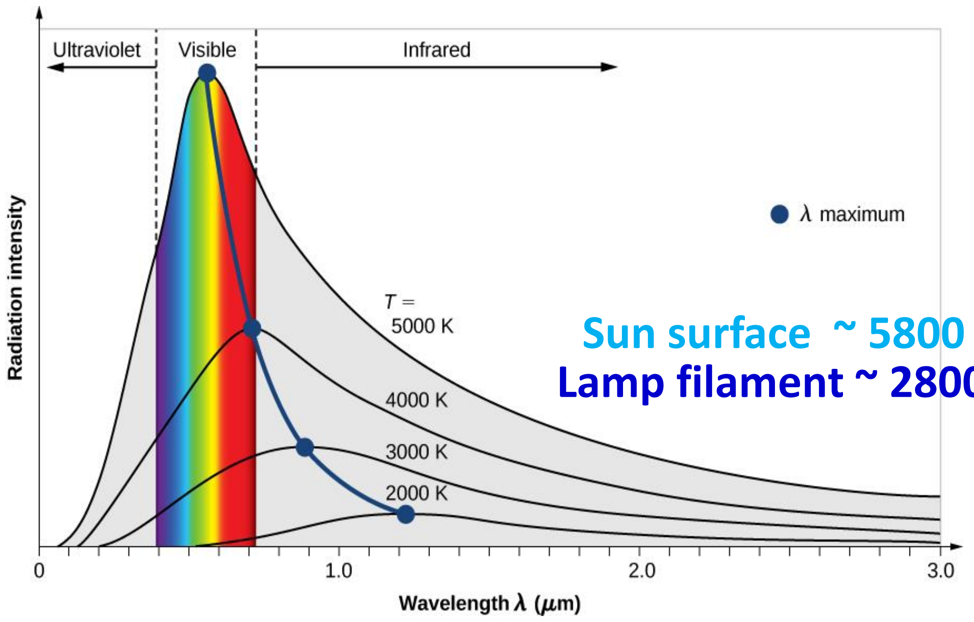
Yellow

White

Red

Black-body Radiation (1860-1901)

How does the intensity of radiation vary with wavelength (at different temperatures)?



Sun surface ~ 5800 K

Lamp filament ~ 2800 K

Wien's Law

$$\lambda_{\max} T = \text{const}$$

Very useful in predicting temperatures

S-B Law

Energy emitted per unit time

$$H = A\sigma T^4$$

BBR curves are "universal"

Depends only on the T of the body

Independent of the size, shape or material of the body

Black-body Radiation (1860-1901)

temperature. The relation between λ_m and T is given by what is known as **Wien's Displacement Law**:

$$\lambda_m T = \text{constant} \qquad (11.15)$$

1893

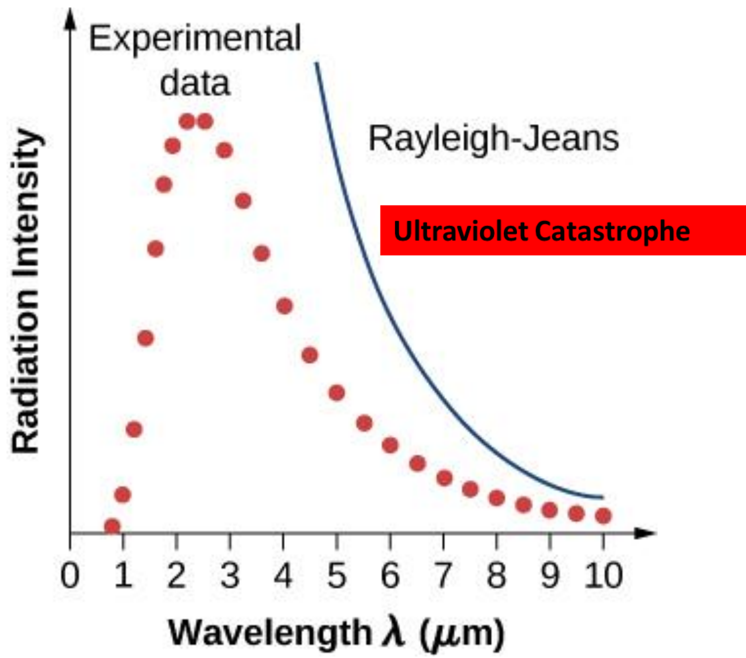
temperature. For a body, which is a perfect radiator, the energy emitted per unit time (H) is given by

$$H = A\sigma T^4 \qquad (11.16)$$

where A is the area and T is the absolute temperature of the body. This relation obtained experimentally by Stefan and later proved theoretically by Boltzmann is known as **Stefan-Boltzmann law** and the constant σ is called Stefan-Boltzmann constant. Its value in SI units

The most significant feature of the blackbody radiation curves in Fig. 11.18 is that they are *universal*. They depend only on the temperature and not on the size, shape or material of the blackbody. Attempts to explain blackbody radiation theoretically, at the beginning of the twentieth century, spurred the quantum revolution in physics, as you will learn in later courses.

Black-body Radiation (1860-1901)



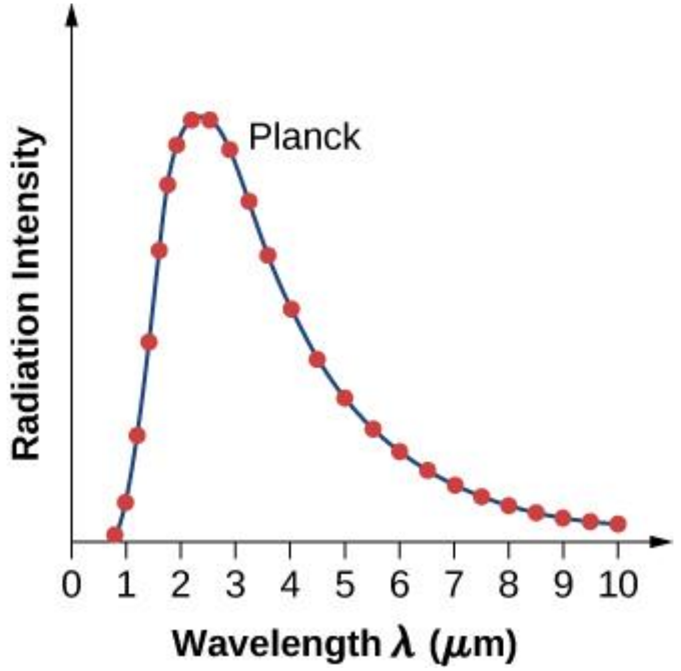
Rayleigh–Jeans (1900)

Sources of radiation are atoms in a state of oscillation (classical oscillators)

Max Plank (1901)

The elementary oscillators could emit and absorb EM radiation ONLY in discrete packets

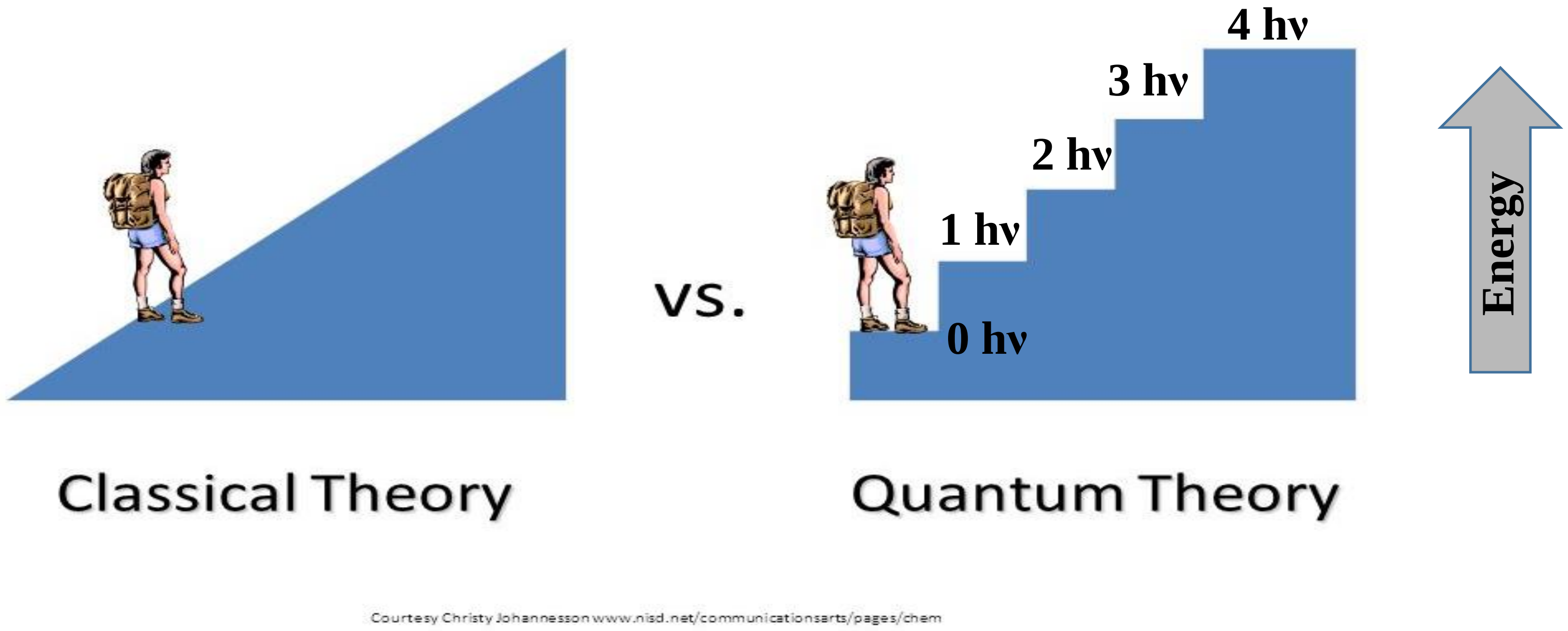
$$E = nh\nu \quad h \sim 6.6 \times 10^{-34} \text{ SI units}$$



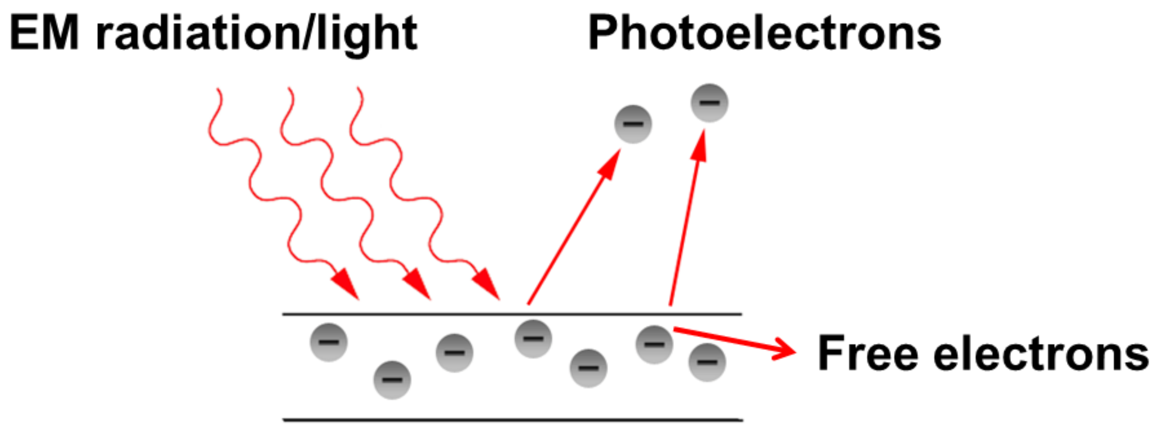
Birth of Quantum Physics !!

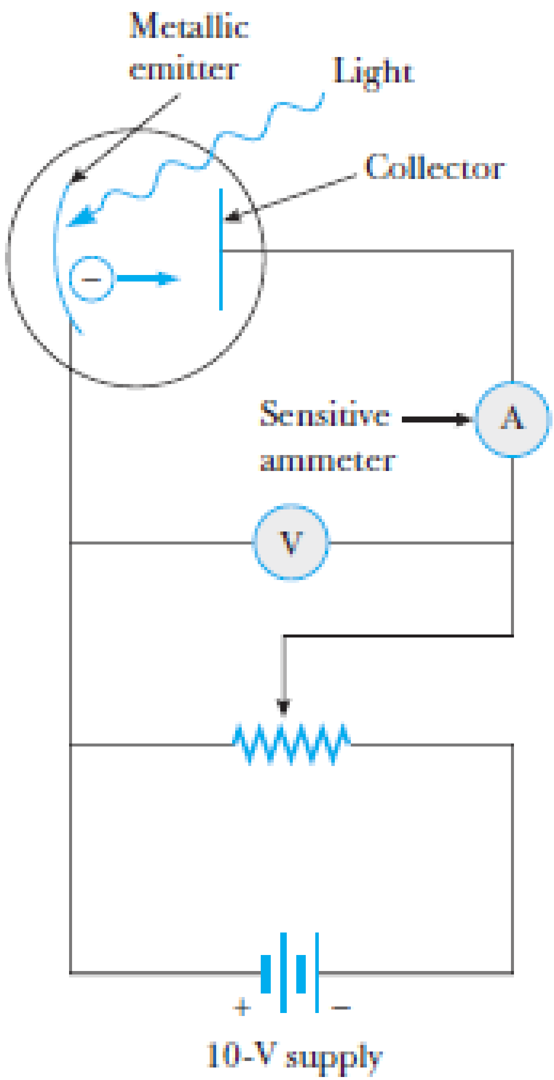
Birth of Quantum Physics (1900)

- **Planck's Quantum theory**
- The e.m radiation emitted by the black body is a discrete packets of energy known as quanta. This means the **energy** of the e.m radiation is **quantised**.
- The **energy** of the radiation depends on its **frequency.**



Photoelectric Effect (1887-1905)





Heinrich Hertz

Target metal (Cathode) and a positive electrode (anode) are placed in an evacuated glass tube.

Cathode is bombarded with light of known frequency

Photoelectrons are emitted and collected at anode

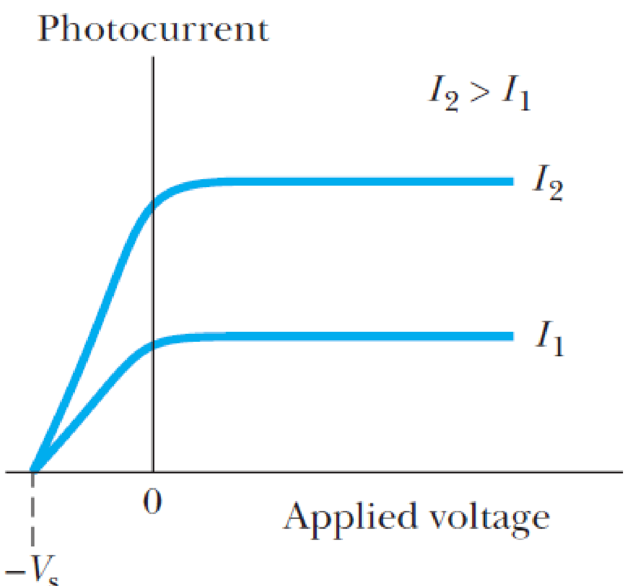
Photoelectric current is produced and measured.

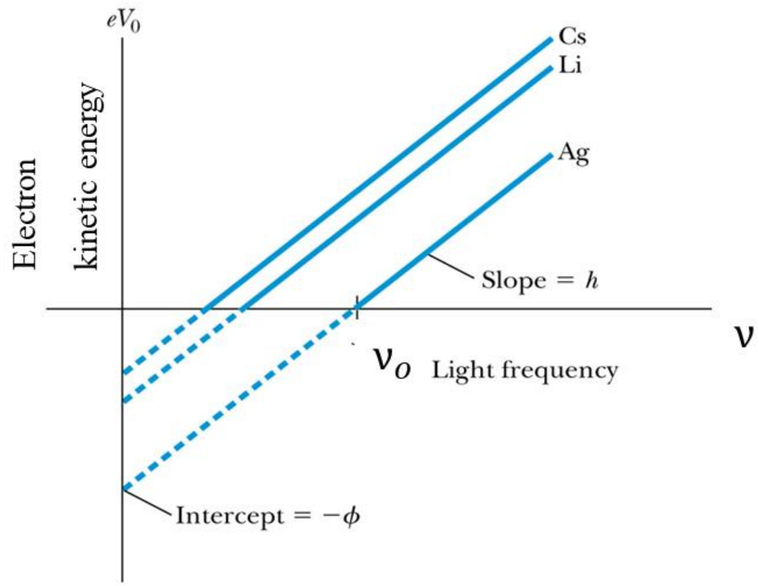
Photoelectric current increases with increase in positive Voltage and eventually reaches a constant value, saturation current

Saturation current, Im is defines as the maximum constant value of photocurrent in when all photoelectrons have reached the anode

The kinetic energy of the photoelectrons is **independent of the light intensity**

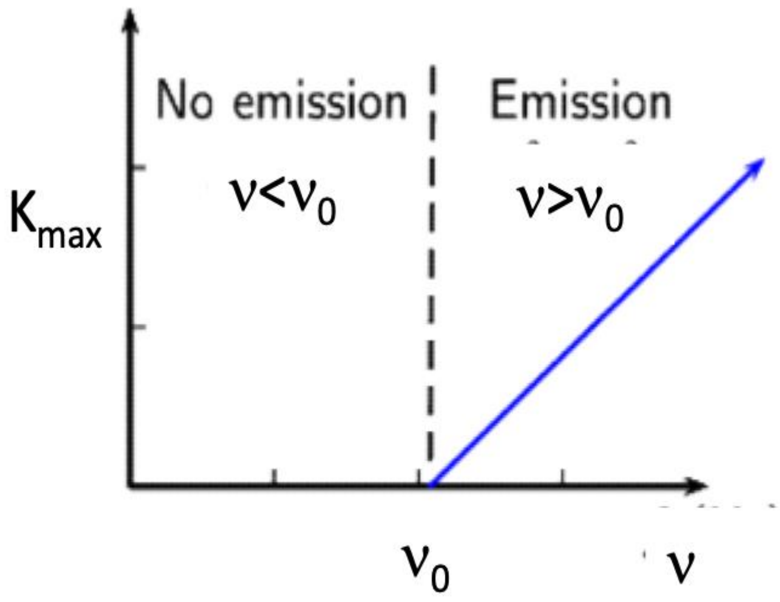
The kinetic energy of the photoelectrons, for a given emitting material, depends only on the **frequency** of the light. Classically, the kinetic energy of the photoelectrons should increase with the light intensity and not depend on the frequency





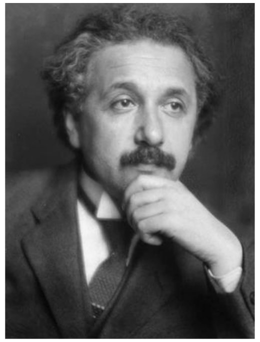
There was a **threshold frequency** of the light, below which no photoelectrons were ejected (related to the work function ϕ of the emitter material). The existence of a threshold frequency is completely inexplicable in classical theory

Failure of Classical theory of light: Frequency, NOT Intensity decides the threshold of photoelectron emission.



Einstein's Theory of P.E effect (1905)

Einstein suggested that the electromagnetic radiation field is not evenly distributed over the wave front but quantized into particles called ***photons*** having energy,



Albert Einstein

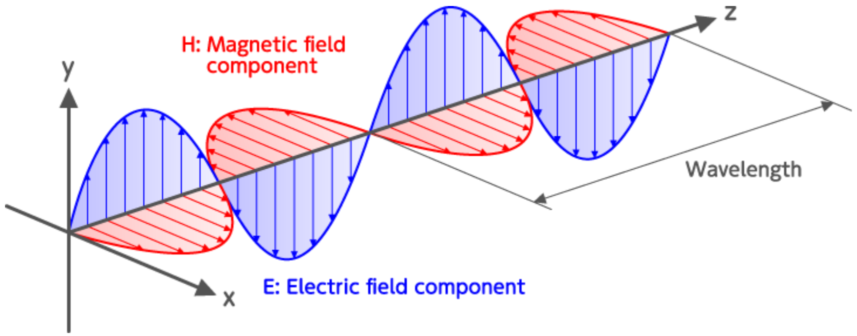
Einstein's quantization of Photon energy (1905)

$$K_{\max} = h\nu - \Phi_0 = h\nu - h\nu_0 = eV_0$$

$$K_{\max} = h(\nu - \nu_0)$$

Classical vs Quantum Picture

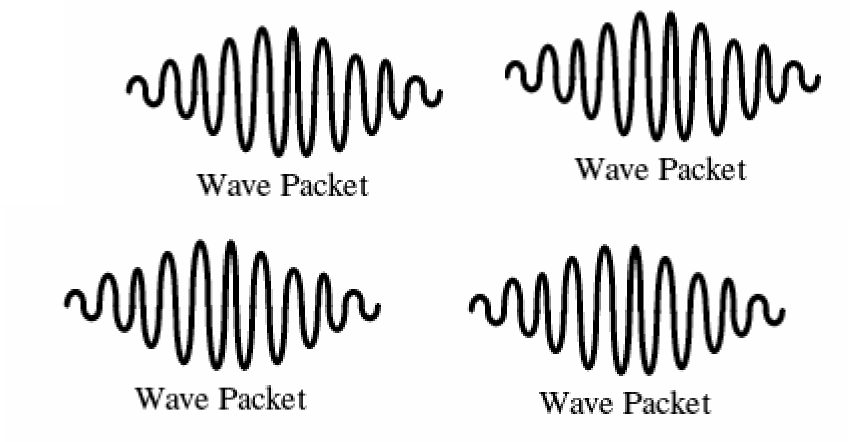
Classical view of travelling waves



Energy depends on Intensity not on frequency

$$E_{classical} = K_B\ T$$

Photon picture of travelling waves



Energy depends on frequency

$$E_{quantum} = \text{nh}\nu = \frac{nhc}{\lambda}$$

n = 0, 1, 2, 3….

Hydrogen Spectra (1888-1913)

Atomic Spectra of Hydrogen

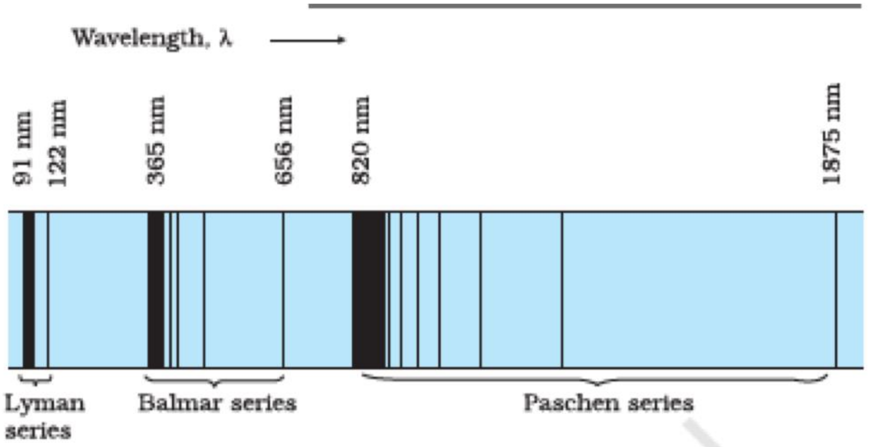
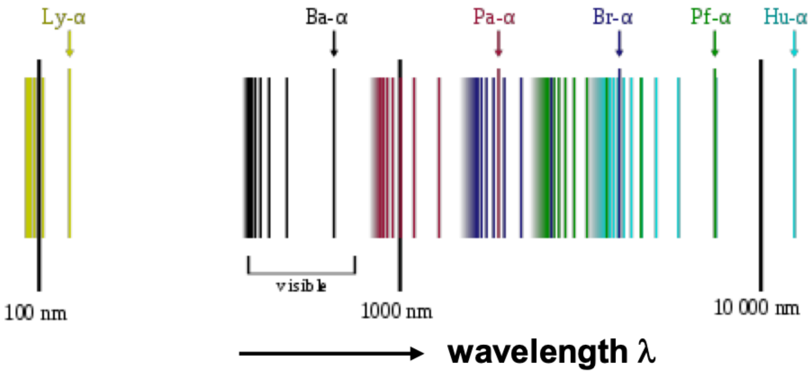


FIGURE 12.5 Emission lines in the spectrum of hydrogen.



Johannes Rydberg

$$\boxed{\frac{1}{\lambda_{\text{vac}}} = R_H\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \quad (1888)}$$

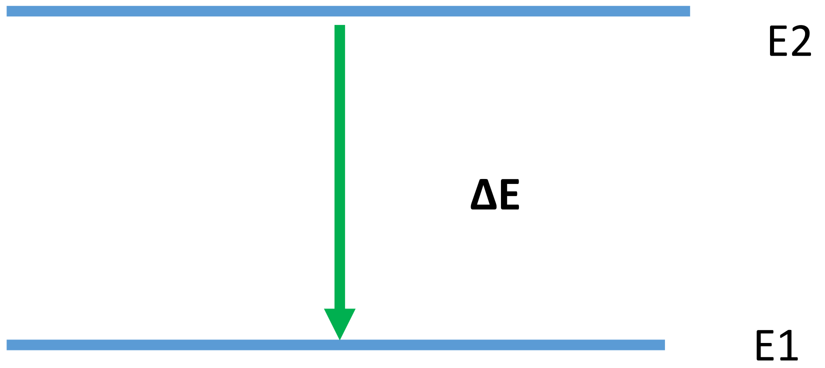
Niels Bohr

Bohr model of Hydrogen atom **(**1913**).**

Question about laser pointer ?

$E_{quantum}$ = nhν = $\frac{nhc}{\lambda}$

n = 0, 1, 2, 3….



ΔE = E2-E1

Recommended Readings

1. Black-body radiation, section 3.2 in page 68, and (optional) section 3.3 in page 77.

2. Photoelectric effect, section 3.4 in page 80.

3. The Bohr atom, section 4.3 in page 125.