King Saud University
College of Science
Physics & Astronomy Dept.

PHYS 111 (GENERAL PHYSICS 2)

CHAPTER 40: Introduction to Quantum physics

LECTURE NO. 10

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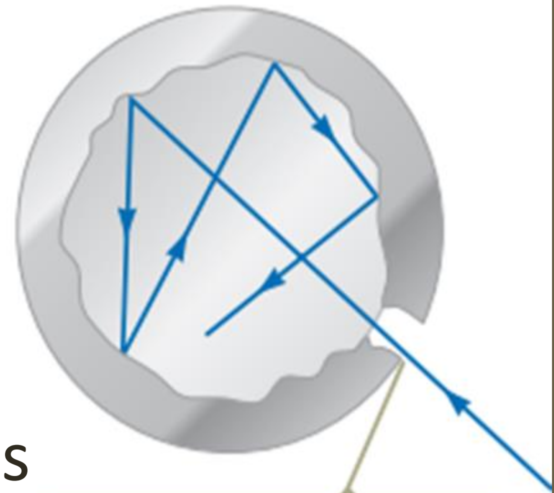
40.1 Blackbody Radiation and Planck's Hypothesis

- An object at any temperature emits electromagnetic waves in the form of thermal radiation from its surface. The characteristics of this radiation depend on the temperature and properties of the object's surface.
- At room temperature, the wavelengths of thermal radiation are mainly in the infrared region and hence the radiation is not detected by the human eye.
- As the surface temperature increases, the object eventually begins to glow visibly red. At sufficiently high temperatures, the glowing object appears white

From a classical viewpoint, thermal radiation originates from accelerated charged particles in the atoms near the surface of the object.

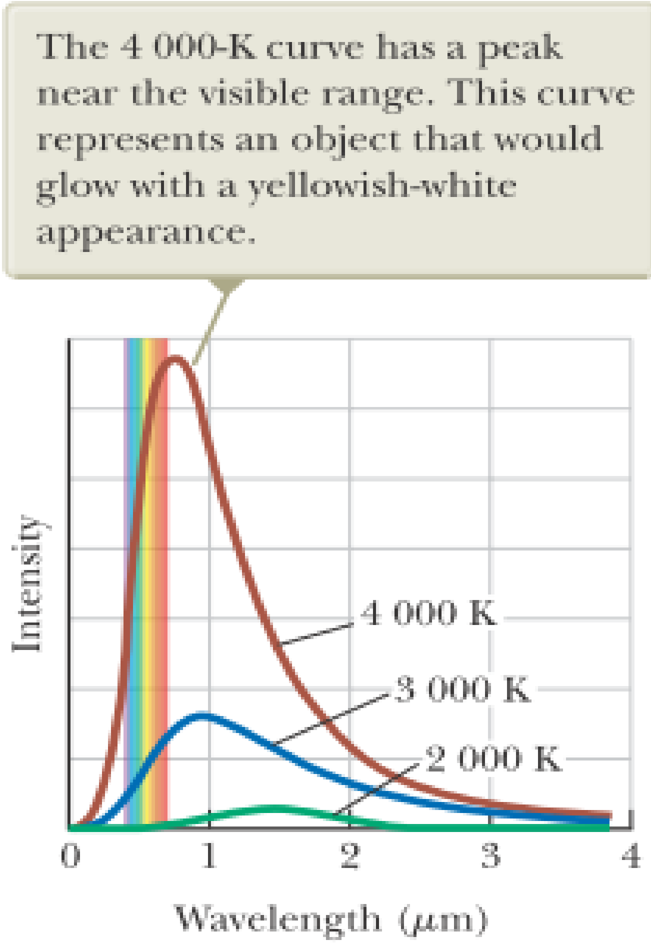
A black body: is an ideal system that absorbs all radiation incident on it. The electromagnetic radiation emitted by the black body is called blackbody radiation.

A good approximation of a black body is a small hole leading to the inside of a hollow object . Any radiation incident on the hole from outside the cavity enters the hole and is reflected a number of times on the interior walls of the cavity; hence, the hole acts as a perfect absorber.



The opening to a cavity inside a hollow object is a good approximation of a black body: the hole acts as a perfect absorber.

The wavelength distribution of radiation from cavities was studied experimentally in the late 19th century. The figure shows how the intensity of blackbody radiation varies with temperature and wavelength.



The following two consistent experimental findings were seen as especially significant:

1. The total power of the emitted radiation increases with temperature.

Stefan's law ▶ $P = \sigma A e T^4$

where P is the power in watts radiated at all wavelengths from the surface of an object, $\sigma = 5.5670 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2} \cdot K^4$ is the Stefan Boltzmann constant, A is the surface area of the object in square meters, e is the emissivity of the surface, and T is the surface temperature in kelvins. For a black body, the emissivity is e = 1 exactly.

2. The peak of the wavelength distribution shifts to shorter wavelengths as the temperature increases. This behavior is described by the following relationship, called **Wien's displacement law:**

$$\lambda_{max} T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K}$$

◀ Wien's displacement law

where λ_{max} is the wavelength at which the curve peaks and T is the absolute temperature of the surface of the object emitting the radiation. The wavelength at the curve's peak is inversely proportional to the absolute temperature; that is, as the temperature increases, the peak is "displaced" to shorter wavelengths

A successful theory for blackbody radiation must predict the shape of the curves in the previous figure , the **temperature dependence** expressed in **Stefan's law**, and the **shift of the peak** with temperature described by **Wien's displacement law**.

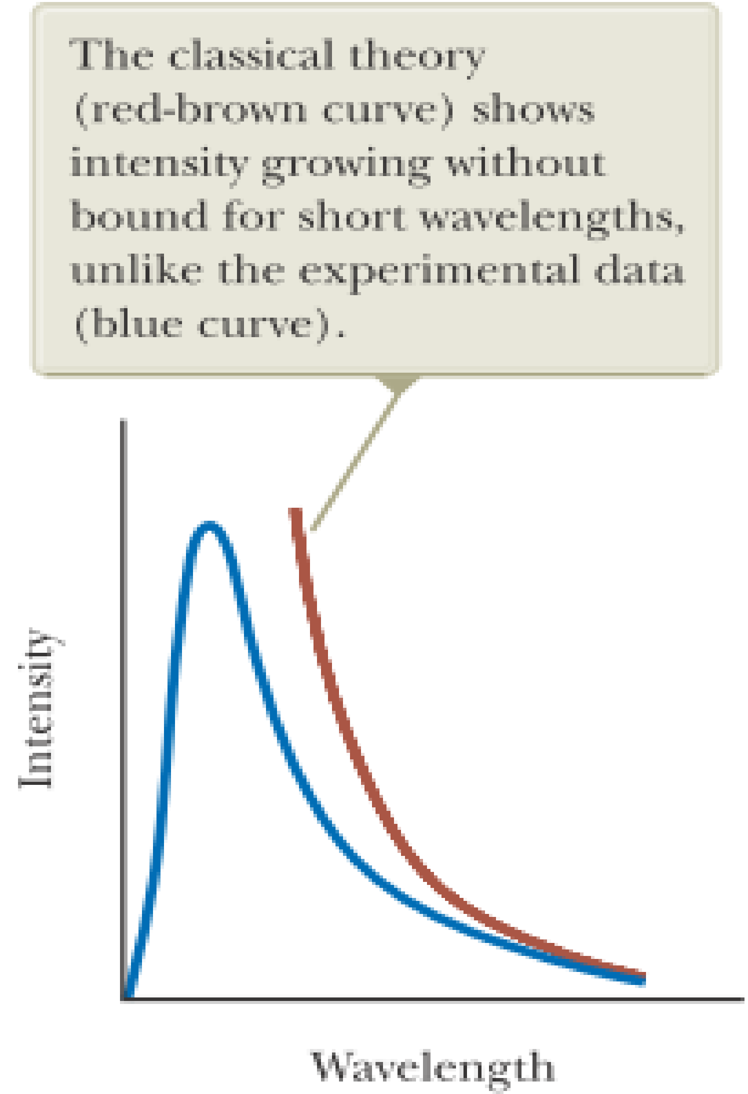
$$I(\lambda, T) = \frac{2\pi c k_B T}{\lambda^4}$$ ◀ Rayleigh–Jeans law

we define $I(\lambda, T)d\lambda$ to be the intensity, or power per unit area, emitted in the wavelength interval dλ.

where k_B is Boltzmann's constant.

An experimental plot of the blackbody radiation spectrum, together with the theoretical prediction of the **Rayleigh–Jeans law**, is shown n below .

At long wavelengths, the Rayleigh–Jeans law is in reasonable agreement with experimental data, but at short wavelengths, major disagreement is apparent.



In 1900, Max Planck developed a theory of blackbody radiation that leads to an equation for $I(\lambda, T)$ that is in complete agreement with experimental results at all wavelengths. In discussing this theory, we use the outline of properties of structural models:

1. Physical components:

Planck assumed the cavity radiation came from atomic oscillators in the cavity walls .

2.Behavior of the components:

(a) The energy of an oscillator can have only certain discrete values E_n:

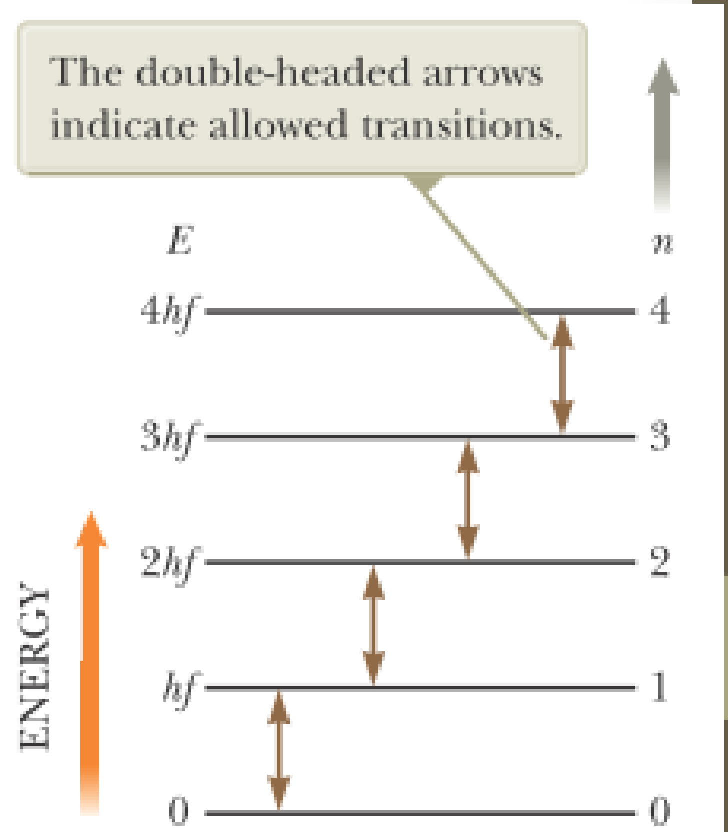
$$E_n : nhf$$

where ***n*** is a positive integer called a quantum number, f is the oscillator's frequency, and h is a parameter Planck introduced that is now called Planck's constant. Because the energy of each oscillator can have only discrete values.

(b) The oscillators emit or absorb energy when making a transition from one quantum state to another. The entire energy difference between the initial and final states in the transition is emitted or absorbed as a single quantum of radiation.

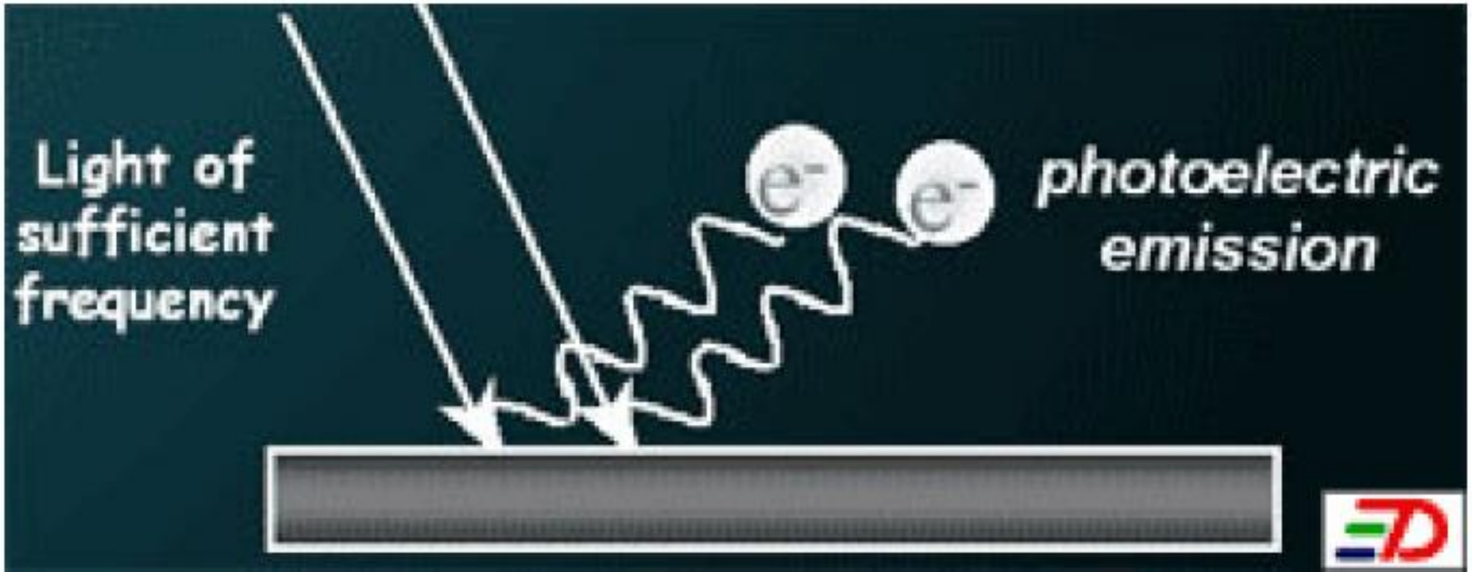
Using this approach, Planck generated a theoretical expression for the wavelength distribution that agreed remarkably well with the experimental curves in first Figure:

$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda k_B T} - 1\right)}$$



40.2 The Photoelectric Effect

- One of the most popular concepts concerning Quantum Mechanics is called , "The Photoelectric Effect". In 1905, Albert Einstein published this theory for which he won the Nobel Prize in 1921.
- *When light strikes a material, electrons are emitted. The radiant energy supplies the work necessary to free the electrons from the surface."*



40.2 The Photoelectric Effect

- **The energy of the light particle (photon) is given by $E = hf$**, where the constant h = 6.6×10^{-34} [J s] is Planck's constant.
- The energy of the light particle (photon) must overcome the

binding energy (work function ϕ)of the electron to the nucleus.

$$hf > \varphi$$

- The **work function ϕ** represents the minimum energy with which an electron is bound in the metal and is on the order of a few electron volts.
- If the energy of the photon exceeds the binding energy ϕ, the electron is emitted with a kinetic energy

$$K_{max} = hf - \phi$$

◀ Photoelectric effect equation

40.2 The Photoelectric Effect

- K_{max} is independent of the light intensity. The maximum kinetic energy of any one electron, which equals $hf - \varphi$, depends only on the light frequency and the work function. If the light intensity is doubled, the number of photons arriving per unit time is doubled, which doubles the rate at which photoelectrons are emitted. The maximum kinetic energy of any one photoelectron, however, is unchanged.

- No electrons are emitted if the incident light frequency falls below some **cutoff frequency f_c** , whose value is characteristic of the material being illuminated. No electrons are ejected below this cutoff frequency regardless of the light intensity.

$$0 = hf_c - \varphi$$

40.2 The Photoelectric Effect

The cutoff frequency $\boldsymbol{f_c}$ is related to the work function through the relationship

$$\boldsymbol{f_c = \frac{\varphi}{h}}$$

The cutoff frequency f_c corresponds to a cutoff wavelength $\boldsymbol{\lambda_c}$
Where

Cutoff wavelength ▶ $$\lambda_c = \frac{c}{f_c} = \frac{c}{\phi / h} = \frac{hc}{\phi}$$

and c is the speed of light. Wavelengths greater than λ_c incident on a material having a work function ϕ do not result in the emission of photoelectrons.

Example 40.3 The Photoelectric Effect for Sodium

A sodium surface is illuminated with light having a wavelength of 300 nm. As indicated in Table 40.1, the work function for sodium metal is 2.46 eV.

(A) Find the maximum kinetic energy of the ejected photoelectrons.

$$E = hf = \frac{hc}{\lambda}$$

$$K_{\max} = \frac{hc}{\lambda} - \phi = \frac{1\,240 \text{ eV} \cdot \text{nm}}{300 \text{ nm}} - 2.46 \text{ eV} = 1.67 \text{ eV}$$

(B) Find the cutoff wavelength λ_c for sodium.

$$\lambda_c = \frac{hc}{\phi} = \frac{1\,240 \text{ eV} \cdot \text{nm}}{2.46 \text{ eV}} = 504 \text{ nm}$$

Summary

- Blackbody Radiation and Planck's Hypothesis
- The Photoelectric Effect

The End