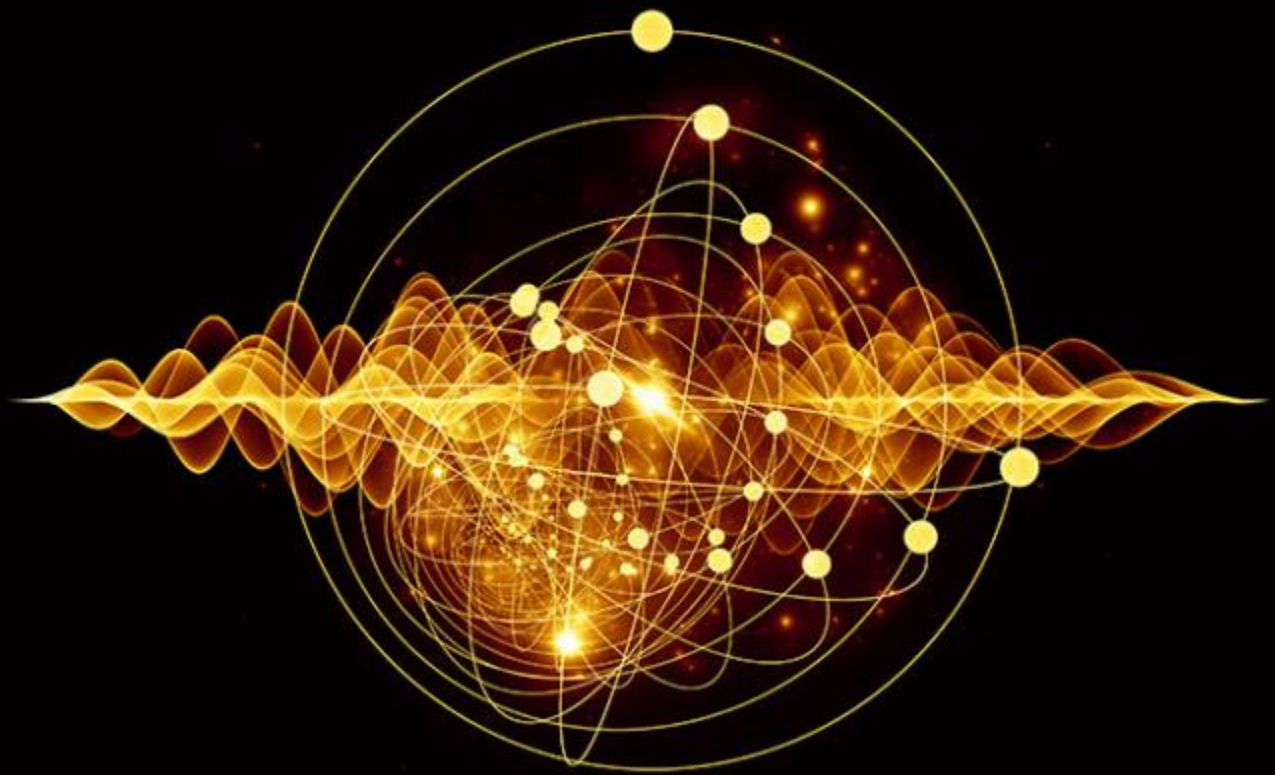
Part III

Modern Physics

Chapter 40

Introduction to Quantum Physics



Dr. Sheren Alsalmi

In this chapter you will Cover:

Chapter 40
(Serway-9th edition)

40.1 Blackbody Radiation and Planck's Hypothesis

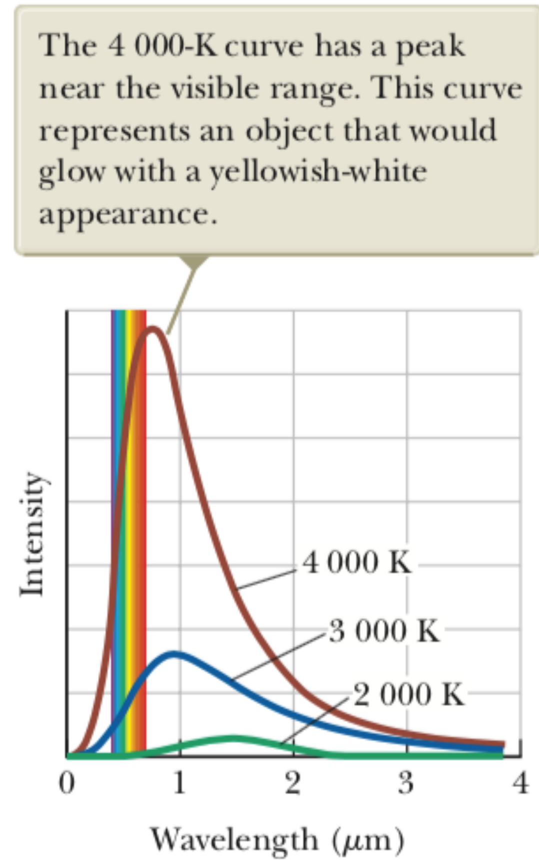
40.2 The Photoelectric Effect

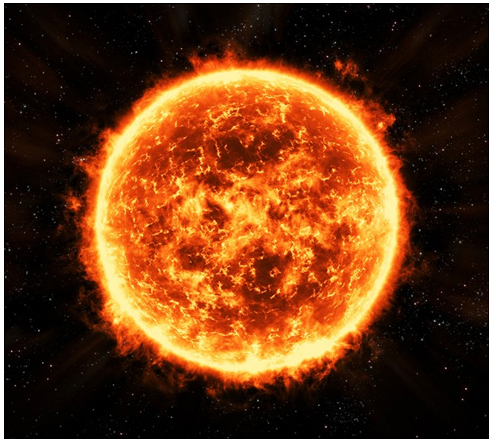
40.5 The Wave Properties of Particles

Introduction

40.1 Blackbody Radiation and Planck's Hypothesis

- Objects at any temperature emits electromagnetic waves in the form of thermal radiation.
- The characteristics of this radiation depend on the temperature and properties of the object's surface
- the radiation consists of a continuous distribution of wavelengths from all portions of the electromagnetic spectrum

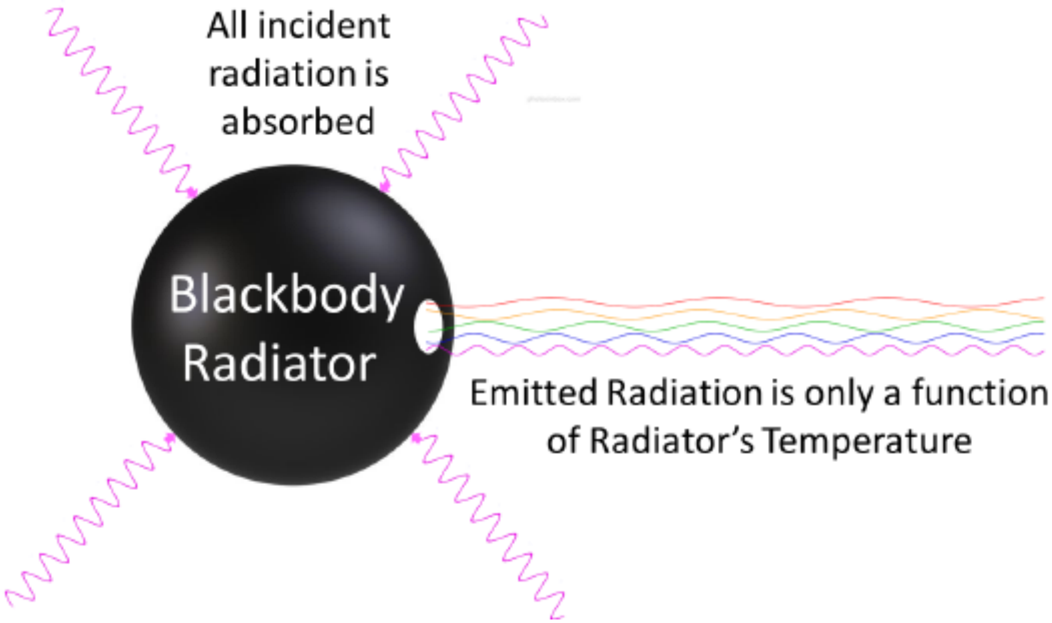


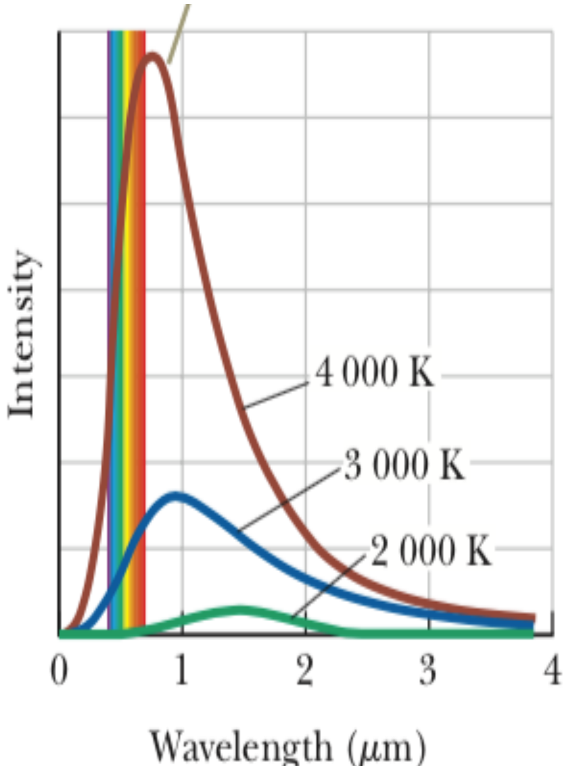


Dr. Sheren Alsalmi

40.1 Blackbody Radiation and Planck's Hypothesis

- **The Blackbody** : is an ideal system that absorbs all radiation incident on it. The radiation emitted from the blackbody is called the **blackbody radiation**.
- The nature of the radiation leaving the cavity through the hole depends only on the temperature of the cavity walls and not on the material of which the walls are made.





40.1 Blackbody Radiation and Planck's Hypothesis

Classical point of view (inadequate):

- radiation is originated from accelerated electrons
- The wavelength distribution of blackbody radiation was studied experimentally in the late 19th century.
- Some significant experimental findings when studying the blackbody radiation:

The total power of the emitted radiation increases with temperature.

$$P = \sigma A e T^4$$

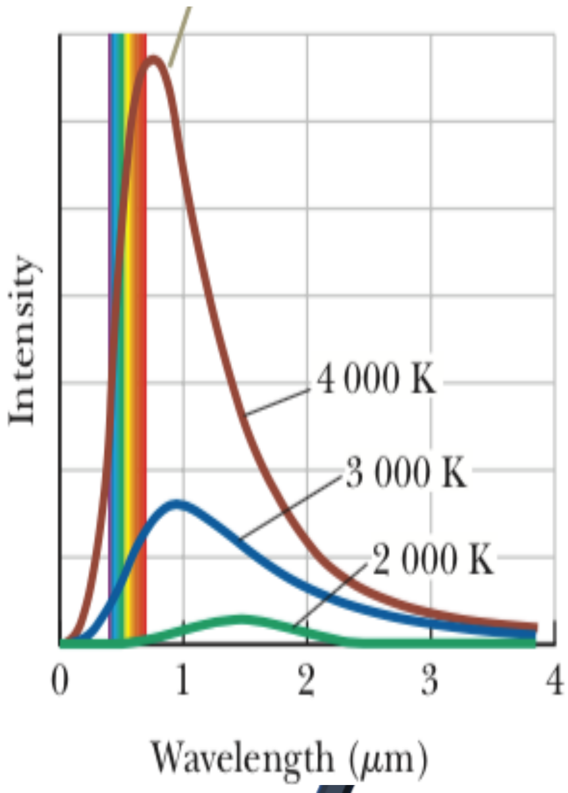
Stefan's law

where P is the power in watts of electromagnetic waves radiated from the surface of the object, σ is a constant equal to $5.6696 \times 10^{-8} W/m^2 . K^4$, A is the surface area of the object in square meters, e is the emissivity, and T is the surface temperature in kelvins.

The peak of the wavelength distribution shifts to shorter wavelengths as the temperature increases.

$$\lambda_{max}T = 2.898 \times 10^{-3}\text{m . K}$$ Wien's displacement law

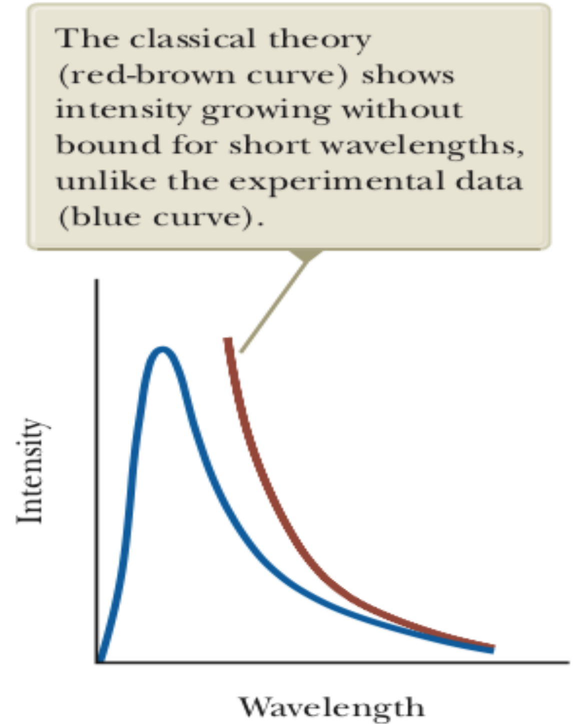
where λ_{max} is the wavelength at which the curve peaks and T is the absolute temperature of the surface of the object emitting the radiation. The wavelength at the curve's peak is inversely proportional to the absolute temperature; that is, as the temperature increases, the peak is "displaced" to shorter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

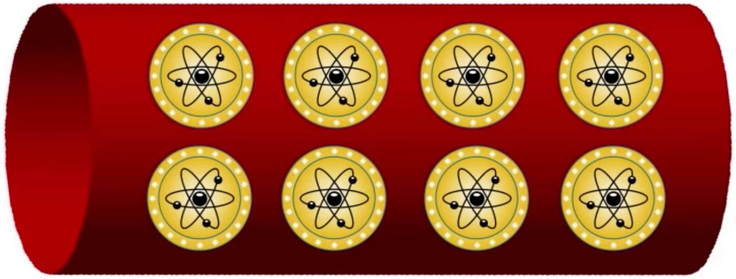


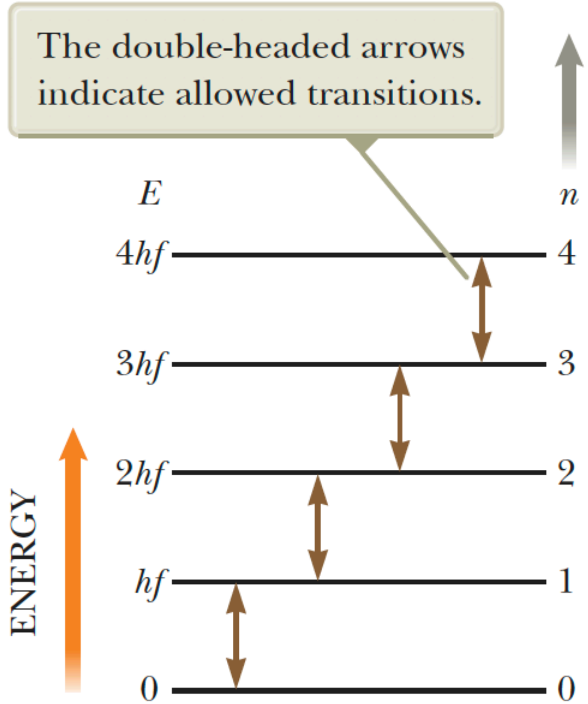
Rayleigh-Jeans Law:

$$I(\lambda, T) = \frac{2\pi c k_B T}{\lambda^4}$$

- Classical attempt to explain the blackbody radiation
- Failed at low λ
- This mismatch of theory and experiment was so disconcerting that scientists called it the *ultraviolet catastrophe*






The double-headed arrows indicate allowed transitions.
E
n
4hf
3hf
2hf
hf
0
4
3
2
1
0
ENERGY


© Bettmann/CORBIS

Max Planck

Planck's Hypothesis:

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 introduced in Chapter 21:

1. *Physical components:*
   Planck assumed the cavity radiation came from atomic oscillators in the cavity walls in Figure 40.1.
2. *Behavior of the components:*
   (a) The energy of an oscillator can have only certain *discrete* values E_n:

$$E_n = nhf \tag{40.4}$$

(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. If the transition is from one state to a lower adjacent state—say, from the $n = 3$ state to the $n = 2$ state—Equation 40.4 shows that the amount of energy emitted by the oscillator and carried by the quantum of radiation is

$$E = hf \tag{40.5}$$

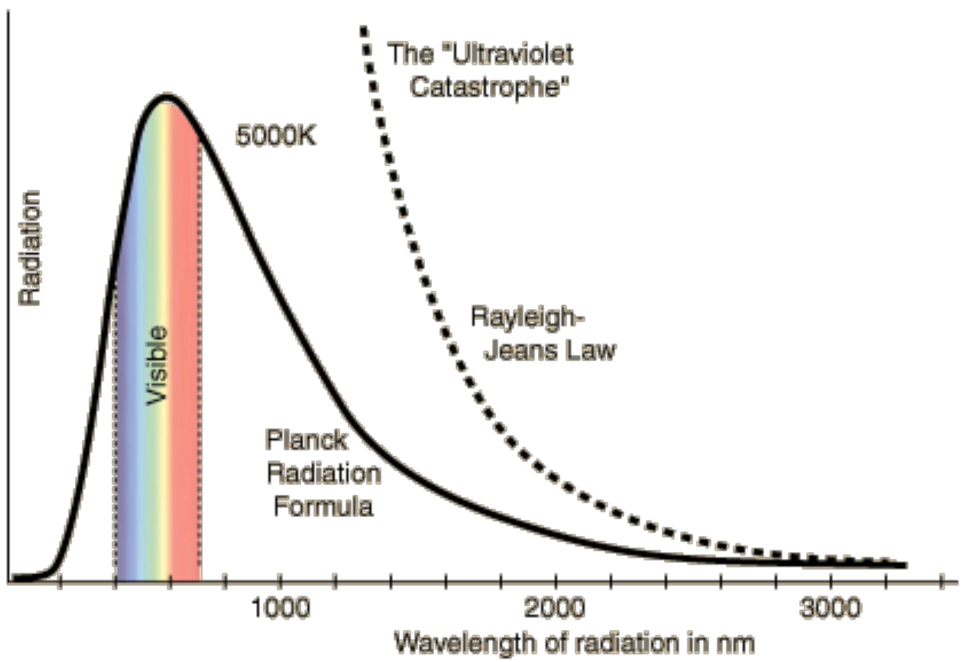
Using this approach, Planck generated a theoretical expression for the wavelength distribution that agreed remarkably well with the experimental curves in Figure 40.3:

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

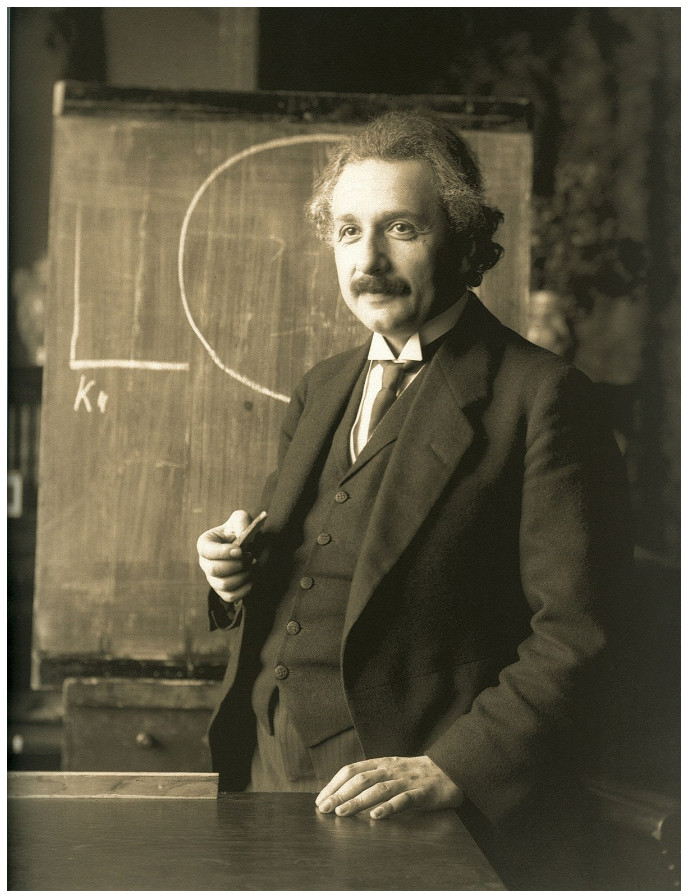
◀ **Planck's wavelength distribution function**

Planck's constant ▶

$$h = 6.626 \times 10^{-34}\,\text{J}\cdot\text{s}$$



- In 1905, Einstein Albert Einstein used Planck’s concept of the quantization of energy to explain the photoelectric effect.
- Einstein postulated that electromagnetic waves split into wave packets carrying “photons” quanta of energy



Measuring our body temperature:

- Yes, your body emits thermal radiation
- Infrared (can not be seen by human eye.
- Now, Suppose you have a fever 1°C above normal

Figure 40.8 An ear thermometer measures a patient's temperature by detecting the intensity of infrared radiation leaving the eardrum.

Measuring our body temperature:

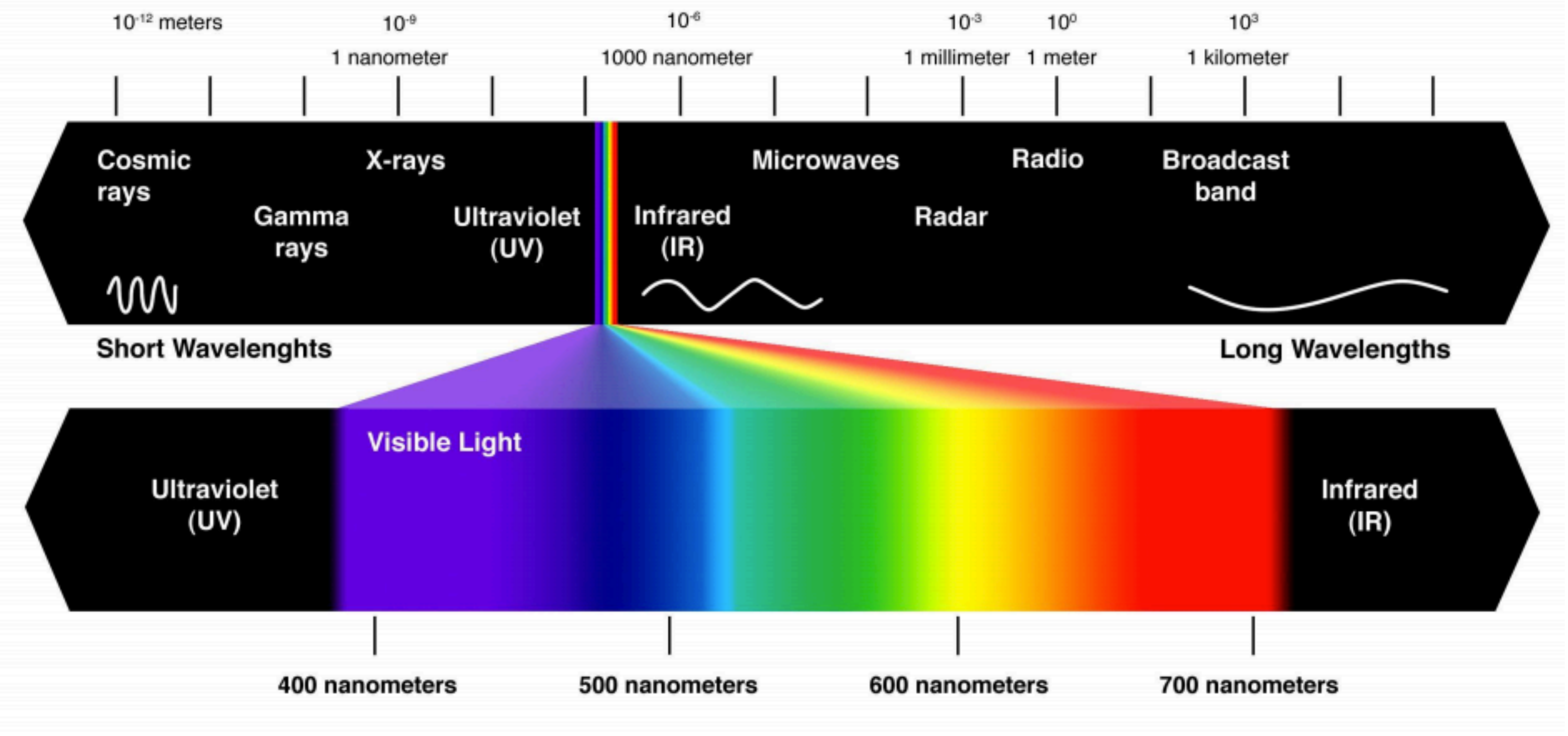
$$\frac{T_{\text{fever}}}{T_{\text{normal}}} = \frac{38°\text{C} + 273°\text{C}}{37°\text{C} + 273°\text{C}} = 1.003\,2$$

$$\frac{P_{\text{fever}}}{P_{\text{normal}}} = \left(\frac{38°\text{C} + 273°\text{C}}{37°\text{C} + 273°\text{C}}\right)^4 = 1.013$$

Figure 40.8 An ear thermometer measures a patient's temperature by detecting the intensity of infrared radiation leaving the eardrum.

Example 40.1 Thermal Radiation from Different Objects

(A) Find the peak wavelength of the blackbody radiation emitted by the human body when the skin temperature is 35°C.


10⁻¹² meters
10⁻⁹
1 nanometer
10⁻⁶
1000 nanometer
10⁻³
1 millimeter
10⁰
1 meter
10³
1 kilometer
Cosmic rays
X-rays
Gamma rays
Ultraviolet (UV)
Infrared (IR)
Microwaves
Radar
Radio
Broadcast band
Short Wavelenghts
Long Wavelengths
Visible Light
Ultraviolet (UV)
Infrared (IR)
400 nanometers
500 nanometers
600 nanometers
700 nanometers

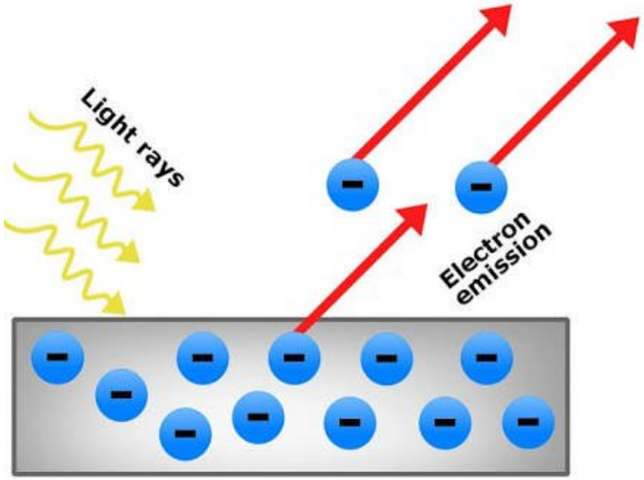
(B) Find the peak wavelength of the blackbody radiation emitted by the tungsten filament of a lightbulb, which operates at 2 000 K.

(C) Find the peak wavelength of the blackbody radiation emitted by the Sun, which has a surface temperature of approximately 5 800 K.

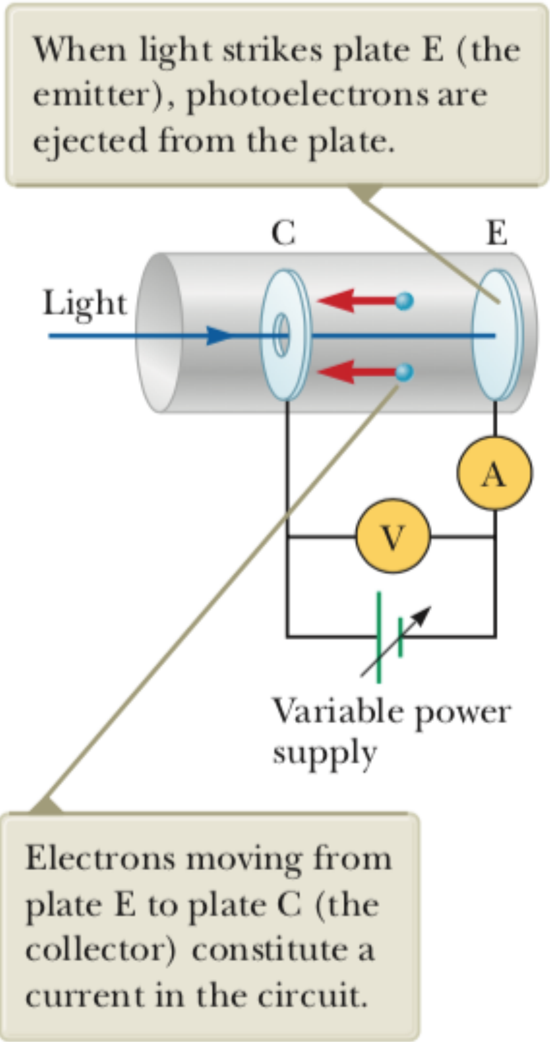

1600
Newton
Faraday
1900
Coulomb
Maxwell

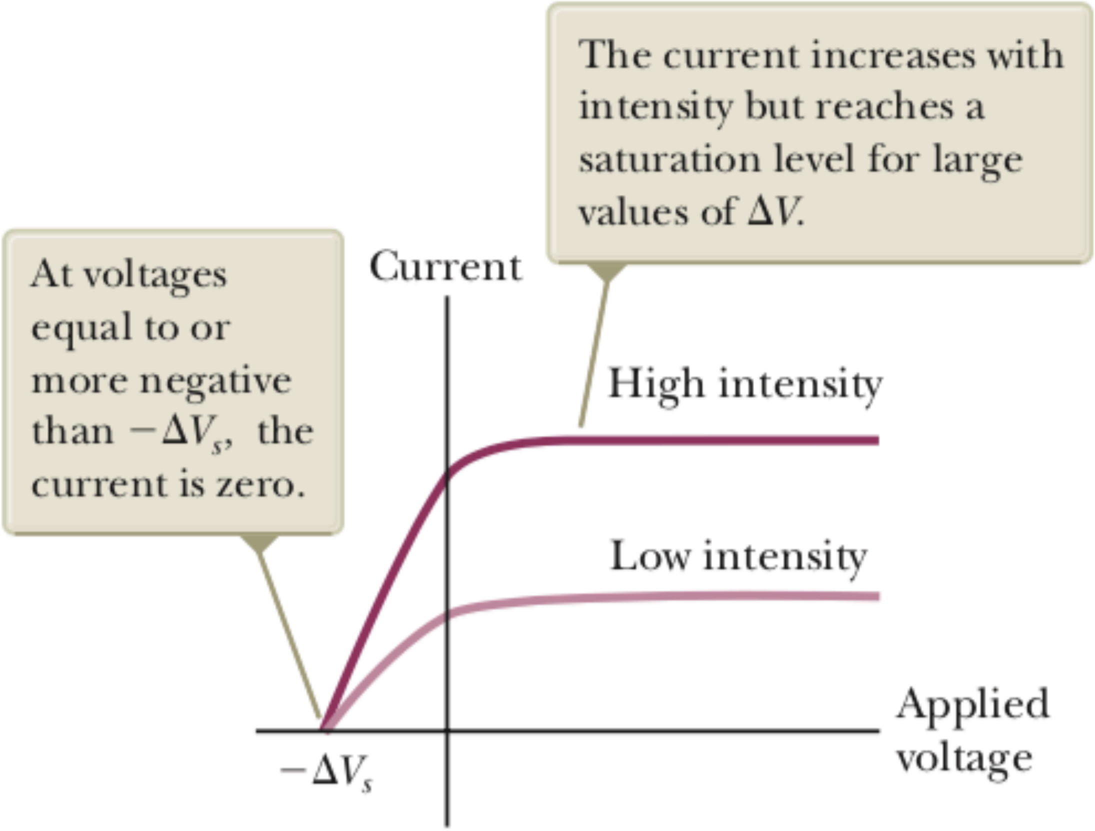

1900
Planck
Einstein
De Broglie
1920's

40.2 Photoelectric Effect



40.2 Photoelectric Effect





The Stopping potential: is the negative potential difference required to stop the ejection of electrons from the metal surface when light is directed onto the metal in the photoelectric experiment.

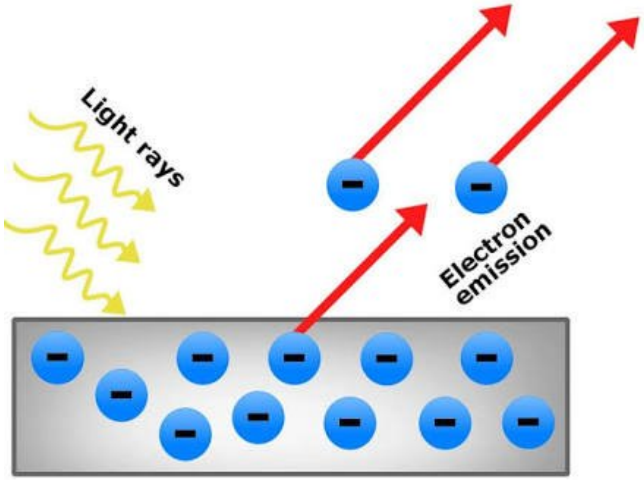
Play for Fun!

https://javalab.org/en/photoelectric_effect_2_en/

Classical point of view:

K.E vs. Light intensity?

Ejection vs. Light frequency?



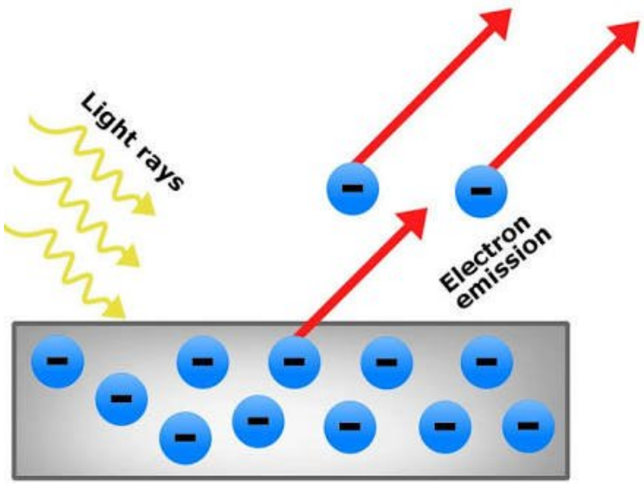
Time (incidence - ejection)

K.E vs. Light frequency?

Classical point of view:

K.E vs. Light intensity? ✓

Ejection vs. Light frequency? ✗



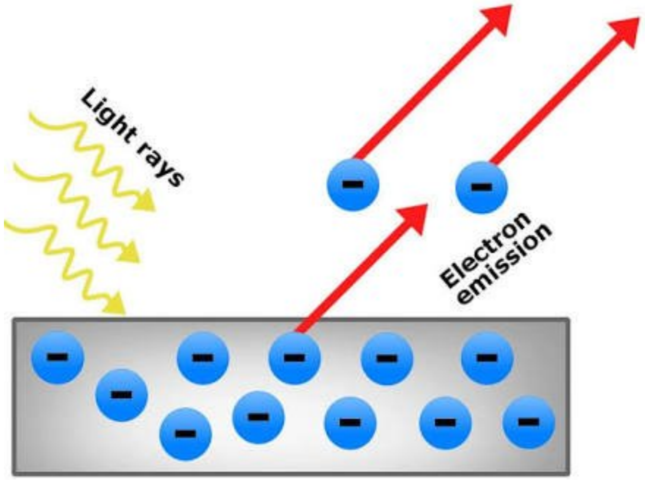
Time (incidence - ejection) ✓

K.E vs. Light frequency? ✗

Quantum point of view:

K.E vs. Light intensity?

Ejection vs. Light frequency?



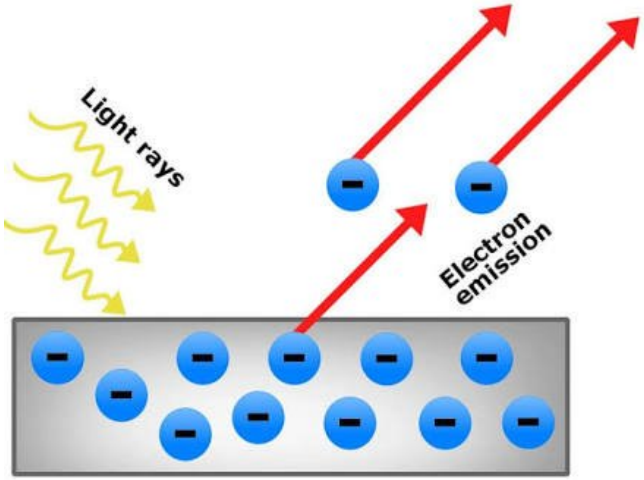
Time (incidence - ejection)

K.E vs. Light frequency?

Quantum point of view:

K.E vs. Light intensity? ✗

Ejection vs. Light frequency? ✓



Time (incidence - ejection) ✗

K.E vs. Light frequency? ✓

1. Dependence of photoelectron kinetic energy on light intensity

Classical prediction: Electrons should absorb energy continuously from the electromagnetic waves. As the light intensity incident on a metal is increased, energy should be transferred into the metal at a higher rate and the electrons should be ejected with more kinetic energy.

Experimental result: The maximum kinetic energy of photoelectrons is *independent* of light intensity as shown in Figure 40.10 with both curves falling to zero at the *same* negative voltage. (According to Equation 40.8, the maximum kinetic energy is proportional to the stopping potential.)

2. Time interval between incidence of light and ejection of photoelectrons

Classical prediction: At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal. This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.

Experimental result: Electrons are emitted from the surface of the metal almost *instantaneously* (less than 10^{-9} s after the surface is illuminated), even at very low light intensities.

3. **Dependence of ejection of electrons on light frequency**

Classical prediction: Electrons should be ejected from the metal at any incident light frequency, as long as the light intensity is high enough, because energy is transferred to the metal regardless of the incident light frequency.
Experimental result: 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.

4. **Dependence of photoelectron kinetic energy on light frequency**

Classical prediction: There should be *no* relationship between the frequency of the light and the electron kinetic energy. The kinetic energy should be related to the intensity of the light.
Experimental result: The maximum kinetic energy of the photoelectrons increases with increasing light frequency.

Einstein Model for the photoelectric effect:

Einstein Model for the photoelectric effect:

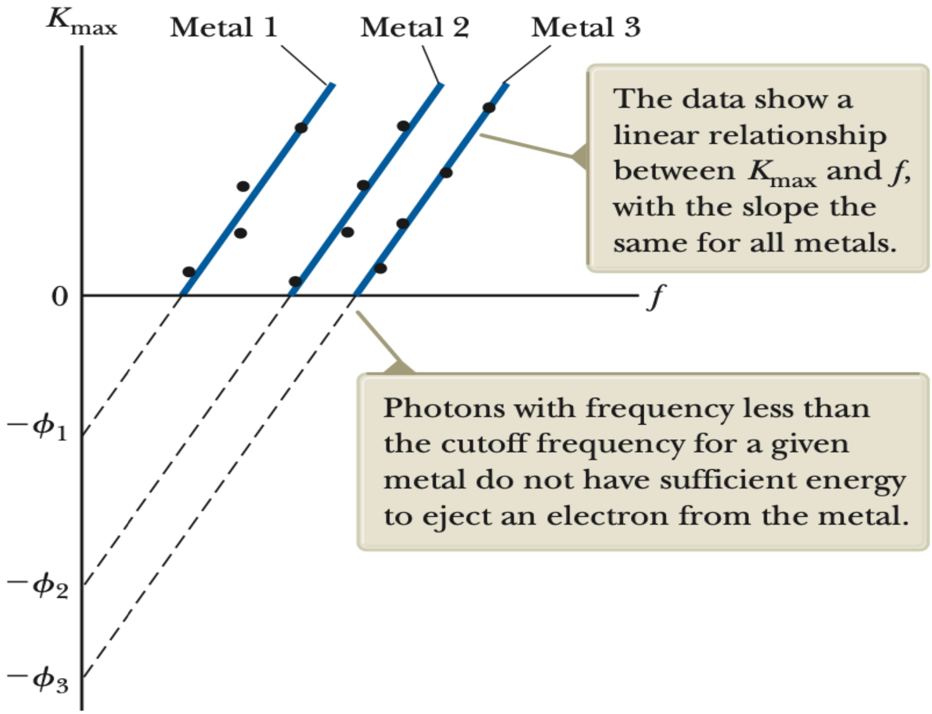
- Light from any source is quantized, and these quanta are called “photons”
- A photon of incident light gives *all* its energy hf to a *single* electron.
- In order to eject electron from the metal surface, we need to give it energy higher than the energy that binds the electron to the metal.
- **The work function (ϕ):** is the minimum energy required to remove an electron f rom the metal

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

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

Table 40.1 Work Functions of Selected Metals

Metal	ϕ (eV)
Na	2.46
Al	4.08
Fe	4.50
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14

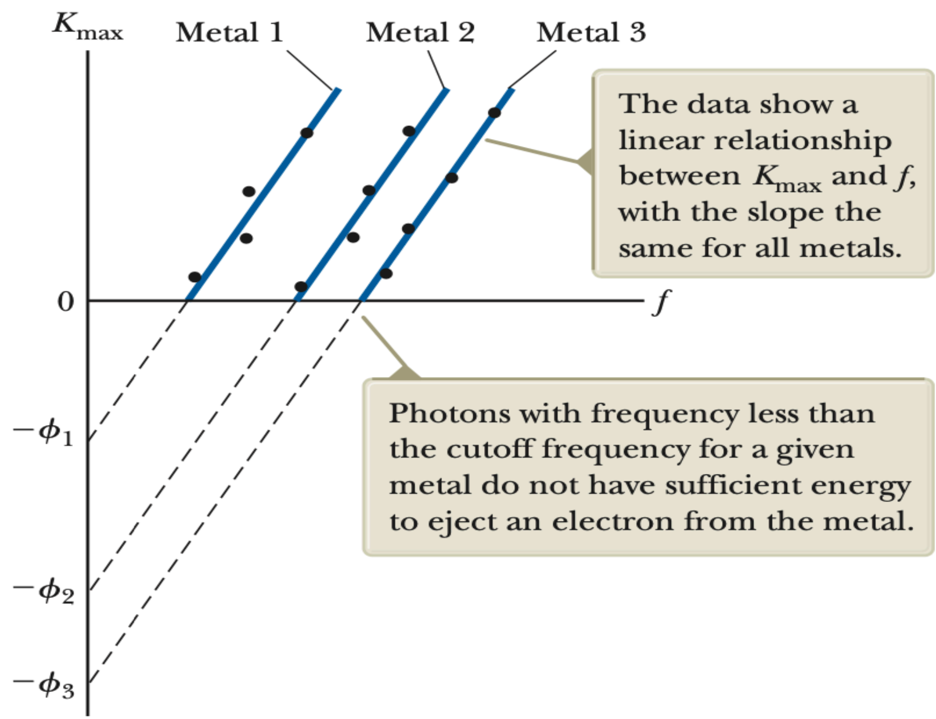

K_{max}
Metal 1
Metal 2
Metal 3
The data show a linear relationship between K_{max} and f, with the slope the same for all metals.
0
f
Photons with frequency less than the cutoff frequency for a given metal do not have sufficient energy to eject an electron from the metal.
$-\phi_1$
$-\phi_2$
$-\phi_3$

- **The cutoff frequency (f_c):** for a metal surface is the minimum frequency of incident radiation below which photoelectric effect does not occur.

$$f_c = \frac{\phi}{h}$$

- **The cutoff wavelength (λ_c):** is the radiation wavelength of radiation associated with the cutoff frequency

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



Example Application of the photoelectric effect: Photomultipliers

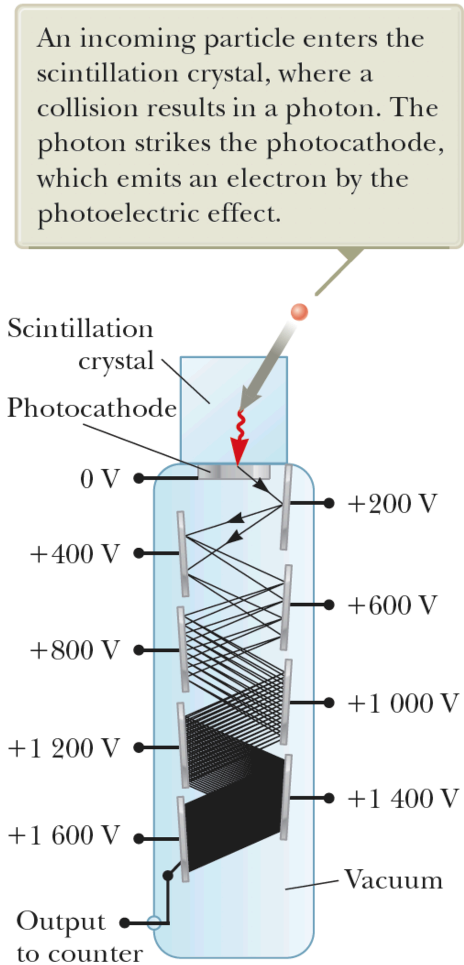


Figure 40.12 The multiplication of electrons in a photomultiplier tube.

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.

(B) Find the cutoff wavelength λ_c for sodium.

40.5 The Wave Properties of Particles

- **De Broglie's hypothesis:** All matter exhibits wave-like properties, and the wave length of the matter is related to its linear momentum as:

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

de Broglie wavelength


SPL/Getty Images

Louis de Broglie
French Physicist (1892–1987)

The frequency is :

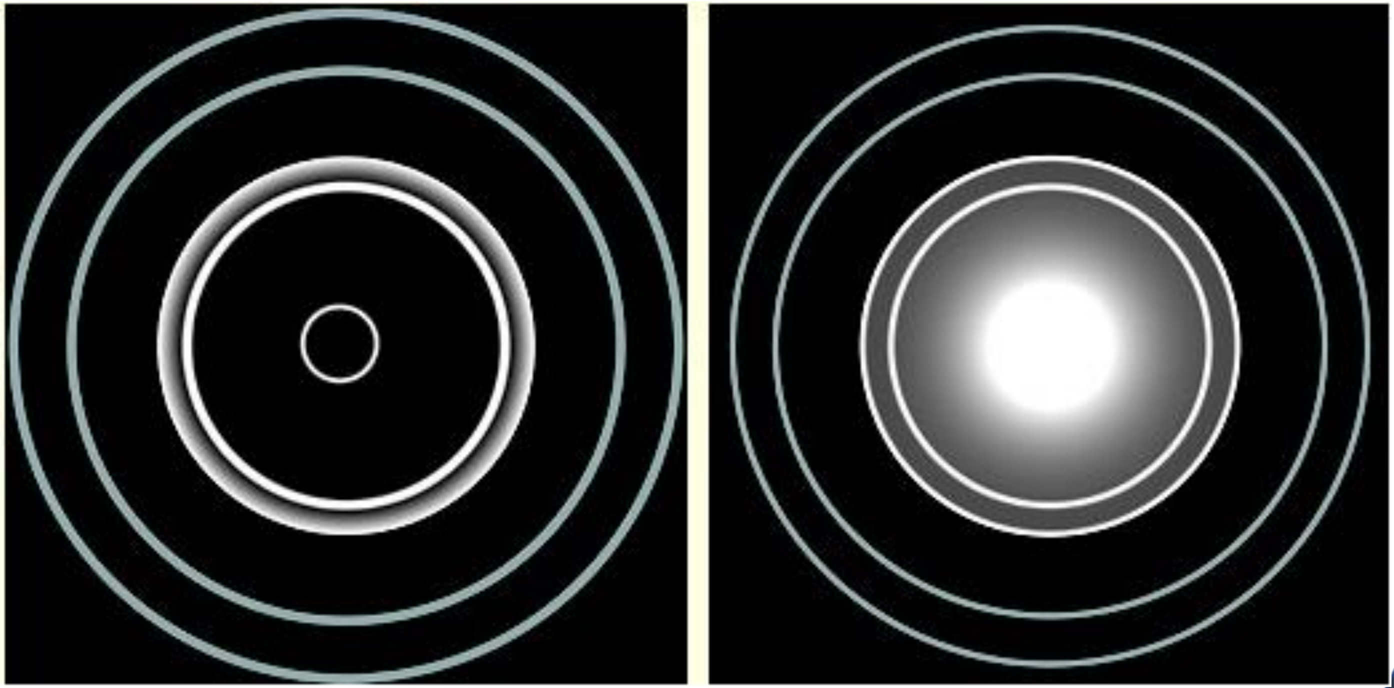
$$f = \frac{E}{h}$$

The principle of complementarity states that:

the wave and particle models of either matter or radiation complement each other.

The Davisson-Germer Experiment:

- When performing an experiment by scattering the low-energy electrons from nickel target, the electrons were noticed to be diffracted.
- The experiment provided the first confirmation of the wave properties proposed by de Broglie



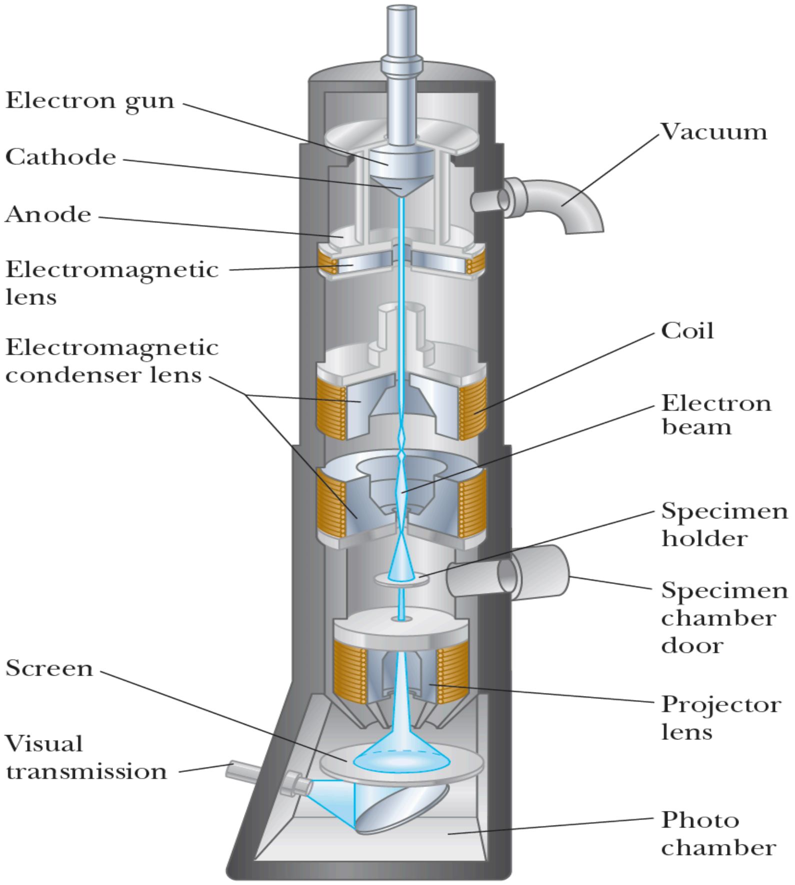
Example 40.5 Wavelengths for Microscopic and Macroscopic Objects

(A) Calculate the de Broglie wavelength for an electron ($m_e = 9.11 \times 10^{-31}$ kg) moving at 1.00×10^7 m/s.

(B) A rock of mass 50 g is thrown with a speed of 40 m/s. What is its de Broglie wavelength?

The Electron Microscope:

- Relies on the wave properties of the electrons.
- Principle: uses accelerated electrons (very small wavelength) to reveal the substructure of the a thin flat sample (up to the nano level)



a

Steven Allen/Brand X Pictures/Jupiter Images

b