Part III: Modern Physics

❑ **40.1 Blackbody Radiation and Planck's Hypothesis**

❑ **40.2 The Photoelectric Effect**

❑ **40.5 The Wave Properties of Particles**

Problems remained from classical mechanics that the special theory of relativity didn't explain.

❑ Attempts to apply the laws of classical physics to explain the behavior of matter on the atomic scale were consistently unsuccessful.

❑ Problems included:

1. Blackbody radiation

2. The electromagnetic radiation emitted by a heated object

3. Photoelectric effect

4. Emission of electrons by an illuminated metal

Between 1900 and 1930, another revolution took place in physics.

- A new theory called quantum mechanics was successful in explaining the behavior of particles of microscopic size.

- The first explanation using quantum theory was introduced by Max Planck.

–Many other physicists were involved in other subsequent developments

Max Karl Ernst Ludwig Planck : 23 April 1858 – 4 October 1947) was a German theoretical physicist whose discovery of energy quanta won him the Nobel Prize in Physics in 1918.
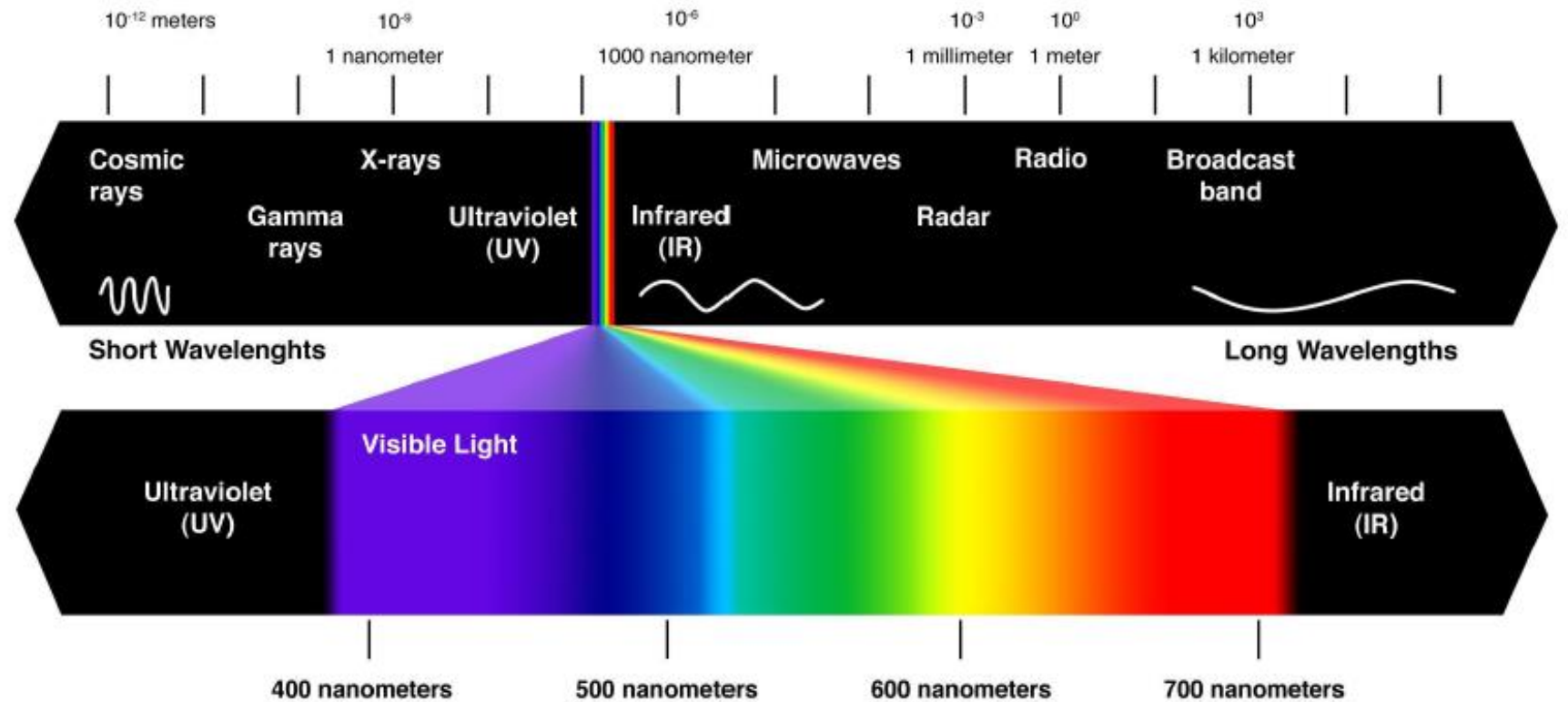
Blackbody Radiation

An object at any temperature is known to emit thermal radiation.

❑ Characteristics depend on the temperature and surface properties.

❑ The thermal radiation consists of a continuous distribution of wavelengths from all portions of the em spectrum.

❑ At room temperature, the wavelengths of the thermal radiation are mainly in the infrared region.

❑ As the surface temperature increases, the wavelength changes.

❑ It will glow red and eventually white.

The basic problem was in understanding the observed distribution in the radiation emitted by a black body.

❑ **Classical physics didn't adequately describe the observed distribution.**

❑ **A black body is an ideal system that absorbs all radiation incident on it.**

❑ **The electromagnetic radiation emitted by a 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.

❑ The hole acts as a perfect absorber.

❑ The nature of the radiation leaving the cavity through the hole depends only on the temperature of the cavity.
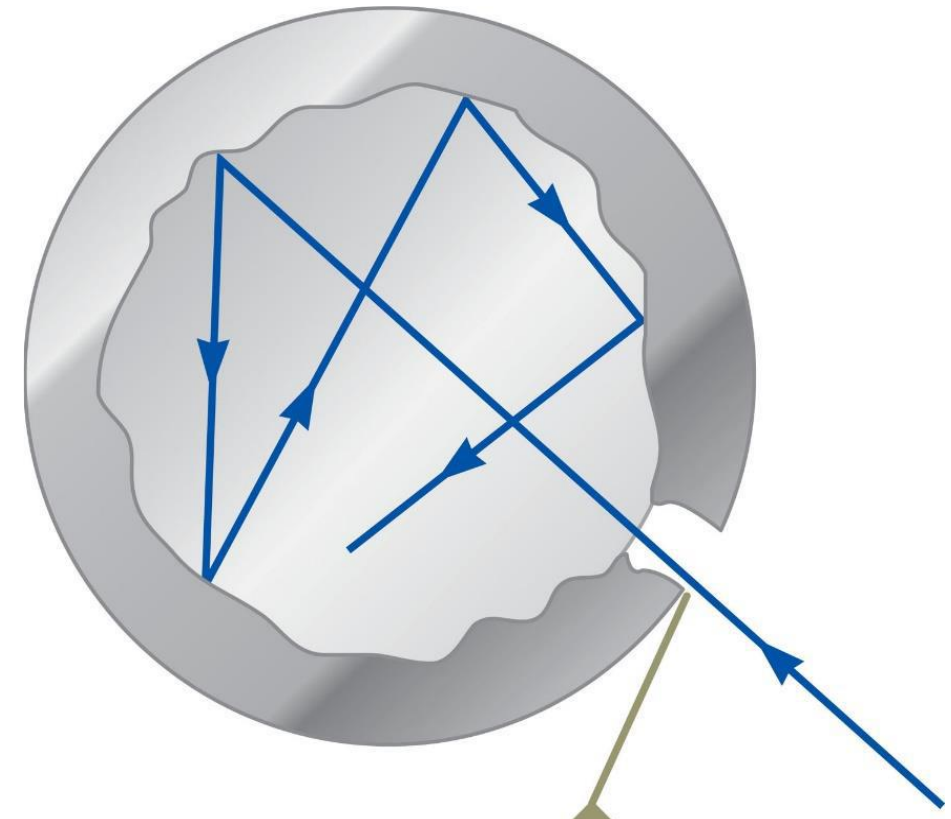
The opening to a cavity inside a hollow object is a good approximation of a black body: the hole acts as a perfect absorber.

The total power of the emitted radiation increases with temperature.

❑ Stefan–Boltzmann law :

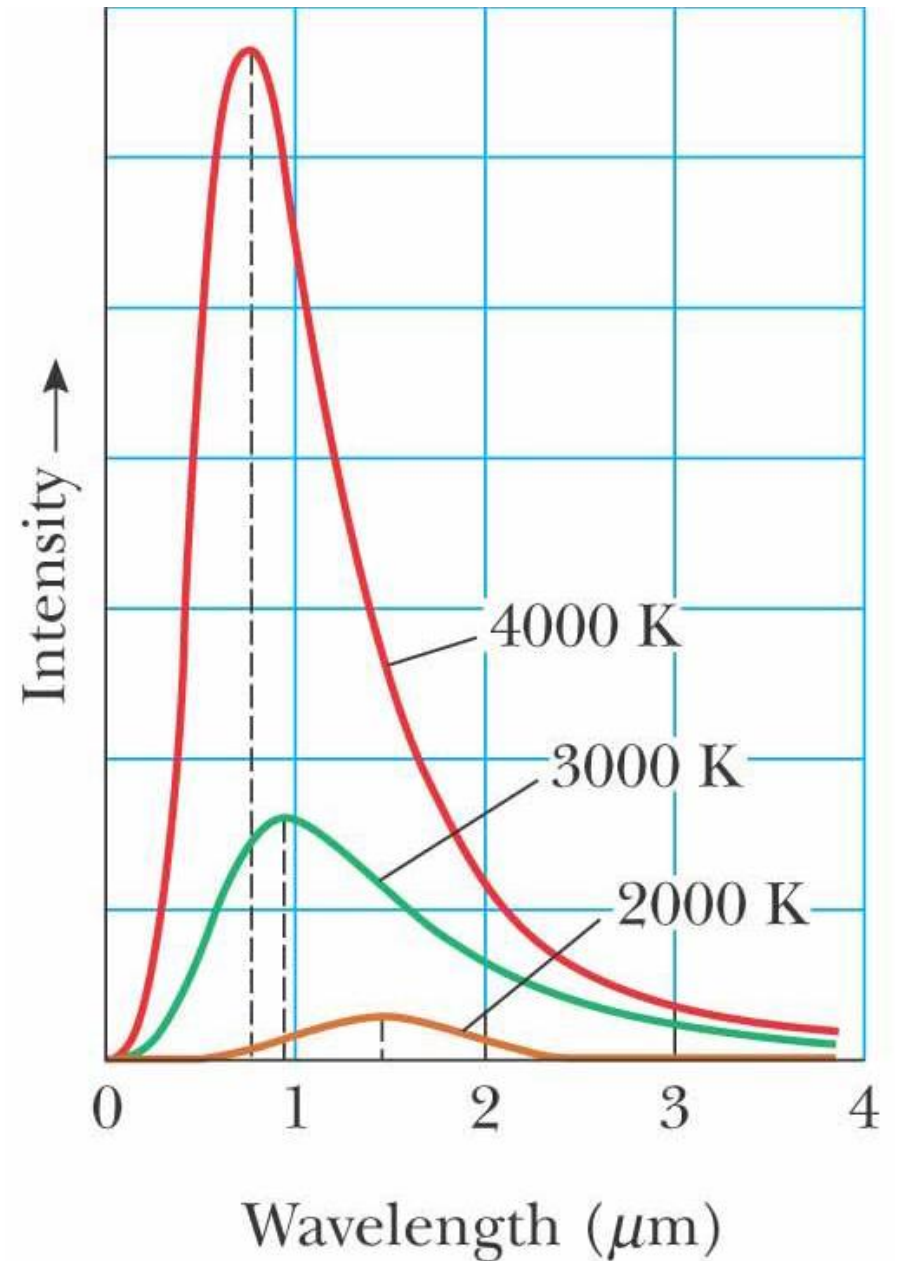P= σ A ε T^4 (The constant σ is called the Stefan–Boltzmann constant)

▪ The emissivity, ε, of a black body is 1, exactly

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

▪ Wien's displacement law

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

$$\lambda_{max} \, \alpha \, \frac{1}{T} \quad \Rightarrow \lambda_{max} = \frac{0.2898 X 10^{-2}}{T} \, m$$

$$\lambda_{max} \, T = 0.2898 X 10^{-2}$$

$$\lambda_1 \, T_1 = \lambda_2 \, T_2$$

مثال 1 ص557: درجة حرارة جسم الإنسان الخارجية تكون في حدود C°35 ، ما هو طول الموجة التي عندها أعلى شدة لإشعاعات المنبعثة من الجسم؟

$$\lambda_{max} = \frac{0.2898x10^{-2}}{T+273} = \frac{0.2898x10^{-2}}{35+273} = 9.409 \times 10^{-6} m = 940.9 nm$$

مثال 2 ص557: أعلى شدة للموجات الضوئية المنبعثة من الشمس هى للون الأصفر-البرتقالي وطوله الموجي 500 nm ، أحسب درجة حرارة الشمس بالدرجات المئوية؟

$$\lambda_{max} = \frac{0.2898x10^{-2}}{T+273} \Rightarrow T = \frac{0.2898x10^{-2}}{\lambda_{max}} - 273$$

$$= \frac{0.2898x10^{-2}}{500 \times 10^{-9}} - 237 = 5523^{\circ}c$$

❑ **The intensity increases with increasing temperature.**

❑ **The amount of radiation emitted increases with increasing temperature.**

❑ **The area under the curve**

❑ **The peak wavelength decreases with increasing temperature.**

•An early classical attempt to explain blackbody radiation was the **Rayleigh-Jeans law.**

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

•At long wavelengths, the law matched experimental results fairly well.
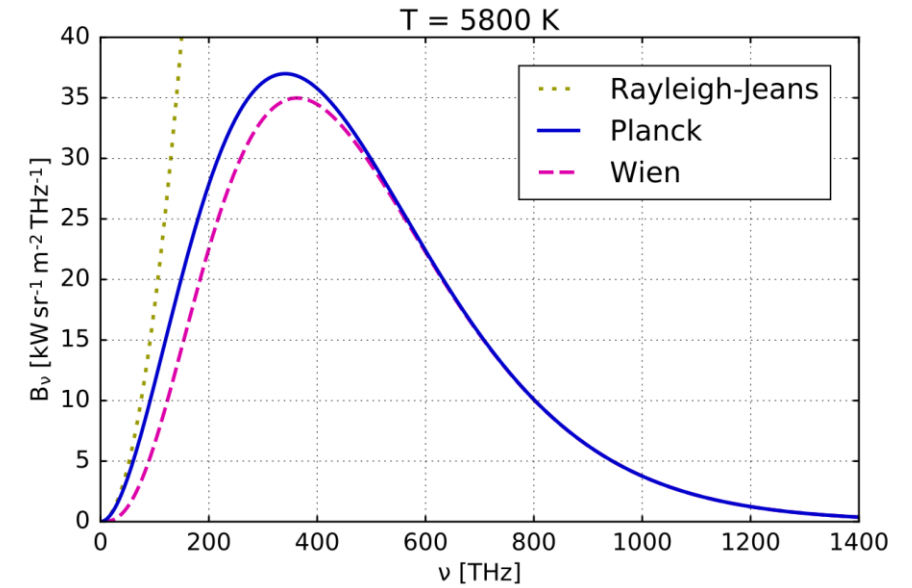
At short wavelengths, there was a major disagreement between the Rayleigh-Jeans law and experiment.

•This mismatch became known as the **ultraviolet catastrophe**.

–You would have infinite energy as the wavelength approaches zero.

The classical theory (red-brown curve) shows intensity growing without bound for short wavelengths, unlike the experimental data (blue curve).

Intensity

Wavelength
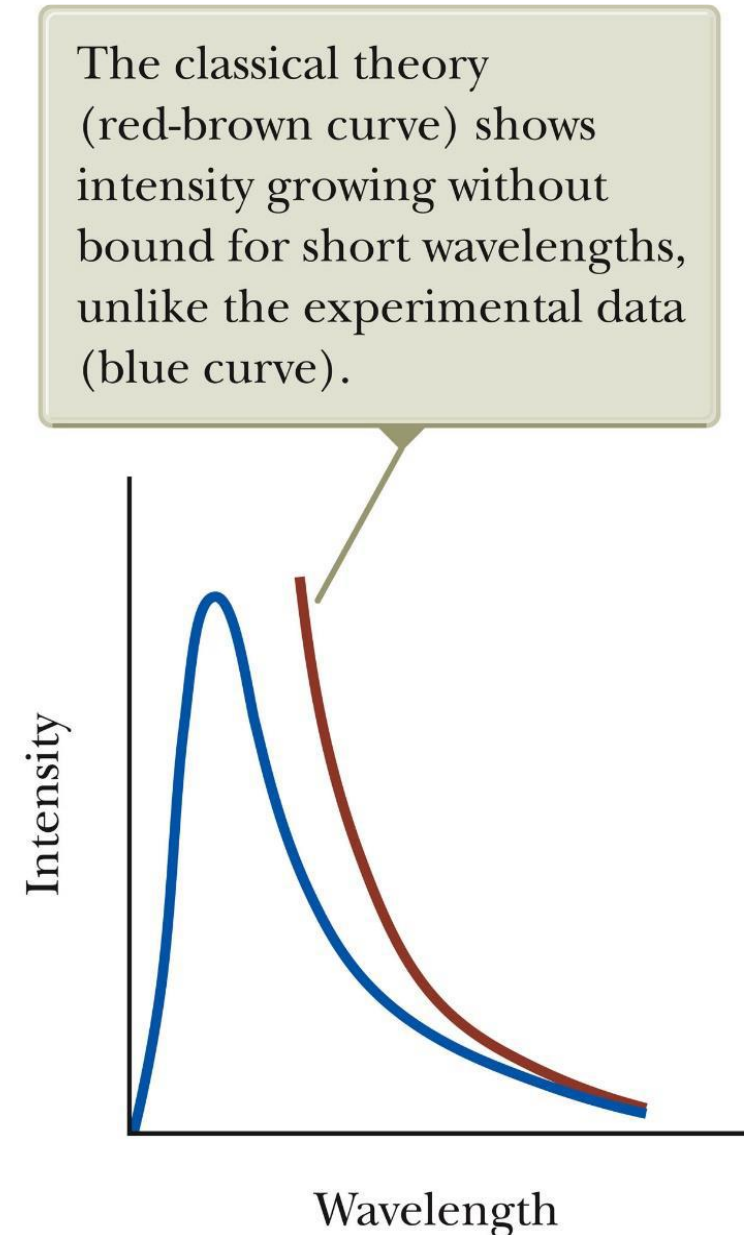
In 1900 Planck developed a theory of blackbody radiation that leads to an equation for the intensity of the radiation.

❑ This equation is in complete agreement with experimental observations.

❑ He assumed the cavity radiation came from atomic oscillations in the cavity walls.

❑ Planck made two assumptions about the nature of the oscillators in the cavity walls.

The energy of an oscillator can have only certain discrete values E_n.

$$E_n = n\,h\,f$$

n is a positive integer called the quantum number
f is the frequency of oscillation
h is Planck's constant

❑ This says the energy is quantized.

❑ Each discrete energy value corresponds to a different quantum state.

❑ Each quantum state is represented by the quantum number, n.

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.

❑ An oscillator emits or absorbs energy only when it changes quantum states.

❑ The energy carried by the quantum of radiation is E = h f.

An energy-level diagram shows the quantized energy levels and allowed transitions.

❑ Energy is on the vertical axis.

❑ Horizontal lines represent the allowed energy levels.

❑ The double-headed arrows indicate allowed transitions.

The double-headed arrows indicate allowed transitions.

E n

$4hf$ ——————————— 4

$3hf$ ——————————— 3

$2hf$ ——————————— 2

hf ——————————— 1

0 ——————————— 0

ENERGY
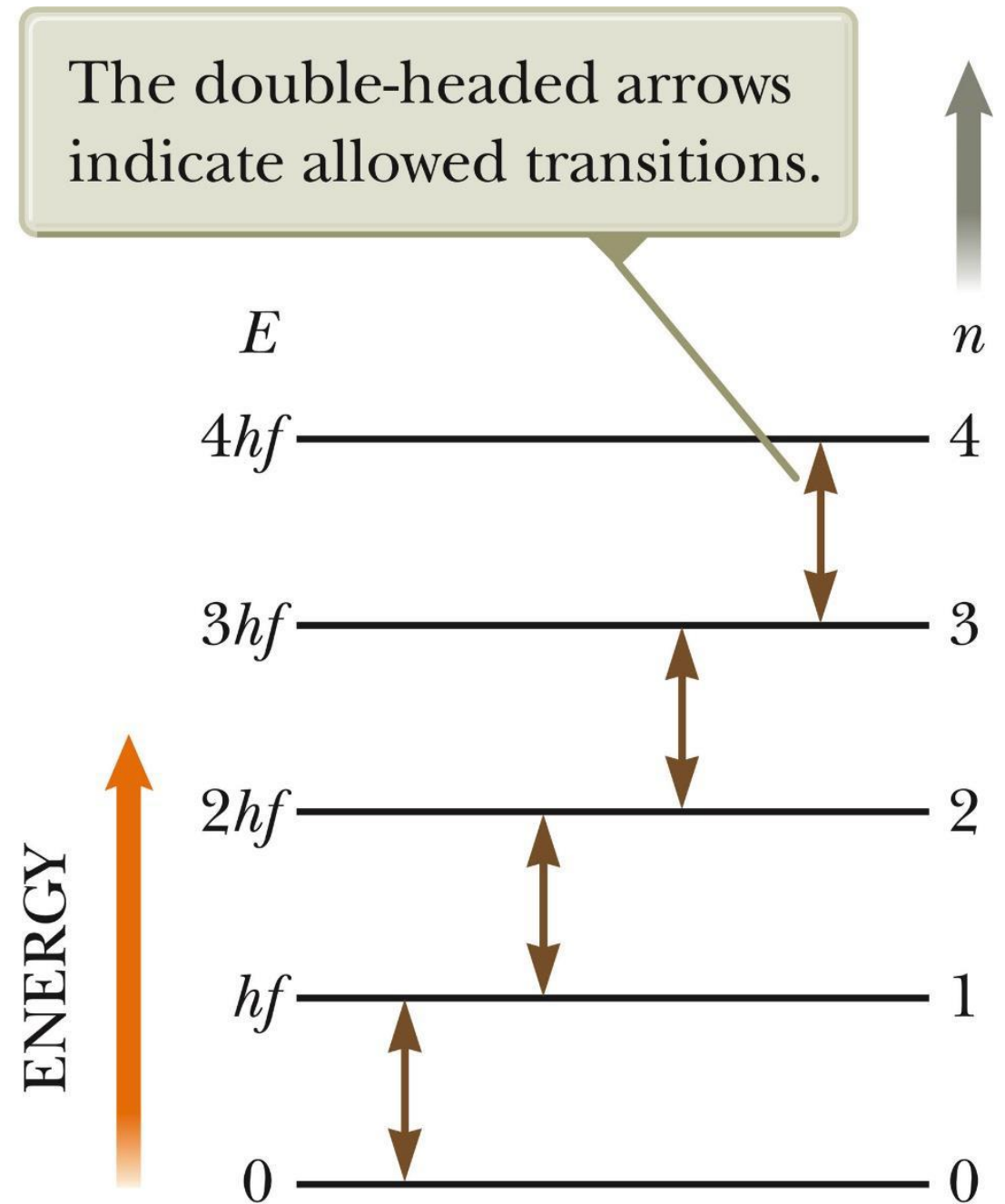
مثال 4 ص558: متوسط القدرة المتولدة من الشمس يساوي تقريباً W10^{26} x 3.98 ، وإذا كان متوسط طول الموجات المنبعثة من الشمس 500 nm. أحسب عدد الفوتونات المنبعثة في الثانية الواحدة؟

$$\because P(W) = \frac{E(j)}{t(s)} \Rightarrow E = Pt = nhf \Rightarrow n = \frac{Pt}{hf} = \frac{\lambda Pt}{hc}$$

$$\therefore n = \frac{500 \times 10^{-9} \times 3.98 \times 10^{26} \times 1}{6.63 \times 10^{-34} \times 3 \times 10^{8}}$$

$$\therefore n = 1 \times 10^{45} \, photon/\sec$$

مثال 5 ص558: محطة إذاعية تبث برامجها بقدرة100 kW وعلى تردد مقداره 150.92 MHz، كم عدد الفوتونات المنبعثة من برج الإذاعة في الثانية الواحدة؟

$$E = Pt = nhf \Rightarrow n = \frac{Pt}{hf}$$

$$\therefore n = \frac{100 \times 10^3 \times 1}{6.63 \times 10^{-34} \times 150.92 \times 10^6}$$

$$\therefore n = 9.99 \times 10^{29} \ photon/\sec$$

❑ **The average energy of a wave is the average energy difference between levels of the oscillator, weighted according to the probability of the wave being emitted.**

❑ **This weighting is described by the Boltzmann distribution law and gives the probability of a state being occupied as being proportional to** $e^{-E/K_B T}$

where E is the energy of the state.
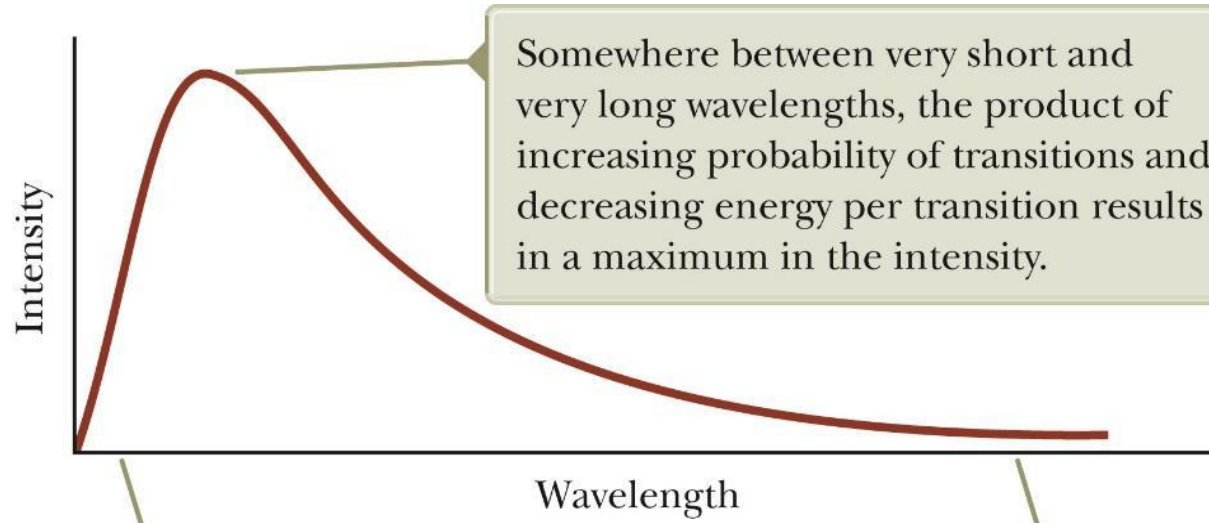
Somewhere between very short and very long wavelengths, the product of increasing probability of transitions and decreasing energy per transition results in a maximum in the intensity.

At short wavelengths, there is a large separation between energy levels, leading to a low probability of excited states and few downward transitions. The low probability of transitions leads to low intensity.
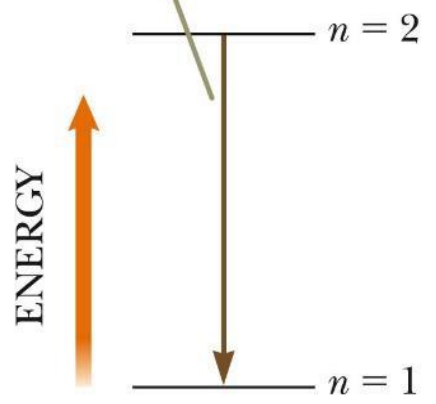
At long wavelengths, there is a small separation between energy levels, leading to a high probability of excited states and many downward transitions. The low energy in each transition leads to low intensity.

Intensity

Wavelength

ENERGY

$n = 2$

$n = 1$

ENERGY

$n = 7$
$n = 6$
$n = 5$
$n = 4$
$n = 3$
$n = 2$
$n = 1$
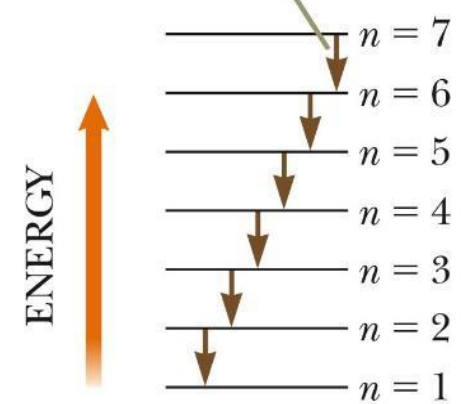
Planck generated a theoretical expression for the wavelength distribution.

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

h = 6.626 x 10-34J.s

❑ h is a fundamental constant of nature.

❑ At long wavelengths, Planck's equation reduces to the Rayleigh-Jeans expression.

❑ At short wavelengths, it predicts an exponential decrease in intensity with decreasing wavelength.

❑ This is in agreement with experimental results.

Einstein and Planck's Results

Einstein redefined Planck's results by assuming the oscillations of the electromagnetic field were themselves quantized.

❑ In other words, Einstein proposed that quantization is a fundamental property of light and other electromagnetic radiation.

❑ This led to the concept of photons.

Photoelectric Effect

❑ The **photoelectric effect** occurs when light incident on certain metallic surfaces causes electrons to be emitted from those surfaces.

❑ The emitted electrons are called **photoelectrons.**

❑ They are no different than other electrons.

❑ The name is given because of their ejection from a metal by light in the photoelectric effect

☐ **When the tube is kept in the dark, the ammeter reads zero.**
☐ **When plate E is illuminated by light having an appropriate wavelength, a current is detected by the ammeter.**
☐ **The current arises from photoelectrons emitted from the negative plate and collected at the positive plate.**

When light strikes plate E (the emitter), photoelectrons are ejected from the plate.

C   E

Light

A

V

Variable power supply

Electrons moving from plate E to plate C (the collector) constitute a current in the circuit.
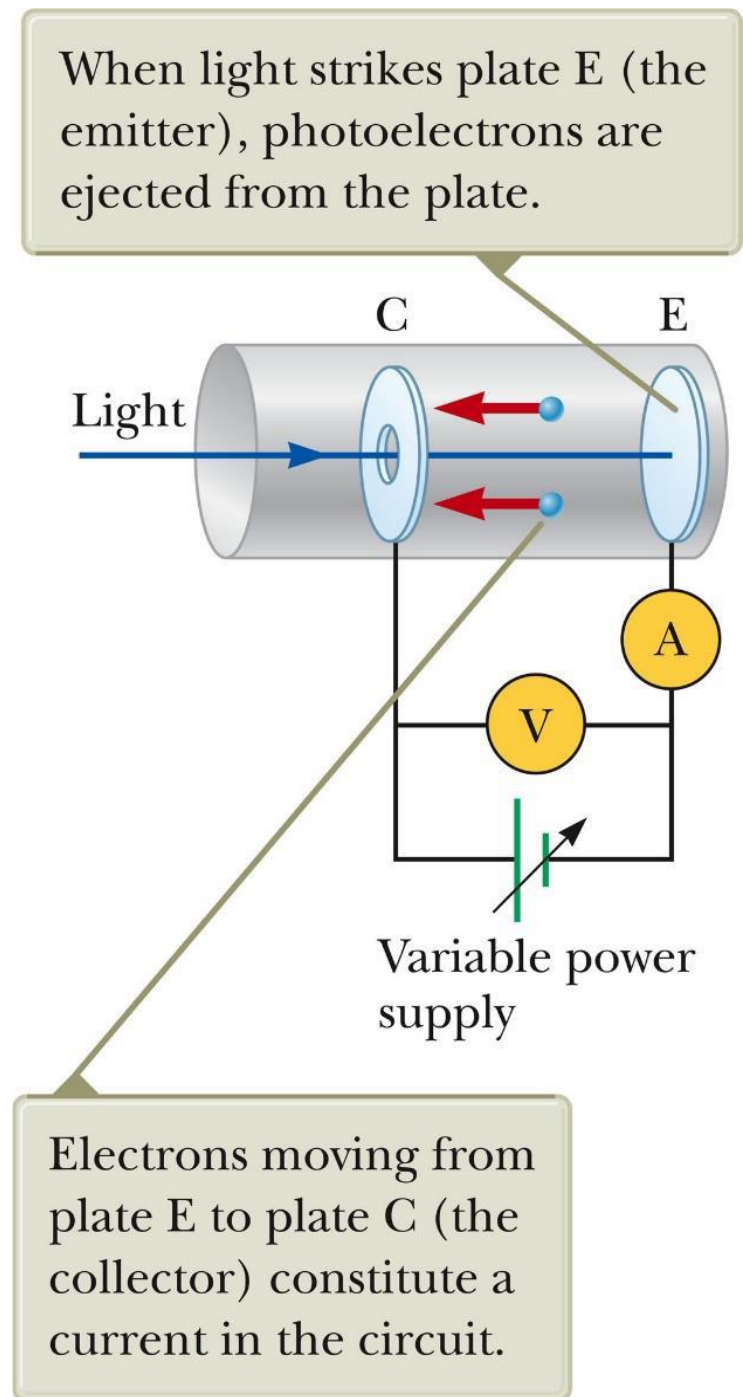
At large values of DV, the current reaches a maximum value.

❑ All the electrons emitted at E are collected at C.

❑ The maximum current increases as the intensity of the incident light increases.

❑ When DV is negative, the current drops.

❑ When DV is equal to or more negative than DVs, the current is zero.

The current increases with intensity but reaches a saturation level for large values of ΔV.

At voltages equal to or more negative than $-\Delta V_s$, the current is zero.

Current

High intensity

Low intensity

$-\Delta V_s$

Applied voltage
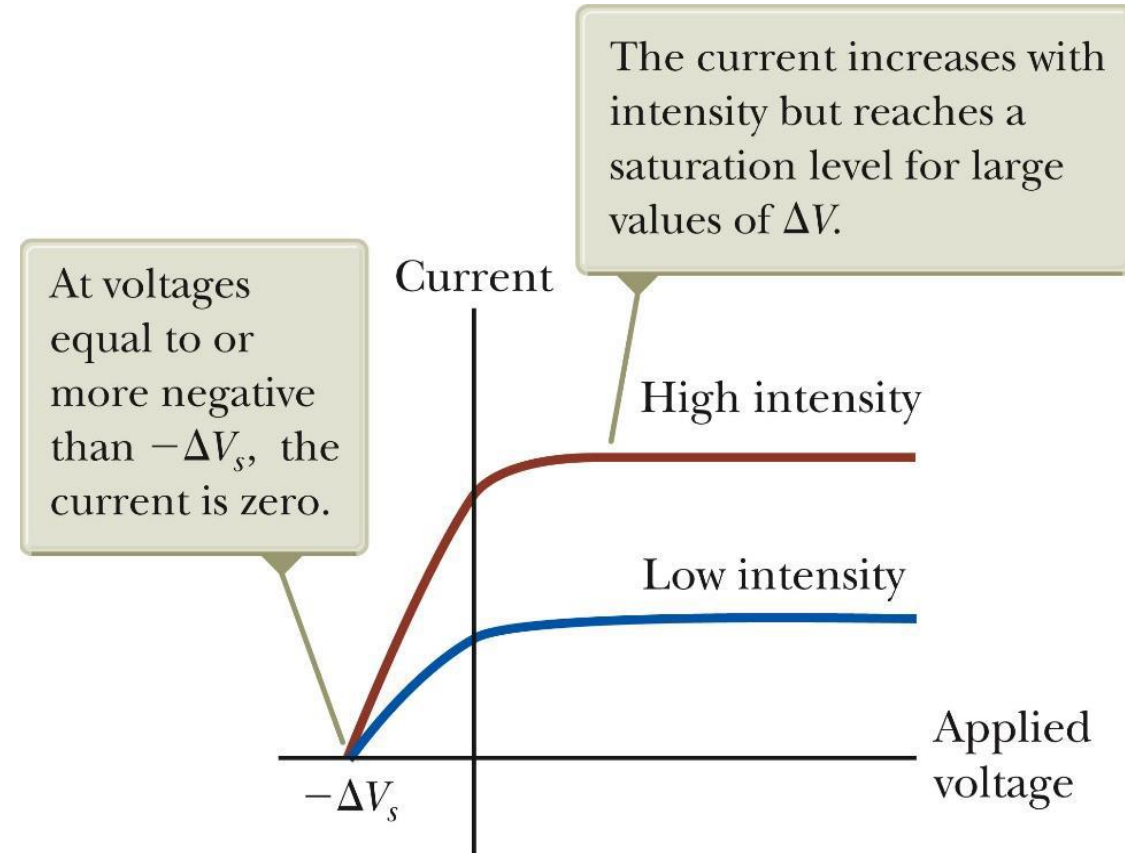
Dependence of photoelectron kinetic energy on light intensity

❑ **Classical Prediction**

Electrons should absorb energy continually from the electromagnetic waves.

As the light intensity incident on the metal is increased, the electrons should be ejected with more kinetic energy.

❑ **Experimental Result**

The maximum kinetic energy is independent of light intensity.

The maximum kinetic energy is proportional to the stopping potential (DV_s).

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 almost instantaneously, even at very low light intensities.

Dependence of ejection of electrons on light frequency

❑ Classical Prediction

•Electrons should be ejected at any frequency as long as the light intensity is high enough.

❑ Experimental Result

•No electrons are emitted if the incident light falls below some cutoff frequency, f_c.

•The cutoff frequency is characteristic of the material being illuminated.

•No electrons are ejected below the cutoff frequency regardless of intensity.

Dependence of photoelectron kinetic energy on light frequency

❑ **Classical Prediction**
- There should be no relationship between the frequency of the light and the electric 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.

The experimental results contradict all four classical predictions.

•Einstein extended Planck's concept of quantization to electromagnetic waves.

•All electromagnetic radiation of frequency f from any source can be considered a stream of quanta, now called photons.

•Each photon has an energy Eand moves at the speed of light in a vacuum.

–E = hf

•A photon of incident light gives all its energy to a single electron in the metal.

Photoelectric Effect, Work Function

Electrons ejected from the surface of the metal and not making collisions with other metal atoms before escaping possess the maximum kinetic energy K_{max}.

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

Φ is called the work function of the metal.

The work function represents the minimum energy with which an electron is bound in the metal.

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

Note: Values are typical for metals listed. Actual values may vary depending on whether the metal is a single crystal or polycrystalline. Values may also depend on the face from which electrons are ejected from crystalline metals. Furthermore, different experimental procedures may produce differing values.

Photon Model Explanation of the Photoelectric Effect

Dependence of photoelectron kinetic energy on light intensity

–K_{max} is independent of light intensity.

–K depends on the light frequency and the work function.

•Time interval between incidence of light and ejection of the photoelectron

–Each photon can have enough energy to eject an electron immediately.

•Dependence of ejection of electrons on light frequency

–There is a failure to observe photoelectric effect below a certain cutoff frequency, which indicates the photon must have more energy than the work function in order to eject an electron.

–Without enough energy, an electron cannot be ejected, regardless of the fact that many photons per unit time are incident on the metal in a very intense light beam.

Dependence of photoelectron kinetic energy on light frequency

–Since Kmax= hf–φ

–A photon of higher frequency carries more energy.

•A photoelectron is ejected with higher kinetic energy.

•Once the energy of the work function is exceeded

–There is a linear relationship between the maximum electron kinetic energy and the frequency.
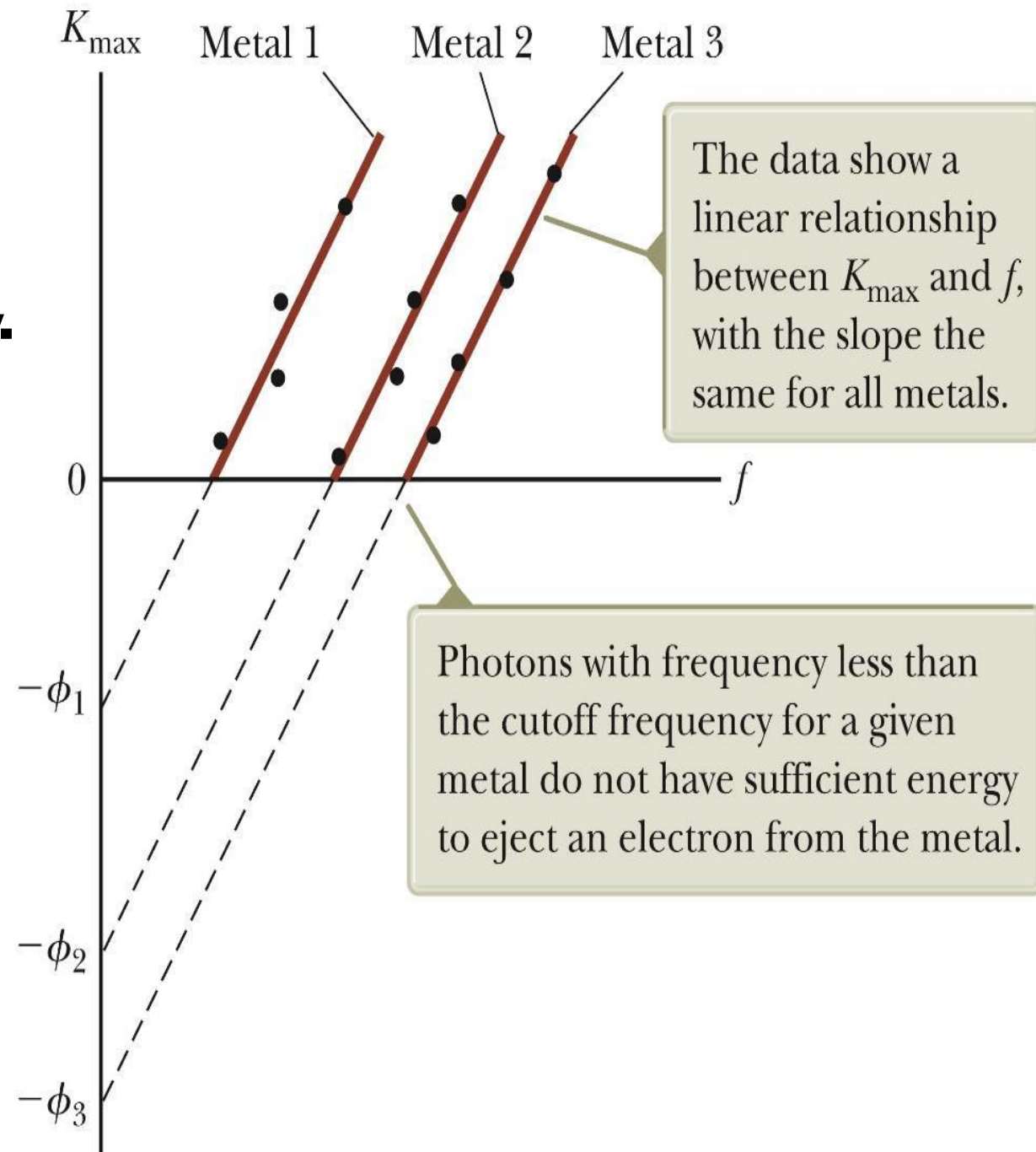
The lines show the linear relationship between K and f.

❑ The slope of each line is h.

❑ The x-intercept is the **cutoff frequency**.

❑ This is the frequency below which no photoelectrons are emitted.

The cutoff frequency is related to the work function through $f_c = \varphi / h$.

•The cutoff frequency corresponds to a cutoff wavelength.

$$\lambda_c = \frac{c}{f_c} = \frac{hc}{\varphi}$$

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

K_{max} Metal 1   Metal 2   Metal 3

0 ——————————————— f

The data show a linear relationship between K_{max} and f, with the slope the same for all metals.

Photons with frequency less than the cutoff frequency for a given metal do not have sufficient energy to eject an electron from the metal.

$-\phi_1$

$-\phi_2$

$-\phi_3$

سقط ضوء طول موجته 300 nm على سطح معدن الصوديوم الــــــذي
دالة الشغل له تساوي 2.46 eV ، احسب :

أ– الطاقة الحركية القصوى للإلكترونات الضوئية المنبعثة .

ب– طول الموجة التي يقف عندها انبعاث الإلكترونات .

$$hf = W + K_{\max} \Rightarrow K_{\max} = hf - W = 4.14 - 2.46 = 1.68 eV$$

$$K_{\max} = hf - W = 0 \Rightarrow hf_0 = W \Rightarrow h\frac{c}{\lambda_0} = W \Rightarrow$$

$$\lambda_0 = 5.05 \times 10^{-7} m = 505 nm$$

ر- تيار الإلكترونات المنبعث من خلية كهروضوئية بســـبب ســقوط شعاع ضوئي طول موجته 300 nm ينقطع تماما عنـــد اســتعمال جهد إيقاف كهربي مقداره 0.625 V احسب دالة الشغل (W) لهذا المعدن المستعمل في الخلية الكهروضوئية .

Solution

$E = h\,f = W + K_{max}$

$E = h\,f = W + e\,V$

$E = h\,f = \{(6.62 \times 10^{-34})(3 \times 10^8 / 300 \times 10^{-9})\}/1.6 \times 10^{-19} =$

$E = 4.1\ eV$

$W = 4.1 - e\,V$

$W = 4.1 - 0.625$

$W = 3.475\ eV$

٧ – دالة الشغل W لعنصر البوتاسيوم تساوي 2.24 eV . إذا اســـتعمل هذا العنصر في خلية كهروضوئية وأضيء بضوء طــــول موجتـــه 312.5 nm احسب :

أ– أعلى طاقة حركية للإلكترونات الضوئية المنبعثة .

ب– الجهد الكهربي الذي ينقطع عنده التيار .

جـــ– الطول الموجي للضوء الساقط الذي يتوقف عنده انبعـــاث الإلكترونات من عنصر البوتاسيوم .

Solution

$E = h f = W + K_{max}$

$f = c/l = 3 \times 10^8 /312.5 \times 10^{-9} = 9.6 \times 10^{14} \, Hz$

$E = h f = (6.62 \times 10^{-34})(9.6 \times 10^{14}) / 1.6 \times 10^{-19} = 2.24 + K_{max}$

$K_{max} = 3.97 - 2.24 = 1.73 \, eV$

$e V_o = hf - W = 1.73$

$V_o = 1.73/1.6 \times 10^{-19} = 1.08 \times 10^{19} \, V.$

$hf_o = W$

$f_o = W/h = c/\lambda_o =$

$\lambda_o = c \times h /W = (3 \times 10^8)(6.62 \times 10^{-34})/(2.24 \times 1.6 \times 10^{-19}) = 554 \, nm$

Louis de Broglie

- French physicist

- Originally studied history

- Was awarded the Nobel Prize in 1929 for his prediction of the wave nature of electrons

Louis de Broglie postulated that because photons have both wave and particle characteristics, perhaps all forms of matter have both properties. The de Broglie wavelength of a particle is

$$\lambda = h/P = h/mv$$

·In an analogy with photons, de Broglie postulated that a particle would also have a frequency associated with it

•These equations present the dual nature of matter:

Particle nature, p and E

Wave nature, λ and *f*

The principle of complementarity states that the wave and particle models of either matter or radiation complement each other. Neither model can be used exclusively to describe matter or radiation adequately.
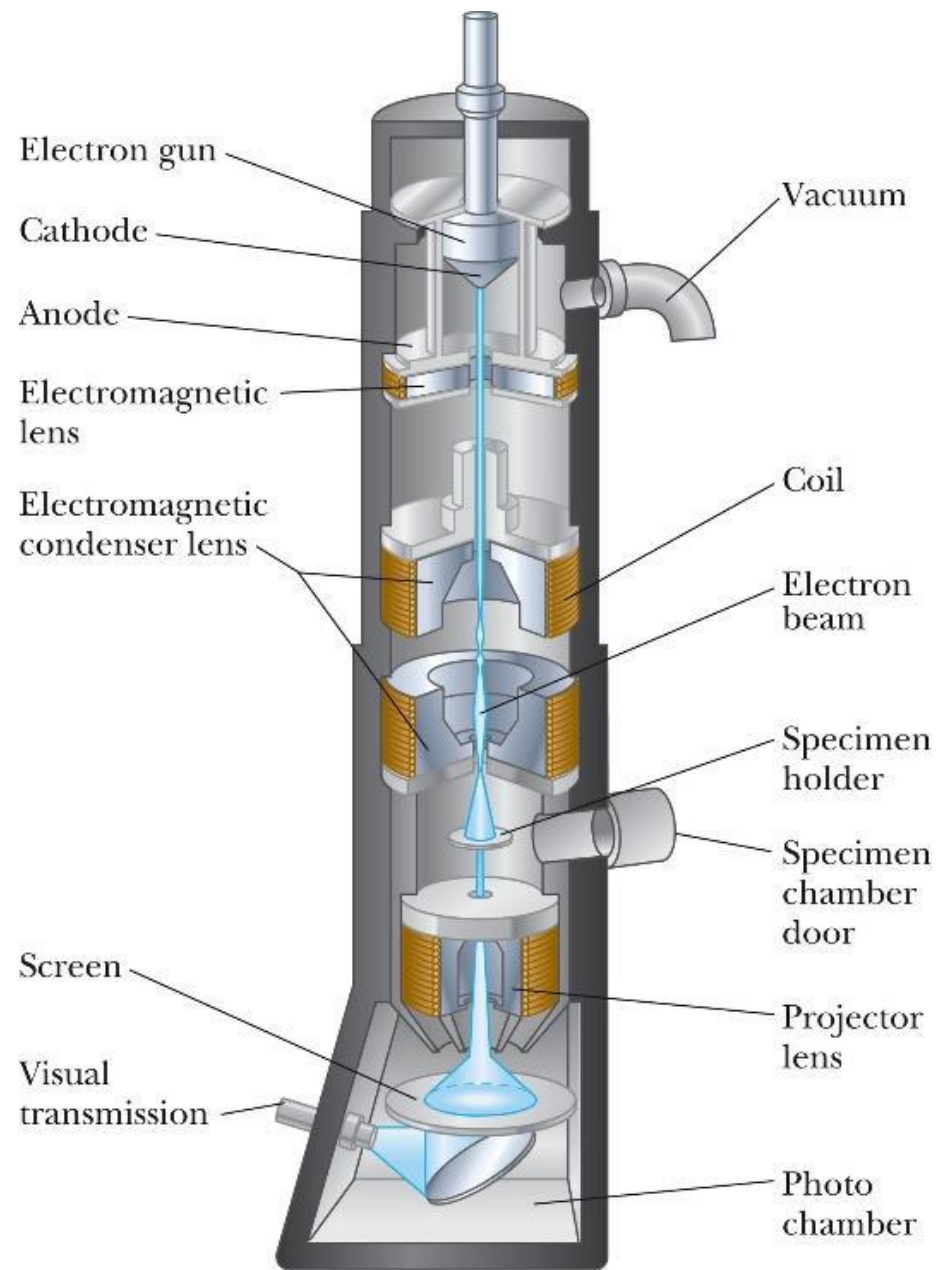
Davisson - Germer Experiment

- If particles have a wave nature, then under the correct conditions, they should exhibit diffraction effects.
- Davisson and Germer measured the wavelength of electrons.
- This provided experimental confirmation of the matter waves proposed by de Broglie.

Mechanical waves have materials that are "waving" and can be described in terms of physical variables.

❏ A string may be vibrating.

❏ Sound waves are produced by molecules of a material vibrating.

❏ Electromagnetic waves are associated with electric and magnetic fields.

❏ Waves associated with particles cannot be associated with a physical variable.

Electron Microscope

❏ The electron microscope relies on the wave characteristics

   of electrons.

❏ Shown is a transmission electron microscope

❏ Used for viewing flat, thin samples

❏ The electron microscope has a high resolving power because

   it has a very short wavelength.

❏ Typically, the wavelengths of the electrons are about 100

   times shorter than that of visible light.

Electron gun
Cathode
Anode
Electromagnetic lens
Electromagnetic condenser lens
Screen
Visual transmission
Vacuum
Coil
Electron beam
Specimen holder
Specimen chamber door
Projector lens
Photo chamber

a

b