Chapter 40

Introduction to Quantum Physics

40.1 Blackbody Radiation and Planck's Hypothesis

40.2 The Photoelectric Effect

Need for Quantum Physics

•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:

- Blackbody radiation
  - The electromagnetic radiation emitted by a heated object
- Photoelectric effect
  - Emission of electrons by an illuminated metal

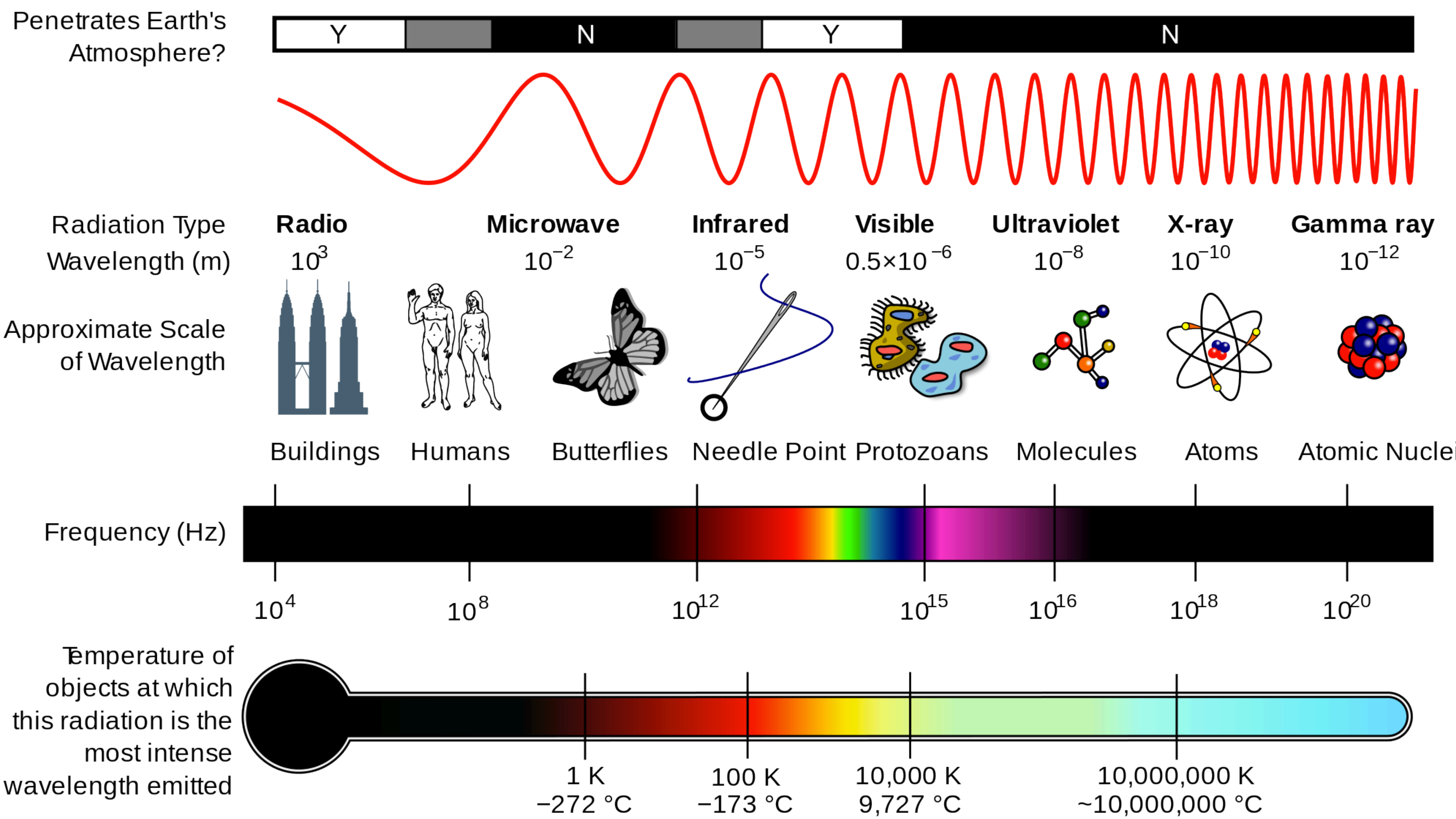
Quantum Mechanics Revolution

- 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

40.1 Blackbody Radiation

- An object at any temperature is known to emit therm radiation.
  - Characteristics depend on the temperature and surface properties.
  - The thermal radiation consists of a continuous distribution of wavelengths from all portions of the electromagnetic 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.

EM spectrum


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^3
Microwave
10^−2
Infrared
10^−5
Visible
0.5×10^−6
Ultraviolet
10^−8
X-ray
10^−10
Gamma ray
10^−12
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

40.1 Blackbody Radiation

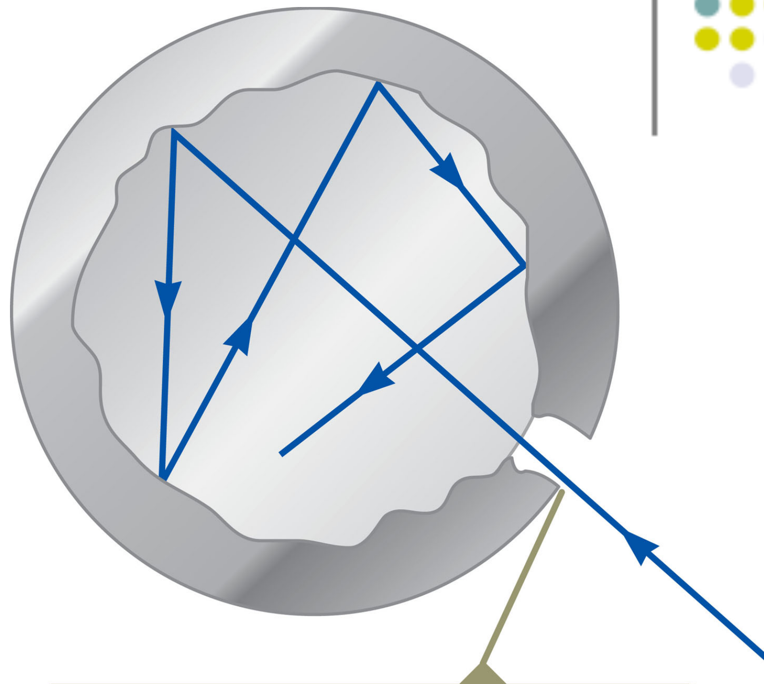
Blackbody Radiation, cont.

- 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**.

40.1 Blackbody Radiation

Blackbody Approximation

- 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.

40.1 Blackbody Radiation

Blackbody Experiment Results

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

- Stefan's law (from Chapter 20):

  $P = \sigma A e T^4$

  Where σ is the Stefan–Boltzmann constant, equal to 5.670 10^8 $W/m^2.K^4$, A is the surface area, e is emissivity and T is the surface temperature in kelvins $T_k=273+T_c$

  – The emissivity, e, of a black body is 1, exactly

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

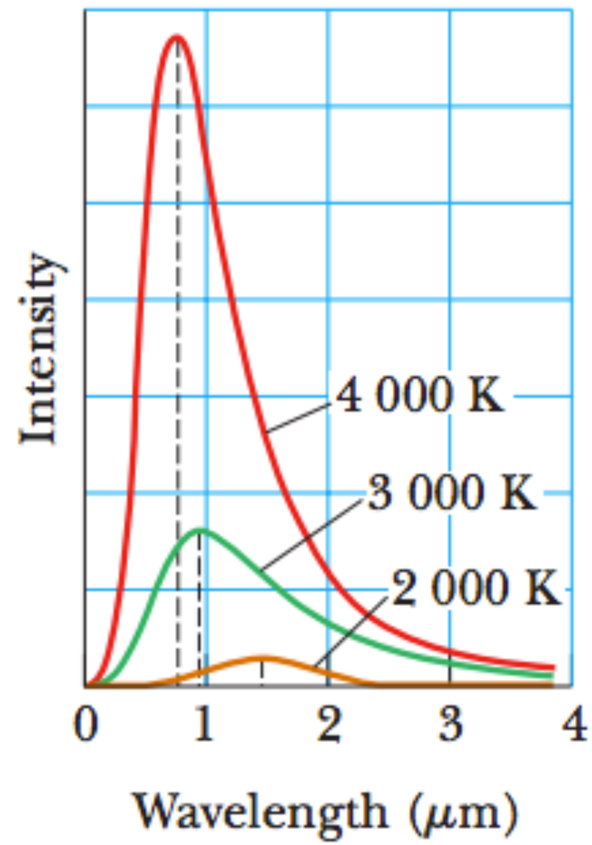
- Wien's displacement law

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

40.1 Blackbody Radiation

Intensity of Blackbody Radiation, Summary

- 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.



40.1 Blackbody Radiation

Rayleigh-Jeans Law

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

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

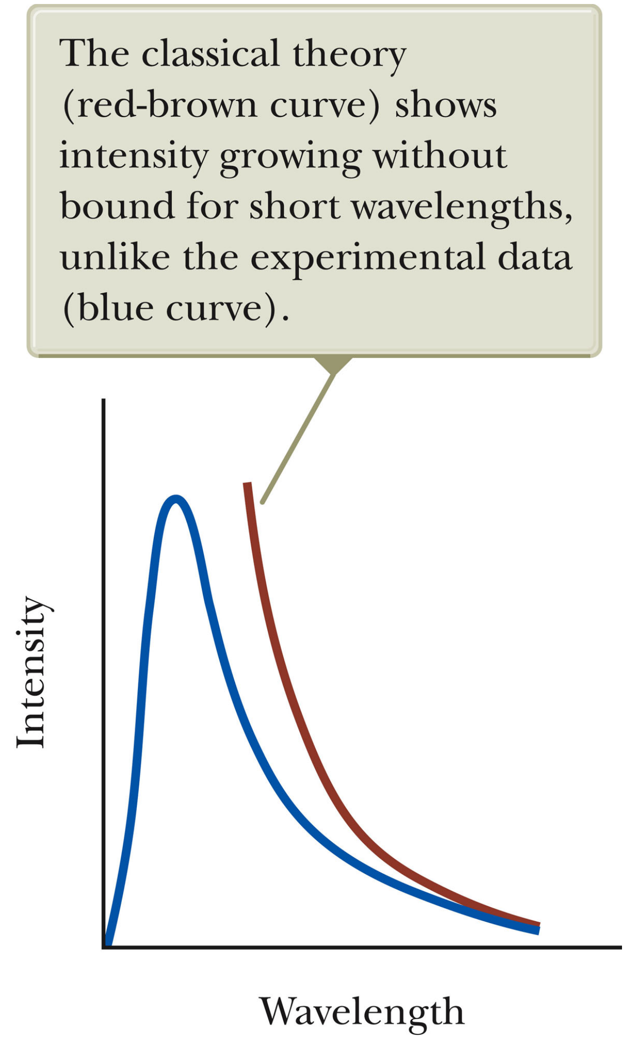
•Where *I(λ,T) is* the intensity, c is speed light, and k_B is Boltzmann's constant

•At long wavelengths, the law matched experimental results fairly well.

40.1 Blackbody Radiation

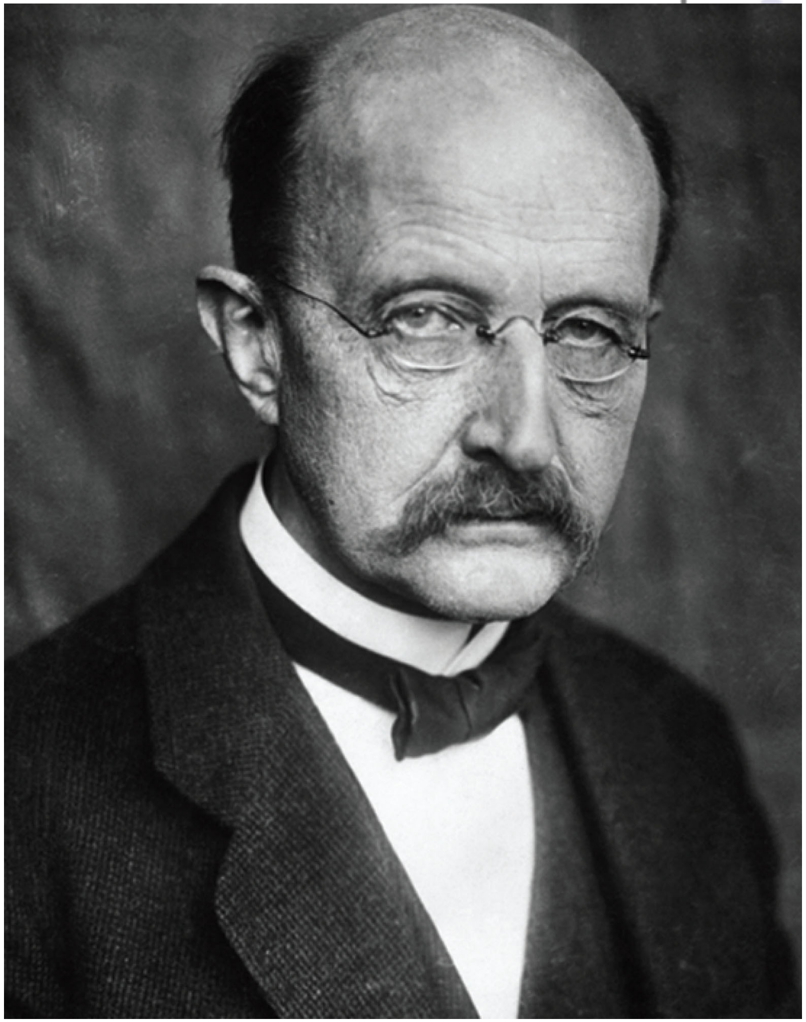
Rayleigh-Jeans Law, cont.

- 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.



40.1 Blackbody Radiation

Max Planck



- 1858 – 1847
- German physicist
- Introduced the concept of "quantum of action"
- In 1918 he was awarded the Nobel Prize for the discovery of the quantized nature of energy.

40.1 Blackbody Radiation

Planck's Theory of Blackbody Radiation

- 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.

40.1 Blackbody Radiation

Planck's Assumption, 1

1. 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, When the oscillator is in the n=1 quantum state, its energy is hf ; when it is in the n=2 quantum state, its energy is 2hf ; and so on.
  - f is the frequency of oscillation
  - h is Planck's constant

40.1 Blackbody Radiation

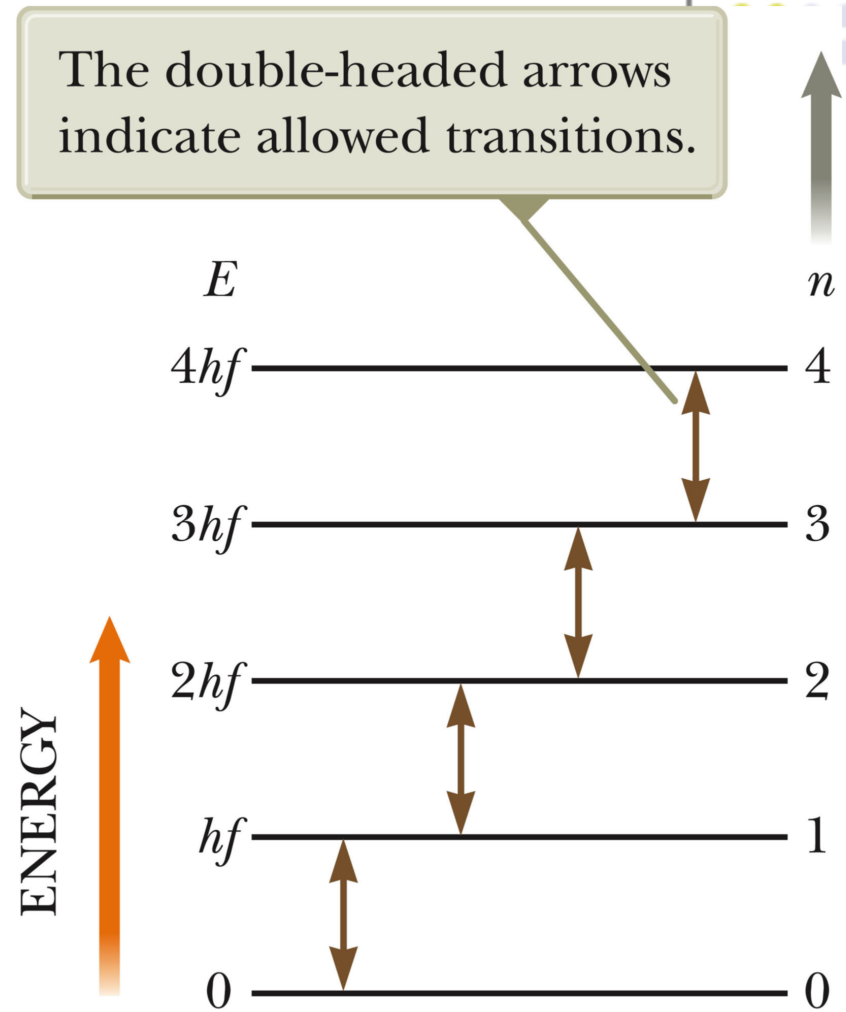
Planck's Assumption, 2

2. 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 $E = hf$.

40.1 Blackbody Radiation

Energy-Level Diagram

- 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.



40.1 Blackbody Radiation

Planck's Wavelength Distribution Function

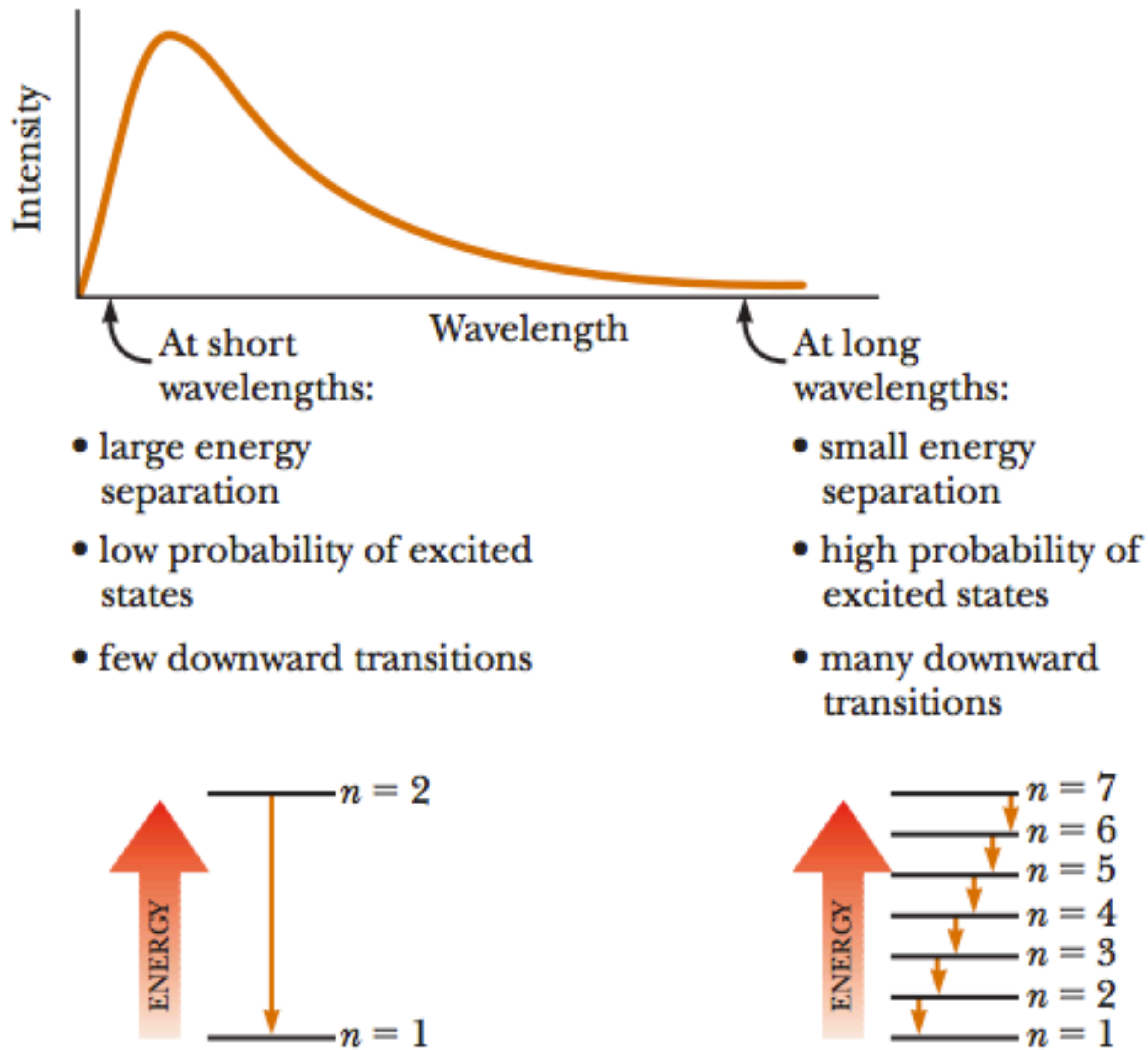
- Planck generated a theoretical expression for the wavelength distribution.

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

- This function includes the parameter h, which Planck adjusted so that his curve matched the experimental data at all wavelengths.

- The value of this parameter is found to be independent of the material of which the black body is made and independent of the temperature; it is a fundamental constant of nature. The value of h, Planck's constant,

  - $h = 6.626 \times 10^{-34}$ J·s
  - h is a fundamental constant of nature.
  - This is in agreement with experimental results.


Intensity
Wavelength
At short wavelengths:
• large energy separation
• low probability of excited states
• few downward transitions
At long wavelengths:
• small energy separation
• high probability of excited states
• many downward transitions
ENERGY
n = 2
n = 1
ENERGY
n = 7
n = 6
n = 5
n = 4
n = 3
n = 2
n = 1

40.1 Blackbody Radiation

Einstein and Planck's Results

•Einstein re-derived 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.

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.

SOLUTION

Conceptualize Thermal radiation is emitted from the surface of any object. The peak wavelength is related to the surface temperature through Wien's displacement law (Eq. 40.2).

Categorize We evaluate results using an equation developed in this section, so we categorize this example as a substitution problem.

Solve Equation 40.2 for λ_{max}:

$$(1) \quad \lambda_{max} = \frac{2.898 \times 10^{-3}\ \text{m} \cdot \text{K}}{T}$$

Substitute the surface temperature:

$$\lambda_{max} = \frac{2.898 \times 10^{-3}\ \text{m} \cdot \text{K}}{308\ \text{K}} = 9.4\ \mu\text{m}$$

This radiation is in the infrared region of the spectrum and is invisible to the human eye. Some animals (pit vipers, for instance) are able to detect radiation of this wavelength and therefore can locate warm-blooded prey even in the dark.

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

SOLUTION

Substitute the filament temperature into Equation (1):

$$\lambda_{max} = \frac{2.898 \times 10^{-3}\ \text{m}\cdot\text{K}}{2\,000\ \text{K}} = 1.4\ \mu\text{m}$$

This radiation is also in the infrared, meaning that most of the energy emitted by a lightbulb is not visible to us.

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

SOLUTION

Substitute the surface temperature into Equation (1):

$$\lambda_{max} = \frac{2.898 \times 10^{-3}\ \text{m}\cdot\text{K}}{5\,800\ \text{K}} = 0.50\ \mu\text{m}$$

This radiation is near the center of the visible spectrum, near the color of a yellow-green tennis ball. Because it is the most prevalent color in sunlight, our eyes have evolved to be most sensitive to light of approximately this wavelength.

What If? Suppose the oscillator makes a transition from the $n = 5.4 \times 10^{33}$ state to the state corresponding to $n = 5.4 \times 10^{33} - 1$. By how much does the energy of the oscillator change in this one-quantum change?

Answer From Equation 40.5, the energy carried away due to the transition between states differing in n by 1 is

$$E = hf = (6.626 \times 10^{-34}\ \text{J}\cdot\text{s})(0.56\ \text{Hz}) = 3.7 \times 10^{-34}\ \text{J}$$

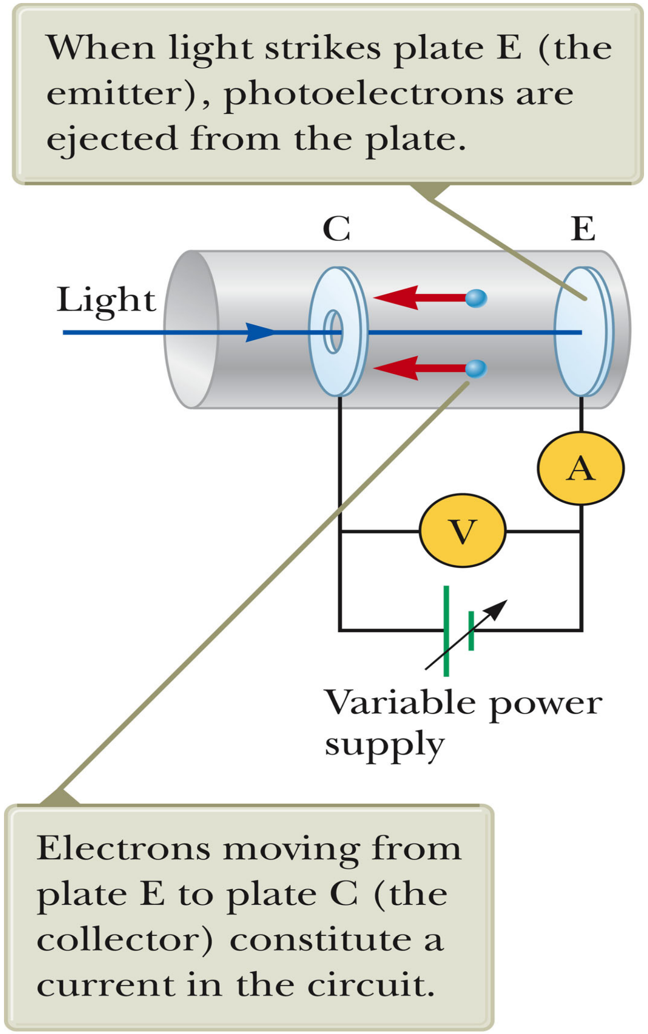
40.2 Photoelectric Effect

- 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.

40.2 Photoelectric Effect

Photoelectric Effect Apparatus

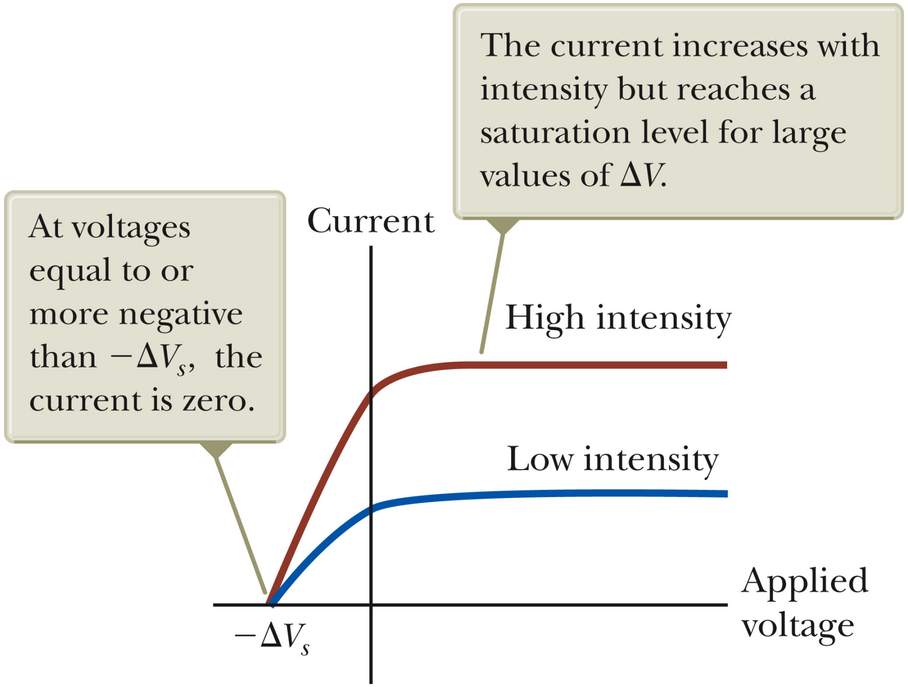
- When the tube is kept in the dark, the ammeter reads zero.
- When plate E is illuminated by light having an appropriate wavelength, a current is detected by the ammeter.
- The current arises from photoelectrons emitted from the negative plate and collected at the positive plate.



40.2 Photoelectric Effect

Photoelectric Effect, Results

- At large values of ΔV, 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 ΔV is negative, the current drops.
- When ΔV is equal to or more negative than ΔV_s, the current is zero.



40.2 Photoelectric Effect

Photoelectric Effect Feature 1

- 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 (ΔV_s).

40.2 Photoelectric Effect

Photoelectric Effect Feature 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 almost instantaneously, even at very low light intensities.

40.2 Photoelectric Effect

Photoelectric Effect Feature 3

- 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.

40.2 Photoelectric Effect
Photoelectric Effect Feature 4

- 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.

40.2 Photoelectric Effect

Photoelectric Effect Features, Summary

- 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 E and 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.

40.2 Photoelectric Effect

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.

40.2 Photoelectric Effect

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.

40.2 Photoelectric Effect

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.

40.2 Photoelectric Effect

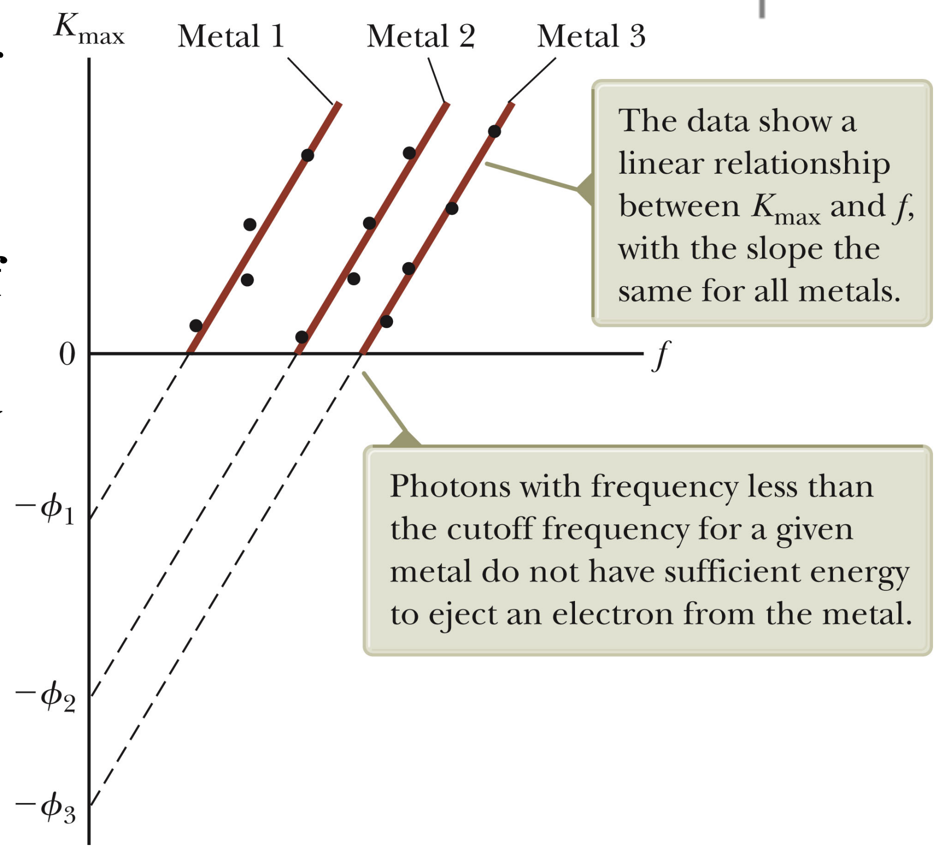
Photon Model Explanation of the Photoelectric Effect, con

- Dependence of photoelectron kinetic energy on light frequency
  - Since $K_{max} = hf - \varphi$
  - 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.

40.2 Photoelectric Effect

Cutoff 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.



40.2 Photoelectric Effect

Cutoff Frequency and Wavelength

- The cutoff frequency is related to the work function through $f_c = \varphi / h$.
- The cutoff frequency corresponds to a **cutoff wavelength.**

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

- 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. The work function for sodium metal is 2.46 eV.

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

SOLUTION

Conceptualize Imagine a photon striking the metal surface and ejecting an electron. The electron with the maximum energy is one near the surface that experiences no interactions with other particles in the metal that would reduce its energy on its way out of the metal.

Categorize We evaluate the results using equations developed in this section, so we categorize this example as a substitution problem.

Find the energy of each photon in the illuminating light beam from Equation 40.5:

$$E = hf = \frac{hc}{\lambda} = \frac{1\,240 \text{ eV}\cdot\text{nm}}{300 \text{ nm}} = 4.13 \text{ eV}$$

From Equation 40.9, find the maximum kinetic energy of an electron:

$$K_{\text{max}} = hf - \phi = 4.13 \text{ eV} - 2.46 \text{ V} = 1.67 \text{ eV}$$

(B) Find the cutoff wavelength λ_c for sodium.

SOLUTION

Calculate λ_c using Equation 40.10:

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