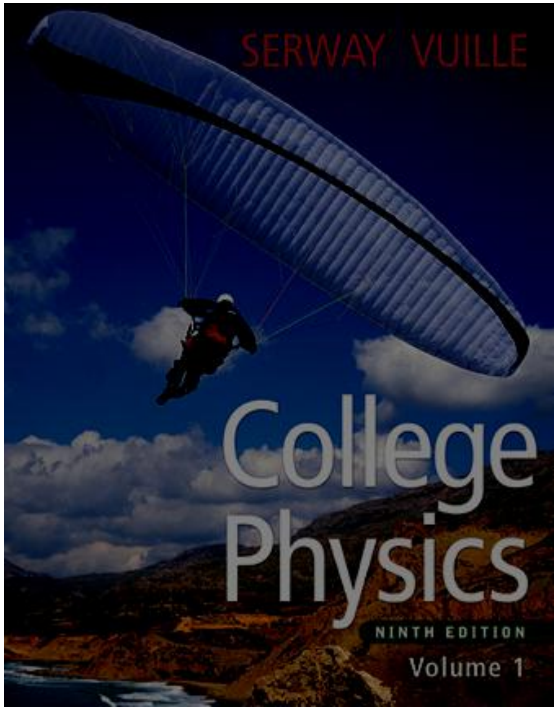

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Chapter 27

Quantum Physics

Need for Quantum Physics

- Problems remained from classical mechanics that relativity didn’t explain.
- Blackbody Radiation
  - The electromagnetic radiation emitted by a heated object
- Photoelectric Effect
  - Emission of electrons by an illuminated metal
- Spectral Lines
  - Emission of sharp spectral lines by gas atoms in an electric discharge tube

Development of Quantum Physics

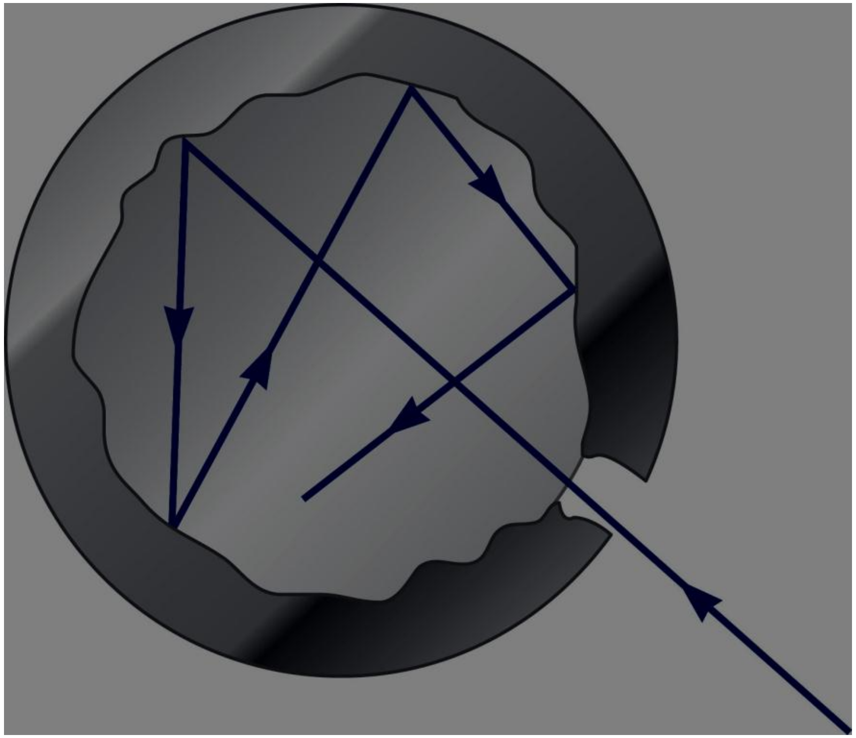
- 1900 to 1930
  - Development of ideas of quantum mechanics
    - Also called wave mechanics
    - Highly successful in explaining the behavior of atoms, molecules, and nuclei
- Involved a large number of physicists
  - Planck introduced basic ideas.
  - Mathematical developments and interpretations involved such people as Einstein, Bohr, Schrödinger, de Broglie, Heisenberg, Born and Dirac.

Blackbody Radiation

- An object at any temperature emits electromagnetic radiation.
  - Also called *thermal radiation.*
  - Stefan's Law describes the total power radiated.
  - The spectrum of the radiation depends on the temperature and properties of the object.
- The spectrum shows a continuous distribution of wavelengths from infrared to ultaviolet.

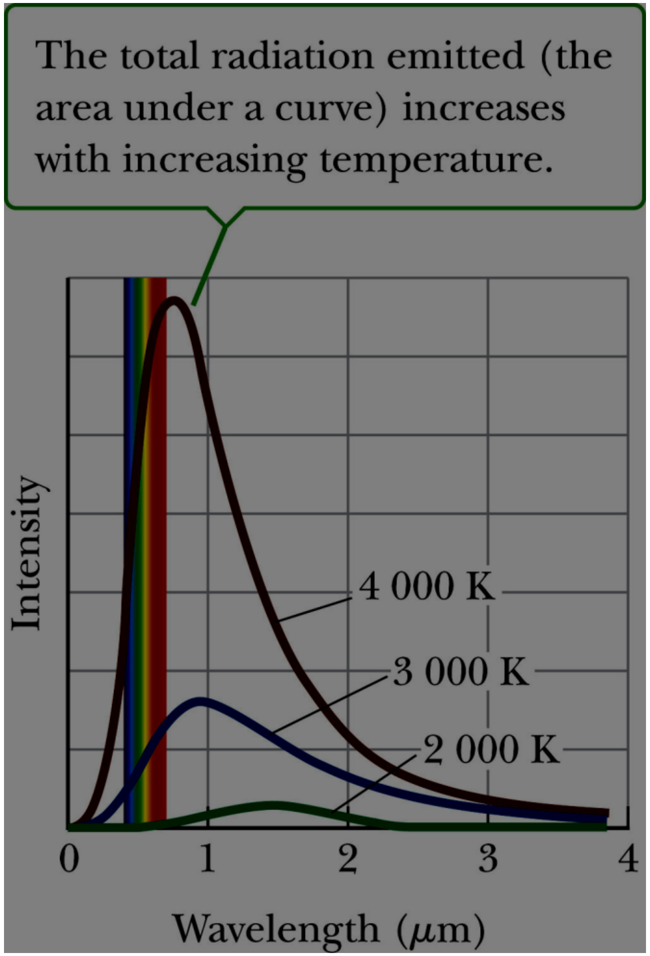
Blackbody Radiation – Classical View

- Thermal radiation originates from accelerated charged particles.
- Problem in explaining the observed energy distribution
- Opening in a cavity is a good approximation
- The nature of the radiation emitted through the opening depends only on the temperature of the cavity walls.



Blackbody Radiation Graph

- Experimental data for distribution of energy in blackbody radiation
- As the temperature increases, the total amount of energy increases.
  - Shown by the area under the curve
- As the temperature increases, the peak of the distribution shifts to shorter wavelengths.



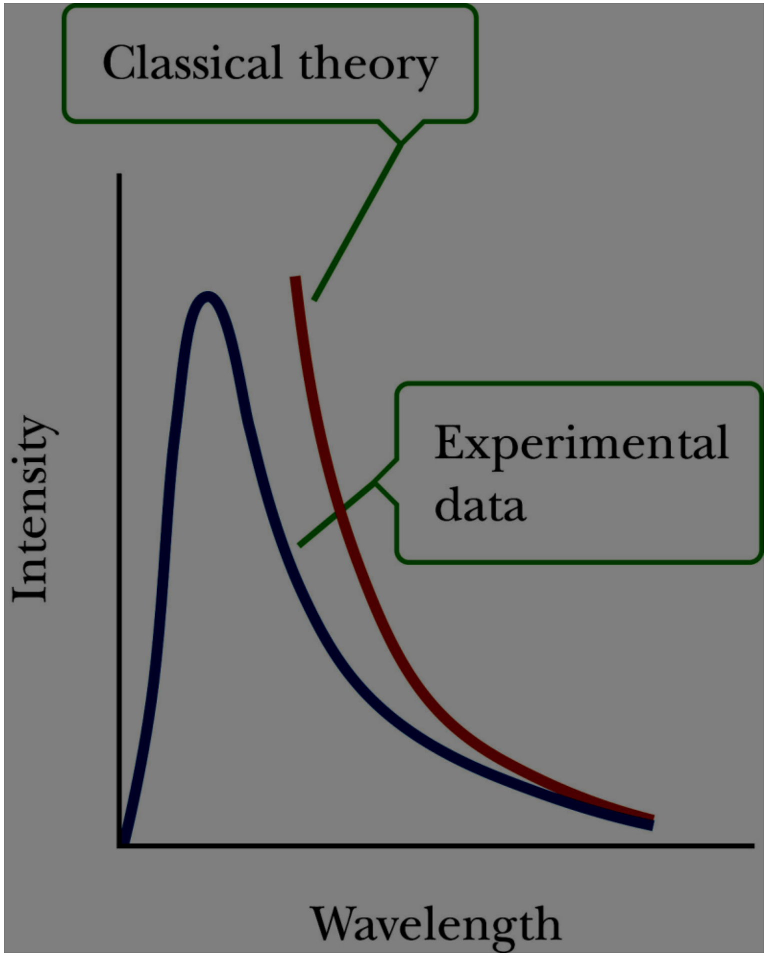
The total radiation emitted (the area under a curve) increases with increasing temperature.

Wien’s Displacement Law

- The wavelength of the peak of the blackbody distribution was found to follow *Wein’s Displacement Law.*
  - $\lambda_{max} T = 0.2898 \times 10^{-2}$ m • K
- λ_{max} is the wavelength at which the curve peaks.
- T is the absolute temperature of the object emitting the radiation.

The Ultraviolet Catastrophe

- Classical theory did not match the experimental data.
- At long wavelengths, the match is good.
- At short wavelengths, classical theory predicted infinite energy.
- At short wavelengths, experiment showed no energy

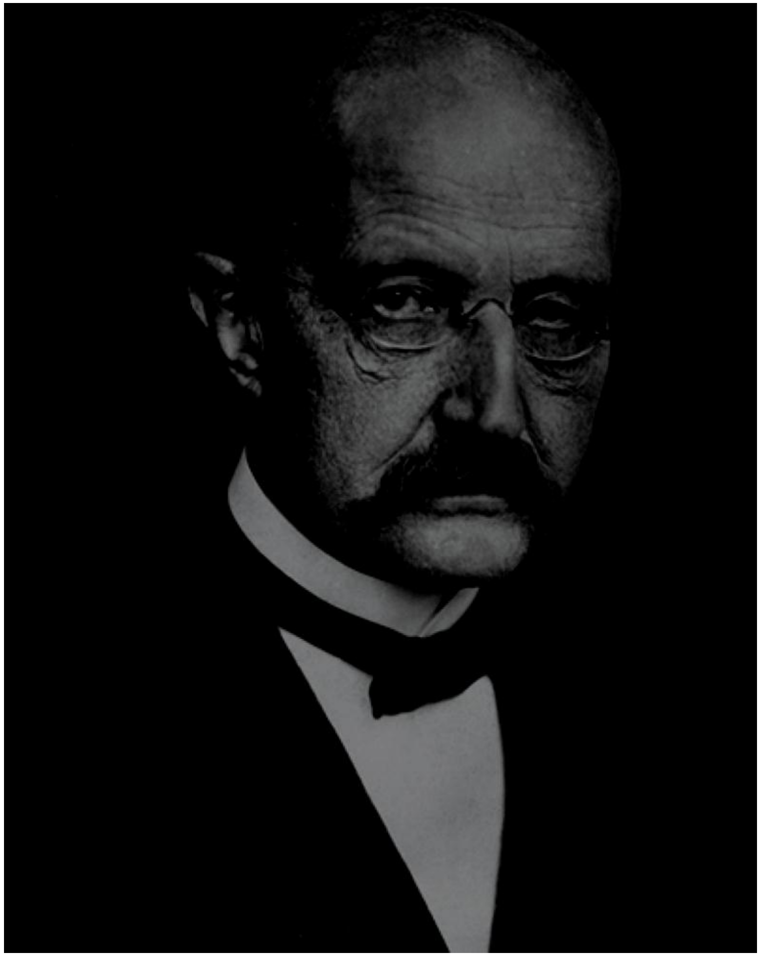


Planck's Resolution

- Planck hypothesized that the blackbody radiation was produced by *resonators.*
  - Resonators were submicroscopic charged oscillators.
- The resonators could only have *discrete energies.*
  - $E_n = n\,h\,f$
    - n is called the *quantum number*
    - ƒ is the frequency of vibration
    - h is *Planck's constant*, 6.626×10^{-34} J s
- Key point is quantized energy states

Max Planck

- 1858 – 1947
- Introduced a “quantum of action,” h
- Awarded Nobel Prize in 1918 for discovering the quantized nature of energy



Quantized Energy

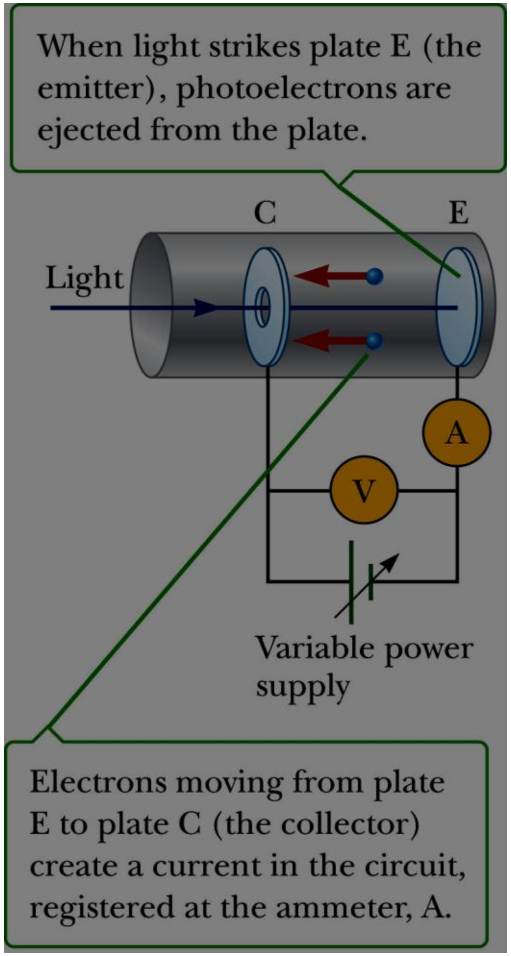
- Planck’s assumption of quantized energy states was a radical departure from classical mechanics.
- The fact that energy can assume only certain, discrete values is the single most important difference between quantum and classical theories.
  - Classically, the energy can be in any one of a continuum of values.

Photoelectric Effect

- When light is incident on certain metallic surfaces, electrons are emitted from the surface.
  - This is called the *photoelectric effect.*
  - The emitted electrons are called *photoelectrons.*
- The effect was first discovered by Hertz.
- The successful explanation of the effect was given by Einstein in 1905.
  - Received Nobel Prize in 1921 for paper on electromagnetic radiation, of which the photoelectric effect was a part

Photoelectric Effect Schematic

- When light strikes E, photoelectrons are emitted.
- Electrons collected at C and passing through the ammeter create a current in the circuit.
- C is maintained at a positive potential by the power supply.

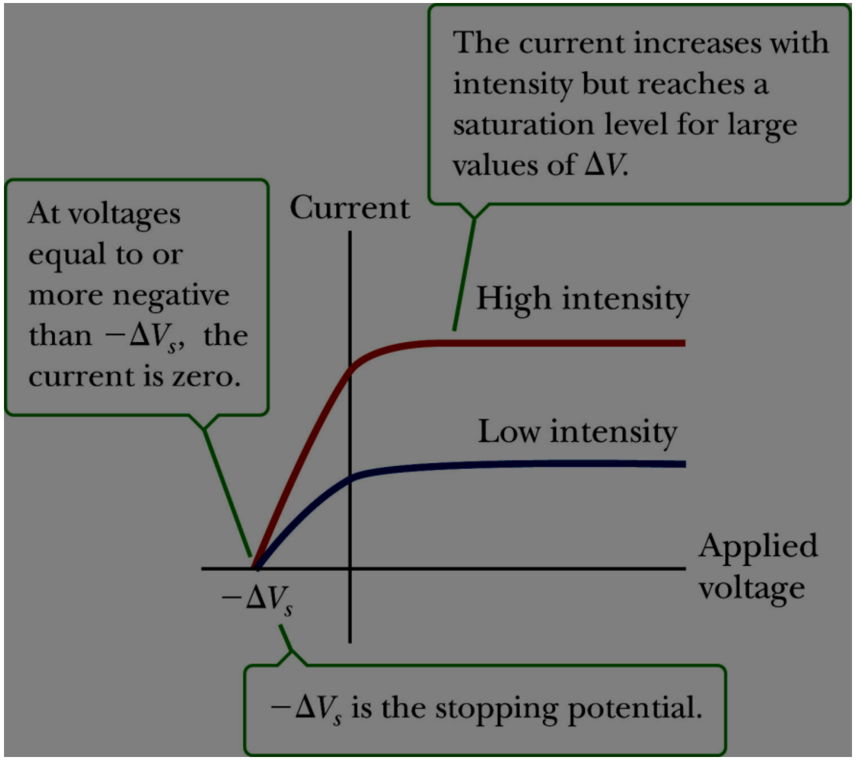


When light strikes plate E (the emitter), photoelectrons are ejected from the plate.

Electrons moving from plate E to plate C (the collector) create a current in the circuit, registered at the ammeter, A.

Photoelectric Current/Voltage Graph

- The current increases with intensity, but reaches a saturation level for large ΔV's.
- No current flows for voltages less than or equal to $-\Delta V_s$, the *stopping potential.*



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.

$-\Delta V_s$ is the stopping potential.

More About Photoelectric Effect

- The stopping potential is independent of the radiation intensity.
- The maximum kinetic energy of the photoelectrons is related to the stopping potential: $KE_{max} = e⍰V_s$

Features Not Explained by Classical Physics/Wave Theory

- No electrons are emitted if the incident light frequency is below some *cutoff frequency* that is characteristic of the material being illuminated.
- The maximum kinetic energy of the photoelectrons is independent of the light intensity.

More Features Not Explained

- The maximum kinetic energy of the photoelectrons increases with increasing light frequency.
- Electrons are emitted from the surface almost instantaneously, even at low intensities.

Einstein’s Explanation

- A tiny packet of light energy, called a photon, would be emitted when a quantized oscillator jumped from one energy level to the next lower one.
  - Extended Planck’s idea of quantization to electromagnetic radiation
- The photon’s energy would be $E = hƒ$
- Each photon can give all its energy to an electron in the metal.
- The maximum kinetic energy of the liberated photoelectron is $KE_{max} = hƒ - \phi$
- ϕ is called the *work function* of the metal

- Photoelectrons are created by absorption of a single photon, so the energy of that photon must be greater than or equal to the work function, else no photoelectrons will be produced. This explains the cutoff frequency.
- From Equation 27.6, *KE*max depends only on the frequency of the light and the value of the work function. Light intensity is immaterial because absorption of a single photon is responsible for the electron’s change in kinetic energy.
- Equation 27.6 is linear in the frequency, so *KE*max increases with increasing frequency.
- Electrons are emitted almost instantaneously, regardless of intensity, because the light energy is concentrated in packets rather than spread out in waves.

Explanation of Classical “Problems”

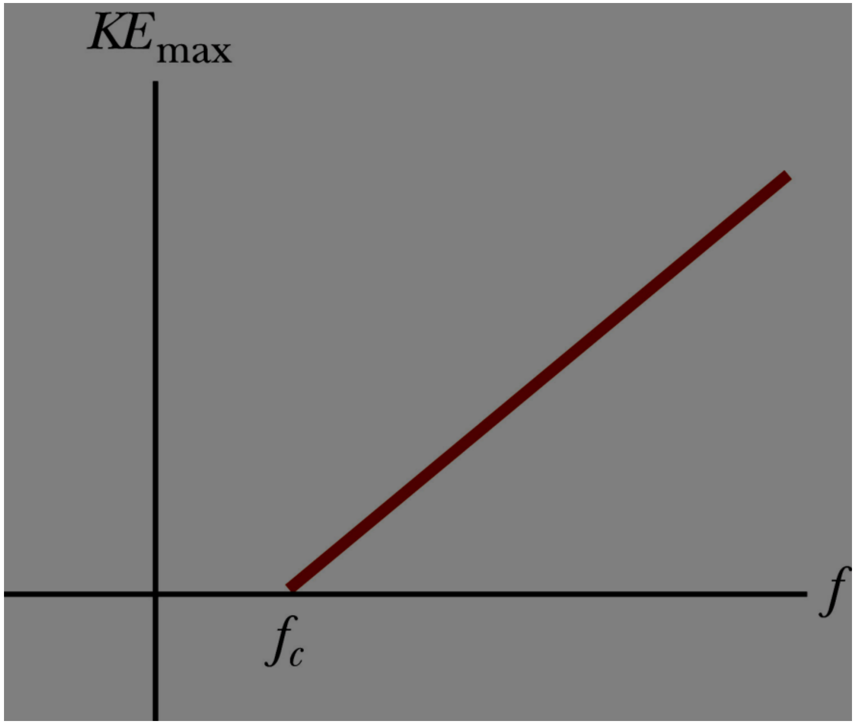
- The effect is not observed below a certain cutoff frequency since the photon energy must be greater than or equal to the work function.
  - Without this, electrons are not emitted, regardless of the intensity of the light
- The maximum KE depends only on the frequency and the work function, not on the intensity.
  - The absorption of a single photon is responsible for the electron’s kinetic energy.

More Explanations

- The maximum KE increases with increasing frequency.
- The effect is instantaneous since there is a one-to-one interaction between the photon and the electron.

Verification of Einstein’s Theory

- Experimental observations of a linear relationship between KE and frequency confirm Einstein’s theory.
- The x-intercept is the cutoff frequency.



Cutoff Wavelength

- The cutoff wavelength is related to the work function.

$$\lambda_c = \frac{hc}{\phi}$$

- Wavelengths greater than λ_C incident on a material with a work function ϕ don’t result in the emission of photoelectrons.

Photocells

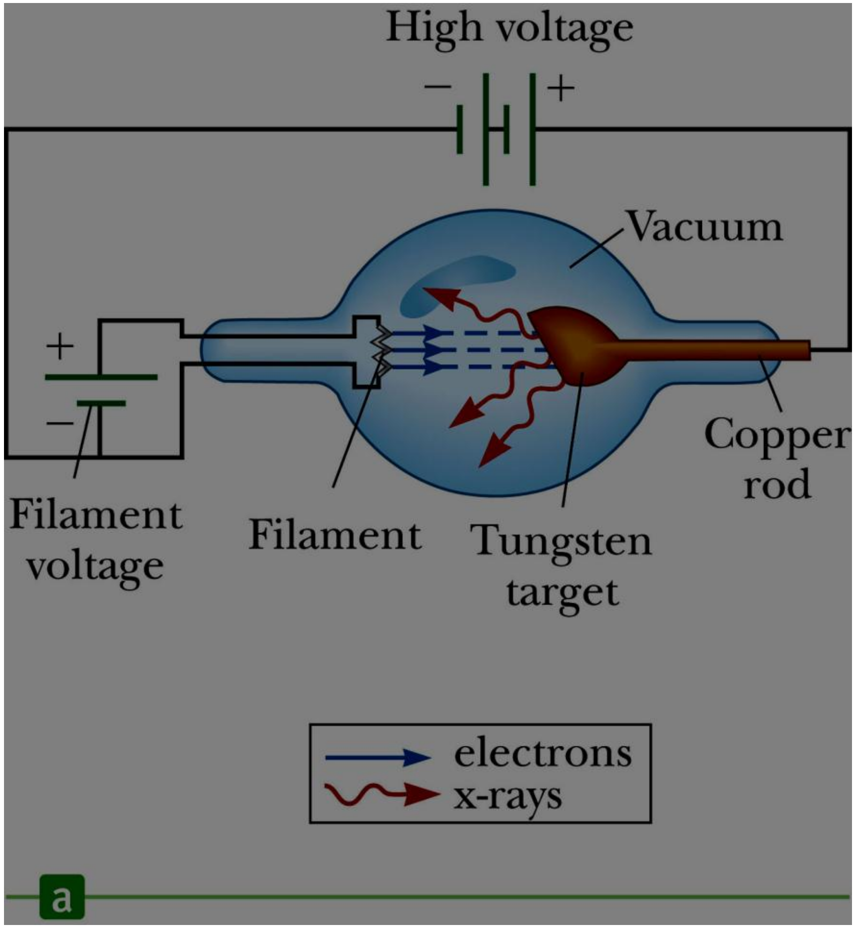
- Photocells are an application of the photoelectric effect.
- When light of sufficiently high frequency falls on the cell, a current is produced.
- Examples
  - Streetlights, garage door openers, elevators

X-Rays

- Discovered and named by Röntgen in 1895
- Later identified as electromagnetic radiation with short wavelengths
  - Wavelengths lower (frequencies higher) than for ultraviolet
  - Wavelengths are typically about 0.1 nm.
  - X-rays have the ability to penetrate most materials with relative ease.

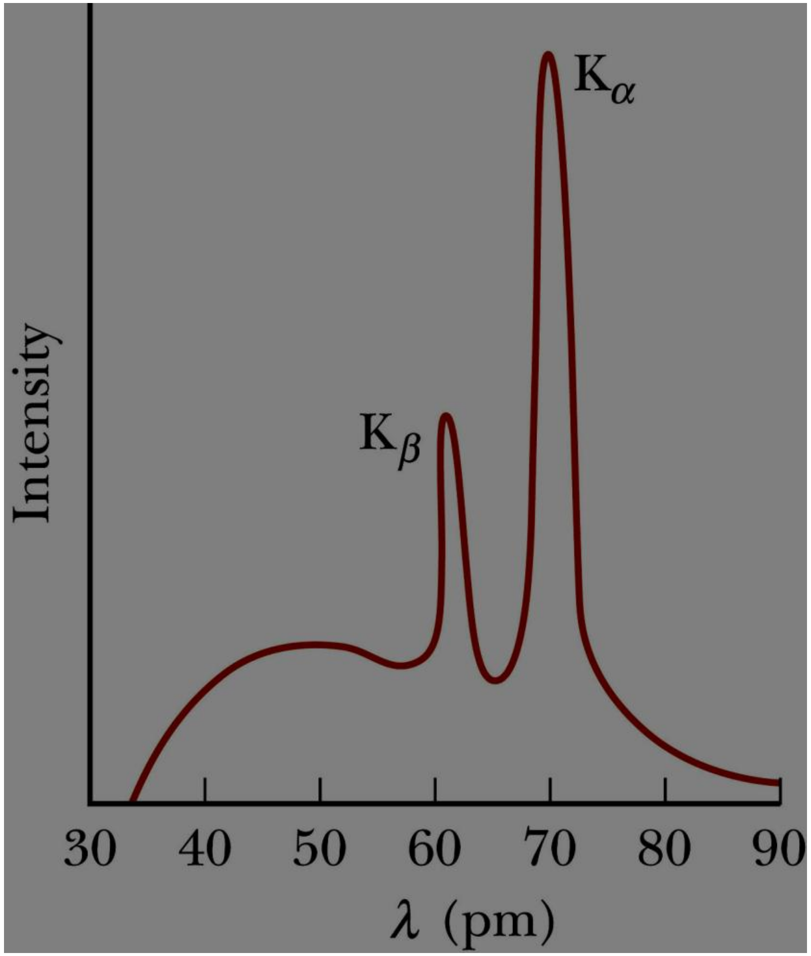
Production of X-rays, 1

- X-rays are produced when high-speed electrons are suddenly slowed down.
  - –Can be caused by the electron striking a metal target
- Heat generated by current in the filament causes electrons to be emitted.
- These freed electrons are accelerated toward a dense metal target.
- The target is held at a higher potential than the filament.



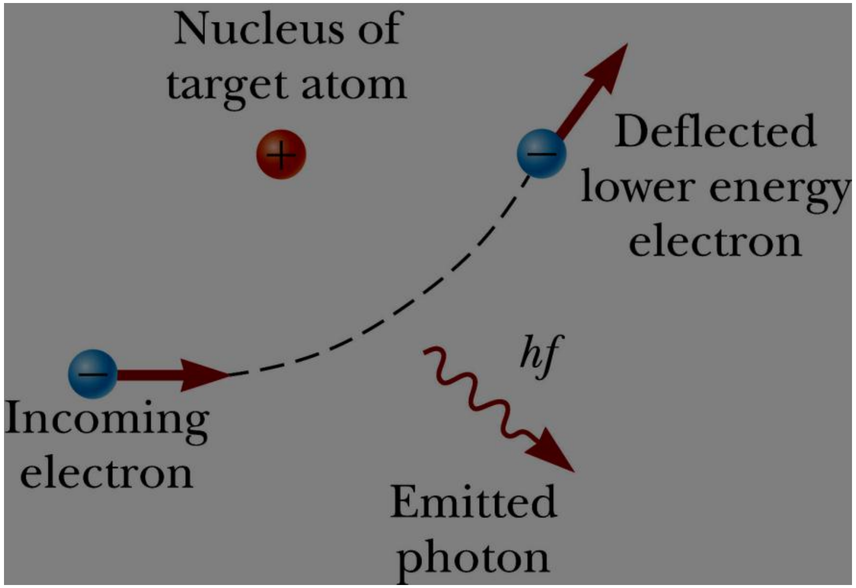
X-ray Spectrum

- The x-ray spectrum has two distinct components.
- Continuous broad spectrum
  - Depends on voltage applied to the tube
  - Sometimes called **bremsstrahlung**
- The sharp, intense lines depend on the nature of the target material.



Production of X-rays, 2

- An electron passes near a target nucleus.
- The electron is deflected from its path by its attraction to the nucleus.
  - This produces an acceleration
- It will emit electromagnetic radiation when it is accelerated.



Wavelengths Produced

- If the electron loses all of its energy in the collision, the initial energy of the electron is completely transformed into a photon.
- The wavelength can be found from

$$e\Delta V = hf_{\text{max}} = \frac{hc}{\lambda_{\text{min}}}$$

Wavelengths Produced, Cont.

- Not all radiation produced is at this minimum wavelength.
  - Many electrons undergo more than one collision before being stopped.
  - This results in the continuous spectrum produced.

A sodium surface is illuminated with light of wavelength 0.300 μm. The work function for sodium is 2.46 eV.

Calculate **(a)** the energy of each photon in electron volts, **(b)** the maximum kinetic energy of the ejected photoelectrons,

and **(c)** the cutoff wavelength for sodium

$$c = f\lambda \quad \rightarrow \quad f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\ \mathrm{m/s}}{0.300 \times 10^{-6}\ \mathrm{m}}$$

$$f = 1.00 \times 10^{15}\ \mathrm{Hz}$$

$$\begin{aligned} E = hf &= (6.63 \times 10^{-34}\ \mathrm{J{\cdot}s})(1.00 \times 10^{15}\ \mathrm{Hz}) \\ &= 6.63 \times 10^{-19}\ \mathrm{J} \\ &= (6.63 \times 10^{-19}\ \mathrm{J})\left(\frac{1.00\ \mathrm{eV}}{1.60 \times 10^{-19}\ \mathrm{J}}\right) = \boxed{4.14\ \mathrm{eV}} \end{aligned}$$

$$KE_{\max} = hf - \phi = 4.14\ \text{eV} - 2.46\ \text{eV} = 1.68\ \text{eV}$$

$$\phi = 2.46\ \text{eV} = (2.46\ \text{eV})(1.60 \times 10^{-19}\ \text{J/eV})$$

$$= 3.94 \times 10^{-19}\ \text{J}$$

$$\lambda_c = \frac{hc}{\phi} = \frac{(6.63 \times 10^{-34}\ \text{J}\cdot\text{s})(3.00 \times 10^{8}\ \text{m/s})}{3.94 \times 10^{-19}\ \text{J}}$$

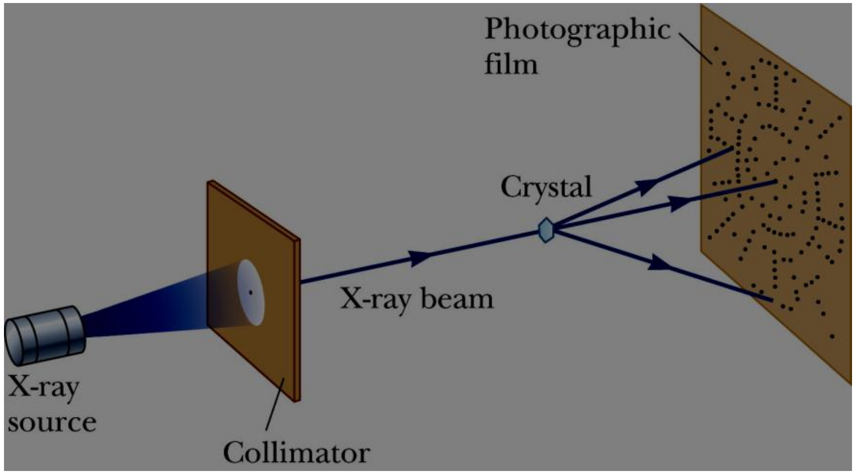
$$= 5.05 \times 10^{-7}\ \text{m} = 505\ \text{nm}$$

Diffraction of X-rays by Crystals

- For diffraction to occur, the spacing between the lines must be approximately equal to the wavelength of the radiation to be measured.
- The regular array of atoms in a crystal can act as a three-dimensional grating for diffracting X-rays.

Schematic for X-ray Diffraction

- A beam of X-rays with a continuous range of wavelengths is incident on the crystal.
- The diffracted radiation is very intense in certain directions.
  - These directions correspond to constructive interference from waves reflected from the layers of the crystal.
- The diffraction pattern is detected by photographic film.



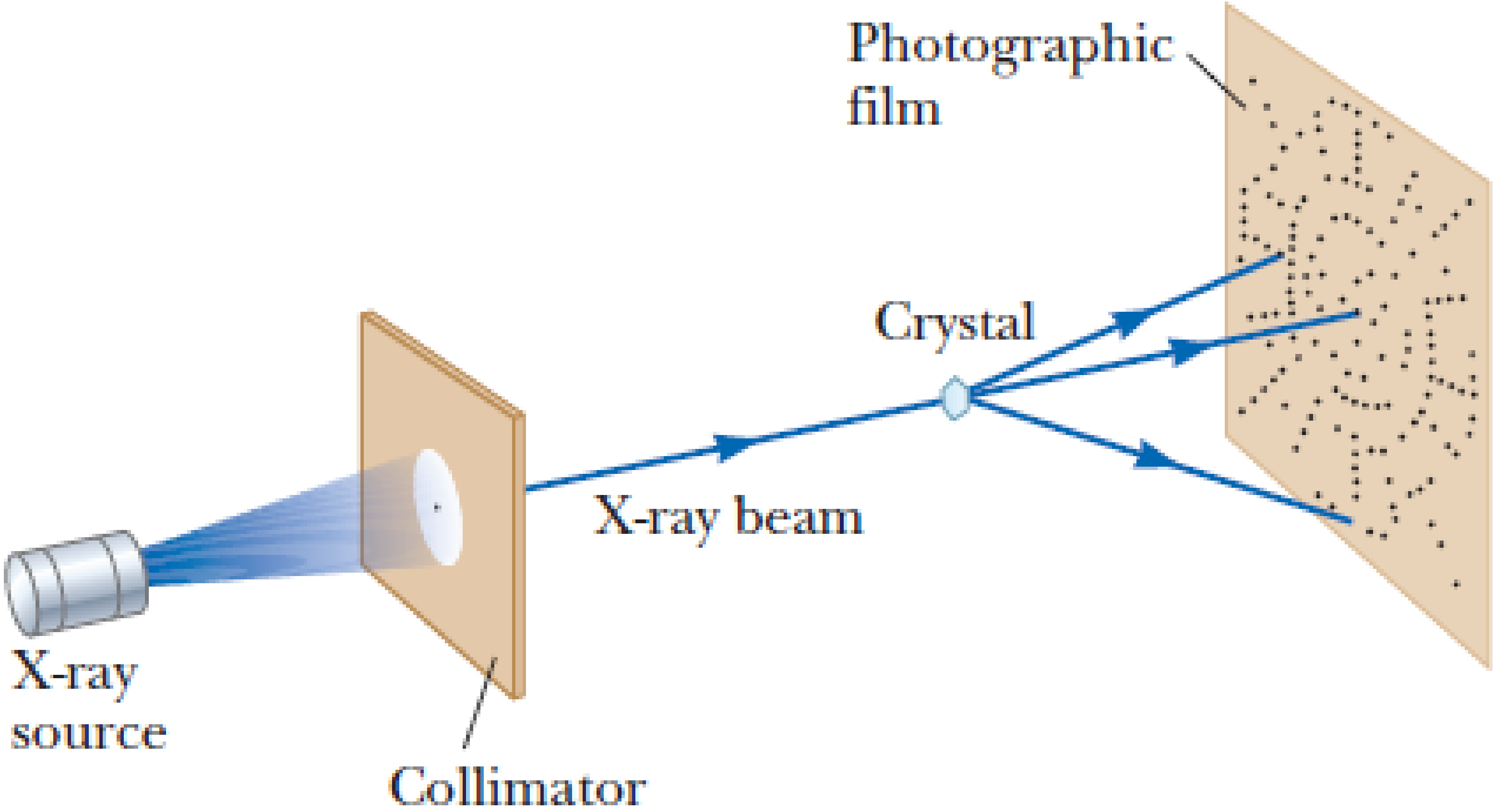
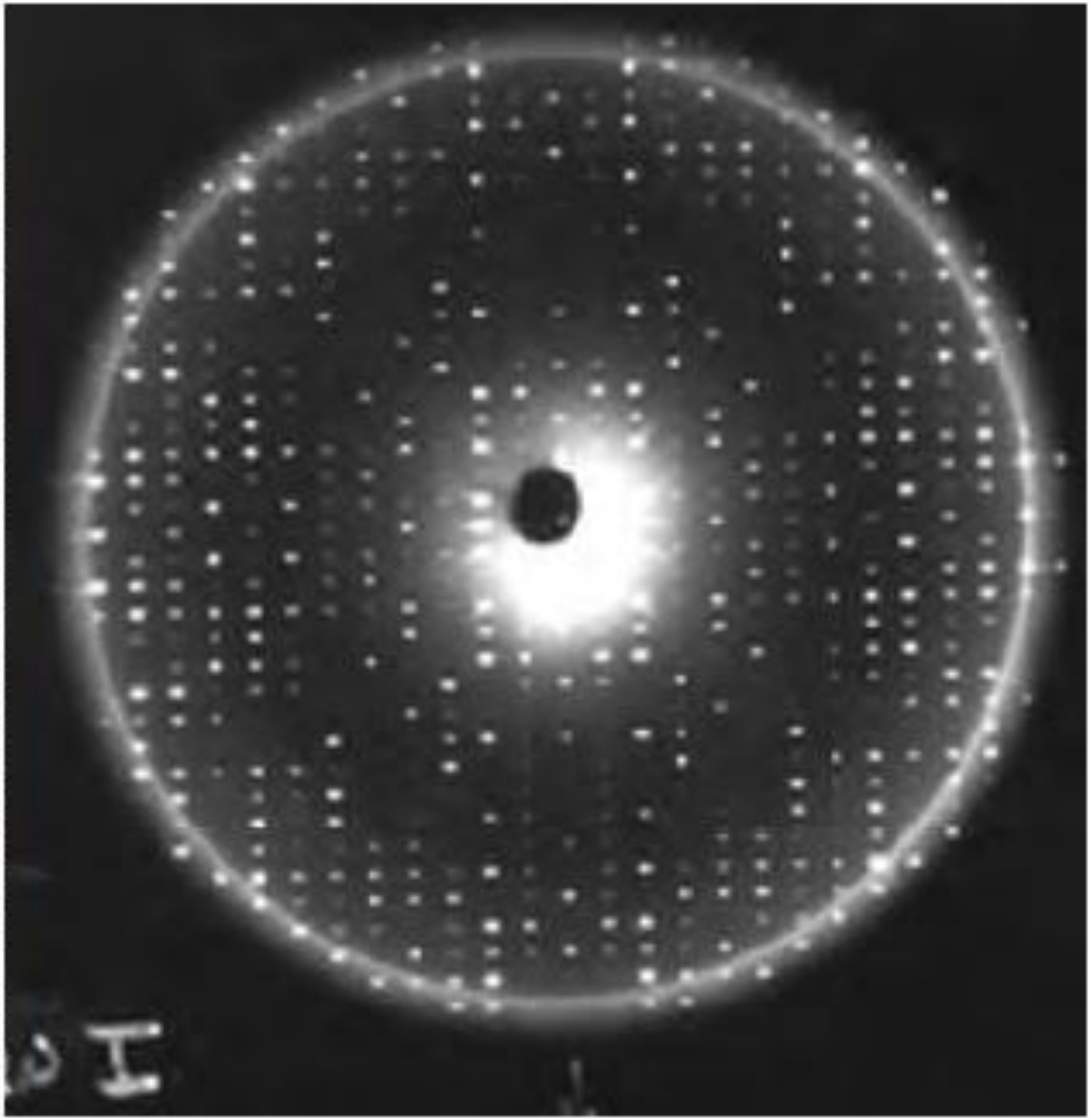
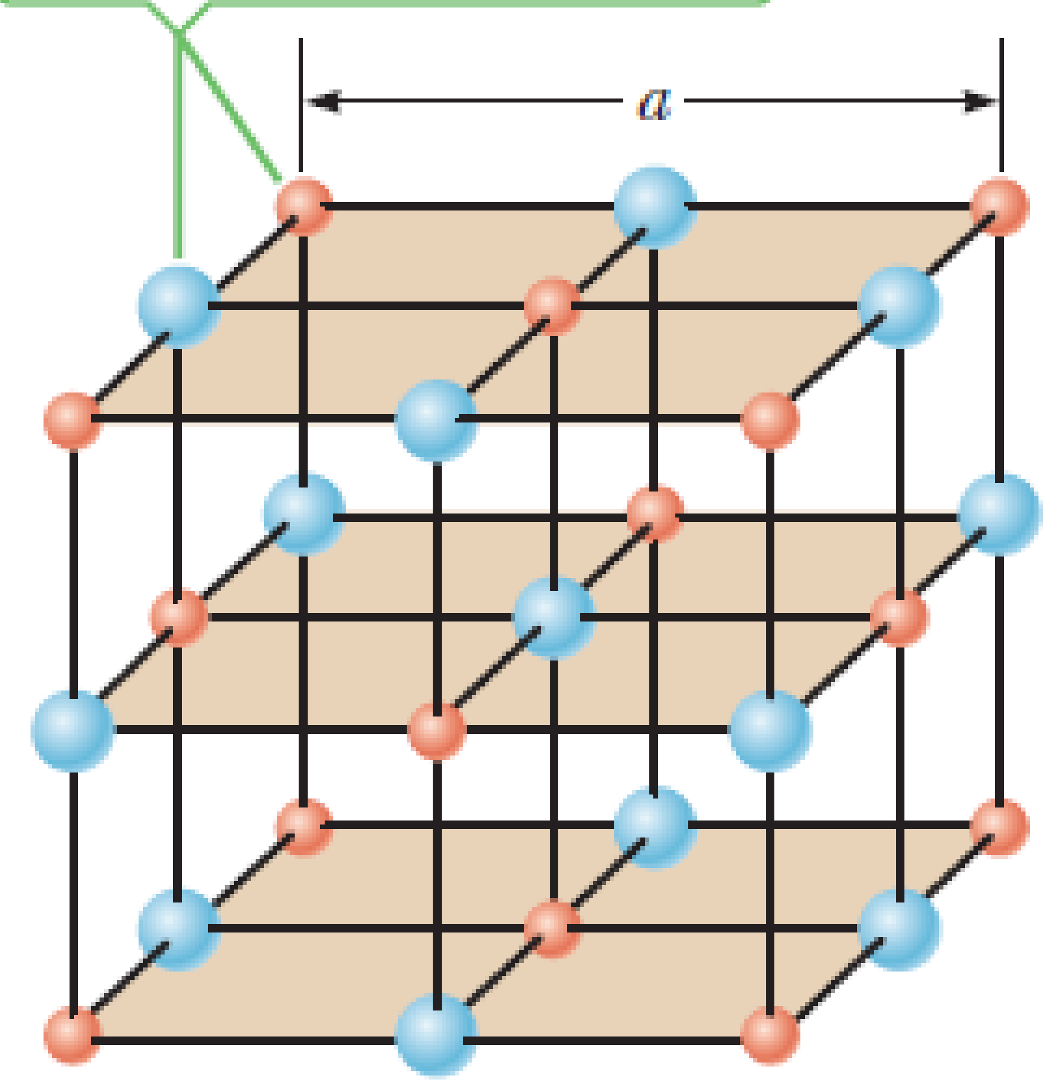

Photographic film
Crystal
X-ray beam
X-ray source
Collimator

Photo of X-ray Diffraction Pattern

- The array of spots is called a *Laue* pattern.
- The crystal structure is determined by analyzing the positions and intensities of the various spots.



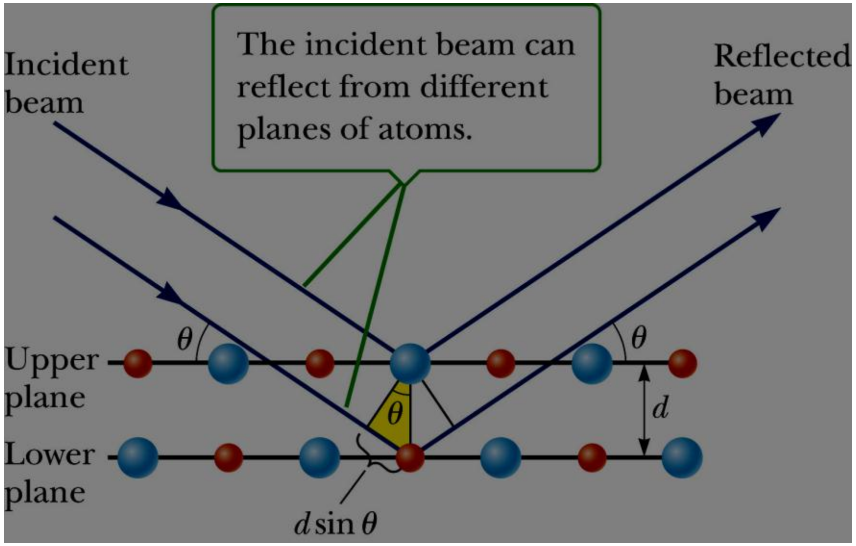
Courtesy of NASA MARSHALL SPACE FLIGHT CENTER/0101745



The blue spheres represent Cl^- ions, the red spheres Na^+ ions.

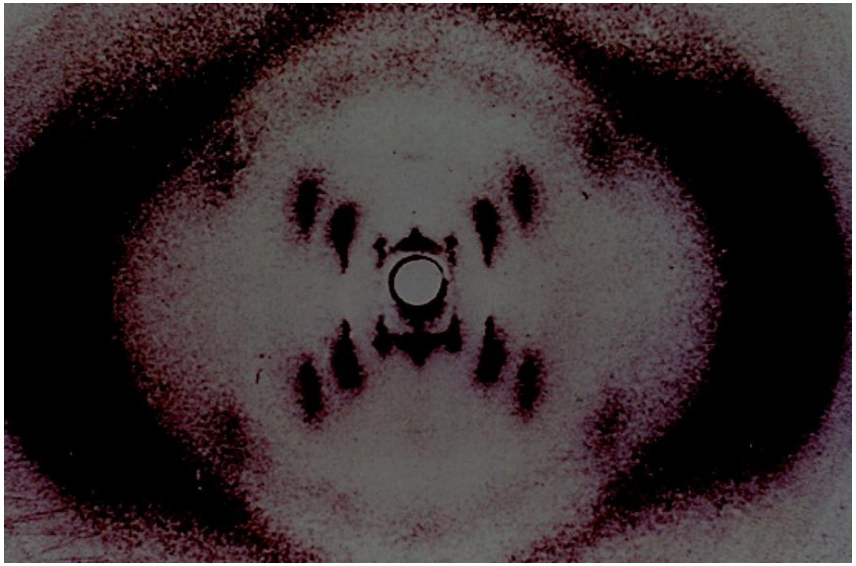
Bragg’s Law

- The beam reflected from the lower surface travels farther than the one reflected from the upper surface.
- If the path difference equals some integral multiple of the wavelength, constructive interference occurs.
- *Bragg’s Law* gives the conditions for constructive interference.
  - $2 d \sin \theta = m \lambda$, $m = 1, 2, 3\ldots$



Uses of X-Ray Diffraction

- X-ray diffraction is used to determine the molecular structure of proteins, DNA, and RNA.
- X-rays with λ = 0.10 nm are used.
- The geometry of the diffraction pattern is determined by the lattice arrangement of the molecules.
- The intensities are determined by the atoms and their electronic distribution in the cell.
- Picture shows an x-ray diffraction photo of DNA



Arthur Holly Compton

- 1892 – 1962
- Discovered the Compton effect
- Worked with cosmic rays
- Director of the lab at U of Chicago
- Shared Nobel Prize in 1927

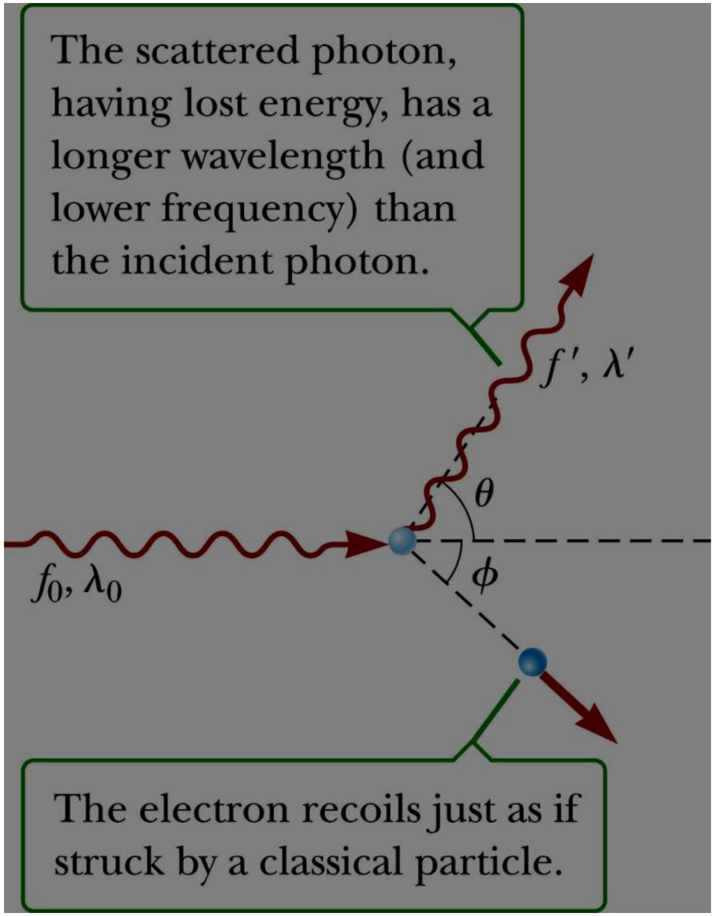
The Compton Effect

- Compton directed a beam of x-rays toward a block of graphite.
- He found that the scattered x-rays had a slightly longer wavelength that the incident x-rays.
  - This means they also had less energy.
- The amount of energy reduction depended on the angle at which the x-rays were scattered.
- The change in wavelength is called the *Compton shift.*

Compton Scattering

- Compton assumed the photons acted like other particles in collisions.
- Energy and momentum were conserved.
- The shift in wavelength is

$$\Delta\lambda = \lambda - \lambda_o = \frac{h}{m_e c}(1-\cos\theta)$$


The scattered photon, having lost energy, has a longer wavelength (and lower frequency) than the incident photon.

The electron recoils just as if struck by a classical particle.

Compton Scattering, Final

- The quantity $h/m_e c$ is called the *Compton wavelength.*
  - Compton wavelength = 0.002 43 nm
  - Very small compared to visible light
- The Compton shift depends on the scattering angle and not on the wavelength.
- Experiments confirm the results of Compton scattering and strongly support the photon concept.

Photons and Electromagnetic Waves

- **Light has a dual nature. It exhibits both wave and particle characteristics.**
  - Applies to all electromagnetic radiation
  - Different frequencies allow one or the other characteristic to be more easily observed.
- The photoelectric effect and Compton scattering offer evidence for the particle nature of light.
  - When light and matter interact, light behaves as if it were composed of particles.
- Interference and diffraction offer evidence of the wave nature of light.

Louis de Broglie

- 1892 – 1987
- Discovered the wave nature of electrons
- Awarded Nobel Prize in 1929

Wave Properties of Particles

- In 1924, Louis de Broglie postulated that **because photons have wave and particle characteristics, perhaps all forms of matter have both properties.**
- Furthermore, the frequency and wavelength of matter waves can be determined.

de Broglie Wavelength and Frequency

- The *de Broglie wavelength* of a particle is

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

- The frequency of matter waves is

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

Dual Nature of Matter

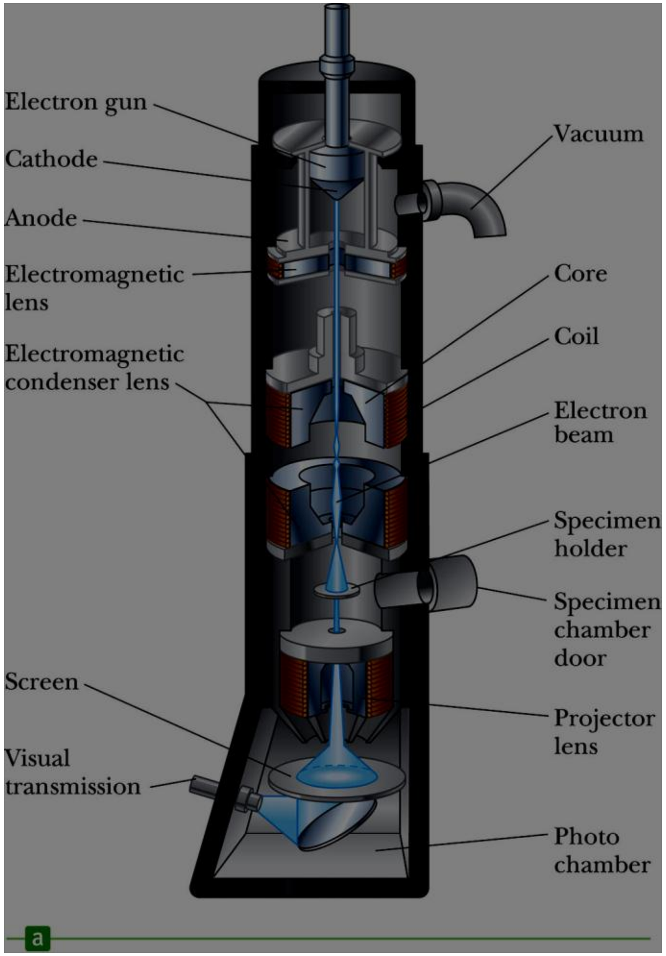
- The de Broglie equations show the dual nature of matter.
- Each contains matter concepts.
  - Energy and momentum
- Each contains wave concepts.
  - Wavelength and frequency

The Davisson-Germer Experiment

- They scattered low-energy electrons from a nickel target.
- They followed this with extensive diffraction measurements from various materials.
- The wavelength of the electrons calculated from the diffraction data agreed with the expected de Broglie wavelength.
- This confirmed the wave nature of electrons.

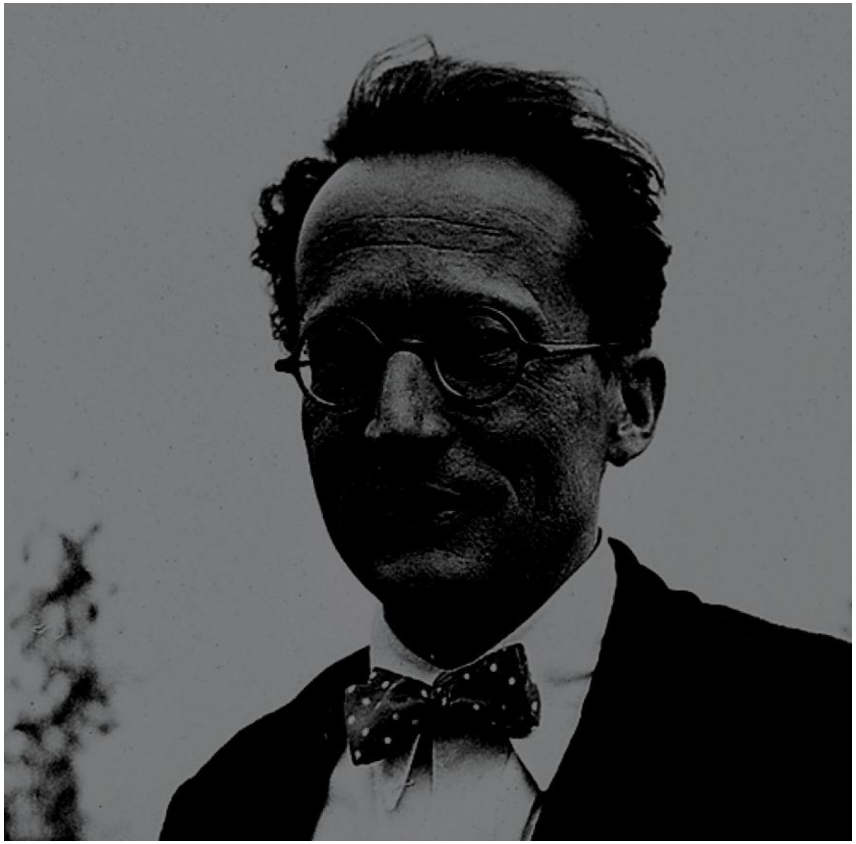
The Electron Microscope

- The electron microscope depends on the wave characteristics of electrons.
- Microscopes can only resolve details that are slightly smaller than the wavelength of the radiation used to illuminate the object.
- The electrons can be accelerated to high energies and have small wavelengths.



Erwin Schrödinger

- 1887 – 1961
- Best known as the creator of wave mechanics
- Worked on problems in general relativity, cosmology, and the application of quantum mechanics to biology



The Wave Function

- In 1926 Schrödinger proposed a wave equation that describes the manner in which matter waves change in space and time.
- Schrödinger's wave equation is a key element in quantum mechanics.
- Schrödinger's wave equation is generally solved for the *wave function*, Ψ.

The Wave Function, Cont.

- The wave function depends on the particle’s position and the time.
- The value of Ψ^2 at some location at a given time is proportional to the probability of finding the particle at that location at that time.
  - Actually gives the probability per unit volume

Werner Heisenberg

- 1901 – 1976
- Developed an abstract mathematical model to explain wavelengths of spectral lines
  - Called *matrix mechanics*
- Other contributions
  - Uncertainty Principle
    - Nobel Prize in 1932
  - Atomic and nuclear models
  - Forms of molecular hydrogen

The Uncertainty Principle

- When measurements are made, the experimenter is always faced with experimental uncertainties in the measurements.
  - Classical mechanics offers no fundamental barrier to ultimate refinements in measurements.
  - Classical mechanics would allow for measurements with arbitrarily small uncertainties.

The Uncertainty Principle, 2

- Quantum mechanics predicts that a barrier to measurements with ultimately small uncertainties does exist.
- In 1927 Heisenberg introduced the *uncertainty principle.*
  - If a measurement of position of a particle is made with precision Δx and a simultaneous measurement of linear momentum is made with precision Δp_x, then the product of the two uncertainties can never be smaller than $h/4\pi$

The Uncertainty Principle, 3

- Mathematically,

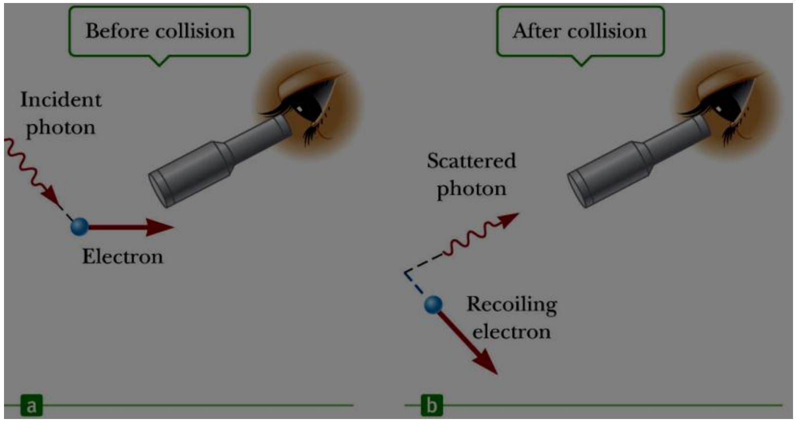
$$\Delta x \Delta p_x \geq \frac{h}{4\pi}$$

  - It is physically impossible to measure simultaneously the exact position and the exact linear momentum of a particle.

- Another form of the principle deals with energy and time:

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

Thought Experiment – The Uncertainty Principle



- A thought experiment for viewing an electron with a powerful microscope
- In order to see the electron, at least one photon must bounce off it.
- During this interaction, momentum is transferred from the photon to the electron.
- Therefore, the light that allows you to accurately locate the electron changes the momentum of the electron.

Uncertainty Principle Applied to an Electron

- View the electron as a particle.
- Its position and velocity cannot both be known precisely at the same time.
- Its energy can be uncertain for a period given by $\Delta t = h / (4\pi \Delta E)$