Quantum Physics

Selected Topics

Why Was There a Need for Quantum Physics?

Problems remained from classical mechanics that relativity didn't explain.

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1. ***Blackbody Radiation***

The electromagnetic radiation emitted by a heated object

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2. *Photoelectric Effect*

Emission of electrons by an illuminated metal

Why Was There a Need for Quantum Physics?

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3. *Spectral Lines*

Emission of sharp spectral lines by gas atoms in an electric discharge tube

Development of Quantum Physics

1897 to 1927 –
"Thirty Years That Shook Physics" (Gamow)

- **Development of ideas of quantum mechanics (Also called wave mechanics)**

- **Highly successful in explaining the behavior of atoms, molecules, and nuclei**

Development of Quantum Physics

1897 to 1927 –
"Thirty Years That Shook Physics"

- **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, Dirac**

Blackbody Radiation

An object at any temperature emits electromagnetic radiation (sometimes called *thermal radiation*).

Stefan's Law describes the total power radiated.

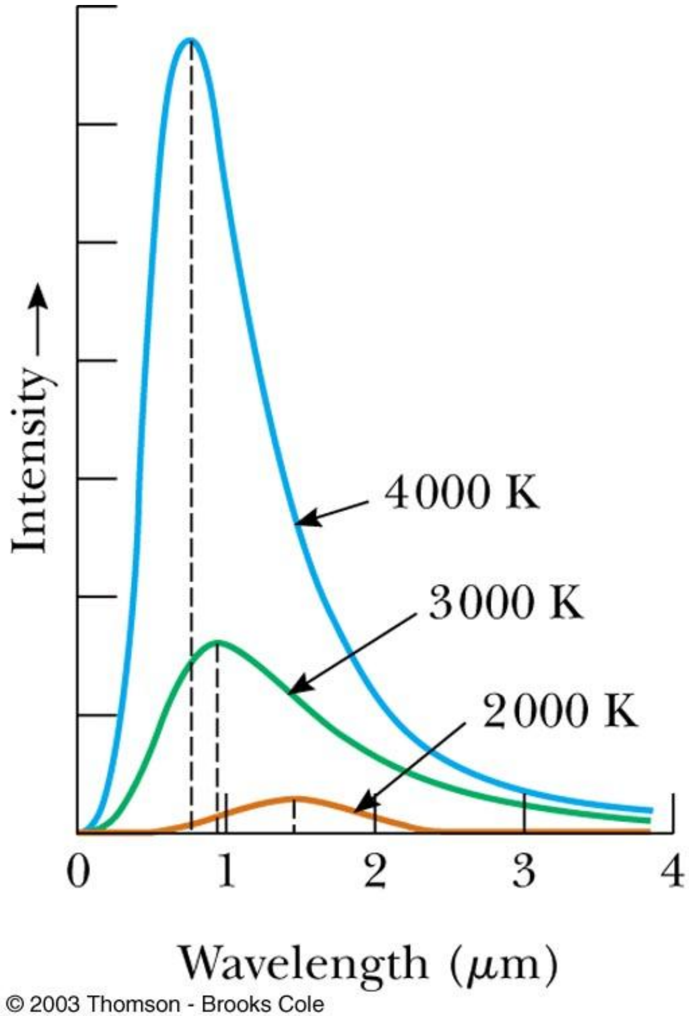
$$\mathscr{P} = \sigma A e \;\; T^4 - T_0^4$$

The *spectrum* of the radiation depends on the temperature and properties of the object.

Blackbody Radiation Graph

As the temperature increases, the total amount of energy increases.

The area under the curve is the total radiated energy.



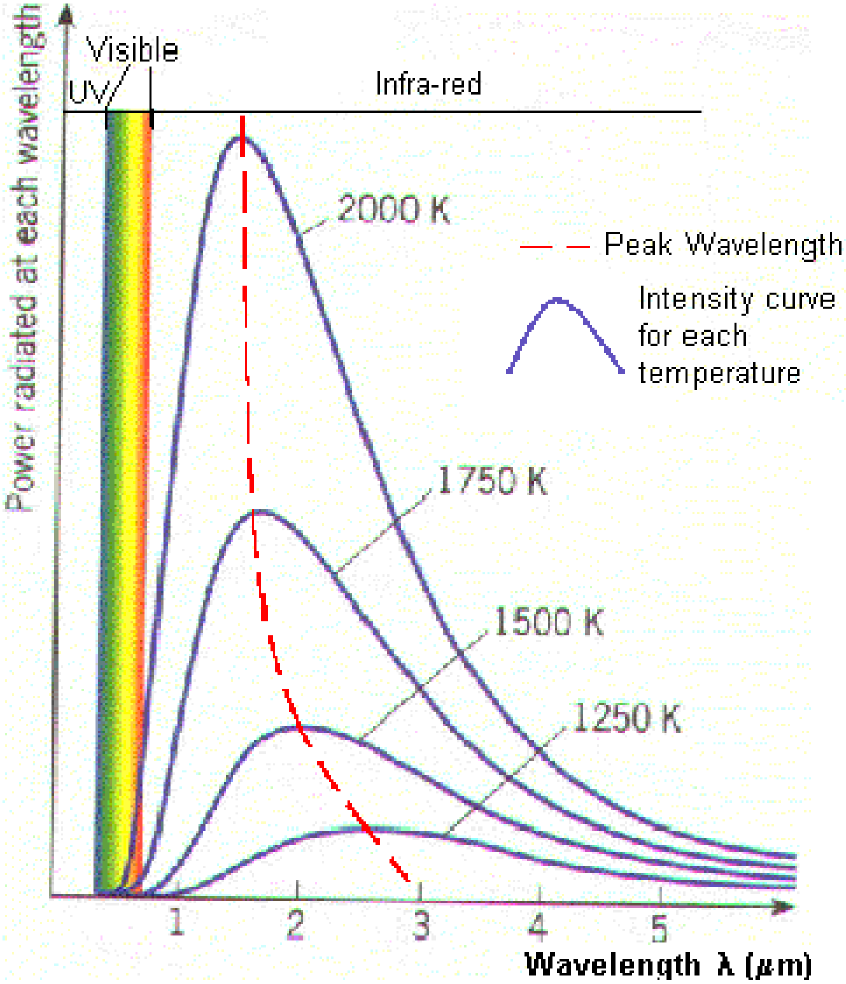
As the temperature increases, the peak of the distribution shifts to shorter wavelengths.

Wien's Displacement Law (1893)

The wavelength (λ_{max}) of the peak of the blackbody distribution follows

***Wein's Displacement Law*:**

$$\lambda_{max} T = 0.2898 \times 10^{-2}\ \mathrm{m \cdot K}$$



Theory vs. Experiment – Theory Loses

Rayleigh and Jeans (early 20th century), using statistical physics and classical thermodynamics developed an expression for intensity of blackbody radiation:

$$I = \frac{8\pi k_{\mathrm{B}} T}{\lambda^4}$$

This matched experiment fairly well at long wavelengths, but…

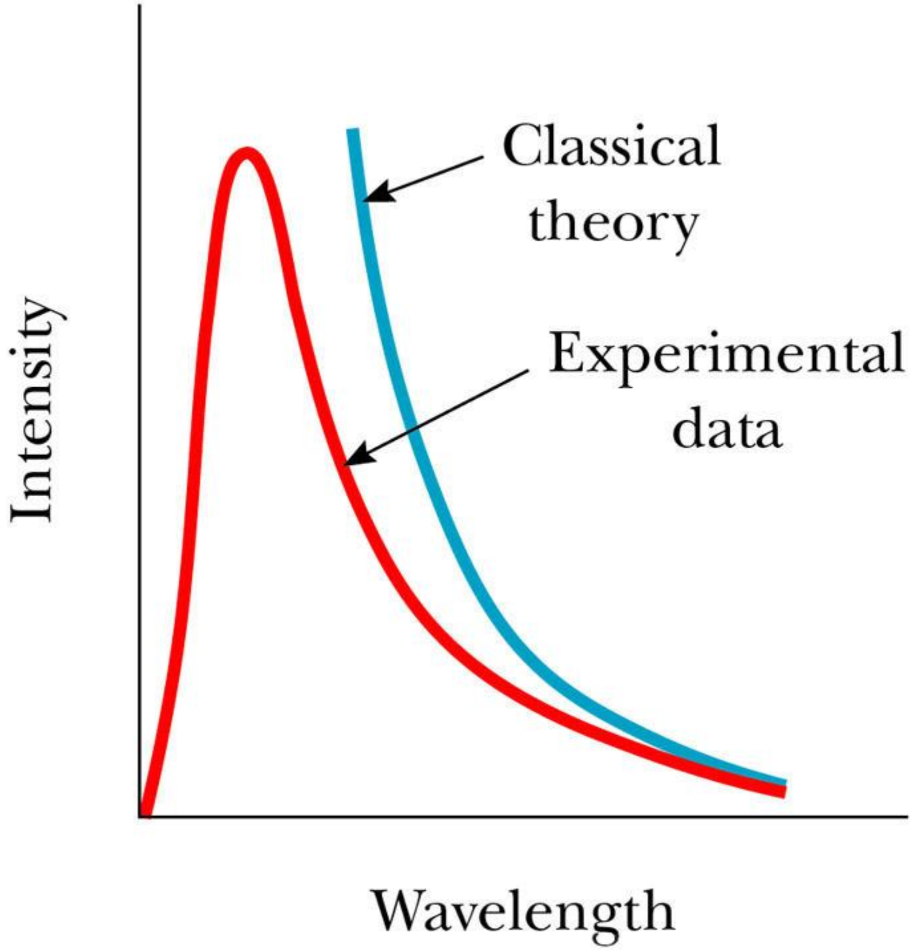
Theory vs. Experiment – Theory Loses

…at short wave lengths

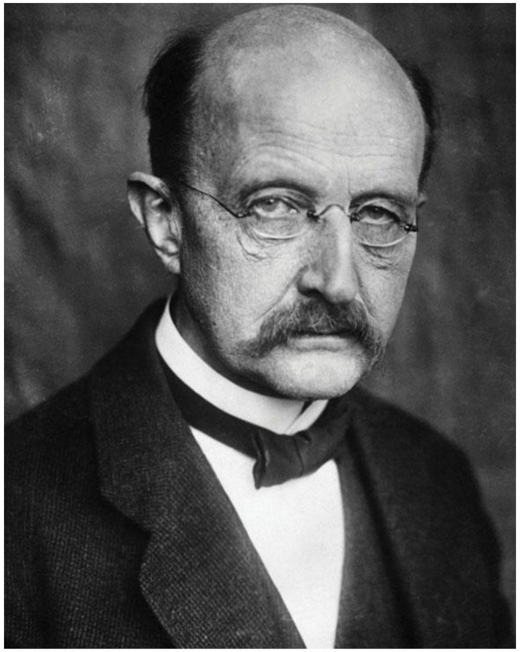
(1) Rayleigh-Jeans predicted *infinite energy*!

(2) Experiment showed energy fell off to zero.

This contradiction is called the *ultraviolet catastrophe*.



Planck's Resolution



In 1900 Max Planck proposed: blackbody radiation is produced by *resonators* (submicroscopic charged oscillators).

These resonators can only have *discrete energies:*

$E_n = nhf$

n is called the *quantum number.*

f is the frequency of vibration.

h is *Planck's constant*, 6.626 x 10^{-34} J·s.

Key point: quantized energy states.

Planck's result matched the experimentally observed intensity:

$$I = \frac{8\pi hc}{\lambda^5}\left[\frac{1}{e^{hc/\lambda k_{\mathrm{B}}T} - 1}\right]$$

Planck's "Constant of Action" - Variations

$$h = 6.63\times10^{-34}\ \mathrm{J\cdot s}$$

$$h = 4.14\times10^{-15}\ \mathrm{eV\cdot s}$$

$$\hbar = \frac{h}{2\pi} = 1.05\times10^{-34}\ \mathrm{J\cdot s}$$

$$\hbar = \frac{h}{2\pi} = 6.58\times10^{-16}\ \mathrm{eV\cdot s}$$

http://www.lon-capa.org/~mmp/applist/blackbody/black.htm

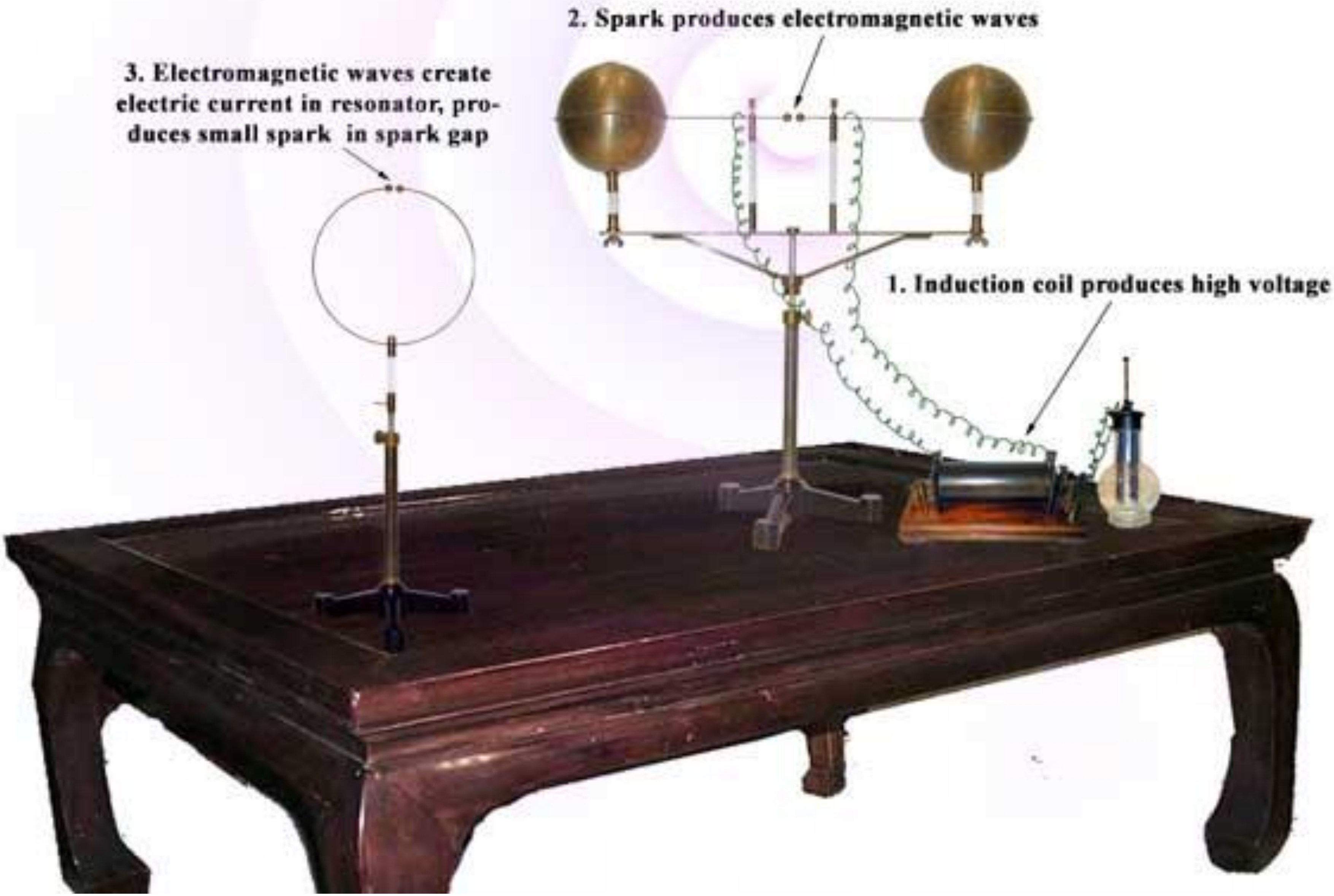
Quantum Physics

Selected Topics - 2

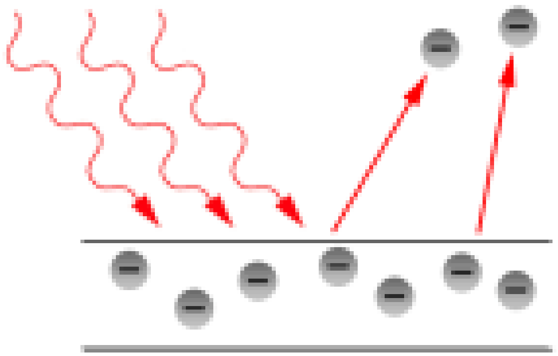
The Photoelectric Effect

First observed by Hertz in 1887 in his spark gap apparatus (earliest transmission of radio waves).

Hertz's Spark Gap Transmitter

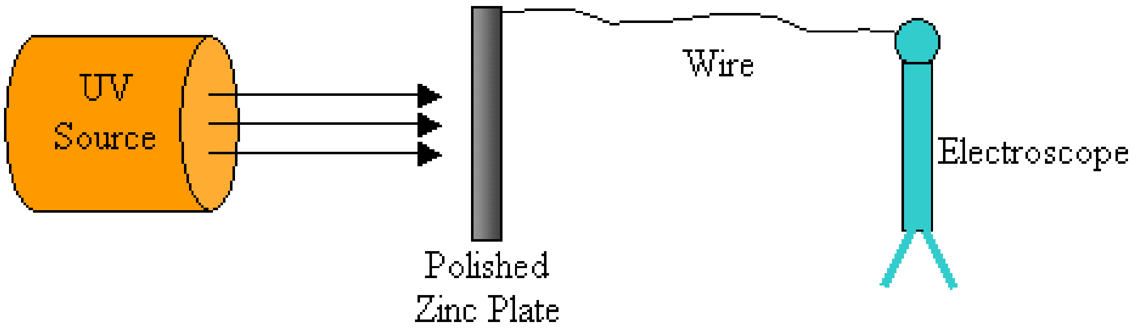


When light is incident on certain metallic surfaces, charges are emitted from the surface.



Apparatus used in class

Hertz's setup



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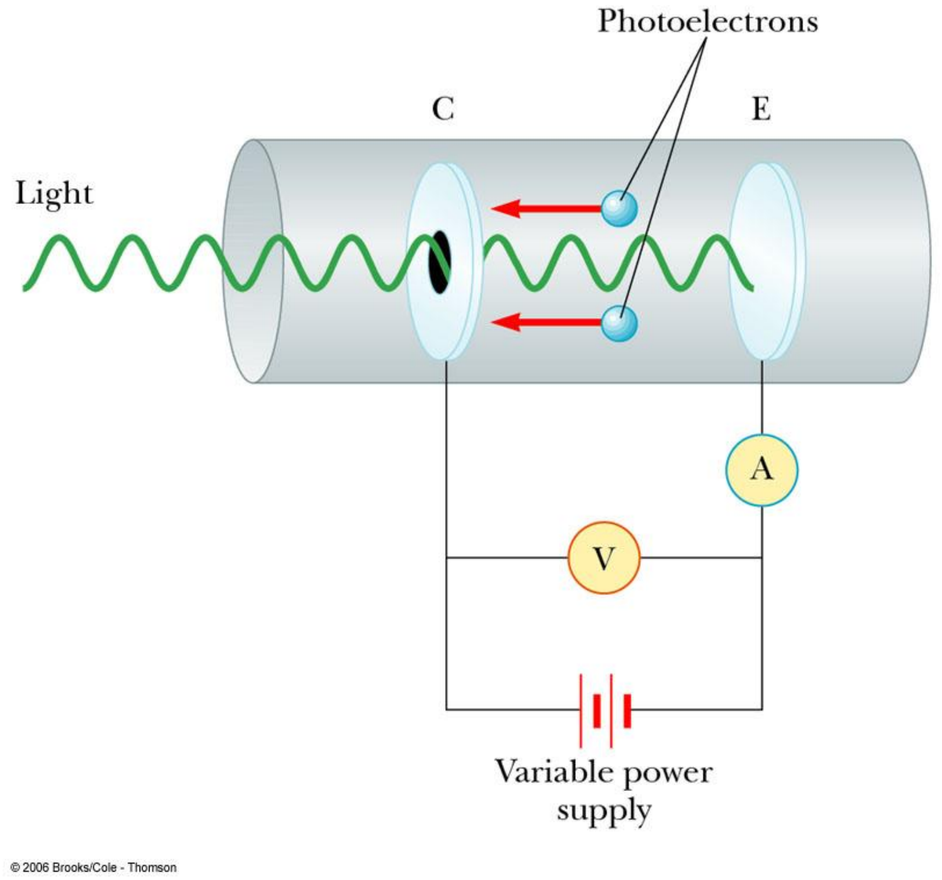
- Emitted electrons have a range of kinetic energies (up to some maximum value KE_{max})
- KE_{max} depends on frequency and type of material

Photoelectric Effect Schematic



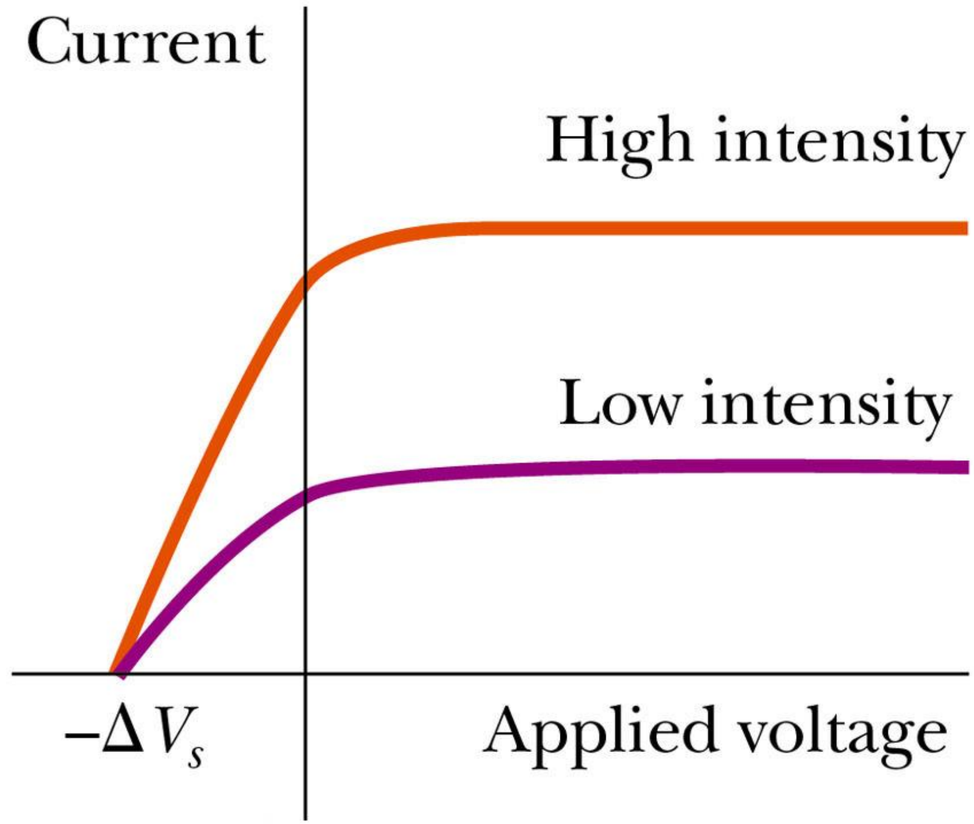
When light strikes E, photoelectrons are emitted.

Electrons collected at C and passing through the ammeter are a current in the circuit.

C is maintained at a positive potential by the power supply.

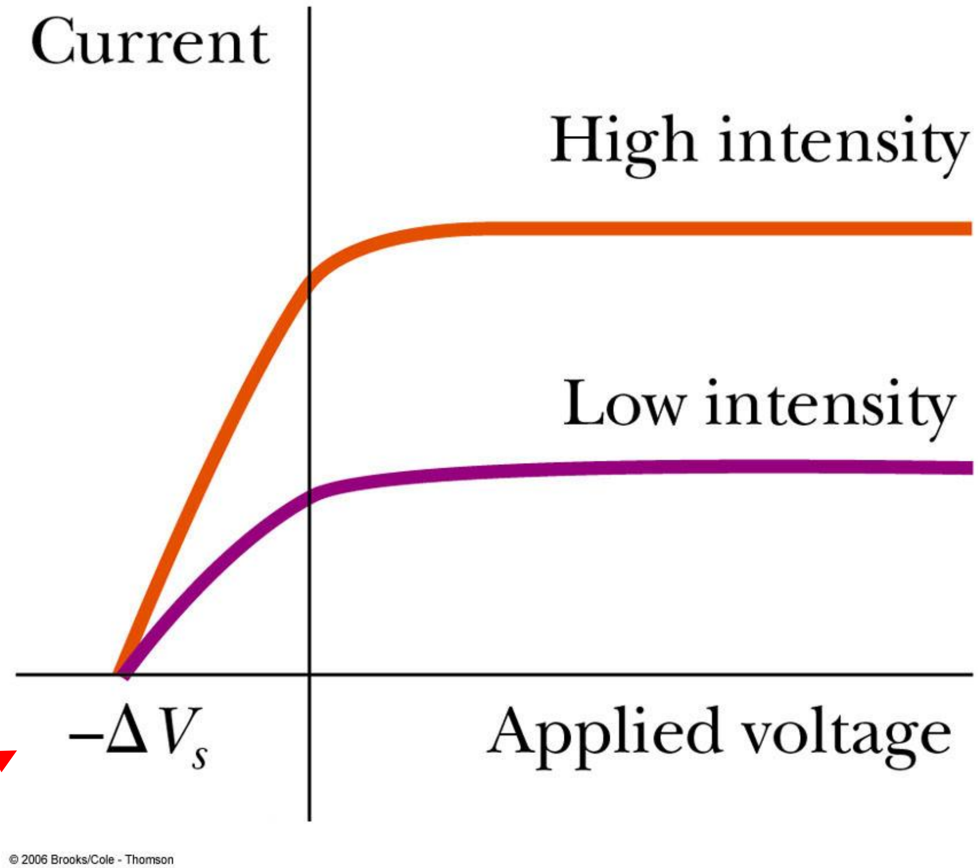
Photoelectric Current/Voltage Graph

The current increases with intensity, but reaches a saturation level for large applied voltage (ΔV).



Photoelectric Current/Voltage Graph

There is no current for voltages less than or equal to $-\Delta V_s$, the *stopping potential*.



The stopping potential is independent of the radiation intensity.

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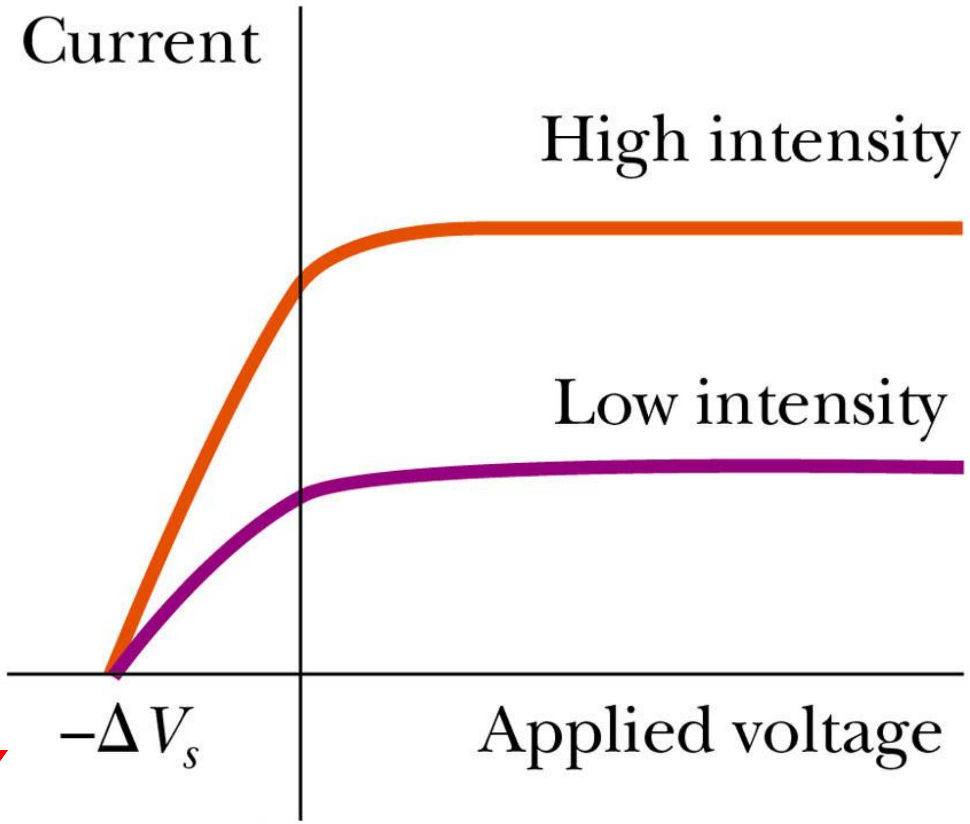

The maximum kinetic energy of the photoelectrons is related to the stopping potential: $KE_{max} = -\Delta V_s$.

Einstein's Explanation

- A tiny packet of light energy, called a *photon*, is emitted when a quantized oscillator jumps from one energy level to the next lower one.

  (This extended Planck's idea of quantization to the electromagnetic radiation itself.)

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Each photon can give all its energy to an electron in the metal.

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  (This extended Planck's idea of quantization to the electromagnetic radiation itself.)
- The photon's energy is $E = hf$.

Each photon can give all its energy to an electron in the metal.
- The maximum kinetic energy of the liberated photoelectron is $KE_{max} = hf - \phi$.

ϕ is called the *work function* of the metal.

Practice with these Applets

http://www.lon-capa.org/~mmp/kap28/PhotoEffect/photo.htm

http://phet.colorado.edu/new/simulations/sims.php?sim=Photoelectric_Effect

http://www.walter-fendt.de/ph14e/photoeffect.htm

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.

(If the photon energy is less than the work function, 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.

Explanation of Classical "Problems"

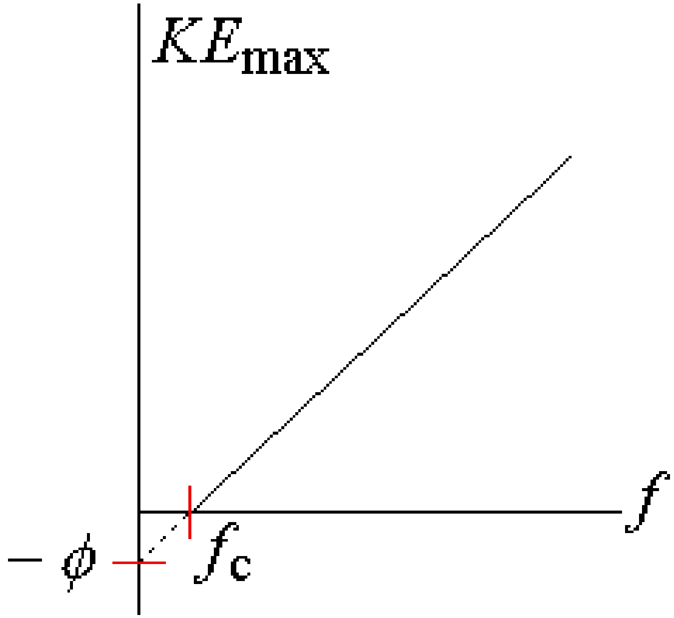
-The maximum *KE* increases with increasing frequency.

- 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 show a linear relationship between photoelectron KE_{max} and frequency.

The x-intercept is the cutoff frequency f_c.



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

$$\text{If } KE_{max} = 0,\ hf_c = \frac{hc}{\lambda_c} = \phi$$

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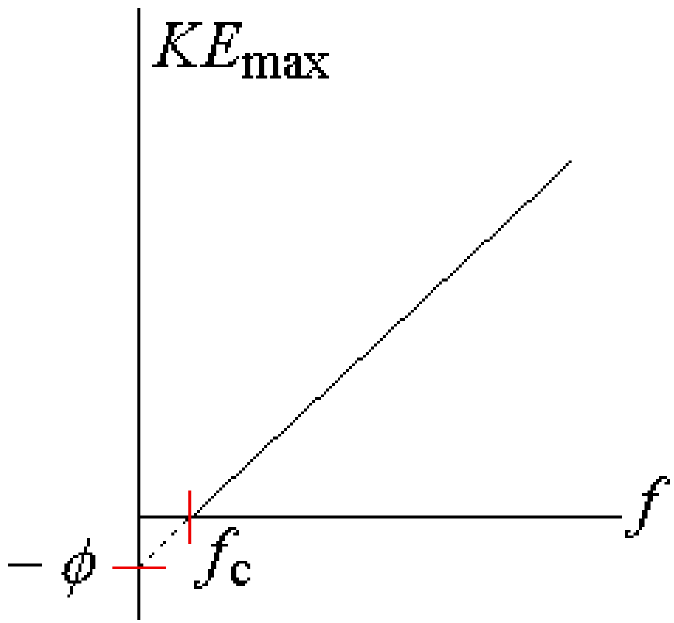

The x-intercept is the cutoff frequency f_c. The *slope* of the line is Planck's constant h.

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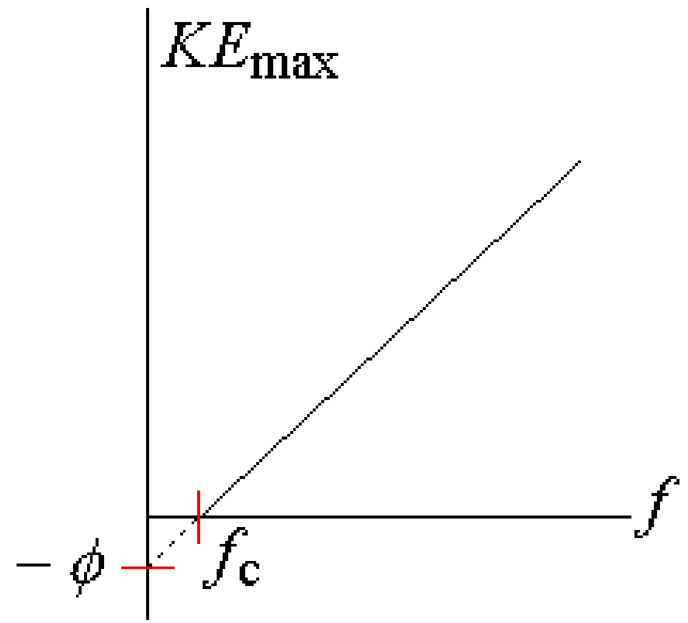


The *x*-intercept is the cutoff frequency f_c.

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

The *slope* of the line is Planck's constant *h*.

$$\text{If } KE_{max} = 0,\ hf_c = \frac{hc}{\lambda_c} = \phi$$

The *y*-intercept is the work function ϕ.

Cutoff Wavelength

The cutoff wavelength is related to the work function

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

If the wavelength of the incident radiation is greater than λ_c, photoelectrons will not be emitted.

Quantum Physics

Selected Topics - 3

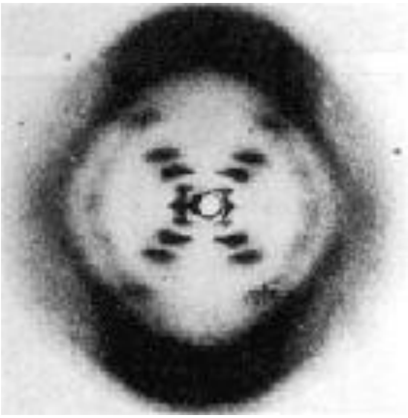
X-Rays

Discovered and named by Roentgen in 1895.

X-rays are a form of electromagnetic radiation with short wavelengths (less than for ultraviolet, typically about 0.1 nm).

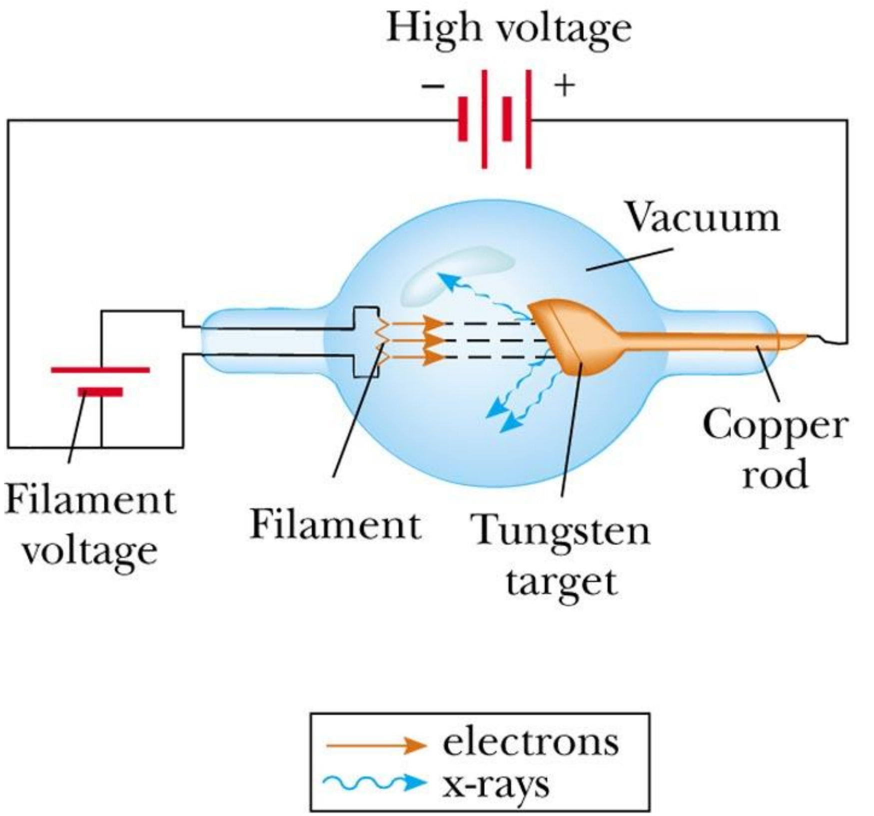
X-rays have the ability to penetrate most materials with relative ease.

X-ray diffraction photograph of DNA by Rosalind Franklin →



Production of X-rays

X-rays are produced when high-speed electrons are suddenly slowed down (when an electron strikes a metal target, for example).



(a)

A current in the filament causes electrons to be emitted.

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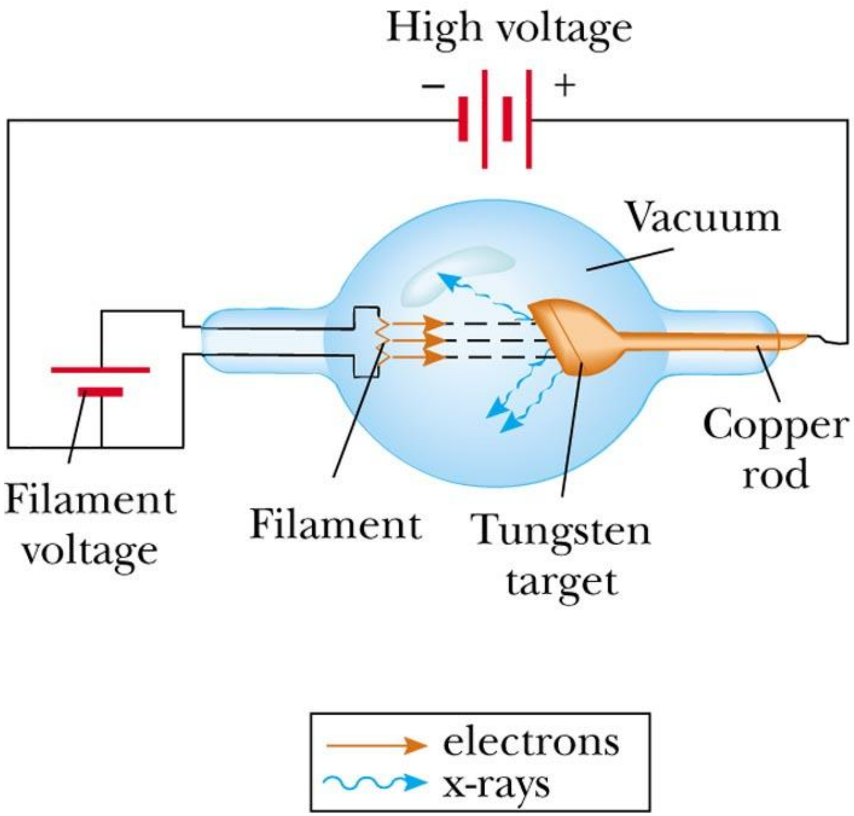

(a)

These freed electrons are accelerated toward a dense metal target.

Production of X-rays

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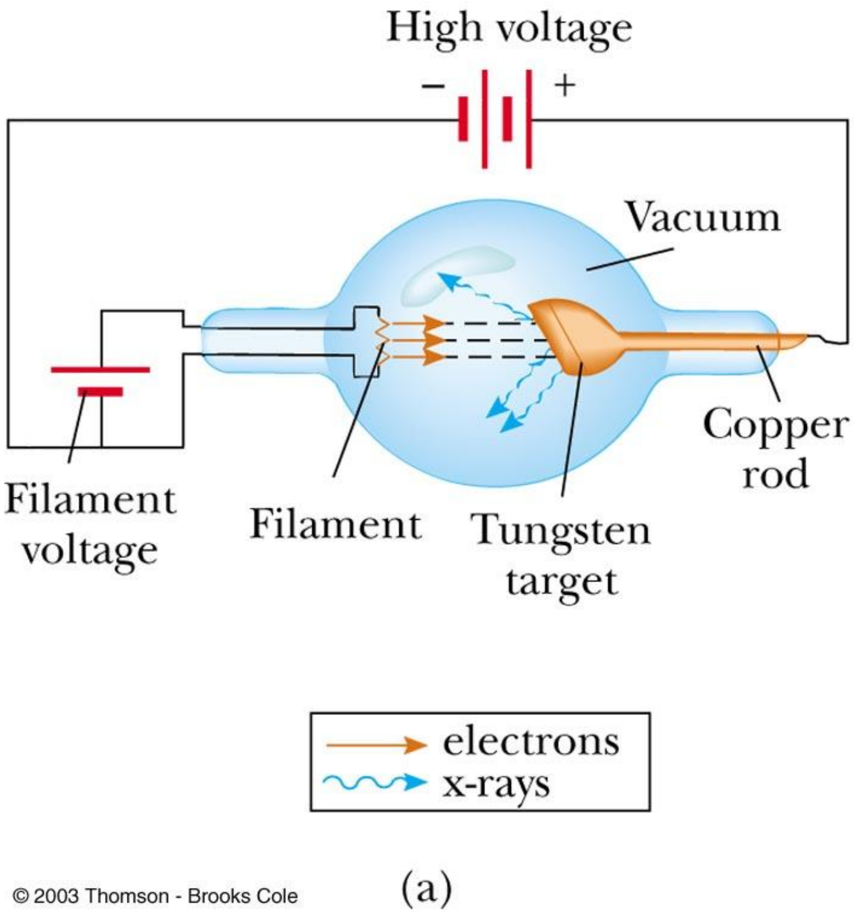


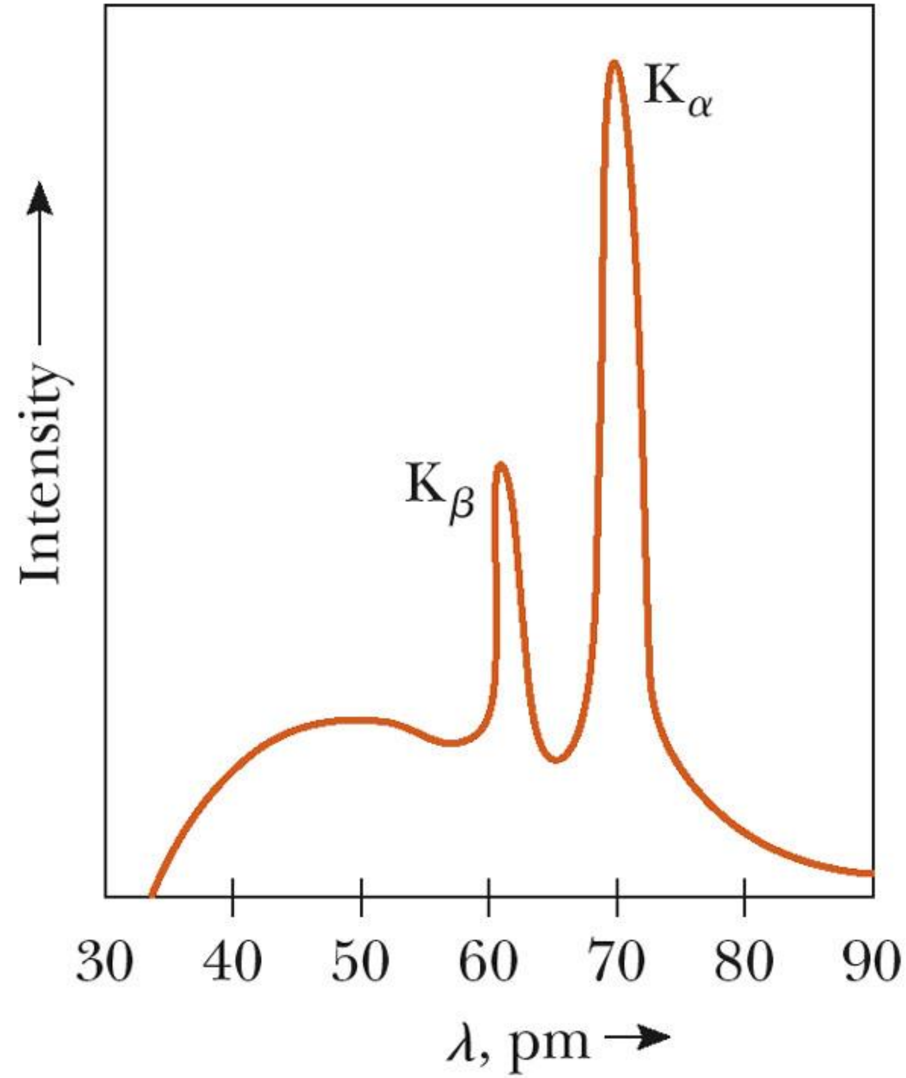
The target is held at a higher potential than the filament.

X-ray Spectrum

The x-ray spectrum has two distinct components

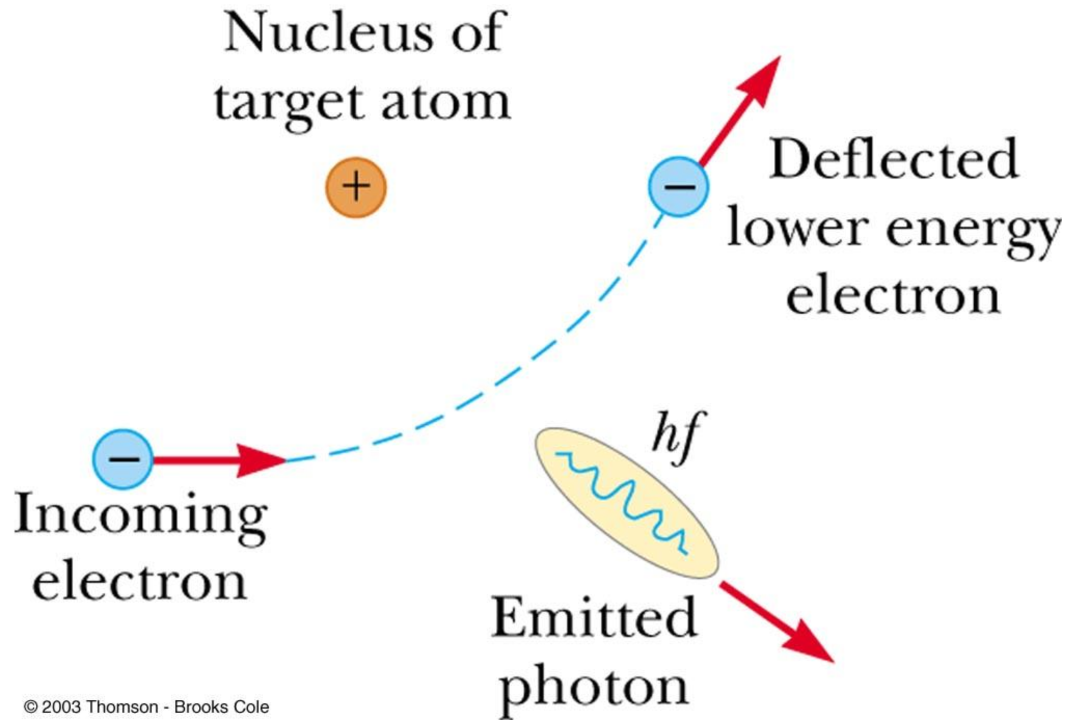
1 - Continuous broad spectrum

> **Depends on voltage applied to the tube. Sometimes called *bremsstrahlung* (“*braking radiation*”).**



X-ray Spectrum

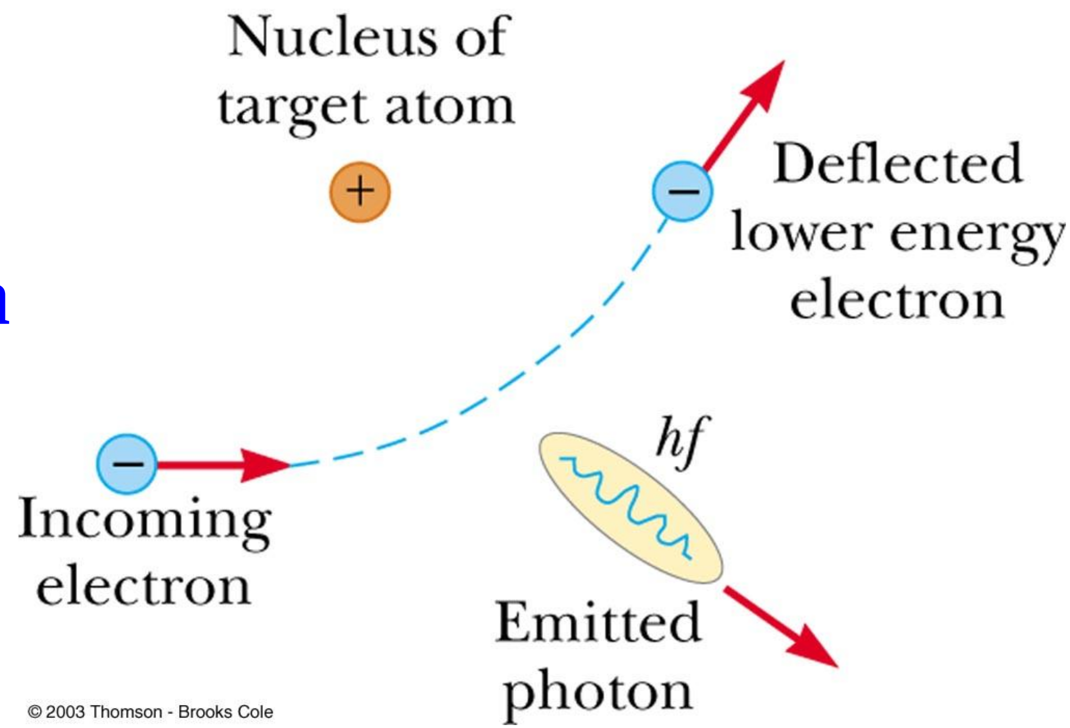
An electron passes near a target nucleus and is deflected from its path by its attraction to the nucleus.



This attracting force produces an acceleration. The accelerated electron emits electromagnetic radiation (*bremsstrahlung*).

X-ray Spectrum

An electron accelerated through a potential difference ΔV has a kinetic energy $e\Delta V$.

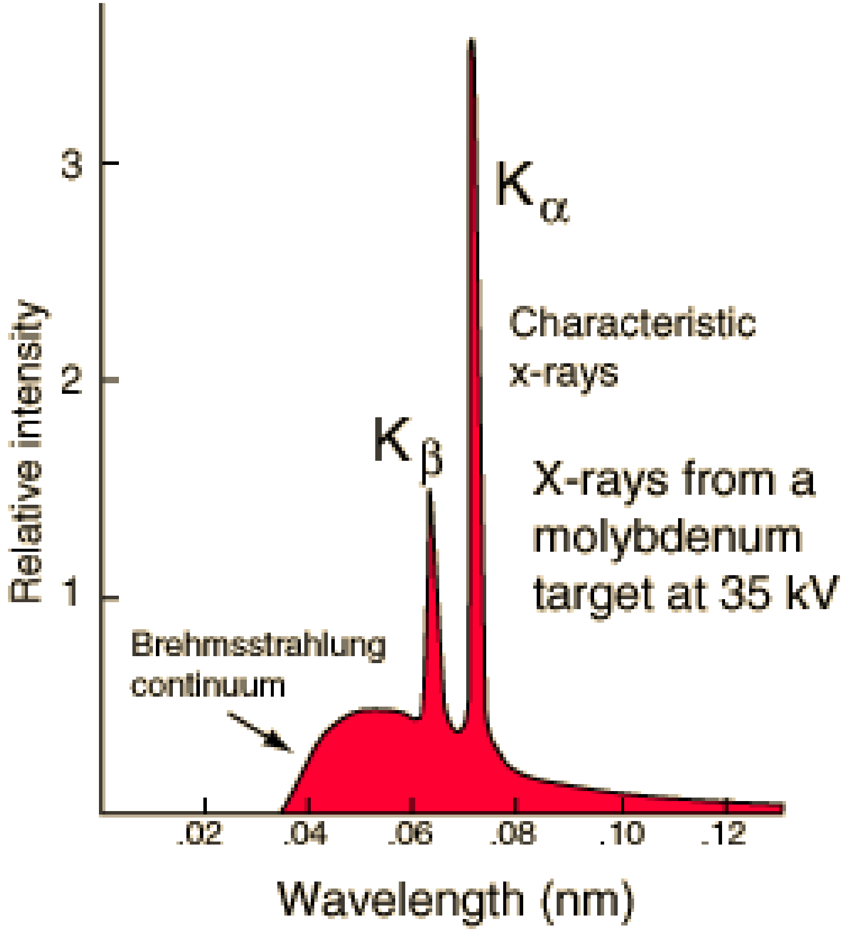


If all this energy is "lost" in a single encounter with a nucleus, this is the energy of the photon of maximum energy: $e\Delta V = hf_{max}$. The shortest wavelength radiation that can be produced is

$$\lambda_{min} = \frac{hc}{e\Delta V}.$$

X-ray Spectrum

2 – Characteristic Spectrum



The bombarding electrons can also eject electrons from the inner shells of the atoms of the metal target.

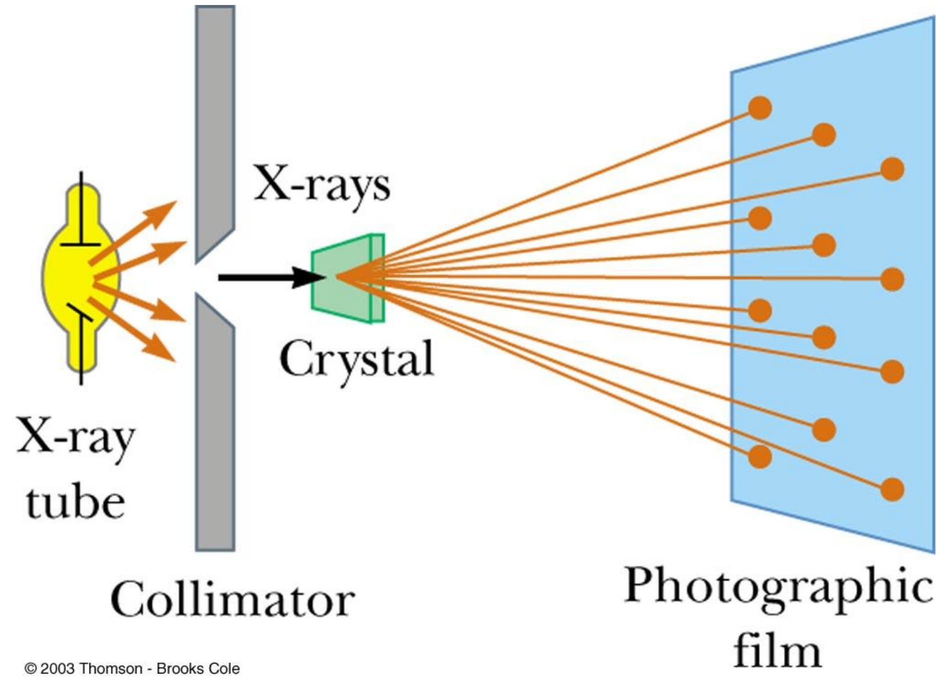
The quick filling of those vacancies by electrons dropping down from higher levels gives rise to sharply defined "characteristic x-rays".

X-Ray Diffraction

For diffraction to occur, the spacing between the lines must be approximately equal to the wavelength of the radiation to be measured.

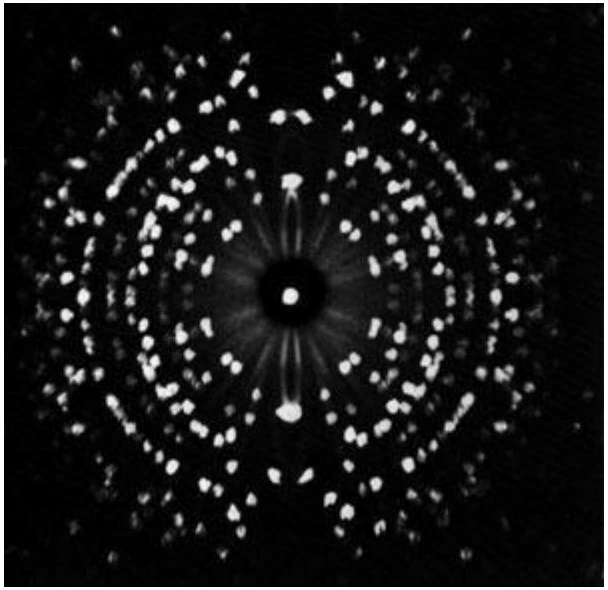
The regular array of atoms in a crystal can act as a three-dimensional grating for diffracting X-rays.

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 or a digital image processor.

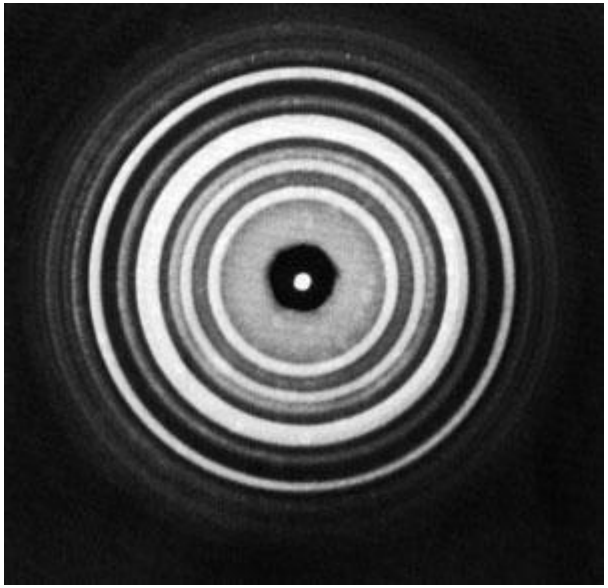
X-ray diffraction pattern for a single alum crystal.



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

X-ray Powder Diffraction

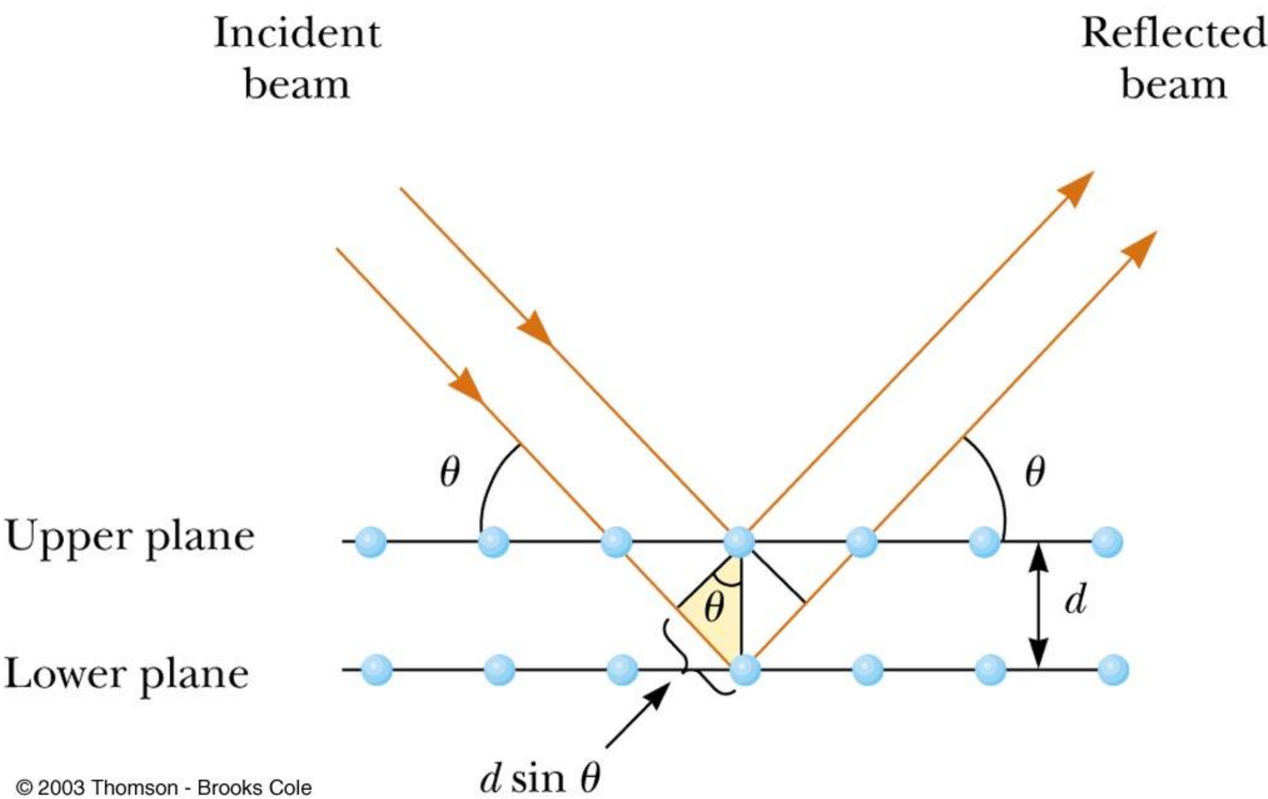
The sample consists of a collection of many small crystallites with random orientations.



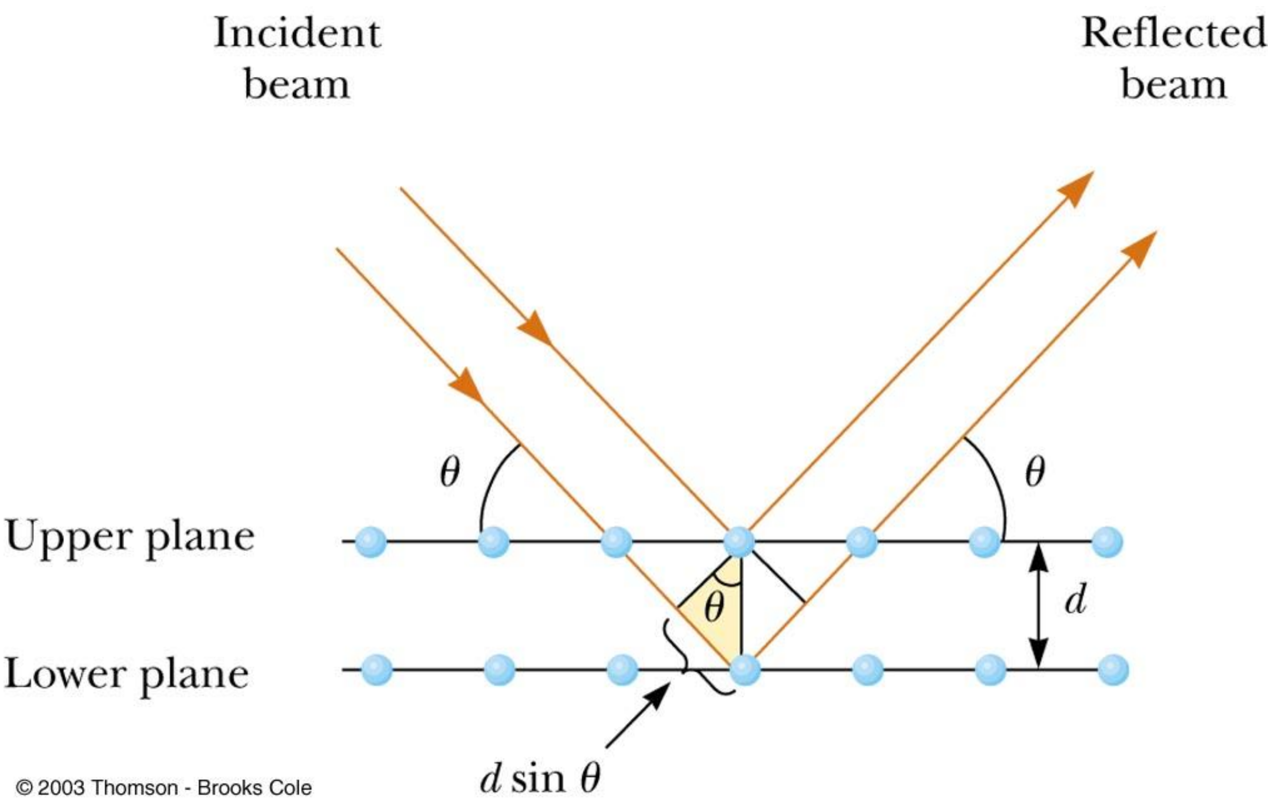
X-ray diffraction pattern for powdered alum crystals.

Bragg’s Law

The beam reflected from the lower surface travels farther than the one reflected from the upper surface.



Bragg's Law



If the path difference equals some integral multiple of the wavelength, constructive interference occurs. *Bragg's Law* gives the conditions for constructive interference:

$$2d\sin\theta = m\lambda,\ m = 1, 2, 3\ldots$$

Quantum Physics

Selected Topics - 4

Photons and Electromagnetic Waves

Light has a dual nature. It exhibits both wave and particle characteristics. (This applies to all electromagnetic radiation.)

Different frequencies allow one or the other characteristic to be more easily observed.

Photons and Electromagnetic Waves

Light has a dual nature. It exhibits both wave and particle characteristics. (This applies to all electromagnetic radiation.)

The *photoelectric effect* and *Compton scattering* (see text Section 27.5) offer evidence for the particle nature of light.

When light and matter interact, light behaves as if it were composed of particles.

Photons and Electromagnetic Waves

Light has a dual nature. It exhibits both wave and particle characteristics. (This applies to all electromagnetic radiation.)

Interference **and** ***diffraction*** **offer evidence of the wave nature of light.**

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.

The *de Broglie wavelength* of a particle is related to the particle's <u>momentum</u>:

$$\lambda = \frac{h}{p} = \frac{h}{m\upsilon}$$

The *frequency* of a matter wave is related to <u>wave energy</u>:

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

***de Broglie wavelength*:**

$$\lambda = \frac{h}{p} = \frac{h}{m\upsilon}$$

Matter wave *frequency*:

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

The de Broglie equations show the dual nature of matter.

Each contains particle concepts:

***energy* and *momentum*.**

Each contains wave concepts:

***wavelength* and *frequency*.**

Many experiments have confirmed this.