Classical vs Quantum Mechanics

Rutherford's model of the atom: electrons orbiting around a dense, massive positive nucleus

Expected to be able to use classical (Newtonian) mechanics to describe the motion of the electrons around the nucleus.

However, classical mechanics failed to explain experimental observations

Resulted in the development of Quantum Mechanics - treats electrons as both a particle and a wave

Problems with Classical Mechanics

Experimental results could not be explained by classical mechanics

Blackbody Radiation - emission of light from a body depends on the temperature of the body

Photoelectric Effect - emission of electrons from a metal surface when light shines on the metal

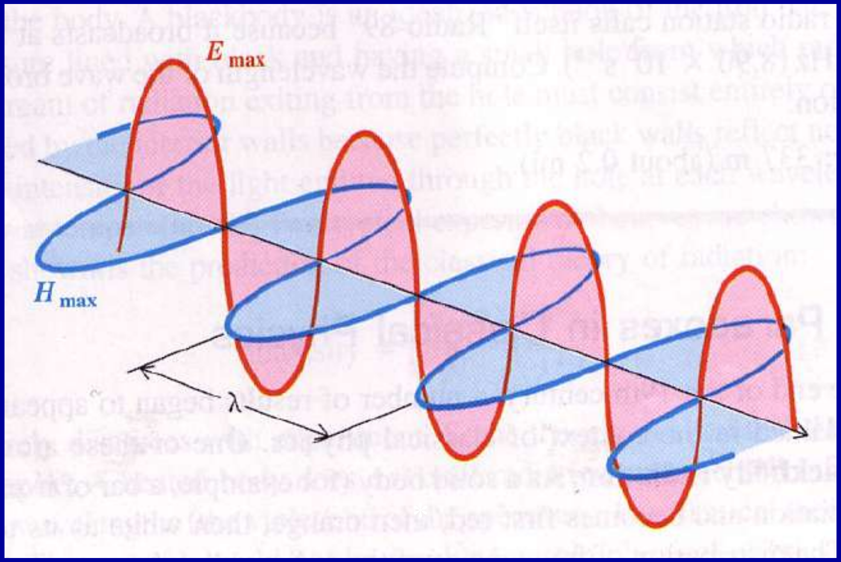
Stability of atom: Classical physics predicts the electron to continuously emit energy as it "orbits" around the nucleus, falling into the nucleus

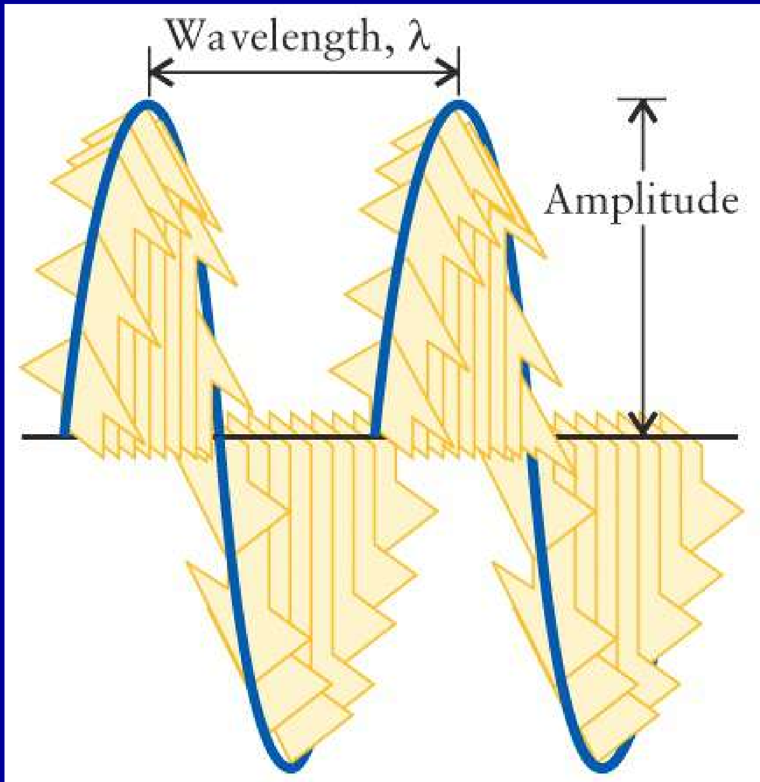
Electromagnetic Radiation

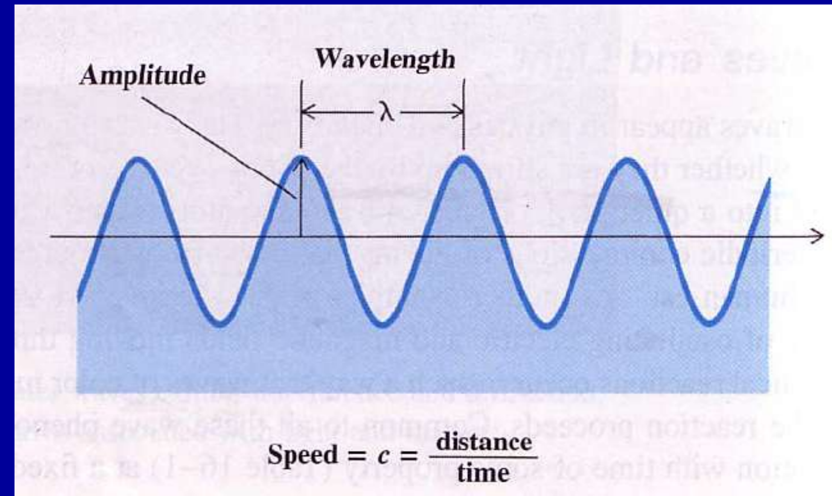
The observations involved the interaction of light with matter - spectroscopy.

Spectroscopy is used to investigate the internal structure of atoms and molecules.

Electromagnetic radiation, or light, consists of oscillating electric and magnetic fields.







Electric field vector - oscillates in space with a **FREQUENCY**, ν (Hz or second^{-1})

1 Hz = 1 s^{-1}

WAVELENGTH (λ): distance between two points with the same amplitude (units: distance)

AMPLITUDE: Height from center line to peak

Intensity = $(\text{amplitude})^2$

Speed of the wave = frequency (s^{-1}) x wavelength (m)

Speed of light (c) = $\nu \lambda$

Speed of light in vacuum (c_o) = 2.99792458×10^8 m/s
(~ 670 million miles per hour)

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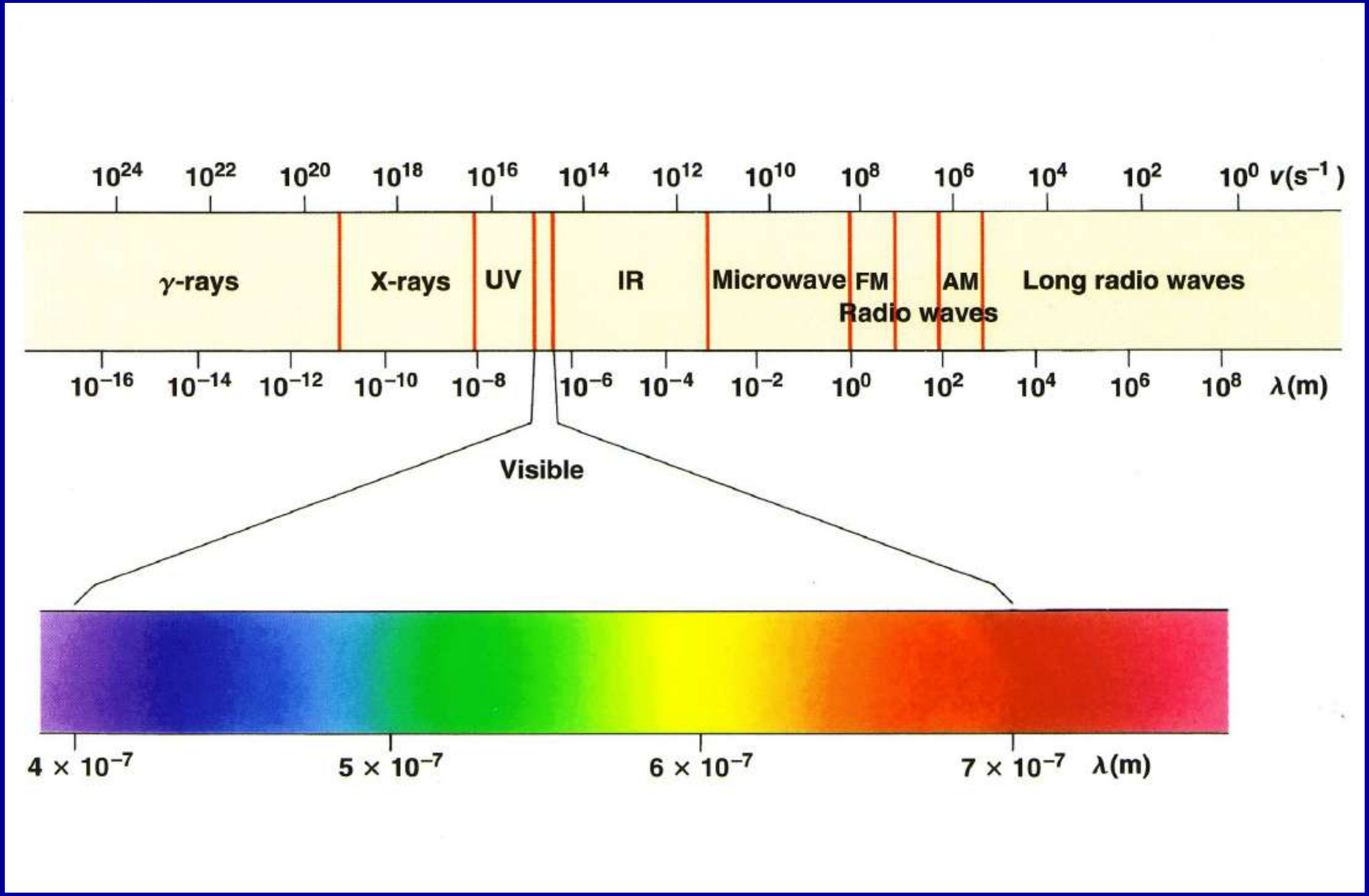
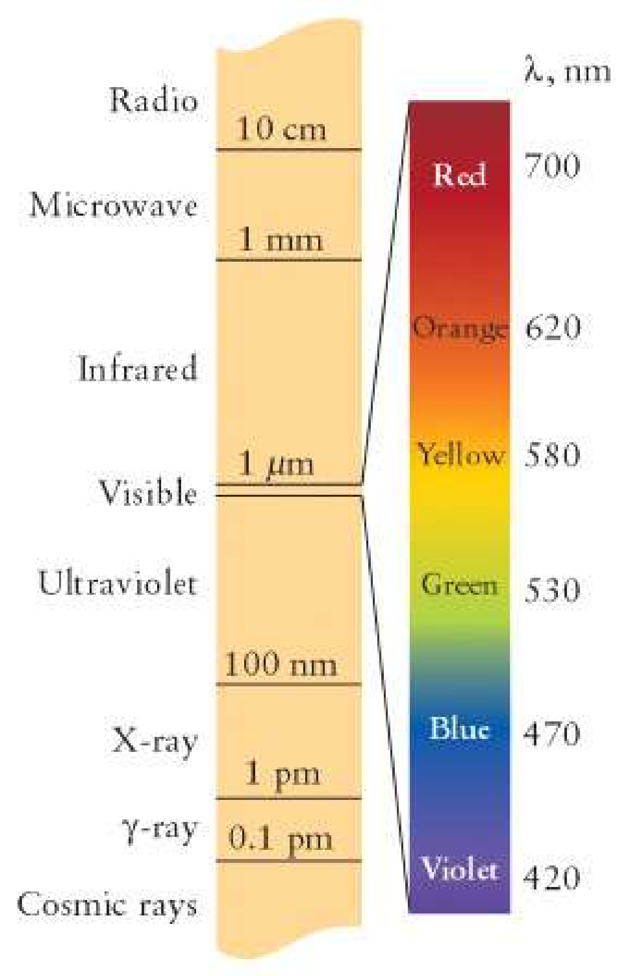


The "color" of light depends on its frequency or wavelength; long wavelength radiation has a lower frequency than short wavelength radiation

If the wavelength of light is 600 nm, its frequency is

$\sim (3 \times 10^{8}\ ms^{-1}) / (600 \times 10^{-9}\ m) = 5 \times 10^{14}\ s^{-1}$ (Hz)



1 μm (micron) = 10^{-6} m

1 nm (nano) = 10^{-9} m

1 pm (pico) = 10^{-12} m

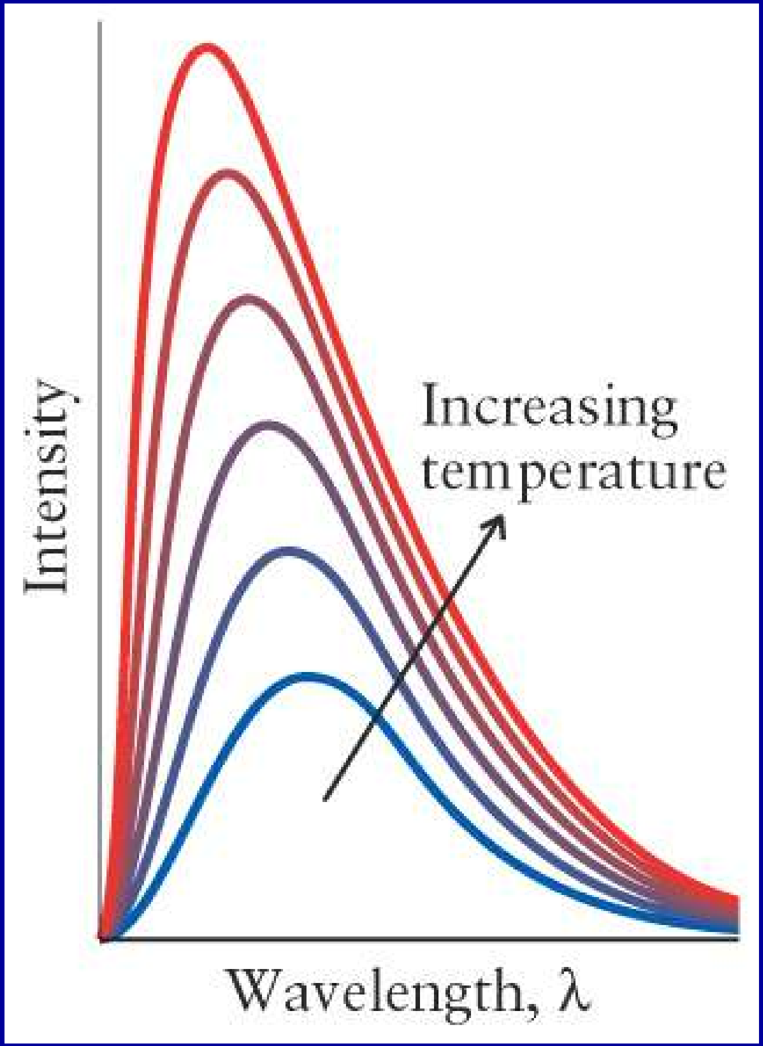
Blackbody Radiation

As an object is heated, it glows more brightly

The color of light it gives off changes from red through orange and yellow toward white as it gets hotter.

The hot object is called a black body because it does not favor one wavelength over the other

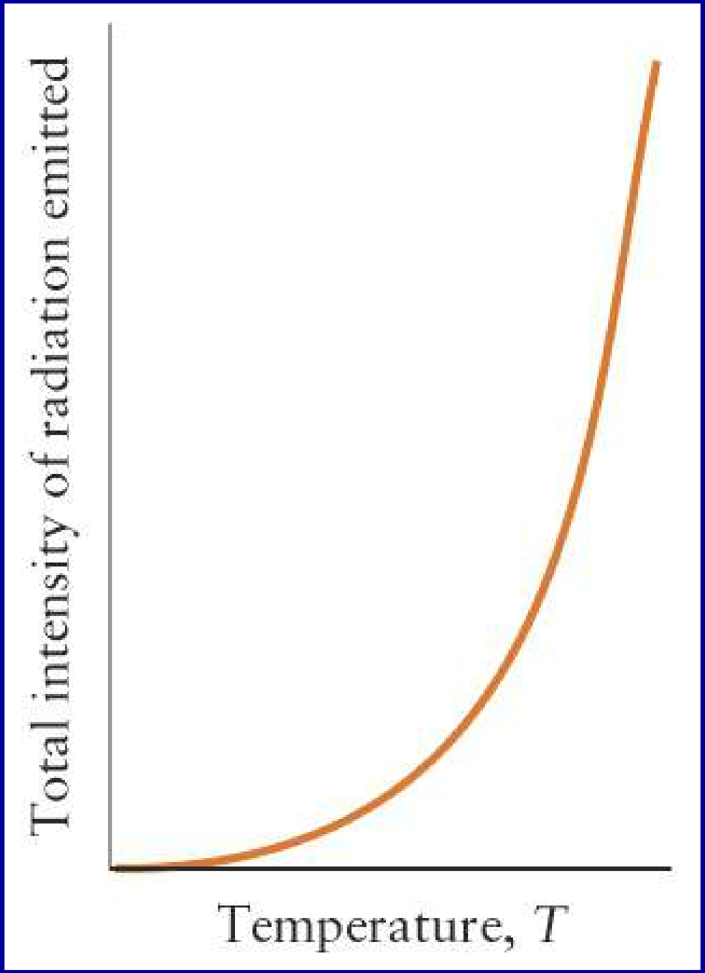
The colors correspond to the range of wavelengths radiated by the body at a given temperature - black body radiation.

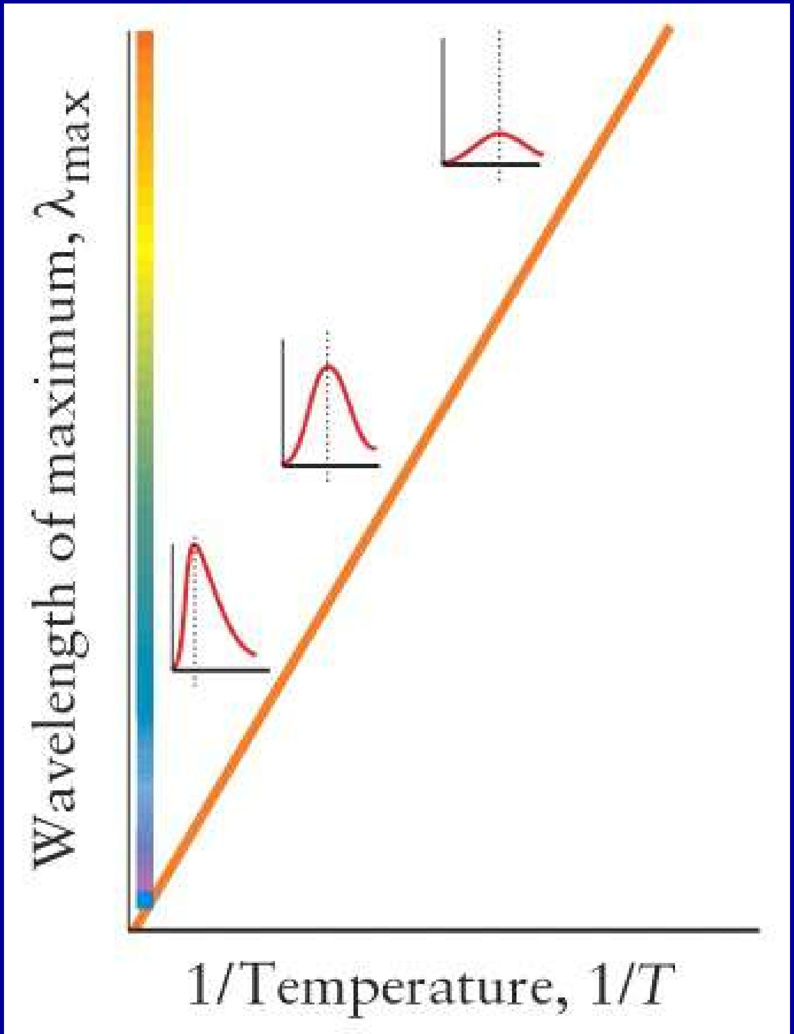


Black-body radiation

Stefan-Boltzmann Law: total intensity of radiation emitted over all wavelengths proportional to T^4

$$\frac{\text{Power emitted (watts)}}{\text{Surface area (meter}^2\text{)}} = \text{constant x } T^4$$





$\lambda_{max} \propto$ l/TWien's law

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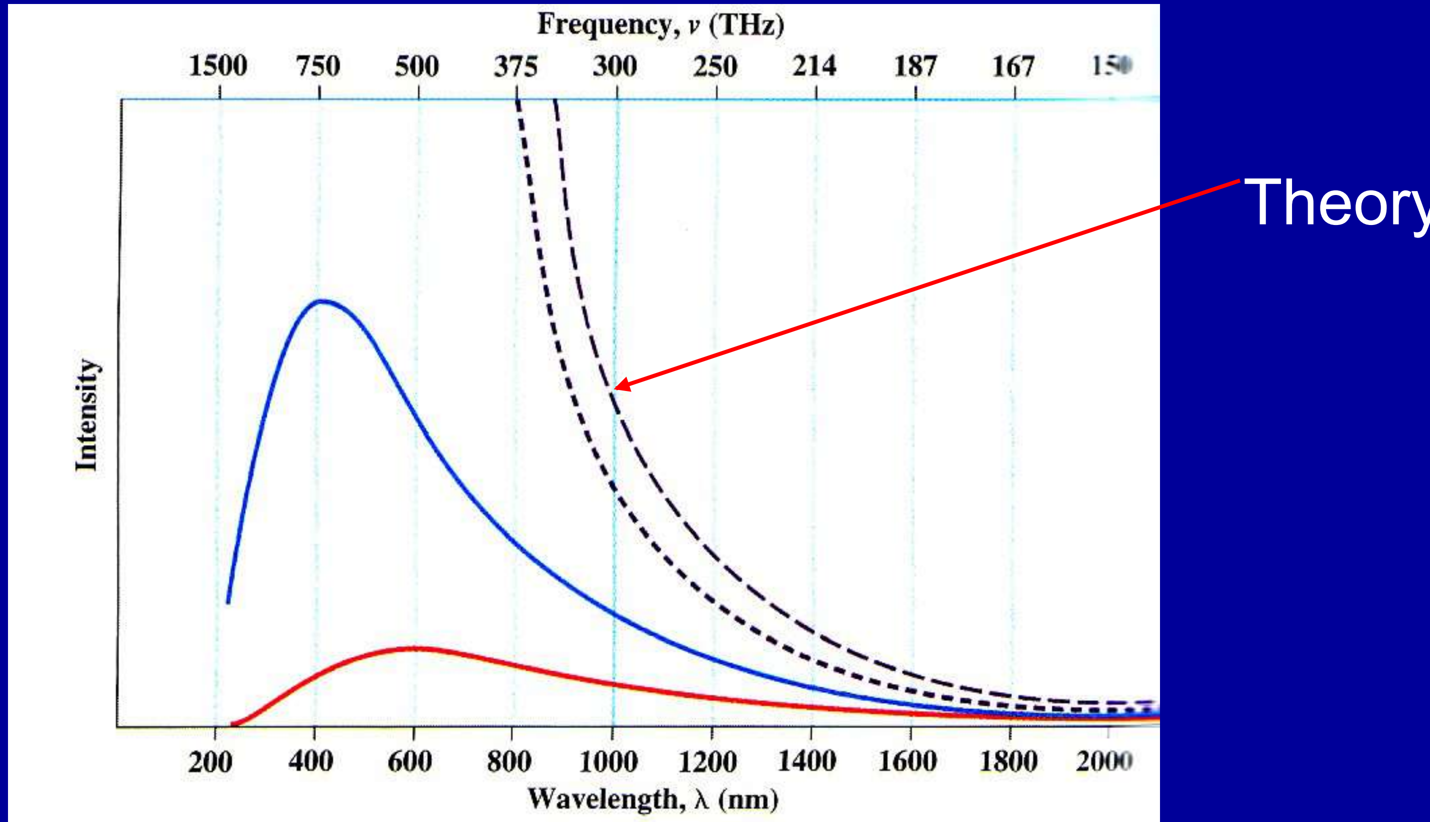


Classical physics predicts that any black body at non-zero temperatures should emit ultra-violet and even x-rays .

Experimental observations: “Ultraviolet catastrophe”*

Quanta

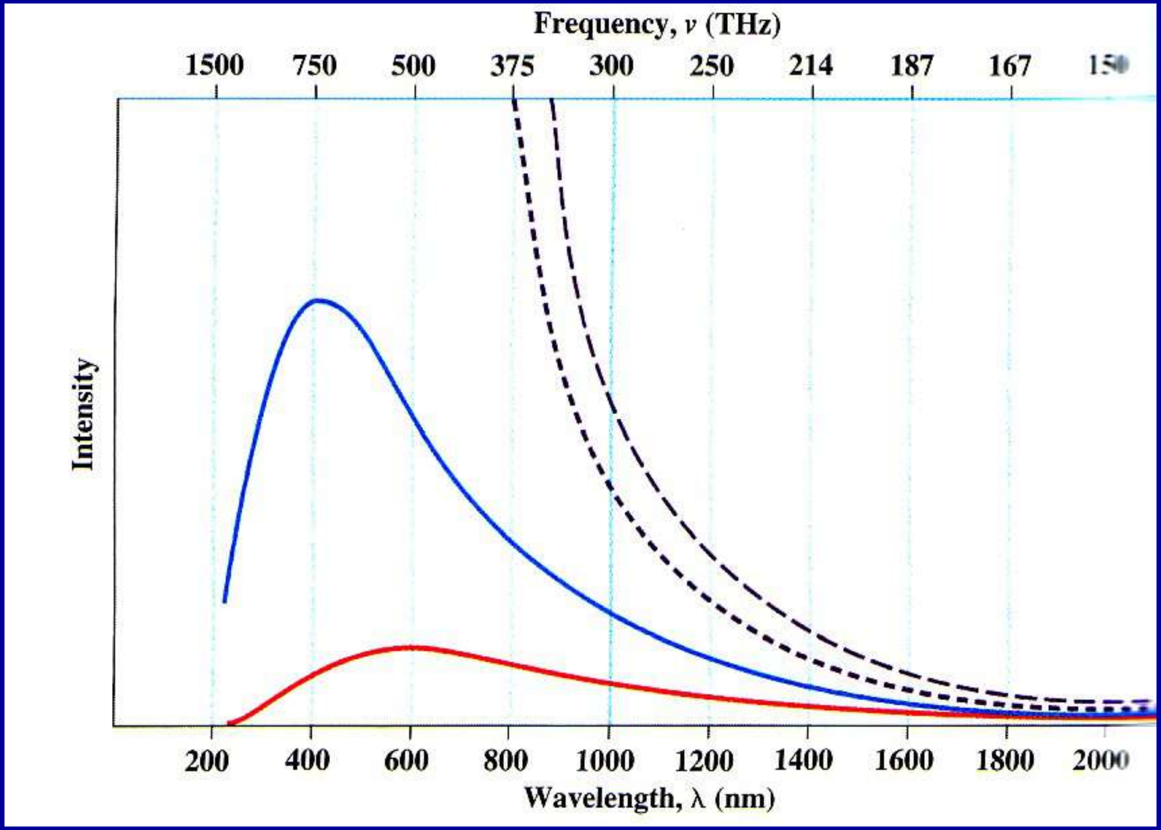
Max Planck (1900) - proposed that exchange of energy between matter and radiation occurs in packets of energy called QUANTA.

Planck proposed: an atom oscillating at a frequency of ν can exchange energy with its surroundings only in packets of magnitude given by

$E = h\nu$

h: Planck's constant 6.626×10^{-34} J s

Radiation of frequency ν (= E / h) is emitted only if enough energy is available



Large packets of energy are scarce

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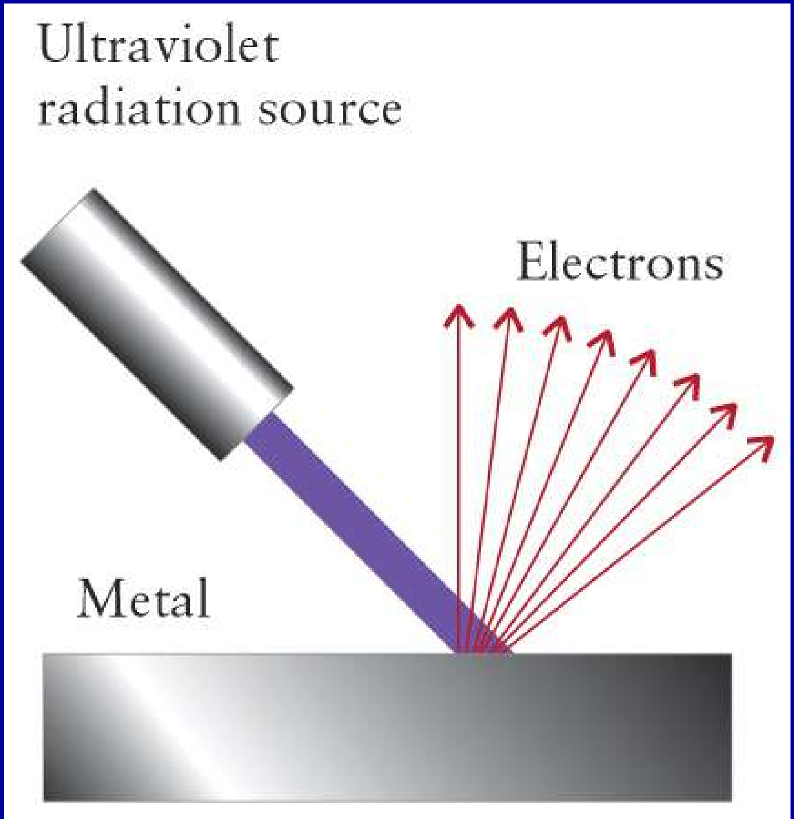
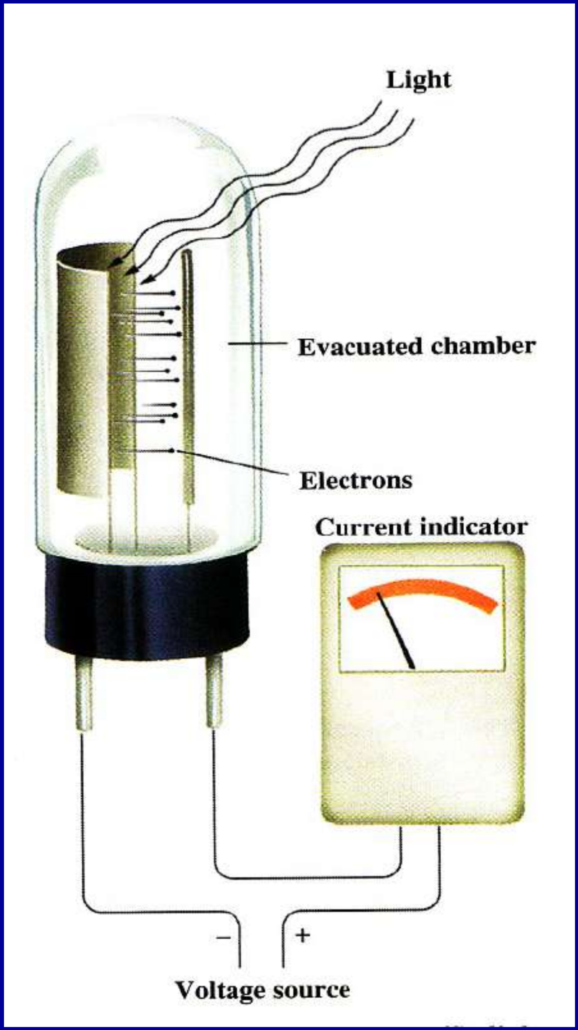
Photoelectric Effect

Further evidence of Planck’s work came from the photoelectric effect - ejection of electrons from a metal when its surface is illuminated with light





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Experimental observations when the metal was illuminated by ultraviolet light:

No electrons are ejected unless the radiation has a frequency above a certain threshold value characteristic of the metal

Electrons are ejected immediately, how ever low the intensity of the radiation

The kinetic energy of the ejected electron increases linearly with the frequency of the incident radiation.

Einstein proposed that electromagnetic radiation consist of particles, called PHOTONS.

Each photon can be regarded as a packet of energy $E = h\nu$ where ν is the frequency of the light.

The photons of energy, $E_{photon} = h\nu$, collide with the electron in the metal.

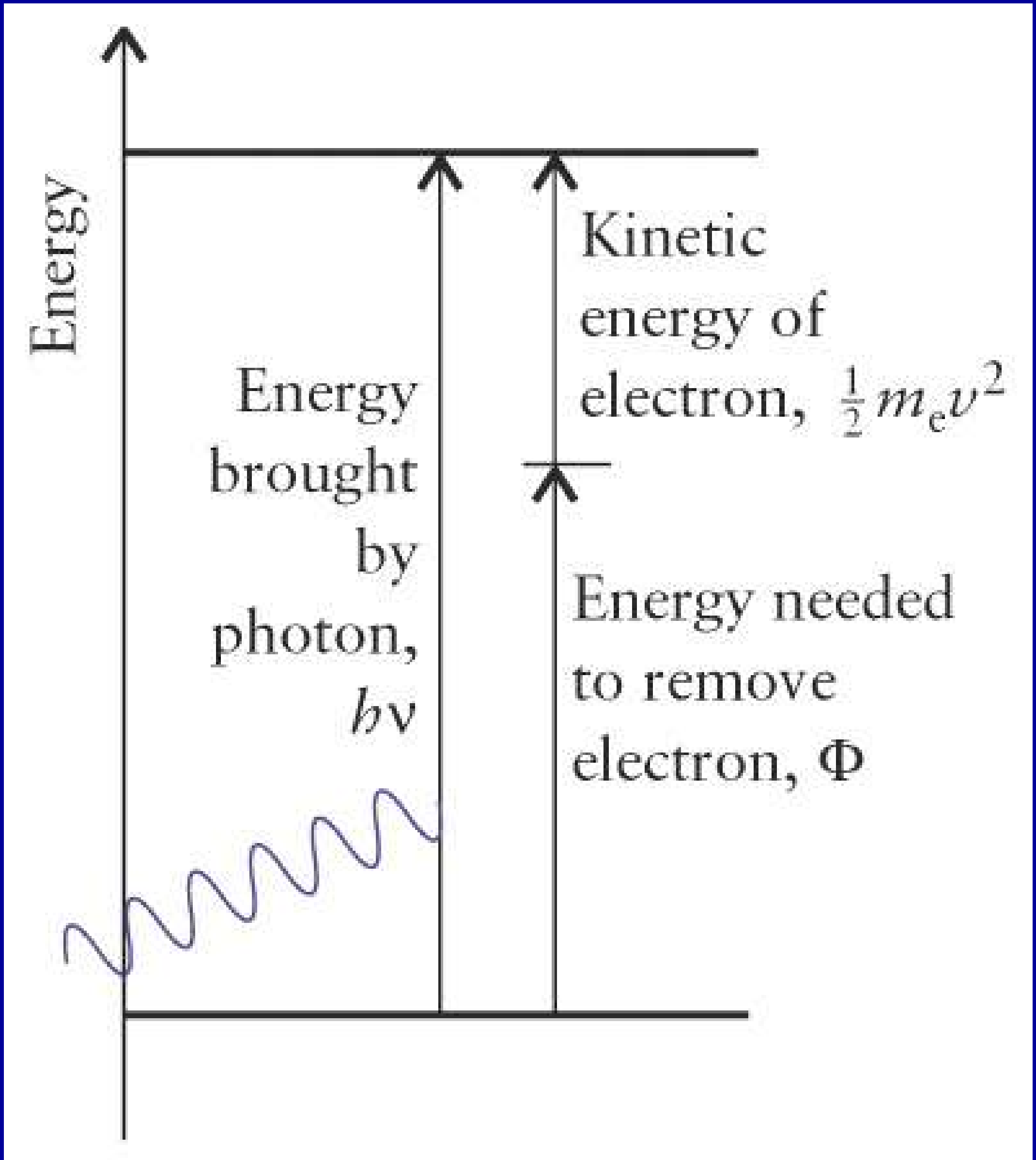
Electrons in the metal require a minimum amount of energy to be ejected from the metal - workfunction (Φ)

If $E_{photon} < \Phi$ electrons will not be ejected even at high intensity of the light

If $E_{photon} > \Phi$, the kinetic energy of the electrons ejected, E_K,

$E_K = 1/2\ mv^2 = h\ \nu - \Phi$

KE of the electron increases linearly with frequency of the radiation



Energy
Kinetic
energy of
electron, $\frac{1}{2}m_e v^2$
Energy
brought
by
photon,
$h\nu$
Energy needed
to remove
electron, Φ

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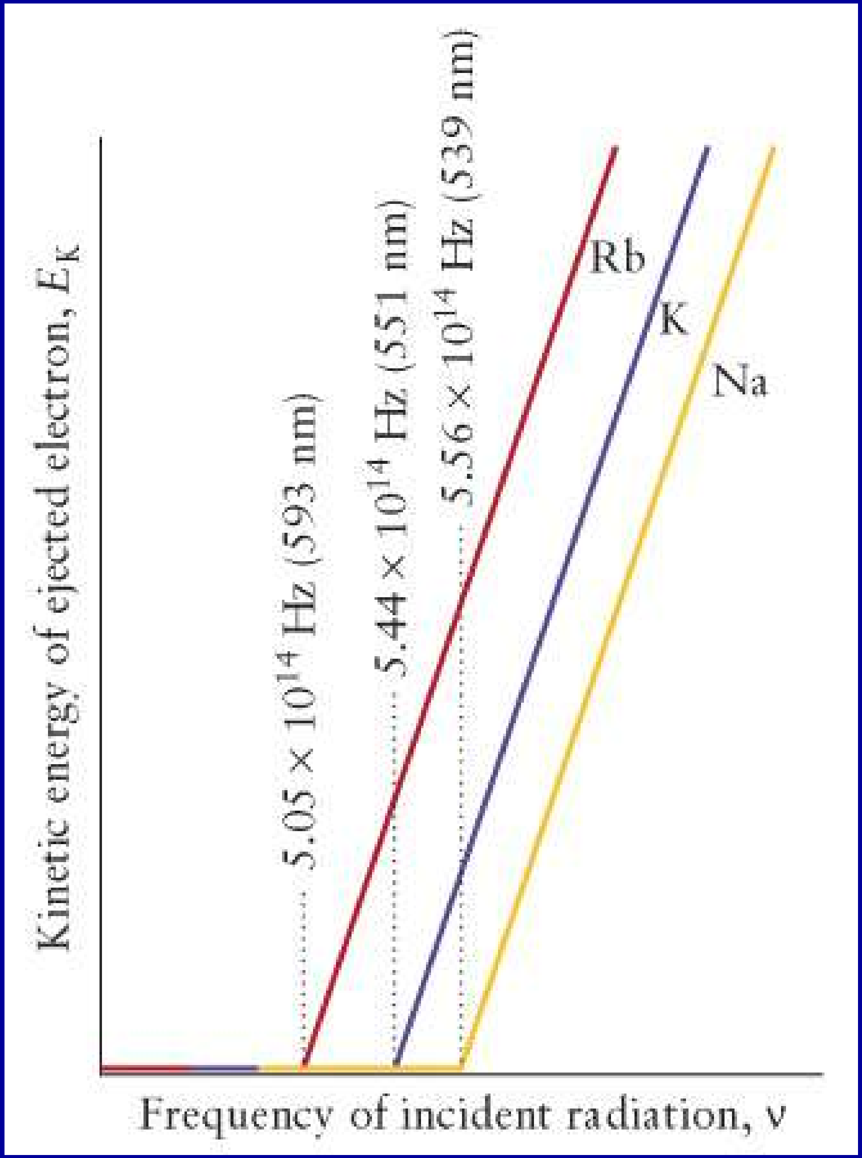

Kinetic energy of ejected electron, E_K
5.05×10^{14} Hz (593 nm)
5.44×10^{14} Hz (551 nm)
5.56×10^{14} Hz (539 nm)
Rb
K
Na
Frequency of incident radiation, ν

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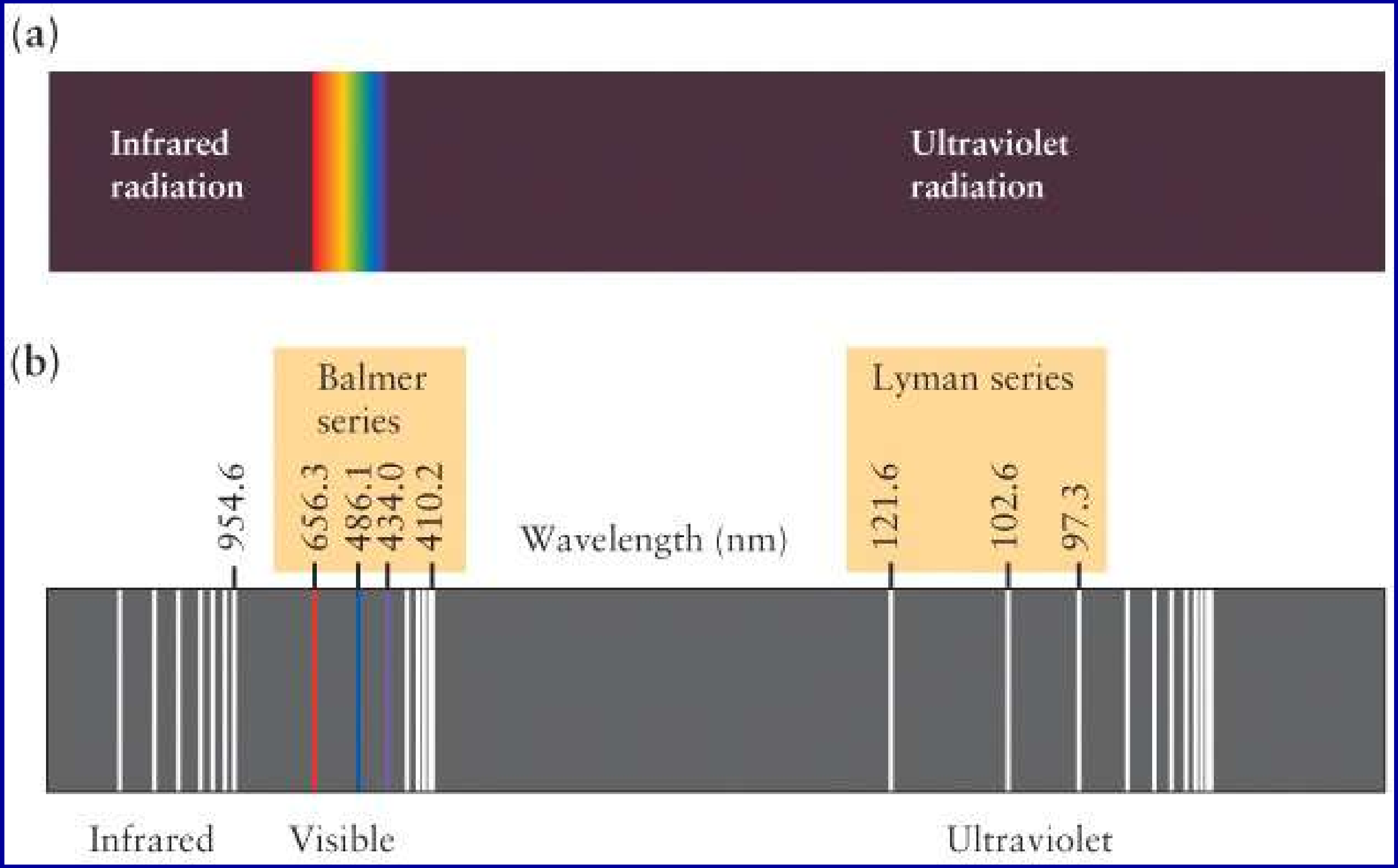
Calculate the energy of each photon of blue light of frequency 6.40 x 10^{14} Hz. What is the wavelength of this photon?

$E = h\,\nu = (6.626 \times 10^{-34}\ J\ s)\ (6.40 \times 10^{14}\ s^{-1}) = 4.20 \times 10^{-19}\ J$

$\lambda = c / \nu = 467\ nm$

Atomic Spectra and Energy Levels

Evidence for the validity of quantum mechanics came from its ability to explain atomic spectra



White light dispersed through a prism

Light emitted by H atoms - observe spectral lines.

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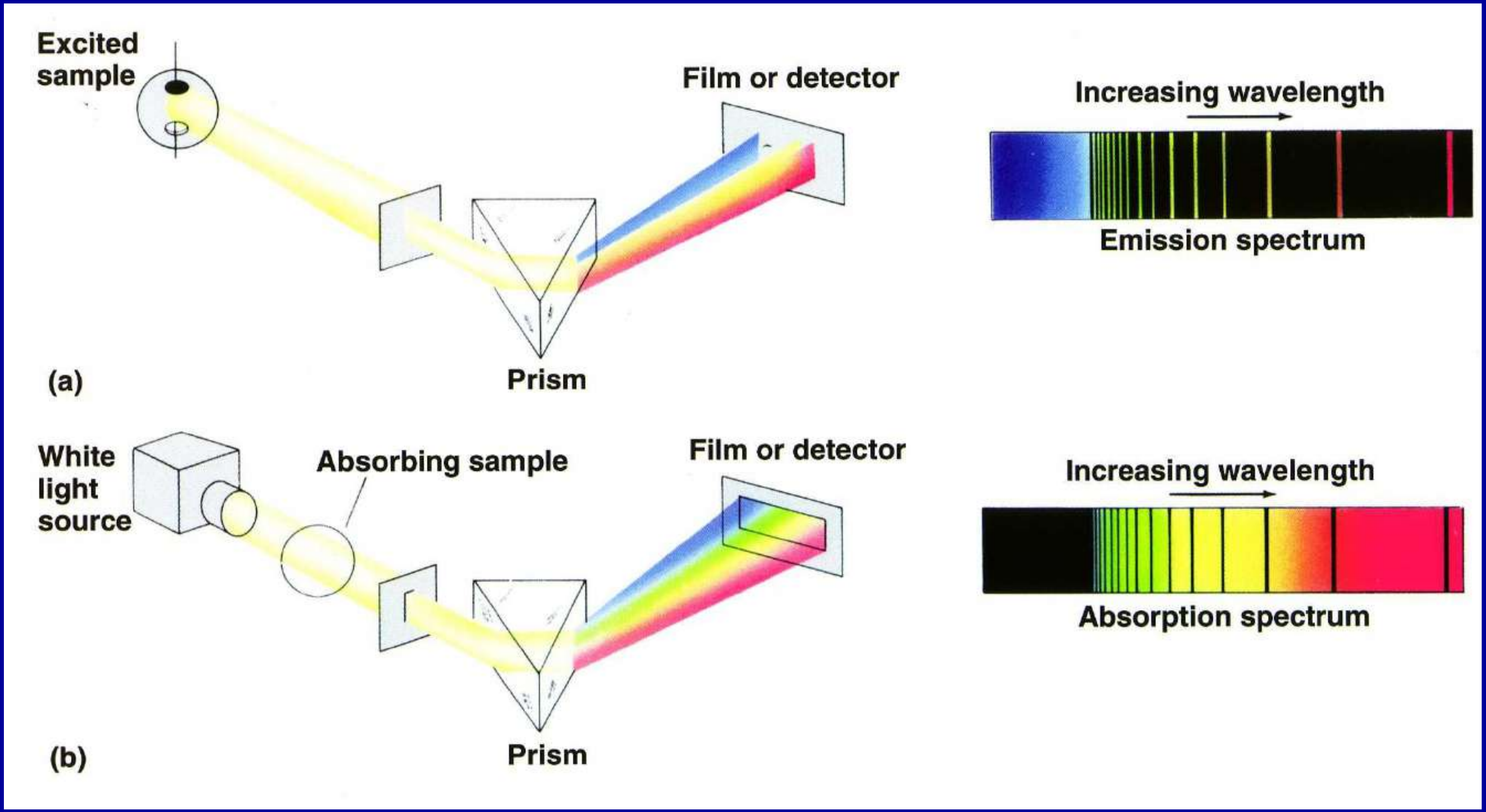
Excited sample
Film or detector
Increasing wavelength
Emission spectrum
(a)
Prism
White light source
Absorbing sample
Film or detector
Increasing wavelength
Absorption spectrum
(b)
Prism

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Spectra of the Hydrogen Atom

Experimental observations

J. Balmer: identified a pattern in the frequencies of the lines in the spectrum of the H atom

$$\nu = \left(\frac{1}{2^2} - \frac{1}{n^2}\right) 3.29 \times 10^{15}\ s^{-1} \qquad n = 3, 4, \ldots$$

A more complete description of the H atom spectrum is

$$\nu = \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) 3.29 \times 10^{15}\ s^{-1}$$

$n_1 = 3, 4, \ldots$

$n_2 = n_1 + 1, n_1 + 2, \ldots$

Lyman series: $n_1 = 1$ Balmer series: $n_1 = 2$

Paschen series: $n_1 = 3$ Brackett series: $n_1 = 4$

Pfund series: $n_1 = 5$