The Experimental Basis of Quantum Theory

Thornton and Rex, Ch. 3

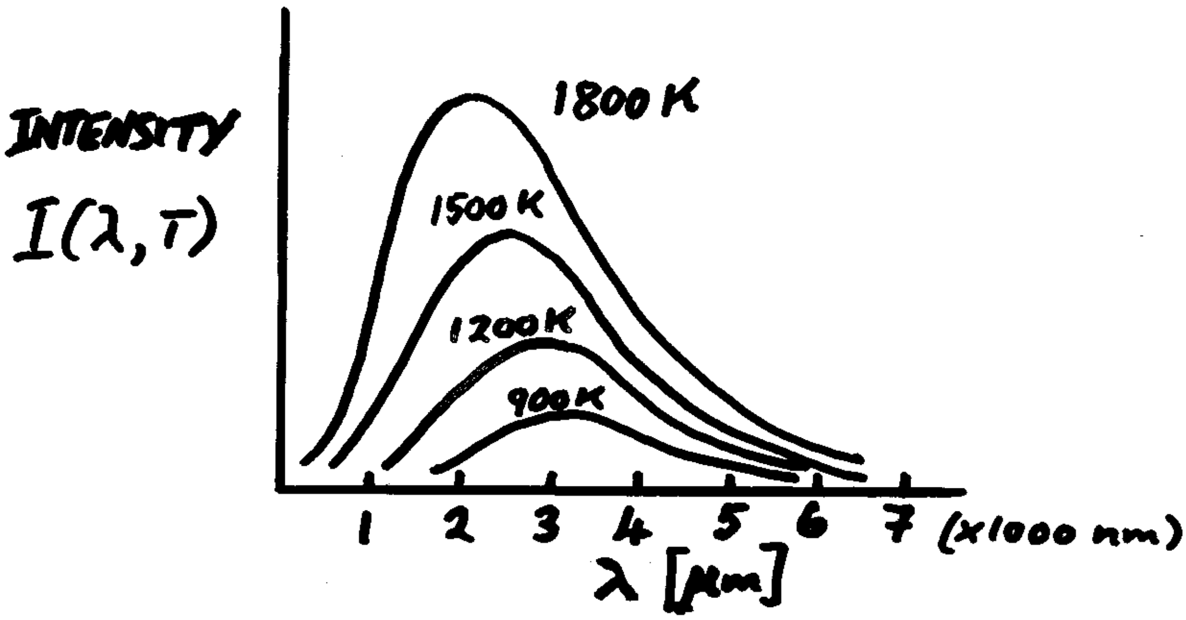
Blackbody Radiation

As an object gets hot, it radiates energy.

How does the radiation depend on temperature?

What is the distribution among frequencies (or wavelengths)?

BLACKBODY RADIATION



- MAXIMUM OF THE DISTRIBUTION SHIFTS TO SMALLER WAVELENGTHS AS THE TEMPERATURE INCREASES :-

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

WIEN'S DISPLACEMENT LAW

- TOTAL POWER $= R(T)$

$$= \int_0^\infty I(\lambda, T)\, d\lambda = \varepsilon \sigma T^4$$

STEFAN-BOLTZMANN LAW

WITH ε = EMISSIVITY AND σ = S-B CONSTANT

$$= 5.67 \times 10^{-8} \ \text{W}/\text{m}^2\text{K}^4$$

Max Planck, prof. at University of Berlin, attempted an explanation in 1900, adding one new and strange assumption:

Each oscillation mode can not absorb just any amount of energy. Each mode can only absorb energy in packets of fixed size.

It described the data perfectly!

The size of each energy packet (now termed a quantum) is proportional to the frequency of the mode:

$$E = h\nu$$

The proportionality factor (Planck's constant) is

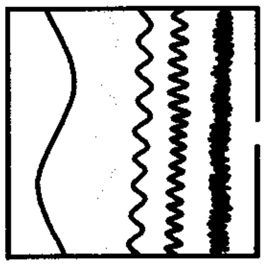
$$h = 6.63 \times 10^{-34} \text{ J s.}$$

The above formula was first presented at a meeting of the German Physical Society on Dec. 14, 1900.
The birthday of Quantum Physics!

Max Planck derived:

$$I(\lambda,T) = \frac{2\pi c^2 h}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

Planck's Radiation Law



Important new assumption:

The energy in each frequency mode ν can only come in integer multiples of some fundamental unit (quanta): $E = h\nu$

with

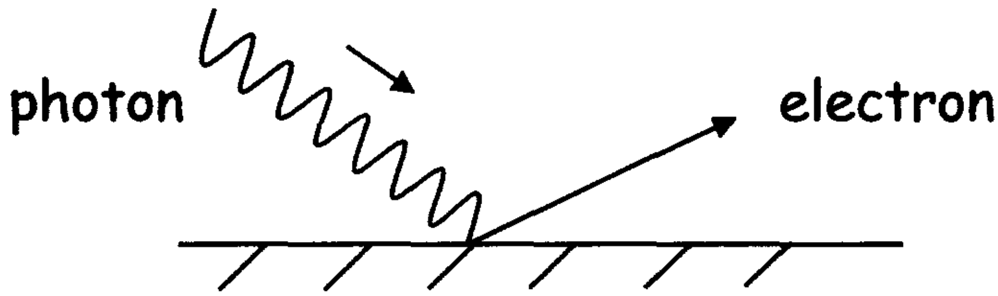
$$h = 6.6261 \times 10^{-34}\ \mathrm{J \cdot s}$$
$$= 4.1357 \times 10^{-15}\ \mathrm{eV \cdot s}$$

The S-B law and Wien's law both follow from Planck's formula.

The Photoelectric Effect

1887 - Hertz:

Visible or UV light on metal surface may release electrons



Classical theory says energy of electrons should increase with intensity of light.

However, this was not the case.

Experiments (Lenard) showed:

1) KE of photoelectrons depends only on ν (frequency) of light, <u>independent</u> of I (its intensity).

2) # of photoelectrons is proportional to I

3) For a given metal, there is a minimum ν, below which no photoelectrons are emitted.

4) The photoelectrons are emitted instantaneously, independent of I.

Classical theory could not explain these observations.

1905 - Einstein explained:

Electromagnetic radiation transferred in discrete bundles of energy ("photons"). The energy of each photon is

$$E = h\nu$$

The KE of an emitted photoelectron is

$$KE = h\nu - \phi$$

- $h\nu$ is Energy of the incident photon
- ϕ is the binding energy of electron to the metal surface (the work function).

The KE of the electrons can be measured by applying a positive voltage to the surface and noting when the photoelectric current stops. This voltage is called the stopping potential.

3.34 WHAT IS THE THRESHOLD FREQUENCY FOR PHOTOELECTRONS FROM LITHIUM ($\phi = 2.9\ eV$)?

$$E_{PHOTON} = KE_{ELECTRONS} + \phi$$

AT THRESHOLD $KE_{ELECTRONS} = 0$

$$\therefore \quad E_{PHOTON} = \phi = 2.9\ eV$$

$$\therefore \quad h\nu = 2.9\ eV$$

$$\therefore \quad \nu = \frac{2.9}{h} = \frac{2.9}{4.14 \times 10^{-15}}$$

$$\therefore \quad \nu = 7.00 \times 10^{14}\ Hz$$

$$(\lambda = c/\nu = 429\ nm)$$

WHAT IS THE STOPPING POTENTIAL IF $\lambda = 400\ nm$?

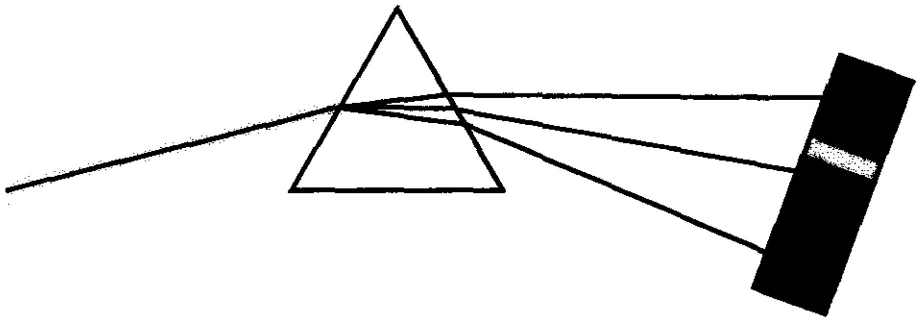
$$E_{PHOTON} = \frac{1243}{400} = 3.11\ eV$$

$$KE_{ELECTRONS} = E_{PHOTON} - \phi$$

$$= 3.11 - 2.9 = 0.21\ eV$$

SO ELECTRONS WILL BE STOPPED WITH A POTENTIAL OF 0.21 V.

Spectral Lines



• 1814-1824: Von Fraunhofer discovered absorption lines in sun.

• 1850's: Kirchhoff discovered characteristic emission lines of elements

• 1859: Kirchoff and Bunsen discovered new elements, Cesium and Rubidium, by first observing their spectral lines.

- 1885: Balmer found a formula for the wavelengths of the spectral lines in Hydrogen:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{4} - \frac{1}{n^2}\right)$$

where n=3,4,5,...

The constant R_H is Rydberg's constant:

$$R_H = 1.096776 \times 10^7 \, m^{-1}$$

- 1890: Rydberg found a more general formula for the spectral lines of Hydrogen:.

$$\frac{1}{\lambda} = R_H \left(\frac{1}{m^2} - \frac{1}{n^2} \right)$$

where both n and m are integers with n>m.

Visible light is in the approximate range

$400 \text{ nm} < \lambda < 700 \text{ nm}$

m=1: *Lyman series* => Ultraviolet (UV)

($\lambda < 122$ nm)

m=2: Balmer series

n=3: $\lambda = 657$ nm

n=4: $\lambda = 486$ nm

n=5: $\lambda = 434$ nm

n=6: $\lambda = 410$ nm

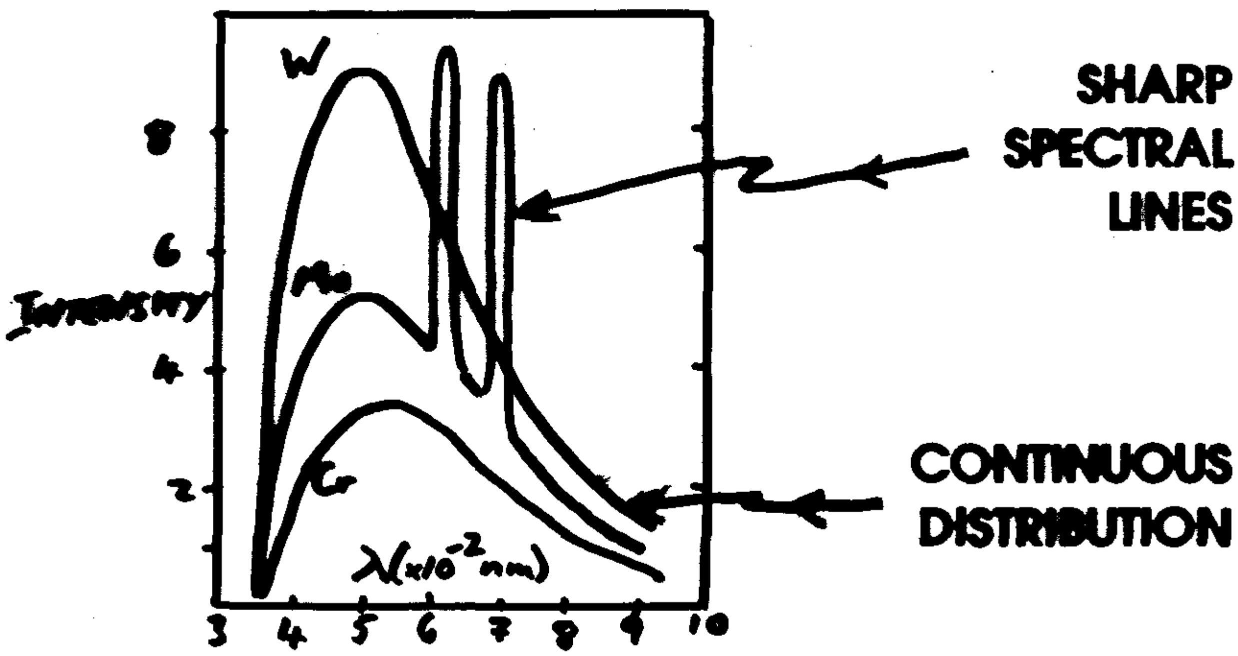
n>7: Ultraviolet ($\lambda < 397.1$ nm)

m=3: Paschen series => Infrared (IR)

($\lambda > 820$ nm)

X RAY SPECTRA

IF WE LOOK AT THE WAVELENGTH DISTRIBUTION OF X-RAYS PRODUCED BY BOMBARDING ELECTRONS ON A HIGH-Z TARGET. (FIG. 3.17)



IF THE VOLTAGE OF THE X-RAY TUBE IS ● VOLTS, THEN THE ENERGY OF THE ELECTRONS WHEN THEY HIT THE TARGET IS ● ELECTRON VOLTS. THIS ENERGY CAN BE USED TO KNOCK ATOMIC ELECTRONS OUT OF THE MATERIAL OF THE ANODE. THIS RESULTS IN THE SHARP SPECTRAL LINES (AS WE WILL SEE IN THE NEXT TOPIC).

OR IT MAY HAPPEN THAT THE ELECTRON BEAM IS SLOWED DOWN SUDDENLY IN THE HEAVY ANODE MATERIAL. THIS SUDDEN DECELERATION (WHERE THE ELECTRON GIVES UP ITS ENERGY SUDDENLY) GIVES RISE TO A <u>DISTRIBUTION</u> OF RADIATION CALLED BREMSSTRAHLUNG (GERMAN FOR BRAKING RADIATION). THE SMALLEST POSSIBLE WAVELENGTH OF THE BREMSSTRAHLUNG CORRESPONDS TO THE MAXIMUM LOSS OF ENERGY I.E. WHEN THE ELECTRON LOSES <u>ALL</u> OF ITS ENERGY, ●.

$$\lambda_{MIN} = \frac{hc}{●} = \frac{1243}{●}$$

$$E = h\nu = \frac{hc}{\lambda}$$

WITH λ IN nm AND ● IN VOLTS.

FOR EXAMPLE, A WAVELENGTH CUTOFF OF $\lambda_{MIN} \simeq 3.5 \times 10^{-2}$ nm CORRESPONDS TO A VOLTAGE OF

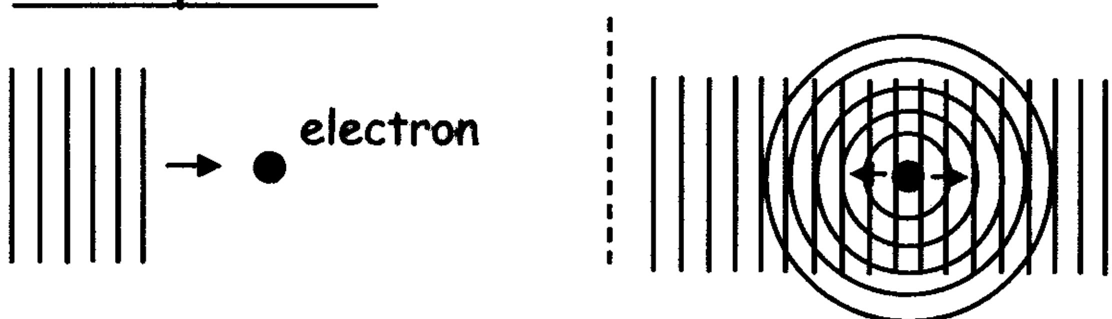
$$V = \frac{1243}{3.5\times10^{-2}} \simeq 35500 \text{ VOLTS}.$$

Compton Scattering

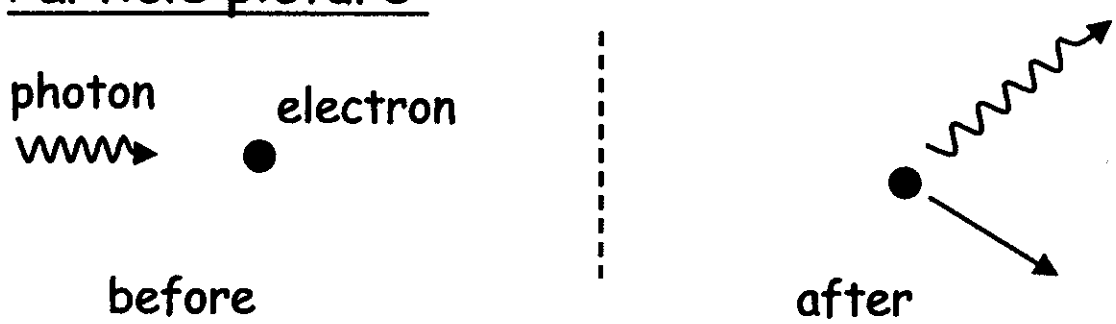
• Photoelectric effect, X-ray spectra suggest that photons, as well as being electromagnetic waves, also act like particles.

• This effect is even more pronounced in scattering of X-rays off electrons.

Wave picture:



Particle picture:



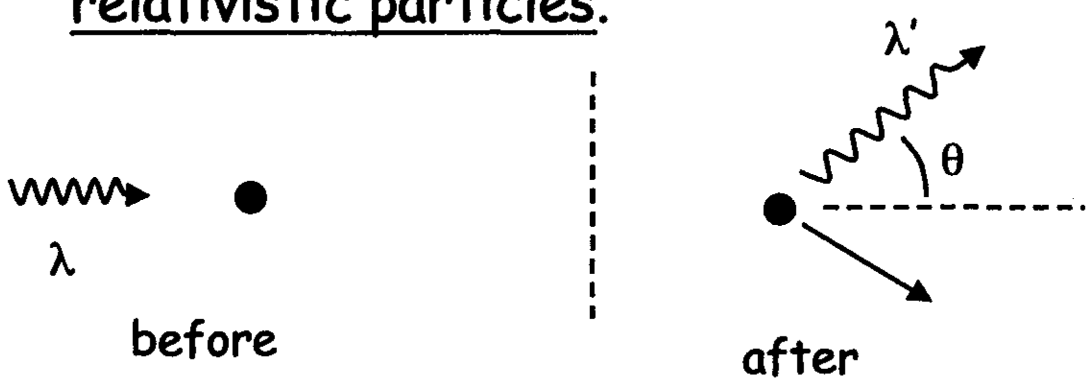
- 1923 -
  Experiments by Arthur Compton.
  He observed:

  Some component of the scattered wave (especially at backward-scattering angles) has a longer wavelength than the incoming wave.

$$\lambda' > \lambda$$

- This could not be understood purely in terms of light as a wave.

- Compton showed that it was understandable as a scattering of relativistic particles.



The formula for the shift in wavelength is

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta)$$

with

λ' the scattered wavelength

λ the incoming wavelength

θ the scattering angle

m the electron mass

The combination

$h/(mc) = 2.43 \times 10^{-12}$ m $= 2.43 \times 10^{-3}$ nm

is called the Compton wavelength of the electron.