

## PHY202 – Quantum Mechanics

### Summary of Topic 1: Early days of quantum physics

#### Historical background

Towards the end of the 19th century, classical physics provided an adequate explanation of all known phenomena. The only major exceptions were:

- propagation of light in vacuum versus ether. That led to the development of the theory of relativity.
- black body radiation, heat capacity of molecules, photoelectric effect. That led to the development of quantum mechanics.

#### Black body radiation

A black body is by definition a perfect absorber.

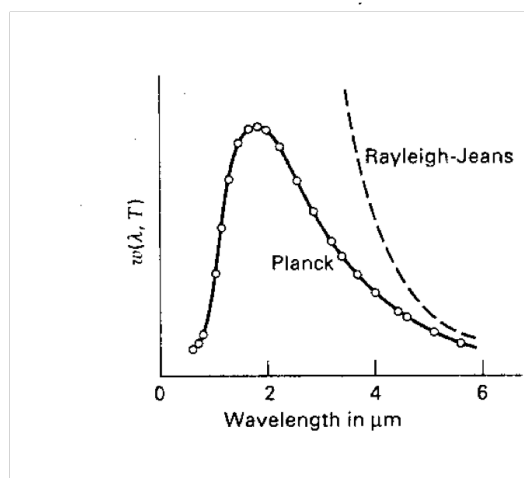
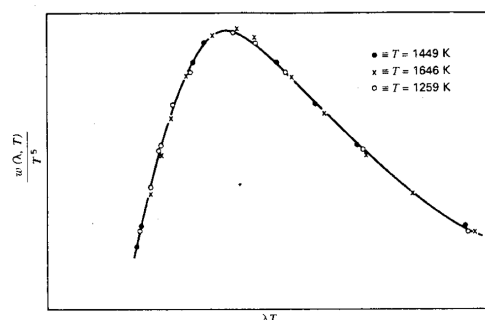
The energy density per unit wavelength,  $w(\lambda, T)$ , emitted by the surface of a black body is a universal function of wavelength and temperature.

The assumption from classical physics that the energy density satisfies *equipartition* implies that

$$w(\lambda, T) \rightarrow \infty \quad \text{as} \quad \lambda \rightarrow 0$$

This is known as the ultraviolet catastrophe.

Planck (1900) obtained the correct expression for  $w(\lambda, T)$  by assuming that the energy emitted and absorbed by the surface of a black body is *quantised* in units of  $h\nu$ , where  $h$  is Planck's constant ( $h = 6.63 \times 10^{-34} \text{ Js}$ ) and  $\nu$  is the frequency.



### The photoelectric effect

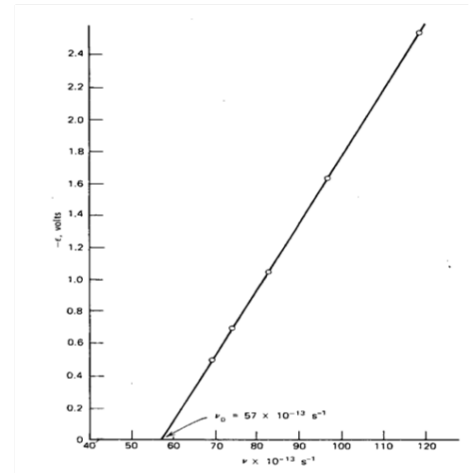
The kinetic energy of electrons emitted from the surface of a metal when light of frequency  $\nu$  is radiant upon it is

$$KE = \frac{1}{2}m_e v^2 = h\nu - W \quad W = \text{workfunction}$$

Properties: the KE is not proportional to the light intensity, although the number of electrons ejected is. There is a minimum frequency of light for the effect to take place. This could not be explained in terms of classical physics with light treated as waves.

Einstein (1905) used the idea of quantised energy to explain the photoelectric effect. The energy is quantised in units of  $h\nu$ .

$$E = h\nu$$



### Wave-Particle Duality

In 1916 Einstein suggested that light carries quanta of momentum as well as energy. Light particles are called photons.

In 1923 de Broglie suggested a particle with a momentum  $p$  has an associated wavelength  $\lambda$ ,

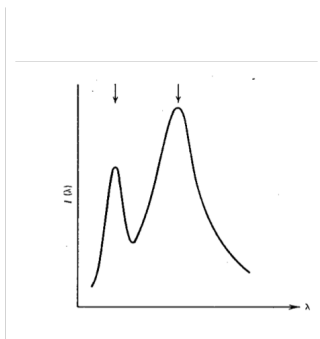
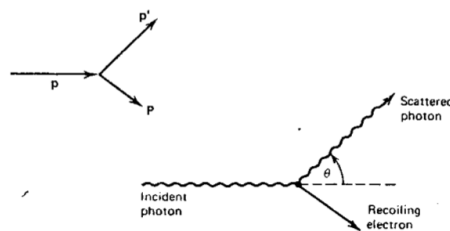
$$\lambda = \frac{h}{p}$$

### Waves as particles: Compton scattering

Compton (1923) found that the change of wavelength of X-rays scattered from electrons in aluminium foil satisfies

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

By treating light as particles and using  $E = h\nu = hc/\lambda = pc$  (as  $p = h/\lambda$ ), and conservation of energy and momentum this expression is easily derived.



### Particles as waves I: Double Slit Diffraction

Particles incident on a parallel pair of slits show on a screen behind a diffraction pattern characteristic of waves.

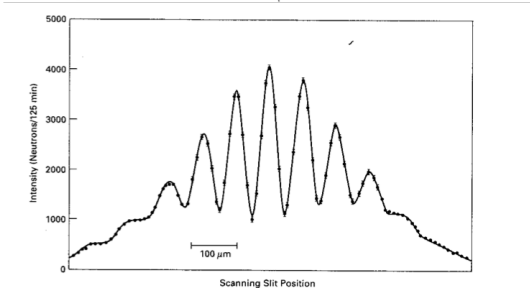
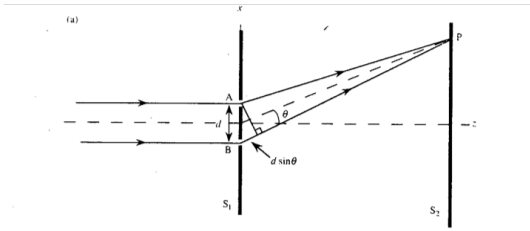
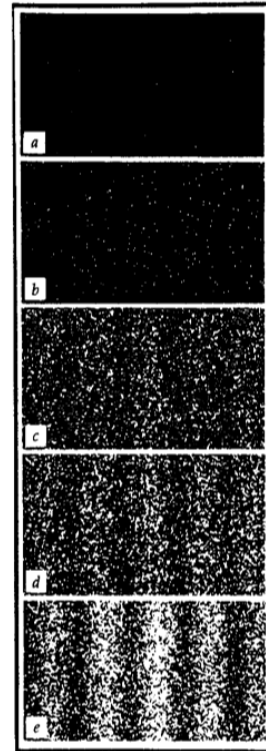


Figure 1-9 Double slit diffraction pattern for neutrons with wavelength  $\lambda = 18.5 \text{ \AA}$ . (From A. Zeilinger, R. Gähler, C. G. Shull, W. Treimer, and W. Mämppe, *Rev. Mod. Phys.* **60**:1067 (1988), by permission.)

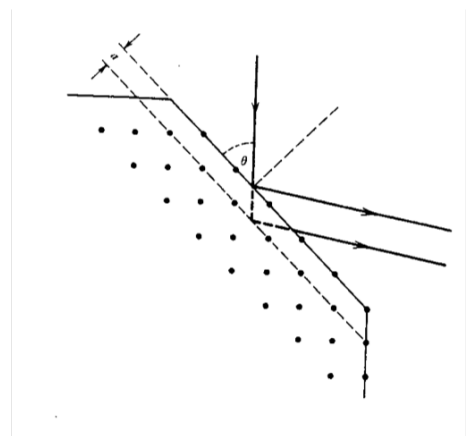


See video from <http://www.hqrd.hitachi.co.jp/em/index.cfm>

### Particles as waves II: Electron Diffraction in Solids

Davisson and Germer (1925) and Thompson (1927) diffracted electrons from crystalline structures according to Bragg's Law of diffraction

$$n\lambda = 2d \sin \theta$$



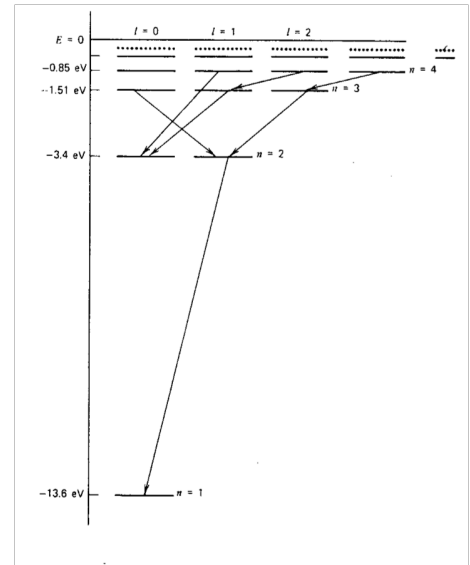
Interference patterns demonstrate the fundamental property of superposition, characteristic of waves.

## The Bohr Atom

According to classical physics, atoms should be unstable.

Quantum physics resolves this.

- Atomic system exists in a discrete set of stationary states.
- Radiation is absorbed or emitted in discrete quanta during a transition between states:  $E_f - E_i = h\nu$
- Angular momentum  $L$  is also quantised:  $n\hbar = L$ , where  $\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34} \text{Js}$  ( $\hbar$  is called h-bar)



## Heisenberg Uncertainty Principle

Measurement of physical variables is different in the quantum world from the classical world.

During the process the measured system becomes disturbed and is no longer the same.

In particular, for some pairs of variables it is impossible to know their exact values simultaneously.

For example, the minimum uncertainty in the particle's position  $x$  and momentum  $p_x$  is

$$\Delta x \Delta p_x \approx h$$

We will see later that the exact statement is that  $\Delta x \Delta p \geq \frac{\hbar}{2\pi}$ .

### Further reading:

See, e.g., Phillips, Ch. 1.