Physics II (PHY123)

Safwan Uddin Ahmed
Lecturer
Department of
Computer Science and Technology

Chapter 3

The Modern Physics

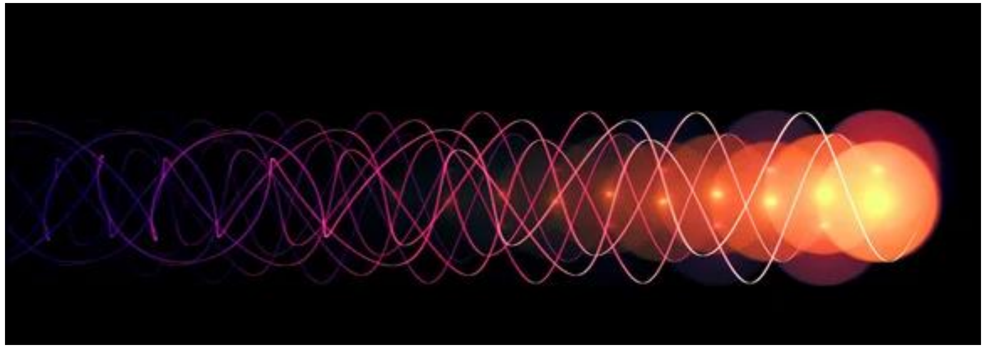
The Quantum Mechanics

Classical physics, also known as Newtonian Physics ➔ deals with the macroscopic world!!!

Quantum physics ➔ deals with the microscopic world!!!

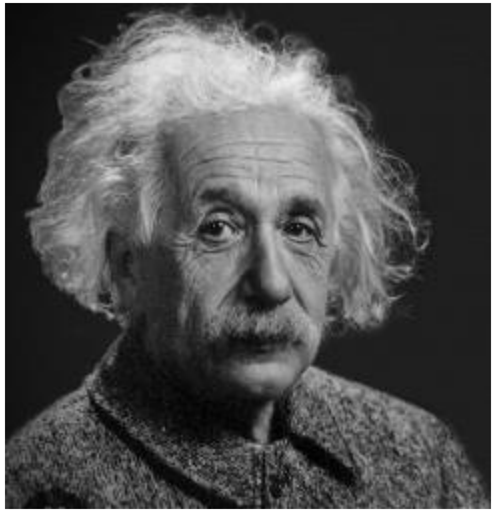
What is ***quantum***?

Quantities are found only in certain minimum (*elementary*) amounts or integer multiples of those elementary amounts; these quantities are then said to be *quantised*. The elementary amount that is associated with such a quantity is called the **quantum**.



The Quantum Mechanics

Classically, light is an electromagnetic wave with frequency $f = c/\lambda$

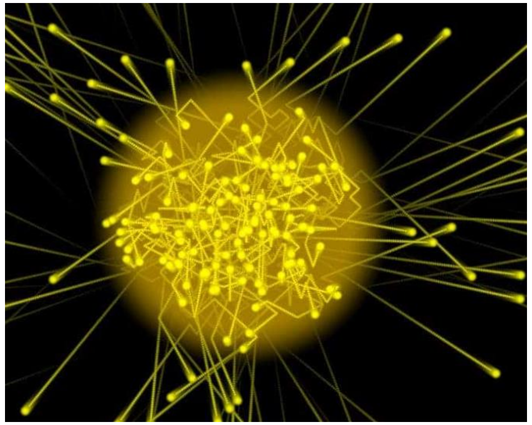


In 1905, Einstein proposed that ***em*** radiation is *quantised* and is made up of ***photons***.

The energy of a photon is given by:

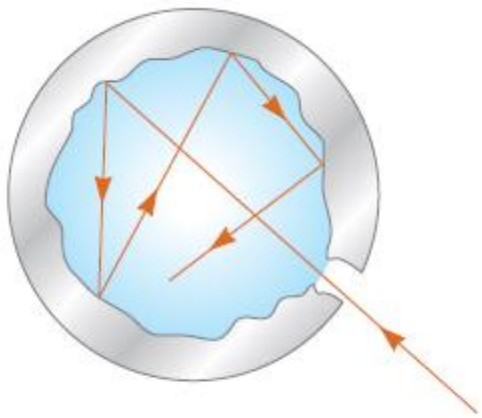
$$E = hf$$

h: Planck's constant and has a value of 6.634×10^{34} J.s



Thermal Radiation

An ideal black-body



Thermal radiation: radiation emitted by an object due to its temperature is thermal radiation.

Blackbody radiation: an ideal system that absorbs all the radiation incident upon it.

The intensity distribution is defined as the spectral radiance and is given by:

$$S(\lambda) = \frac{\text{intensity}}{\left(\begin{array}{c}\text{unit}\\ \text{wavelength}\end{array}\right)} = \frac{\text{power}}{\left(\begin{array}{c}\text{unit area}\\ \text{of emitter}\end{array}\right)\left(\begin{array}{c}\text{unit}\\ \text{wavelength}\end{array}\right)}.$$

Thermal Radiation

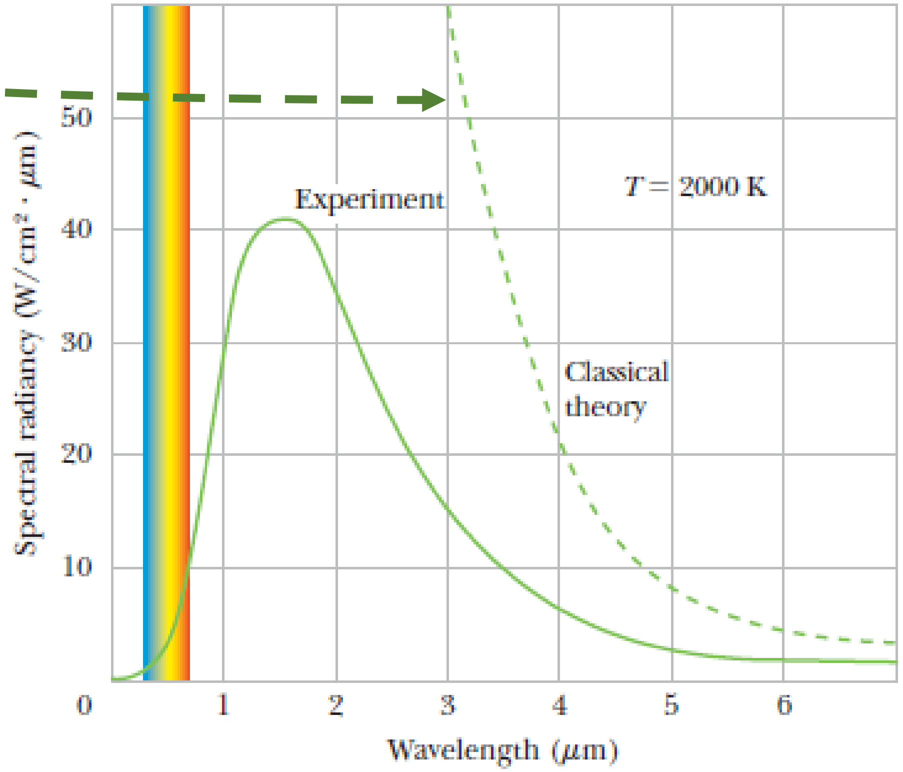
The Classical Theory:

- Thermal radiation originates from the accelerated charged particles
- Charged particles act like an antenna
- They absorb radiation and then emit
- Thermally agitated particles can have a distribution of energy which accounts for the continuous spectrum of radiation emitted by the object

Thermal Radiation

According to the classical theory:

$$S(\lambda) = \frac{kT}{\lambda^4}$$



- Experimental results match well with the theory at larger wavelength λ
- At shorter wavelengths, this theory is not a good approximation

Thermal Radiation

In 1900, Max Planck hypothesised:

$$S(\lambda) = \frac{k'}{\lambda^5}\frac{1}{(e^{b}-1)}$$

Where, $b = \frac{hc}{\lambda kt}$

$$\boxed{\text{Thus; } S(\lambda) = \frac{k'}{\lambda^5}\frac{1}{(e^{\frac{hc}{\lambda kt}}-1)}}$$

➔ The presence of hc/λ suggests that thermal radiation is quantized and is in the form of photon!!!

Thermal Radiation

<u>Einstein's Solution:</u>

- The energies that the cavity wall atoms are emitting are quantised
- The quantisation is in the form of photons, i.e. with energies: hf

Thermal Radiation

The Properties/Characteristics of Thermal Radiation:

- The higher the temperature, the shorter the wavelength of the most intense part of the radiant spectrum.

If λ_{max} is the wavelength at which the radiation emitted by a cavity at temperature T has its maximum intensity, the above qualitative statement can be expressed as:

$$\lambda_{max} T = constant$$

The constant has the value $2898\ \mu m - k$ and the equation is known as the Wien's displacement law.

Thermal Radiation

The Properties/Characteristics of Thermal Radiation:

- As the temperature of the black-body increases, the intensity of the emitted thermal radiation also increases rapidly. If the radiant intensity is *I*, and the temperature of the object is T (in kelvin), the mentioned statement can be expressed as:

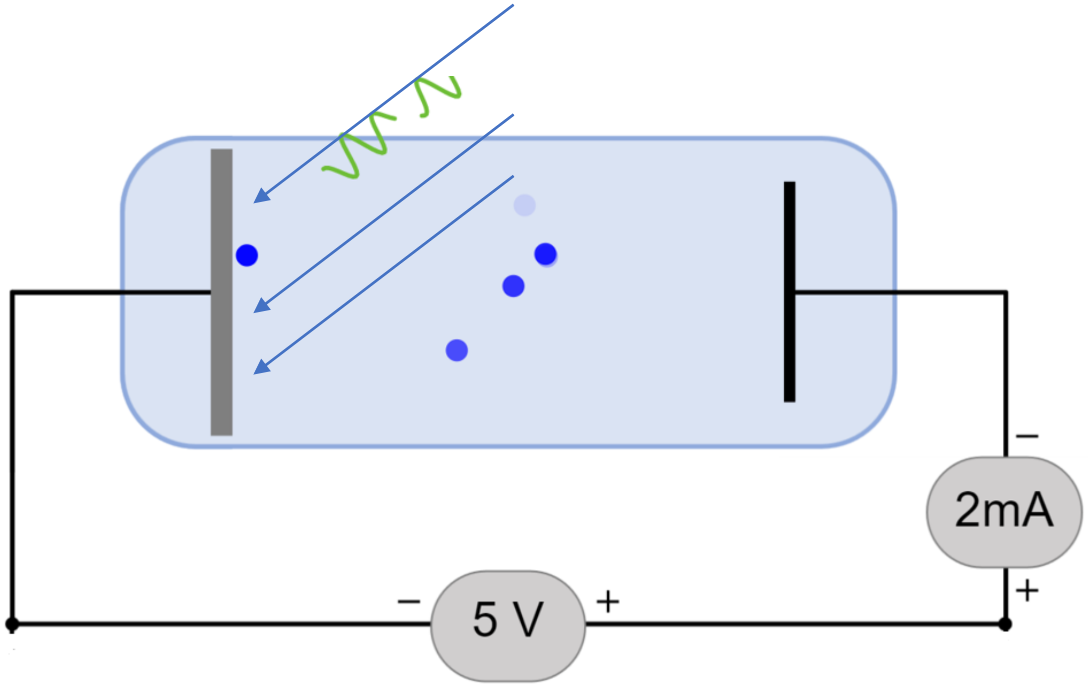
$$I = \sigma T^4$$

σ is a universal constant called the Stefan-Boltzmann constant. It's presently accepted value is $\sigma = 5.67 \times 10^{-8}$ W/m^2 – k^4. The above equation is known as the Stefan-Boltzmann law.

The Photoelectric Effect

- Light of wavelength λ incident on C
- Energy of the photons hitting C, E = hf
- A voltage is applied between A and C
- A current is detected through the ammeter **A**
- This current is *photocurrent,* and the electrons are *photoelectrons*
- In the reverse situation, the voltage that stops the electron with the maximum KE is called the *stopping potential* and is given by:

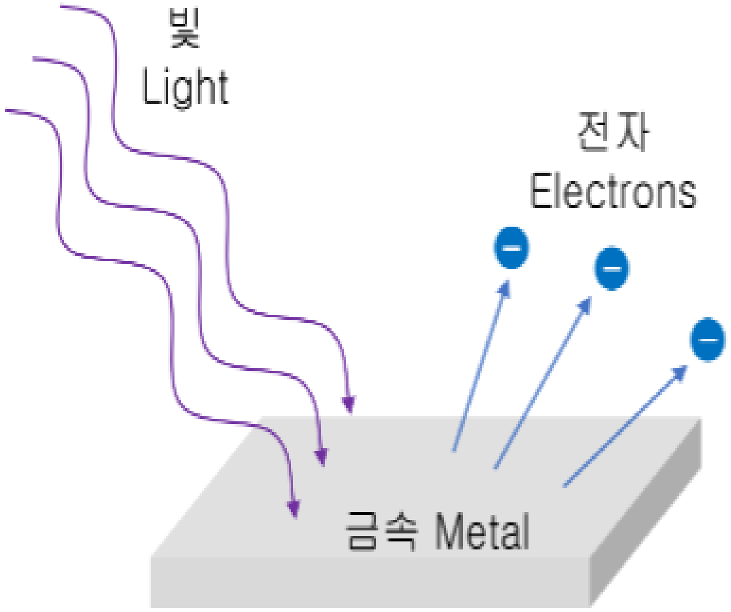
$$K_{max} = eV_{stop}$$



The Photoelectric Effect

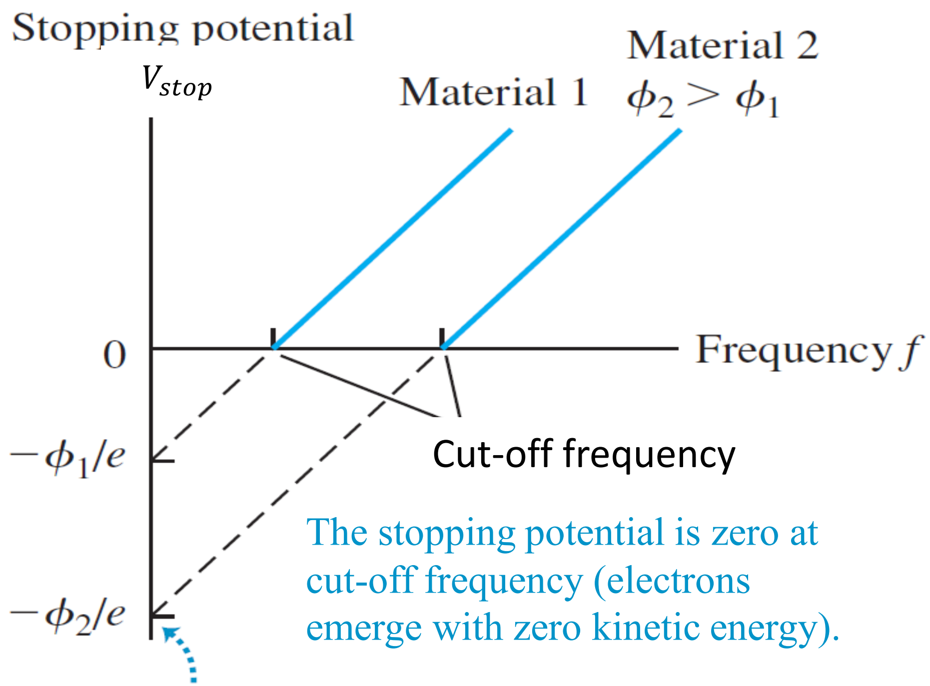
- The minimum frequency required to trigger the photoelectric effect is the *cut-off frequency.*
- The electrons must overcome the *work function* ϕ of the metal to participate in the photoelectric effect.
- Work function is a material property
- The requirement for the photoelectric effect is:

$$hf_{cut-off} \geq \phi$$



The photoelectric equation: $hf = k_{\max} + \phi = eV_{stop} + \phi$

The Photoelectric Effect



For each material,

$$eV_{stop} = hf - \phi$$

$$\Rightarrow V_{stop} = \frac{h}{e} f - \phi$$

The Photoelectric Effect

The effect of the intensity of light on the KE of the electron:

Classical prediction:

The amplitude of the electric field is greater ➔ electrons get more energetic kick ➔ higher KE of electron

Observation:

No matter what is the intensity of the light is, the energy of the electrons are the same for all.

Quantum Interpretation:

The increase in the intensity increases the number of photon but not the photon energy. So it does not affect the energy of the photoelectrons!!!

Photon and Momentum

When a photon interacts with matter ➔ energy and momentum are transferred

$$E = mc^2$$

$$\Rightarrow E = (mc)c$$

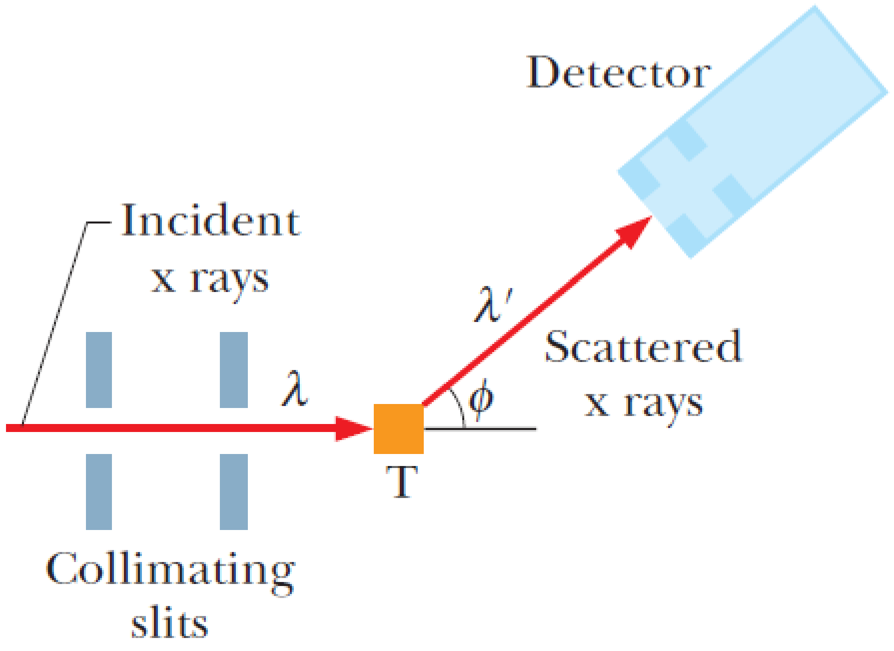
$$\Rightarrow hf = (mc)c$$

$$\Rightarrow \frac{hc}{\lambda} = pc$$

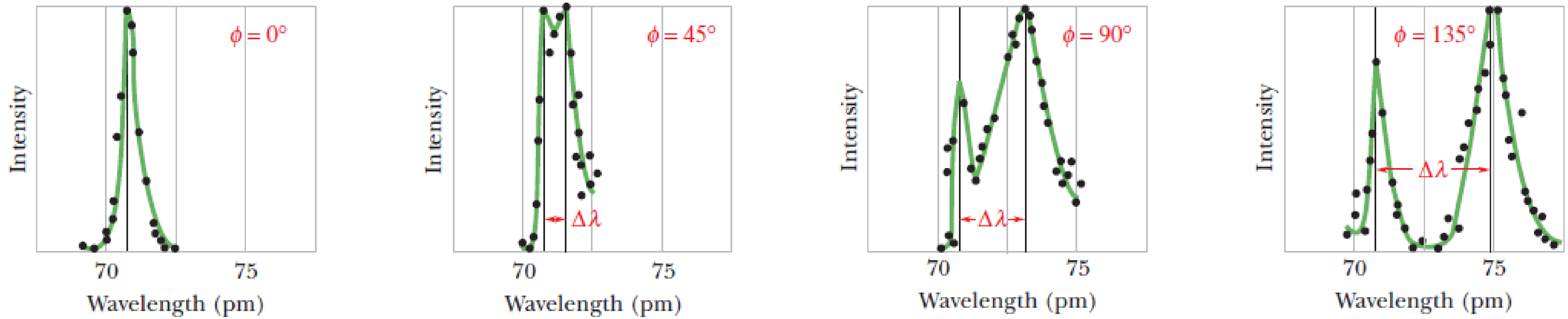
$$\Rightarrow h/\lambda = p$$

The Compton Effect

- Beam of x-ray (of wavelength λ) incident upon a graphite target
- X-ray scattered in different directions
- Observation: two prominent intensity peaks
  - One centered at the incident wavelength λ
  - The other one at a larger wavelength λ'



The Compton Effect



মেট্রোপলিটন ইউনিভার্সিটি
Metropolitan University

The Compton Effect

Classical Theory (The Wave-Model Prediction):

- e’s oscillates in response to the oscillating electric field of x-ray
- e’s act as miniature antennas
- They absorb and re-radiate the x-ray
- Re-radiation is the acquired energy as scattered waves in different directions
- e’s oscillates in the same frequency as the incident x-ray
- Re-radiation is also in the same frequency!

Fails to explain the wavelength shift!!!

মেট্রোপলিটন ইউনিভার্সিটি
Metropolitan University

The Compton Effect

<u>Quantum Theory (The Particle-Model Prediction):</u>

- Consider x-ray (em radiation) as a photon
- Collision between two particles (photon-electron)
- e is at rest
- Incident photon transfer portion of its energy and momentum to the resting electron
- Electron recoils ➔ gains KE
- Scattered photon fly-off with an angle ϕ and has wavelength λ' (lesser energy)

The Compton Effect

According to the law of conservation of energy:
Energy of incident photon = Energy of scattered photon + KE of electron

$$hf = hf' + k$$

After the collision, the x-ray is scattered with an angle ϕ and with wavelength λ'.

We have to take into account the relativistic expression for the KE of the electron:

$$k = mc^2(\gamma - 1)$$

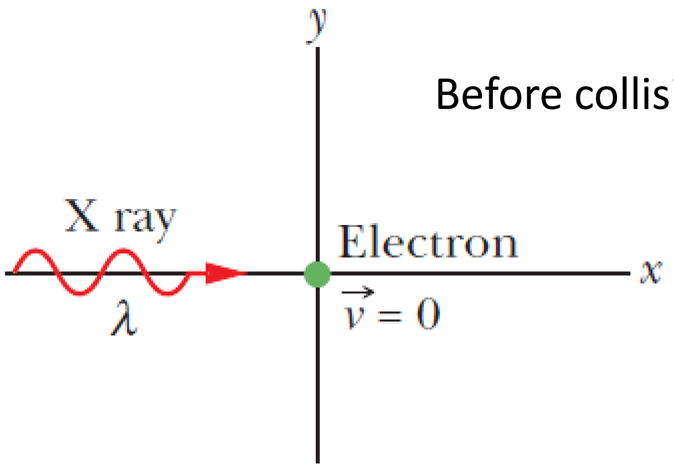
Finally, we have:

$$hf = hf' + mc^2(\gamma - 1)$$

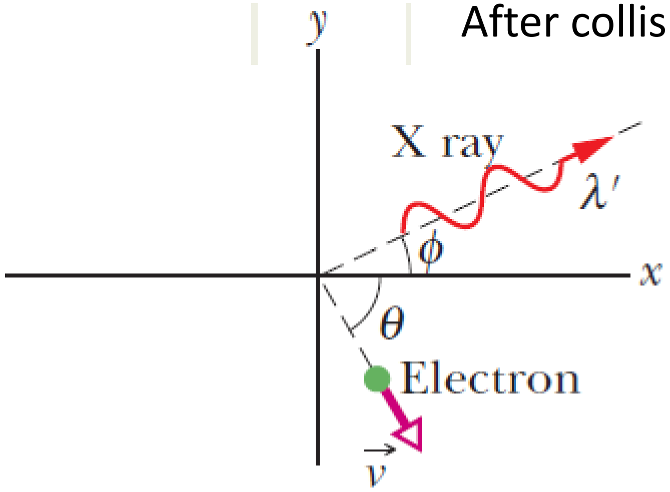
$$\Rightarrow \frac{hc}{\lambda} = \frac{hc}{\lambda'} + mc^2(\gamma - 1)$$

$$\Rightarrow \lambda' - \lambda = \frac{h}{mc}(1 - cos\phi)$$

$$\Rightarrow \Delta\lambda = \frac{h}{mc}(1 - cos\phi)$$



Before collision



After collision

Matter Wave

So far, we have discussed the particle nature of the light i.e. em radiation ➔ photon

Symmetry of nature leads to the idea that elementary particles such as electrons proton must also have wave nature!!!

Proposed by Louis de Broglie

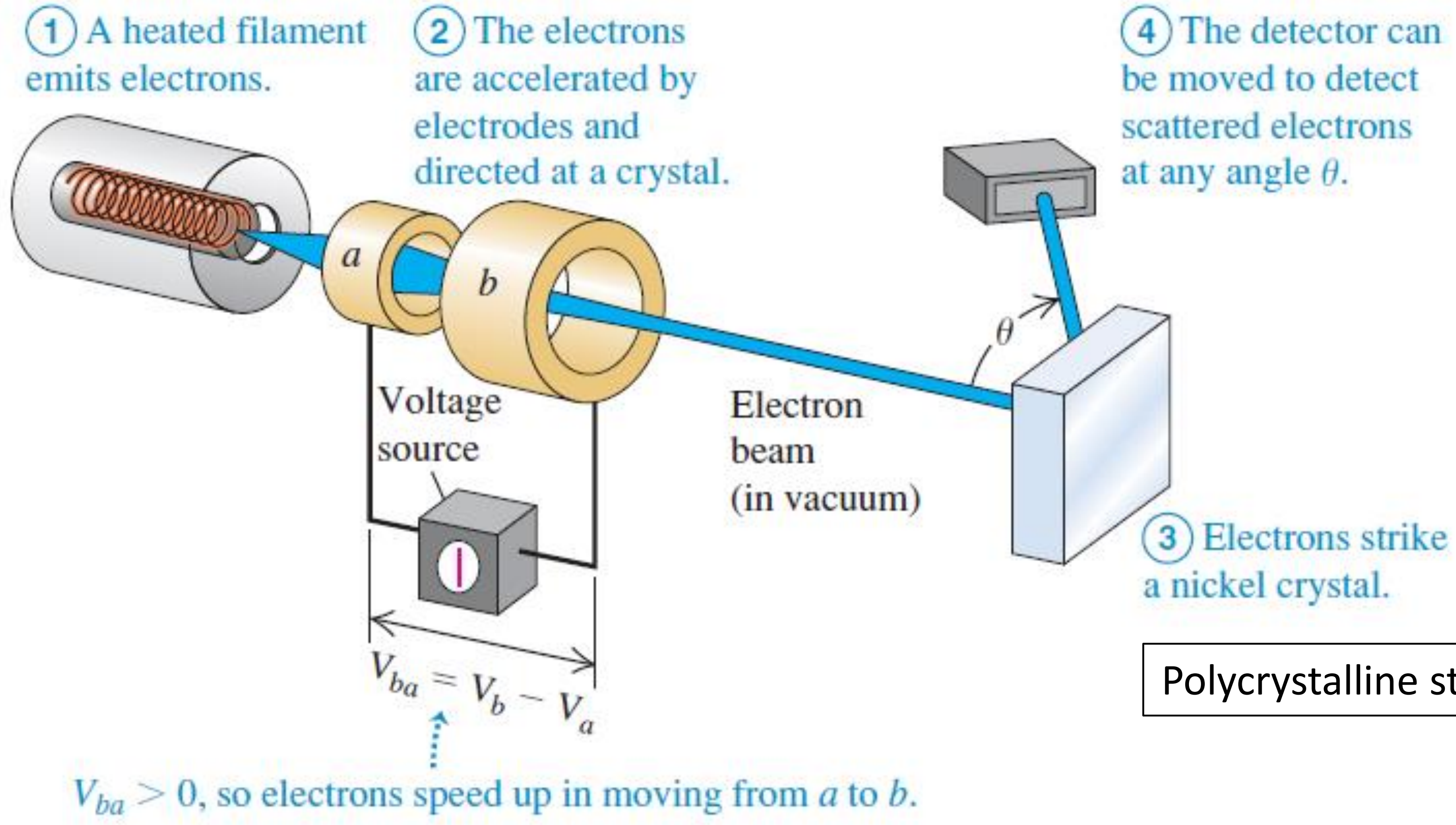
The concept that every particle and quantum quantity can be described both as a particle and a wave is called the ***wave-particle duality***!

Matter-wave, also known as the de Broglie wave and is given by

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

মেট্রোপলিটন ইউনিভার্সিটি
Metropolitan University

Matter Wave



Polycrystalline structure

The Davisson-Germer Experiment

Matter Wave

Vacuum broke → air went in → formed an oxide layer on the nickel target → Heated the sample to remove the oxide layer

↓

Different result than before

↓

Observed intensity maxima and minima

↓

Hypothesis: the post-heated nickel is acting like one large crystal that has evenly spaced planes that act like diffraction grating for electrons

↓

Repeated the experiment with this sample and the same result was observed

↓

Conclusion: electrons behave like waves and have de Broglie wave, $\lambda = \frac{h}{P}$

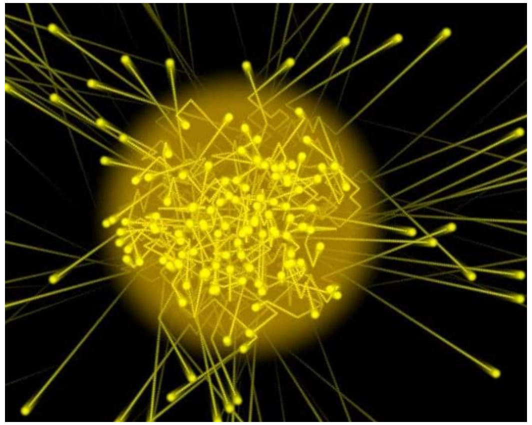
মেট্রোপলিটন ইউনিভার্সিটি
Metropolitan University

Heisenberg’s Uncertainty Principle

Newtonian/Classical Mechanics: location and motion can be determined precisely

Quantum Physics: cannot determine the location and motion simultaneously

Because the detection itself alters the motion/position of the particle



মেট্রোপলিটন ইউনিভার্সিটি
Metropolitan University

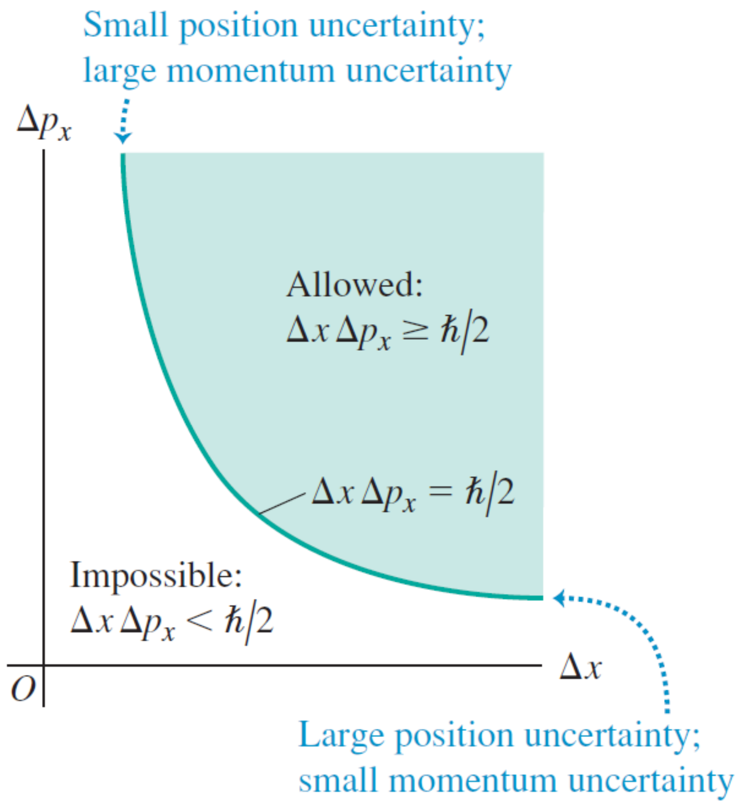
Heisenberg’s Uncertainty Principle

<u>Heisenberg’s uncertainty principle:</u>
It is not possible to measure the position and momentum of a particle with unlimited precision

If the uncertainty in position of an atomic particle along the x-direction is Δx and the uncertainty in momentum is ΔP_x the we have:

$$\Delta x \Delta P_x \geq \frac{h}{2\pi}$$

The more precise the location the greater the uncertainty in momentum and vice-versa.



Wave Function

In quantum mechanics, to describe the displacement associated with matter wave, Austrian physicist Erwin Schrödinger introduced a quantity $\psi(x,t)$ and named it wave function. It is a function of space and time. $\psi(x,t)$ has the following form:

$$\psi(x,t) = A + iB$$

where A and B are real number and i is a complex number where $i^2 = -1$.

The probability of finding a particle at a time interval and between position x and $x + dx$ is given by

$$P(x)dx = |\psi|^2 dx$$

The wave-function for a free particle moving along x-direction is given by

$$\psi(x,t) = \psi_o e^{i(kx-\omega t)}$$

where ψ_o is the amplitude of the wave.

Wave Function

Properties of wave function:

1. Wave function $\psi(x,t)$ is a complex quantity as it contains the imaginary number $i^2 = -1$

2. If we multiply $\psi(x,t)$ with it's complex conjugate $\psi^*(x,t)$, the product $\psi\psi^* dx$ is a real quantity and it gives the probability that the particle will be found between position x and $x + dx$.

Schrödinger Equation

The one-dimensional Scroedinger equation is given by:

$$-\frac{h^2}{8\pi^2 m}\frac{d^2\psi(x,t)}{dx^2}+U(x)\psi(x)=E\psi(x)$$