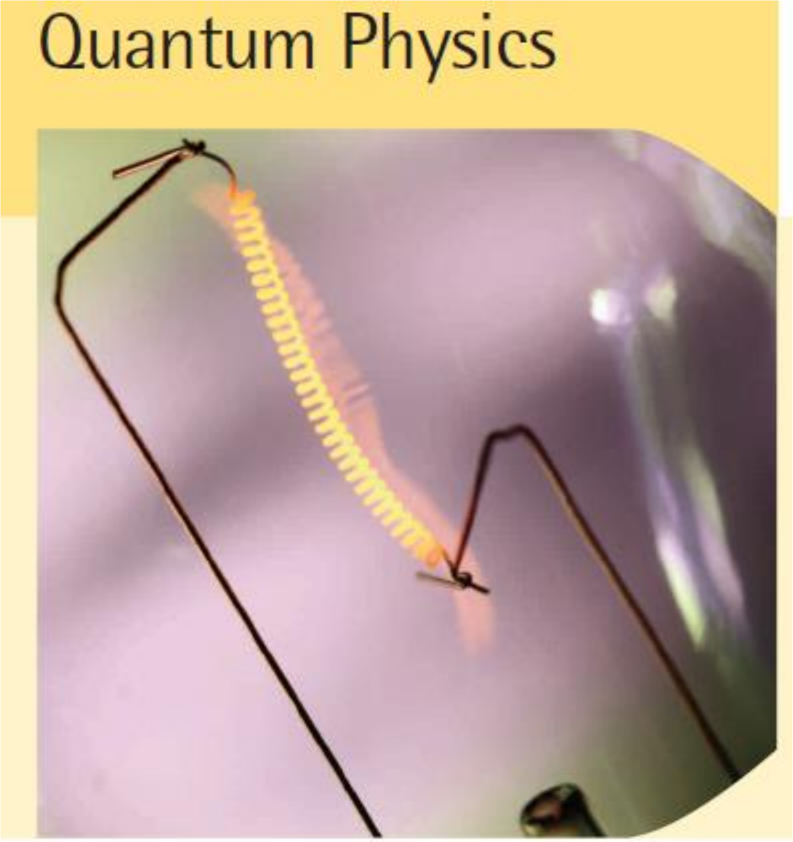
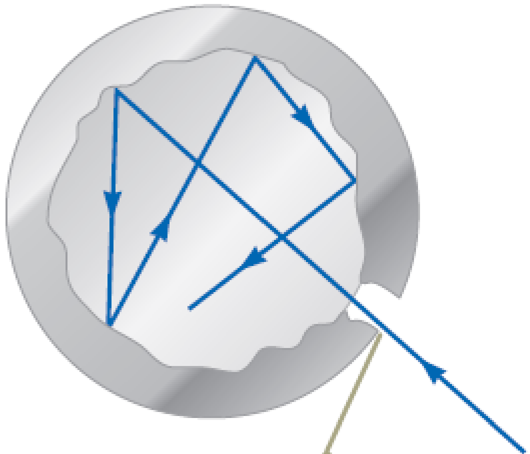
Chapter 3

QUANTUM PHYSICS

OBJECTIVES:

- To learn certain experimental results that can be understood only by particle theory of electromagnetic waves.
- To learn the particle properties of waves and the wave properties of the particles.
- To understand the uncertainty principle.





The opening to a cavity inside a hollow object is a good approximation of a black body: the hole acts as a perfect absorber.

Figure 40.1 A physical model of a black body.

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Figure 40.2 The glow emanating from the spaces between these hot charcoal briquettes is, to a close approximation, blackbody radiation. The color of the light depends only on the temperature of the briquettes.

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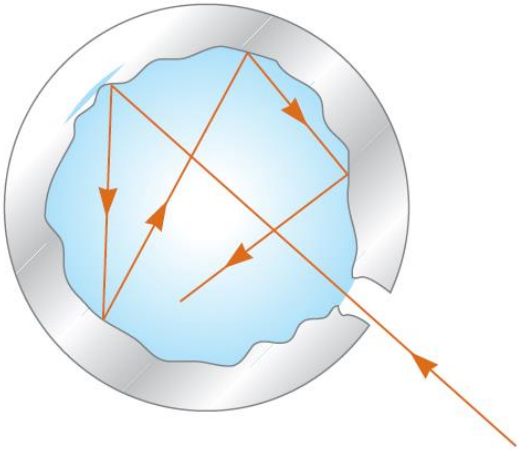
Figure 40.8 An ear thermometer measures a patient's temperature by detecting the intensity of infrared radiation leaving the eardrum.

A **black body** is an ideal system that absorbs all radiation incident on it

Blackbody Radiation and Planck's Hypothesis

- The electromagnetic radiation emitted by the black body is called **black-body radiation.**



Basic laws of radiation

(1) All objects emit radiant energy.

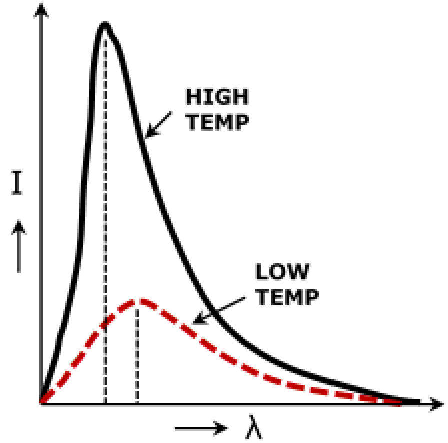
*(2) Hotter objects emit more energy (per unit area) than colder objects. (**Stefan's Law**)*

$$P = \sigma A\, e\, T^4$$

The ratio between the re-emitted energy of a usual object and the re-emitted energy of a blackbody at the same temperature of the object is called emissivity.

*(3) The peak of the wavelength distribution shifts to shorter wavelengths as the black body temperature increases. (**Wien's Displacement Law**)*

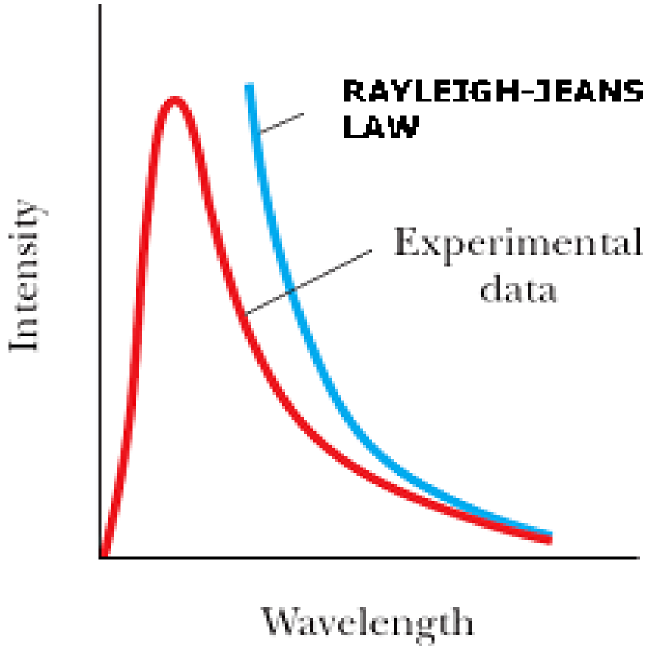
$$\lambda_m T = constant$$



(4) **Rayleigh-Jeans Law**: **The intensity or power per unit area $I\ (\lambda,T)d\lambda$**, emitted in the wavelength interval λ to $\lambda+d\lambda$ from a blackbody is given by

$$\mathrm{I}(\lambda,T)=\frac{2\pi c k_B T}{\lambda^4}$$

- It agrees with experimental measurements **only for long wavelengths**.
- *It predicts an energy output that diverges towards infinity as wavelengths become smaller and is known as the* ***ultraviolet catastrophe***.



The radius of our Sun is 6.96 x 10^8 m, and its total power output is 3.77 x 10^{26} W. (a) Assuming that the Sun's surface emits as a black body, calculate its surface temperature. (b) Using the result, find λ_{max} for the Sun.

$\sigma = 5.670 \times 10^{-8}\ W/m^2K^4$

Ans: 5750 K, 504 nm

Planck's Law

23 April 1858 – 4 October 1947 ‘

A German theoretical physicist whose discovery of energy quanta won him the Nobel Prize in Physics in 1918

(5) Planck's Law: The intensity or power per unit area $I(\lambda,T)d\lambda$, emitted in the wavelength interval λ to $\lambda+d\lambda$ from a blackbody is given by

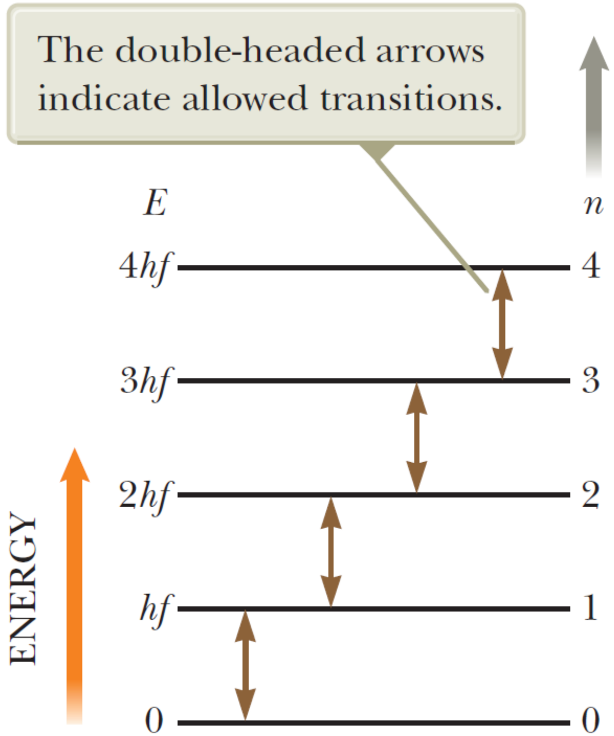
$$I(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$

Assumptions of this law are:

- **Energy of an oscillator in cavity walls:**

  $$E_n = n\,h\,f$$

- **Amount of emission / absorption of energy will be integral multiples of hf.**



The results of Planck's law:

- The denominator [$exp(hc/\lambda kT)$] tends to infinity faster than the numerator (λ^{-5}), thus resolving the ultraviolet catastrophe and hence arriving at experimental observation:

$$I(\lambda, T) \rightarrow 0 \text{ as } \lambda \rightarrow 0.$$

- For very large λ, $I(\lambda, T) \rightarrow 0$ as $\lambda \rightarrow \infty$.

$$exp\left(\frac{hc}{\lambda kT}\right) - 1 \cong \frac{hc}{\lambda kT} \Rightarrow \mathrm{I}(\lambda, T) \rightarrow 2\pi c \lambda^{-4} kT$$

- From a fit between Planck's law and experimental data, Planck’s constant was derived to be $\boldsymbol{h} = \mathbf{6.626 \times 10^{-34}}$ **J-s.**

A blackbody at 7500 K consists of an opening of diameter 0.050 mm, looking into an oven. Find the number of **photons** per second escaping the hole and having wavelengths between 500 nm and 501 nm.

Ans: 1.30×10^{15}/s

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

$$I(\lambda,T)=\frac{2x3.14x6.63x10^{-34}x(3x10^8)^2}{(500x10^{-9})^5}\frac{1}{e^{\frac{6.63x10^{-34}x3x10^8}{500x10^{-9}x1.38x10^{-23}x7500}}-1}$$

$=2.63x10^{14}$ **W/m³**

I.dλ is the intensity emitted in the wavelength interval dλ

$$I\,d\lambda=\frac{Power}{Area}=\frac{P}{A}=\frac{n}{A}\left(\frac{hc}{\lambda}\right)\ where\ A\ is\ the\ area$$

$$n=\frac{I(d\lambda)\,(\lambda)(A)}{hc}=1.3x10^{15}\ /sec$$

dλ = 1nm

λ = 500 nm

A = 1.96x10^{-9} m^2

Photoelectric Effect

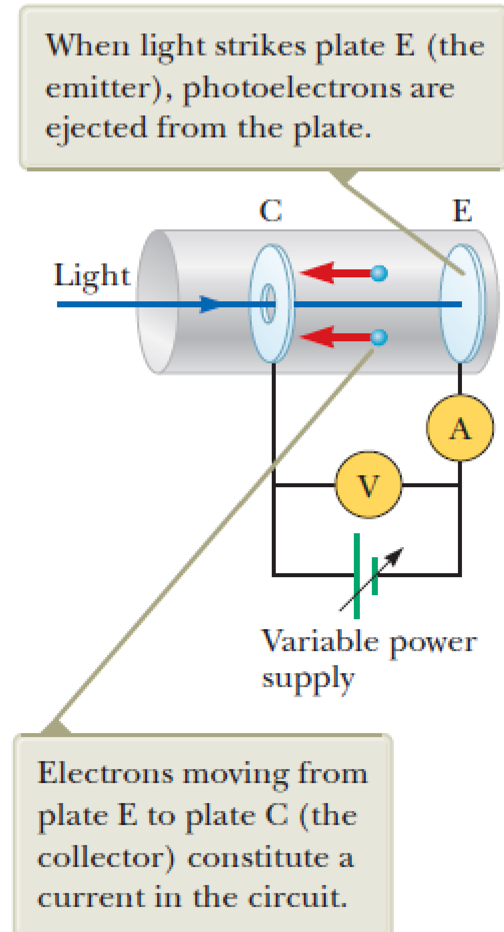
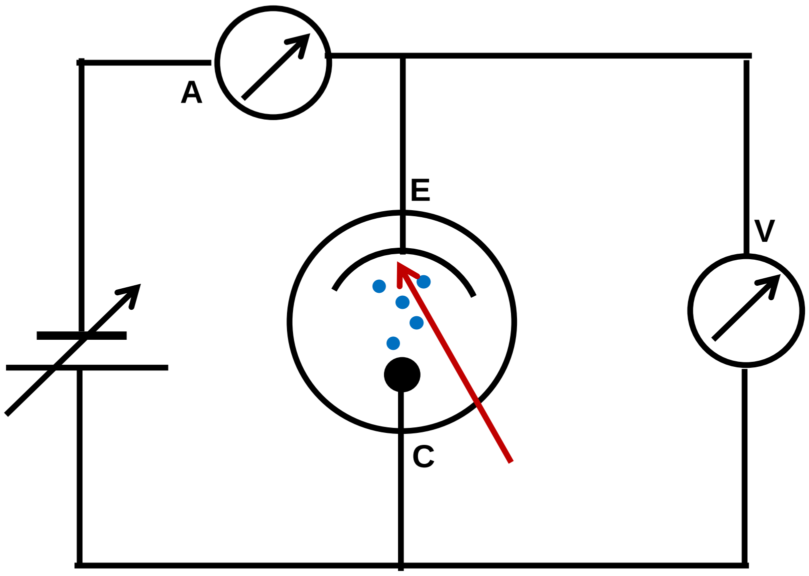


Figure 40.9 A circuit diagram for studying the photoelectric effect.

Photoelectric Effect

Ejection of electrons from the surface of certain metals when it is irradiated by an electromagnetic radiation of suitable frequency is known as **photoelectric effect**.



Photoelectric Effect (T – Evacuated glass/ quartz tube, E – Emitter Plate / Photosensitive material / Cathode, C – Collector Plate / Anode, V – Voltmeter, A - Ammeter)

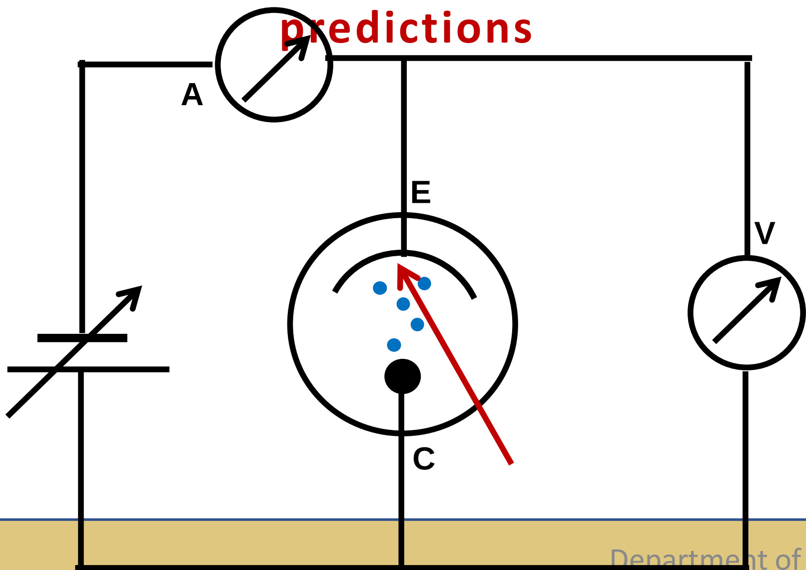
Classical Predictions

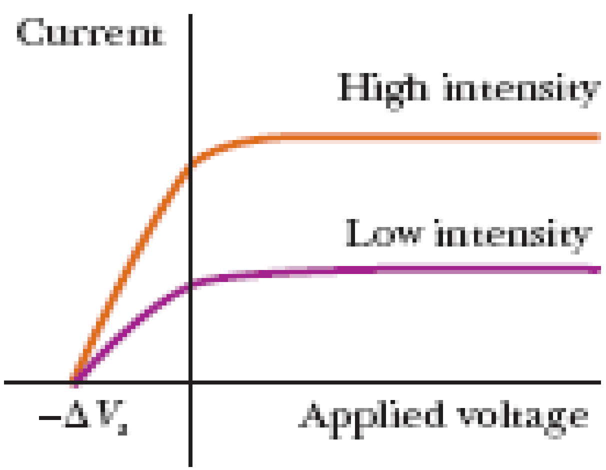
1. Electrons ejection should be frequency independent.
2. KE of the electrons should increase with intensity of light.
3. Measurable/ larger time interval between incidence of light and ejection of photoelectrons.
4. K_{MAX} should not depend upon the frequency of the incident light.

Experimental Observations

1. No photoemission for frequency below threshold frequency
2. K_{MAX} is independent of light intensity.
3. Instantaneous effect
4. KE of the most energetic photoelectrons is, $K_{MAX} = e\,\Delta V_s$ & it increases with increasing f.

Experimental results contradict classical predictions





Einstein’s Interpretation of electromagnetic radiation:

Einstein's Interpretation of electromagnetic radiation:

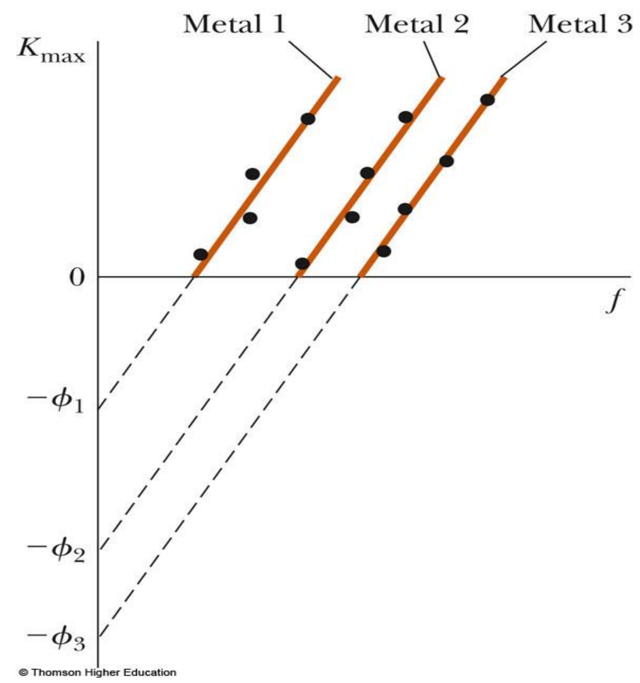
1. Electromagnetic waves carry discrete energy packets (light quanta called photons now).
2. The energy E, per packet depends on frequency f: E = hf.
3. **More intense light corresponds to more photons, not higher energy photons.**
4. Each photon of energy E moves in vacuum at the speed of light: $c = 3 \times 10^8$ m/s and each photon carries a momentum, p = E/c.

Einstein's photoelectric equation

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

Does the stopping potential depend on the frequency of light?

$\phi = hf_c$ where f_c is the cut off frequency



The stopping potential for photoelectrons released from metal 1 is 1.48 V larger compared to that in metal 2. If the threshold frequency for the first metal is 40.0 % smaller than for the second metal, determine the work function for each metal.

Ans: $\varphi_2 = 3.7$ eV $\varphi_1 = 2.22$ eV

Let ΔVs_1 and ΔVs_2 be the stopping potentials for the 1st and 2nd metals, respectively. Let Φ_1 and Φ_2 be the work functions of metal 1 and metal 2 respectively, f_{c1} and f_{c2} are the corresponding threshold frequencies.

$$\boldsymbol{Given: \ \Delta V s_1 = \Delta V s_2 + 1.48\ V} \qquad \boldsymbol{f_{c1} = 0.6 f_{c2}}$$

Multiplying both sides by h

$$\boldsymbol{h f_{c1} = 0.6 h f_{c2} \Longrightarrow \boxed{\Phi_1 = 0.6\Phi_2}}$$

From Einstein equation, $$e\Delta Vs = hf - \phi$$

Rearranging the equation; $$e\Delta Vs + \phi = hf$$

For the first metal, $$e\Delta Vs_1 + \phi_1 = hf \longrightarrow (1)$$

For the second metal, $$e\Delta Vs_2 + \phi_2 = hf \longrightarrow (2)$$

Equating (1) and (2) and substituting the given conditions, we get,

$$1.48eV + \cancel{e\Delta Vs_2} + 0.6\phi_2 = \cancel{e\Delta Vs_2} + \phi_2$$

$$1.48eV = (1 - 0.6)\phi_2 = 0.4\phi_2 \Longrightarrow \phi_2 = 3.7\ eV$$

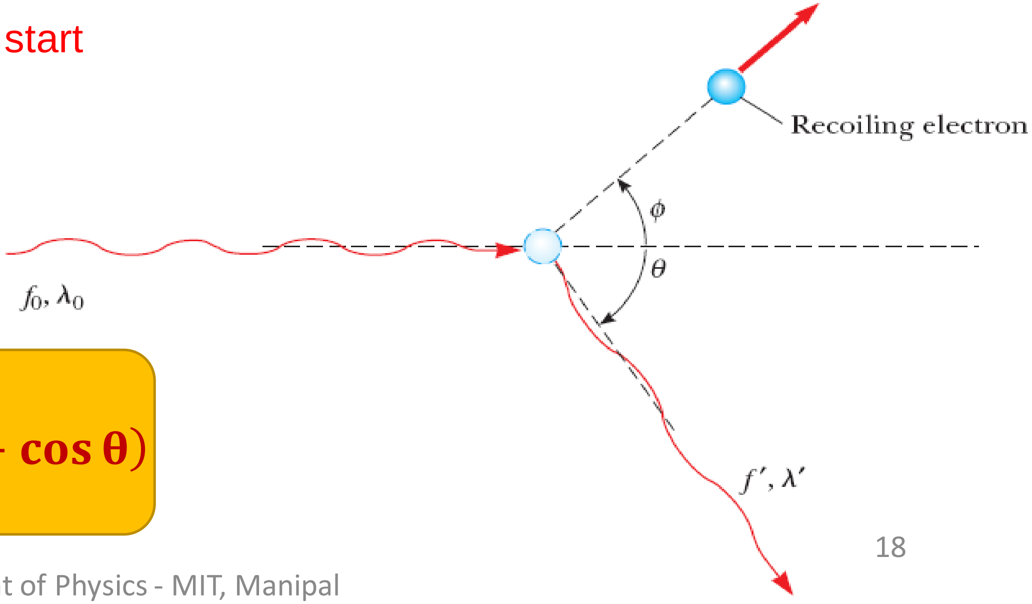
$$\Phi_1 = 0.6\Phi_2$$

$$\phi_1 = 2.22\ eV$$

Compton Effect

Arthur Holly Compton
American Physicist (1892–1962)

Carrom men and one striker, arranged at the start of a game



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

Compton Effect

When X-rays are scattered **by free/nearly free electrons**, they suffer a change in their wavelength which depends on the scattering angle.

Classical Predictions:

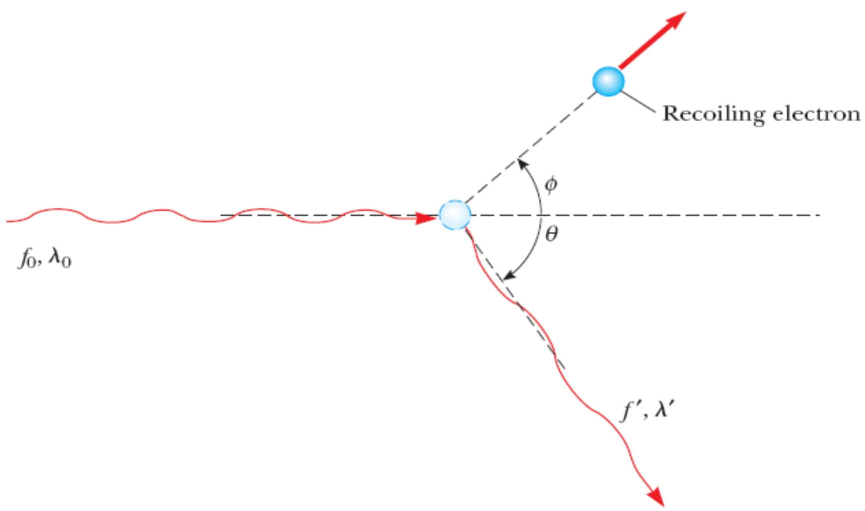
Effect of oscillating electromagnetic waves on electrons:

(a) oscillations in electrons, re-radiation in all directions

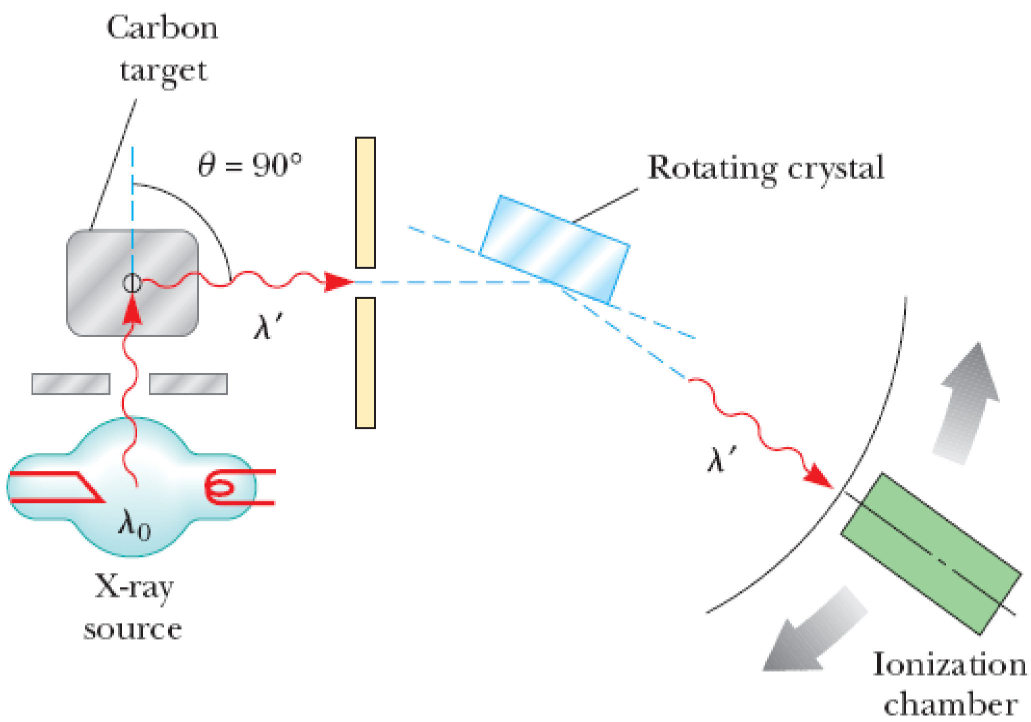
(b) radiation pressure - electrons accelerate in the direction of propagation of the waves

Different electrons will move at different speeds after the interaction.

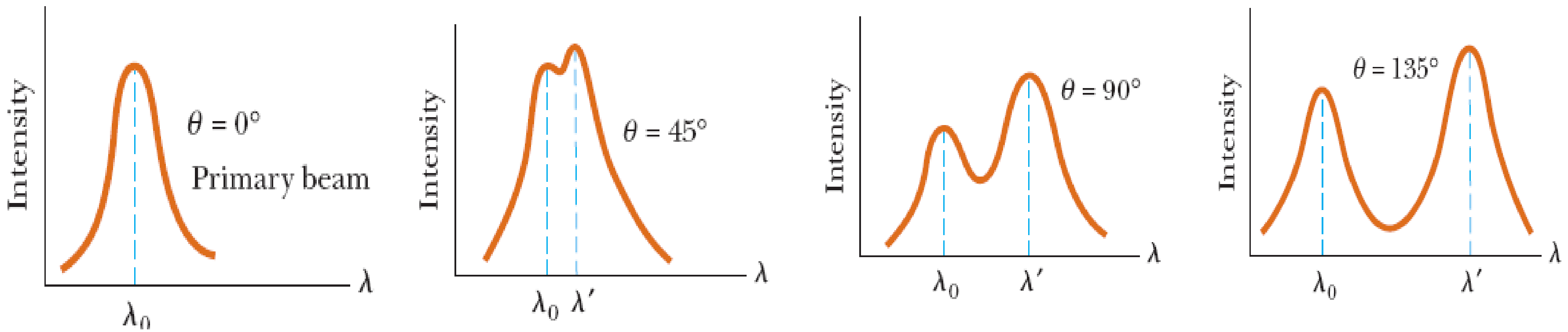
The scattered wave frequency should show a distribution of Doppler-shifted values



Schematic diagram of Compton's apparatus



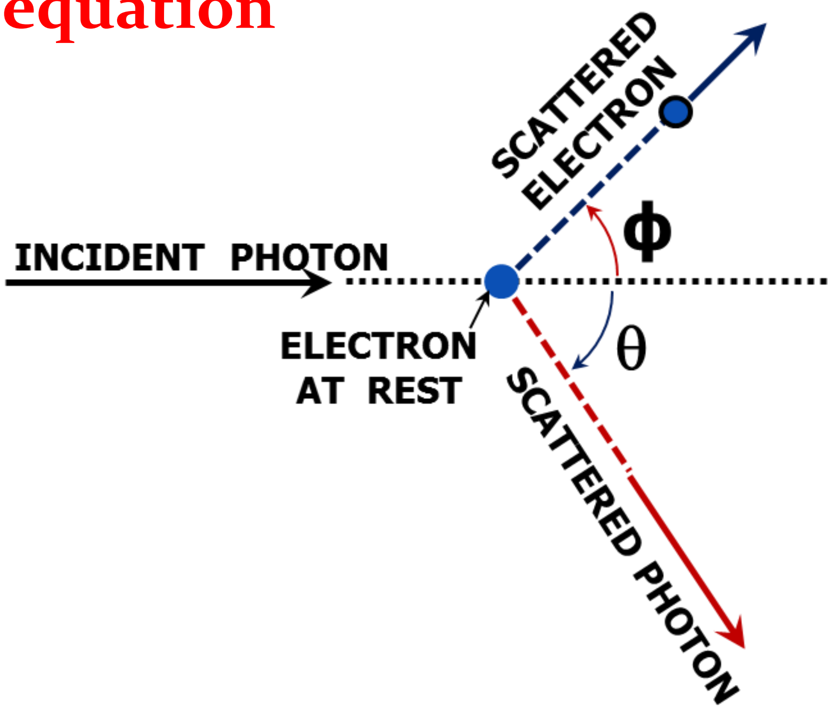
Graph of scattered x-ray intensity versus wavelength



Derivation of the Compton shift equation

Photon is treated as a particle having energy $E = hf_o = hc/\lambda_o$ and zero rest energy. **Photons collide elastically with free electrons initially at rest as shown in figure.**

In the scattering process, the total energy and total linear momentum of the system must be conserved.



λ_o = wavelength of the incident photon

$p_o = h/\lambda_o$ = momentum of the incident photon

$E_o = hc/\lambda_o$ = energy of the incident photon

λ' = wavelength of the scattered photon

$p' = h/\lambda'$ = momentum of the scattered photon

$E' = hc/\lambda'$ = energy of the scattered photon

Relativistic equations:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

v = speed of the electron

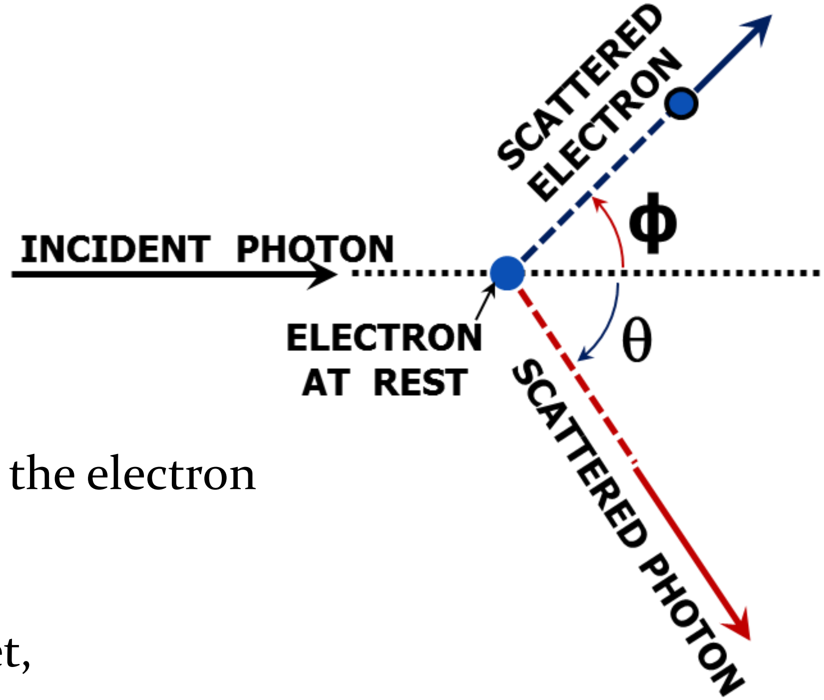
m = mass of the electron

p = γ m v = momentum of the electron where

$E = \sqrt{p^2c^2 + m^2c^4}$ = total relativistic energy of the electron

K = E – m c² = kinetic energy of the electron

By using above relations and simplifying, we will get,



Conservation of energy: $E_o = E' + K$

Conservation of momentum:

x-component: $p_o = p' \cos\theta + p\cos\phi$

y-component: $0 = p' \sin\theta - p\sin\phi$

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

ie, $E_o = E' + (E - m c^2)$

Or $E_o - E' + m c^2 = E = \sqrt{p^2c^2 + m^2c^4}$

Squaring both the sides, $(E_o - E')^2 + 2(E_o - E')\, mc^2 + \cancel{m^2c^4} = p^2c^2 + \cancel{m^2c^4}$

For conservation of momentum, x-component: $p_o = p' \cos\theta + p \cos\phi$

y-component: $0 = p' \sin\theta - p \sin\phi$

Rewriting these two equations

$$p_o - p' \cos\theta = p \cos\phi$$

$$p' \sin\theta = p \sin\phi$$

Squaring both the sides and adding,

$$p_o^2 - 2p_o p' \cos\theta + p'^2 = p^2$$

Substituting this p^2 in the equation :

$(E_o - E')^2 + 2(E_o - E')\, mc^2 = p^2c^2$, one gets

$$(E_o - E')^2 + 2(E_o - E')\, mc^2 = (p_o^2 - 2p_o p' \cos\theta + p'^2)c^2$$

Substituting photon energies and photon momenta one gets

$$\left(\frac{hc}{\lambda_o} - \frac{hc}{\lambda'}\right)^2 + 2\left(\frac{hc}{\lambda_o} - \frac{hc}{\lambda'}\right) mc^2 = \left(\frac{hc}{\lambda_o}\right)^2 - 2\left(\frac{hc}{\lambda_o}\right)\left(\frac{hc}{\lambda'}\right)\cos\theta + \left(\frac{hc}{\lambda'}\right)^2$$

Simplifying one gets

$$\cancel{\left(\frac{hc}{\lambda_o}\right)^2} - 2\left(\frac{hc}{\lambda_o}\right)\left(\frac{hc}{\lambda'}\right) + \cancel{\left(\frac{hc}{\lambda'}\right)^2} + 2\,hc\left(\frac{1}{\lambda_o} - \frac{1}{\lambda'}\right) mc^2 = \cancel{\left(\frac{hc}{\lambda_o}\right)^2} - 2\left(\frac{hc}{\lambda_o}\right)\left(\frac{hc}{\lambda'}\right)\cos\theta + \cancel{\left(\frac{hc}{\lambda'}\right)^2}$$

i.e., $$-\frac{hc}{\lambda_o\lambda'} + \left(\frac{1}{\lambda_o} - \frac{1}{\lambda'}\right) mc^2 = -\frac{hc}{\lambda_o\lambda'}\cos\theta$$

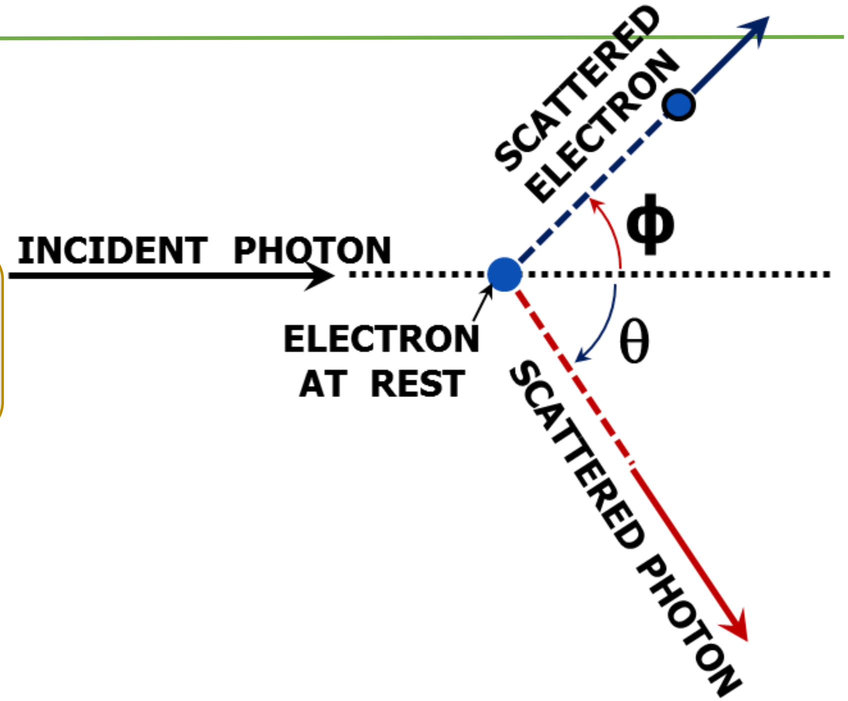
OR, $$\left(\frac{\lambda' - \lambda_o}{\lambda_o\lambda'}\right) mc^2 = \frac{hc}{\lambda_o\lambda'}(1 - \cos\theta)$$

Compton shift:

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

THE COMPTON EFFECT

Compton shift $\lambda' - \lambda_o = \dfrac{h}{mc}(1 - \cos\theta)$



Q: A 0.00160 nm photon scatters from a free electron. For what photon scattering angle does the recoiling electron have kinetic energy equal to the energy of the scattered photon?

Ans: $\theta = 70^o$

COMPTON EFFECT - SUPPLIMENTARY INTRODUCTION	
PARTICLE PARAMETERS	**PHOTON** PARAMETERS
$p_{PARTICLE} = \gamma m v$, $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$	$p_{PHOTON} = \frac{E}{c} = \frac{h}{\lambda}$
$E_{PARTICLE} = \gamma m c^2$	$E_{PHOTON} = hf = hc / \lambda$
REST ENERGY: $E_o = m c^2$	NO REST ENERGY FOR PHOTON $m_{PHOTON} = 0$
$E_{PARTICLE} = E_o + K_{PARTICLE}$	$E_{PHOTON} = K_{PHOTON}$
$K_{PARTICLE} = (\gamma - 1) m c^2$	$K_{PHOTON} = E_{PHOTON}$
$E^2 = p^2c^2 + m^2c^4$	$E_{PHOTON} = pc$, $c = f \lambda$

Photons and Electromagnetic Waves [Dual Nature of Light]

- Light exhibits diffraction and interference phenomena that are only explicable in terms of wave properties.

- Photoelectric effect and Compton Effect can only be explained taking light as photons / particle.

- This means true nature of light is not describable in terms of any single picture, instead both wave and particle nature have to be considered. In short, ***the particle model and the wave model of light complement each other.***

de Broglie Hypothesis –

Wave Properties of Particles

Louis de Broglie postulated that because photons have both wave and particle characteristics, perhaps all forms of matter have both properties. This highly revolutionary idea had no experimental confirmation at the time. According to de Broglie, electrons, just like light, have a dual particle–wave nature.

The proposal that matter exhibits both wave and particle properties was regarded as pure speculation.

Louis de Broglie

French Physicist (1892–1987)

De Broglie was born in Dieppe, France. At the Sorbonne in Paris, he studied history in preparation for what he hoped would be a career in the diplomatic service. The world of science is lucky he changed his career path to become a theoretical physicist. De Broglie was awarded the Nobel Prize in Physics in 1929 for his prediction of the wave nature of electrons.

de Broglie Hypothesis - Wave Properties of Particles

Wavelength associated with particle of mass **m** moving with velocity **v** is given by

de Broglie wavelength: $\boldsymbol{\lambda = \frac{h}{p} = \frac{h}{mv}}$

The momentum (p) of an electron accelerated through a potential difference of ΔV is

$$p = m\,v = \sqrt{2\,m\,e\,\Delta V}$$

Frequency of the matter wave associated with the particle is $\frac{E}{h}$, where E is total relativistic energy of the particle.

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

SJ: Section 40.5 P-35 An electron has a kinetic energy of 3.0 eV. (a) Find its wavelength. (b) Also find the wavelength of a photon having the same energy. Mass of an electron is 9.1×10^{-31} Kg

(a) 0.709 nm (b) 413.3 nm

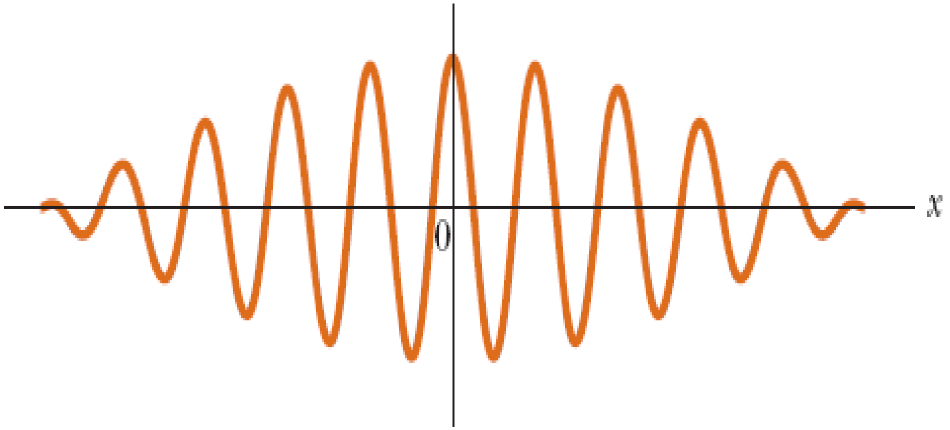
Calculate the energy and momentum of a photon of wavelength 700 nm. Planck's constant h = 6.625×10^{-34} Js , speed of light in vacuum is 3×10^{8} m/s ; 1 eV = 1.6×10^{-19} J

Energy = 1.78 eV or 2.8×10^{-19} J
and momentum = 9.45×10^{-28} Kg.m/sec

An electron and a proton both moving at nonrelativistic speeds have the same de Broglie wavelength. Which of the following quantities are also the same for the two particles?

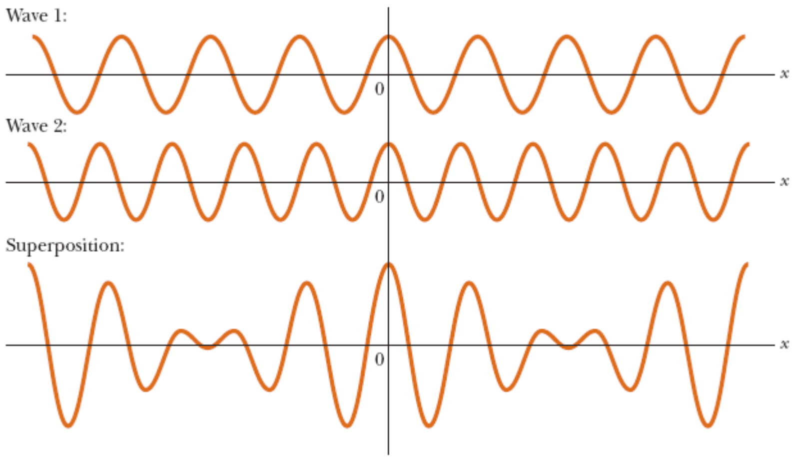
(a) speed **(b)** kinetic energy **(c)** momentum
(d) frequency

The Quantum Particle

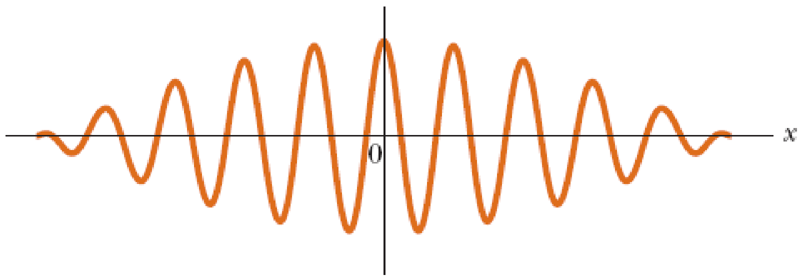


The Quantum Particle

If we add up large number of waves such that constructive interference takes place in small localized region of space a **wavepacket**, which represents a quantum particle can be formed.



Superposition of two waves



Wave packet

Mathematical representation of a wave packet:

$$y_1 = A\cos(k_1 x - \omega_1 t) \quad \text{and} \quad y_2 = A\cos(k_2 x - \omega_2 t)$$

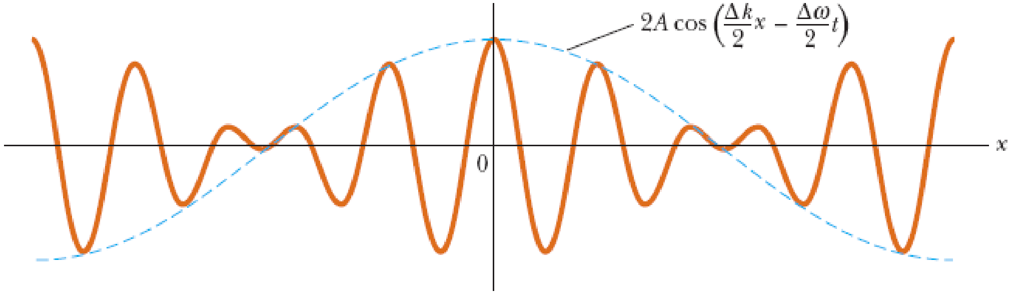
$$\text{where } k = 2\pi/\lambda, \qquad \omega = 2\pi f$$

The resultant wave $y = y_1 + y_2$

cos a + cos b =
2 cos (a-b)/2*cos (a+b)/2

$$y = 2A\left[\cos\left(\frac{\Delta k}{2}x - \frac{\Delta\omega}{2}t\right)\cos\left(\frac{k_1+k_2}{2}x - \frac{\omega_1+\omega_2}{2}t\right)\right]$$

where $\Delta k = k_1 - k_2$ and $\Delta\omega = \omega_1 - \omega_2$.



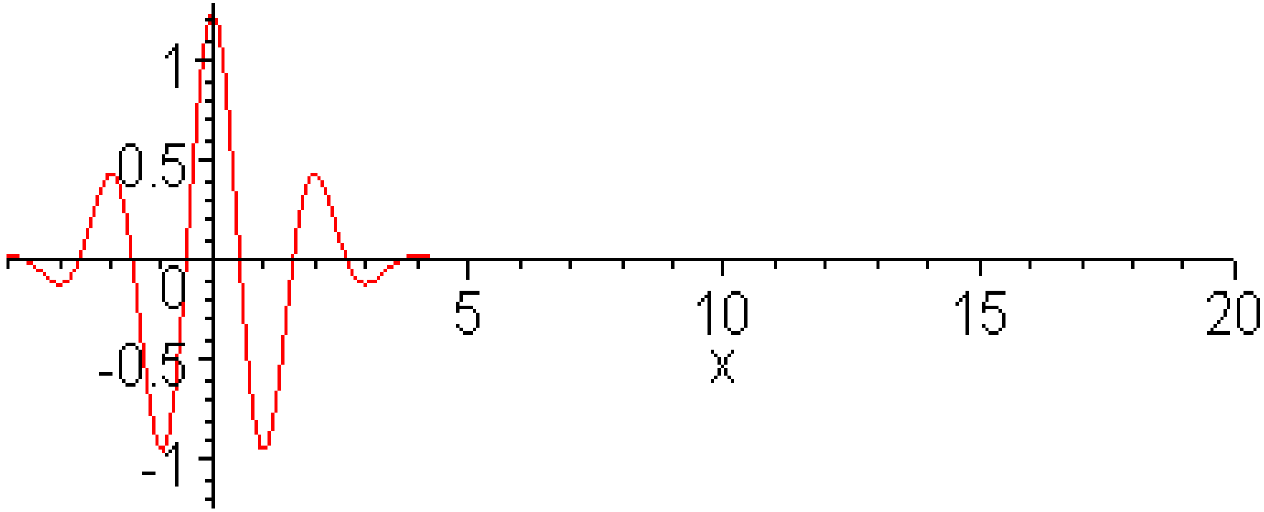
Phase speed, the speed with which wave crest of individual wave moves, is given by

$$v_p = f\lambda \quad \text{or} \quad v_p = \frac{\omega}{k}$$

Group speed, the speed of the wave packet, is given by

$$v_g = \frac{\left(\frac{\Delta\omega}{2}\right)}{\left(\frac{\Delta k}{2}\right)} = \frac{\Delta\omega}{\Delta k}$$

$$v_g = v_p - \lambda \left(\frac{dv_p}{d\lambda} \right)$$



Relation between group speed (v_g) and phase speed (v_p):

$$v_P = \frac{\omega}{k} = f\,\lambda \qquad \therefore \qquad \omega = k\,v_P$$

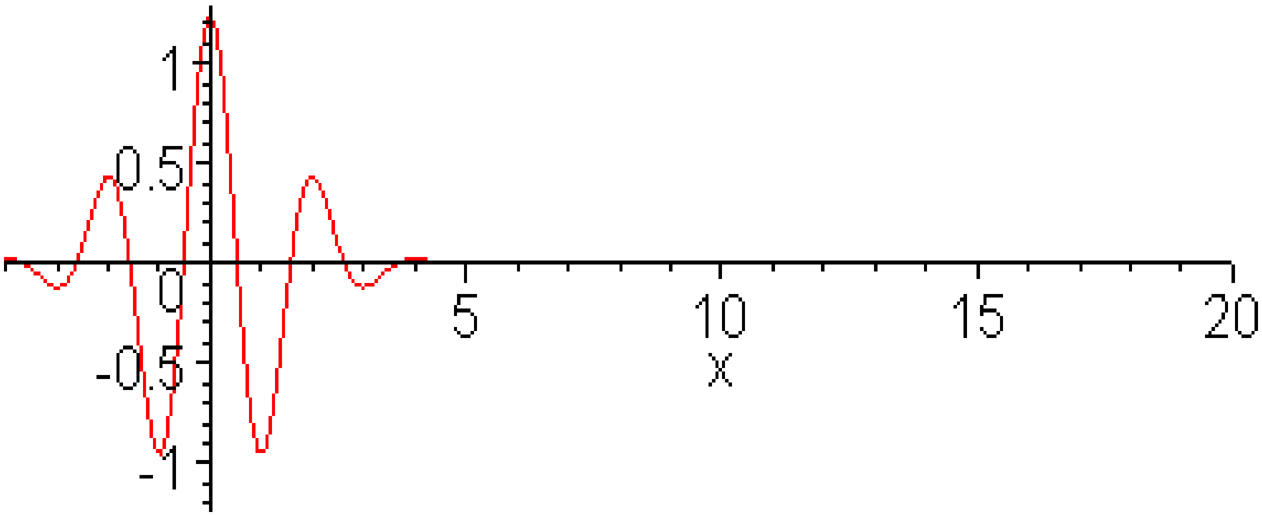
$$k = \frac{2\pi}{\lambda}$$

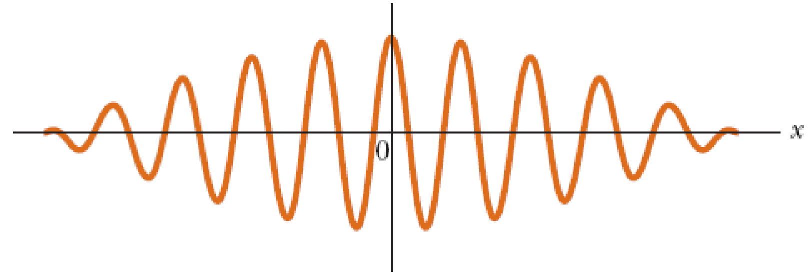
But $v_g = \dfrac{d\omega}{dk} = \dfrac{d(kv_P)}{dk} = k\,\dfrac{dv_P}{dk} + v_P$

$$\frac{dk}{d\lambda} = -\frac{2\pi}{\lambda^2}$$

Substituting for k in terms of λ, we get

$$\boxed{v_g = v_P - \lambda\left(\frac{dv_P}{d\lambda}\right)}$$





Relation between group speed (v_g) and particle speed (u):

$$\omega = 2\pi f = 2\pi \frac{E}{h} \quad \text{and} \quad k = \frac{2\pi}{\lambda} = \frac{2\pi}{h/p} = \frac{2\pi p}{h}$$

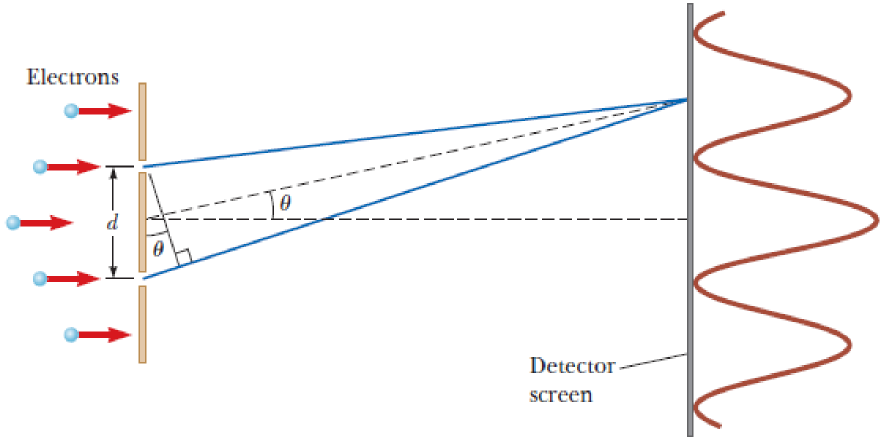
$$v_g = \frac{d\omega}{dk} = \frac{\frac{2\pi}{h}\, dE}{\frac{2\pi}{h}\, dp} = \frac{dE}{dp}$$

For a classical particle moving with speed u, the kinetic energy E is given by

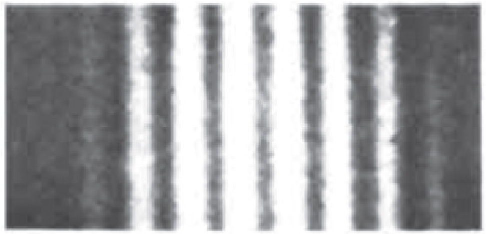
$$E = \tfrac{1}{2} m u^2 = \frac{p^2}{2m} \quad \text{and} \quad dE = \frac{2p\, dp}{2m} \quad \text{or} \quad \frac{dE}{dp} = \frac{p}{m} = u$$

$$\boldsymbol{v_g = \frac{d\omega}{dk} = \frac{dE}{dp} = u}$$

Double–Slit Experiment Revisited

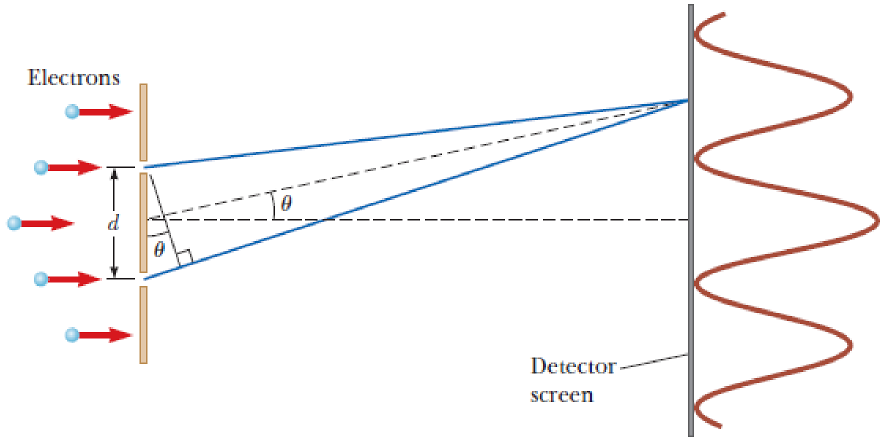


(a)

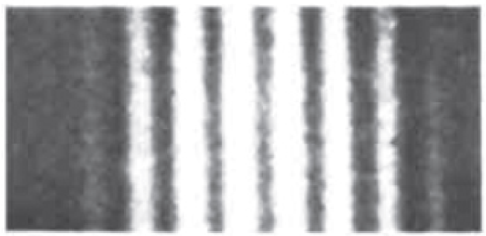


(b)

Double–Slit Experiment Revisited



(a)



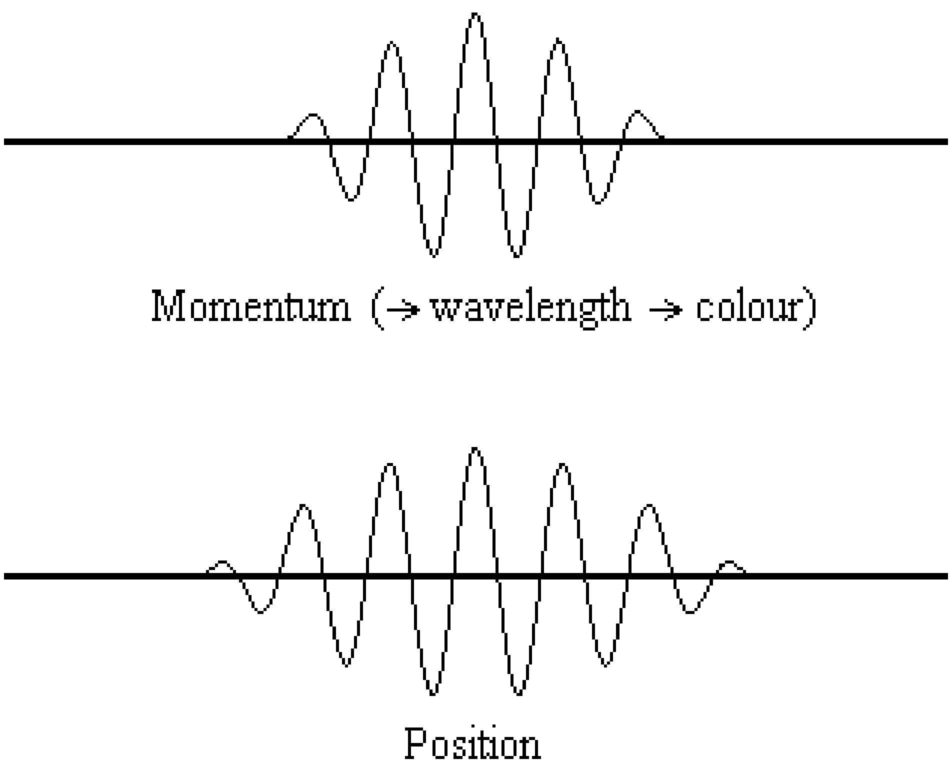
(b)

(a) Schematic of electron beam interference experiment, (b) Photograph of a double-slit interference pattern produced by electrons

$d \sin\theta = m\lambda$, where m is the order number and λ is the electron wavelength.

The electrons are detected as particles at a localized spot on the detector screen at some instant of time, but the probability of arrival at the spot is determined by finding the intensity of two interfering waves.

UNCERTAINTY PRINCIPLE



Werner Heisenberg
German Theoretical Physicist
(1901–1976)

Uncertainty Principle

Heisenberg uncertainty principle: It is fundamentally impossible to make **simultaneous measurements** of a particle's position and momentum with infinite accuracy.

$$(\Delta x)(\Delta p_x) \geq h/4\pi$$

One more relation expressing uncertainty principle is related to energy and time which is given by

$$(\Delta E)(\Delta t) \geq h/4\pi$$

SJ: P-SE 40.9 The Line Width of Atomic Emissions

The lifetime of an excited atom is given as 1.0×10^{-8} s. Using the uncertainty principle, compute the line width Δf produced by this finite lifetime?

Solution: The minimum Δf *is* $\Delta f = \dfrac{\Delta E}{h} = \dfrac{h}{4\pi h \Delta t}$

$$\Delta f = \frac{1}{4\pi\Delta t} = \frac{1}{4\pi(1x10^{-8}s)} = 8\ x10^{6}\ Hz$$

SJ: Section 40.8 P-51 Use the uncertainty principle to show that if electrons were confined inside an atomic nucleus of diameter 2x 10^{-15} m, it would have to be moving relativistically, while a proton confined to the same nucleus can be moving non-relativistically.

Mass of the electron $=m_e=9.1\text{x}10^{-31}$ Kg

Mass of the proton $=m_p = 1.67\text{x}10^{-27}$ Kg

Solution: With Δx = 2x10^{-15}m, $\Delta p_x \geq \frac{h}{4\pi\Delta x}$ = 2. 6x10^{-20}kg m/s. The uncertainty in momentum is approximated to the root-mean-square momentum $\sqrt{\frac{3}{2}}\Delta p_x$, so we take $p_{rms} \approx$ 3x10^{-20}kg m/s .

For an electron, the non-relativistic approximation $p = m_e v$ would predict $v \approx$ 3x10^{11}m/ s, while v cannot be greater than c.

For a relativistic motion,

$E = [(mc^2)^2 + (pc)^2]^{1/2} \approx 56\text{MeV} = \gamma m_e c^2$, $\gamma \approx 110 = \frac{1}{\sqrt{1-v^2/c^2}}$

so v ≈ 0. 999 96c.

For a proton, $v = \frac{p}{m}$, gives v = 1.8x10^{7}m/s, less than one-tenth the speed of light. (mass of the proton is 1.67x10^{-27} Kg)

INTRODUCTION TO QUANTUM PHYSICS

QUESTIONS

1. Explain (a) Stefan's law (b) Wien's displacement law (c) Rayleigh-Jeans law. [1 EACH]
2. Sketch schematically the graph of wavelength vs. intensity of radiation from a blackbody. [1]
3. Explain Planck's radiation law. [2]
4. Write the assumptions made in Planck's hypothesis of blackbody radiation. [2]
5. Explain photoelectric effect. [1]
6. What are the observations in the experiment on photoelectric effect? [5]
7. What are the classical predictions about the photoelectric effect? [3]
8. Explain Einstein's photoelectric equation. [2]

INTRODUCTION TO QUANTUM PHYSICS

QUESTIONS

10. Which are the features of photoelectric effect-experiment explained by Einstein's photoelectric equation? [2]
11. Sketch schematically the following graphs with reference to the photoelectric effect: (a) photoelectric current vs applied voltage (b) kinetic energy of most-energetic electron vs frequency of incident light. [1EACH]
12. Explain compton effect. [2]
13. Explain the experiment on compton effect. [5]
14. Derive the compton shift equation. [5]
15. Explain the wave properties of the particles. [2]
16. Explain a wavepacket and represent it schematically. [2]
17. Explain (a) group speed (b) phase speed, of a wavepacket. [1+1]
18. Show that the group speed of a wave packet is equal to the particle speed. [2]
20. Explain Heisenberg uncertainty principle. [1]