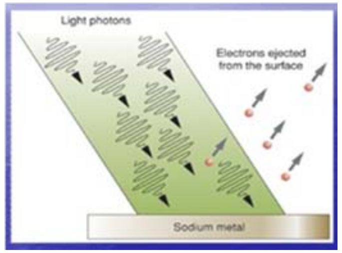
26.1The Photoelectric Effect

First observed by Heinrich Hertz in 1887 - light shining on a metal plate causes electrons to be knocked loose (ejected) from the metal plate.
Several aspects of the phenomena could not be explained in terms of an electromagnetic wave:



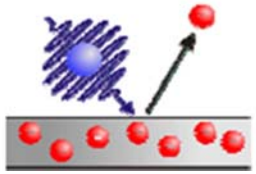
Increasing the brightness of the light did not eject faster electrons - think of light as a wave - brighter light (bigger amplitude wave) should eject more energetic (faster) electrons.
Energy and number of ejected electrons depends on light(frequency) - for some metals, red light would not eject any electrons at all even it very high - blue lights ejects very fast electrons even if very dim.
The electrons were emitted immediately - no time lag - if light is dim, expect a delay while the waves wiggle the electrons and break them loose.

The Photoelectric Effect

"The phenomenon that when light shines on a metal surface, electro are emitted"

One type of experiment with the photoelectric effect involves shining light of a single frequency onto the metal plate and adjusting the potential difference V between the metal plate and the collector

- If electrons are hitting the collector, there is a current reading in the ammeter

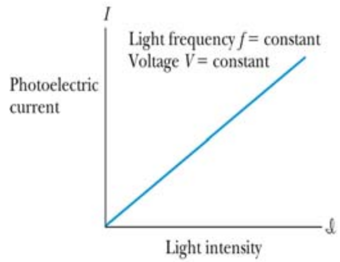


Photoelectric Effect Schematic

- **When light strikes E, photoelectrons are emitted**
- **Electrons collected at C and passing through the ammeter are a current in the circuit**
- **C is maintained at a positive potential by the power supply**

Photo-electric effect observations

- A)The kinetic energy of the photoelectrons is **independent of the light intensity**.
- B)The kinetic energy of the photoelectrons, for a given emitting material, depends only on the **frequency** of the light.

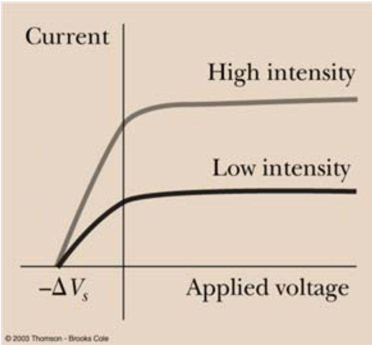


- C)When photoelectrons are produced, their **number** (not their kinetic energy) is proportional to the intensity of light.

d)Also, the photoelectrons are emitted almost instantly following illumination of the photocathode, independent of the intensity of the light.

Photoelectric Current/Voltage Graph

- The current increases with intensity, but reaches a saturation level for large ΔV's
- No current flows for voltages less than or equal to $-\Delta V_s$, the *stopping potential*
- The stopping potential is independent of the radiation intensity



Cutoff Wavelength

- The cutoff wavelength is related to the work function

$$\lambda_c = \frac{hc}{w}$$

- Wavelengths greater than λ_C incident on a material with a work function w don't result in the emission of photoelectrons

A specific value of V can be found at which the ammeter reading just drops to zero

. This is called the stopping potential (*V_{stop}).*

• When the potential is at *V_{stop} the most energetic electrons were turned* back just before hitting the collector.

• This indicates that the maximum kinetic energy of the photoelectrons, *$K_{max} = e\,V_{stop}$ where e is the elementary charge*

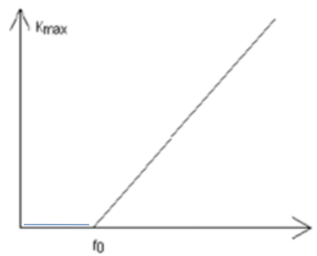
.

interestingly, it was found that *K_{max} does not depend upon* the intensity of the incident light.

• It is difficult to explain this observation with classical

When the maximum kinetic energy is plotted as a function of frequency a graph like that on the right results.

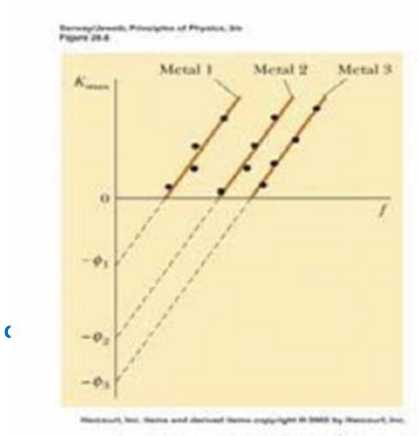
• Note that there is no photoelectric effect if the light is below a certain cutoff frequency, *f_0. This* occurs no matter how bright the incident light is.



Dependence of maximal kinetic energy of electrons on the frequency of light

Photoelectric effect graphs for three different metals are shown a tright..

- **Looking at the second form of the photoelectric equation, several pieces of information can be determined from the graphs.**
  - **The work function of each metal can be determined by taking the negative y-intercept of each line.**
  - **The cutoff frequency of each metal can be determined by taking the x intercept o each line**
  - **Note that all three lines have the same slope. This slope is Planck's constant**



Features Not Explained by Classical Physics/Wave Theory

- No electrons are emitted if the incident light frequency is below some *cutoff frequency* that is characteristic of the material being illuminated
- The maximum kinetic energy of the photoelectrons is independent of the light intensity
- The maximum kinetic energy of the photoelectrons increases with increasing light frequency
- Electrons are emitted from the surface almost instantaneously, even at low intensities

Explanation of Classical "Problems"

- The effect is not observed below a certain cutoff frequency since the photon energy must be greater than or equal to the work function
  - Without this, electrons are not emitted, regardless of the intensity of the light
- The maximum KE depends only on the frequency and the work function, not on the intensity
- The maximum KE increases with increasing frequency
- The effect is instantaneous since there is a one-to-one interaction between the photon and the electron

Quantum Theory of The Atom

– In 1901, Max Planck suggested light was made up of 'packets' of energy:

–

$$E = nhf$$

E (Energy of Radiation)

v (Frequency)

n (Quantum Number) = 1,2,3…….n

h (Planck's Constant, a Proportionality Constant)

6.626×10^{-34} J.s) or h =4.135×10^{-15} ev.s

6.626×10^{-34} kg.m^2/s

– Atoms, therefore, emit only certain quantities of energy and the energy of an atom is described as being ***"quantized"***

– Thus, an atom changes its *energy state* by emitting (or absorbing) one or more ***quanta***

Photons

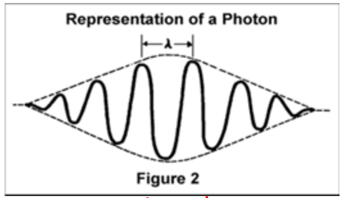


Figure 2

Quantum theory describes light as a particle called a **photon with wave**

According to **quantum theory**, a **photon** has an **energy** given by

$E = h\nu = hc/\lambda$ (*h* Planck's constant $= 6.6\times10^{-34}$ J.sec) or h = 4.135×10^{-15} eV.s ,

The energy of the light is proportional to the frequency, and inversely proportional to the wavelength! The higher the frequency (lower wavelength) the higher the energy of the photon!

10 photons have an energy equal to ten times a single photon.

The **quantum theory describes experiments to astonishing precision**, whereas the **classical wave description cannot**.

Einsteins explanation

proposed an explanation for the photoelectric effetc which would play a large role in his receiving the Nobel Prize in Physics in 1921.

• Rather than the classical model of light as a continuous wave, Einstein viewed light as discrete packets of energy called photons. hf , 2hf ,3hf…… nhf

• Taking advantage of Planck's discovery of the quantization of energy, Einstein determined that each photon had energy *E=hf*. The energy transferred to an electron • by light was no longer considered to depend on intensity, but on frequency

Einstein's Explanation

The electrons are bound to the material by attractive forces. Hence, work must be done to free an electron:

$$hf = KE_{max} + w$$

Incident photon energy

Maximum kinetic energy of dislodged electron

Minimum work required to free electron

"Work function", depends on the material

Einstein 's Explanation

- Energy from the light beam is transferred to the electrons in the solid by photons which have an energy related to the frequency of the beam.
- The photon's energy would be $E = hf$
- ***Each photon can give all its energy to an electron in the metal***
- The electron is considered to be in a well of height frequency which is called the ***work function*** of the metal
- Because of energy conservation the maximum kinetic energy of the liberated photoelectron is

$$KE = hf - w$$

Work Function

Work function is: The minimum amount of energy that has to be given to an electron to release it from the surface of the material and varies depending on the material

Threshold Frequency

$hf_o = w$

$\frac{hc}{\lambda_o} = w$

c = speed of light

λ_o = wavelength

Light as a Particle (Photon)

- Light propagates as quanta of energy called photons
- Photons
  - A) move with speed of light
  - B) have no mass
  - C) electrically neutral
- **Energy of a photon or electromagnetic wave:**

$$E = hf = \frac{hc}{\lambda}$$

where

h = Planck's constant

f = frequency of a light wave - number of crests passing a fixed point in 1 second

c = velocity of light

λ = wavelength of a light wave - distance between successive crests

Example 26.1

Light is incident on the surface of a metal for which the work function is 2eV (a) what is the minimum frequency the light can have and cause the emission of electron ? (b) If the frequency of the incident light is $2x10^{14}$Hz what is the maximum kinetic energy of the electron?

example

What is the wavelength in nm of orange light, which has a frequency of $4.80 \times 10^{14}\ s^{-1}$?

solution

$c = \lambda \times \nu$

$$\lambda = \frac{c}{\nu} = \frac{2.998 \times 10^8\ m\ s^{-1}}{4.80 \times 10^{14}\ s^{-1}} = 6.25 \times 10^{-7}\ m$$

$$6.25 \times 10^{-7}\ m \times \frac{1\ nm}{1 \times 10^{-9}\ m} = 625\ nm$$

example

What is the maximum kinetic energy of electrons emitted from a zinc surface if they are stopped by a 16 N/C uniform electric field over a distance of 3.0cm?

First calculate the voltage $E = V/d$

$V = E\,d$

$(16N/C).(0.03m)$

$V = 0.48V$

Second, calculate the maximum kinetic energy…

$E_{k\,max} = e\,V_{stop}$

$= (1.6 \times 10^{-19}C)\,(0.48V)$

$E_{k\,max} = 7.68 \times 10^{-20}$ J

example

What is threshold frequency of a material with a work function of 10eV?

Since the value for the work function is given in electron volts, we might as well use the value for Planck's constant that is in eV s.

$W = h\,f_o$

$f_o = W / h$

$= (10eV) / (4.14 \times 10^{-15}eVs)$

$f_o = 4.14 \times 10^{-14}$ Hz

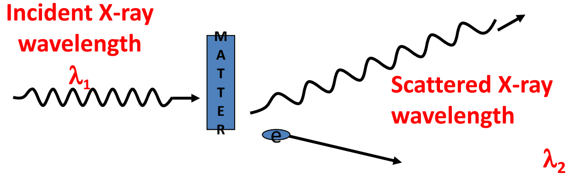
Home work : 26-1, 26-3 ,26-4

26.3 XRAYS

The Compton Effect

In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.

Louis de Broglie



$\lambda_2 > \lambda_1$

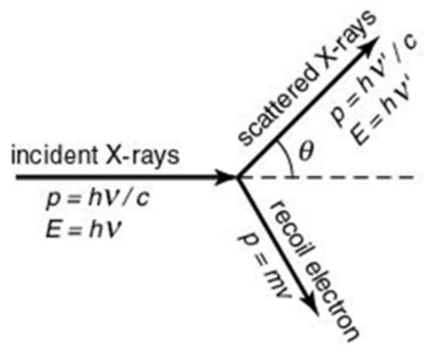
Electron comes flying out

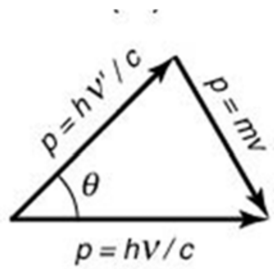
Compton directed a beam of x-rays toward a block of graphite
He found that the scattered x-rays had a slightly longer wavelength that the incident x-rays This means they also had less energy the amount of energy reduction depended on the angle at which the x-rays were scattered
The change in wavelength is called the *Compton shift*
The Compton shift depends on the scattering angle and not on the wavelength

Compton effect was first observed by Arthur Compton in 1923 and this discovery led to his award of the 1927 Nobel Prize in Physics. The discovery is important because it demonstrates that light cannot be explained purely as a wave phenomenon. Compton's work convinced the scientific community that light can behave as a stream of particles (photons) whose energy is proportional to the frequency.
The change in wavelength of the scattered photon is given by:

$$hf' = hf - E_{el}$$

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - Cos\,\theta)$$

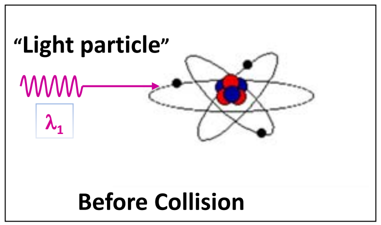


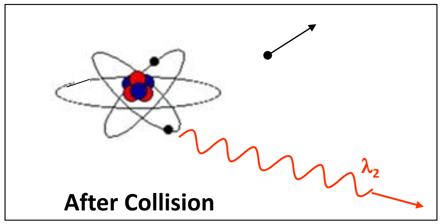


$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

$$\lambda_C^e = \frac{h}{m_e c} \approx 2.43\times10^{-12}\,m$$

Interpretation of Compton Effect





The Compton Effect **describes** **collisions of light with electrons** **perfectly** if we treat **light as a particle** with:

p = h/λ and **E = hν**
= hc/λ = (h/λ)*c*
= pc

example

In the Compton scattering the experiment the incident x ray have a frequency of 10^{20} Hz at certain angle the outgoing x ray have frequency of 8×10^{19} Hz find the energy of the recoiling electron in electron volts

$$E_{el} = hf - hf' = h(f - f')$$

$$= (4.135\times10^{-15}\,ev.s)(10^{20}\,Hz - 8\times10^{19}) = 82.700\,eV$$

Example:

Determine the change in the photon's wavelength that occurs when an electron scatters an x-ray photon (a) at θ=180° and (b) θ=30°.

$\Delta\lambda=\lambda_c(1-\cos\theta)$

(a) $\Delta\lambda=2.43\times10^{-12}$ m $(1-\cos180°)$ → -1

$\Delta\lambda=4.86\times10^{-12}$ m

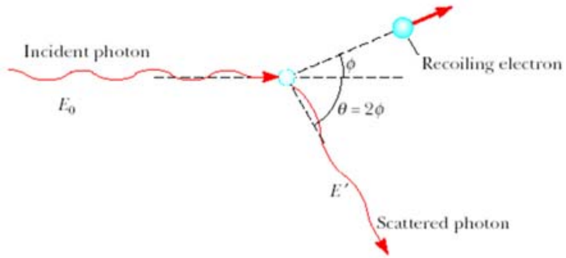
(b) $\Delta\lambda=2.43\times10^{-12}$ m $(1-\cos30)$ → 0.134

$\Delta\lambda=(0.134)\times(2.43\times10^{-12}\text{ m})$

$\Delta\lambda=3.26\times10^{-13}$ m

Example

A 0.700-MeV photon scatters off a free electron such that the scattering angle of the photon is twice the scattering angle of the electron (Fig.). Determine (a) the scattering angle for the electron and (b) the final speed of the electron.

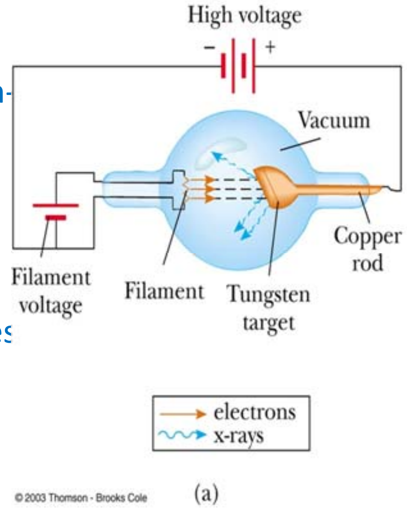


X-Rays

- Electromagnetic radiation with short wavelengths
  - **Wavelengths less than for ultraviolet**
  - **Wavelengths are typically about 0.1 nm**
  - **X-rays have the ability to penetrate most materials with relative ease**
- **Discovered and named by Roentgen in 1895**

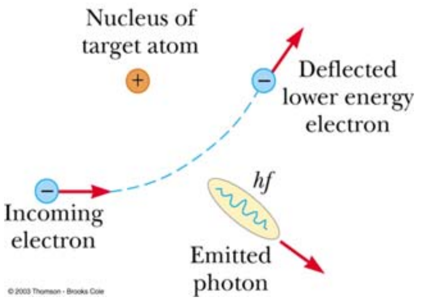
Production of X-rays

- X-rays are produced when high-speed electrons are suddenly slowed down
  - Can be caused by the electron striking a metal target
- A current in the filament causes electrons to be emitted
- These freed electrons are accelerated toward a dense metal target



Production of X-rays

- An electron passes near a target nucleus
- The electron is deflected from its path by its attraction to the nucleus
  - This produces an acceleration
- It will emit electromagnetic radiation when it is accelerated

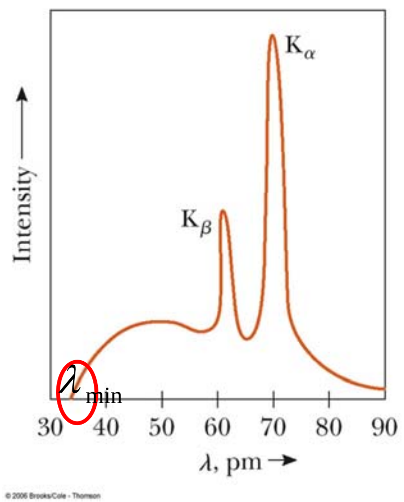


The maximum x-ray energy, and minimum wavelength results when the electron loses all its energy in a single collision, such that

$e\Delta V = hf_{max} = hc/\lambda_{min}$ or therefore $\lambda_{min} = \dfrac{hc}{e\Delta V}$

X-ray Spectrum

- The x-ray spectrum has two distinct components
- 1) Bremsstrahlung:
- A continuous broad spectrum, which depends on voltage applied to the tube
- 2) The sharp, intense lines, which depend on the nature of the target material



$e\Delta V = hf_{max} = hc/\lambda_{min}$

$$\lambda_{min} = \frac{hc}{e\Delta V}$$

Example

An electron is accelerated through 50,000 volts
What is the minimum wavelength photon it can produce when striking a target?

Minimum wavelength ⟷ Maximum energy

$$\lambda_{min} = \frac{hc}{V} = \frac{6.6\times10^{-34}\times3\times10^{8}}{50000} = .0248nm$$

Examples

What is the energy of a copper x-ray if it has momentum $4.267\text{x}10^{-24}$ kgm/s?

a. 0.5 keV
b. 2.0 keV
c. 8 keV
d. 0.25 MeV
e. 8 MeV

(8). If the accelerating voltage in a X ray tube is doubled, the minimum X ray wavelength is multiplied by a factor of
(a) 1 (b) 1/2 (c) 2 (d) 1/4

Electrons in an X ray tube are accelerated through a potential difference of 20,000 V. What is the maximum frequency of the X rays that are produced?
(a) 20,000 Hz (b) 2.07×10^{18} Hz (c) 4.83×10^{18} Hz (d) 9.66×10^{18} Hz

Home work   : 26 -16 , 26 – 17 , 26 – 18 and 26 -19