PHYS-3301

Lecture 3

Aug. 29, 2024

Chapter. 3
Wave & Particles I

EM-"Waves" behaving like "Particles"

Outline:

- **Blackbody Radiation (Plank; 1900; 1918*)**
- **The Photoelectric Effect (Einstein; 1905; 1921*)**
- **The Production of X-Rays (Rontgen;1901; 1901*)**
- **The Compton Effect (Compton; 1927; 1927*)**
- **Pair Production (Anderson; 1932; 1936*)**
- **Is It a Wave or a Particle? → Duality?**

The Planck's Black-Body Radiation Law:

The Energy (E) in the electromagnetic radiation at a given frequency (f) may take on values restricted to

$$E = nhf$$

where:

n = an integer

h = a constant ("Planck Constant") $h \approx 6.626 \times 10^{-34}\, J \cdot s$

Blackbody Radiation: A New Fundamental Constant

Plank's spectral energy density is the critical link between temperature and E&M radiation.

Interestingly, although the assumption *E = nhf* might suggest EM radiation behaving as an integral number of particles of energy *hf*, he hesitated at the new frontier - others carried the revolution forward.

For the discovery, Plank was awarded the Nobel prize in 1918 !!

Experimental Fact:

$E = nhf$

BUT Why should the energy of an Electromagnetic wave be "Quantized"? (n= integer)

No Explanation until 1905 Albert Einstein

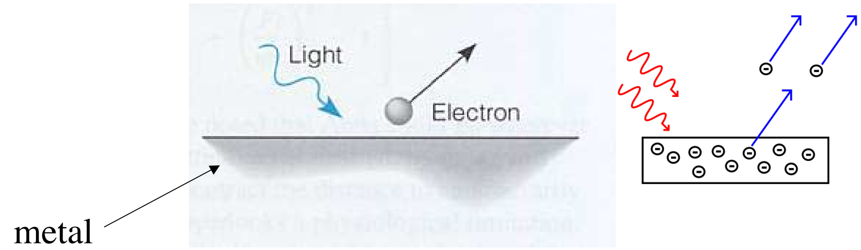
The Photoelectric Effect

A wave is a Continuous Phenomenon **?**

The Photoelectric Effect

(Albert Einstein 1905)

Albert Einstein postulated the existence of quanta of light -- **photons** -- which, when absorbed by an electron near the surface of a material, could give the electron enough energy to escape from the material.



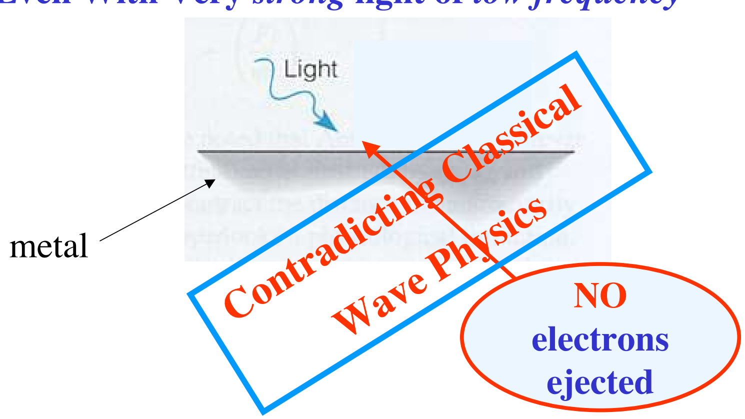
Phenomenon observed long time before Einstein,

and something very strange was observed:

The Photoelectric Effect

(Albert Einstein 1905)

Even With Very *strong* light of *low frequency*

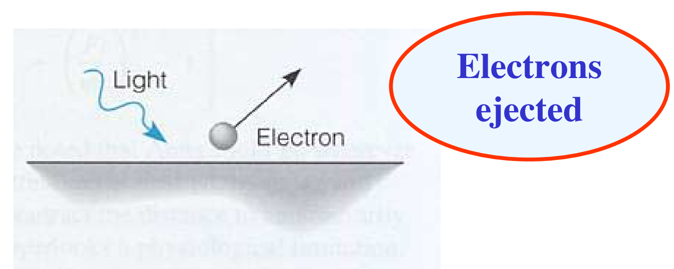


The Photoelectric Effect

(Albert Einstein 1905)

Even With Very-Very *weak* light intensity,

but of *high enough frequency*



Planck's Law
(E = nhf)

Photoelectric Effect
(Threshold frequency)

Albert Einstein proposed:

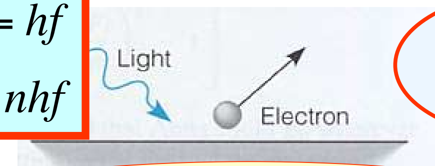
The light is behaving as a collection of *particles* called *"photons"* each of them having energy

$$E = hf$$

The Photoelectric Effect
(Albert Einstein 1905)

Even With Very-Very *weak* light intensity, but of *high enough frequency*

$$E_{photon} = hf$$
$$E_{beam} = nhf$$



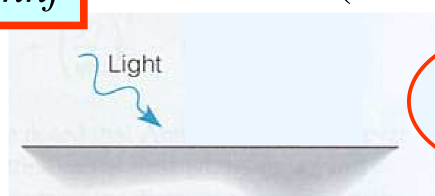
Electrons ejected

What happens is that 1 PHOTON ejects 1 ELECTRON

Example (1): Very intensive light beam, low frequency light

$E_{photon} = hf$ ← **SMALL (below the threshold)**

$E_{beam} = nhf$ ← **LARGE (n is large)**



NO Electrons ejected

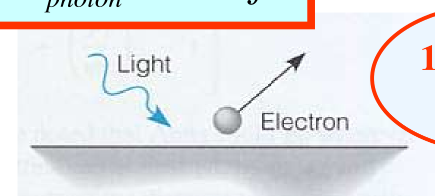
There is no PHOTON capable of ejecting an ELECTRON

Example (2): SINGLE PHOTON

Very weak light beam of high frequency

$E_{photon} = hf$ ← **LARGE (above the threshold)**

$E_{beam} = E_{photon} = nhf$



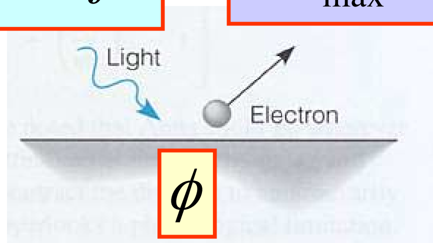
1 electron ejected

The PHOTON ejects 1 ELECTRON

Energy Conservation:

$$E_{photon} = hf$$

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



ϕ

Also known at that time:

Metal	Work Function ϕ (in eV)
Potassium	2.2
Sodium	2.3
Magnesium	3.7
Zinc	4.3
Chromium	4.4
Tungsten	4.5

To free an electron from the metal, one has to "pay" a certain amount of energy

the *Work Function*

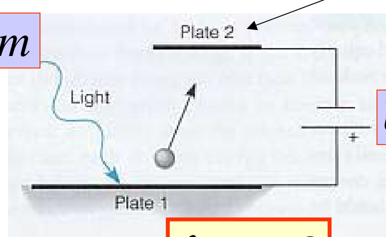
Example 2.1

Light of 380-nm wavelength is directed at a metal plate, plate 1 (Figure 2.1). To determine the energy of electrons ejected, a second metal plate, plate 2, is placed parallel to the first, and a potential difference is established between them. Photoelectrons ejected from plate 1 are found to reach plate 2 as long as the potential difference is no greater than 2.00 V. Determine (a) the work function of the metal, and (b) the maximum-wavelength light that can eject electrons from this metal.

- Determine the max. wavelength light that can eject electrons from this metal.

Repels electrons

$\lambda = 380nm$

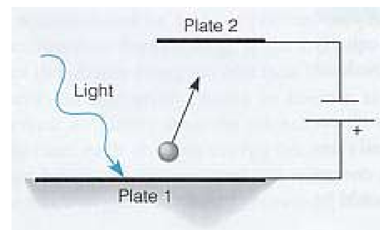


$U < 2Volts$

$\phi = ?$

$\lambda_{max} = ?$

$f_{min} = ?$



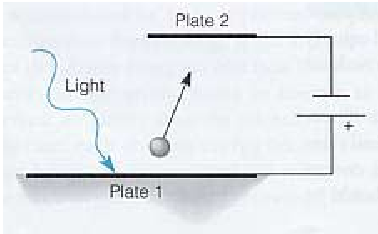
$KE_{max} = hf - \phi$

Solution

- Electrons are ejected from plate 1 with a certain max. KE.
- If none have enough KE to surmount the electrostatic PE difference (qV), no electrons will reach place 2.
- qV ((=1.6x10^{-19} C) (2V) = 3.2 x 10^{-19} J = 2 eV) is the max. that can be surmounted, so the max KE must be 2 eV.
- Using the equation,

$$3.20 \times 10^{-19}\ \text{J} = (6.63 \times 10^{-34}\ \text{J·s})\left(\frac{3 \times 10^{8}\ \text{m/s}}{380 \times 10^{-9}\ \text{m}}\right) - \phi$$

$$\Rightarrow \quad \phi = 2.03 \times 10^{-19}\ \text{J} = 1.27\ \text{eV}$$



- **Determine the max. wavelength (λ') light that can eject electrons from this metal.**
- **The limit of ejecting electrons occurs when an incoming photon has only enough energy to free an electron from the metal, with none left for KE.**

$$0 = hf' - \phi = (6.63 \times 10^{-34}\ \text{J·s})\left(\frac{3 \times 10^{8}\ \text{m/s}}{\lambda'}\right) - 2.03 \times 10^{-19}\ \text{J}$$

$$\Rightarrow \quad \lambda' = 978\ \text{nm}$$

Problems

1. The work function of tungsten surface is 5.4eV. When the surface is illuminated by light of wavelength 175nm, the maximum photoelectron energy is 1.7eV. Find Planck's constant from these data.

$$K_e = hf - W = h\frac{c}{\lambda} - W$$

Problems

1. The work function of tungsten surface is 5.4eV. When the surface is illuminated by light of wavelength 175nm, the maximum photoelectron energy is 1.7eV. Find Planck's constant from these data.

$$K_e = hf - W = h\frac{c}{\lambda} - W \qquad h = \frac{(K_e + W)\lambda}{c} = \frac{(1.7eV + 5.4eV)\times 1.75\times 10^{-7} m}{3\times 10^{8} m/s} = 4.1\times 10^{-15} eV\cdot s$$

$$= 4.1\times 10^{-15} eV\cdot s \times 1.6\times 10^{-19} J/eV = 6.6\times 10^{-34} J\cdot s$$

2. The threshold wavelength for emission of electrons from a given metal surface is 380nm.
(a) what will be the max kinetic energy of ejected electrons when λ is changed to 240nm?
(b) what is the maximum electron speed?

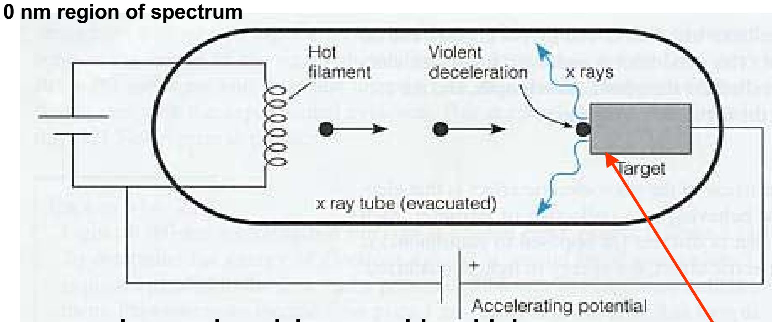
(a) $h\frac{c}{\lambda_0} = W \qquad K_e = h\frac{c}{\lambda_1} - W = h\frac{c}{\lambda_1} - h\frac{c}{\lambda_0} = hc\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_0}\right) = 1.9eV$

(b) $K_e = m_e v^2/2 \qquad v = \sqrt{\frac{2K_e}{m_e}} = 8.2\times 10^{5} m/s$

The Production of X-Rays (Wilhelm Roentgen 1901)

(The "opposite" of the Photoelectric Effect)

We use the name X-rays for EM radiation whose wavelengths are in the 10^{-2} nm to 10 nm region of spectrum

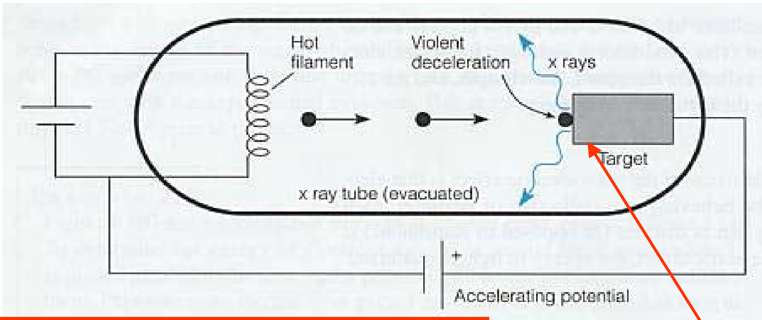


X-rays can be produced by smashing high-speed electrons into a metal target. When they hit, these decelerating charge produce much radiation, called…

Bremsstrahlung

The Production of X-Rays (Wilhelm Roentgen 1901)

(The "reverse" of the Photoelectric Effect)



Photon = wave

CLASSICAL physics:
Radiation covers entire spectrum ← **Bremsstrahlung**

SURPRISE:

Experiments indicate a cutoff wavelength:

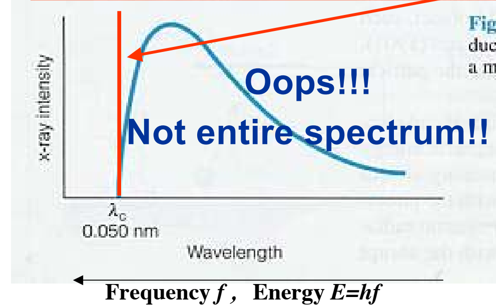


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

There is no classical explanation for so sharp a termination of the spectrum

1 photon -> 1 electron
(?) 1 electron -> 1 photon (?)

SURPRISE:

Experiments indicate a cutoff wavelength:

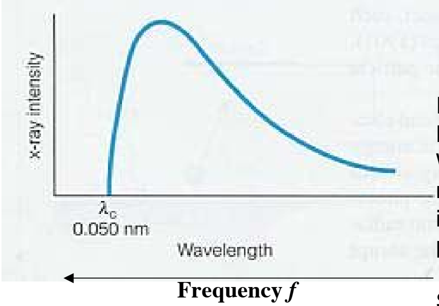


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

If the radiation is quantized, the minimum E allowed at f is "hf" (single photon). We can't produce half a photon, so if multiple electrons don't combine their Es into a single photon, no photon could be produced of E > KE of a single electrons.

Setting the KE of an incoming electron = E of one photon

INDEED:

$$25\ \text{keV} = h\frac{c}{\lambda}$$

$$\Rightarrow \quad \lambda = \frac{(6.63 \times 10^{-34}\ \text{J·s})(3 \times 10^{8}\ \text{m/s})}{(25 \times 10^{3}\ \text{eV})(1.6 \times 10^{-19}\ \text{J/eV})} = 5.0 \times 10^{-11}\ \text{m} = 0.050\ \text{nm}$$

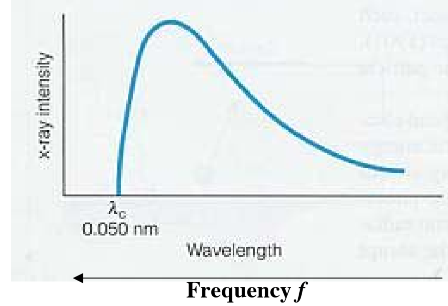


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

INDEED:

1 electron -> 1 photon