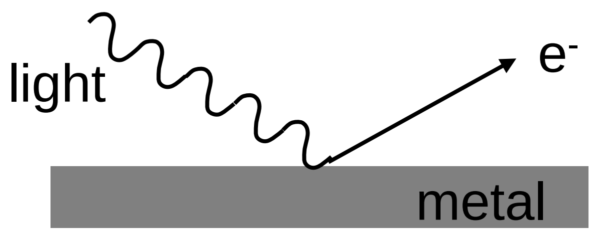
Chapter 3

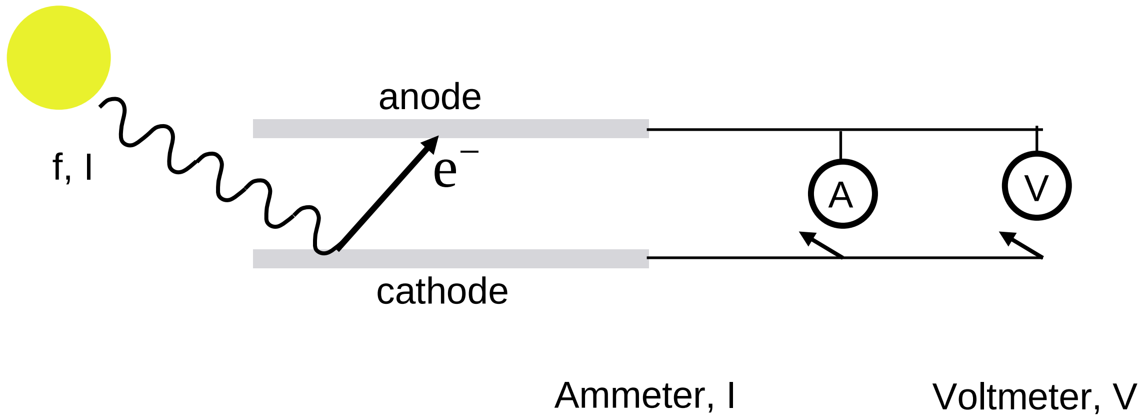
- So light was found to be a wave in the early 1800's…everyone was happily studying optics. Maxwell (1860's) established that light was made up of electronic and magnetic fields that were oscillating:

- As we will soon see a very interesting phase of physics was about to begin. You have already learned about relativity. One of the first "loose ends" that hinted at the emergence of quantum mechanics was called the *photoelectric effect*.

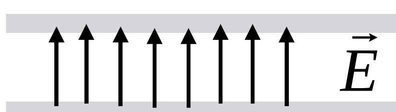


- Various experimentalist came across this feature and saw that many different metals showed this same feature.
- Let's construct an idealize experiment to understand the properties of the photoelectric effect.

Photoelectric Effect Setup



- Mode #1 (Close ammeter switch)
  - Ammeter has R~0
  - Measure I
  - I proportional to # of electrons liberated by the light
- Mode #2 (open ammeter switch, close voltmeter switch)
  - Voltmeter has R ~ infinite
  - Measure Potential difference between plates $\Delta\phi$.
  - Electrons collected on the anode remain on the anode. It becomes negatively charged while the cathode becomes positively charged.



  - Electrons liberated from the cathode will find it harder and harder to get to the anode.

$$U = q\,\Delta\phi$$

  - So electrons will need a kinetic energy of at least

$$K = U = q\,\Delta\phi$$

Note about Units (aside)

- When dealing with particles a convenient unit to work in for energy is an “electron-volt” (eV)

  $1 \text{ eV} = e(1 \text{ Volt}) = (1.6 \times 10^{-19} \text{ C})(1.0 \text{ V}) = 1.6 \times 10^{-19} \text{ J}$

This is defined as change in kinetic energy of an electron when it moves through a potential difference of 1 volt.

➔ Also use:

$1 \text{ KeV} = 1000 \text{ eV} = 10^3 \text{ eV}$

$1 \text{ MeV} = 10^6 \text{ eV}$

$1 \text{ GeV} = 10^9 \text{ eV}$

$1 \text{ TeV} = 10^{12} \text{ eV}$

Since we know from Relativity that the rest energy of a particle is equal to

$E = mc^2$

$m = E/c^2$

A convenient unit for mass is

$1 \text{ eV}/c^2$

$1 \text{ KeV}/c^2 = 10^3 \text{ eV}/c^2$

$1 \text{ MeV}/c^2 = 10^6 \text{ eV}/c^2$

$1 \text{ GeV}/c^2 = 10^9 \text{ eV}/c^2$

Mass proton ~ $1 \text{ GeV}/c^2$ ($938 \text{ MeV}/c^2$) = 1.67×10^{-27} Kg

$M_{\text{top quark}} = 175 \text{ GeV}/c^2$ (Most massive fund. part. known)

Predictions: Wave Model

- We would like to answer several questions with the PE experiment
  - How does the # of electrons ejected change with the intensity of light?
  - What happens with very low intensities?
  - What happens as the frequency of light changes?
  - What is the maximum KE of the electrons ejected (for a fixed I, f)? How does this change when we change I and f?
- We can use what we know about the EM wave model for light to make several predictions:

(A) How will an electromagnetic wave eject an electron?

(B) Effect of Intensity?

Rough Quantitative Estimate:
(Assume all E falling on an atom is delivered to 1 ele.)

Implies rate of electrons should be proportional to I.

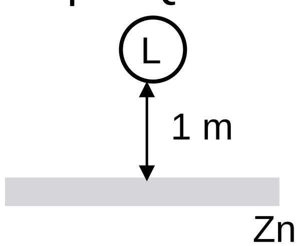
Photoelectric Effect

- (C) At low I the time to eject the first electron should be long. (Invert previous eq.)

$$\frac{\text{Time}}{\text{Electron}} = \frac{\text{Eject}}{I\,d^2}$$

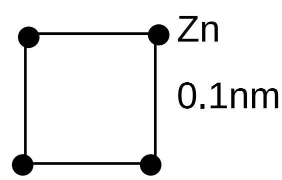
So this could be very long (“seconds”). Let’s see by a specific example:

Example Q3x.4:

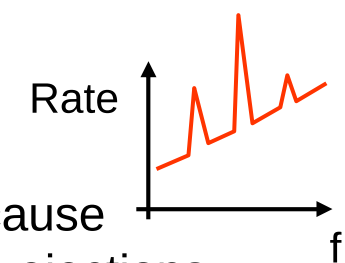


λ=590nm

I=3.2 W/m^2
3.2 (J/s)/m^2

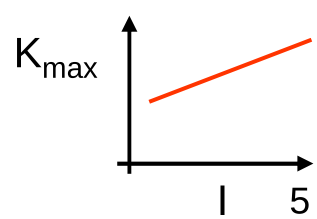


We should be able to measure this.



(D) Changing the frequency of the light might cause complicated changes in the rate of electron ejections (resonance effects) and the properties of the metals.

(E) The Kinetic Energy of the electrons will most certainly depend on the I. It may also depend in a complicated way on the f and properties of the metal.



Results of Our Experiment

- (1) At large I and fixed f:
- (2) At low I (even very low)
- (3) At constant I:
- (4) If $f < f_{cutoff}$
- (5) If f constant,
- (6) If $f > f_{cutoff}$

No modification to the wave model can explain what has happened in this “experiment”

Photon (Particle) Model

- In 1905 not all the results were known but Albert Einstein made a radical proposal. Light was made up small particles (later called photons, γ). The energy of the photon

“Plank’s Constant”

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

frequency Wavelength

$$h = 4.15\times10^{-15}\,\mathrm{eV}\cdot\mathrm{s}$$
$$= 6.63\times10^{-34}\,\mathrm{J}\cdot\mathrm{s}$$
$$hc = 1240\,\mathrm{eV}\cdot\mathrm{nm}$$

- This model correctly predicted the other observations which we described. These were experimentally verified in 1916 and in 1921 Einstein was awarded the Nobel Prize in Physics (*Not for special or general relativity!)*
- As part of Einstein’s model he suggested that each electron was ejected as the results of the absorption of a single γ. In this case,

$$K = hf - W = hc/\lambda - W$$

where W is called the “work function” which is the minimum energy required to remove an electron from the metal.

Let’s see how this explains all of our observations.

Photon Model Predictions

(1) At large I and fixed f:

(2) At low I

(3) At constant I, N_e

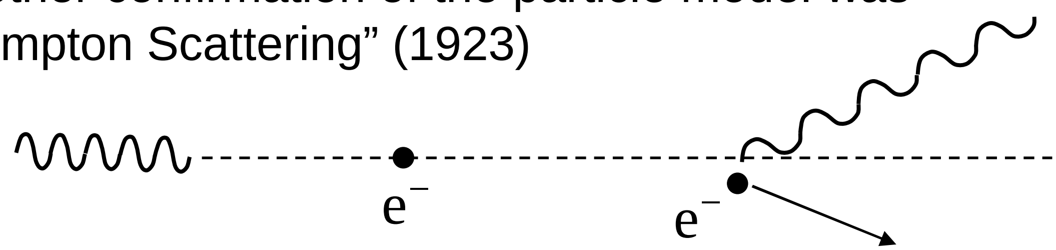
(4) If $f < f_{cutoff}$.

Photon Model Predictions

- (5)

- (6) If $f > f_{cutoff}$

- Another confirmation of the particle model was "Compton Scattering" (1923)



- Scattering of x-Rays off of electrons behave just like two particles.

OK light is a particle right?...Only one problem, the particle model does not explain diffraction or interference.

➔ *<u>Neither</u> model works completely!*