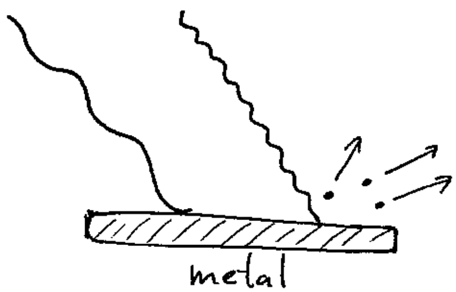
Name:

Physics 200 Tutorial 8:

Photons and the Photoelectric Effect

In this tutorial, you will perform a simulated experiment to test Einstein's prediction for the photoelectric effect, and also work through the derivation of another important prediction of the photon picture of light known as the Compton Effect.



The basic setup for the photoelectric effect is shown. A metal is illuminated with light (or other electromagnetic radiation). For short enough wavelength, it is observed that electrons are emitted from the metal. If the wavelength is too long, no electrons are emitted regardless of intensity. Einstein proposed an explanation based on the photon picture of light. The central points are:

-due to the Coulomb attraction of the positively charged nuclei, there is some minimum energy W required to remove an electron from the metal

-electrons are liberated from the metal in events where a single photon transfers energy to an electron

-no electrons will be liberated unless the energy of the photons is greater than W, so we must have $hf = hc/\lambda > W$

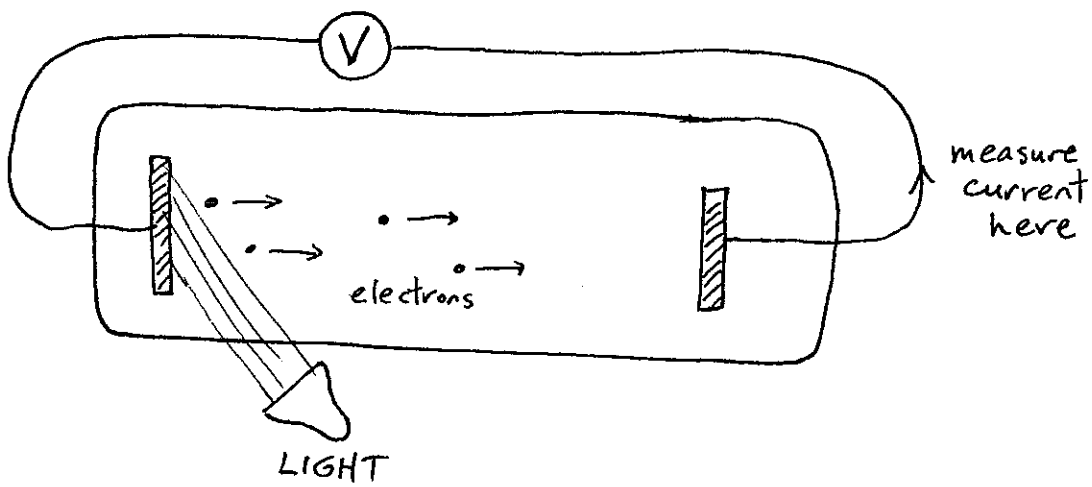
These observations explain why no photons are emitted if the wavelength is too large, but to really test the model, we want to make a quantitative prediction and verify it experimentally.

Einstein pointed out that if the incident photons have energy E=hf, and if there is a minimum energy W required to liberate an electron from the metal, the most kinetic energy that an electron could have would be

$$E^{K}_{max} = hf - W$$

Since h and W are constants (for a given metal), this predicts a linear relationship between maximum electron kinetic energy and frequency.

In order to actually measure the maximum electron kinetic energy, Millikan came up with this experiment:



Here, a battery is used to create a potential difference between the metal on the left side and the metal on the right side (which are connected in a circuit). In order to make it to the right side (and flow through the wire back to the original metal plate) the kinetic energy of the emitted electron must be at least *eV*, the difference in potential energy for the two sides.

As soon as we make eV larger than $E^K{}_{max}$, no electrons are able to pass, so no current will be observed in the wire. Thus, the maximum kinetic energy of the electrons is equal to e, the electric charge, times the voltage at which the current stops

$$E^K{}_{max} = eV_{stop}$$

Question 1

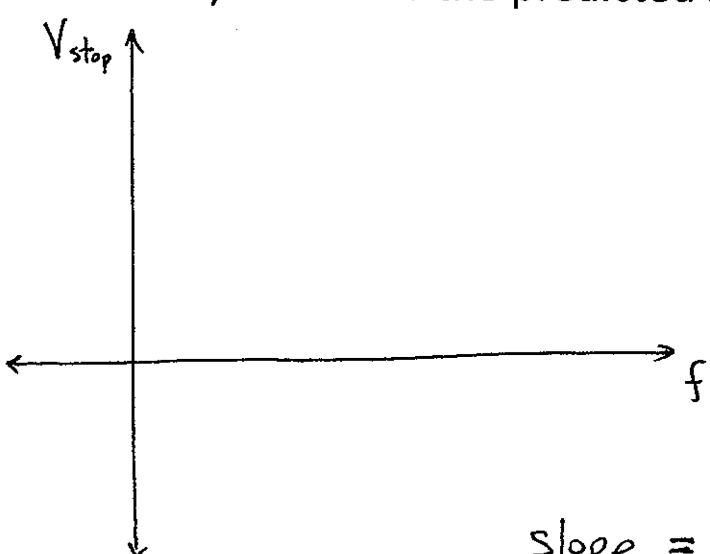
In this question, you will do a simulated photoelectric effect experiment to test the photon picture of light. You can find the photoelectric effect simulation here:

http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect

(or Google "PHET photoelectric" or get it from my memory stick)

a) Based on the photon model, what is the predicted relationship between the stopping voltage V_{stop} and the light frequency?

b) Make a graph of this relationship below. Indicate on your diagram the places where the curve intersects the V and f axes (in terms of W and h). Calculate the predicted slope. → use $h = 6.6 \times 10^{-34}$ J·s, $e = 1.6 \times 10^{-19}$ C



slope =

c) Now, choose the metal sodium as the sample. What is the maximum wavelength light that can eject electrons?

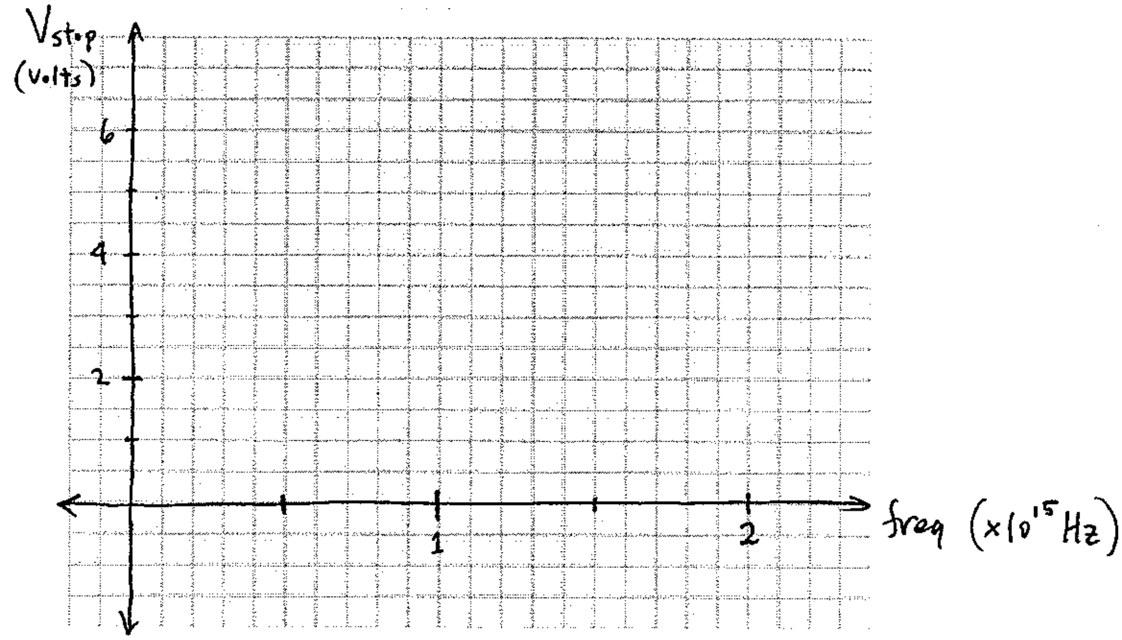
d) What is the work function W for sodium?

e) Fill in the following table:

Wavelength(nm)	Frequency (10^{15}Hz)	Stopping Voltage
193		
244		
350		
538		
750		

★ Does the stopping voltage depend on what intensity you use? ★ WHY?

f) Plot the results below, and estimate the slope (in the region where wavelength is small enough to eject electrons).

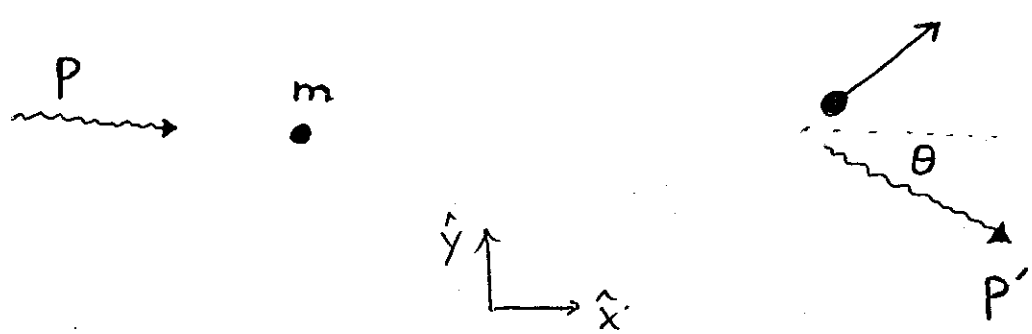


Do the results agree with your predictions from part b)?

② THE COMPTON EFFECT

If light is really made up of photons which behave like massless particles with a specific energy and momentum, we should be able to analyze collisions between photons and other particles using ordinary relativity forulae. In a famous example of this, Compton was able to explain using the photon picture of light why X-rays scattering off electrons are observed to have a shifted wavelength after the scattering. This work earned Compton a Nobel prize, and the observed shift in wavelength is known as the Compton effect. Let's reproduce his explanation:

BEFORE: AFTER:



The basic observation of Compton was that the wavelength of a scattered photon is shifted by an amount that depends only on the scattering angle. The photon picture of such a scattering is shown on the previous page. Let's use energy and momentum conservation to analyze the collision.

a) Suppose a photon with momentum p scatters off a particle of mass m. What are:

The initial total energy:

The initial x-momentum:

The initial y-momentum:

b) If the photon scatters at an angle θ, and is observed to have a final momentum of magnitude p', what are:

The photon's energy:

The photon's y-momentum:

after scattering — The photon's x-momentum:

answer in terms of θ, p', c

c) By momentum conservation, what are the x and y momenta of the electron after the collision?

x - momentum:

y - momentum:

(answer in terms of p, p', θ, c)

d) Using your answers from b) and c), what is the total energy after the collision? Don't use energy conservation yet.

e) By energy conservation, the energy from d) must equal the energy in a). Use this to determine p' in terms of p, m, θ, and c. (Hint: isolate the square root on one side of the equation and square both sides).

f) Use your result from e) to show that the shift in wavelength is

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

g) If X-rays of wavelength 0.1nm scatter directly backwards from electrons in a thin film of metal, what is the wavelength of the scattered electrons?

h) Why isn't the Compton effect observed for ordinary light reflecting from a metal?

③ Prove that it is impossible for a free electron to absorb a photon.

BEFORE:

AFTER: