The Photoelectric Effect

PHYS 220 - Fall 2025

1 Theory

A full treatment is given in in te class reading on the course website. The following explanation has been paraphrased from the equipment manuals referenced at the end of this document.

An important question addressed in this course involves the description of light. At a macroscopic scale, light can be shown to behave as a wave. That is, it is possible to quantitatively discuss the speed, c, wavelength, λ, and frequency, ν, and to demonstrate the wave-like behaviors of reflection, refraction, interference and diffraction. However, at the atomic level, it becomes necessary to consider light as a discrete particle, or packet of energy known as a photon.

According to Planck's law of radiation, the emission and absorption of radiation is associated with transitions or jumps between two energy levels within an oscillating system. The amount of radiant energy emitted or absorbed by such a system is quantized, with a specific value of

$$E = h\nu \tag{1}$$

where E equals the energy of the photon, ν is the frequency of the radiation, and h is a fundamental constant that became known as Planck's constant. This represents an important departure from the analogy with mechanical waves as the energy of light depends on the color, not the amplitude of the wave.

The photoelectric effect provides a convincing demonstration of this principle. When light strikes a metal target, electrons can be emitted from the surface and detected as a measurable photocurrent. Einstein postulated that the energy of an incident photon is transferred to a surface electron. Some of the energy is needed to liberate the electron from the metal. This amount of energy is known as the work function, W, and depends on the type of metal. The rest of the energy becomes the kinetic energy of the electron, up to a maximum value, KE_{max}.

This maximum kinetic energy is measured using a phototube, which is simply two electrodes enclosed in a vacuum tube. Light strikes the larger target cathode, and the photocurrent is detected at the anode. It is possible to apply a potential difference, V, and establish an electric field in the opposite direction of the current to slow the emitted electrons. At a specific value known as the stopping potential, V_0, the photocurrent is reduced to zero, meaning that all electrons including those with the most kinetic energy $KE_{\max}$, are completely deflected. This also means that the energy of those electrons can be expressed as qV_0. Einstein's equation describing the photoelectric effect is thus:

$$E = h\nu = KE_{\max} + W = qV_0 + W. \tag{2}$$

One important implication is that the intensity of light will increase the total number of photons, but it will not increase the energy of the individual photons, or the stopping potential. This also suggests that for a target of given W, there will be a threshold frequency, ν_0, below which no photocurrent can be produced.

The predictions of this theory provide the foundation for an experiment to determine the value of Planck's constant and to verify the photon model of light. The accepted value of Planck's constant $h = 6.63 \times 10^{-34}\mathrm{J} \cdot \mathrm{s}$ in SI units. However, at the atomic scale, it can be more convenient to work with electron-Volts (eV).

2 Preliminary Questions

1. Sodium metal has a work function of 2.28 electron volts (eV). Note: $1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$. Light of wavelength λ is incident on the metal surface.
   (a) What is the maximum wavelength of incident light that can produce a photoelectric effect (*i.e.*, that can lead to the emission of electrons from the sodium metal surface)?
   (b) If light of wavelength $\lambda = 400\mathrm{nm}$ is incident on sodium, determine the maximum kinetic energy of the emitted electrons. Also find the stopping potential.

3 Notes on Equipment

The 3B Scientific Planck's Constant Apparatus uses specific LED's as a light source instead of spectral lines. It is intended to illustrate the concept of stopping potential, to determine Planck's constant, and to investigate the relationship between V_0 and intensity. The photocell is highly sensitive, so the following precautions are necessary:

1. The protective cover should never be removed
2. When the experiment is completed, slide the empty sleeve over the collector tube of the photocell.
3. Keep the apparatus secure so that it does not get shaken and do not expose it to extreme temperatures, high humidity, moisture or direct sunlight

4 Procedure

4.1 Simulation

The circuit in a photoelectric apparatus is typically a simple one, however, the photocell is usually shielded and not easily seen. A versatile simulation of the photocell and the circuit used to apply the stopping potential is available at: http://phet.colorado.edu/en/simulation/photoelectric. Although it is possible to simulate the entire lab activity with this applet, we will use it to illustrate some basic functions of the photocell.

1. Open the applet and adjust the different variables. Specifically, note what happens in the simulation when you:
   (a) Increase the intensity slider to 100%.
   (b) Change the wavelength of the light to different values.
   (c) On a wavelength setting that emits electrons, change the potential applied by the battery.
2. Investigate the concept of stopping potential:
   (a) Set the intensity to 100%, the wavelength to a color that emits electrons and the battery to 0.00 V. Note what happens to the electrons in the simulation.
   (b) What happens to the electrons and the value of current when you increase the battery potential in the positive direction? In the negative direction?
   (c) Find and record the value of battery potential when the current first registers 0.
   (d) Does this value of potential change when you change the intensity of the light? When you change the wavelength of the light? Which has a bigger effect?
3. Investigate work function and threshold frequency:
   (a) Reset the intensity to 100%, the wavelength to a color that emits electrons and the battery to 0.00 V.
   (b) Increase the wavelength until the current first registers zero, and then slightly beyond. Note what happens to the electrons in the simulation. Find the lowest wavelength that does not emit electrons, and record this value as the threshold wavelength
   (c) Change the metal target from the menu. Repeat the previous steps to determine the threshold wavelength for all available targets. Note that this is easy in the simulation, but it would be considerably more difficult and expensive in an experimental setup.
   (d) Determine the threshold frequency and corresponding photon energy for each of the metal targets.

4.2 Measurement of Planck's constant.

Following Equation 2, we will measure the stopping potential for several frequencies of light.

1. Plug in the transformer to supply power to the apparatus
2. Set the intensity of the light source to 75%
3. Insert the plug for the first light source into the LED connector socket
4. Push together the jaws of the clip for the sleeve over the collector tube of the photocell and remove the tube
5. Push the LED unit fully onto the collector tube of the photocell until the jaws of the clip snap into place
6. Set the fine and coarse adjustment knobs for the voltage to a central position
7. Wait a few minutes, then slowly turn the coarse setting knob until the photoelectric current measured by the nanoammeter is approximately 0.
8. Use the fine setting knob to optimize the calibration. Turn it around until the display oscillates between 0 and -0.
9. Record the voltage as the stopping potential V_0
10. Repeat this measurement for the other four LEDs.

4.3 Measurement of stopping voltage V_0.

Using a similar set-up as before, we experimentally determine the stopping voltage

1. Set the fine and coarse adjustment knobs for the voltage to 0. The nanoammeter's reading of -1. indicates saturation.
2. Slowly turn the coarse setting knob until the photoelectric current measured by the nanoammeter provides actual data. Record the voltage and the photocurrent.
3. Increase the voltage in increments of your choosing. Record the voltage and photocurrent for a series of these increments.
4. Change the intensity to a different value, and repeat these steps.
5. Change to a different LED and obtain similar data sets for two different intensities.

4.4 Stopping voltage V_0 and light intensity

1. Select an LED, set the light to maximum intensity, and determine the stopping voltage.

2. Reduce the intensity to zero in a series of steps and determine the stopping voltage in each case.

3. After the experiment, close the plastic cover back over the tube.

5 Analysis

1. Simulation: Make a table of the threshold frequency, ν_0, and work function, W, for each of the metal targets. Compare with known values, and identify the unknown metal target.

2. Determining Planck's constant:

   (a) Determine the frequencies, ν, of the LEDs

   (b) Plot the stopping potential V_0 as a function of frequency ν for the data from Section 4.2. Assuming Einstein's equation is applicable, perform a straight-line fit to the data and determine the slope and y-intercept of the line. From the slope, calculate your experimental value of Planck's constant h.

   (c) Estimate the uncertainty in the slope and y-intercept. Express your result as: experimental value $\pm$ uncertainty. Compare your result for h to the accepted value, taking the uncertainty and the units (SI or eV) into account.

   (d) From the y-intercept of the V_0 vs ν graph, determine the work function of the photosensitive material (including its uncertainty). This comparison is best expressed in units of eV. Compare your value of W to data on the work function for metals.

3. Measurement of stopping voltage: Plot the photocurrent I as a function of applied voltage V for the data obtained in Section 4.3. Plot the high and low light intensity data for both LEDs on the same set of axes. For each graph, determine the stopping potential.

4. Stopping voltage and light intensity:

   (a) Based on your data and previous graph of the measurement of stopping voltage, is there a relation between the light intensity and the photocurrent? If so, describe the relation qualitatively.

   (b) Examine the data taken in Section 4.4. Is there a relation between the light intensity and the stopping potential? If so, describe the relation qualitatively.

5. Describe qualitatively the predictions of Einstein's photon theory of the photoelectric effect concerning:
   (a) the relative size of the photocurrent for the two light intensities in the data of Section 4.3.
   (b) the stopping potentials for the two light intensities in the data of Sections 4.3 and 4.4.
6. Overall, do your experimental results support Einstein's theory? Explain.

6 References

- Equipment Instructions (abbreviated EI1) for Sargent-Welch Planck's Constant Apparatus
- Equipment Instructions (abbreviated EI2) for PASCO h/e Apparatus and Accessory Kit
- Equipment Instructions (abbreviated EI3) for 3B Scientific Planck's Constant Apparatus (U10700-115)
- Thornton and Rex, Modern Physics 3$^{\text{rd}}$ edition, pp. 103-111
- Tipler and Llewellyn, Modern Physics 5$^{\text{th}}$ edition, pp. 127-132