EXPERIMENT NO. 3

The Photoelectric Effect

Reference: Physics for Scientists and Engineers, Serway & Jewett, Section 40.2

Purpose: The purpose of this experiment is to investigate some aspects of the classical and quantum descriptions of the properties of light, and then to use the h/e apparatus to make an accurate determination of Planck's constant.

Theory: In 1901, Max Planck published his law on radiation, in which he proposed that the energy levels in an oscillator are not continuously distributed in energy, but are quantized. In 1905 Einstein showed that Planck's law implied that the emission and absorption of electromagnetic radiation by matter, including the emission of what we refer to as "light", involves quanta of energy. These quanta have subsequently become known as "photons". The energy lost or gained by the system corresponds to the emission or absorption of photons with energy $E = h\nu$ where E is the radiant energy, ν is the frequency of the radiation, and h is known as the Planck constant. Einstein used this concept to explain certain aspects of photoelectric emission, a phenomenon whereby light striking a material sometimes causes electrons to be emitted. In particular, prior to Einstein's work, the classical (or wave) model describing the properties of electromagnetic radiation incorrectly predicted that the energy of emitted photoelectrons should increase as the intensity or amplitude of the source light increased. However, it had been known for some time from experimental measurements that this increase in energy does not occur. In practice, it was observed that the kinetic energy (KE) of the ejected electrons was dependent on the frequency of the source light, and independent of the intensity. While only the magnitude of the photoelectric current (i.e. the number of electrons emitted/unit time) was dependent on the intensity of the source. Einstein showed that the quantization of energy levels in solids, together with the conservation of energy, resulted in the following relationship:

$$E = h\nu = KE_{\max} + w_o$$

where E is the energy of the incident photon, $KE_{\max}$ is the maximum energy of the emitted photoelectron, and w_o is called the work function of the metal, and represents the minimum energy required to remove an electron from the surface of the metal. It's value depends on the composition of the photocathode.

In the experimental apparatus used here, light from a Hg source is incident on the cathode of a vacuum tube. Incident photons are absorbed by electrons in this cathode promoting them to higher energy. If this energy exceeds the work function, then electrons will be emitted from the cathode. Since the electron uses w_o of its initial energy to escape the metal, it leaves the cathode with a maximum kinetic energy $KE_{\max}$. Normally, these electrons would reach the anode of the vacuum tube and be collected and measured as a photoelectric current. However, in the apparatus you will be using, a reverse potential (V) is applied between the anode and the cathode, which stops the photoelectrons from reaching the anode. KE_{max} can be determined by measuring the minimum potential, V, required for stopping the photoelectrons and thus reducing the photoelectric current to zero. Relating the kinetic energy to the stopping potential gives:

$$KE_{\max} = V\,e$$

where e is the elementary charge on an electron: 1.602 x 10^{-19} coulombs.

Therefore the Einstein equation becomes:

$$h\,\nu = V\,e + w_o \qquad (1)$$

Procedure

The basic set - up of the apparatus is outlined in the following diagram:

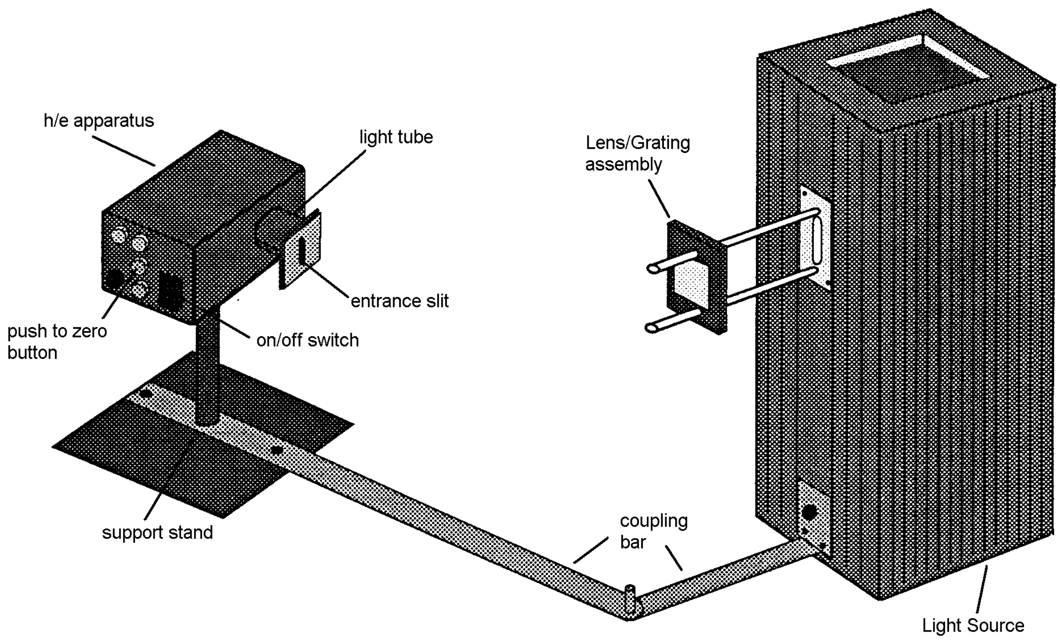


Figure 1: The experimental configuration

Note that the light source should always be on the right, and the h/e apparatus will be moved in a clockwise fashion (as viewed from above) towards the light source.
Turn the light source on and allow it several minutes to come up to full intensity. The Hg light source is polychromatic (composed of many wavelengths). In order to separate the source light into it's component (monochromatic) wavelengths, a diffraction grating is used. Swing the support base towards the light source and note the pattern of coloured lines. There are multiple images of the pattern. Each image consisting of all the coloured lines is called a diffraction order. Starting from a position directly opposite the light source, the first (and brightest) image

of the coloured lines will be what is referred to as the "first order". The second set of lines constitutes the second order, and so on. Due to intensity and angle limitations, you may only be able to see one or two of the possible colours in the third order spectrum.

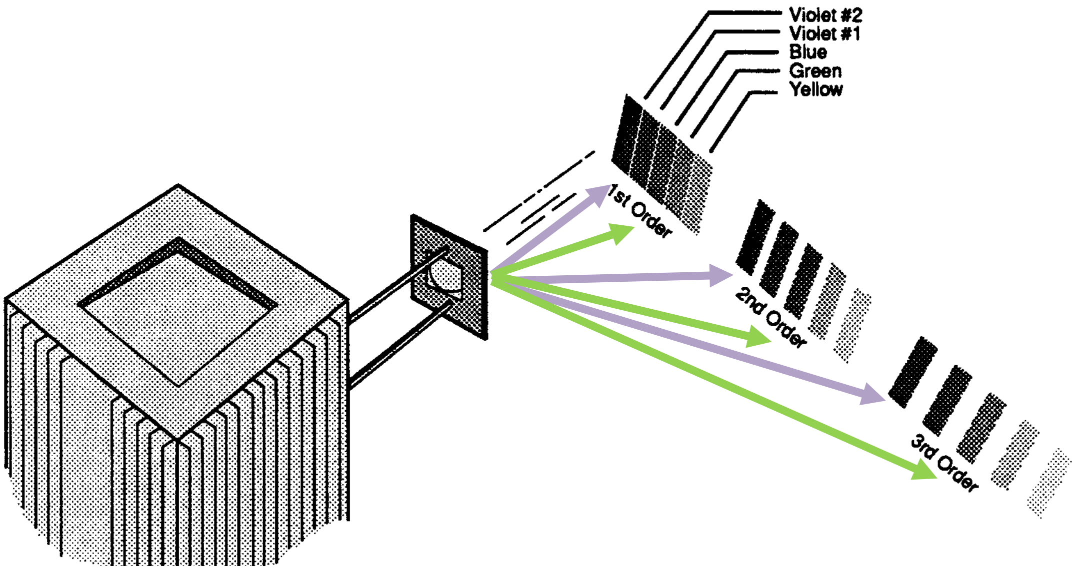


Figure 2: Illustrating the spatial separation of diffraction orders. Note the increasing angular separation between the violet and green lines as the order increases.

Position the h/e apparatus so that any of the 1st order lines falls on the white mask near the entrance slit. Loosen the thumbscrew located on the top of the lens/grating assembly, and adjust the position of the assembly so that a sharp, focussed image of the slit is produced on the mask. Now, position any of the individual coloured lines directly onto entrance slit. Rotate the hinged light shield (the tube directly behind the white mask) out of the way (see Figure 3) to reveal the opening to the inside of the h/e unit.

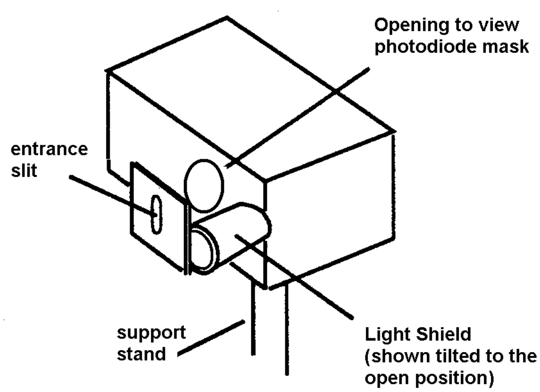


Figure 3: Opening the Light Shield

Inside you will see a white photodiode mask, which has a small rectangular window. This window allows the light to reach the cathode of the vacuum tube. Rotate the h/e apparatus on its support stand so that the same coloured line falls directly on this window. It is imperative that you adjust this so that there is NO overlap of any of the adjacent coloured lines. Make further adjustments to the lens/grating assembly to make the image on the photodiode mask (inside the h/e unit) as sharp as possible. Secure the lens/grating by tightening the thumbscrew, and return the light shield to it's closed position.

Connect the digital multi-meter (DMM) to the terminals on the h/e apparatus. Turn the DMM on. Put the selector to the 2V range on the DC voltage scale.

You are provided with a green and a yellow filter. These can be attached (magnetically) to the white mask area surrounding the entrance slit. Every time you make a measurement involving either one of these two colours you must use the corresponding colour filter.

Theory of Operation:

In experiments with the h/e apparatus, monochromatic light is incident on the cathode plate of a vacuum photodiode tube that has a low work function. Photoelectrons ejected from the cathode are collected at the anode.

The photodiode tube and its associated electronics have a small capacitance (charge storage) which becomes charged by the photoelectric current. When the potential (voltage) on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero and the anode - to - cathode voltage stabilizes. This final voltage between the anode and cathode is therefore the stopping potential of the photoelectrons.

To allow a direct measurement of the stopping potential, the anode is connected to a unity gain amplifier which has an ultra-high input impedance ($>10^{12}\ \Omega$). The output of this amplifier is connected to the output jacks on the h/e apparatus.

Part A : Wave model of light vs quantum model.

Adjust the position of the h/e unit so that any first order line falls on the entrance slit. Make sure (open the light tube to check) that it is the only colour hitting the mask inside the h/e unit. Place the variable transmission (%T) filter over the slit so that light only passes through the section marked 100%. Turn the h/e apparatus on. Wait for the DMM reading to stabilize and record the stopping potential enough times to get a good average value for the stopping potential. In each case, between measurements, press and hold the "push to zero" button and wait for the DMM reading to reach zero volts.

In the next set of experiments, **simultaneously** release the "push to zero" button and start the stopwatch. Measure the time it takes for the DMM to return to the stopping potential reading. Repeat this three times in order to achieve a consistent (average) result. Move the variable transmission filter over to the next section (80%) and repeat the process. Repeat until you have tested all five sections of the filter. Adjust the h/e apparatus to a different colour 1st order line, and repeat the entire process again.

<u>Part B:</u> The relationship between energy and frequency.

The accepted wavelengths for the five Hg spectral lines are 365nm (violet 2), 405nm (violet 1), 436nm (blue), 546nm (green) and 578nm (yellow). These lines appear in each order.

Using lines in the first order spectrum, measure the stopping potential for each wavelength. Do this three times for each wavelength, zeroing the detector between each measurement. Remember to use the corresponding filter when you measure the yellow or green lines.

Go to the second order and repeat these measurements. If you can see any 3rd order lines measure them as well.

<u>Analysis of results</u>

Part A:

- Describe the effect that passing different amounts of same coloured light through the variable transmission filter has on the stopping potential and thus the maximum energy of the photoelectrons liberated from the cathode, as well as the charging time required after the “press to zero” button is released.
- Describe the effect that different colours of light had on the value of the stopping potential and thus the maximum kinetic energy of the photoelectrons.
- Defend whether or not the results of this experiment support a wave or a quantum model of light. Be specific.
- Suggest reasons for the slight drop in measured stopping potential as the intensity of the source light is decreased.
- For one wavelength, plot a graph of I/I_o vs. average time to reach the stopping potential on 1 cycle semi- log paper. Draw the best straight line fit to the points. What does this plot suggest about the relationship between the intensity of the light and the photoelectric current?

Part B:

- What optical frequencies (in Hz) are emitted from the source? Use $c = 3.0 \times 10^8$ m/s.
- Calculate the average stopping potential for each wavelength emitted. Plot this average stopping potential vs. frequency on linear graph paper.
- From the plot, determine a value for the Planck constant “*h*”, and the work function “w_o” of the cathode metal. Take $e = 1.602 \times 10^{-19}$ coulombs.
- Use a reasonable estimate in the uncertainty in your average stopping potentials to draw in error limits to your data points. Draw in maximum and minimum slopes and use these to assist you in determining an absolute uncertainty in your *h* and w_o values.
- Compare your value of *h* to the accepted value of 6.63×10^{-34} J·s. Does your uncertainty estimate agree with the difference between your measured values and the standard value?

Critical analysis of this experiment

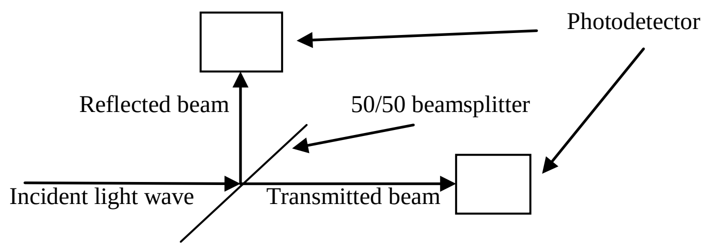
The PE effect, on its own, does not yield any information on the quantization of the EM field, it simply confirms that energy levels for particles such as electrons in atoms and solids are quantized and that their energy is given by solutions to the Schroedinger equation.
If energy levels in matter are quantized, then differences in energy must be quantized, independent of the radiation field. A transition between two quantized energy levels can then be excited by applying a **classical** EM field having the required energy difference. This is the "semi-classical" description of the PE effect: one in which the energy levels for electrons are quantized while the applied radiation (the light wave) is described by a classical EM wave. This model is consistent with all the observations that you have made in this experiment.

Questions:

1. Can you think of some other property of photons that could be used to "prove" that they have particle-like characteristics?

2. Do the photoelectrons ejected by light of a given wavelength all have the same energy, or would you expect a range of energies? What would be a possible explanation for a range of observed electron energies when emission was excited with photons having a single energy?

3. What would happen to the measured photocurrents in each detector in the following experiment if you were able to reduce the intensity of the light wave to a very low level? Would this be a way to distinguish between the wave and particle descriptions of the photoelectric effect?



4. Why is the optical frequency of a given spectral line the same in all three orders of the diffraction grating?