# Experiment 332: The Photoelectric Effect

## Aim

To investigate the photoelectric effect and deduce the value of Planck's constant, $h$.

The purpose is to give you an opportunity to design your own investigation using the equipment provided, based on an understanding of both the theory and equipment.

## References

There are numerous references which may be of use to you, for example:

1. Any Stage 1 "Modern Physics" or Stage 2 "Quantum Physics" textbook.
2. Optics textbooks such as E. Hecht, "Optics", Addison-Wesley.
3. Rudnick and Tannhauser, "Concerning a widespread error in the description of the photoelectric effect", pp 796-798, Am.J.Phys, **44** (1976).
4. Relevant sections of the PASCO pamphlets.

## Introduction

The emission of electrons from a metal surface when light is shone on it is called the Photoelectric Effect. The dependence of the maximum kinetic energy of the electrons on the frequency of the light, and on its intensity, was explained by Albert Einstein and is given by

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

where $\phi$ is the work function of the metal, and $h$ is Planck's constant. This explanation was one of the initial successes of the quantum theory of light.

## The Apparatus

This experiment has two set-ups (A and B) in order for two students to undertake this experiment simultaneously. They are both fully working, but one is newer and possesses different capabilities. Make it clear in your report first which setup you used.

### A: Diffraction Grating Apparatus

In this experiment, the metal surface from which electrons are emitted has been prepared in vacuum and sits inside a vacuum photocell (to the left on Fig. 1). The electrons, after they are ejected, strike the anode of the photocell which is connected to the high-impedance input of the amplifier. As more electrons accumulate on the anode its potential rises (negatively) until the voltage difference between it and the cathode is sufficient to repel even the highest energy electrons. This voltage difference is measured at the output of the amplifier by the DVM.

The source of light is a mercury vapour lamp with a narrow exit slit (to the right in Fig. 1). The light from this slit passes through a combined focussing lens and (blazed) diffraction grating which splits it into four orders, two on each side of the straight-through position. A fluorescent screen is fitted in front of the

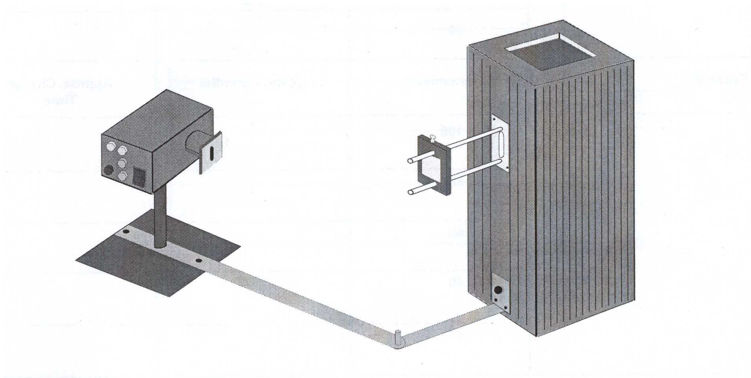

Figure 1: Experimental apparatus, setup A

entrance mask of the photocell, and on it five bright lines may be seen in each order, referred to subsequently as yellow, green, blue, violet and ultraviolet ($\lambda = 577$, 546, 436, 405, 365 nm). These are the lines to be used for the experiment.

Three filters are provided. The first two, yellow and green, should always be placed on the outside of the fluorescent screen whenever the corresponding lines are being used. The third consists of strips of differing densities of computer generated dots, and gives areas of effective transmission varying from 100 % down to 20 %.

**Things to Note:**

1. To ensure full intensity, the light should be switched on at least 5 minutes before any data is taken.
2. The positions of the diffracted orders can be located either by swinging the fluorescent screen round, or by using apiece of white paper.
3. The beam may be focussed on the slot in the screen by sliding the lens/grating along its mounting rods.
4. The light passing through the slot in the screen should enter the photocell through its mask. To arrange this, flip the cylindrical light shield out of the way and rotate the screen/photocell module. Then fix the position by tightening the screw on the vertical mount, and put the shield back. In subsequent measurements, check periodically that the orientation is still correct as the screw does not have much purchase.
5. Before each DVM measurement, zero the voltage at the amplifier output using the button provided. Take care as the orientation of the photocell should not be disturbed.

## B: Straight-facing Apparatus

Mechanically, this setup (seen in Fig. 2) is much simpler to the diffraction grating apparatus. The full light of the mercury lamp shines upon the photocell and the individual spectral-lines of mercury are selectively filtered by five corresponding filters selectable on a turn-style. Also adjustable on the turn-style are three apertures (of 2 mm, 4 mm, and 8 mm diameter) to adjust the intensity of light incident on the cathode.

This setup differs from the previous one in an important way. Here, the anode and cathode in the photocell are connected in a series circuit. Thus, when the mercury light is shone on the cathode, ejected electrons are given the energy necessary to stimulate a photo-current. This current is measured directly by a current amplifier connected in series with the anode and cathode (via BNC coaxial cable).

Also connected in series, is an adjustable DC power supply. This voltage is connected in reverse bias relative to the photo-current (with the negative lead connected to the anode) and so acts to repel the electrons back toward the cathode. By setting this voltage such that the measured current is zero, you are able to discern the energy of the ejected electrons. A DVM connected in parallel can measure this voltage more accurately.

Figure 2: Experimental apparatus, setup B

**Before you start:**

1. Check that the caps are on both the lamp and the photocell enclosure at first, and that the DC voltage is turned to zero.
2. To ensure full intensity, the mercury lamp should be switched on at least 10 minutes before any data is taken.
3. You can adjust the separation between the mercury light source and the photocell by loosening the thumscrews on the track behind each module. The recommended distance is 35 cm.
4. Check that the anode lead (marked ‘A’) is connected to the negative terminal of the power supply and the ground lead is connected to the positive terminal. If you wish to take current measurements with forward bias voltages, simply swap the leads.
5. Turn the current amplifier range to $10^{-13}$ (Amps) for the most accurate, but sensitive resolution. Increase this if you are graphing higher current ranges. Zero the reading by pushing in the SIGNAL button and adjusting the calibration dial, then pushing the SIGNAL button out again. Note that there exists a ‘dark current’ marked as $\leq 2$ pA.
6. Remember to replace the cap over the photocell enclosure after taking measurements.

**Warning: The mercury lamp is very hot when on, especially the top face. Handle with care.**

# Procedure

Overall it is for you to decide how to put Einstein’s theory of the photoelectric effect to the test using the equipment provided. Clearly, you will need a good understanding of the theory in order to do so (particularly what the maximum electron kinetic energy is dependent on and independent of). It is also important to keep the following in mind:

> Although it is often said that a theory can be disproved by a single discrepant result (i.e. one which disagrees with it), in practice this is very difficult to accomplish, especially for well established theories such as the photoelectric effect. If an experimenter finds their results, after taking into account an error analysis (which, as you know, is a measure of their confidence in their measurements), seem at odds with those predicted, the first thing they must do is turn back to their experiment and try to determine if something about its nature is responsible for the discrepancy.
>
> In other words, science, and experimentation in particular, is a questioning process which involves continuous refinement until we believe we understand everything well enough to have confidence in our ability to convince others of our results and conclusions.

The following steps are provided as a guide to help you develop your investigation. Note that they are iterative, i.e. you may find you need to backtrack one or two steps as you work your way through. If, after you have worked the allocated number of sessions you still have unanswered experimental questions, do not be too concerned. (Note that the questions listed below may also be of help to you).

1. Familiarise yourself with the theory and the equipment provided. Make sure you understand its operation and determine features which you think are of particular relevance to your investigation.

2. Based on your results from Step 1, devise a procedure to rigorously test Einstein's theory.

   **Hints:**

   (a) Be sure that you can justify the decisions you make on the basis of both your understanding of the theory and the equipment available.

   (b) Make your testing as rigorous as you can, e.g. ensure you have several sets of data from which you can calculate $h$.

   (c) It will probably be useful to record, for each DVM measurement, the approximate time for the voltage to reach equilibrium. It can sometimes take as much as a minute.

   (d) You may find it helpful to talk over *your* ideas with a demonstrator.

3. Conduct the experiment you have devised. Ensure you do some preliminary analysis as you go so you can adjust your data collection procedure if necessary.

   After you have carried out an initial analysis determine if you need to return to Step 1 or 2 in order to refine your understanding of the equipment or modify your data collection technique.

## Questions

1. What is your best estimate of the value of Planck's constant? If you have omitted some of your results in obtaining this value, you should justify this. Compare with the accepted value, and discuss sources of error.

2. From your results, you can derive a value for the work function. Which work function is that?

3. What does your investigation and results tell you about the difference between frequency and intensity as they relate to the nature of light.

   **Bonus questions for apparatus A:**

4. The shortest wavelength of the five is approximately 360 nm. Isn't that in the ultraviolet? Why can you see it?

5. Why is it necessary to use the green and yellow filters when working with those lines? What happens if you don't, and why?

6. Why is there a wide variation in the times taken for the DVM to read the equilibrium voltages?

## The Report

Your report must include:

1. The procedure you decided upon using and a *justification* for it.

2. Results and analysis.

3. Discussion of any unanswered issues and, where possible, how you would proceed to investigate them.

4. Conclusion about the success or otherwise of your investigation and the validity of the theory/experimental results.

5. Answers to the listed questions (distributed through the report as you wish).

If your investigation went through an iterative process be sure to include a discussion of its development in your report.

## List of Equipment

1. Digital voltmeter (DVM).

**Apparatus A:**

1. Mercury light source.
2. Combined focussing lens and diffraction grating.
3. Intensity filters for 100 %, 80 %, 60 %, 40 %, 20 % transmissions.
4. Wavelength filters for yellow and green light.
5. Photocell with low work function cathode + high input impedance ($> 10^{13}\ \Omega$), unity gain amplifier.

**Apparatus B:**

1. Photoelectric effect ensemble.
2. DC current amplifier.
3. Adjustable DC power supply.

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