Experiment 6

The photoelectric effect

In this experiment we will determine the Planck's constant through photoelectric effect. Explaining the somewhat puzzling result — the stopping potential measured as the voltage produced by a photocell depends on the wavelength and, therefore, on the energy of the incident photons, but not in the intensity of the incident light — led to the beginnings of quantum physics. The experiment yields an excellent estimate of the Planck's constant.

6.1 Introduction

Photoelectric effect has a place of pride in the history of experimental Physics as one of the watershed experiments that led to the development of Quantum Mechanics. It is also what Albert Einstein got his Nobel Prize for. Since the apparatus is relatively simple, almost every undergraduate Physics major runs into this experiment at some point, and the web is full of reports of mostly poor quality. However, when the experiment is done well, it is a very reliable way of measuring the Planck constant, $h = 6.62607015\times10^{-34}$ Js (as established at the General Conference on Weights and Measures in 2018).

The Einstein photoelectric equation relates the kinetic energy K of the emitted electron to the frequency of the radiation falling on the emitter and the energy required to extract the electron from the material

$$K = h\nu - W_s = h\nu - eV\,, \tag{6.1}$$

where the extraction energy W_s, known as the work function of the material, is written as the product of the magnitude of the electron charge e and a retarding electric potential V . Electrons will be emitted only if $h\nu > eV$.

If the emitter is used as the cathode of a vacuum cell and connected to the other electrode, or anode, a current will exist in the circuit as long as light of sufficiently short wavelength falls on the cathode. If a retarding potential is applied between anode and cathode by an external source, the current will be reduced. The current will be zero if the retarding potential is set at the value $V_0 = h\nu/e$. In the experiment you will measure the retarding potential required to stop the photoelectric current as a function of frequency, or reciprocal wavelength: $c = \nu\lambda$ and therefore, $\nu = c/\lambda$ where c is the speed of light. A value of h will be determined from the graph of the "stopping" potential V_0 as a function of ν.

6.2 The apparatus

There are two versions of the apparatus available in the lab. One is a modified version of the LEAI-51 "Plancks Constant Apparatus" from Lambda Scientific (the 'Lambda apparatus', shown in Fig. 6.1), and another is custom-built and uses a research-grade Heathkit 619 electrometer (the 'Heathkit apparatus'). There are subtle differences between the two setups, but the basic principle is the same: a monochromatic light shines on a photocell and the voltage required to stop the photocurrent is measured. In both setups, the source of monochromatic light is the mercury (Hg) discharge lamp with a dedicated power supply. This is potentially a dangerous device!

> **CAUTION:** *Do not look into the Hg lamp, prolonged exposure can damage your eyesight. The power supply is a source of high voltage, do not touch the contacts when the power supply is on. Avoid quickly power-cycling the lamp: after it is turned off, it must cool down for at least 20 mins before you may turn it back on.*

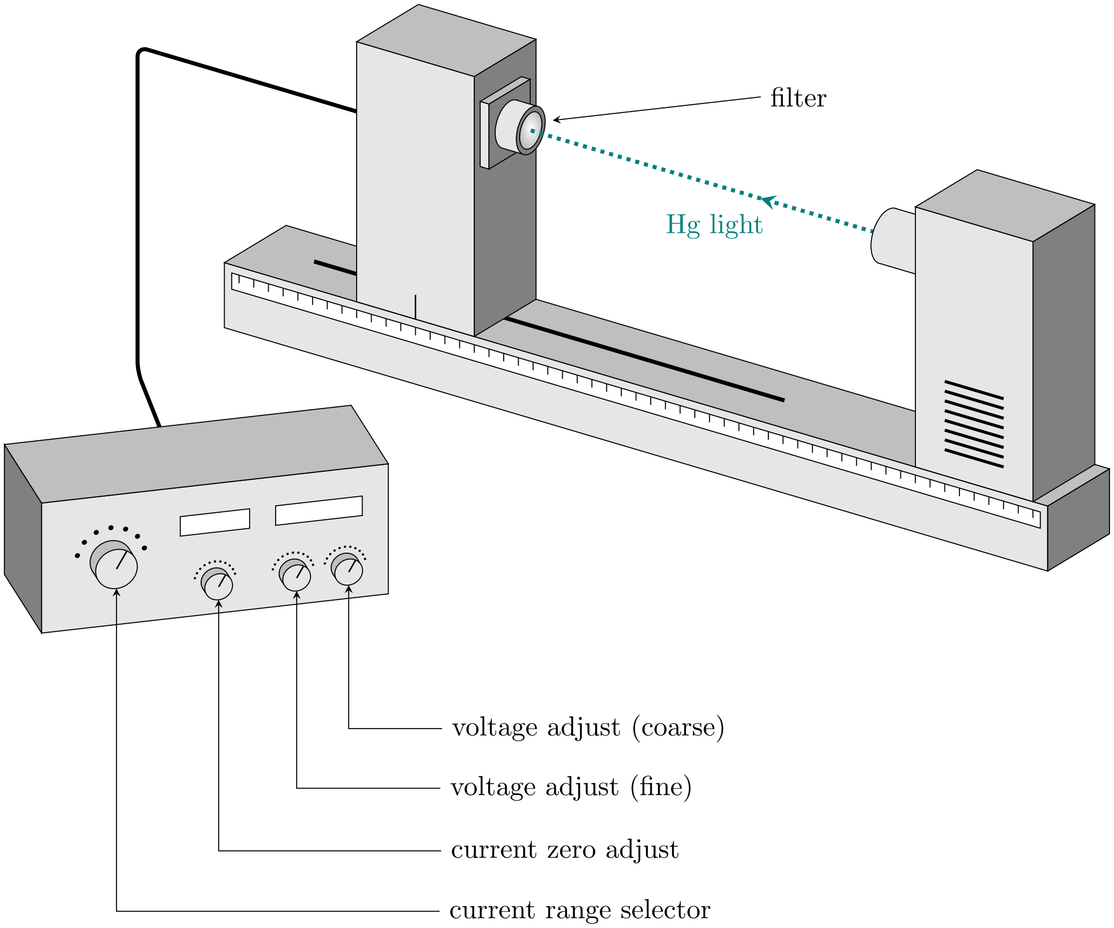

Figure 6.1: The LEAI-51 “Plancks Constant Apparatus” from Lambda Scientific. The photocell is on the left and the Hg source on the right. The photocell position can be adjusted by sliding the photocell enclosure along the track, its position monitored on the scale on the side of the track. An opening on the front of the photocell enclosure offers a snug fit to the interchangeable monochromatic filters. This drawing in tikz is by C.Wilson.

Table 6.1: Wavelengths (in air) of some of the strong lines of mercury (Hg) and the matching bandpass filters. Hg data from the National Institute of Standards and Technology (NIST); filter calibration data from Newport. For the 577-nm filter only the nominal values are available.

Hg lines		Available filters	
intensity (relative)	λ, nm	center λ, nm	1/2-power width, nm
600	365.0153	365.15	11.30
1000	398.3931	405.49	11.10
400	404.6563	405.49	11.10
1000	435.8328	435.35	9.70
500	546.0735	546.90	9.40
50	576.9598	577	10
60	579.0663	577	10
25	708.190	701.40	23.6

The mercury lamp needs to warm up, its output may be unstable during the first 10-15 mins. Make sure you turn it on and give it time to warm up before recording any measurements.

The mercury emission spectrum has a number of well-known lines, as seen in Table 6.1 where some strong lines are listed. A series of high-quality narrow-band filters are provided. These filters are extremely delicate and their optical surfaces, front and back, must not be touched by hand, or wiped with cloth. Each filter is mounted in a ring that can be safely handled and inserted into the opening in front of the photocell; they fit both the Lambda and the Keithley setups. Whenever not in use, they must be placed in their storage slots, and the lid of the box replaced.

The filters typically have the bandwidth of $\lesssim$ 10 nm (see the calibration data for each filter, provided at the apparatus) and so select just one of the Hg lines at a time. The filters fit snugly into the openings in front of the photocell and this helps to reduce the amount of stray light reaching it, but it is best to conduct the experiment in a darkened room. The photocell has a potassium cathode and a ring anode (see Fig. 6.2) arranged so that the light can reach the cathode without striking the anode and causing the emission of electrons from the anode material, or from small amounts of potassium unintentionally deposited on the anode in the manufacturing of the cell. The photocell is mounted in its enclosure in such a way that the light enters through the middle in the ring and illuminates only the cathode.

Figure 6.2: An LD Didactic photocell, type 558 77. The potassium coating on the back surface of the cell is the cathode, and the wire ring suspended above it is the anode.

To adjust the intensity of the incident light, the distance between the lamp and the photocell can be varied, in both setups.

In the Lambda apparatus, the voltage is adjusted systematically, and the resulting current is measured, with readings displayed on the front panel of the LEAI-51 control box (see Fig. 6.1). With the incident Hg light blocked, the ammeter display can be zeroed with the 'current zero' knob. This compensates for the offset due to the dark current that flows when there is no light falling on the cathode in the photocell. The applied voltage is set with the 'voltage adjust' knobs. A good strategy is to explore the entire range of voltages, from -2 V to 30 V, in coarse steps, to get the overall feel for the range of responses, and then "zoom in" to the range of particular interest where non-linear changes in photocurrent occur, -2 V to +2 V. A typical set of results one might see is presented in Fig. 6.3. For retarding voltages that exceed V_0, the photocur-

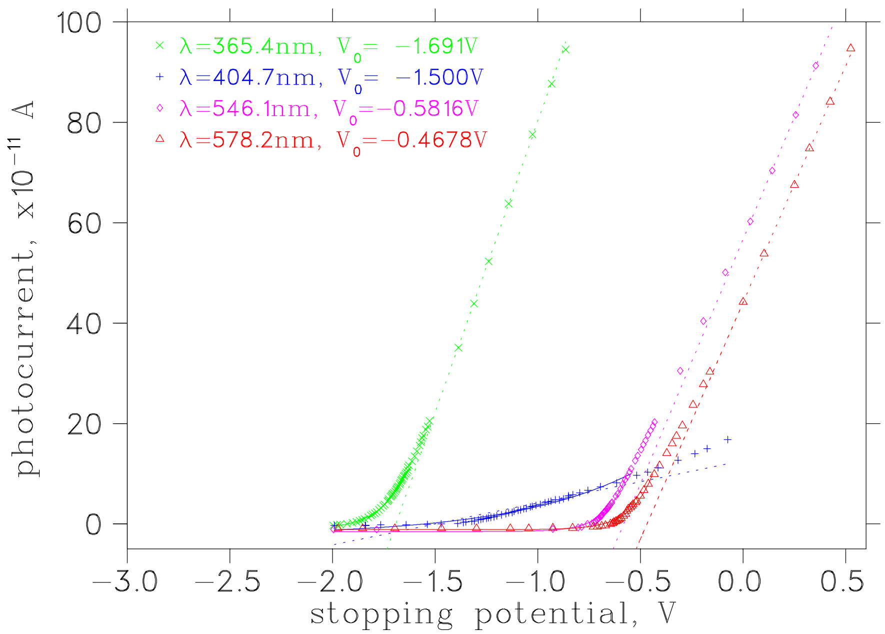

Figure 6.3: A set of measurements for four different bandpass filters, obtained on the Lambda apparatus. The stopping potential value can be obtained by a linear fit and extrapolation to zero photocurrent (the x-intercept, dotted lines) or by a fit to a Shockleys diode equation, for $I \leq 8 \times 10^{-11}$ A (solid lines).

rent is seen to be essentially zero, since the dark-current and contact-EMF were compensated for by the current zero adjustment, so the stopping potential value can be obtained by a linear fit and extrapolation to zero photocurrent.

In the Keithley apparatus the (same type of) cell is connected to a small low-leakage capacitor that gets charged by the photocurrent. As the capacitor charges, the counter voltage between the capacitor plates rises, the photo current is reduced, and eventually the voltage across the capacitor reaches a steady value. This value is the stopping potential (plus any contact EMFs arising from the connections between circuit elements, plus the offset due to the dark current). The offset voltages are unknown, but since data analysis involves fitting to a *slope* of the $V(\nu)$ dependence, these offsets do not affect the result, as long as they do not depend on wavelength and intensity (which they may, unfortunately).

The steady potential reached by the capacitor is measured by an electrometer rather than a voltmeter. The input impedance of the electrometer is so high that it does not provide any significant current drain of the charge of the capacitor. (This is not the case for everyday voltmeters, such as the one built into the Lambda control box). The current generated by a photocell is quite small, so it may take a few minutes for the voltage on the capacitor to reach its steady value. The capacitor must be discharged between measurements; the ‘zero check’ on the electrometer serves this purpose.

Fig. 6.4 shows a typical data set, and the resulting data fits, performed in two different ways: as an intersection of two straight line segments, one for the high enough counter voltages that the photocurrent is essentially constant, and one from the linear region of I *vs.* V dependence; the two segments intersect at V_0. The second way is to fit all data (above zero current) to an exponential function, but allow an additional parameter of a vertical offset, to account for the offset voltages, the so-called Shockleys diode equation (see LD Physics Leaflet P6.1.4.4 for the details of this method). You may want to perform both forms of data analysis and to compare the results. The third line in Fig. 6.4 is the result of a direct measurement of stopping voltage using Keithley electrometer.

Make a graph of stopping potential V_0 as a function of reciprocal wavelength (or ν) and determine the Planck’s constant and the apparent work function of potassium.

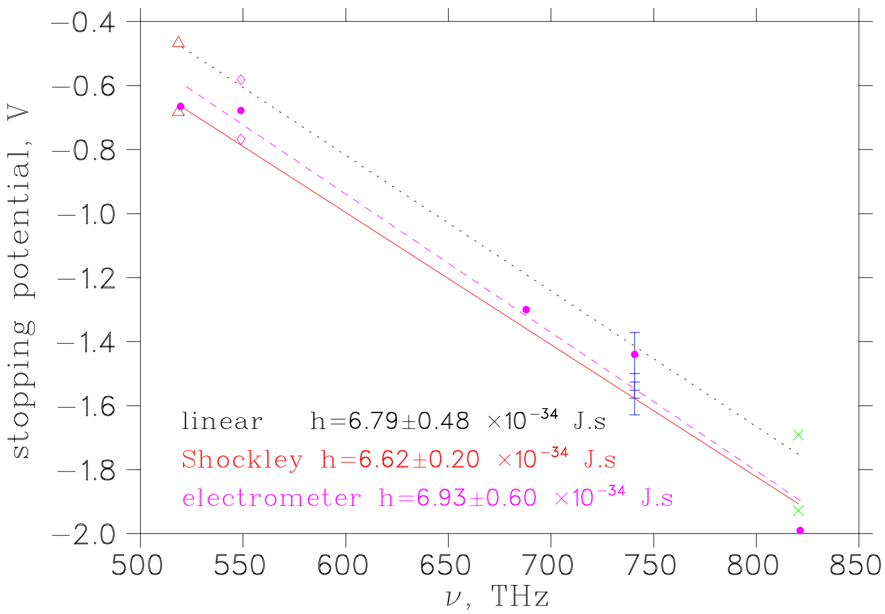

Figure 6.4: The results from the fits of Fig. 6.3 exhibit an approximately linear dependence on $\nu = c/\lambda$, from the slope of which is h can be calculated, using a linear extrapolation (dotted line) or a fit to a Shockleys diode equation (solid line). The points are colour-coded to match Fig. 6.3. In addition, a set of direct measurements of the stopping potential V_0 obtained on the Keithley electrometer is presented (magenta circles, dashed line). Linear fits reveal the relationship $V_0(\nu) = h\nu/e$, from which h can be determined.

6.3 Measurement checklist

Review this manual, and the reference materials provided, to develop your own checklist before coming to the lab. Be sure to include it in your lab report, and comment on how well it worked. Devise a plan to explore the way the photocurrent depends both on the wavelength and on the intensity of incoming light. Determine Plank's constant.

References

Note that some of the links below require the class password for access.

- Resolutions of the 26th CGPM. Bureau International des Poids et Mesures (BIPM). 2018-11-16. `https://www.bipm.org/utils/common/pdf/CGPM-2018/26th-CGPM-Resolutions.pdf`. Retrieved 2021-02-22.
- LEAI-51 Apparatus for Determining Planck's Constant. Lambda Scientific Systems, Miami, FL. `https://www.physics.brocku.ca/Courses/3P91/References/Planck/LEAI-51_Manual.pdf`
- Determining Plank's constant: Counter voltage method. Leybold Physics Leaflets, P6.1.4.4. LD Didactic GmbH. Hürth, Germany. `https://www.physics.brocku.ca/Courses/3P91/References/Planck/p6144_e.pdf`.
- Photo cell for determining Plancks constant Photocell. Instruction Sheet 558 77. Leybold Didactic GmbH. Hürth, Germany. `https://www.physics.brocku.ca/Courses/3P91/References/Planck/55877e.pdf`.