Imperial College London

A1. The Photoelectric Effect.

Head of Experiment: Prof Mike Damzen

The following experiment guide is NOT intended to be a step-by-step manual for the experiment but rather provides an overall introduction to the experiment and outlines the important tasks that need to be performed in order to complete the experiment. Additional sources of documentation may need to be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must be cited in the references of the report.

3rd Year Lab Module, Version 1.3: Revised September 2022.
James McGinty

DETERMINATION OF PLANCK'S CONSTANT BY PHOTOEMISSION

Objectives

To observe the phenomenon of photoemission, and to obtain a value of the fundamental constant *h*. You should become familiar with:

- measurement of low light levels and of low currents
- critical analysis of data that cannot be modelled in a simple manner
- the influence of systematic errors and uncertainties

This experiment does **NOT** yield an accurate value of h, but you should learn about how to extract as much information as possible from an imperfect experimental set-up (just as in most research situations!).

Background

The cardinal rules of photoemission are:

- Electrons are ejected only if the incident light energy (proportional to frequency) is sufficient for electrons to overcome the electrostatic barrier at the surface of the emitter (the work function). Thus, the incident light must be above some critical frequency.
- The energy distribution of the emitted electrons depends on the light frequency, but not its intensity.

Einstein's explanation of the photoelectric effect in terms of quantisation of light into discrete photons was much more satisfactory than the wave explanation at the time and played a key role in the foundations of quantum theory.

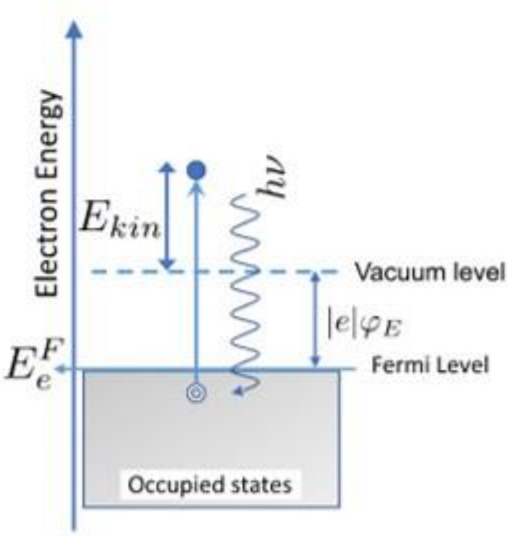

Figure 1: Energy diagram for electron photoemission. E_e^F – Fermi level of emitter, E_{kin} - kinetic energy of photo electron, $h\nu$ - photon energy, φ_E – emitter work function.

The simple picture (see Fig. 1) suggests that any surplus energy of the emitted electrons is transferred to kinetic energy, which needs to be positive definite and given by:

$$E_K \leq h\nu - |e|\varphi_E \tag{1}$$

where φ_E is the work function of the metal emitting the photo electrons.

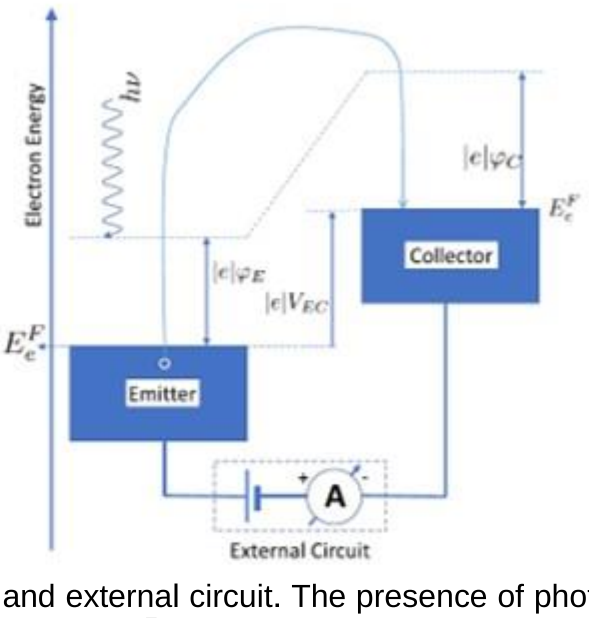

Figure 2: Photocell and external circuit. The presence of photocurrent is subject to $V_{EC} \leq V_{EC}^*$ and $h\nu \geq \varphi_E$. E_c^F – Fermi level of collector, φ_C – collector work function, V_{EC}^* - cut off voltage.

However, an isolated electron emitter would become positively charged and the current would soon cease. By connecting the emitter (or photocathode) to a collector (see Fig. 2), the current can be maintained. The emitter should have a low work function φ_E, and for this experiment, the collector work function φ_C should be large.

From Fig. 2 it can be seen that the external circuitry of the experiment set-up has a variable potential difference applied between the emitter and the collector. The emitted photoelectrons therefore need to have sufficient energy to overcome the applied potential $V_{EC} = V_E - V_C$, plus the built-in potential $(\varphi_C - \varphi_E)$, if they are to reach the collector and produce a photocurrent. This is expressed mathematically as:

$$E_K \geq |e|V = |e|\left(V_{EC} + \varphi_C - \varphi_E\right) \tag{2}$$

As the potential difference V is increased, the barrier will eventually exceed the maximum kinetic energy of the electrons and at this point, no photoelectrons will be able to surmount it and create a photocurrent. This voltage is known as the cut off voltage, V_{EC}^*. This cut off voltage is obtained by substituting Eqn.1 into the above expression and assuming the equality relation:

$$V_{EC}^* = \frac{h\nu}{|e|} - \varphi_C; \qquad h\nu \geq |e|\varphi_E$$

Experiment

On the bench you should find

- The Leybold photocell is constructed with a potassium emitter and a platinum wire loop collector, so that emitter can be illuminated with very little light falling on the collector.
- A mercury light source, which takes about 20 minutes to stabilise after switching on.
- Interference filters, each of which picks out a strong mercury line:
  - 405 nm (violet)
  - 436 nm (blue)
  - 546 nm (green)
  - 578 nm (yellow)
- Lenses
- Neutral density filters
- Keithley Picoammeter Model 485
- A variable voltage source

Experimental Set-up

Set up the optics along a well-defined axis so that light from the source that has passed through the interference filter falls fairly uniformly on the emitter, and make sure that stray light is minimised. The experimental set-up is shown schematically in Fig. 3. Consider carefully how light should pass through the interference filters, e.g. should it be diverging, converging or collimated. A high precision filter characterisation system is available and spending some time using this to determine your filters centre wavelengths and band pass may give you useful insights here.

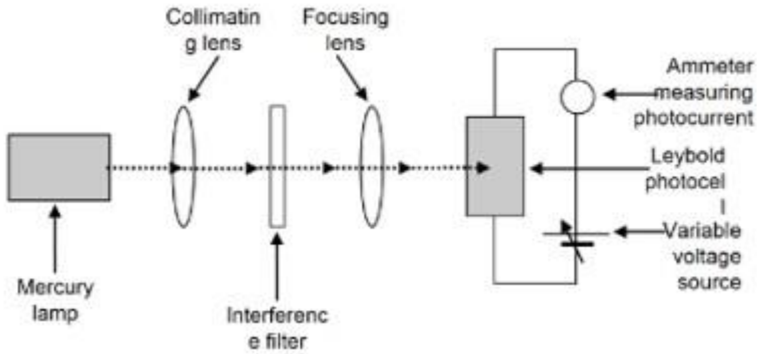

Figure 3: Experimental set-up for measuring Planck's constant via the photoelectric effect.

Measurements:

a) Select the mercury line that gives the smallest photocurrent.
b) Make a preliminary plot of photocurrent over the range −9 to +9V.
c) Think carefully about what data you will need to take to establish/estimate V_{EC}^{*}; you need to consider that the photocell response is not ideal.
d) Check that the stray light photocurrent is sufficiently small compared to that in (a) so it will not significantly affect how you establish/estimate V_{EC}^{*}.
e) Using the neutral density filters, measure the photocurrent as a function of voltage. This will enable you to demonstrate that V_{EC}^{*} is independent of light intensity.
f) Based on what you have deduced in (b), take more detailed measurements of the photocurrent as a function of V_{EC} for each of the four different mercury lines, and establish/estimate V_{EC}^{*} at the different frequencies (you might well try more than one way of doing so).
g) Measure the quantum efficiency of this photocell; a power meter is available in the lab.

N.B. You have several variables, and you could take vast amounts of data. You need to plan carefully as you go along about what data will be useful!

Reporting:

- The description of the equipment should be brief, but sufficient to allow a self-contained explanation of what you have done to set it up optimally.
- Ensure that the graphical information is concise and can be referred to easily.
- Demonstrate adequate understanding of photoemission process using concepts in solid state physics and quantum mechanics.
- Describe how you have dealt with the non-ideal behaviour of the photocell.

Assessment Criteria:

The closeness of your estimate of h to its known value will **NOT** affect your mark! In addition to the standard criteria:

- Your approach(es) to establishing/estimating V_{EC}^{*} will be important, as will be your estimates of the uncertainties in doing so.
- There should be some discussion of why the photocell response is not simple.
- Students at UG level tend to be in the habit of conducting experiments trying to get the data to be as close to the desired value as possible but since it is not even possible in this case, it is much more interesting though theoretically demanding to determine what are the other factors affecting the measurement of h and you should certainly address these issues.

References:

Millikan's Experiment
R.A. Millikan, Phys. Rev. 7 18 & 355 (1916).

A detailed discussion of the complications that arise in attempting to measure h/e by this approach is in
R.G. Keesing, Euro. J. Phys. 2 139 (1981).

More about photoemission
H. Ibach & H. Lüth, Solid State Physics (Springer 1995)

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RISK ASSESSMENT AND STANDARD OPERATING PROCEDURE

1. PERSON(S) CARRYING OUT THIS ASSESSMENT – This assessment has been carried out by the head of experiment.	
Name (Head of Experiment)	James McGInty
Date	25th September 2022

2. PROJECT DETAILS.						
Project Name	The Photoelectric Effect				Experiment Code	A1
Brief Description Of Project Outline	To measure the cut-off voltage for photoemitted electrons as a function of wavelength and thus obtain a value for Planck's constant.					
Location	Campus	South Ken	Building	Blackett	Room	408

3. HAZARD SUMMARY – Think carefully about all aspects of the experiment and what the work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank.			
Manual Handling	X	Electrical	X
Mechanical	X	Hazardous Substances	X
Lasers	X	Noise	X
Extreme Temperature	X	Pressure/Steam	X
Trip Hazards	X	Working At Height	X
Falling Objects	X	Accessibility	X
Other	X		

4. CONTROLS – List the multiple procedures which may be carried out during the experiment along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past the experimental setup even when you aren't around.	
Brief description of the procedure and the associated hazards	**Controls to reduce the risk as much as possible**
Use of 240v Mains Powered Equipment	Isolate Socket using Mains Switch before unplugging or plugging in equipment.
Accessibility	All bags/coats to be kept out of aisles and walkways.
High Pressure Mercury Lamp	May generate ozone; high temperatures; ultra-violet light. Avoid proximity to lamp when operating; avoid direct exposure to UV. Protect eyes and hands.
Low Level Lighting	All bags/coats to be kept out of aisles and walkways. Switch on main light when not working on experiment.
Heavy Optical Bench	Avoid moving bench if possible.

5. EMERGENCY ACTIONS – What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario.