Experiment A3. The Photoelectric Effect

Objectives

This is an important experiment in quantum physics, because it illustrates both the wave and particle nature of light. You will observe the wave-like properties of light with a diffraction grating and the particle-like (quantum) nature of light through the photoelectric effect. The latter measurements will give you an estimate of Planck's constant, and the work function of the cathode of a photodiode.

Prework Questions

1. What are the predictions of quantum versus classical theory regarding the energy of electrons ejected from a surface due to the photoelectric effect?

2. If a particular metal has a work function of 2.4 eV, will the photoelectric effect be observed if green light is shone onto the surface of the metal? Explain.

3. Make a sketch of how you think, in this experiment, the voltage between the cathode and anode in the phototube would vary with time once light starts falling on the cathode.

Introduction

Our understanding of light has evolved over the centuries. Newton believed light was made of *corpuscles* and that was the opinion of most scientists until Thomas Young's two slit experiment of 1801 which established the *wave* nature of light. Then, in 1864, James Clerk Maxwell revealed the connection between electricity, magnetism and waves, establishing that light was an electromagnetic wave.

By 1900, scientists believed so strongly in the pure wave nature of light that even Max Planck, the first scientist to propose energy quantisation for light and atoms, believed the quantisation of *black-body radiation* was merely a mathematical trick that would some day be explained away.

Philipp Lenard also discovered data from his 1902 photoelectric experiments that seemed to confirm light energy quantisation. Finally, in 1905 Einstein pointed out that quantisation was a real effect that proved light can behave like a *particle* as well as a *wave*. Einstein received the Nobel prize in 1921 for this realisation, and his formulation of equation (1). Quantisation (photon particle theory) explained both black-body radiation and the photoelectric effect, with Planck's constant found to be identical in both experiments.

Experiment background

When a beam of light shines on a metal or semiconductor surface, electrons may be ejected from the surface. This is the *photoelectric effect*.

The photoelectric effect is best explained by treating the beam of light as a stream of photons. A photon is a 'packet' or *quantum* of energy.

If the beam is monochromatic, then all the photons have the same energy $E = h\nu$, where ν is the frequency of the light and h is Planck's constant, 6.6261×10^{-34} J s.

When the beam irradiates the surface, a photon may be reflected or it may be absorbed by an electron near the surface causing the electron to be ejected (Fig. A3-1). This ejected electron is known as a *photoelectron*.

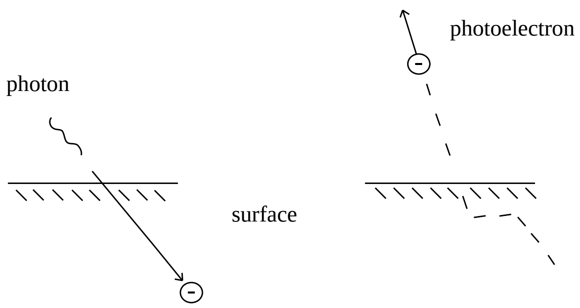

Fig. A3-1 Ejection of a photoelectron.

The kinetic energy of the photoelectron is $\frac{1}{2}mv^2 = h\nu - \phi - W$, where $h\nu$ is the energy imparted by the photon, ϕ is the *work function* of the surface (the energy required for the electron to break free of the cathode surface — its value is a characteristic of the particular material) and W is the energy lost by the electron in collisions as it makes its way to the surface. If $W = 0$ then the kinetic energy will have its largest possible value:

$$\frac{1}{2}mv_{\text{max}}^2 = h\nu - \phi \tag{1}$$

The photoelectrons can have any energy from zero up to this maximum value.

Experimental Apparatus

In this experiment the light source is a mercury lamp and the light-sensitive surface is the cathode of a IP39 phototube (by definition, a *cathode* is a surface from which electrons are emitted). In between the light source and the detector is a slit to collimate the beam, a lens to focus the slit onto the detector, and a grating to disperse the light. Because the spectrum of the mercury lamp has strong emission lines, what you see on the white mask in front of the detector are coloured images of the slit, corresponding to the mercury emission lines ranging from yellow (578 nm) to ultraviolet (365 nm). A schematic diagram of the apparatus is shown in Fig. A3-2 and the most prominent mercury emission lines are listed in Table A3-1.

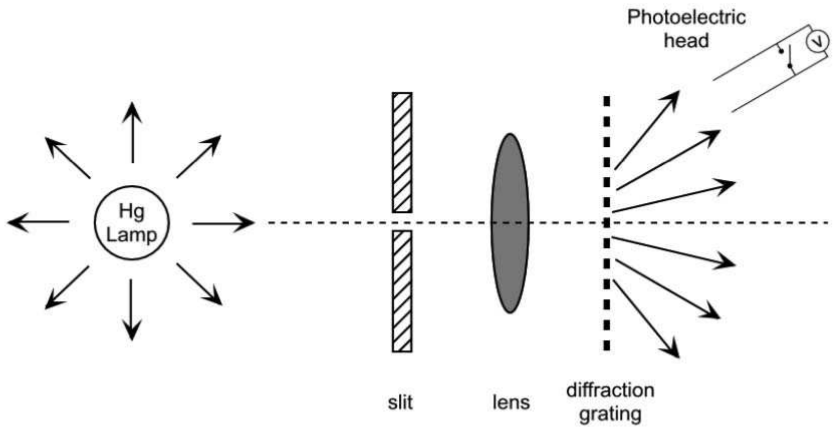

Fig. A3-2 Schematic layout of the apparatus.

Table A3-1 The five most prominent emission lines in the visible mercury spectrum

Colour	Wavelength (nm)	Frequency (Hz)
Yellow	578.012[1]	5.18672×10^{14}
Green	546.074	5.48996×10^{14}
Blue	435.835	6.87858×10^{14}
Violet	404.656	7.40858×10^{14}
Ultraviolet	365.483	8.20264×10^{14}

[1]This line is a doublet with wavelengths 576.959 and 579.065 nm

The diffraction grating: The experiment uses a blazed transmission grating to disperse the spectrum of the Mercury lamp. You will be familiar with the double-slit interference pattern. As we increase the number of slits, while keeping the spacing constant, we obtain maxima in the same positions as with two slits, but the maxima become progressively sharper and narrower. The maxima are called *orders*, and they fall symmetrically about the straight ahead (non-dispersed) direction. In practice a transmission grating is made by ruling fine lines (hundreds to thousands per mm) on a transparent substrate. The blazing means the grating directs more light to the first order spectrum on one side than the other, making the intensity greater on that side.

A reflection grating is made by engraving many parallel groves in a reflecting substrate. The tiny pits on compact discs act as crude reflection gratings.

The phototube: This consists of a semi-circular light sensitive cathode and a wire anode mounted in an evacuated glass envelope (see Fig. A3-4).

> The cathode is coated with a thin layer of a caesium-antimony semiconductor known as ‘S4’. This coating is commonly used in phototubes and photomultiplier tubes to produce a surface which is very sensitive to visible and ultraviolet light. The photocathode response extends from 300 nm to 700 nm, peaking at 400 nm.
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> Visible light falling on the surfaces of most metals will not produce photoelectrons because the energy of a photon $h\nu$ is less than the work function for a metal ϕ. Ultraviolet light is required. However, the coating on the phototube cathode has a low

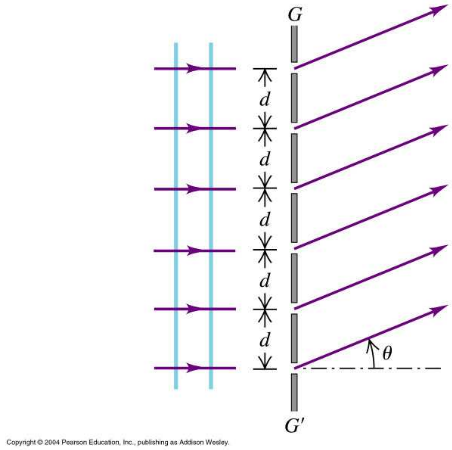

Fig. A3-3 Portion of a transmission diffraction grating. The path difference between adjacent rays is $d\sin\theta$. Constructive interference occurs when $d\sin\theta = n\lambda$, where $n = 1$ corresponds to the first-order spectrum.

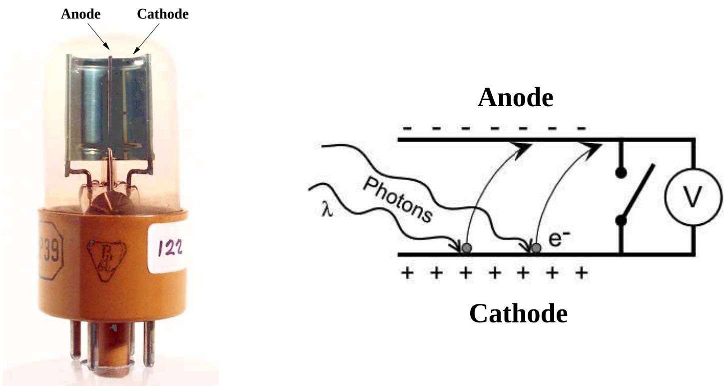

Fig. A3-4 The IP39 vacuum phototube and its equivalent circuit in this experiment.

work function so it responds to visible light. Pure caesium metal could be used but most of the light would be reflected; semiconductors are better absorbers.

The detector box: Monochromatic light entering the detector entrance slit falls on the photocathode. Inside the detector box the phototube is mounted obliquely so that light reflected from the cathode doesn't fall on the anode; the anode itself is masked so that no direct light can fall on it. As shown schematically in Fig. A3-4, the ejected photoelectrons collect on the anode until the potential difference V reaches a value $V_{\rm max}$ corresponding to the highest energy electrons ($eV_{\rm max}$) for that particular wavelength; the electric field between anode and cathode will repel any further photoelectrons. The voltage $V_{\rm max}$ is therefore a direct measure of the maximum kinetic energy $\frac{1}{2}mv_{\rm max}^2$ of the photoelectrons, i.e.,

$$eV_{\rm max} = h\nu - \phi. \qquad (2)$$

Note that in Fig. A3-4 the phototube is depicted as a capacitor, which is exactly how the electrodes are behaving in this experiment. The capacitance C is tiny ($\sim$pF) but as long as the voltmeter resistance R is very large[2], the RC time constant will be long enough to ensure that the recorded voltage is accurate (see Expt. C3).

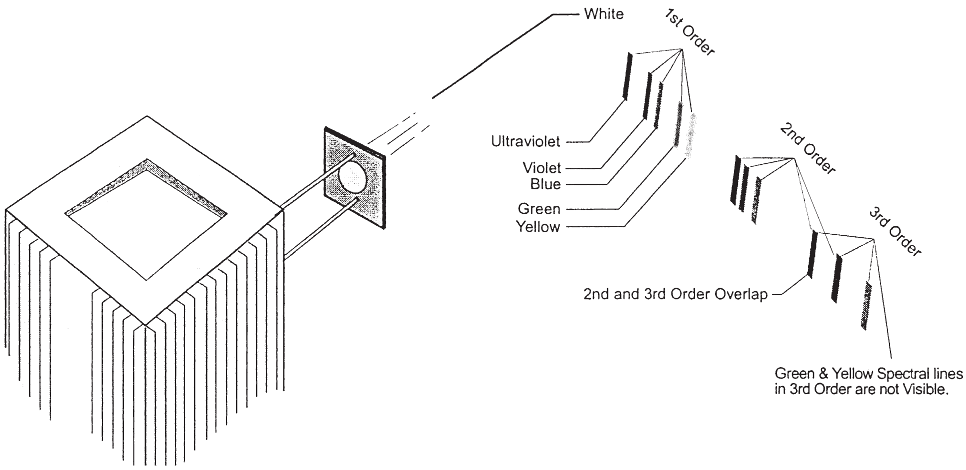

Fig. A3-5 Figure showing the mercury lamp housing, lens and grating holder, and a schematic picture of three spectral orders.

Topic 1. The diffraction grating

Procedure

1. Switch on the mercury lamp and allow it a couple of minutes to warm up. Note that the lamp housing becomes quite hot after a while.

   WARNING: Because of the strong ultraviolet radiation, you should not look directly into the mercury light source, otherwise you may damage your eyes

   Also note that the detector box contains batteries. It may be worthwhile to check that these are OK before proceeding.

2. Use a sheet of paper or the reflective white mask in front of the detector to locate some spectral lines, and establish which order they are (see Fig. A3-5).

3. Position the detector so that a first order spectrum falls on the white mask and the yellow (578 nm) line falls exactly on the entrance slit. The base assembly and pivot arm keep the detector box at the correct distance from the grating for focused light. Slide a sheet of paper under the base assembly and trace carefully along the fixed and movable arms.

   Repeat for the other first-order spectrum on the opposite side of the straight ahead position. Why is this good experimental practice?

4. Remove the paper and measure the two angles of deviation θ (see Fig. A3-3), find the mean and hence calculate the resolution of the grating, $1/d$, in lines per mm. Angles are best measured using trigonometry; a protractor is simply not accurate enough. Estimate the uncertainty in θ and hence in $1/d$.

[2]Note that there is an internal, battery-powered amplifier in the detector box that increases the effective voltmeter resistance R to $> 10^{13}\,\Omega$.

5. Repeat the above procedure for the green line and the middle of the three blue/violet lines (404.7 nm).
6. Calculate the mean grating resolution (and associated uncertainty) based on the three measurements, and compare with the nominal resolution printed on the grating holder.

$\boxed{\textbf{C1}}$ ▷

Topic 2. The photoelectric effect

You have seen in Topic 1 how we used the wave nature of light to explain diffraction. Now you will collect data to test two predictions of the quantum description of light, namely that the energy of the ejected photoelectrons depends *only* on the frequency of the incident photons, and *not* on the intensity.

Setup

Determine which side has the brighter first order lines; this is the side favoured by the blaze of the grating. Check that the emission lines from the mercury lamp are focussed sharply on the white reflective mask on the detector box. Focus can be adjusted by sliding the lens/grating assembly back and forth on its support rods and securing with the thumbscrews. The correct focus position has the lens/grating assembly near the end of its travel.

Turn on the battery that powers the internal amplifier in the detector box, and connect the digital voltmeter (DVM) to the output terminals.

Procedure

1. Start with the brighter first-order spectrum and adjust the position of the detector box carefully so that only one of the spectral lines falls on the entrance slit of the detector. If you select the green or yellow spectral line, it is *essential* to place the corresponding coloured filter over the white reflective mask.
2. Wait till the DVM voltage stabilises then record the stopping voltage. Repeat or the other four lines.
3. Repeat the above steps for the other first-order spectrum, with the detector on the opposite side of the white light (undispersed) position. Note whether there is a systematic difference between the voltages recorded for the two orders.
4. Plot the mean stopping potential (and associated uncertainty) versus frequency. Apply a linear fit to the data and determine the best-fit slope and intercept (and their uncertainties).
5. Use equation 2 and your data to determine a value (1) for Planck's constant, and (2) for the work function of the photocathode (in electron volts), given that $e = 1.602 \times 10^{-19}$ C.

   Comment on the agreement or otherwise between your measured value for h and the accepted value of 6.6261×10^{-34} J s.

6. Based on your calculated work function, what is the longest wavelength the phototube can detect? In what region of the electromagnetic spectrum does this fall?

$\boxed{\textbf{C2}}$ ▷

Topic 3. Stopping voltage versus intensity

In this topic we test whether the maximum kinetic energy of the photoelectrons (and therefore the stopping voltage) is independent of the incident intensity, as predicted by the quantum theory. In analysing the results from this topic it is important to be aware of the limitations of the equipment, in particular the fact that the voltmeter resistance is not infinite.

Procedure

1. Choose one of the first-order spectra and set the ultraviolet 365.5 nm line on the entrance slit of the detector box.

   Place the variable transmission filter in front of the white reflective mask so that the light passes through the section marked 100%. Wait until the DVM voltage stabilises then record the stopping voltage.

   Now cover the entrance slit with a sheet of paper or black cloth and measure the time it takes for the DVM voltage to decay to $1/e$ of its initial value. This time is the *time constant* ($= RC$) of the voltmeter circuit (see Expt. C3). Assuming the effective voltmeter resistance R is $10^{13}\,\Omega$, estimate the capacitance C of the phototube and the initial discharge current.

2. Tabulate the stopping voltage with the 100%, 80%, 60%, 40% and 20% transmission sections of the variable transmission filter in front of the entrance slit. It is important to allow time for the voltage to stabilise after changing the transmission level.

   If you want to check that your measurement is valid, you can discharge the capacitor with the pushbutton on the detector box each time you change the transmission level. The time it takes for the DVM to reach equilibrium is a measure of the net charging current. This is a clue for answering the questions below.

3. Repeat step 2 for the blue (435.8 nm) and green (546.1 nm) spectral lines, remembering to include the coloured filter for the latter.

4. Repeat the two steps above for the other first-order spectrum. Note which spectrum had the brighter lines.

5. Plot, on the same graph, stopping voltage versus transmission percentage for each of the three lines and the two orders.

$\boxed{\textbf{C3}}$ ▷

Questions:

1. Can you determine a clear pattern between intensity and the stopping potential?

   Does this contradict quantum theory?

2. Why do some lines show a much stronger dependence of stopping voltage on intensity than others?

3. Attempt to explain what you observe in Topic 3 in terms of the simple equivalent circuit in Fig. A3-4.

4. Why is a filter needed in front of the detector to record the correct stopping voltages for the green and yellow lines, but not for the other lines? [Hint: look at the second order spectrum using a sheet of white paper.]

Conclusion

Summarise your results and the consequences for the quantised nature of light.

$\boxed{\textbf{C4}}$ ▷