Experiment II

PHOTOELECTRIC EFFECT

I. INTRODUCTION

Most of the experiments which have been described before in this manual have been c*lassical*, i.e., physical quantities such as energy and momentum have been treated as *continuous* and hence infinitely divisible. For example, light has been represented as continuous, sinusoidally varying electric and magnetic fields. As we have found, this classical description is excellent for quantitatively describing macroscopic (large scale) phenomena, such as diffraction and interference. However, as we proceed to the study of microscopic phenomena, i.e., phenomena which occur at the atomic level, we will find that the classical models are inadequate. For example, the fact that atoms emit only specific, discrete colors of light, cannot be explained by a classical model. In order to explain the processes which occur at an atomic scale we must use the concepts which have come to be known as *quantum theory*. Since classical models work well for most macroscopic cases, it is clear that quantum theory must converge to the classical theory for common macroscopic phenomena.

Prior to our understanding of quantum theory three observations existed which had defied understanding on classical grounds. These observations were:

1. The black body radiation spectrum,
2. Emission and absorption of discrete line spectra,
3. The photoelectric effect.

Black Body Spectrum

A hot furnace with a small hole in it radiates energy through the hole Such an arrangement is referred to as a *black body*. If we measure the radiation coming out of the hole, we observe a broad, continuous range of wavelengths. The exact shape of this intensity vs. wavelength spectrum is soley determined by the *temperature* of the furnace. Yet, until 1900 no classical theory could explain the observed black body spectrum.

By departing from classical ideas, Planck was able, in 1900, to derive an equation which fit the observed spectrum. He found it necessary, to his admitted distaste, to make a radical assumption. Planck reasoned that, *if* the harmonic oscillators (associated with the radiation mechanism) were restricted to certain discrete energies, *then* the correct form for the black body spectrum could be derived mathematically. Even Planck considered this assumption to be a "fudge" and assumed that someone would eventually find the correct model.

Classically, a harmonic oscillator can have any energy given by:

$$E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 \tag{1}$$

Planck proposed that an oscillator of frequency f could have energies only in integral multiples of f. That is,

$$E \propto nf \tag{2}$$

where n is an integer. The constant of proportionality h is now called *Planck's constant*. In terms of h the equation becomes

$$E = nhf \tag{3}$$

Einstein extended the notion to say that if the oscillator could have only discrete, quantized energies, then perhaps the energy emitted by the oscillator also came in discrete, quantized bundles, which were named *photons*, each having energy

$$E = hf \tag{4}$$

This assumption of quantized energy bundles was sufficient to explain the photoelectric effect. It was for his theoretical work in this area that Einstein was awarded the Nobel Prize in physics in 1921. As you perform the experiment you will see how differently the old and new theories succeed in predicting the effects you observe.

SUMMARY OF CLASSICAL AND QUANTUM MODELS OF LIGHT

Classical model of light

According to classical electromagnetic theory:

a. Light is a wave, consisting of sinusoidally oscillating electric and magnetic fields, having a characteristic frequency.

b. The fields vary smoothly and continuously.

c. The intensity of light is proportional to E^2 , the square of the electric field

d. The energy carried by light is proportional to its intensity.

e. The frequency of the waves has no bearing on their energy.

Quantum model of light

The quantum model of Planck and Einstein is very different from the classical model given above. According to the quantum model:

a. Light comes in small wave packets (photons), having a characteristic frequency.

b. Photons are discrete, and only whole photons can be emitted or absorbed in any physical process.

c. The intensity of light is given by the number of photons per time, which strike a surface area.

d. The energy contained in photons is proportional to their frequency.

e. The intensity of light has no bearing on the energy of each photon.

Photo-electric Effect

Experimentally it was found that when light strikes a metallic surface, charges are ejected from the surface. It is this charge ejection under exposure to light that is called the *photoelectric effect*. J. J. Thomson measured e/m (the charge to mass ratio) of the ejected particles and thus demonstrated that they were electrons. These ejected electrons are often referred to as *photo-*

electrons. Using the quantum model of light outlined above, the photo-electric effect may be described as follows:

A photon, striking a metal surface, gives up its energy to an electron in the metal. Some energy is required to liberate the electron from the metal. This energy is commonly called the *work function*, W_0. The remainder of the electron's energy goes into kinetic energy. Energy conservation for this process is given by:

$$hf = KE_{\max} + W_0 \tag{5}$$

where KE_{max} is the kinetic energy of the electron after leaving the surface if no energy has been lost by inelastic collisions within the material. Using the relationship $f\lambda = c$

$$KE_{\max} = \frac{hc}{\lambda} - W_0 \tag{6}$$

where λ is the wavelength of the light and c is the speed of light.

Electron Energy

Recall that if an electron starts at rest and is allowed to accelerate through a potential difference V, then the electron gains kinetic energy given by

$$KE = eV \tag{7}$$

where e is the charge on the electron. Conversely, if an electron starts with a kinetic energy eV and is forced to *decelerate* through a potential difference V, then the electron will lose all of its kinetic energy and come to rest. Note that if e is expressed as the number of charges (not Coulombs, for example), then the units of eV are referred to as *electron-volts*, a very convenient unit. These ideas will be of importance later in this experiment.

II APPARATUS

Detector

In this experiment we shine light onto a curved metallic surface (the *cathode*) inside a vacuum tube shown in Fig. 1. Electrons are ejected from the surface by the light and may strike the central wire (the *anode*).

The detector electronics may be used in two modes:

I (current) mode

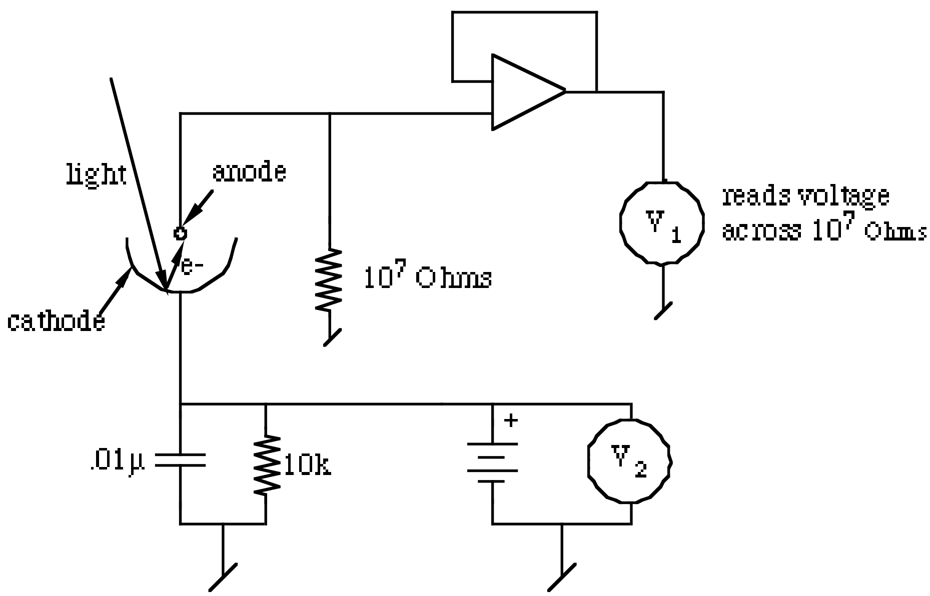

Fig. 1 Schematic diagram of photo-detector circuit in I (current) mode.

When the detector switch is in the *I* (current) position, a voltage may be applied between the cathode and the anode either to attract the electrons to the anode or to repel them from the anode. If the electrons reach the anode, they pass through the $10^7\Omega$ resistor. The meter V_1 measures the *voltage* across that resistor. Ohm's Law may be used to calculate the electron current.

V (voltage) mode

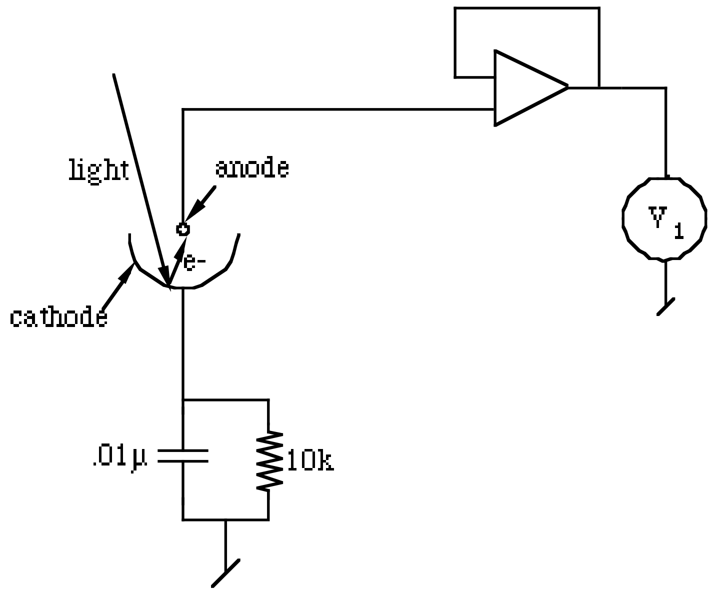

Fig. 2 Schematic diagram of photo-detector circuit in V (voltage) mode.

When the detector switch is in the *V* (voltage) position, the power supply and the $10^7\Omega$ resistor are automatically disconnected from the circuit. In this mode, as light strikes the cathode, electrons are removed from the cathode and deposited on the anode. This process is similar to charging a capacitor. The more the anode becomes negatively charged, the greater the repulsive force on the next electron, which approaches the anode. As negative charge builds up on the anode and positive charge builds up on the cathode, a potential *V* between the two also increases. *V* will become a maximum when the most energetic electrons leaving the cathode are slowed to rest just as they reach the anode.

The kinetic energy required for the next electron to move from cathode to anode is thus given by eq.(7). Thus, the maximum voltage built up between the cathode and anode is given by those electrons which leave the cathode with the maximum kinetic energy:

$$KE_{\max} = eV_{\max} \tag{8}$$

With this apparatus the time required to build up the charge and voltage to a maximum value is a fraction of a second.

Using eq.(8) in eq.(6) gives

$$eV_{\max} = \frac{hc}{\lambda} - W_0 \, . \tag{9}$$

Eq.(9) is just a re-statement of energy conservation for the photo-electric process.

Light Source

A high intensity mercury lamp, having five distinct wavelengths is provided. In order to separate the different wavelengths a slit is placed at the lamp opening and a lens and diffraction grating create images of the slit, with different wavelengths being diffracted to different angles. A swivel arm holds the detector at the angles for each wavelength. Since it is possible that different wavelengths coming from different diffraction orders can be diffracted into the same angle, yellow and green filters are provided to pass only one wavelength at a time. A slide containing wire meshes will serve to vary the intensity of the light. The light source is shown in Fig. 2.

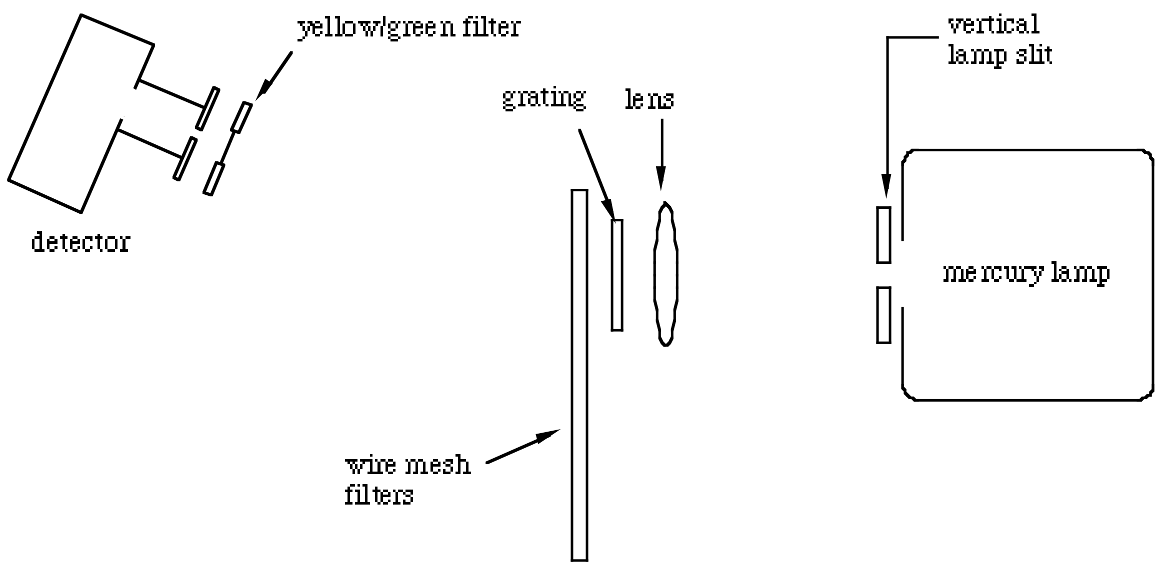

Fig.2 Photo electric effect apparatus

The wavelengths from the Mercury lamp are shown below:

Color	Wavelength (nm)
Yellow	578.0
Green	546.1
Blue	435.8
Violet	404.7
U.V.	365.0

III. EXPERIMENTAL PROCEDURE

This section will be best understood if read in the lab while viewing the apparatus.

Caution: Do not look at the mercury light or its reflection! Do not use it as a reading lamp! The UV present can damage your eyes.

Preliminary adjustments

Turn on the mercury lamp and allow it to warm up for several minutes to attain full intensity.

Caution: The lamp housing becomes hot! To maintain proper cooling, do not place anything on top of the lamp.

Leave the lamp on for the entire lab period, since the lamp may not restart while it is hot. Align the optical rail so that the illumination is centered on the lens/grating assembly. A spectrum may be projected onto a piece of paper at the detector position. Note that the spectrum appears symmetrically on both sides of the optical rail, and that it is brighter on one side. Choose the brighter side throughout the experiment. Move the detector assembly along the rail until the spectral lines are clearly resolved (i.e., they should not overlap) and only one line enters the detector slit at a time. The plane of the detector slit is coated with a fluorescent material which makes the ultra-violet lines visible.

Taking Data

1. Current vs. voltage (Green line only)

This first set of measurements will help you understand the workings of the detector and help clarify how the tube potentials affect the current.

Set the detector switch to the *I* (current) position. Place the green filter at the entrance slit of the detector. The filter is held in place with its magnetic strip. Use the green line (546.1 nm) to measure and record the detector output current vs. detector input voltage for both positive and negative voltages. Zero intensity correction: Cover the detector slit with your hand and note the reading on the meter may be different from zero. This small offset should be subtracted from all intensity readings. Be sure that the meters and power supply are plugged in consistently, with the black or common jacks connected to the shield side of the coaxial cable. Connected correctly, the currents should be negative. Use the plotting software (e.g., Graphical Analysis) to plot the current (represented by the voltage across the 10^7 ohm resistor) on the y-axis, and the power supply voltage on the x-axis. From you graph, answer the following questions:

a. Does the negative current increase without bound as the voltage increases negatively? Why?

b. Does the current go to zero when the voltage = 0? Why?

c. What is the trend in the current as the voltage becomes more positive. Why?

d. Is there any voltage for which the current goes to zero? What is the significance of that voltage?

2. Current vs. Intensity (Green line only)

Set the detector voltage to about –5 volts. Measure and plot the current vs. light intensity. You should vary the intensity by using the screen mesh filters.

3. Charging voltage vs. wavelength

Set the detector switch to the *V* position. Recall that in this mode, the detector meter V_1 will read the voltage to which the detector and its wiring are charged.

a. Move the detector to the yellow line and place the yellow filter over the detector slit. Measure the charging voltage for the yellow line.

b. Without moving the detector, vary the intensity of the yellow line using the screen mesh filters. How does the charging voltage depend on the intensity?

c. Repeat the measurements of 3a. and 3b. for the green line (use the green filter) and for the other spectral lines (remove the filter).

4. Analysis

The interpretation of your data is crucial to understanding which model is the truer representation of light. Compare each of your observations of parts 2 and 3 to the properties *a.* through *e.*, for both the classical and quantum models outlined in the introduction. There is no guarantee that your data will address all of the characteristics listed in the two models.

With which model are your measurements consistent?

Another test of the quantum model is to see whether your data are consistent with the photo-electric formula, eq.(9). To do so, use the results of part 3 and plot the detector voltage as a function of $1/\lambda$. What is the shape of your plot? Is this shape consistent with quantum predictions of eq.(9)? What is the physical significance of the slope? Calculate Planck's constant and compare your value with a literature value given on the inside back cover of this manual. Because there are other complications not discussed here, this experiment is not a good method for measuring Planck's constant precisely, but should yield the right order of magnitude. What is the significance of the V intercept? With which model are your data consistent?