

# The Photoelectric Effect and Measuring Planck's Constant

## Goals:

The primary goal of this experiment is to measure Planck's constant, by determining the stopping voltage for various wavelengths of light. Included in this will be the verification of the concept that the stopping voltage depends on the wavelength of the incident light. Additionally, one may verify that the stopping voltage does not depend on the intensity of the incident light.

## Introduction:

Read A.C.Melissinos, *Experiments in Modern Physics*, p. 18-27

The observation and explanation of the photoelectric effect was one of the cornerstones of what is called modern physics. Planck previously had shown that radiation was "quantized" when emitted from his study of blackbody radiation. The photoelectric effect shows that radiation is still "quantized" when it is absorbed. What is observed in a photoelectric experiment is that when light strikes a surface electrons are ejected from the surface under certain conditions. These conditions include that the wavelength of the light was shorter than a specific limit particular to the material of which the surface consist. Equally important is that this wavelength limit does not depend on the intensity of light striking the surface. The number of ejected electrons does depend on the light's intensity.

The upshot of this is that light consist of indivisible little bit we now call photons and each photon has an energy

$$E = h \nu = hc / \lambda \quad (1)$$

At the beginning of the twentieth century, this was quite a surprise because the two slit experiment had clearly shown that light was a wave and the energy of a wave depends on its amplitude. Light was recognized as an electromagnetic phenomena that was well described by Maxwell's equations. In these equations there is nothing to hint at the discrete nature of light because the amplitude of a wave seems to be continuously variable..

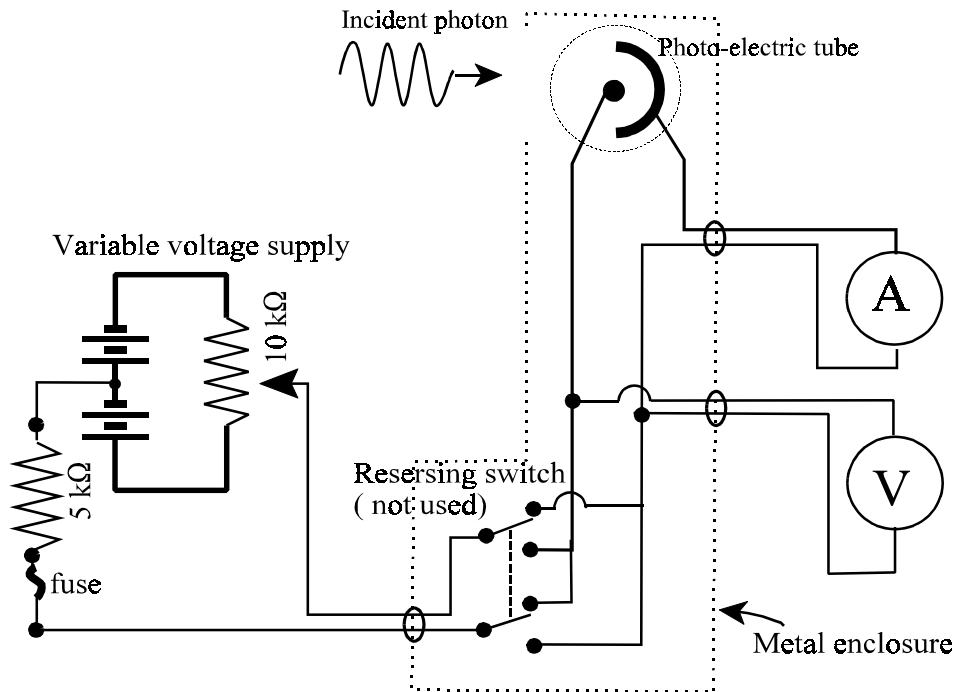
In a solid, electrons are bound by a certain amount of energy and the minimum binding energy is called the *work function*,  $\Phi$ . The work function is analogous to the minimum binding energy or ionization energy of an electron in an atom. Now considering only those electrons that are bound by an energy  $\Phi$ : If the energy of the incident photon is less energy than  $\Phi$  then the absorbing electron remains bound,. But if the energy of the incident photon is greater than the electron will be ejected from the surface. The ejected electron it will have a kinetic energy, K.E. given by:

$$K.E. = h \nu - \Phi. \quad (2)$$

In this experiment, electrons are ejected from a cathode, a voltage is applied between the cathode and an anode. This voltage can be adjusted such that it attracts the ejected electrons to the anode or repels them. Adjusting the cathode-to-anode voltage, V, provides a way to measure the kinetic energy of the ejected electrons. When the voltage is such that it just stops the electrons then:

$$e V_{STOP} = K.E. = \frac{h c}{\lambda} - \Phi \quad . \quad (3)$$

where  $e$  is the charge of the electron. Please see: A.C.Melissinos, *Experiments in Modern Physics*, p. 18-27 for further details and important information about analyzing the data.



**Figure 1** Basic electrical circuit for the photoelectric effect.

### Procedure

The basic experiment is to illuminate the photoelectric tube with a single known wavelength, and measure the current as a function of voltage for the range of -25 volts to +25 volts. Then repeat the process for other known wavelengths.

To do this one must complete the wiring and setup the optics. To setup the optics, turn on the light source by plugging it into the wall outlet. Next direct the light onto the grating, and examine the light from the grating in both zeroth and first orders. This should help you place the photoelectric tube. You may need to change the grating to light source distance for best results.

When measuring I-V (current vs voltage) curves it is always a good idea to do a few quick measurements to find the range of currents to be measured and to learn the general shape of the curve. One can then determine which parts of the I-V curve is most interesting or at least useful in determining the parameters of interest. Once this is known, one can make better use of the lab time by making most of the measurements in the important region(s). This process may require an early sample data analysis and calculation of the parameters and errors.

One can measure the dark current of the system (power supply, meters and photoelectric tube) by simply blocking the light inlet of the photoelectric tube assembly and measuring the

current as a function of the applied voltage. One can then refine the photoelectric data by subtracting this dark current curve from the current vs voltage curves taken when light is present.

If one is careful one can vary the intensity of the light by varying the location of the detector.

### Procedural hints

- A. The electrometer uses vacuum tubes and needs time (at least 15 minutes) to both warmup and stabilize.
- B. The light source needs at least 5 minutes to warmup.
- C. The expected current is very small ( $\sim 1 \text{ nA} = 10^{-9} \text{ A}$ ) and the measurement of small currents is not easy. The stray electric and magnet field in the room can change enough because of a person moving to induce currents in the system. Additionally, when dealing with the measurement of small currents even small capacitive effects can cause noticeable delays in the circuit reaching a steady state.
- D. The “zero” of the electrometer should be set at the lowest scale that will be used and then checked for the other scales.
- E. Avoid contact with and movement close to the various wires and cables, to avoid induced currents. Do not have your book laying on the cables!
- F. Control stray light.
- G. Consider placing the photocathode near the focal plane of the optics.
- H. Consider setting up the optics so that the anode is not directly illuminated.

### Questions:

1. How are you going to determine the wavelength of the light used in this experiment?
2. What is the range of wavelengths and frequencies associated of visible light?
3. Is this experiment limited to the visual portion of the spectra? If not what are the limits in this experiment and what are the causes of these limits?
4. Which colors of light are more energetic and thus more likely to produce photoelectrons?
5. The observation of the photoelectric effect occurred before there were vacuum tubes need to amplify small currents into something that could be measured with a meter. How was the photoelectric effect originally observed?
6. Why is the actual photoelectric cathode and anode in a vacuum?
7. What causes the delays in the circuit reaching a steady state in terms of current flow?
8. What is the focal length of the concave grating used in this experiment?
9. What is the dispersion of the grating?
10. Consider the problem of measuring the photocurrent as a function of intensity. To vary the intensity, one might vary the distance from the light source to the photocathode. Should the results yield  $I \propto 1/r^2$ ? If so from where is  $r$  measured? Would this procedure need to be modified, if one uses the grating to select a specific wavelength of light? If so, how? How does the finite size of the detector complicate this measurement?
11. Why can one see more violet bands on a sheet of white paper than on the white wall?
12. Is there any advantage or disadvantage to using higher orders?
13. How does one decide what the optimal widths of the slits at the lamp and the detector unit

are?

14. How does the variable power supply work and manage to produce positive and negative voltage?
15. Why should the ammeter (electrometer) be connected between the voltmeter and the photo-electric tube rather than between the voltmeter and the power supply?
16. What is the smallest current that you measure in this experiment and how many electrons per second is this current?
17. What is the cause of the dark current?
18. The work function is related to the binding energy of the least bound electrons in the material. Were all electrons ejected by photons in this experiment originally bound by an energy exactly equally to the work function,  $\phi$ ?
19. If electrons are ejected from the cathode, but the anode to cathode voltage prevents these electrons from reaching the anode, where do these electrons go?

### Data Analysis

The data of interest is the current associated with electrons ejected by incident light from the cathode and captured by the anode. Unfortunately, the measured current includes dark current (current when no light is present) and the current associated with electrons ejected by incident light from the anode and captured by the cathode. (Note in this case, in a formal sense, the names cathode and anode should be reversed, but this would only confuse the situation.) Thus the measured current is the sum of three currents: the cathode-to-anode current, the anode-to-cathode current and the dark current. Because different spectral lines have different intensities the maximum photocurrent associated with each line will vary. This variation makes it difficult for one to find a consistent method of “picking off” the stopping potential from the graph. A further difficulty encountered in the data analysis is the smallness of the current when the applied voltage is near the stopping potential. Please see: A.C. Melissinos, *Experiments in Modern Physics*, p. 18-27 for further details and important information about analyzing the data.

### Introduction to Solids and Fermi Dirac Statistics

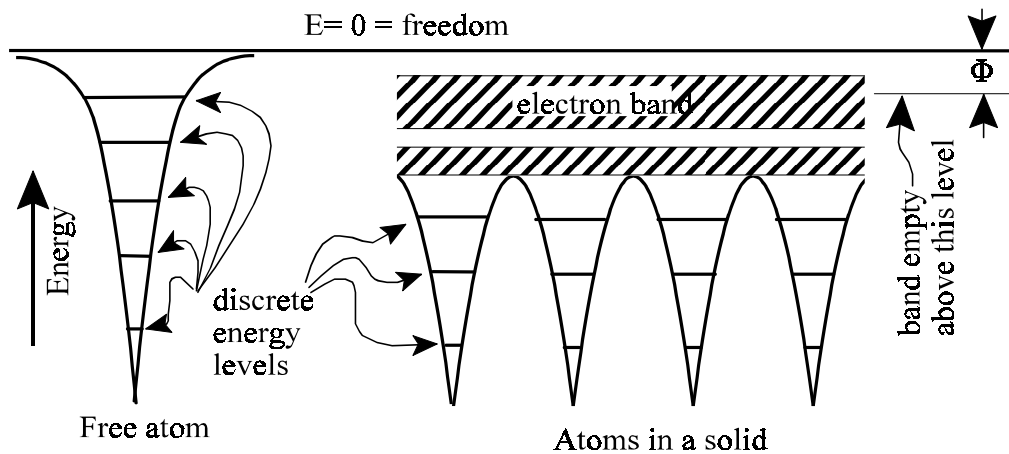
An electron in a free atom can only occupy certain discrete energy levels and no two electrons can occupy the same quantum state (spin and energy). In a solid the rules are similar. The inner shell electrons are tightly bound to individual atoms but the outer, more loosely bound electrons are “shared” throughout the material. For these shared electrons, the discrete energy levels associated with the individual free atoms are blurred into a band of energy levels. The energy levels and bands need not be occupied and typically only the lower energy levels and the bottom of the band is filled. In free atoms, the amount of energy needed to free one of the electrons is called the ionization potential, and in solids it is called the work function,  $\Phi$ .

To release an electron from the surface of the solid, a photon must have an energy at least as great as the work function. That is

$$h\nu \geq \Phi \quad \text{or} \quad \lambda \leq \frac{hc}{\Phi} \quad (4)$$

If the incident photon has more energy than this lower limit, the excess energy will appear in the form of kinetic energy of the ejected electron.

$$\text{K.E.} = h\nu - \Phi = \frac{hc}{\lambda} - \Phi . \quad (5)$$



**Figure 2** Energy levels in a free atom and in a collection of bound atoms in a solid. In the solid the less tightly bound energy levels overlap to form an electron band. Just as energy levels in an atom need not be populated, the electron bands in a solid may be unoccupied or only partially filled. The energy needed to free the least bound electrons in the solid is called the work function,  $\Phi$ , and is shown at the right.

In a solid the electron bands represent permitted electron energy levels, but not all of the permitted bands are populated and some bands may be only partially filled as shown in the upper band in fig.2. The transition energy from populated to unpopulated levels is called the “Fermi energy” and determines the minimum binding energy or work function,  $\Phi$ . At absolute zero this transition is a step function, but at any other temperature there are at least a few thermally excited electrons. The probability,  $P(E)$  that a permitted electron energy level,  $E$ , is populated is given by the Fermi-Dirac distribution function:

$$P(E) = \frac{1}{e^{(E-\mu)/kT} + 1} . \quad (6)$$

Here,  $\mu$  is the chemical potential which at the low temperatures limit equals the Fermi energy, and  $k$  is the Boltzmann constant,  $k = 1.38 \times 10^{-23} \text{ J/K} = 8.62 \times 10^{-5} \text{ eV/K}$ . At room temperature the Fermi-Dirac distribution function is almost a step function.

Even if the unwanted dark current and anode to cathode currents could magically be forced to be zero, the shape of the  $I$  vs  $V$  curve would still be complicated. This current is effected by a number of factors including:

- 1) The geometry of the cathode and electrode especially near the stopping voltage. In this case not all of the electrons ejected from the cathode are collected by the anode.
- 2) The distribution of populated energy levels in the solid. This includes the shape of the Fermi-Dirac distribution. The electrons in the solid are not all bound by the same energy. The work function  $\Phi$  is just an approximate minimum binding energy. Electrons that are bound slightly more tightly than this will be ejected with a little less kinetic energy. These electrons can be stopped with a slightly lower voltage than the “official” stopping voltage.

3) The depth ( in term of binding energy) of the band from which the electrons are ejected. This is related to the width of the I vs V from the stopping potential to full forward saturation ( where the photocurrent levels off to a constant value).