Photo-electric effect: a determination of *h*.

Purpose
To determine Planck's constant using the photoelectric effect, in which light removes electrons from a metallic electrode.

Key concepts
> Photons
> Monochromator
> Diffraction grating
> Photoemission
> Stopping potential
> Work function

Introduction
The photoelectric effect was first observed a little over 100 years ago; it is the emission of electrons from a surface when exposed to short wavelength light. The effect was not explainable using the wave theory of light, which was prevalent at the time. In 1905, however, Einstein explained the effect, based on Planck's quantum theory of light emission and absorption. It is readily understandable in terms of the complete absorption of incident **photons** each with energy $h\nu$, where ν is the frequency of the light beam. This energy is transferred to electrons in the surface, which results in a linear relationship between the energy of the absorbed light photon and the maximum energy of the emitted electron.

For many years the experiment to check this prediction was carried out by applying a retarding potential between the anode and cathode of a vacuum tube and measuring the voltage needed to bring the current of photo-emitted electrons to zero. This was a difficult measurement because it not only required measurement of a very small current but, more importantly, the current did not go to zero at a well-defined potential.

With the development of very sensitive solid-state amplifiers (integrated circuits), another technique became possible. In the equipment used in the present experiment, electrons knocked out of a cathode (-) strike a wire ring anode (+). As this ring charges up, its potential decreases relative to the cathode and electrons need greater and greater energies to overcome this potential difference. Eventually, when the potential difference equals the maximum energy of the photo-emitted electrons (the stopping potential), no more electrons are collected, causing the potential to stop increasing.   A photocell similar to the one used in the experiment is on the lab-bench. The large metallized surface is the cathode, and the ring is the anode.

Measuring the stopping potential is not so simple! A voltmeter typically measures potential by measuring the current developed across a large resistance. However, if a typical digital voltmeter (DVM) input resistance of a few MΩ were placed directly

across the anode-cathode system (capacitance C~10-20 pF), the time constant RC of the system would be a small fraction of a millisecond. Unless the photocurrent charging time were very much less than this, charge leakage from the anode would be so large that the anode potential could never reach the stopping potential. Modern field-effect transistors have input resistances up to $\sim 10^{14}\Omega$. Using such a transistor to make a unity gain amplifier or buffer makes it possible to have such a very large input resistance, but with a low resistance at the output of the circuit, i.e. the DVM is buffered or separated from the input circuit. The output voltage is the same as the input voltage, but the voltmeter resistance does not affect the time constant of the circuit. Here, an integrated circuit operational amplifier which uses a field effect transistor is used to provide such a buffer. You will learn more about this type of circuit in Physics 4051.
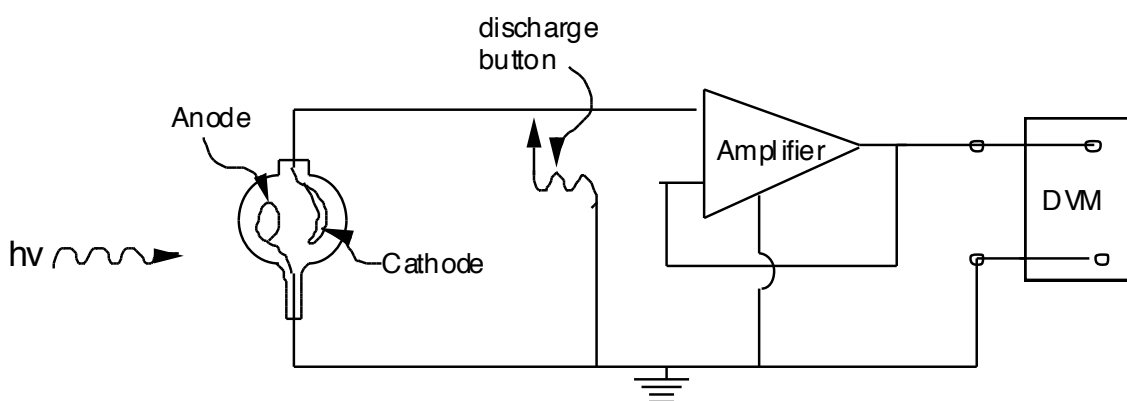

Figure 1. Schematic of a typical circuit diagram for reading out photoelectrons

In the present experiment light photons of various energies $E = hv = hc/\lambda$ are provided by a small incandescent bulb. Various wavelengths can be selected by a **monochromator,** which consists of a diffraction grating and some mirrors. The experiment consists of, first, calibrating the monochromator, i.e. determining the relationship between wavelength and monochromator dial reading, and then shining known wavelengths on to the photocathode of the photocell and measuring the corresponding stopping potentials.

As part of your preparation for the lab, you should construct and explain the key equations for calibrating the spectrograph and for connecting the wavelength with the stopping potential and Planck's constant. If we determined Planck's constant from single measurement, what would the error propagation formula be?

Procedure:

A. Calibration of the monochromator
Look inside the monochromator to see how it operates (top swings open). The angle of the diffraction grating to the incident light beam is adjusted by means of a multi-turn dial. Calibration consists of determining the relationship between dial reading and the wavelength of the light emerging from the output slit. You are provided with a mercury lamp, which provides several sharp lines of well-known wavelengths:

yellow	579.05 nm
yellow	576.96
bright green	546.07
blue	491.60
bright blue	435.84
faint blue	434.75
faint blue	433.92
violet	407.78
violet	404.66

1. Find the photodiode and make sure that the front of the enclosure tube is protected with a rubber stopper.

2. We will be using a separate spectroscopic Hg lamp with its own power supply. The supply that powers the fancy DVM is labeled "Photoelectric Effect Apparatus".   Toggle the detector (not Lamp) switch on the power supply to "on" and also the power push button on the DVM. Do it **now** because it takes 20 minutes for the DVM to warm up.

3. Turn the metal knob above the input slit to make a slit width of approximately 0.5 mm.

4. Turn on the Hg light and adjust the light position and the input mirror to focus an intense beam of light on the slit.

5. Remove the photoelectric detector assembly (keep it upright) and insert the eyepiece.

6. Find a bright line. Move the eyepiece to obtain a sharp image and put the cross hairs in the X orientation.

7. Obtain dial readings for as many of the Hg lines listed above as possible. Make a graph of dial reading vs. wavelength λ. The points should lie on a smooth line which is almost straight. Using MATLAB, fit

these data to a straight line using a simple linear fit as discussed in the statistics notes. You should include the errors on your dial reading, but you are assuming that the error on the line's wavelength is negligible. Since this fit only handles errors in y, the dial reading should be on the y-axis. Using the results of your fit, you will be able to determine the wavelength that corresponds to a given dial setting.

If you encounter some difficulty in assigning dial settings to the wavelengths given above, you will probably find it helpful to first plot data only for the most intense lines, then add other data when the overall trend is seen. The relative intensities of the lines can be found either in the *CRC Handbook of Chemistry and Physics* or at http://physics.nist.gov/PhysRefData/ASD/lines_form.html
The spectrum you want is Hg I.

B. Measure electron energy as a function of incident wavelength.

1. Set up the DVM as follows. Voltage range should be set to *Stopping Potential -2 – 0V* and current ranges to 10^{-13}.

2. Set the current amplifier to zero as follows: first *disconnect* the 'A', 'K' and 'down arrow' (GROUND) cables from the back panel of the apparatus. Press the phototube signal button in to *calibrate* setting. Adjust the current calibration knob until the current reads zero. Press the phototube signal button again to get back to the *measure* setting.

3. Replace the Hg lamp with the incandescent lamp. Adjust the lamp position and input mirror so that the light beam is narrow and focused on the slit.

4. Set the monochromator for a wavelength in the green (~ 530 nm). Remove the eyepiece and hold a piece of white paper over the exit port of the monochromator. Verify that you see a bright green spot (square in shape) centered on the exit port. Adjust the focus on the entrance slit so that the spot is as bright as possible. Now put the detector in place on the exit port. Connect the detector to the digital voltmeter.

5. *Reconnect* the 'A', 'K' and 'down arrow' (Ground) cables to the back of the apparatus.

6. Adjust the *voltage adjust* knob until the current on the ammeter is zero, meaning that the photoelectrons are no longer getting to the anode.

7. Make these stopping voltages versus wavelength measurements over as wide a range of wavelengths as possible, with some measurements close to the threshold wavelength. It may be more efficient to first select a new voltage differential and then adjust the wavelength dial until you once again get a zero current, but there are many ways to do it. Record your methodology as well as your data.

8. Widen the slit width to 2 mm and repeat steps 6-7. You have enough time in this lab to do at least two complete stopping potential curves. Two or more curves allow you (a) determine whether the energy of the ejected electrode depends on light intensity and (b) get a handle on the systematics of the experiment.

C. Analysis.

Plot stopping potential vs. $1/\lambda$.   Determine the slope of this graph and compare it with the accepted value of Planck's constant (in eV-s). Use MATLAB and make sure to put the data with the largest error on the y-axis so the linear fit can properly evaluate the fit and the χ-squared.

Find the work function of the photocathode by properly evaluating the intercept of your fit. Look online for typical work functions and make a guess as to what the photocathode material must be. We don't actually know what it is for sure, we want you to look it up and give some possible options.

Explore your systematics. Make sure you make a chi plot for your fit and evaluate whether the fit is linear, if you have outliers or problems at the ends of your fit where your calibration may no longer be applicable. Explain any systematic effects that you find. Did you underestimate or overestimate your errors? If so, you should go back and evaluate whether a reasonable change in your input errors really would affect your fit or not. Evaluate the differences between the low intensity and high intensity runs and state whether your experiment depends on intensity within the errors that you have actually assigned (i.e. how many sigma do the two results differ?) Since you already know that it should not, according to Einstein, then finding out that they differ by 20 sigma is a big clue that your errors were underestimated. Go back and fix your analysis.