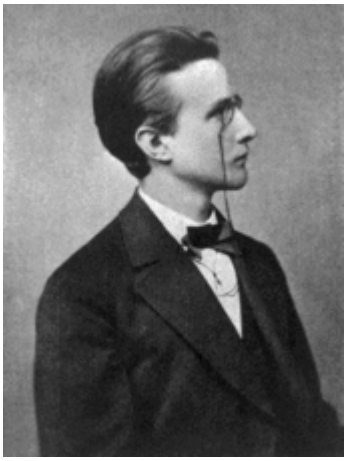
Planck's Constant v2.0


Max Planck in 1878

Background. The classical Rayleigh-Jeans law predicts that the spectral emission of a blackbody (i.e. object having perfect emissivity at a given temperature) increases at shorter wavelengths. Experiment shows good agreement with this law at long wavelengths (infrared), but emission goes to zero – not infinity as predicted – when the wavelength becomes shorter. This is known as the ultraviolet catastrophe. Reconciling theory and experiment led Max Planck to develop a quantum model for light. The quantum particle of light is known as a *photon*.

In 1901, Planck published the quantum law of radiation. It postulates that any oscillator has a discrete set of possible energies. The oscillator can never have energy between these states. Emission and absorption of energy by the oscillator is associated with quantum jumps. For light, this corresponds to jumps in the radiant energy: $E = h\nu$, where E is the quantum energy, ν is the frequency of the electromagnetic radiation, and h is Planck's Constant, a fundamental constant of nature.

In the photo-electric effect that is studied in this experiment, light striking a material causes electrons to be emitted. The classical theory of electromagnetism as formulated by Maxwell's Equations shows that increasing the intensity of light is accompanied by greater field amplitude. From this perspective, conservation of energy predicts that electrons liberated from a surface by the photo-electric effect will have commensurately larger energy as the light intensity increases.

Some experiments in the late 19th century showed this prediction to be incorrect: the energy of the photo-electrons remained *constant* as the light intensity increased. The *rate* of photo-electron emission, however, did increase. Einstein used Planck's model to explain the photo-electric effect with a simple algebraic equation:

$$h\nu = K + W \qquad (1)$$

where K is the kinetic energy of the photo-electron and W is the work function of the surface. Light at a given frequency ν acts as a stream of photons with energy $h\nu$. If a photon has enough energy to overcome the surface work-function energy, an electron is liberated; the remaining energy appears as the kinetic energy of the electron. This kinetic energy can be directly measured.

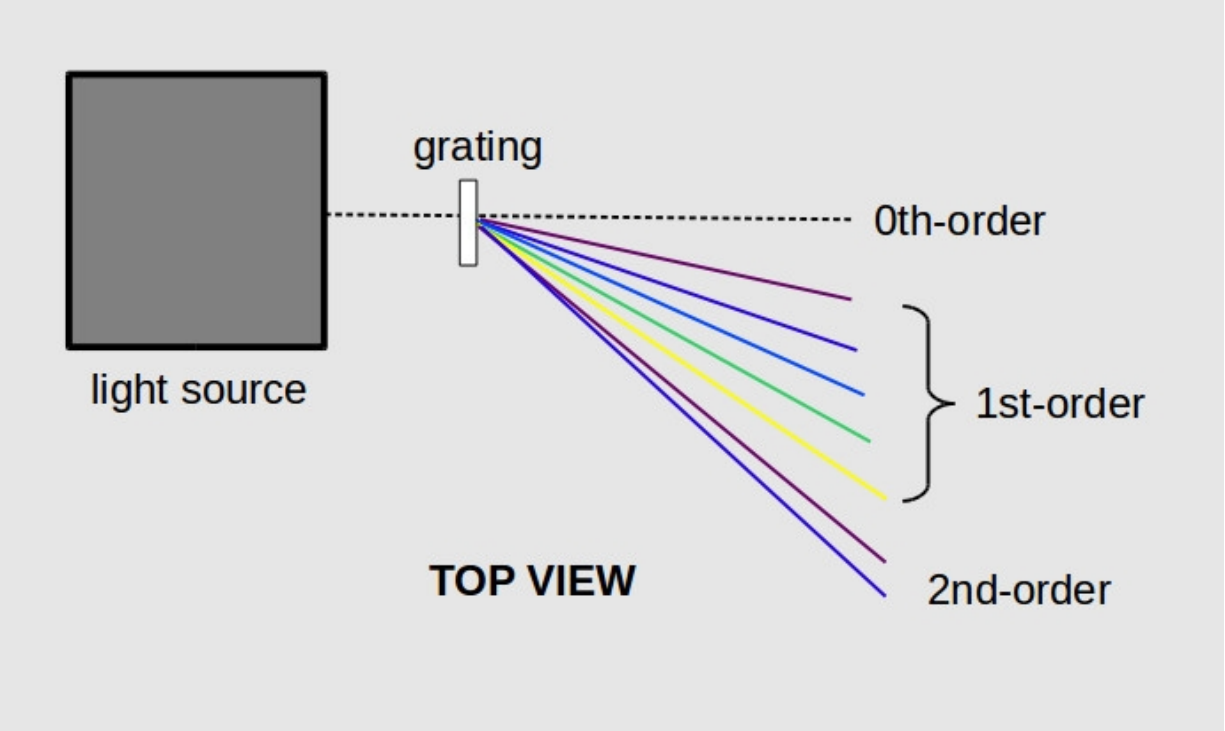


Figure 1: Diffraction of white light from a mercury lamp into multiple orders.

Experiment. To verify Equation (1), a source of light with a variety of selectable frequencies is required. This light is derived from an electrical discharge in mercury vapor (Figure 1). Hg atoms are excited in the discharge, then relax to lower energy states by giving up their excess energy as light. A transmission grating diffracts the white light emission output. The white light of Hg is composed of different colors, five of which are readily observed in this experiment. The wavelength and frequency of each are listed in Table I and provide the experimental calibration. Wavelength (λ) and frequency (ν) are related by $\lambda = c/\nu$, where c is the speed of light.

YELLOW	578 nm	518.672 THz
GREEN	546.074 nm	548.996 THz
BLUE 1	435.835 nm	687.858 THz
BLUE 2	404.656 nm	740.85 THz
VIOLET	365.483 nm	820.264 THz

TABLE I. Wavelength and frequency of the five Hg lines used in this experiment. Note that the yellow line is actually a two wavelength doublet at 578 and 580 nm.

The photo-electric effect takes place in a separate photo-tube. The diffraction grating spatially separates the different colors, allowing only photons at a selected wavelength to strike the cathode inside the photo-tube. The photo-tube is positioned at various

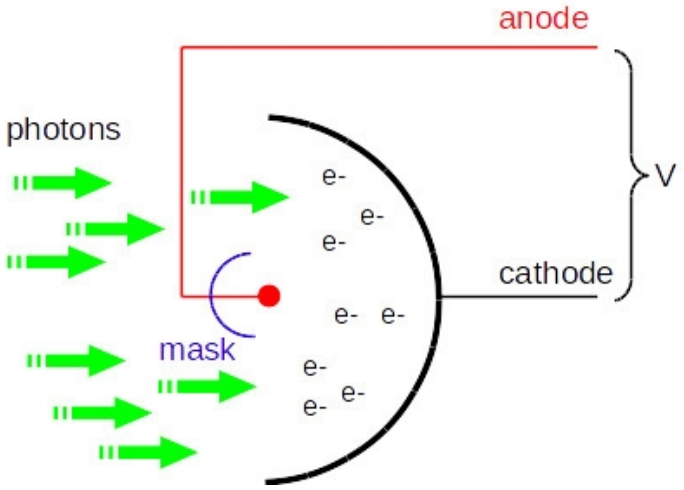


Figure 2: Conceptual diagram of the photo-tube.

wavelengths in the diffraction pattern of the light shown in Figure 1. Photons at a selected wavelength irradiate the cathode, causing it to emit electrons (e-). This is shown in Figure 2. Some of the negatively charged photo-electrons are collected at the wire anode, which is protected from the incoming light by a mask.

The physically separated anode and cathode behave as half of a cylindrical capacitor; the incoming light acts as a current source to charge up this capacitor (C) with electrons. The total charge (Q) and potential difference on this capacitor are governed by a fundamental equation from electrostatics: $Q = CV$.

The capacitance value of the photo-tube is not needed to analyze the experiment, but its behavior must be understood. The equivalent circuit in Figure 3 can be helpful. The generation of photo-electrons is represented by the current source. Charge Q on the capacitor builds up as individual electrons are collected. The capacitor potential increases in tandem. This continues until a potential V is reached, corresponding to the kinetic energy of each photo-electron: $K = eV$, where e is the fundamental electron charge. When the potential V maintains a steady, constant value, then the static condition described by Equation (1) has been attained. Because electrons are no longer accumulated, the final value of V is called the stopping voltage.

In Part 1 of this experiment, the stopping voltage is read with a digital voltmeter. The voltmeter cannot be placed directly on the photo-tube, however, because it would drain significant charge and distort the measurement. A unity-gain buffer amplifier is used to dramatically reduce (but not eliminate) charge leakage and gives a more accurate reading (Figure 3). This is because the input impedance of the buffer amplifier is many orders of magnitude larger than a digital voltmeter. The photo-tube charging time is measured in Part 2 and provides additional insight.

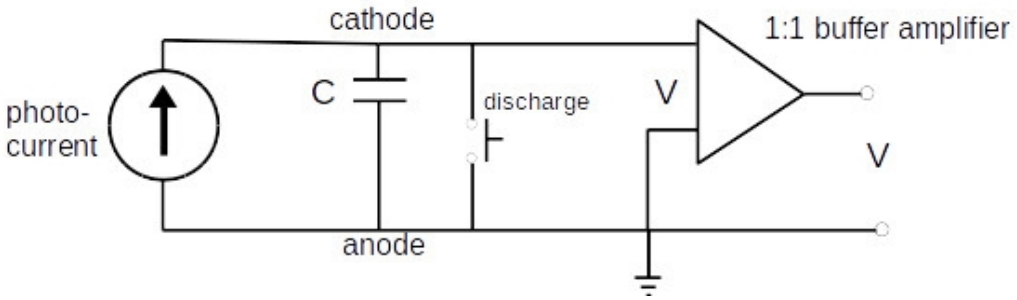


Figure 3: Equivalent circuit of the photo-tube and readout electronics.

Equipment and setup. The apparatus is shown in Figure 4. You will need a digital voltmeter for Part 1 and an oscilloscope for Part 2. There are also yellow and green filters, and a variable transmission filter that is used to adjust intensity.

Part 1. Check the battery voltage on the detector box. Plug in the Hg light source, turn it on, and let it warm up for a few minutes. Assemble the transmission grating/lens assembly on the two rods as shown. You can observe the diffracted colors as shown in Figure 1. The grating diffracts into positive and negative orders, but is blazed to be more efficient (brighter) in the positive direction so work on that side. Flip the grating 180° if necessary. The different colors are selected by rotating the detector box about the pivot point.

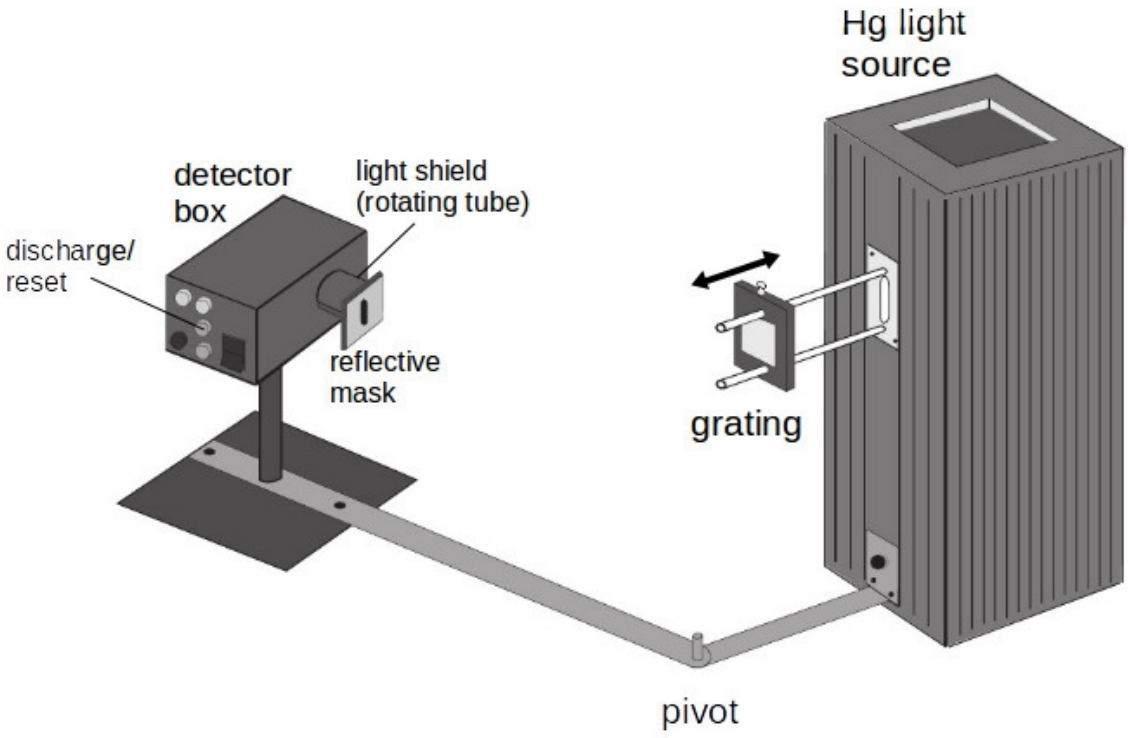


Figure 4: Experimental setup.

Light can be focused on the reflective mask by sliding the grating back and forth as shown in Figure 4. Roll the light tube out of the way to reveal the white photo-tube mask. The goal is to center the various colors on both the slotted aperture of the reflective mask aperture and on the photo-tube mask. It is important to carefully align the experiment so that only one color illuminates the photo-tube. Proper alignment should be checked for each color position.

Connect a digital multi-meter to the corresponding terminals and turn on detector power. Best results are obtained in a darkened lab. It is also necessary to place the corresponding filters on the reflective mask when measuring the yellow and green lines. No filters are used with the blue/violet lines. Make a chart in your notebook to record the steady-state voltage for each of the five Hg spectral lines in the first-order diffraction pattern. Begin each measurement by pressing the discharge button, then wait until the stopping voltage has stabilized. Make measurements with all 5 colors, then do a second data run. A second source of data is the colors in the second-order diffraction, but they will be weaker. Make two sets of measurements for as many second-order spectral lines as possible.

Part 2. Select one of the five available spectral lines of the Hg discharge; be sure to use the corresponding filter if green or yellow are chosen. Align the experiment as in Part 1. Use the transmission filter to attenuate the light to five different levels: 100, 80, 60, 40, and 20%. Record the steady-state stopping potential for each.

Next measure the photo-tube charging time. This can be done crudely with the multimeter or more carefully by using an appropriate BNC adapter to connect the output to an oscilloscope. The discharge button on the detector box defines the start time of this measurement. Time how long it takes the voltage to reach the stopping potential. Measure this charging time for each of the five intensity levels passing through the transmission filter. You will likely see the effect of body capacitance when the pushbutton is pressed, so it will be necessary to make several measurements. Can you quantify the rate of charge *leakage* from the photo-tube?

Repeat for a different spectral line.

Analysis. The data you acquired in Part 1 is sufficient to determine the validity of Equation (1). A least-squares linear curve fit should give the value of the two unknowns: Planck's Constant and the work function energy of the photo-tube cathode surface. Hint: use energy units eV. Compare your value of h to the accepted value and make an error analysis to explain discrepancies.

The data acquired in Part 2 can be used to make a classical interpretation of the photo-electric effect. What does the intensity dependence of the stopping potential show? What does the intensity dependence of the charging times show?

The photon model of light predicts that the stopping potential will remain perfectly constant for different intensities. Is this the case? Explain any experimental deviations from this prediction.

Why does the transmission grating produce brighter diffraction on one side of the zero order beam path?