Experiment 5

Planck's Constant

5.1 Introduction

The emission and absorption of light was an early subject for investigation by the German physicist Max Planck. As he attempted to formulate a theory to explain the spectral distribution of emitted light based on a classical wave model, he ran into considerable difficulty. Classical theory (Rayleigh-Jeans Law) predicted that the amount of light emitted from a black body would increase dramatically as the wavelength decreased, whereas experiment showed that it approached zero. This discrepancy became known as the ultraviolet catastrophe.

Experimental data for the radiation of light by a hot, glowing body also showed that the maximum intensity of emitted light departed dramatically from the classically predicted values (Wien's Law). In order to reconcile theory with laboratory results, Planck was forced to develop a new model for light called the quantum model. In this model, light is emitted in small, discrete bundles of energy or quanta, later called photons.

The relationship between the classical and quantum theories for the emission and absorption of light can be investigated with our apparatus. In combination with a mercury vapor light source an accurate determination of the ratio h/e and thus of h, Planck's constant, is possible. This constant has turned out to be one of the most important fundamental constants in all of modern physics.

5.2 Background Theory

5.2.1 Planck's Quantum Theory

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws. But as scientists continued working, inconsistencies that couldn't easily be explained began showing up in some areas of study.

In 1901 Planck published his law of radiation. In it he stated that an oscillator, or any similar physical system, has a *discrete* set of possible energy values or levels; energies between these values never occur. He went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation $E = h\nu$, where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature, later known as Planck's constant.

Planck's constant was found to have significance beyond relating the frequency and energy of light, and became a cornerstone of the quantum mechanical view of the atomic and subatomic world. In 1918 Planck was awarded the Nobel prize for introducing the quantum theory of light.

5.2.2 The Photoelectric Effect

In the photoelectric effect, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum theory, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of electrons emitted (or the photoelectric current). In the early 1900's several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using his famous equation, for which he received the Nobel prize in 1921:

$$E = h\nu = KE_{max} + W_0 \tag{5.1}$$

where KE_{max} is the maximum kinetic energy of the emitted photoelectrons, and W_0 is the energy needed to remove them from the surface of the material (the work function). E is the energy supplied by the quantum of light known as a photon.

5.2.3 The h/e Experiment

A photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum W_0 of its energy to escape the cathode, leaving it with a maximum energy of KE_{max} in the form of kinetic energy. Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and cathode, the photoelectric current can be stopped. KE_{max} can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero. In our experiment the stopping potential is measured directly, rather than by monitoring the photoelectric current, see later. Relating kinetic energy to stopping potential V gives a linear relation between V and the frequency ν. Plotting V vs ν allows the extraction of the constants h and W_0 from a least squares fit.

5.3 Equipment and Setup

Fig. 5.1 shows the setup using a mercury vapor light source and the h/e apparatus. Apart from the equipment shown in Fig. 5.1 only a digital voltmeter is required. Before proceeding check the two battery voltages. Minimum values are indicated on the h/e apparatus. Note that the unit can also be powered using a dual ± 9 V power supply.

The grating is blazed to produce the brightest spectrum on one side only. During your experiment you may need to turn the lens/grating assembly around in order to have the brightest spectrum on a convenient side of your lab table.

Turn on the light source and allow it to warm up for five minutes. Check the alignment of the light source and the aperture by looking at the light shining on the back of the lens/grating assembly. If necessary, adjust the back plate of the light aperture assembly by loosening the two retaining screws and sliding the aperture plate left or right until the light shines directly on the center of the lens/grating assembly.

Connect a digital voltmeter (DVM) to the OUTPUT terminals of the h/e apparatus.

Set the h/e apparatus directly in front of the light source. By sliding the lens/grating assembly back and forth on its support rods, focus the light onto the white reflective mask of the h/e apparatus (Fig. 5.2).

Roll the light shield of the apparatus out of the way to reveal the white photodiode mask inside the apparatus. Rotate the h/e apparatus until the image of the aperture is centered on the window in the photodiode mask. Then tighten the thumbscrew on the base support rod to hold the apparatus in place.

Slide the lens/grating assembly back and forth on its support rods, until you achieve the sharpest possible image of the aperture on the window in the photodiode mask. Tighten the thumbscrew on the lens/grating assembly and replace the light shield.

Turn the power switch ON. Rotate the h/e apparatus about the pin of the coupling bar assembly until one of the colored maxima in the first order shines directly on the slot in the white reflective mask. Rotate the h/e apparatus on its support base so that the same spectral maximum that falls on the opening in the white reflective mask also falls on the window in the photodiode mask. The white reflective mask on the h/e apparatus is made of a special fluorescent material. This allows you to see the ultraviolet line as a

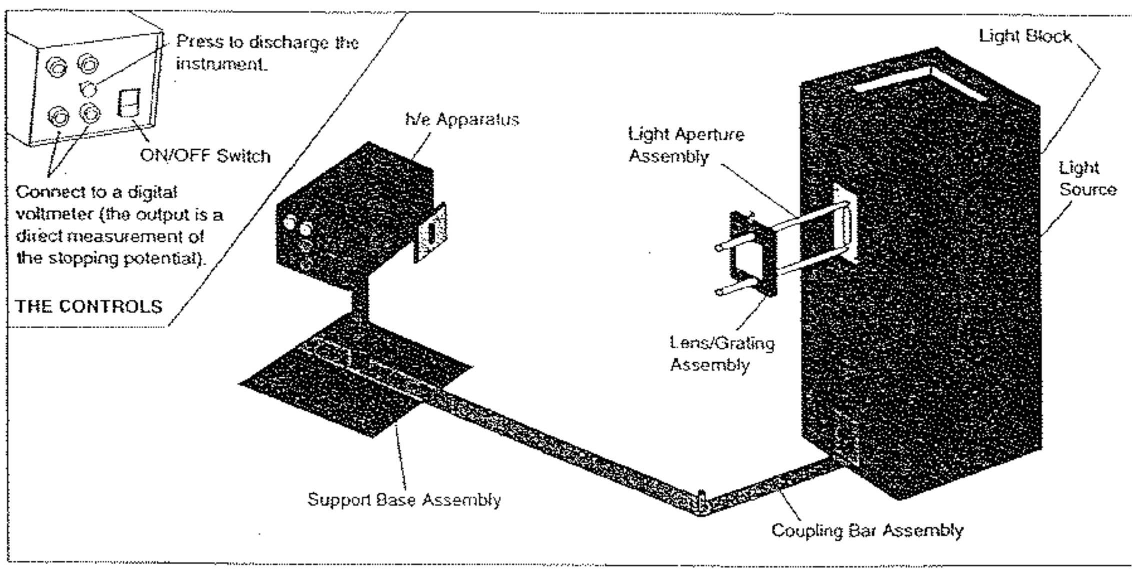


Figure 5.1: Equipment setup using a mercury vapor light source and the h/e apparatus.

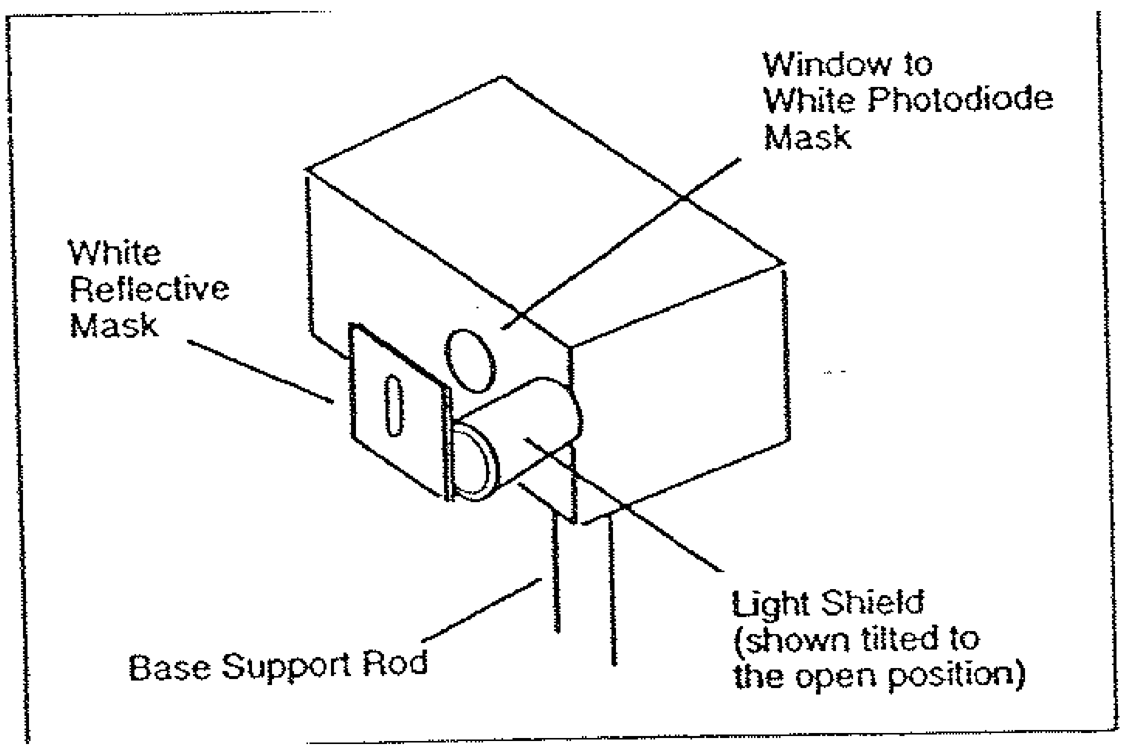


Figure 5.2: h/e Light Shield

blue line, and it also makes the violet line appear more blue. You can see the actual colors of the light if you hold a piece of white non-fluorescent material in front of the mask. The palm of your hand works in a pinch, although it fluoresces enough that the UV line will still be visible.

→ Important: when making measurements it is important that *only one* color falls on the photodiode window. There must be *no* overlap from adjacent spectral maxima.

Press the PUSH TO ZERO button on the side panel of the h/e apparatus to discharge any accumulated potential in the unit's electronics. This will assure the apparatus records only the potential of the light you are measuring. Note that the output voltage will drift with the absence of light on the photodiode.

Read the output voltage on your DVM. It is a direct measure of the stopping potential for the photoelectrons. See the Technical Information section at the end of this writeup for an explanation. For some apparatus, the stopping potential will temporarily read high and then drop down to the actual stopping potential voltage.

5.3.1 Using the Filters

The h/e apparatus includes three filters: one green and one yellow, plus a variable transmission filter. The filter frames have magnetic strips and mount to the outside of the white reflective mask of the h/e apparatus. Use the green and yellow filters when you're using the green and yellow spectral lines. These filters limit higher frequencies of light from entering the h/e apparatus. This prevents ambient room light from interfering with the lower energy yellow and green light and masking the true results. It also blocks the higher frequency UV light from the higher order spectra which may overlap with lower orders of yellow and green, see Fig. 5.3. In general you should make sure that room light does not interfere with your results, i.e. test by switching off the room lights.

The variable transmission filter consists of computer-generated patterns of dots and lines that vary the intensity (not the frequency) of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

5.4 Experiment 1: The Photon Theory of Light

According to the photon theory of light, the maximum kinetic energy, KE_{max}, of photoelectrons depends only on the frequency of the incident light, and is independent of the intensity. Thus the higher the frequency of the light, the greater its energy. In contrast, the classical wave model of light predicted that KE_{max} would depend on light intensity, i.e. the brighter the light, the greater its energy.

Both of these assertions will be investigated here.

5.4.1 Procedure

Part A

Set up the equipment, check (and adjust if necessary) focus and alignment as described earlier. Connect your DVM. Adjust the apparatus so that only one of the spectral colors falls upon the
opening of the photodiode mask. If you select the green or yellow line, use the corresponding filter. Place the variable transmission filter in front of the white reflective mask (and over the colored filter, if one is used) so that the light passes through the 100% section and onto the photodiode. Record the DVM reading.

Press and release the instrument discharge button, and observe how much time is required to return to the recorded voltage.

Move the variable transmission filter to the next section, record the new DVM reading, and the time to recharge after the discharge button has been pressed and released. Repeat these steps for all five sections of the filter. Important: for consistent results you want to measure the recharge time to reach the *same* voltage for each of the five intensities.

Repeat the entire procedure using a second color from the spectrum.

Part B

You can easily see five colors in the mercury spectrum. Adjust the apparatus so that only one of the yellow bands falls upon the photodiode, and use the yellow filter. Record the DVM voltage. Repeat the process for each color. Be sure to use the green filter when measuring the green line.

5.4.2 Analysis

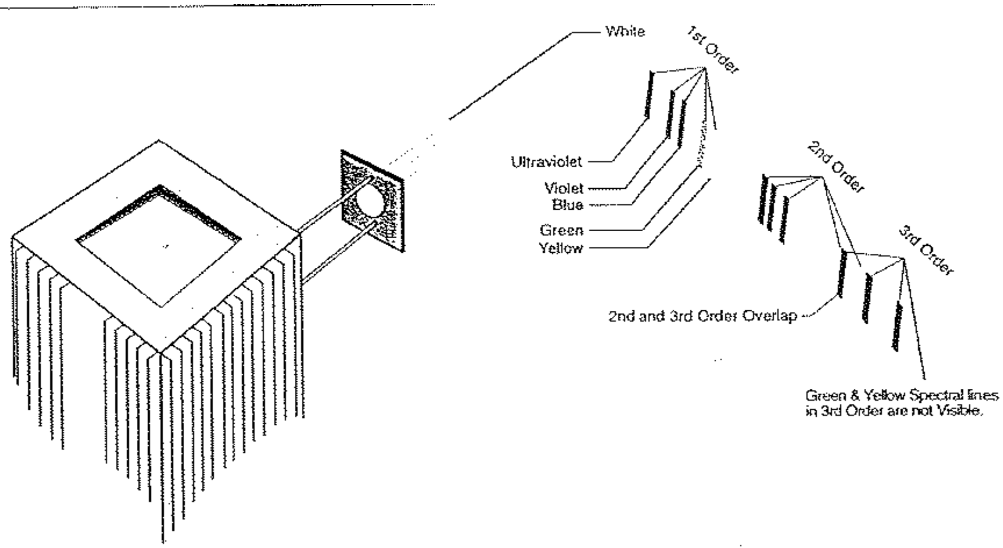
Plot your charging time results.

Describe the effect that passing different amounts of the same colored light through the variable transmission filter has on the stopping potential and thus on the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.

Describe the effect that different colors of light had on the stopping potential and thus on the maximum energy of the photoelectrons.

Defend whether this experiment supports a wave or a quantum/photon model of light based on your lab results.

Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.



All values except wavelength for yellow line are from *Handbook of Chemistry and Physics, 46th ed.* The wavelength of the yellow was determined experimentally using a 600 line/mm grating.

➤ **NOTE:** The yellow line is actually a doublet with wavelengths of 578 and 580mm.

Color	Frequency (Hz)	Wavelength (nm)
Yellow	5.18672E+14	578
Green	5.48996E+14	546.074
Blue	6.87858E+14	435.835
Violet	7.40858E+14	404.656
Ultraviolet	8.20264E+14	365.483

Figure 5.3: The expected three orders of light gradients you should see.

5.5 Experiment 2: Determination of h

According to the quantum/photon model of light, the energy of light is directly proportional to its frequency. With careful experimentation the constant of proportionality, Planck's constant h, can be determined.

5.5.1 Procedure

Make sure focus and alignment are still ok. For each color in the first order measure and record the stopping potential (don't forget the yellow and green filters). Repeat these five measurements to test for reproducibility.

Move to the second order and repeat the above process, i.e. take two sets of readings.

5.5.2 Analysis

Plot all your results. Perform four linear least squares fits to your four data sets, and determine h and W_0 for each fit. Then calculate your final results (incl. errors!) for h and W_0 as a weighted average. Compare with the accepted value of h, and comment on the quality of your result.

5.6 Technical Information on the h/e Apparatus

In the h/e apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, W_0. Photoelectrons ejected from the cathode collect on the anode.

The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilizes. This final voltage between the anode and cathode is therefore the stopping potential.

To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultrahigh input impedance ($> 10^{13}\Omega$), and the output from this amplifier is connected to the output jacks. This high impedance, unity gain ($V_{out}/V_{in} = 1$) amplifier lets you measure the stopping potential with a DVM. Note that while the impedance of this amplifier is very high, it is not infinite, and some charge will leak off. Thus charging the apparatus is analogous to filling a bath tub with different water flow rates while the drain is partly open.

Due to the very high input impedance, once the capacitor has been charged from the photodiode current it takes a long time to discharge this potential through some leakage. Therefore a shorting switch ("Push to zero") enables the user to quickly bleed off the charge. However, the op-amp output will not stay at zero volts after the switch is released since the op-amp input is floating.

Due to variances in the assembly process, each apparatus has a slightly different capacitance. When the zero switch is released, the internal capacitance along with the user's body capacitance coupled through the switch is enough to make the output voltage jump and/or oscillate. Once photoelectrons charge the anode, the input voltage will stabilize.