THE PHOTOELECTRIC EFFECT

"It seems to me that the observations associated with ... the production of cathode rays by ultraviolet light ... are more readily understood if one assumes that the energy of light is discontinuously distributed in space."
- A. Einstein (1905)

In this experiment, you will investigate the particle nature of light. Prior to Einstein's explanation of the photoelectric effect, it was assumed that light energy was distributed continuously in space, and was a function of light wave amplitude only. However, based on the experimental observations made of the photoelectric effect, Einstein argued that light energy must be quantized in small packets of energy proportional to the frequency of the light. The constant of proportionality is h, Planck's constant. These packets of light energy, or light particles, came to be known as photons.

The particle nature of light usually can not be observed, due to the insignificant size of a single photon relative to most everyday objects. However, in the photoelectric effect, light energy incident on a target material is acquired by individual electrons near the material's surface, permitting some of them to escape. The small size of the target electrons means that they usually interact with only a single photon at a time, and the quantization of light energy can be observed by examining the amount of kinetic energy the escaping electrons possess. The experiment you will perform involves measuring the maximum amount of kinetic energy possessed by electrons leaving a metal surface as a function of the frequency of the light shining on it. Using Einstein's theoretical equation for the photoelectric effect, you will then be able to calculate the value of h, the "size" of an individual packet of light energy.

The light source you will use for the experiment is a mercury vapor lamp. The spectrum produced by an excited monatomic vapor, such as that of mercury, consists of particular discrete wavelengths characteristic of the particular element of the vapor. This is in contrast to the continuous spectrum of an incandescent solid and the band spectrum of an excited molecular vapor. In order to verify Einstein's interpretation of the photoelectric effect, we must have a means of either isolating a particular spectral line, or, if that is not possible completely, to know which of the lines remaining in the beam is responsible for the result we are obtaining. Spectral lines can be completely isolated for study, through use of expensive instrumentation. However, by the use of inexpensive filters, sufficient isolation can be accomplished to obtain at least "ball-park" results. The latter method will of necessity be used here.

The experiment will consist of several parts. First, you will observe the line spectrum produced by a mercury vapor lamp. Second, you will, by means of colored filters, isolate or at least reduce the number of emitted spectral lines. Third, you will shine the filtered light from the lamp on a № 929 phototube constructed from cesium antimonide, CsSb, and observe the photoelectric effect as function of frequency by means of an electric circuit described in that section. Based on your results from this part, you will calculate h, as well as the work function ϕ and the threshold frequency ν_0 for CsSb.

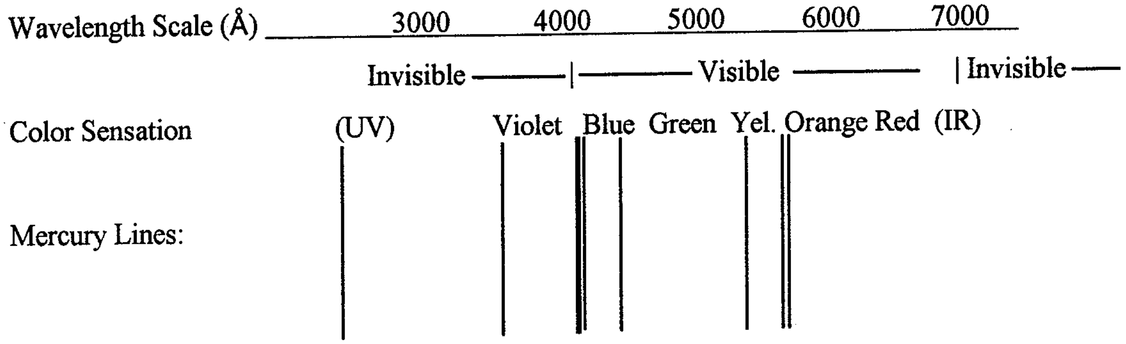
I. THE MERCURY SPECTRUM

Each station has been provided with a mercury germicidal lamp, a slotted metal mask, three filters -- orange, green, and blue -- and a replica diffraction grating. The latter device, which looks more or less like an ordinary sheet of transparent plastic, has on it a large number of parallel grooves, 300 to each millimeter, which act like slits and produce interference maxima and minima. In principle, the device acts similarly to the double slit (studied in Physics 142), but allows the transmitted light to be of far greater intensity and, because of the very close spacing of the grooves, separates in any given order (except $n = 0$) the interference maxima for different wavelengths, so that a spectrum may be seen.

Before turning on the mercury lamp, have the slotted metal mask (slit vertical) in place in the filter holder of the lamp. NEVER LOOK DIRECTLY INTO THE LAMP. It produces UV light which can be damaging to the eye. Now turn on the lamp and examine the light through the slide with the grating. The best method is to place the grating in the filter holder of the lamp, and then hold a piece of paper six to twelve inches away from the lamp, until the diffraction pattern from the light passing through the grating becomes distinct. Because of the room illumination and the other lamps, there will be some spurious images, but if the grating is correctly oriented (grooves vertical) you should be able to see, in addition to the zeroth-order composite mercury light at center, the first and perhaps higher orders of some of the lines in the visible region of the mercury spectrum on both sides of center. You will of course not be able to see the portions of the spectrum to which the eye is completely insensitive (the UV and the IR), and which lines of the visible region you do see will depend both on their relative intensity (since they vary considerably in this respect) and on the relative sensitivity of the eye at the particular wavelength. The sensitivity of the eye is greatest at about 5500 Å (green) and falls off to zero at about 4000 Å (far violet) and 7000 Å (far red). This sensitivity curve is shown on Page 7. Chances are you will see at least the following three strong lines:

Yellow	5770-5790 Å (a doublet)
Green	5461 Å
Blue	4359 Å

The spectrum of the sufficiently intense lines of Hg in the UV and visible regions is given in the chart below. There are many other lines in the spectrum, but they are too weak to be observed except by photographic methods. <u>Study this chart very carefully</u>, and make sure you understand every aspect of it. Because of the fact that the envelope of the lamp is of quartz, a material which is transparent to wavelengths as short as 1800 Å, the UV wavelengths of mercury are present in the beam from the lamp.



Wavelength (Å)	2536	3650	4047/78	4359	5461	5770/90
Frequency (10^{14} Hz	11.8	8.21	7.41	6.88	5.49	5.19
Energy (eV) per photon	4.89	3.40	3.06	2.84	2.27	2.14
Relative Intensity	Very Strong	Strong	Strong	Strong	Strong	Moderate

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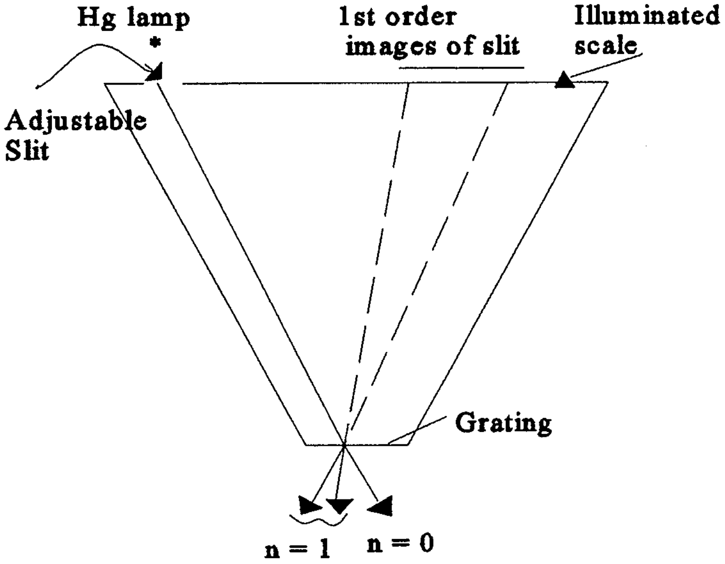
Note that the line intensity depends not only on the energy per photon but also on the relative <u>number</u> of photons undergoing the particular electronic transition in the atom as compared with the numbers in other transitions.

To enable yourself to check out the details of the spectrum better than you can with the grating alone, use one of the commercial spectrometers set up in the room (when it is available, not necessarily immediately). Using this instrument, you will probably be able to see additional lines and will also be able to verify roughly (to two significant figures) the wavelengths of the visible lines. Below is a sketch showing how this instrument works. The heart of it is the grating, and you will see that fundamentally it works just like the grating at your station.



At some time during the period, go to the instrument, look at the composite Hg light at the left and the 1st-order spectral lines at the right, verify roughly the wavelengths in the chart of those able to be seen and their color, and record your results in a table such as that given below. The mercury source must be positioned directly behind the slit in order to assure the strongest slit images. Record the relative apparent intensities (strong, moderate, absent, etc.), then taking into account the relative eye sensitivities and relative actual intensities given in the table, decide whether your results for apparent intensities are reasonable. It is not necessary to have the preceding experimental procedure completed in order to proceed with the other parts of the experiment which follow.

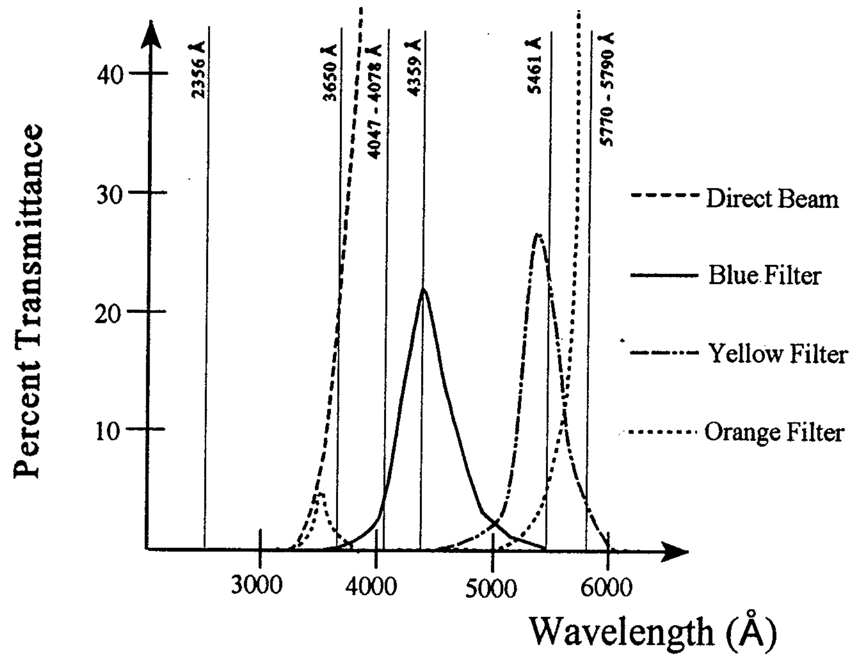
Intensity of spectral lines from Mercury vapor lamp				
λ (Å)	Color	Relative Apparent Intensity	Relative Eye Sensitivity	Relative Actual Intensity
5770-5790			0.9	Moderate
5461			1.0	Strong
4359			0.03	Strong
4047-4078			~ 0	Strong
3650			0	Strong
2536			0	Very strong

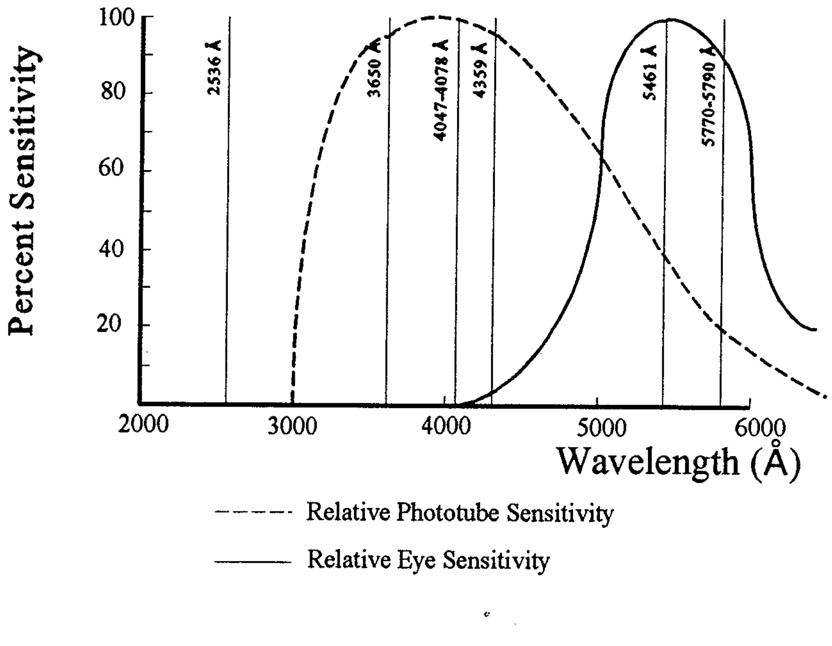
II. THE EFFECT OF FILTERING

The color of the filter, which is simply the composite color of the range of wavelengths remaining in the transmitted beam when white light (all visible wavelengths) is incident on the filter, gives you an idea of what region of the spectrum is transmitted by the filter (and what absorbed by it). You therefore have a rough idea of which Hg spectral lines might be passed by a given filter. The guesswork is reduced by observing the filtered beam through a diffraction grating, and/or referring to transmittance curves obtained with more elaborate instruments. We shall do both.

Study carefully the set of traces (obtained by the latter method) on page 6, and note which Hg lines are passed by each colored filter. Notice that filters usually pass more than one line. For example, note that the blue filter passes the 4359 Å blue line best but also passes the 4047-4078 Å doublet to a certain extent. Now, using the grating at your station, verify qualitatively, as best you can, the information given by the traces. While observing the spectrum, hold each filter in turn in the beam from the lamp, and note the effect on the lines. Record your results in the table below. You cannot observe the 3650 Å UV line with the naked eye. However, using the graphs on page 6, indicate which filter(s) should pass this line as well. Do the traces correspond with your observations?

EFFECT OF FILTERS				
Hg line				(-) Line Eliminated (√) Transmitted Poorly (√√) Transmitted Well
λ(Å)	Color	Orange Filter	Green Filter	Blue Filter
5770-5790				
5461				
4359				
4047-4078				
3650				


Percent Transmittance
40
30
20
10
2356 Å
3650 Å
4047 - 4078 Å
4359 Å
5461 Å
5770 - 5790 Å
3000
4000
5000
6000
Wavelength (Å)
----- Direct Beam
—— Blue Filter
—-·· Yellow Filter
······· Orange Filter

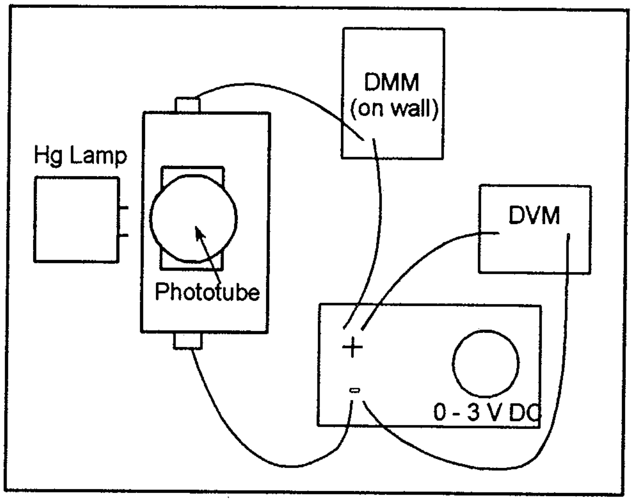

Percent Sensitivity
100
80
60
40
20
2536 Å
3650 Å
4047-4078 Å
4359 Å
5461 Å
5770-5790 Å
2000
3000
4000
5000
6000
Wavelength (Å)
----- Relative Phototube Sensitivity
—— Relative Eye Sensitivity

III. DETERMINATION OF THE PHOTOELECTRIC WORK FUNCTION OF CsSb AND PLANCK'S CONSTANT

It should be apparent from your results in Part II that it is possible by means of the filters to isolate reasonably well some of the mercury lines. We shall use these wavelengths in conjunction with a photoelectric cell, or phototube, to determine Planck's constant, at the same time determining the work function and threshold frequency of the material used in the cathode of the phototube.

The 929 phototube has in it a semi-cylindrical photocathode of cesium antimonide, CsSb, a material with a low work function, plus a central wire on the cylindrical axis as an anode. Just as the eye varies in its response to different wavelengths, the phototube does also. The limeborosil glass envelope passes radiation down to 3000 Å. This means that the strong 2536 Å UV line from the mercury lamp is blocked but that the 3650 Å UV line and above can produce effects. The complete sensitivity curve is found on page 6.

The idea behind the experiment is straightforward. You will shine the filtered light from the mercury vapor lamp on the cathode of the phototube. According to Einstein's theory, the electrons at the surface of the cathode absorb single photons from the light, and gain all the energy carried by the photons. If the energy absorbed is sufficient, the electron is enabled to overcome the energy barrier at the cathode surface (this energy barrier corresponds to the work function ϕ of the material), and escape with a kinetic energy, E_K. Therefore, when light of sufficiently high frequency shines on the cathode, a current is generated as the electrons ejected from the cathode flow to the anode, completing the circuit. Our circuit is given to the right in schematic form.



On one side of the metal shield covering the phototube is a double aperture through which the light may enter. The strip between apertures is intended to block that part of the beam which would otherwise fall directly on the anode, sometimes complicating matters by causing photoemission from anode as well as cathode.

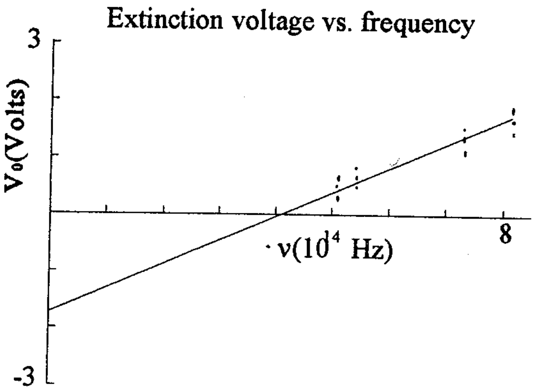
By controlling the voltage difference between the cathode and the anode, we are able to control the potential energy barrier, eV, faced by each electron as it crosses over to the anode. For a given frequency of light, there will be a certain voltage, called the extinction voltage, V_0, at which the energy barrier is equal to the maximum kinetic energy of the ejected electrons, the electrons are stopped and the current in the circuit goes to zero. By recording the extinction voltage required for a given frequency of light, we can calculate the amount of energy carried by a photon of that frequency and the work function of the material.

We can now go ahead with finding the extinction voltage associated with each of the filters (as well as for the direct beam). However, we must remember that the filters do not isolate perfectly the spectral lines from the lamp. You must use your data from parts I and II, as well as the Einstein theory of the photoelectric effect, in order to judge correctly which of the spectral lines passed by the filter is responsible for the photoemission from the cathode being stopped by the extinction voltage. It might seem profitable to use a combination of filters in some cases to produce greater isolation, but a study of the curves will show that nothing would be gained in connection with the Hg spectrum by doing this.

Remove the slit from the lamp. Place the orange filter in the holder, turn on the lamp and place it snugly against the extender, perhaps covering with the rubbing cloth (for Part D) to help in shielding from the room lights. Start with zero source voltage and advance the voltage just to the point where the current is exactly zero. (If a further increase shows a negative current, this is probably an indication that there is some anode emission, despite our precautions. The best we can do is to make a note of this and consider it a source of error in our measurements. Practice a few times before recording voltages. Now bring the current to zero and read the extinction voltage V_0. Record in a table such as that given below. Repeat twice, and record all three readings. Repeat the procedure, in succession, for the green and blue filters and the direct beam. If that order is followed, you should find that the extinction voltages obtained are in the order of lowest to highest.

Filter	Voltage V_0			Line Responsible	
	Trial 1	Trial 2	Trial 3	λ(Å)	ν (Hz)

Plot your experimental points on coordinates V_0 vs. ν, and draw the straight curve which best represents the points. Let the V_0 scale range from +3 to -3 volts. Plot all three trials for each filter. Extend the curve with a broken line through the negative V_0 axis at $\nu = 0$. Using a large slope triangle, measure and record on the curve its slope, in units of volts/hertz. Also record the V_0-intercept, in volts, and the ν-intercept, in Hz.



Use these values in connection with the Einstein photoelectric equation

$$h\nu = \phi + E_{K\,max}$$

and the extinction-voltage relationship

$$eV_0 = E_{K\,max}$$

to determine both Planck's constant h and the cesium-antimonide work function ϕ and threshold frequency ν_0. <u>You must be careful to use the correct units.</u> Show all calculations (in algebraic form), as should always be done, and put your results in a table, as follows:

	Experimental Value	Published Value
Planck's constant h (J● sec)		
Work function ϕ of CsSb (eV)		1.8 eV
Threshold frequency ν_0 of CsSb (Hz)		
Threshold wavelength λ_0 (= c/ν_0) of CsSb (Å)		6800 Å