

LC-4: Photoelectric Effect Lab Worksheet

Name _____

In this lab you investigate the photoelectric effect, one of the experiments whose explanation by Einstein forced scientists into accepting the ideas of quantum mechanics. In the photoelectric effect, light knocks electrons out of a metal, which are then detected by an electrical circuit.

Electrons are ejected because the light transfers energy to electrons in the metal. A particular electron absorbs energy from the light. It uses some of that energy to break free of the metal: the amount of energy required to break free is called the Work Function of the metal. The remaining energy shows up as kinetic energy of motion of the electron.

The experimental observation is that electrons with a range of energies are ejected from the metal, and that the maximum electron kinetic energy observed depends on the *frequency* of the light, but does *not* depend on its *intensity*.

Einstein's solution is that light is 'quantized', meaning that its energy increases only in steps of hf , where h is a constant (Planck's constant), and f is the frequency of light. An equivalent interpretation is that light is made up of particles called photons, each with energy hf . Another classic experiment, Compton scattering, showed that light interacts with electrons just as if they were both colliding balls, if the photon light 'ball' has energy $E = hf$ and momentum $p = E/c$.

In your experiment you will use different frequencies of light to knock electrons out of a metal, measure the maximum kinetic energy in each case, and determine the relation between that maximum KE and the light frequency.

The pieces of your experiment are:

- 1) A mercury vapor light source.
- 2) A diffraction grating to separate the different wavelengths from the mercury lamp, and a lens to make an image of these wavelengths on a photoelectric tube
- 3) The photodetector and track from the interference lab. You will use this to determine the mercury wavelengths.
- 4) A photoelectric tube containing two metal plates, one from which the light will eject electrons, and one that will collect the ejected electrons. The tube is inside a black box that says 'h/e apparatus'. It needs to be switched on because the box also contains an amplifier.

There are four parts to this lab:

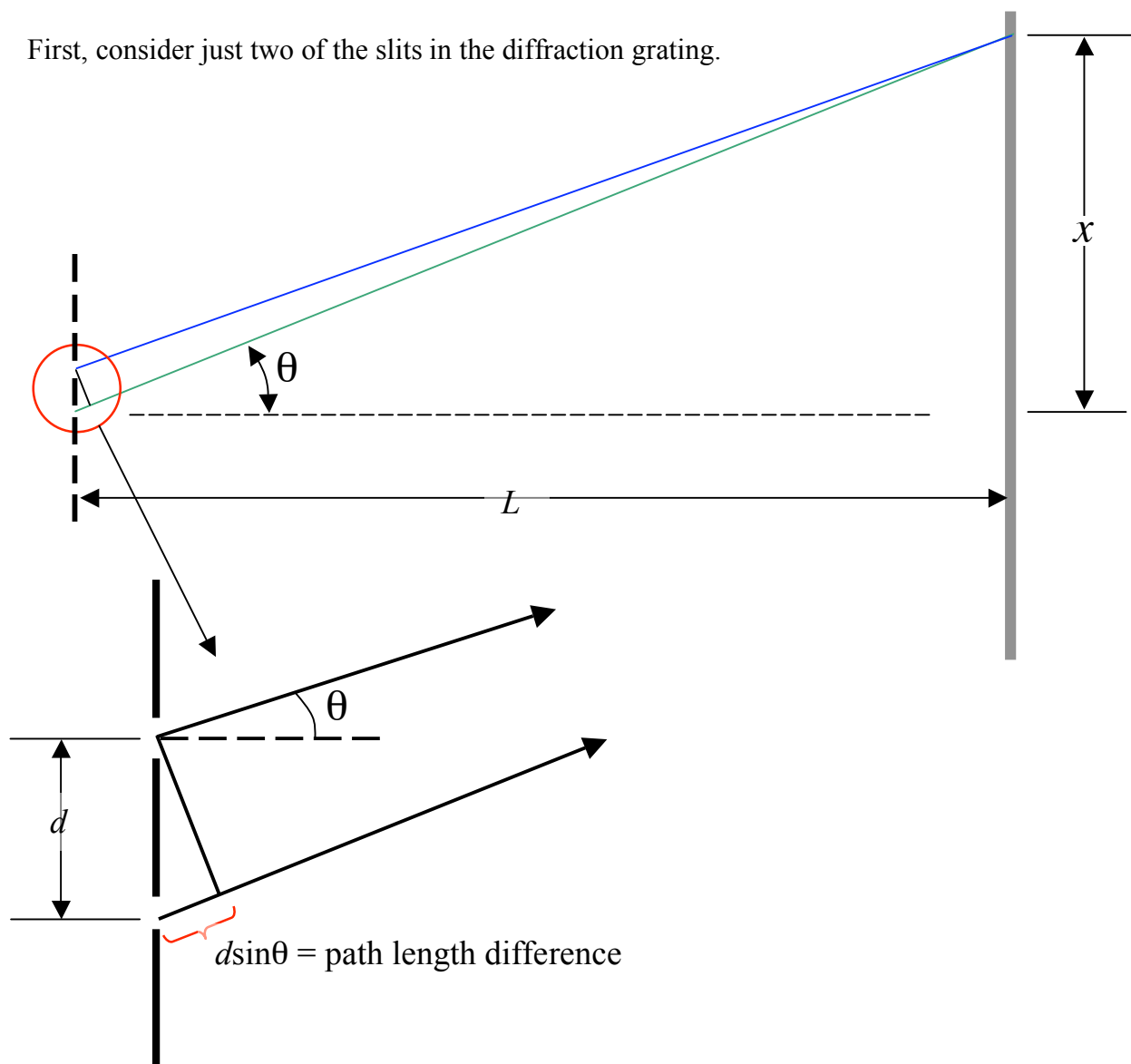
- A) Measure the different wavelengths of light produced by the mercury lamp.
- B) Measure the photoelectric stopping potential for each wavelength and find wavelength dependence (this will let you determine Planck's constant.)
- C) Measure the dependence of the stopping potential on light intensity.
- D) Measure the time 'charging time' of the photoelectric tube to learn something about the distribution of the ejected electrons.

Experiment A: Measure the wavelengths of the light coming from the mercury lamp.

Turn on the mercury lamp now to let it warm up

The mercury vapor lamp uses a *diffraction grating* to disperse the different wavelengths of light. Its effect is similar to a prism, but its operating principle is that of the two-slit interference phenomenon you looked at last week. Instead of just two slits separated by 0.4 mm, your diffraction grating has thousands of very narrow slits at a pitch of 600 ‘slits’/mm. And instead of using a single wavelength (red), you are using light from the mercury lamp, which contains many colors. Each individual color will give you a diffraction pattern like you saw last week.

First, consider just two of the slits in the diffraction grating.



- A1) Think about the light arriving at the point on the screen shown. What is the condition for constructive interference of the two waves from the two adjacent slits shown at the location (answer in terms of d , θ , and λ)

A2) Assuming that this constructive interference condition for two neighboring slits is met, what is the path length difference between waves originating from pairs of slits $2d$ apart? $3d$ apart? nd apart?

A3) Suppose you measure that constructive interference occurs at a distance x from the central maximum on the screen. Write an equation for the x -distance on the screen from the central maximum at which constructive interference occurs. Answer in terms of λ , d , and L .

Note: If you are considering using the ‘small-angle approximation’, look at the angle to the yellow line and see if you think it is small. If you are not using that approximation, don’t read this.

A4) Determine the wavelength of the spectral lines from the mercury lamp (use the computer and the movable photodetector, and the DataStudio settings file from the interference lab LC-1_IntDiff.ds).

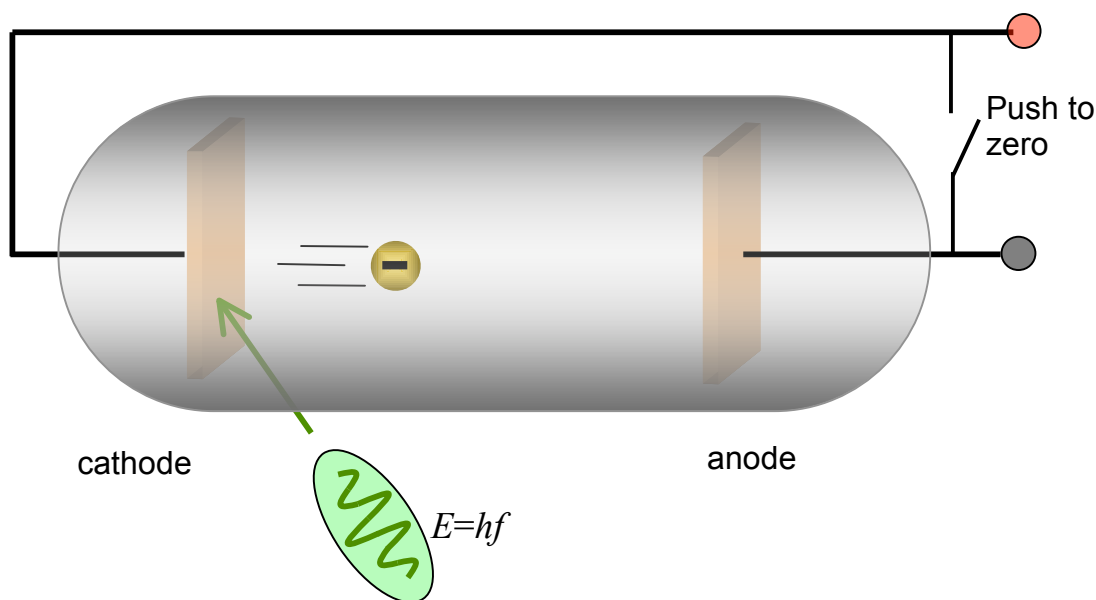
- i) Put the photodetector about 21 cm from the diffraction grating, and adjust the grating/lens position to give a reasonably focused image of the lamp slit on the photodetector wheel.
- ii) You may need to adjust the photodetector gain (slide switch on top) to get a good signal. You might also change the photodetector slit.
- iii) Make sure the motion of the photodetector is perpendicular to the undiffracted beam lamp.

NOTE: one of the lines is in the ultraviolet, and only visible to your eye when the material it strikes fluoresces. The photodetector is not sensitive to the UV line.

Line #	Line color	distance from central peak (cm)	Wavelength (nm)
1	UV		365.48 nm
2			
3			
4			
5			

Experiment B: Measure the 'stopping potential' for each different wavelength to verify the quantum nature of light and to determine Planck's constant.

Your photoelectric tube is shown below.



- B1) Suppose the photon transfers some energy to an electron in the cathode so that it has 1 electron-volt (eV) of energy after it is ejected. How fast is it traveling ($m_e=9.11 \times 10^{-31}$ kg, $e=1.6 \times 10^{-19}$ C)?
- B2) The ejected electron leaves the anode and ends up on the cathode. What is the direction of the electric field after this charge transfer? What is the direction of the resulting force on the electrons?
- B3) What is the maximum kinetic energy of an ejected electron (cathode work function = W , incoming light has frequency f)?
- B4) The anode continues to charge up as electrons ejected from the cathode arrive. At what electric potential difference relative to the cathode will the anode stop charging?

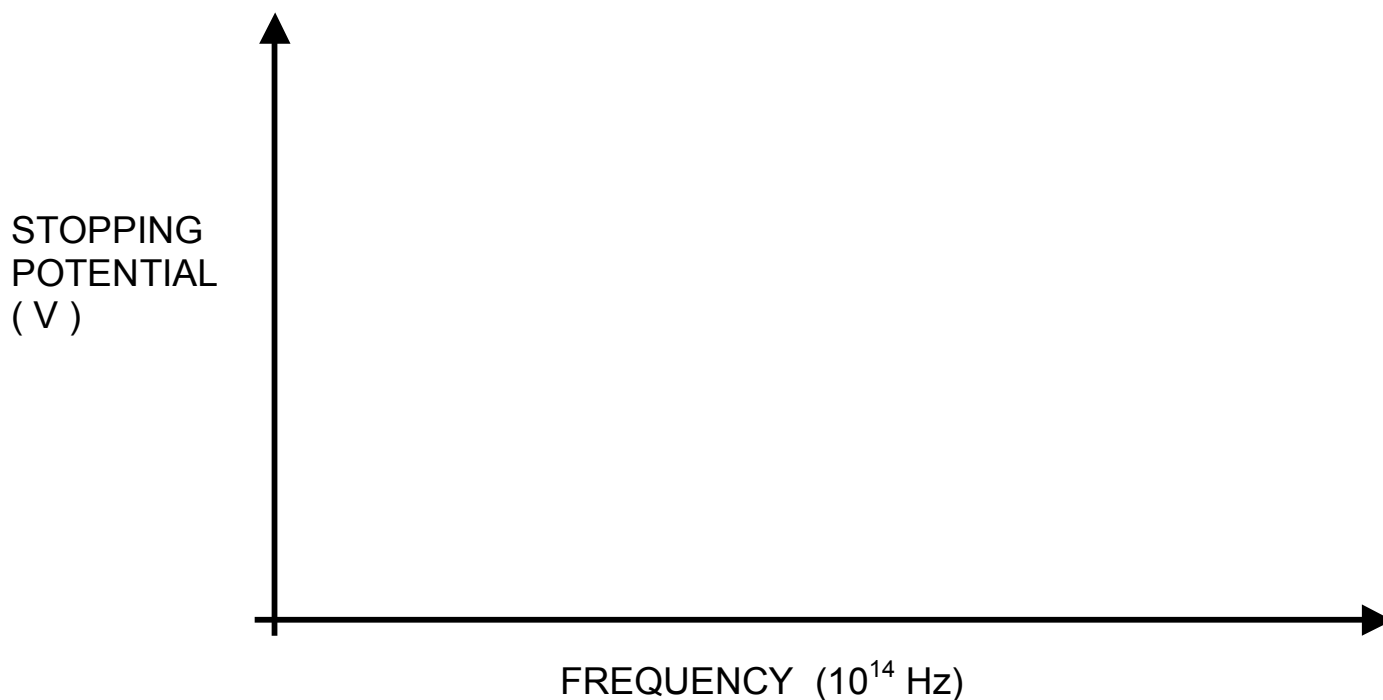
B5) Measure the equilibrium potential difference between the anode and the cathode for the five different wavelengths from the mercury lamp shining on the cathode by connecting the Keithley voltmeter to the outputs of the photoelectric tube.

Important Notes:

- 1) The black box containing the photoelectric tube also contains some buffering electronics. This must be turned on with the switch on the side.
- 2) You'll need to refocus the lens to get a sharp image on the reflective mask.
- 3) The light needs to shine on the cathode. To do this, swing the black tubular light shield behind the white reflective mask out of the way, and visually make sure the light hits the window in the photodiode mask. Swing the light shield back into place.
- 4) The white reflective mask, and also the photodiode mask, fluoresce, so the UV line shows up, and you should use it to make measurements.
- 5) Any little bump is likely to misalign the tube, so that the light no longer goes through the window of the phototube mask. If you are getting unusual results, check this.
- 6) For the green and yellow wavelengths, you must put on the green and yellow filters to block out other colors from the room lights.

Wavelength (nm)	Frequency (10^{14} Hz)	Stopping potential (volts)

Plot the data below.



B6) Use the data to determine the work function of the cathode (in electron-volts (eV)), and a numerical value for Planck's constant h . Compare to the accepted value of 4.136×10^{-15} eV-sec.

Experiment C *Intensity dependence of the photoelectric effect*

C1) Explain why the stopping potential should in theory not depend on the light intensity.

C2) Included in your kit is a filter that lets you vary the intensity to 20%, 40%, 60%, 80%, or 100% of its original value. Choose one wavelength, and measure the stopping potential for each of these using the Keithley meter. Don't forget to also use the green or yellow filter if you use the green or yellow wavelength.

Transmission percentage	Stopping potential
20%	
40%	
60%	
80%	
100%	

C3) Does the stopping potential depend on intensity?

C4) What **does** depend on the intensity?

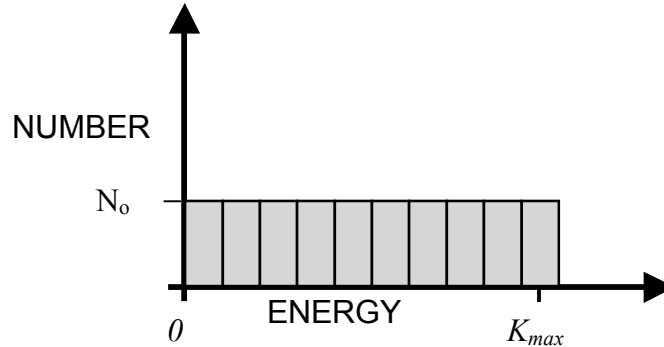
Experiment D *Distribution of kinetic energies of ejected electrons.* Electrons in the metal absorb *all* of the photon's energy (the photon disappears, and the electron has that much more energy), but the electrons in the metal have a distribution of energies, with some moving faster than others. The ejected electrons with the most kinetic energy (these are the ones that determine the stopping potential) are the ones that were already moving fastest inside the metal. You measured the stopping potential in Experiment B.

In this experiment, you try to see if anything you measure in this lab can tell you something about the distribution of electron kinetic energies. About the best we can do is distinguish a spread in energies from no spread, but that is something!

Notes: Assume that the travel time of the electrons to the anode is negligible. That is, the time it takes for an electron to travel to the anode is much less than the time to wait before the next electron is ejected.

D1) First assume that there is **no** spread in the kinetic energy of ejected electrons, and that all of the electrons are ejected from the cathode with the maximum kinetic energy K_{max} and that they travel directly to the anode. Assume that they are ejected at a rate of N electrons / sec. If the anode/cathode capacitor has a capacitance of C , calculate the time-dependence of the voltage difference assuming that it starts out at zero volts when the light is turned on.

D2) Now assume that all energies from zero up to the maximum K_{max} are equally likely for the ejected electrons. Note that when the potential difference is V , all electrons with $K < eV$ can no longer make it to the anode. The rate of ejecting electrons is still N electrons/sec, but the kinetic energies are spread over the range $0 < K < eV$, and not all of them make it to the cathode.



Suppose it takes N_0 electrons to charge the anode to K_{max}/e . And that the electrons are ejected from the cathode at a rate of $(N_0/2)$ per second. Start from $t=0$, when anode potential is zero.

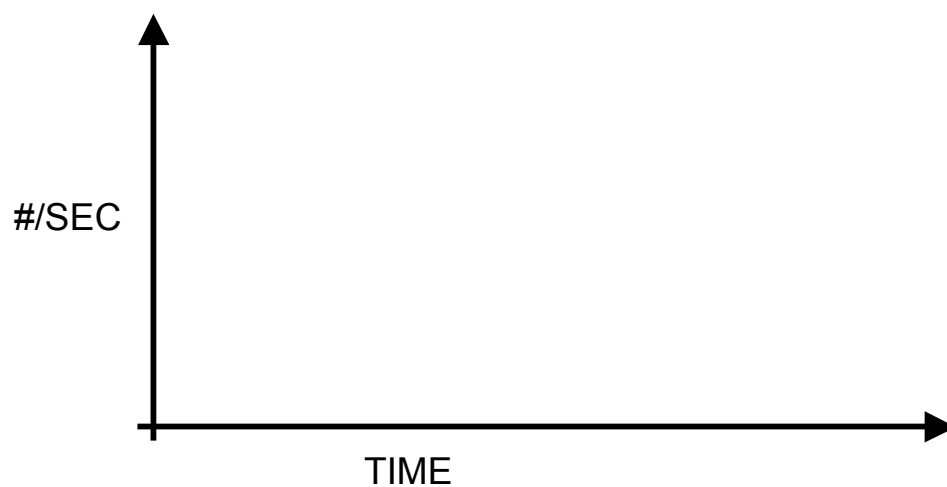
- i) After 1 second, how many electrons have reached the anode (ignore the changing anode electrostatic potential)?

- ii) After this one second, what is the potential difference between the anode and the cathode in terms of K_{max} ?

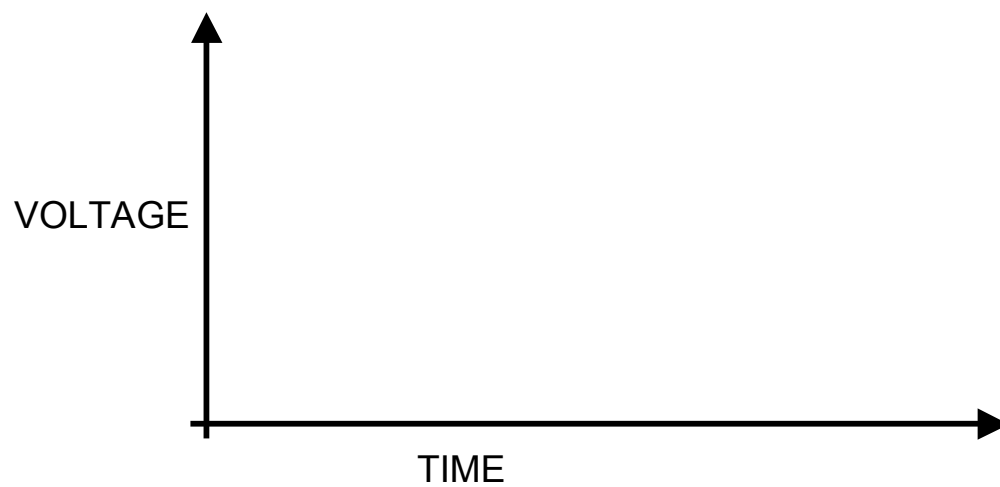
- iii) During the next second, how many electrons reach the anode (assume anode is fixed at the potential of part ii)?

- iv) After this time (two seconds), what is the potential difference between the anode and the cathode in terms of K_{max} ?

v) Using this reasoning, sketch the # of electrons per second reaching the anode for all times. This is the current, $I(t)$.



vi) Sketch the potential of the anode as a function of time (explain your reasoning).



EXPLAIN:

D3) Now figure this out mathematically:

i) What is the charge per second (current) reaching the anode at $t=0$, when the anode is at zero potential

ii) Suppose that the anode potential at time t is $V(t)$, and has a capacitance C . How much charge per second is reaching the anode at time t ?

$$I(t) = ?$$

iii) What is the charge on the anode when it is at potential V ?

iv) Using “charge is time-integral of the current”, write $V(t)$ in terms of an integral of the current

v) Combine these to get an equation for $I(t)$.

vi) Directly substitute $I(t) = I(0)\exp(-t/\tau)$ to find τ that makes this a solution.

v) Find the voltage as a function of time from this.

D3) Now measure the time dependence of the charging using the computer.

- i) You will need to **disconnect** the Keithley multimeter and connect the phototube to input A of the computer interface.
- ii) Also put a 20% neutral density filter over the white reflective mask to reduce the intensity.
- ii) Make sure the tube is still aligned, then GENTLY push the 'push to zero' button and recording the data with DataStudio (use the LC-4.ds settings file). The 'push to zero' button discharges the capacitor.

NOTE: On most of the setups, there is a large spike in the data from the capacitance of your hand when you push the button. Use one of the violet or ultraviolet lines for this to get a large final voltage and hence large charging time, so that most of the data is far from the spike. Describe your results below.

D4) Which of the energy distribution scenarios is your result more like?

D5) Change the intensity (different part of filter) and record the data again. How does the data compare?