Lab 2: Wave-Particle Duality of Light

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Adapted from Physics 391 lab manual by Carl Akerlof

1 Introduction

This lab session has two main parts. First, we will shine light on small slits and observe diffraction patterns. The diffraction patterns shown constructive and destructive interference, a wave phenomenon we studied in Lab 1: Wave Equations. In the second part, we will investigate the photoelectric effect. This involves shining light on a metal and recording the energy needed for the light to free an electron from the surface of the metal. The surprising (and Nobel prize winning) result shows no dependence on the light intensity, proving light is *quantized*; that is, it comes in discrete bundles of energy. This is exactly what we would expect from a particle, not a wave. What is light? As you will see today it has *both* particle and wave-like properties.

2 Interference and Diffraction

Diffraction and interference are common phenomena intrinsic to wave propagation. **Diffraction** is the result of wave propagation that spreads a beam of light from a linear path. **Interference** refers to the effects caused by the coherent addition of wave amplitudes that travel different paths. If the waves are in phase then **constructive interference** occurs and if the waves are out of phase then **destructive interference** occurs. These types of interference were previously investigated in Lab 1: Wave Equations.

The experiments for single and multiple slit diffraction are already set up for you. Observe the two experiments and then answer the following questions for each.

2.1 Single Slit Diffraction

The simplest diffraction phenomenon to calculate is the pattern produced by parallel light beams passing through a single slit. The geometry for this situation is shown in Figure 1. Notice that the waves are moving from left to right and that the waves entering the slit are in phase (and constructively interfere) but that waves diffracted at an angle θ can be out of phase (and destructively interfere). The expected diffraction interference pattern is shown in Figure 2.

The location of the destructive interference (dark bands) tells us the wavelength of the light. This can be seen in Figure 2, where the red, green and violet light have different shapes. The location of the dark bands are:

$$\sin\theta = n\frac{\lambda}{a} \tag{1}$$

where n is the number of the dark band, counting out from the peak in the center, a is the slit width (20 microns) and θ is the angle at which the n^{th} dark band appears.

Question 1 Using Equation 1 and Figure 2, calculate the wavelength λ for red, green and violet light. Use $a = 20$ microns$= 20 \times 10^{-6}$m.

Question 2 Why does the presence of single-slit interference suggest that light is a *wave*? Do classical particles exhibit destructive interference?

Question 3 What is the relationship between slit size a and the (angular) distance between neighboring minima? If the slit gets smaller, do the minima get closer together or farther apart? Hint: only Equation 1 is needed to answer this question.

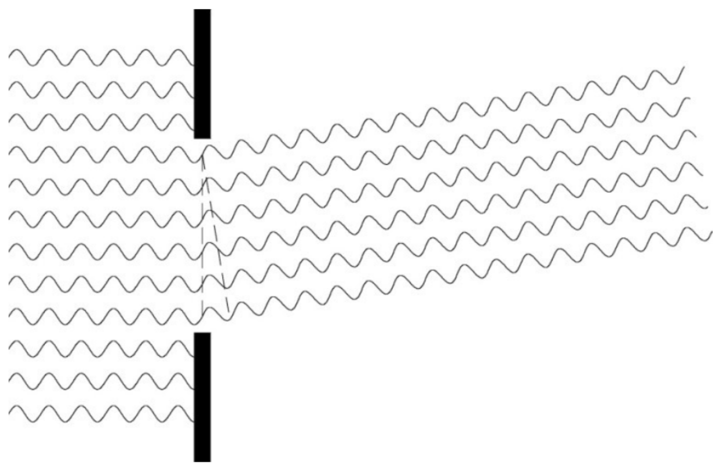

Figure 1: The geometry for single slit diffraction. Light rays passing through the slit diffracted by an angle θ can destructively interfere because they travel a different distance and go from in phase to out of phase. The minimum intensity occurs when $a \sin\theta = \lambda$ where a is the slit width and λ is the wavelength.

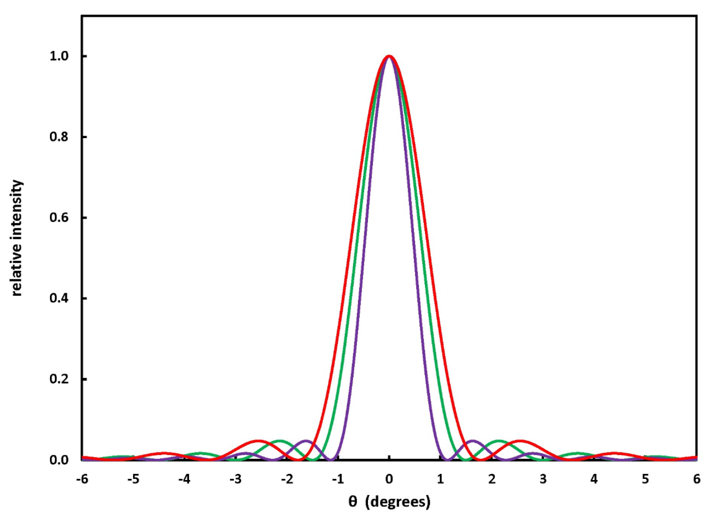

Figure 2: Expected light intensity patterns for red, green, and violet light with a slit width $a = 20$ microns.

2.2 Multiple Slit Diffraction

The intensity of a single slit can be generalized to N parallel slits spaced by a distance b as

$$I = I_0 \sin^4\theta \left(\frac{\sin(\pi a/\lambda)}{\pi a \lambda}\right)^2 \left(\frac{\sin(\pi b/\lambda)}{\pi b \lambda}\right)^2 \tag{2}$$

where a is again the width of the slit. Take images of the diffraction pattern for with 10 micron, 3.33 micron, and 1.66 micron spacing.

Question 4 How does the spacing change with the three different line densities?

3 The Photoelectric Effect

In this next section of the lab, we investigate the particle properties of light. Photons are small electromagnetic energy packets, each with an energy given by $E = hf$. Now imagine that we shine light on a conducting material. The electrons on the surface of the conducting material are bound to atomic nuclei with a broad range of **binding energies**. If the photon's energy hf is greater than the binding energy, the electron can be freed from the atom and ejected from the conductor. The smallest binding energy is called the work function ϕ of the metal, in units of volts. In this experiment, $\phi \approx 1.3$ volts. Since electrons are bound with a continuum of different binding energies, most of which are larger than ϕ, the maximum energy of an ejected electron occurs when the energy "price" the photon has to pay to free the electron is the smallest. This occurs for electrons bound with precisely the minimum energy ϕ:

$$E_{\text{max}} = hf - e\phi \tag{3}$$

where e is the charge of the electron: $e = 1.6 \times 10^{-19}$ Coulombs. f is the frequency of the light and h is Planck's constant, which we aim to measure today.

The first step in this experiment is to determine E_{max} for red, green, and violet light with wavelengths of 635, 532 and 405 nm, respectively. That is, to **determine the energy of ejected electrons**. A special circuit is used to perform this task. The circuit is completed by the flow of ejected electrons from the Cs_3Sb metal to the anode. A voltage is applied to fight against the flow of electrons. When an electron is liberated with 1 electron-volt of energy, it means that as long as the applied voltage $V_r < 1$ volt, then the electron can pay the energy "price" to overcome the voltage barrier and reach the anode. A diagram of the setup is shown in Figure 3. A photo of the setup connected to the current and voltage meters is shown in Figure 4.

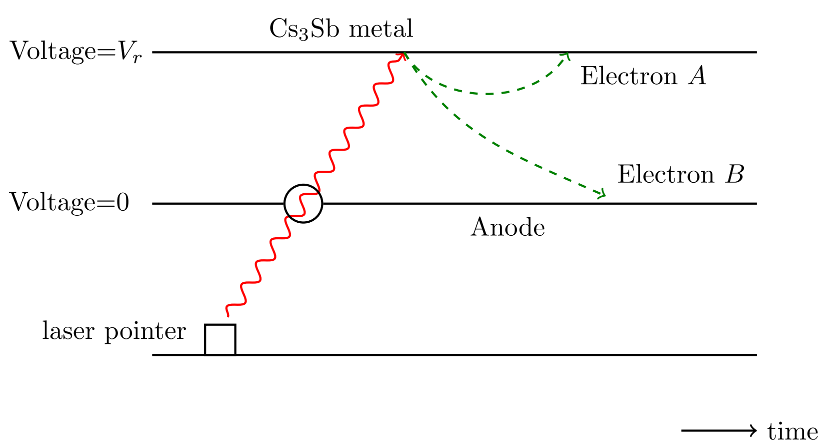

Figure 3: A diagram of the photoelectric effect setup. Light rays hit the metal surface, liberating photoelectrons. Electron A does not have enough energy to overcome the voltage difference and is repelled by the anode. Electron B has enough energy to overcome the voltage difference V_r and reach the anode. In this lab we change the value of V_r until the flow of electrons stops.

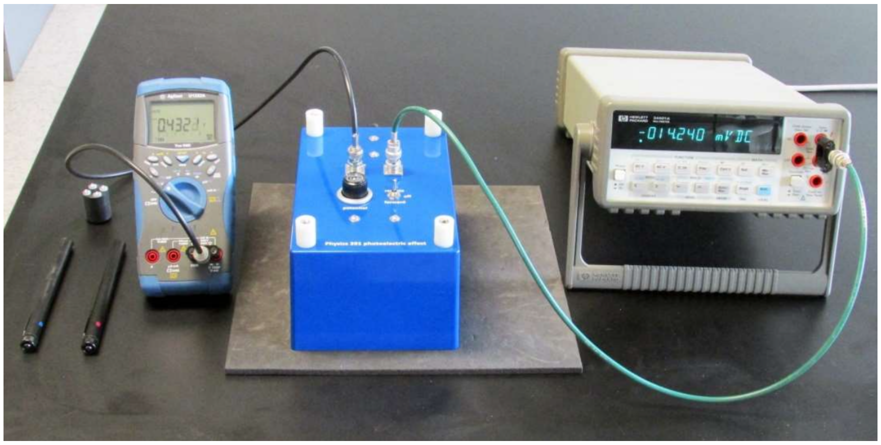

Figure 4: The photoelectric effect appartus connected for measurements.

Question 5 What is the frequency for the three laser pointers? You will need these numbers later to determine Planck's constant. Remember from Lab 1 that $v = \lambda f$ and use 299792458 m/s for the speed of light.

Experiment 1 Perform the following steps to measure the photoelectric current for each laser pointer at several values of V_r. The values of V_r you should use as input for each laser pointer are listed in the Jupyter notebook. Record the values of photoelectric current you measure in the Jupyter notebook.

1. Make sure that the DPDT switch is set to **REVERSE**.
2. Slip the laser pointer in to the detector enclosure through the short aluminum tube at one end. There is an O-ring at the end of the tube that sometimes resists this operation so be prepared to smear a very small amount of Vaseline jelly around the end of the laser pointer, taking care not to put any on the end of the pointer where the light beam emerges.
3. During data taking the box should rest on the gray foam pad to avoid extraneous room light.
4. When ready to take data, turn the laser pointer on using the switch at the end of the laser pointer. Turn the laser pointer back off when you have finished taking data for all voltage values.

Experiment 2 Determine the stopping voltage for each laser pointer. The fits are performed using the Jupyter notebook.

Experiment 3 Measure Planck's constant using the stopping voltages. By now you should have values for the frequency f and stopping potential V_s of the three laser pointers. The stopping potentials can be converted to E_{max} as $E_{\text{max}} = eV_s$. Equation 3 tells us that there is a linear relationship between f and E_{max} and that the slope is Planck's constant h. Perform a linear fit to the three pairs of data points (f, E_{max}) and find the slope. These fits can also be performed in the Jupyter notebook.

Question 6 What is the percent error on your measurement of Planck's constant? The standard accepted value for h is 6.626×10^{-34} J s.

Question 7 What is the percent error on your measurement of $\phi = 1.3$ volts? You will need to divide by e to convert your y-intercept into a measurement of ϕ.

Experiment 4 For one of the laser pointers, insert the neutral density filter and repeat the experiment. Perform a fit to find V_s with the filter inserted. Does the result suggest that light is a classical wave (where energy delivered is a function of the wave amplitude)? Why or why not?