What is light? From the time of Isaac Newton (1642-1727) to the beginning of the 20th century, the fundamental nature of light was a topic of hot debate among scientists. Newton proposed in his book *Opticks*, published in 1704, that light consisted of a stream of particles. This was known as the corpuscular theory of light, and with it Newton was able to explain many common phenomena involving light such as reflection and refraction. Most scientists of this period accepted the corpuscular theory, both because it seemed to explain known phenomena and because Newton was its architect. During Newton’s lifetime, however, Dutch physicist and astronomer, Christian Huygens¹ (1629-1695) proposed an alternative theory that also explained reflection and refraction. In Huygens’ theory light consisted of waves. Wave theory was also useful in explaining a phenomena known as diffraction, or the bending of light around sharp edges. In spite of its successes, Huygens’ theory did not receive wide acceptance. All waves known to scientists at the time (sound, water, etc.) needed some sort of medium through which to propagate. But light, can travel to us from the Sun, Moon, and stars through the vacuum of space.

In 1801, Thomas Young conducted an experiment that demonstrated that the phenomenon of interference could only be explained by the wave theory of light. Such behavior could not be explained by the corpuscular theory since, at the time, no known mechanism could explain how particles could combine so as to cancel each other out, as is the case in destructive interference (§ I below). Later work by Maxwell demonstrated that light was actually a high frequency electromagnetic wave (like radio waves) that traveled through space with a speed of $3 \times 10^8$ m/s. By the dawn of the 20th century, the wave theory of light was firmly entrenched in scientific doctrine.

But as resounding as the evidence for the wave behavior of light was, there were still experiments that gave results that could not be explained by wave theory. For example, the photoelectric effect is a phenomenon whereby electrons are ejected from a metallic surface that has been exposed to light. This cannot be reasonably explained by the wave theory. So in 1905, Einstein proposed an alternate explanation, drawing upon the earlier work of Max Planck (1858-1947). He hypothesized that light is composed of discrete packets of energy called photons and that the energy of a photon was proportional to its frequency (or wavelength).

This is the fundamental dual nature of light: at times it exhibits particle-like properties and at times, it exhibits wave-like properties. The best answer to the question “What is light?” is that it is both a wave and a particle; sometimes the wave properties dominate and at other times, the particle properties dominate. For the purposes of this exercise, the wave properties of light are dominant.

Objectives:
- Explore the nature of light
- Learn about and observe diffraction
- Review the three types of spectra and how they are formed
- Construct a rudimentary spectrometer and use it to observe the spectra of various sources
- Determine the composition of an unknown source by observing/measuring its spectrum

Equipment:
- Diffraction demonstration on optical bench (your instructor will show you this)
- Spectrometer pattern and cardstock to make it from; tape/glue/stapler; scissors

¹ Christian Huygens’ chief accomplishment as a physicist was the wave theory of light. As an astronomer, Huygens was the first to recognize the rings of Saturn (1655) and discovered Titan, a moon of Saturn.
- Meterstick
- Diffraction grating (1000 lines/mm)
- Two new razor blades
- High-voltage gas discharge tubes and power supply

Set-Up:
You do not have to work with anyone else, but if it helps you, by all means do so. Remember to credit your collaborators in your write-up. Skim through the exercise before you begin and get familiar with what you’ll be doing. Write up any preliminary information and then begin. Clearly mark answers to questions along the way - don’t make me search for them.

I. INTERFERENCE AND DIFFRACTION

Light waves can add together constructively to give larger waves or they can add together destructively to cancel out. In constructive interference, identical waves that are in phase (i.e. the crests and troughs of both waves correspond with each other) add in such a manner that the combined wave has an amplitude that is twice that of either individual light wave (Figure 1a). In destructive interference, waves that are exactly out of phase (i.e. the crest of one corresponds to the trough of the other) cancel each other out when added together (Figure 1b). Figure 1c shows an intermediate example.

Because of the wave nature of light, it will diffract, or spread out, as it passes through a narrow slit (see Figure 2). The waves can “bend around” the edges of the slit. It is the same phenomenon that makes it possible to hear someone talking around a corner. The only difference is that because the wavelength of light is much shorter, the effect is much smaller.

If you place a screen in front of the slit, the photons that hit the screen along the optical path will interfere constructively, producing a central bright spot, or maximum, directly opposite the slit (Figure 2). Because the wave fronts constructively interfere less the farther you are
from the central maximum, the intensity of the diffraction spot will also decrease. The secondary maxima (next brightest spots) are on either side of the central peak, and so on until the intensity drops to zero. The gaps in the pattern where there is no light represent patches of complete destructive interference. The varying amounts of constructive and destructive interference that create this pattern of bright peaks are caused by the different distances traveled by light rays at different angles after passing through the slit.

Your instructor has a demonstration set up so that you can observe diffraction through a single slit. After you have been through the demonstration, answer these questions.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.
1. Describe/sketch the diffraction pattern.
2. The slit is adjustable. What happens to the pattern when you decrease the width of the slit? When you increase the slit width? If there is a difference, speculate as to why.

II. LIGHT AND THE SPECTROGRAPH

Since most of an astronomer’s information about celestial objects comes to him in the form of light, it is important to understand its properties. Astronomers, both in the laboratory and at the telescope, have spent a great deal of time devising techniques to decode the message of light in order to yield as much information as possible. By examining a mere pinpoint of light, we can now determine many of the physical properties of the body from which the light originates: properties such as temperature and chemical composition.

One of the astronomer’s most useful tools is the spectrograph, which spreads light into its spectrum or rainbow of composite colors. We find that many properties of light can be explained in terms of its behavior as an energy wave. The wavelength of light determines its color: red light is made up of waves almost twice as long as those of violet light. The various colors of light we see are simply waves of different lengths. The order of colors is the same as that seen in a rainbow and can be remembered by the acronym “ROY G BIV,” which stands for red, orange, yellow, green, blue, indigo, and violet. Red light has longer wavelengths and lower energy than bluer light.

In fact, light (more generally, electromagnetic radiation) comes in many colors we can’t see: for example, ultraviolet rays (those responsible for the destruction of Earth’s ozone layer) are those just shorter than violet and infrared.
rays are those just longer than red (Figure 3). Visible light is just a small part of the whole electromagnetic spectrum, which includes x-rays and gamma rays (very short wavelengths and high energies) to radio waves, which have long wavelengths. The white light we see is just a combination of all the colors of visible light.

![Figure 4. Dispersal of light by a prism.](image)

Many spectrographs utilize a prism to spread the light out into its constituent colors. Figure 4 is a schematic representation of this and Figure 5 gives the layout of a basic prism spectrograph. Because prisms work by bending the light by different amounts (it is wavelength dependent), a grating is often a better choice for dispersing the light. A diffraction grating is made by ruling a series of very fine parallel lines (often 20,000-30,000 lines per inch) on a mirror or piece of glass. It produces a spectrum by the more complicated process of diffraction and interference of the light. The grating has an advantage over the prism in that it has equal dispersion at all wavelengths, while prisms disperse blue light more than red. In this exercise, you will use a diffraction grating film to construct a rudimentary spectrometer, which is designed to allow you to measure the positions of spectral lines visually, i.e. without need for a camera or CCD or other imaging detector of any kind.

**ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.**

3. Do prisms bend all wavelengths of light by equal amounts? Why or why not? If not, are longer wavelengths bent more or less than shorter wavelengths?

III. SPECTRA

First, let us review the various kinds of spectra an how they are produced. The three types of spectra are (1) continuous, (2) bright-line or emission spectra, and (3) dark-line or absorption spectra.

A continuous spectrum is produced by a glowing solid, liquid, or gas under certain conditions. A prism, for example, forms a continuous spectrum when white light is transmitted through it (Figure 4). The spectrum appears as a smooth transition of all colors in the visible spectrum from the shortest of the longest wavelength without any gaps between the colors. (Figure 6).
An emission spectrum is produced by a glowing gas, which radiates energy at specific wavelengths, characteristic of the element or elements that make up the gas. The spectrum consists of a number of bright lines against a dark background (Figure 6). Each bright line has a color that represents a specific wavelength (energy).

An absorption spectrum is produced when a cooler gas absorbs specific wavelengths of light passing through it. The wavelengths absorbed are determined by the elements that compose the gas. Since no two elements absorb exactly the same wavelengths, it is possible to determine the elemental composition of the gas by examining the spectra. A dark-line or absorption spectrum appears as a continuous spectrum of all colors with a number of dark lines through it (Figure 6). If the dark lines are closely spaced in some parts, the clumps of dark lines are known as bands.

Figure 6. Types of spectra and their origins.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

4. What is the **ultimate** background source of an absorption spectrum? Emission spectrum?

5. Hold your diffraction grating up to your eye and look at the fluorescent lights in the room. **DO NOT TOUCH THE FILM OF THE GRATING! HOLD IT ONLY BY THE CARDBOARD FRAME!** You should observe a spectrum from the classroom lights. What kind of spectrum is this? Describe/sketch what you see.

IV. ASSEMBLING YOUR SPECTROMETER

Fasten your spectrometer pattern to some cardstock or other heavy paper or cardboard. The rectangular area marked “cut out” is where the pattern will slip onto the meterstick; the square marked “cut out” is where the adjustable slit is to be constructed. **DO NOT USE YOUR NEW, DOUBLE-EDGED RAZOR BLADE TO CUT THE PATTERN OUT!**
To construct the adjustable slit, mount one of the razor blades with tape to the spectrometer scale, along the line marked “align slit here,” with the razor edge facing left, as illustrated in Figure 7a. If you cannot obtain a razor blade, a piece of dark plastic or exposed film, cut with scissors, also makes an adequate slit.

For the other half of the slit, cut out from a piece of cardboard a rectangular piece approximately 2.5 by 6 centimeters and tape the other razor blade to it as illustrated in Figure 7b. This piece will be the moveable half of the slit.

With the moveable half in place on the spectrometer, the total slit assembly will look like the picture in Figure 7c. The loose, moveable piece can be held in place with a strip of paper or cardboard stapled crosswise on the crosspiece, as illustrated in Figure 7c.

The spectrometer is composed of two parts which are held in place by a meterstick. To read correct values, the spectrometer scale is designed to be placed exactly 10.75 inches from the grating.

The spectrometer scale folds toward you along the dotted line and mounts on the meterstick at the 11.75 inch mark, as indicated in Figure 8. The brace fits on the backside to give the scale rigidity. Tape or staple it into place.

Mount the grating 2.5 centimeters (1 inch) from the eye end of the meterstick. The simplest way to do this is to use the sliding crosspiece from the cross-staff to hold the grating and to use paper clips or tape to fasten it to the cross-piece.

Notice that the scale on your spectrometer has been calibrated to read wavelengths over the visible light range. We are using units of Ångstroms; 1 Å = 10⁻⁹ m.
in this manner, you should be able to see a spectrum spread out to the right of the slit along the wavelength scale. If you do not immediately see the spectrum, move the slit back and forth across the light source until you do. You will soon find the proper position. If instead of the spectrum you see a streak of light above and below the slit, turn your grating 90 degrees in its holder and you will then see the spectrum. Figure 9 illustrates how to use the spectrometer to see the spectrum of a source of light.

Figure 9. Use of the spectrometer.

V. SPECTROMETER OBSERVATIONS

You are now going to view high-voltage gas discharge tubes through your spectrometer. These are glass bulbs that have been evacuated and then filled with some rarefied gas. When a high voltage is applied across the electrodes of the bulb, the current causes the atoms to become excited and emit photons at particular wavelengths. You should easily be able to observe this emission. It will resemble the spectra in Figure 10.

For these light sources, you want to see as much detail as possible. You should try to rest the spectrometer on something rigid so that your shakiness does not hinder measurements. Also, narrow down the slit as much as possible while still viewing the spectrum. It should be clear from your observations that the spectrum consists of a series of lines only because the light comes from a long, thin tube. Even if it didn’t, passing the light source through a long, thin slit would cause a line spectrum to appear. The spectrum is actually a series of rectangular images of the slit in the various wavelengths where the source is emitting energy. By changing the width of the slit, the width of the lines in the spectrum can be changed.
If a gas emits energy at two or more wavelengths which are very close together, we would want to use a very narrow slit to be able to see those features as separate entities. A wide slit produces wide lines, which would tend to overlap and hence not be separately resolved. Thus, we increase the resolution of the spectrometer by narrowing the slit, but we pay a price since the amount of light that comes through is also reduced. Try varying the slit width and noticing its effect on the crowded spectrum of neon.

A. Mercury
The blue tube is mercury vapor. It should be apparent that it emits only at certain wavelengths. In particular, you should see a feature in the blue, one in the green, and one in the yellow part of the spectrum. Record these wavelengths.

B. Neon
This spectrum is somewhat more crowded, with numerous emission features close together. With the slit as narrow as practical, observe and describe the neon spectrum, writing down the wavelength of every feature you can see as a distinct feature.

C. Sodium
This is a very simple spectrum. Record the wavelengths you observe.

D. Hydrogen
The hydrogen tube may have a spurious yellow feature due to impurities in the tube and to evaporation of the elements in the glass itself. Ignore the yellow spectral feature in your measurements (it is actually caused by sodium emission). Record the other wavelengths you observe.

E. Fluorescent Light
Observe again the spectrum of the fluorescent classroom lights. Describe the spectrum and write down the wavelengths of any discrete features you see.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.
6. Why does the neon gas glow red when you look at it without the grating?
7. Why does the mercury vapor look blue to the eye?
8. Comparing your measurements of the different discharge tubes to your observations of the fluorescent lights, can you identify the gas inside the fluorescent tube? Give reasons supporting your conclusion.
VI. SPECTROMETER CALIBRATION

To calibrate your spectrometer, you will compare your measurements to standard values. The most important lines of hydrogen, mercury, neon, and sodium are found in Table 1 below. Neon has so many strong lines that are very close together so we will not use neon to calibrate our data. Your instructor will tell you which lamps to use for calibration purposes. Measure and record the wavelengths of each discrete feature you see in the spectra.

Table 1. Wavelengths of spectral lines in Ångstroms.

<table>
<thead>
<tr>
<th>Argon</th>
<th>Hydrogen</th>
<th>Helium</th>
<th>Mercury</th>
<th>Neon</th>
<th>Sodium</th>
</tr>
</thead>
<tbody>
<tr>
<td>4100</td>
<td>4101</td>
<td>4471</td>
<td>4047</td>
<td>4540</td>
<td>5890</td>
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<td>4580</td>
<td>4358</td>
<td>4580</td>
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<td>5461</td>
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</tr>
<tr>
<td>4330</td>
<td>6563</td>
<td>5876</td>
<td>5790</td>
<td>4700</td>
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<tr>
<td>4510</td>
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<td>6150</td>
<td>4790</td>
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</tr>
<tr>
<td>4686</td>
<td></td>
<td></td>
<td>6907</td>
<td>5330</td>
<td></td>
</tr>
</tbody>
</table>

For each of these lines you have observed, calculate the error (observed minus true value). Some of your errors may be negative. Do not take the absolute value. Plot the error versus the observed wavelength for all your measured lines (from the hydrogen, mercury, and sodium tubes) on the same graph. Draw the best fit line to your data. This line can be used to correct all of your other wavelength measurements. It represents a particular kind of error in the instrument. Drawing this plot is a way of calibrating the instrument in order to correct and eliminate this type of error. As long as you do not change your spectrometer construction or the way in which you use it, this will be your calibration curve. If you borrow someone else’s instrument, it will have different errors associated with it.

The scatter of the individual points around the straight line represents another fundamental type of error in your observations. This allows you to estimate the basic accuracy of the observations. To estimate the amount of scatter, measure the separation of each point from the straight line and average their absolute values. Repeated measurements will often reduce the scatter, but it cannot be completely eliminated.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

9. What kind of error is represented by your calibration curve?
10. What kind of error is represented by the scatter in your data?
11. For your instrument, what is the systematic error associated with a reading of 5500 Å?
12. What is the random error of your measurements?
VII. TEST YOUR SPECTROMETER

Now observe the “unknown” gas tube through your spectrometer. Describe what you see and record the wavelengths of any identifiable features. Using the information in Table 1, can you identify your unknown gas? Do not forget to use what you know about your errors to correct your data as much as possible.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

13. Describe/sketch what you see when you observe the spectrum of the unknown gas.
14. Using the information in Table 1, what is your unknown gas?

VIII. REFERENCES