

DIFFRACTION AND SPECTRAL ANALYSIS

INTRODUCTION: In this lab, we look at the light coming from gas discharge tubes. Discharge tubes are evacuated glass tubes that contain a small amount of a particular kind of gas. Fluorescent tubes in fluorescent lights are a good example. A high voltage is then placed across the tube which forces electrons through the gas. As the electrons go from one end of the tube to the other, they bump into many atoms. An atom, when bumped by a fast moving electron, gets one or more of its orbital electrons knocked into a higher orbit. The atom is said to be excited. The atom remains excited for a very short time. Then the electron that was knocked into a higher orbit falls back into its original orbit and in so doing releases a particular wavelength of light. In this way, the discharge tube can be made to glow.

Because the source of light for these tubes is electron transitions, only particular wavelengths of light are present, corresponding to the electron transitions that are occurring. (This is very much unlike a solid body which glows when it is hot. In this case, almost all wavelengths of light are emitted.) In this lab, we shall look at the various wavelengths of light which make up the emission from a gas discharge tube. The collection of wavelengths that make up a tube's total emission is called the tube's "spectrum". The individual frequencies that make up the discharge tube's spectrum are known as "spectral lines". Because these discharged tubes are often used to study spectra, they are often called "spectral tubes".

THEORY: Consider a plane wave (could be sound, light, or waterwaves) that is incident on two slits. (See figure 1). When the wave arrives at the pair of slits, all of the wave is blocked except that which is incident on the slits. From Huygen's principle, the illuminated slits act as wave sources that are in phase with each other.

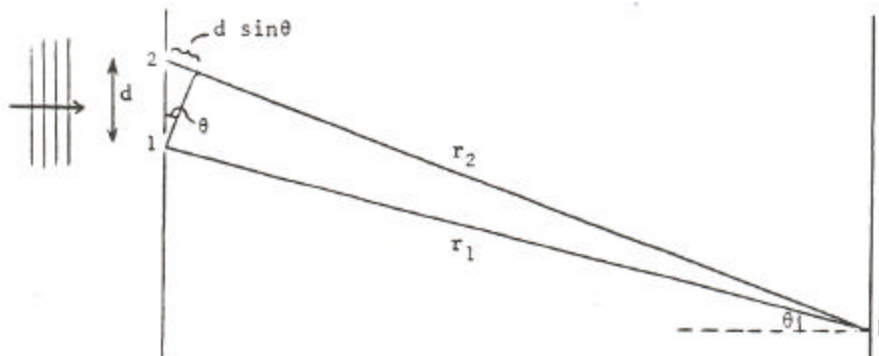


FIGURE 1

Now consider what arrives at point P . Note that P is slightly further away from slit 2 than slit 1. Let the distances between P and the two slits be r_1 and r_2 , as indicated on figure 1. Now, if $r_2 - r_1$

(which is the extra distance that the wave from slit 2 has to travel) just so happens to be $\lambda/2, 3\lambda/2, 5\lambda/2, \dots$ (where λ is the wavelength of the wave), then the wave arriving from slit 2 will be exactly out of phase with respect to the wave arriving from slit 1. Hence, the two waves will cancel and nothing will arrive at P. (These waves are said to interfere destructively.) On the other hand, if $r_2 - r_1$ just so happens to be $\lambda, 2\lambda, 3\lambda, \dots, n\lambda$ (where n is any positive integer), then the waves will be in phase at P and they will constructively interfere. Point P will see an enhanced wave.

Now, from figure 1, $r_2 - r_1$ is just equal to $d \sin \theta$ where d is the distance between the slits.¹ Hence for P to be positioned so that it receives constructive interference, we must have:

$$d \sin \theta = n\lambda$$

$$\text{or} \quad \sin \theta = \frac{n\lambda}{d} \quad (1)$$

θ is the direction angle of point P where the waves are enhanced. Note that for longer wavelengths (greater λ) θ is also bigger. Hence, the locations of constructive interference for longer wavelengths are spread out further than those for shorter wavelengths.

Turning equation (1) around, we get

$$\lambda = \frac{d \sin \theta}{n} \quad (2)$$

In this lab, we shall apply equation (2) to light. Using a diffraction grating (something with many slits, not just two), for which equation (2) is also applicable, we will spread out the spectrum of the light coming from a spectral tube. Measuring the angle θ at which each color is seen (position of constructive interference), and knowing d accurately and n exactly, we can determine λ .

APPARATUS

1. Spectrometer (see figure 2).
2. Gas discharge tubes, mercury and one or two unknown gases.
3. 5000 V discharge tube stand (see figure 3).
4. Replica grating.
5. Flashlight.

WARNING: The discharge tube operates at 5000 volts. Do not plug in the stand until the tube is securely in place in the clamps on the stand.

CAUTION: Do not touch the film of the grating. Handle it only on the sides.

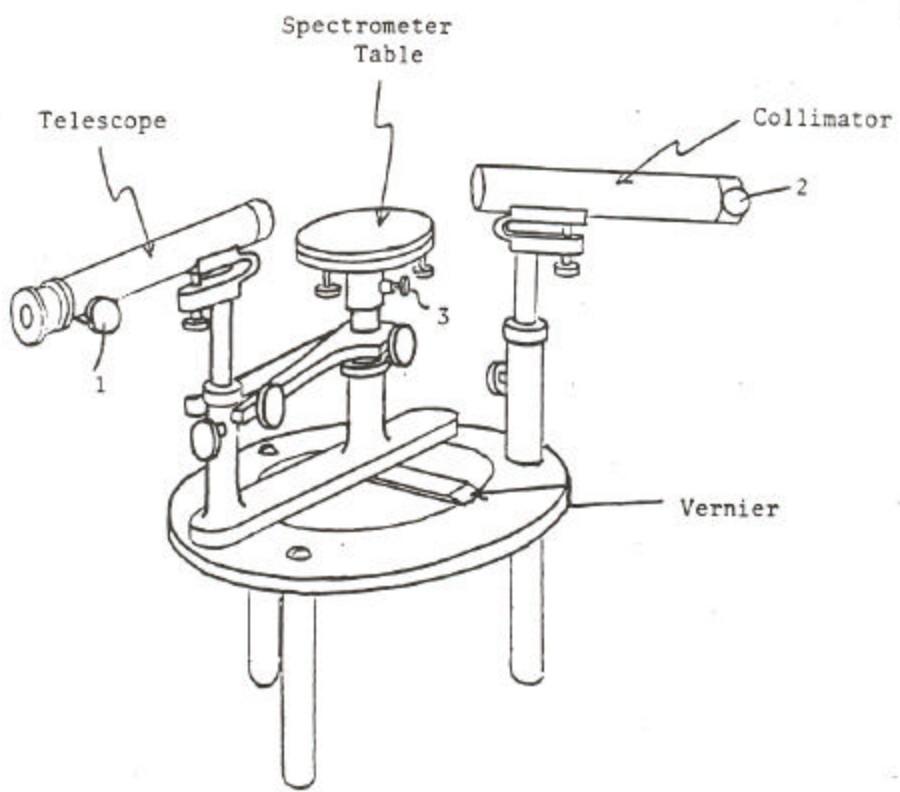


FIGURE 2 The Spectrometer

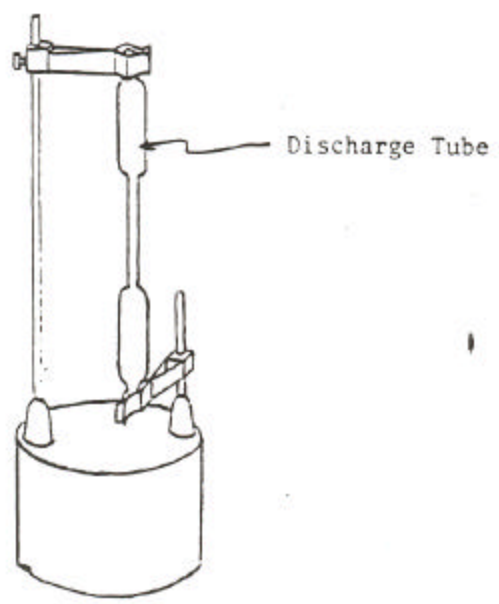


FIGURE 3 The Discharge Tube Stand

EXPERIMENTAL I

1. Set up your spectrometer so that the collimator and telescope are collinear and that light coming from the collimator will pass directly over the center of the spectrometer table. This may require adjusting the various knobs shown in figure 2. Once this is done, the only adjustment that will be made to the spectrometer is to rotate the telescope about the central post (on top of which is the table). Focus the cross hairs by pulling out or pushing in the eyepiece on the telescope (this is not done by adjusting the focusing knob - knob 1).
2. Turn on the mercury vapor discharge tube and place it close to the end of the collimator. Open the collimator slit enough (knob 2) so that you can see a fairly bright yet narrow image of the tube in the telescope. Focus the image using the focusing knob (knob 1). Align the image of the tube with the cross hairs and record the position angle of the telescope (using the vernier).
3. Place the diffraction grating on the table. Make sure that the film itself is over the very center of the table and that the film is perpendicular to the collimator.
4. Now, rotate the telescope until you see the diffraction lines. What colors do you see? You should be able to see a purple, blue, blue-green, green, a pair of yellow-orange lines and if you are careful, an orange and a pair of red lines too. Which colors come first, the ones with the long or short wavelengths? Is this consistent with equation (1)? As you continue to rotate the telescope, you should come across the same sequence of lines again, this time spread a little further apart. These are the $m = 2$ lines. Keep rotating the telescope. Beyond the second pair of yellow-orange lines, you might be able to see a few of the $m = 3$ lines. Why can't you go on indefinitely to see the $m = 4$, $m = 5$, etc. lines?

NOTE: Don't be fooled by spurious effects, like light from other people's lamps or stray light from the hall. You can tell if a line is being produced by a neighbor's lamp by having your lab partner stand in between your grating and the other lamp. If the line disappears, it did not come from your lamp.

NOTE: You should definitely be able to find a purple, blue, green, and the yellow-orange doublet at the very minimum. If instead of two yellow lines you have only one, your slit may be open too wide. Try narrowing it (knob 2).

5. Go back to a bright $m = 1$ line, say the green one. Line it up with the cross hairs and record the position angle of the telescope. Now swing the telescope to the other side of the collimator and find the same $m = 1$ line. Record the position angle of the telescope. Determine the angles θ_1 and θ_2 as shown in figure 4. If $\theta_1 \neq \theta_2$, then your diffraction grating is not perpendicular to the collimator. Here is how to adjust the grating so that it is.

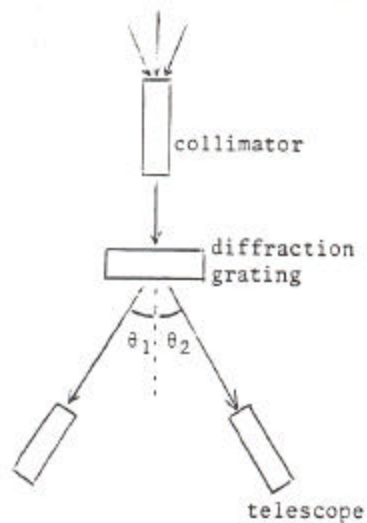


FIGURE 4

- (a) Compute $\theta_{ave} = \frac{\theta_1 + \theta_2}{2}$ and set your telescope to this angle (relative to the collimator direction of course!)
- (b) Loosening knob 3 in figure 2, rotate the table so that the spectral line you were using is aligned with the cross hairs. Retighten knob 3.
- (c) Swing the telescope to the other side of the collimator and find the same line. Record the position angle of the telescope. Now calculate your new values of θ_1 and θ_2 .

Their values should be closer than the previous pair. If, however, they still differ by more than half a degree, go back to

step a) and repeat until the two angles differ by less than half a degree.

6. Now find as many $m = 1$ lines as you can and record the position angles of the telescope for each. Then compute the deflection angle for each line again. The deflection angle for each spectral line that you will use in your calculations will be the average of the two deflection angles found from each side of the collimator. These shouldn't differ by more than half a degree.
7. Look for the $m = 2$ lines and record the deflection angles of each line you see on both sides of the collimator. Look for the $m = 3$ lines if possible. You might record your data in a table resembling the following:

| Spectral line color | $m = 1$ | | | $m = 2$ | | | $m = 3$ | | |
|---------------------|------------|------------|----------------|------------|------------|----------------|------------|------------|----------------|
| | θ_1 | θ_2 | θ_{ave} | θ_1 | θ_2 | θ_{ave} | θ_1 | θ_2 | θ_{ave} |
| purple | | | | | | | | | |
| blue | | | | | | | | | |
| blue-green | | | | | | | | | |
| green | | | | | | | | | |
| yellow I | | | | | | | | | |
| yellow II | | | | | | | | | |

where θ_1 is the deflection angle to the right of the diffraction grating while θ_2 is the deflection angle to the left.

8. Compute the wavelength of each spectral line using equation 2. You will have more than one value for some spectral lines. Use

the average. Are your wavelengths consistent with those known to make up the spectrum of mercury?

EXPERIMENTAL II. (Identification of an unknown gas)

9. Replace the mercury vapor tube with a tube containing an unknown element. Turn on the discharge tube stand.
10. Using the techniques developed in the previous section, find the wavelengths of the light making up the spectrum.
11. Comparing your values of λ (and the colors) to those posted on the spectrum chart, try to determine what was in your tube.
12. If time permits, try another unknown tube.

QUESTIONS

1. An astronomer observing the solar spectrum notices that the spectrum is rather continuous except for some particular wavelengths that don't appear to be there at all. The wavelengths that are missing are measured to be 410.2, 422.7, 434.0, 486.1, 527.0, 589.0, 589.6, and 656.2 nanometers (10^{-9} meters). Assuming that these missing wavelengths are due to absorption by atoms in the solar atmosphere, can you name 4 elements that are found in the upper layers of the sun?
This technique (known as spectral analysis) is extremely useful to astronomers in trying to determine what elements are found in the planets, stars, other galaxies or any other astronomical object.