LIGHT AND SPECTRA

OBJECTIVES

1. **To see how a spectrum varies with the light source or element used to produce it.**
2. **To determine the identity of an element by comparing its spectrum to known spectra**.
3. **To determine the speed of a star toward or away from us with the Doppler Shift of its spectral lines by comparison to a known spectrum at rest.**

PREPARATION

PART 1: SPECTRA AND SPECTRAL LINES

Review the sections in your textbook that cover light and spectra before coming to lab. Bring a scientific calculator and colored pencils with you to the lab.

Recall that light is an electromagnetic wave. The wavelength of an electromagnetic wave is inversely proportional to its energy while its frequency is directly proportional to its energy. A wave with a short wavelength will have a large amount of energy. A wave with a long wavelength will have a small amount of energy. The frequency of an electromagnetic wave is directly proportional to its energy so that a higher frequency is associated with a higher energy.

The spectrum of a light source is produced by either a prism or a grating. A prism is made of solid glass and a grating consists of a very closely spaced grid. Either of these devices spreads out the light passing through it according to its different energies. To understand how a spectrum is produced, we must consider the structure of an atom. The type of rainbow pattern depends directly on the physical properties of the light source. Therefore, we can glean a lot of information about any kind of light source by studying and analyzing its spectrum. A ***continuous spectrum*** showing a full rainbow is produced by an object purely due to its surface temperature, aka the thermal spectrum of a "blackbody". A spectrum that consists only of several narrow, differently colored lines on an otherwise dark background is called an ***emission spectrum*** which is produced by low density heated gases of particular elements. The unique pattern of spectral lines is emitted by the unique energy transitions of the atomic electrons of the involved elements as is explained in more detail below. The last type of spectrum is an ***absorption spectrum*** which comes about when the thermal radiation of a blackbody is passed through a cool gas of particular elements. The resulting spectrum looks like a smooth rainbow interrupted by many narrow black lines. The unique pattern of these black lines correspond to the same unique pattern of unique energy transition of the atomic electrons in the involved gases but this time, the atoms have absorbed these energies and, thereby, removed them from the spectrum.

In a simplified picture of an atom, we would find a nucleus, containing protons and neutrons, surrounded by electrons. The electrons "orbit" the nucleus much like the planets orbit the sun. These orbits are called orbitals, and correspond to particular levels of energy. Only a limited number of electrons can exist in any given orbital. Electrons can change orbitals by changing their energies. If an electron moves to an orbital that is higher (farther away from the nucleus) it must receive an amount of energy equal to the difference in the energy of the two orbitals. This process of receiving energy from an outside source and jumping to a higher energy orbital is called ***absorption.*** If the electron drops down to a lower orbital, it will give up this exact extra energy in the form of electromagnetic radiation of a wavelength directly associated with this exact energy. This process of releasing energy to the outside and dropping to a lower energy orbital is called ***emission***. An electron will generally be found in the lowest orbital it can achieve. When all of the closest orbitals are filled, and there are no spaces, the atom is said to be in the ground state. When electrons absorb extra energy from the outside causing them to jump to a higher energy orbital, that leaves unfilled spaces on the lower orbitals. When this is the case, the atom is said to be excited. Since atoms cannot remain in an excited state for very long time, the higher energy electrons will drop back down to the ground state by emitting the exact energy difference of their jumps as electromagnetic radiation with wavelengths of these exact energies. These are the narrow, bright emission lines of unique wavelengths that we see in the spectrum of this particular element. Every neutral atom in the ground state of a given element has the same number of electrons in the same orbitals and is able to produce the same emission lines.

Since the number of electrons in a neutral atom distinguishes elements from each other, atoms of different elements have orbitals at uniquely different energies. This leads to uniquely different emission lines produced by the excited atoms of different elements. Consequently, each element has its unique pattern of emission lines corresponding directly to its unique energy transitions between its unique orbitals. In that sense, the emission spectra of elements are as unique as fingerprints. Remember that emission lines and absorption lines come from the same electronic orbital transitions and only differ in the direction of the jump (emission = jump from high to low, absorption = jump from low to high). The Sun is essentially a blackbody with cooler gases in its outer layers so it produces an absorption spectrum. By matching up the wavelengths of the absorption lines of the solar spectrum with the wavelengths of emission lines of the elements, we can identify which elements are present in the Sun. In fact, this is how the element helium was first discovered. After matching up the spectral lines of all the elements known on Earth, there was a set of unidentified lines left in the Sun's spectrum. That prompted the prediction of the existence of a new element, helium, named after the Sun which is "helios" in Greek. Studying the spectra of other stars not only revelead that these were all absorption spectra with the spectral lines in the same unique patterns that correspond to the same elements in our own solar system but also that these distinct patterns appeared to be shifted as a whole to slightly longer or shorter wavelengths in different stars. This effect is due to the motion of the star as a whole toward or away from our Solar System.

PART 2: DOPPLER SHIFT

All stars, including the Sun, are moving around the center of the Milky Way Galaxy. Over the course of the varied history of our galaxy, each star has its own unique orbit, speed, and direction even though most stars in the disk of the galaxy orbit the center in a similar, mostly ordered fashion. That is the reason why we see stars remain in the same patterns in the sky (constellations) with any changes being so slight that they are practically imperceptible to a casual observer. When we study the spectra of stars closely, though, we find that the pattern of elemental spectral lines is shifted due to the stars' motion to longer or shorter wavelengths depending on their motion toward or away from us. The lines shift from the typical wavelengths observed in a stationary lab to slightly longer or shorter wavelengths by an amount proportional to the speed of the star. This property is called ***Doppler Shift***. If the star is moving toward the Earth, the pattern of lines will have shorter wavelengths and the spectrum is said to be ***blueshifted***. If the star is moving away from the Earth, the pattern of lines will have longer wavelengths and the spectrum is said to be ***redshifted***. By measuring the amount of the shift, we can determine the speed of the star. We use the following formula:

$$\Delta\lambda / \lambda_o = v / c$$

where:

$\Delta\lambda$ is the shift in wavelength away from the normal wavelength taken from the spectrum of a stationary gas.

λ_o is the wavelength of the line in the spectrum of a stationary gas.

c is the speed of light. Its value is 3×10^8 m/s

v is the speed of the star.

From laboratory experimentation, we know the original wavelengths of the spectral lines of elements in a stationary gas. From the spectrum of the moving star, we can determine the shifted wavelengths of the same gas in the outer layers of the moving star. We subtract for each spectral line the original wavelength from the star's wavelength to get $\Delta\lambda$. Then simply dividing by the the original wavelength, λ_o, and multiplying by the speed of light, c, yields the speed of the star toward or away from us. To simplify things, we will compare only the hydrogen spectrum of the stationary gas here on Earth and that of a moving star.

You have now nearly finished the preparation for the laboratory. If you are unsure of the material, please reread the preparations, consult your textbook or ask questions of your instructor. Answer the questions on the next page and be ready to hand them to your instructor at the start of lab.