Lab 2

Spectroscopy

In this lab you will measure and quantify emission spectra from several different visible light sources.

2.1 Spectral Lines

In physics, we typically use the word *spectrum* to refer to the frequencies of a set of superposed sine waves. One can always think of a signal of some sort as the superposition of sinusoidal waves with different frequencies. *Spectroscopy* is the science of separating a signal into its spectral components in order to determine how much amplitude or intensity each sine wave contributes to an overall signal.

Almost any physical phenomenon (electromagnetic/optical, electrical, acoustical, mechanical, etc.) can be characterized in terms of a spectrum. Examples include transmissions from modern communications devices, the light from distant galaxies, the wobble of a planet due to the motions of its moons, the swaying of a large building during an earthquake, the sound from a high-quality audio system, the x-rays used for a medical exam, the molecules that give plants their colors, and the energies of fundamental particles produced in an accelerator. In each case, the spectral signature allows one to look ‘under the hood’ for insights that would be invisible to a naive observer. Spectral data can be used to probe the physical characteristics of a signal source or the response of a dynamical system to an incoming signal.

In this lab, we will investigate the (visible) spectral properties of common light sources (e.g. sunlight, incandescent bulbs, fluorescent lamps, LEDs). Some sources exhibit a continuous spectrum (e.g. a hot filament of the Sun) while others exhibit a few discrete *spectral lines* (e.g. electrically excited elemental gases). Fig. 2.1 shows a discrete spectrum of an elemental gas superposed on a continuous white-light spectrum.
2.2 Wavelength and Frequency

An optical spectrometer often employs a grating to separate different wavelengths of light into an image. Below is a summary of how wavelength and frequency are connected, as well as how they relate to other properties of photons.

Definitions and relationships

\( k = \frac{2\pi}{\lambda} = 2\pi \tilde{k} \)
\( \omega = \frac{2\pi}{T} = 2\pi f \)
\( c = \lambda f = \frac{\omega}{k} = \frac{\lambda}{T} = \frac{f}{\tilde{k}} \)
\( E = h\omega \quad p = \hbar k \)

- \( f \) = cyclic frequency (cycles/s or Hz)
- \( \lambda \) = wavelength (m)
- \( \omega \) = angular frequency (radians/s)
- \( k \) = angular wavenumber (radians/m)
- \( T \) = period (s)
- \( \tilde{k} \) = cyclic wavenumber (cycles/m)
- \( E \) = energy (J or eV)
- \( p \) = momentum (kg·m/s)

The parameter \( c \) is the speed of light in vacuum (3.0 × 10^8 m/s) and \( \hbar \) is Planck’s constant over \( 2\pi \) (1.055 × 10^-34 J·s = 6.582 × 10^-16 eV·s). Because one can easily interconvert between any two of these quantities, any one of them could serve as a spectral parameter (i.e. the horizontal axis of a spectrum graph). If you know one, you know them all. In this lab, we will use wavelength as the primary spectral parameter.

2.3 Blackbody Spectra

Hot objects glow. In the latter 1800’s scientists discovered that the radiation emitted by hot objects as a function of frequency is approximately the same for all materials. The notion that all materials behave similarly led to the concept of an ideal blackbody radiator.\(^1\)

\(^1\)The name comes from the fact that objects that absorb light better are also able to radiate light the best. Light that falls upon an ideal blackbody is absorbed perfectly before the possibility of reemission.
The Sun is a good example of a blackbody radiator. The light emitted from the Sun is associated with its surface temperature. As another example, a glowing tungsten filament in an ordinary light bulb may be reasonably described as a blackbody radiator. The structure of the material must be sufficiently complex (e.g. a solid or a dense plasmas) to enable absorption and emission at any wavelength. On the other hand, a diffuse atomic vapor can only absorb and emit wavelengths that correspond to allowed energy transitions within the atom, which is not well described by blackbody radiation.

Fig. 2.2 shows the spectrum of blackbody radiation. As the temperature increases, the peak of the curve shifts to shorter wavelengths. The peak is given by Wien’s Displacement Law

\[
\lambda = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{T} \tag{2.1}
\]

### 2.4 Equipment

Hand-held spectrometer, digital spectrometer, Labview-enabled computer, Geisler-tube power supply and a set of Geisler tubes, white LED flashlight.
Quiz

Q2.1 The wavelength and frequency of light can be selected independently. True or False?

Q2.2 Why do elemental gases have discrete rather than continuous spectra?

Q2.3 A red-light photon from a helium-neon laser has a wavelength of \( \lambda = 632.816 \text{ nm} \). Calculate each of the following properties of this photon:

(a) period \( T \)

(b) cyclic frequency \( f \)

(c) angular frequency \( \omega \)

(d) energy \( E \) (in electron-volts, where 1 eV = \( 1.609 \times 10^{-19} \) J)

(e) cyclic wave number

(f) angular wave number \( k \)

(g) momentum \( p \)

Q2.4 For this lab, to calibrate a spectrometer means to establish which correspondence?

(a) wavelength of light vs. detector pixel number

(b) arrival time of light vs. detector readout time

(c) intensity of light vs. detector response
Exercises

A. Qualitative observations

Please use the foot pedals provided to deliver power to the Geisler-tube power supply, as leaving it on continuously greatly shortens the tube lifetimes. Don't insert or remove Geisler tubes unless the power supply is switched off.

L2.1 Use the hand-held spectroscope to study the following light sources: sunlight (if you can find some) or an incandescent desk lamp, fluorescent room lights, mercury Geisler tube. Describe the most important characteristics of each spectrum and explain the physical phenomena underlying their differences. Tips: You are welcome to use books or online resources for extra information. Relevant keywords are “spectroscopy”, “black-body spectrum” and “fluorescent lamp”.

B. Calibration

Connect the digital spectrometer to a USB port on your computer. Use the wall transformer provided to deliver power to the spectrometer. Remove the rubber tips from both ends of the fiber optic and insert one end into the spectrometer. Support the other end of the fiber optic and aim it at a helium Geisler tube source from a distance of about 10 cm.

Find the “digitalspectrometer” program on your computer (there should be a shortcut to the Labs/Physics145 folder on the desktop). This program was written using the Labview software environment. The program should start automatically when you open it. The small red "stop sign" icon will stop it, and the adjacent black arrow icon will restart it. Before reaching the position-sensitive detector, the light is reflected off a finely-divided grating, which causes different wavelengths of light to be reflected in slightly different directions, thereby reaching different detector pixels.

L2.2 Click on “Acquire Single Spectrum” to collect an uncalibrated spectrum. The vertical axis of the graph is intensity, while the horizontal axis is measured in arbitrary units that correspond to the pixels of a position-sensitive CCD detector chip. If necessary, adjust the distance between the fiber optic and the Geisler tube to ensure that you have adequate signal without letting any of the peaks saturate the detector. Print a copy of the graph for your lab notebook – use scissors and scotch tape.

L2.3 You now need to teach the instrument how to convert pixel number into wavelength in nanometers. This process is called calibration. Click on “Calibrate Spectrometer” to open a separate calibration window, and then click “Take Spectrum” to collect another helium gas spectrum.
Note that wavelength is approximately proportional to detector pixel, so that wavelength increases to the right on the graph. The six strongest lines in the helium spectrum should be ultraviolet (invisible to the eye, 388.8 nm), blue-purple (447.2 nm), skip two weaker peaks, green (501.6 nm), yellow-orange (587.6 nm), red (667.8 nm) and infrared (706.5 nm). Use the cursor tool to accurately determine the pixel position of the top of each of peak and enter it into the corresponding space in the calibration window. Take care to make these assignments correctly – a mistake will cause your subsequent measurements to have errors. The hand-held spectrometer may be helpful in figuring out which peak is which. Then click “Fit Spectrum” to perform the calibration, which should convert the horizontal axis of the graph to a wavelength scale.

L2.4 Click “Done with calibration” to return to the main window. Then click “Acquire single spectrum” to obtain a new helium spectrum with a wavelength scale. If the six largest peaks don’t show the correct wavelengths (to within a few nanometers), then your calibration must be repeated. When finished, print your calibrated graph for your lab notebook, clearly labeling the colors and wavelengths of all six peaks.

Do not close the VI – we plan to use the calibration tool to collect additional spectra.

B. Hydrogen Emission Spectrum

L2.5 Acquire a hydrogen spectrum using a hydrogen Geisler tube. Because the hydrogen tubes have relatively short lifetimes, please use a foot pedal to turn your tube on and off, which avoids leaving the tube on too long.

L2.6 The emission lines of hydrogen are calculated as $\frac{1}{\lambda} = R \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$, where $R = 0.010974/\text{nm}$ is the Rydberg constant, and where $n_i$ and $n_f$ are the principle quantum numbers of the initial and final energy levels of a given transition. The well-known Balmer-series lines defined by $n_f = 2$ include four peaks in the visible spectrum (violet, blue, blue-green and red). Identify the four visible Balmer-series lines with the peaks in your spectrum. The hand-held spectrometer should aid in the identification. If you move the Geisler tube back far enough that the intense red peak doesn't saturate the detector, then the violet peak will be too weak to see. Go ahead and saturate the strongest peaks in order to ensure that the violet peak is visible.

L2.7 Use the cursor tool to measure the wavelengths of all four peaks to the nearest nanometer. Check your results against an online reference. Print your graph for your lab notebook and indicate the colors and wavelengths of each of the four peaks.
L2.8 Use the wavelengths that you measured to calculate $n_i$ (should be an integer) for each Balmer line.

C. Incandescent lamp spectrum.

L2.9 Direct the fiber optic towards an incandescent light bulb (use your desk lamp), collect a spectrum and apply the wavelength calibration. Keep the light bulb sufficiently far from the fiber optic so as to avoid saturating the detector (which cuts the top off of the peak). If the fluorescent room lights are off, one should even be able to collect an incandescent spectrum from across the room. Print the graph for your lab notebook.

L2.10 Compare/contrast the shape of your spectrum to that of an ideal black-body spectrum. The non-idealities actually lie with the spectrometer rather than the incandescent bulb. Estimate the peak position of your spectrum and use Wien's Displacement Law to estimate the temperature of the filament.

D. Fluorescent lamp spectrum.

L2.11 Direct the fiber optic towards one of the fluorescent lighting panels in the room, collect a spectrum and apply the wavelength calibration. Observe that pointing the fiber optic directly at a fluorescent lamp easily saturates the detector. To avoid saturation, point the fiber optic slightly away from the panel (or even towards the floor or one of the walls). Use the cursor tool to measure the wavelengths of each of the larger and more well-defined peaks in your spectrum. Print a nice-looking unsaturated spectrum for your lab notebook, and record the wavelengths of the major peaks.

L2.12 Refer to http://en.wikipedia.org/wiki/File:Fluorescent_lighting_spectrum_peaks_labelled.png to identify the origin (e.g. solid-state phosphor, elemental gas, etc.) of each of the peaks that you measured in the previous step. Explain how a fluorescent lamp produces white light. What is the physical difference between the light emitted from a ‘cool white’ fluorescent tube and a ‘warm white’ incandescent bulb?

L2.13 Imagine your fluorescent spectrum as a blackbody spectrum by mentally broadening the peaks until they overlap. Estimate the centroid position of the spectrum and use Wien's Displacement Law to determine its effective temperature. Compare this to the published color temperature (4100 K) of an Octron F032/741 bulb.

L2.14 LED – Measure and describe the spectrum of a white LED flashlight bulb. Is this what you expected? Print the spectrum for your notebook and explain the physical origins of its characteristic features.