

Experiment O2a

Spectroscopy with a High Resolution Scanning Monochromator

The high resolution spectrometer is a precision optical instrument designed for measuring wavelengths in the visible to near infrared part of the spectrum. The purpose of this experiment is to complete a series of measurements that demonstrate both the principles of the spectrometer as well as several concepts in atomic physics. Careful work here will enable you to obtain results to better than 0.05 nm precision, or something like .01%. One feature of the spectrometer that takes getting used to is that it measures light in terms of wave numbers using cm^{-1} as units. In this case $k=1/\lambda$ and not the $2\pi/\lambda$ we are familiar with from modern texts. Since wave number and wavelength are reciprocals, their percentage errors are equal ($\Delta\lambda/\lambda = \Delta k/k$). Thus, for typical red light with wavelength on the order of 630 nm, wave number $\approx 16,000 \text{ cm}^{-1}$. If we can resolve spectral features on the order of about 1 cm^{-1} (as with this spectrometer) this is equivalent to a resolution of about 0.05 nm ($1/16,000 \approx 0.05/630$). In most of the experiments that follow we will more often be interested in measuring the differences (splittings) in spectral lines, rather than their absolute values, so the resolution of the spectrometer rather than its precision is of most interest.

The spectrometer is based on the same basic principles as the simple models you have worked with in earlier labs using interference from a diffraction grating to measure wavelengths of light. In this instrument, the grating works by reflection instead of transmission, and your eye is replaced by a more sensitive photo detector mounted at the output slit. Theoretical resolution of a grating scales with the number of illuminated lines; in the present case the grating is 4 times wider and has twice the number of lines per mm as those you worked with earlier - a factor of 8 improvement in resolution. When properly adjusted, the instrument is capable of resolving $\Delta\lambda \approx .01 \text{ nm}$ at visible wavelengths!

In the simple spectrometer you rotated an optical telescope to view the diffracted light at different angles. Here the grating is rotated instead, using a digital stepping motor under computer control and the diffracted rays are swept across the photodetector. Thus the optical path remains the same for each wavelength while the grating rotates and the instrument functions as a monochromator, similar to the small monochromator used in the photoelectric effect experiment. The computer can then create plots of wave number (corresponding to a particular rotation angle) versus light intensity and provide output files for subsequent analysis. Before beginning the experiments, open the ports on either side of the spectrometer to get a view of the optical path. The beam actually traverses the instrument 4 times, striking the grating twice before exiting to the photomultiplier.

1) Calibrating the Spectrometer

To verify the calibration of the spectrometer and set it up for maximum resolution, we will start with a helium-neon laser, $\lambda=632.8 \text{ nm}$. Mount the laser just outside the entry slit and set the photocell high voltage to about 600 volts. The program which operates the monochromator and collects data is called "atomic.exe." It can be launched via the "monochromator" icon found in the "programs" window on the PC. After starting the program, set the gain to "1" and scan a range of about 100 cm^{-1} centered on the expected peak. You

should see a narrow spike near the center of your plot. Narrow the range to 20 cm^{-1} centered on the peak you found and acquire a high-resolution scan. This will enable you to verify the calibration of the spectrometer as well as determine the resolution since the laser wavelength can be thought of as infinitely narrow. Adjust the entry slit to obtain the narrowest line width and increase the photodetector gain if necessary. Save the calibration file to a floppy disk and record the settings used (limit the file name to 8 characters, not counting the extension). A Mathcad template (spectrum_line_analysis.mcd in the \physics 245 folder on the p: drive) has been created to enable you to easily find the center of the peak and the full width at half the maximum amplitude (FWHM).

2) The Hydrogen Atom

In this experiment we will measure the "red line" in the hydrogen spectrum and verify the wavelength predicted by the Bohr formula. Mount a hydrogen discharge tube in front of the entrance slit using a short-length converging lens to focus the light. Note that this tube has a narrow bore and needs to be carefully aligned. Set the photomultiplier voltage at about 1100 volts and increase the spectrometer gain (in the program) to the X10 setting to compensate for the difference in light intensity compared to the laser. You can optimize the alignment by setting the spectrometer to the red line at 656.3 nm and peaking the photomultiplier output. Use the computer program option that measures the light amplitude at a particular wavelength and repeat as you adjust the alignment. Next record the spectrum for wavelengths between about 650 to 660 nm and analyze your results to find the wavelength and FWHM. The Balmer series occurs for transitions from higher levels to $n=2$. Compare the red wavelength that you observe with what is predicted using the Bohr formula:

$$E_\gamma = E_n - E_2 = - \frac{m e^4}{32 \pi^2 \epsilon^2 \hbar^2} \left[\frac{1}{n^2} - \frac{1}{2^2} \right]$$

From this

$$\frac{1}{\lambda} = R_H \left[\frac{1}{2^2} - \frac{1}{n^2} \right] = 1.097373 \times 10^7 \left[\frac{1}{2^2} - \frac{1}{n^2} \right]$$

3) The Sodium Spectrum

The major region of interest for Sodium is between 580 and 600 nm. There are two lines, called the Sodium D-lines, that are separated by about 0.6 nm. This *fine structure* is right at the edge of the resolving power of garden variety spectrometers, but should be easily separated by our apparatus. (Experiment O4 uses a high-resolution Michelson interferometer to measure this energy difference with a precision of about 1%!) Record the spectrum over this wavelength range adjusting the gain, photomultiplier voltage and/or the distance from the lamp to the entrance slit as needed.

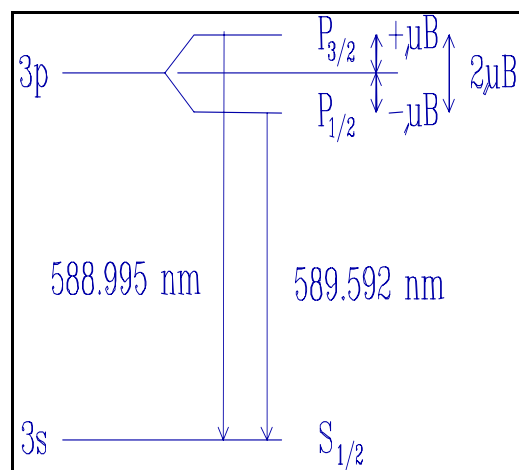


Figure 1

The transitions are from either a $3^2P_{1/2}$ or a $3^2P_{3/2}$

level to a $3^2S_{1/2}$ level, as shown in Fig. 1. Thus the difference in the two photon energies gives us the difference in the two upper states. That difference is attributed to the *spin-orbit interaction*, i.e., the magnetic interaction between the electron spin and the magnetic field that it sees from the nucleus orbiting about the electron in its own reference frame.

Let us do a simple calculation of the magnetic field that the electron would see. We can express the magnetic field that the electron sees by:

$$B = \frac{\mu_0 I}{2r} = \frac{\mu_0 (emv)}{4\pi m r^2} = \frac{\mu_0 eL}{4\pi m r^3} ,$$

where we have used $I = e/(2\pi r/v)$ and $L = mvr$, with m as the electron mass and $\mu_0 = 4\pi \times 10^{-7}$. In a proper quantum mechanical calculation one has merely to replace $1/r^3$ with the average $\langle 1/r^3 \rangle$ and compute this using the proper wavefunctions for the electrons. (This shows the close fundamental relationship between a classical model and a quantum mechanical model of the atom.) In reality, this theoretical expression for the field B can only be crudely estimated, since one would need to have a complete understanding of the penetration of the electron into the core electrons. Here you might want to try a radius of about 0.1 nm (2 Bohr radii) and estimate the angular momentum by the appropriate numerical values multiplied by \hbar .

We can also estimate B from our measurement of the splitting. The magnetic moment μ of the electron in this field will experience a potential energy shift given by:

$$U = \vec{\mu} \cdot \vec{B} = \mu_z B_z$$

with a sign depending on whether the electron spin is parallel or anti-parallel to this field. The magnetic moment is equal to the product of the g-factor, slightly larger than 2.0, the Bohr magneton, $\beta = eh/4\pi m$ which is 9.27×10^{-24} Joules/Tesla, and the z component of the electron spin. Therefore the energy difference between these two states will be:

$$\Delta U = U_{\uparrow} - U_{\downarrow} = (\mu_{\uparrow} - \mu_{\downarrow}) B = 2\beta \left(+\frac{1}{2} - -\frac{1}{2} \right) B = 2\beta B$$

Since the sodium D lines represent transitions from the $P_{3/2}$ and $P_{1/2}$ levels to the same $S_{1/2}$ energy level, you can use your measurement of the energy difference to estimate the magnitude of the magnetic field that is experienced by the electron. (Remember laboratory magnetic fields rarely exceed one Tesla.) How do your two estimates of B compare?

Replace the sodium spectral tube with a high pressure sodium lamp, similar to the ones used in the introductory courses. These are the lamps that are used commercially for street lighting and should be quite familiar to you. After the lamp has had time to warm up, repeat the earlier measurement over a wavelength range from 580 to 600 nm. You should now see the effect of self-absorption. An atom that is a strong emitter in any wavelength will also be a strong absorber. We have seen that sodium is a very strong emitter of the D-lines and therefore should be strongly absorbing at these same wavelengths. An atom radiating a photon of one of these

wavelengths is likely to have the photon absorbed by another atom and can never escape from the discharge tube. Other wavelengths are less likely to be absorbed and thus can escape. This means that the relative intensities of the lines emitted can be radically altered. This is particularly dramatic in the case of the sodium lamp. It accounts for the improved color balance of the new high-pressure lamps over the older low-pressure lamps. Compare the spectra for the low- and high-pressure lamps and see if you can find any evidence to support this assertion.

4) The Nitrogen Molecule

In addition to their atomic spectra, diatomic and polyatomic gasses also produce molecular spectra corresponding to transitions between vibrational and rotational states. Although weaker than the atomic spectra, these lines can be detected with our apparatus. Our effort here is primarily a qualitative one to observe the pattern of molecular lines, so we will not be interested in measuring precise wavelengths.

The narrow capillary tubes have high electron velocities that more often result in collisions which dissociate molecules leaving atoms in excited states. However, down near the bottom of the tube where the electron velocities are lower, it is possible to see the effects of molecular excitations without dissociation. This could involve either excited neutral molecules N_2 or excited molecular ions N_2^+ . In both cases the molecular excitations produce broader lines since each electronic excitation may include a range of vibrational and rotational energies in addition. Of these, it is the vibrational energies that have the larger spacing and are easier to observe.

Theoretical calculations show that quite a few molecular transitions in Nitrogen can be observed between about 588 nm and 606 nm. Set up the Nitrogen spectral tube and acquire a spectrum over this range of wavelengths. You will need the photodiode high voltage to about 1150 volts and may need to open the entry slit a bit more to see these transitions. Because of the large scan range you will need to acquire and save the data in several different files, concatenating them later. How do you explain the pattern you observe in the spectrum?

5) The Mercury Spectrum (optional)

The very bright green line of Mercury is often used in spectroscopic studies. Here we will concentrate on two closely-spaced lines in the yellow part of the spectrum at 577 and 579.1 nm. Use the program atomic to recenter the spectrometer on these two wavelengths while you set up the large Mercury lamp and align it with the input slit to the spectrometer. Reset the input gain to 100 and create a plot scanning about 100 cm^{-1} covering the range you expect for the yellow lines. Compute the splitting (in nm) and measure the FWHM for each of the lines. Is your measured splitting what you expected? What atomic transitions in the Mercury energy level scheme do these lines correspond to?

The Mercury gas you have just observed is under relatively high pressure and it is interesting to observe the same spectrum in a low-pressure cell. Replace the high-pressure Mercury lamp with a Mercury spectral tube mounted in the Cenco high voltage supply and repeat the measurement you just made. You will probably need to increase the photodiode high voltage, but do not exceed about 750 volts. Is the line splitting the same as before? What about line widths? What might account for differences you measure?