

A-8 Optical Spectroscopy

From Physics 191r

Optical Spectroscopy Word version File:A8opticalspec 10.doc

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first experiment: II

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Learning Goals

- Learn to use a grating spectrometer and a cooled, back-thinned CCD camera.
- Observe interference fringes in white light.
- Study ruby fluorescence.
- Measure the Raman shift in hydrogen gas.
- Measure the ortho/para hydrogen ratio as a function of temperature.
- Perform nonlinear curve fits.
- Work safely with lasers.

Introduction

Optical spectroscopy is an important tool for understanding matter by its interaction with electromagnetic radiation. In this experiment you are introduced to several types of experimentation, Raman scattering, fluorescence spectroscopy, and transmission/reflection experiments, using a grating spectrometer. The grating spectrometer is useful from the hard ultraviolet ($\lambda = 100$ nm) to the far infrared (~ 1 mm), spanning a range of order 10^6 in frequency or wavelength. The old fashioned manner of doing spectroscopy was to place a photographic film in the focal plane of a spectrometer, often exposing the film for long periods of time to observe weak signals, with substantial labor to determine frequency and intensity. This time consuming technique had the advantage that a broad spectral range could be observed simultaneously at high resolution. This was replaced with the sensitive photo-multiplier that could detect single photons. A slit was placed in the focal plane of the spectrometer to define the resolution with the photo-multiplier behind the slit. The grating was then rotated or swept in angle to record a spectrum over a large spectral range. A modern revolution for measurement has come about with the introduction of diode arrays or CCD (charge coupled device) detectors. In this case, an array of photodiodes or photosensitive pixels is placed in the focal plane and exposed. Each pixel can have the sensitivity of a photo-multiplier. The advantage over the photographic plate is the high sensitivity and the rapid readout mitigated by computer driven electronics, so that a strong spectrum can be recorded in a few milliseconds, while a weak spectrum can be integrated up for long periods of time (hours) before read-out. In this experiment we use a CCD with 1024 pixels in the horizontal plane, i.e. the plane in which the radiation is dispersed. This CCD is sensitive from the near infrared, about 1 micrometer (1000 nm), to the violet part of the visible, about 400 nm. Current CCDs can be extended into the UV but not much further into the IR. Spectroscopy in the IR has been

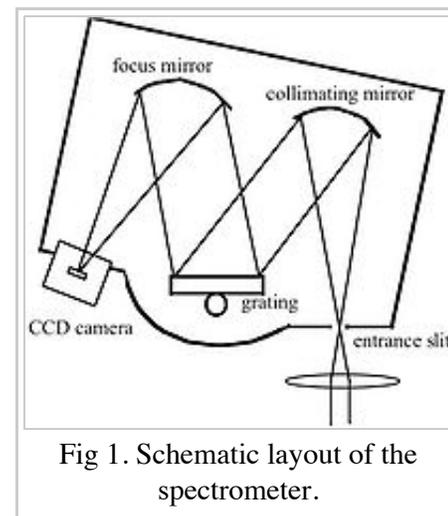


Fig 1. Schematic layout of the spectrometer.

taken over by a method called Fourier Transform Infra Red (FTIR) using Michelson interferometers, which we shall not discuss here.

In this experiment, you will do four things:

- 1. Study signal to noise and calibrate the CCD.
- 2. Transmission/absorption spectroscopy.
- 3. Fluorescence spectroscopy and lifetime of metastable states in ruby.
- 4. Raman scattering from hydrogen gas.

You will be provided with a grating spectrometer, the ISA Triax 320 shown schematically in Figure 1. This is a spectrometer utilizing a modified Czerny-Turner mount. It has an input slit and a CCD in the focal plane. The spectrometer has two gratings (1200 grooves/mm and 300 grooves/mm) that are blazed at 500 nm. The two gratings can be automatically rotated into position (not shown) and enable you to examine spectral regions with higher or lower resolution.

The Charge Coupled Device Camera and Spectrometer

- Familiarize yourselves with the automatic control of the spectrometer (wavelength, grating, and slit adjustment).
- Familiarize yourselves with the Hamamatsu CCD camera (Type No. C7042). See the bench notes on general properties and operation of a CCD.
- Familiarize yourselves with the program “Hamamatsu Main Menu.vi” for doing spectroscopy with a CCD. This program controls the CCD, reads it out, and enables you to plot your spectra as intensity vs. wavelength or frequency.

A light signal from a continuous source fluctuates and this is a form of noise. If the number of photons/second registered on a pixel (or binned superpixel) is N_t then the number of photons in time T is $N = N_t T$. Due to the Poisson statistics of light (see Loudon, *Quantum Theory of Light*, for example) the fluctuation is \sqrt{N} and the signal to noise ratio is $s/n = \frac{N}{\sqrt{N}} = \sqrt{N}$. Other noise sources are dark noise (counts observed with no light falling on the CCD due to thermionic creation of electron hole pairs), which is reduced by cooling, and electronic readout noise (noise/pixel when reading out the CCD). Study and establish these relations experimentally.

In many experiments such as the Raman scattering in hydrogen, it is vital to optimize your signal to noise ratio. You have a white light source shown in Fig. 2 that you can use to create a signal. By changing the lamp voltage, the size of the pinhole, or using attenuators, you can vary the light signal. Study the various sources of noise or fluctuations. An important optimization technique is to use binning on your CCD. Rather than read out all pixels, which can be time consuming, the signal from several pixels can be added up and then read out as a superpixel, or binned pixel. With normal operation, for a given column (optical frequency) you sum all of the pixels to get the signal for that frequency. Many measurements have very small sources of light i.e., focused lasers the size of which can be on the order of several microns. When this light is imaged on the CCD, which may be several mm high, then only a small number of pixels are illuminated. If you

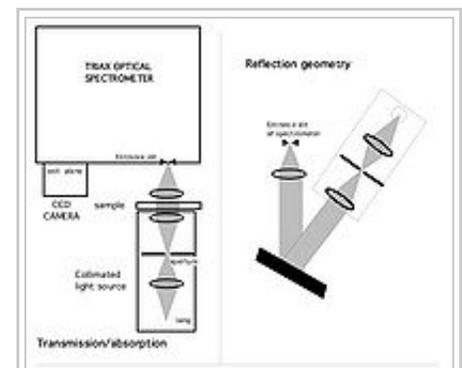


Fig. 2. Optical layouts for transmission showing a collimated white light source and sample, and on the right, a set-up for reflection

sum all of the pixels in a column, then most contribute only noise and no signal. The signal to noise can be greatly enhanced by just summing the pixels that are illuminated. This can be done in the binning software. Test this out by imaging a small illuminated pinhole on the CCD and measure the signal with and without binning and restriction of the signal to illuminated pixels.

After familiarizing yourself with the system, calibrate the CCD by associating a wavelength with each pixel. Use the calibration source shown in Fig. 3, which is a gas discharge with sharp spectral lines, whose positions are given in the bench notes. The software has a calibration procedure.

Return to the set-up of Figure. 2. In the Raman experiment, as well as the ruby fluorescence experiment, you will use a notch filter, which removes a band of light around the laser line. Characterize the filter. It is advertised to reduce the light in the band by 6 orders of magnitude. Unfortunately a spectrometer is not a perfect instrument, and false radiation will fall on the detector, that is, light at the wrong wavelength falls on a pixel, giving a signal. This is particularly a difficult problem if an intense light beam such as a laser falls into the spectrometer, or a very broadband beam. Although the spectrometer is black on the inside (open it up) a black surface may reflect of order 1 or 2%, so that rogue photons can fall onto the detector. How might you improve the characterization of the filter?

Next measure the index of refraction, n , of a piece of glass. We use a glass microscope cover slip coated with partially-reflective surfaces. The signal is also visible from bare cover slips. If the faces are parallel, the cover slip forms a Fabry-Perot resonator. Build a white light collimator as shown in Fig. 2. Select components to get a beam about a centimeter in diameter. It is useful to build this up on optical rail, which is provided. A collimated beam of white light passing through the resonator will form fringes (study the Fresnel Law); the spacing of fringes (measured in wavenumbers) for normal incidence is $\frac{1}{2nd}$ for thickness d . From the fringe spacing and contrast, you can determine the index of refraction n and thickness, d . How does the contrast depend on n and d ? The glass slide is actually a low finesse Fabry-Perot resonator. A very nice way to determine both n and d is to measure the fringe spacing as a function of the angle of incidence of light on the glass slide. Do this.

Fluorescence of Ruby

Set up for fluorescence measurements, shown in Fig. 4. We can understand fluorescence from Fig. 5. The argon laser is used to pump into the ruby U or B bands. These levels nonradiatively decay to the R lines, which are long-lived metastable states, and then radiatively decay to the ground state, emitting light at around 694 nm. In this experiment, you take a piece of ruby and pump it with a laser at 514.5 nm, measuring the R lines. Then you measure the lifetime of the R lines by pumping the lines with a pulsed laser beam (accomplished with a chopper) and studying the decay by detecting the signal with a photodiode. The filter removes the interfering laser beam. Determine the lifetime of the ruby R lines.

Raman Scattering

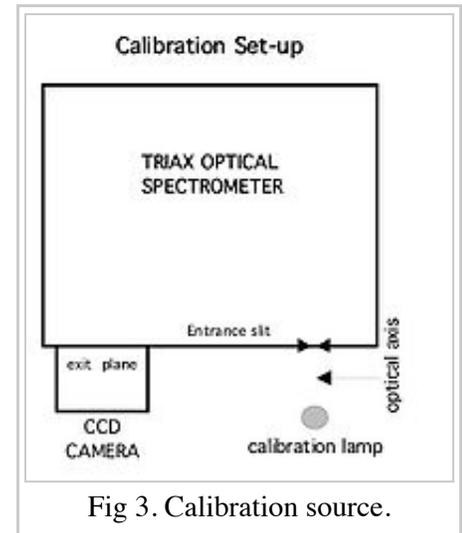
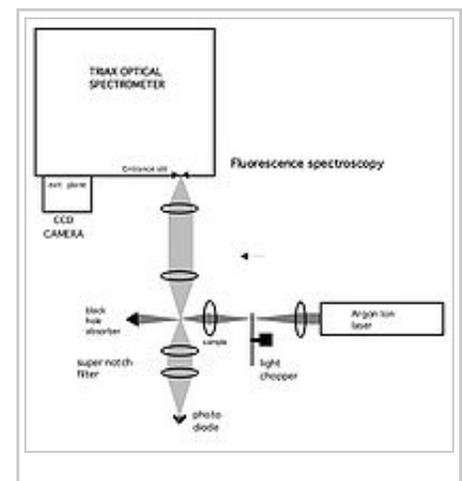


Fig 3. Calibration source.



Raman scattering is a useful method to determine excitations or energy levels in atoms, molecules, solids, and liquids. An incident photon at frequency ν_i can scatter off of a molecule creating an excitation, and shifting in frequency to ν_f . Energy and momentum are conserved. The energy conservation allows you to determine the energy of the excitation by measuring the energy of the scattered photon, knowing the energy of the incident photon. The scattered power is proportional to the incident power or the number of photons/second in an EM mode with energy $h\nu_i$. However, the efficiency is quite small, down by about 10 orders of magnitude from the incident power, so the scattered signal is very weak. Therefore a laser is used for the incident light beam, as shown in the Figure 6, along with the spectrometer for analyzing the scattered light.

Be careful not to get any direct laser light into your eyes; use laser goggles when in doubt about where the beam will shine. Although a right angle scattering geometry can be used, direct or unshifted scattered light will also get into the spectrometer. Unfortunately a spectrometer is not a perfect instrument, i.e., not a perfect filter, and though it passes a tunable band of light onto the detector, the laser light is orders of magnitude more intense than the scattered light and can mask the signal as false radiation. This can be suppressed by using a very narrow band rejection filter, called the super notch filter, which rejects a band around the 532 nm line of the laser, passing the shifted Raman scattered light. Now set up for Raman scattering. The optical alignment must be done with great care in order to see a Raman signal. Some hints are given in the appendix following the references.

In this experiment you study rotational energy levels in molecules, with $E = BJ(J+1)$, where B is the rotational constant and J the rotational quantum number. What are the selection rules for rotational Raman scattering?

Molecular hydrogen has the largest rotational constant of any molecule. Moreover, due to requirements imposed by the spin on the protons, it has two species, ortho and para (see a book on quantum mechanics). As a result it behaves like two separate gases, as thermalization of levels is very slow in the gas phase taking weeks to months to attain equilibrium between the ortho and para states. However, the molecules in even rotational states (para) will be in thermal equilibrium, as well as odd rotational states (ortho). Fill the cell with a sample from the lecture bottle. This will be in equilibrium at room temperature because it has been in the cylinder for a very long time. What are the ortho and para concentrations? Measure the Raman intensities of the lowest ortho and para rotational transitions and compare to theory. Is the intensity directly proportional to the ortho/para concentrations?

Ortho-para can be converted to equilibrium by magnetic interactions. You have a sample of Apache Silica gel, which has magnetic moments on the surface and a large surface area. Dunk the canister into liquid nitrogen and condense the hydrogen on the surface. It will rapidly be catalyzed to equilibrium. **Be careful to only condense the gas in the cell and tubing.** If you introduce more from the hydrogen tank, the pressure may rise above that which the glass cell can sustain when you desorb. Now desorb and measure the ortho-para concentrations. These should be the concentrations for liquid nitrogen temperature equilibrium. Compare to theory.

Fig 4. Optical set-up for studying ruby fluorescence.

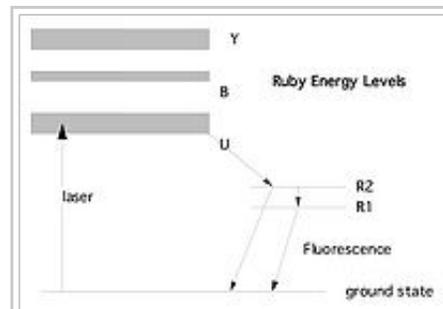


Fig 5. Energy-level diagram for ruby.

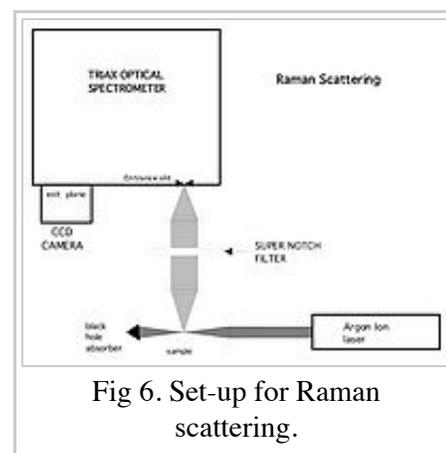


Fig 6. Set-up for Raman scattering.

Future Additions: Raman scattering off of the phonon in diamond; Raman scattering in nitrogen or CO₂ gases.

Apparatus

The apparatus consists of five main units:

- Argon ion laser (Midwest Laser 5490ASL)
- Diode pumped Nd:VYO laser with frequency-doubling crystal (MGL350)
- Grating spectrometer (TRIAX 320)
- CCD camera (Hamamatsu C7042)
- Computer (Dell GX270 with LabVIEW and Hamamatsu spectroscopy software)

And ancillary instrumentation:

- Raman scattering cell
- Gas handling system
- Discharge tubes (argon, neon, etc.)
- White light source
- Supernotch filters (Kaiser Optical Systems)
- Fabry-Perot cavities (microscope slide cover slips with reflective coatings)
- Optical chopper (Stanford Research SR540)
- Photodetector (ThorLabs PDA36A)
- Ruby crystal
- Lenses, filters, pinholes, lens holders, translation and rotation stages and rails
- Oscilloscope (Tektronix 2235)

Light Sources

White light source

The white light source is set up on an eighteen-inch rail. The 12-V transformer, energized by a Variac powers the halogen light bulb. An aluminum shade sits over the bulb to minimize stray light. A lens creates a real image of the filament on a pinhole. A second lens collimates the light that passes through the pinhole. See Figure 2.

Optimize the position of the first lens by making the image on the pinhole as sharp as possible and smaller than the object. Position the second lens roughly by observing the white light beam with a card. Use a mirror to project the light back onto the pinhole. If the lens is positioned properly, the image of the reflected light will be the same size as the pinhole.

Gas Discharge Tubes

Spectral lines from gas discharges are used to calibrate the spectrometer. A wooden box houses the tubes as well as a high voltage transformer. The power chord can be either plugged into a 120-Volt outlet directly or operated from a Variac. A small neon bulb is also available in a bud box, mounted on an optical post.

Argon Ion Laser

The argon ion laser is a turnkey system. Ask for the key and return it at the end of each lab period. If the laser buzzes or loses intensity, contact the faculty or staff for advice on tuning it. A plywood block is used to raise the laser to the correct height for the ruby experiment. See a book such as Siegman for details on ion lasers.

Diode-Pumped Solid State Laser

The DPSS laser contains an infrared diode (808 nm) which pumps a Nd:VYO₄ crystal which lases at 1064 nm. A frequency-doubling crystal converts the light to 532.0 nm. The maximum output power is about 420 mW, about 1% of which is IR. Take precautions to protect your eyes from the IR component of the laser light. A Thorlabs LDC 340 Laser Diode Controller supplies current to the infrared diode. The temperature controller is a small black box near the LDC 340. The temperature controller must be turned on before the laser current. Threshold current is about 450 mA. Absolute maximum current is 2.0 A. The controller has a built in limit to prevent damage to the laser. A rough calibration of output power vs. current is given in the bench notes.

The stability of the laser in constant current mode is poor (5% rms) but adequate to locate the hydrogen Raman signal. When you are ready to take final data, switch over to the constant power mode of the LDC 340. Using constant power mode can improve the stability by a factor of ten or so. An external feedback circuit is needed. Split off a small fraction of the beam with a glass slide. Reflections from glass/air interface are typically 4%, so this beam could be as much as 16mW. Treat it with care. Either this beam, or a second split is used for feedback. The feedback photodetector is a PIN-10D mounted in a white Teflon holder. Plug the photocurrent directly into the "PD ext (AG)" plug on the rear panel of the LDC 340. Do not use a Thorlabs PDA55 or other photodetector with voltage output. Select "P_{PD EXT}" Mode. Now the large dial controls for photocurrent, i.e. the controller will send out whatever laser current is needed to generate a certain current in the feedback photodiode. It's best to do this with the room lights out. You can keep the LED monitor set to display laser current so you will have an idea what the output power is. Choose a photocurrent that gives you approximately 1.8 A laser current. The maximum current is 2.0 A, so the controller has some leeway to keep the power constant.

SAFETY WARNING: THE NOMINAL MAXIMUM POWER OF THE LASERS IS 40 MW AND 350MW, RESPECTIVELY. THE DIRECT BEAM OR SPECULAR REFLECTION OF THE DIRECT BEAM CAN PERMANENTLY DAMAGE YOUR VISION. USE EXTREME CAUTION WHEN ALIGNING THE LASER AND MAKE ABSOLUTELY SURE THAT ALL BEAMS ARE CONTAINED WITHIN THE FOOTPRINT OF THE LAB BENCH. USE BLACK FOAMCORE TO BLOCK STRAY REFLECTIONS AND A BEAMSTOP TO DUMP THE DIRECT BEAM. LASER SAFETY GOGGLES ARE AVAILABLE. USE THEM DURING OPTICAL ALIGNMENT AND WHENEVER ANYTHING IS PLACED IN THE BEAM PATH. ASK THE FACULTY OR STAFF FOR KEYS WHEN YOU ARE READY TO USE THE LASERS AND RETURN THE KEYS AT THE END OF THE LAB PERIOD.

Optics

Several lenses are available. Each lens holder is marked with the Newport part number of the lens and its focal length in millimeters. The lens mounts are to be secured to the optics table with thumbscrews. The position of the spectrometer entrance lens is especially critical, so it is mounted on a small XY translation stage.

Spectrometer

The Triax 320 is a single grating spectrometer. Light passes through an entrance slit and falls upon a spherical

mirror. The entrance lens should be chosen and positioned so that the light that enters the spectrometer fills this mirror for maximum efficiency. The light is focussed onto a diffraction grating that disperses it. A second spherical mirror focuses the light onto the exit plane.

Motors control the entrance slit width as well as selecting the grating and adjusting its angle. A remote control called Hand Scan controls the motors. The entrance slit width ranges from zero to 1000 microns. Fifty to one hundred microns is a typical operating range. Two diffraction gratings are available, one coarse and one fine. The coarse grating has 300 lines per mm and the fine has 1200 lines per mm. The blaze angle is optimized for 500 nm (the center of the visible) for both gratings.

To turn the spectrometer on, first plug in the round dc connector, and then plug in the line cord. The ● key activates the Hand Scan. It will display a version number and ask you to press Enter. The basic functions are accessed through the GoTo menu. Use the up/down arrow keys to scroll through the choices, and the Next and Back keys to change options. Numeric options such as slit width are entered from the numeric keypad. The default grating (number one, option zero) is the fine one. The coarse grating is number two, option one.

Detectors

Photodiode

A photodiode is a p-n junction in which an electron-hole pair can be created by a photon striking the junction. Photodiodes are usually reverse-biased. The electric field in the depletion region separates the electron and hole, creating a current proportional to the light intensity. See Sze §13.3 for a brief discussion of the principles of operation. The Thorlabs PDA36A photodiode is used for the ruby fluorescence measurement.

CCD Camera

A CCD (Charge-Coupled Device) camera consists of an array of pixels, each of which is on the order of ten microns square. Each pixel is basically a sophisticated photodiode. Rather than detect a continuous current from the pixel however, charge is allowed to build up on the device for a certain exposure time, then the charge is detected. For principles of operation, see <http://www.site-inc.com/tutorial.htm>.

A CCD camera is placed in the exit plane of the spectrometer. The camera is a Hamamatsu C7042 with an S7032-1006 sensor array. The CCD array is 1044 pixels wide and 64 pixels high. The image of the entrance slit is also a slit; therefore the vertical dimension contains no unique information. To minimize the time required to transfer data from the camera to the computer, the 64 vertical pixels are binned. A thermoelectric cooler cools the CCD array. It is operated at -20°C to reduce thermal noise.

Data Acquisition - LabVIEW

A Dell GX 270 with a National Instruments PCI interface card and a Hamamatsu LabVIEW program called "Hamamatsu Main Menu.vi" communicates with the CCD camera and processes the data. See the bench notes for documentation from Hamamatsu. Laboratory staff modified the commercial software. The current version is "Hamamatsu_joe10.vi".

Camera Identification

The software incorporates control and constants that identify the camera. The user usually does not change

these:

- camera type: C7042
- device (CCD type): S7032-1006
- CCD Conversion gain: 15.7 microVolts/electron
- area: 1044H x 64V
- device: FFT-CCD
- camera serial number: 3DI876
- device (CCD) serial number: 002

Mode

The user chooses between **Line** and **Area** mode. In line mode, the vertical pixels are binned in the camera and read out together. In area mode, each pixel is read out separately.

Acquisition can be either **Continuous** or **Snap**. In continuous mode, data is read from the camera over and over and each spectral readout replaces the previous one, whereas in snap mode, the camera is read once after the Snap button is pressed. The shutter control is not used, as there is no shutter provided with the camera.

Times

Exposure Time sets the time during which the CCD is illuminated between reads. **Start Period** is the exposure time plus readout time. **Update Time** is the interval between subsequent updates of the spectrum display; it is usually similar to start period. **Elapsed Time** shows the time since the beginning of the current start period; this indicator is useful for long exposures.

The CCD array continues to be illuminated during the readout time. This is significant in area mode, where the readout time is approximately 1/2 second.

Area Mode

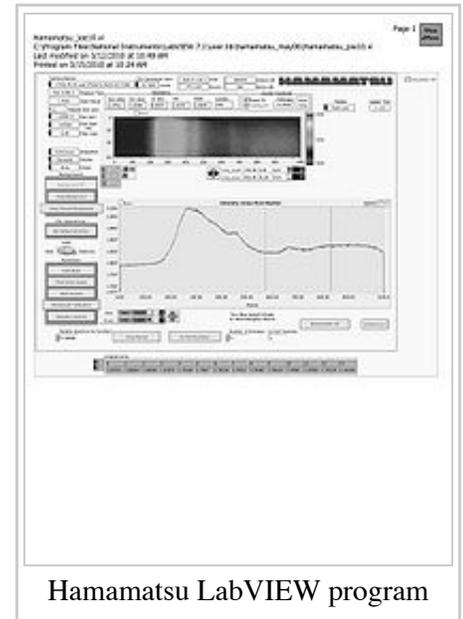
In area mode, each pixel is read out individually. The intensity information, a 2D matrix, is displayed on a grid where colors correspond to intensity.

Software binning crops rows from the the intensity matrix at locations determined by two horizontal red cursors. The intensity graph displays the sum of intensities between the cursors (inclusive). To measure a single row of pixels, put the cursors on the same row.

The units of intensity can be switched between **Volts**, the voltage across a capacitor in the camera which receives charge from the pixels, or number of **Electrons**, this is voltage divided by Conversion Gain. In general in spectroscopy one characterizes the signal strength by number of counts or number of electrons since each electron corresponds to a detected photon.

The array at the bottom of the software window corresponds to the intensity information displayed in the graph.

Line Mode



In line mode, columns of pixels are binned in the camera. The lower graph displays intensity vs. column number whereas the upper graph displays total intensity (between the vertical red and green cursors) as a function of time.

Wavelength Calibration

The columns of pixels can be calibrated by using a source with known wavelengths such as a neon discharge lamp. Illuminate the spectrometer and click the **Wavelength Calibration** button. A separate window pops up and shows the spectrum acquired most recently. Use the black vertical cursor to determine the pixel number in which a peak of known wavelength falls. A catalog of emission spectra lines is included in the Bench Notes. Type the pixel number and the wavelength into the respective columns of the table. Delete old rows after entering at least two known values in the current spectrum. The program calculates a polynomial fit. When you are satisfied with the fit, click **Save Coefficients** to save the calibration. Close the calibration window and click on **Pixels** on the horizontal axis of the intensity graph. This converts the axis to wavelength. Click on **Wavelength** to change back.

Units: nm vs. 1/cm and Raman Scattering

The spectrometer is approximately linear in wavelength, but one may want to use energy units such as inverse centimeters (wavenumbers). After calibrating the pixels to wavelength, click the **Wavenumber off** button to switch units. The software simply calculates

$$Wavenumber(1/cm) = \frac{1}{Wavelength(nm) \times 10^{-7} cm/nm}. \text{ When Wavenumber is activated, a}$$

Wavenumber Shift Off button appears. Enter the laser wavelength in nanometers; the software converts it to inverse centimeters and subtracts. This is useful for Raman scattering as one is interested in the shift of the Raman peak from the laser line.

Background Subtraction

The background subtraction feature allows the user to store a spectrum in memory and automatically subtract it from newly acquired spectra. This is useful when searching for weak signals. **Snap Background** stores the current spectrum in memory. Clicking **Background Off** initiates automatic subtraction. The switch changes to **Subtract Background**; click it again to turn off background subtraction.

Normalization

The normalization feature is similar to background subtraction, except that it divides current spectra by a spectrum stored in memory. One can also multiply spectra by a constant.

BUG: in AREA mode, dividing a spectrum by itself does not give a result near one.

Averaging

When the **Number of Averages** control is greater than one, the display shows a running average.

BUG: strange behavior in SNAP mode.

Saving Data

To save a spectrum, check the **Save** box in the upper left corner of the Intensity Graph. Use **Set Default Directory** to save to your data directory.

Experimental Procedure

- Quantify the noise sources associated with the CCD camera.
- Investigate the camera's binning modes.
- Calibrate the horizontal pixels vs. optical wavelength or wavenumber.
- Characterize the notch filter.
- Observe the Fabry-Perot fringes and measure index of refraction and width of the glass.
- Measure the lifetime of ruby metastable states.
- Measure the hydrogen ortho/para fraction at 300K and 77K.

A note on units

Wavelength: 1 nanometer (nm) = 10 angstroms (Å) = 0.001 microns. Spectrometers are roughly linear in wavelength, but energy is the relevant unit for physics, so both units are used.

$Energy = h\nu = hc/\lambda$. Energy is usually measured with $h = 1$. The usual unit used is not frequency, but inverse centimeters, which is $\nu/c = 1/\lambda$ with wavelength measured in cm. As a scaling $500nm = 20,000cm^{-1}$, or 20,000 wavenumbers.

References and Notes

Additional reading

Articles

I.F. Silvera, Review of Modern Physics 52, 393 (1980). The solid molecular hydrogens in the condensed phase: Fundamentals and static properties (<http://www.fas.harvard.edu/~phys191r/References/a8/Silvera1980.pdf>) . (ortho-para states)

J. van Straaten and I .F. Silvera, Physical Review B 37, 1989 (1988). Equation of state of solid molecular H2 and D2 at 5K (<http://www.fas.harvard.edu/~phys191r/References/a8/VanStraaten1988.pdf>) .(index of refraction measurements)

Monographs

S.M. Sze, Physics of Semiconductor Devices, (John Wiley & Sons, New York, 1981).

A.E. Siegman, An Introduction to Lasers and Masers, McGraw Hill

E. Hecht, Optics, Addison-Welsley, second ed., 1987 (spectrometers, Fabry-perot, Fresnel, etc.)

R. Loudon, The Quantum Theory of Light, Clarendon Press (Poisson Statistics, Raman, etc.)

Bench Notes

- Hamamatsu CCD Camera Specifications (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/hama.pdf)
 - Hamamatsu CCD Pamphlet (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/CCD.pdf)
 - Hamamatsu CCD Interface Manual (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Hama_kit.pdf)
 - Hamamatsu CCD LabVIEW software Manual (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Hama_LV.pdf)
 - Safety Goggles (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Goggles.pdf)
 - Handscan (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Handscan.pdf)
 - 40mW Laser Specifications (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Laser.pdf)
 - 350mW Laser: Manual (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/laser350mw.pdf)
 - 350mW Laser: Power as a Function of Current (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/power_current.gif)
 - Thorlabs LDC340 Laser Diode Controller (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/lcd340.pdf)
 - Newport MT-X Translation Stage (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Newport.pdf)
 - TRIAX Series Spectrometer (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Spectrometer.pdf)
 - SR540 Optical Chopper (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/SR540.pdf)
 - Supernotch Filter (514nm) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/Supernotch.pdf)
 - Supernotch Filter (532nm) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/supernotch_532.pdf)
 - Typical Spectra of Elements (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/TypicalSpectra.pdf)
 - Light Levels and Noise (K.J. Kaufmann) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/lightlevelnoise.pdf)
 - Dell Optiplex 980 Technical Guide (http://www.fas.harvard.edu/~phys191r/Bench_Notes/optiplex-980-tech-guide.pdf)
 - Handbook of CCD Astronomy (Steve B. Howell) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A8/CCD_Howell.pdf)
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- Optics of Spectroscopy (<http://www.horiba.com/us/en/scientific/products/optics-tutorial//?Ovly=1>)

Appendix: Alignment hints for Raman scattering from Hydrogen

The Raman signal is very weak, and great care must be taken to align the optics in order to see the signal. Refer to Figure 6 above.

The position and angle of the spectrometer will be roughly correct from your previous work. Begin by optimizing the spectrometer in the following way. A red laser pointer is available in an adjustable mount. The spectrometer entrance slit should be located above a row of holes on the laser table (call this the Y-axis). Set up the laser pointer so that the red beam is directly above a row of holes and parallel to the table at the same height as the center of the slit. A plumb bob simplifies this process. Also note that the spectrometer has a 1mm horizontal slit, which can be slid into place by shifting the whole spectrometer. With the laser beam entering the slit, adjust the angle of the spectrometer so that the beam falls in the center of the collimating mirror. Next we will align the argon-ion laser. A circular 0.0 – 3.0 variable neutral density filter is in series with the laser beam.

SAFETY WARNING: DURING ALIGNMENT, WORK ONLY WITH THE ATTENUATED BEAM. USE THE ORANGE SAFETY GOGGLES WHENEVER YOU ADD OR REMOVE A COMPONENT TO/FROM THE BEAM PATH.

NEVER PUT YOUR EYE AT THE LEVEL OF THE LASER BEAM.

Remove the plywood block from beneath the argon-ion laser. Choose the position and angle of the laser so that the green beam follows a row of holes (call this the X-axis). The vertical dimension (Z-axis) is not shown in Figure 6. Since the spectrometer slit is vertical, we image a vertical beam onto it. This means that a mirror must be used to change the direction of the laser beam. The intersection of the X-axis with the Y-Z plane is the desired position of the mirror. A half inch mirror mounted in a U-50P is meant for this purpose. Align the mirror so that the green beam is vertical and intersects the red alignment beam. DURING THIS STAGE OF ALIGNMENT, IF EXTREME CARE IS NOT TAKEN, THE VERTICAL BEAM CAN ENTER YOUR EYES WHILE REACHING OVER THE TABLE. Place the beamstop (stack of razor blades) to block the vertical beam above the sample position.

An easy way to choose the position and angle of the mirror is to place a dilute sample of polystyrene microspheres dissolved in water at the desired intersection point. The beams will be visible in the microsphere solution. Your neighbors at the Light Scattering experiment (A7) probably have some old samples you can use. Make sure to transfer the microsphere solution to the square scattering cells. A round test tube acts like a cylindrical lens! The scattering cells are made from optical quality glass. They are fragile and expensive – please use caution. Figure 6 shows a lens focusing the laser beam at the sample location. This should be a very short-focal length lens, 25 mm at most. Insert a lens into the beam path for this purpose. Adjust the position and angle of the lens so that the focus intersects the red alignment beam. After this, the red laser is no longer needed.

Next we desire to locate and align the collecting lens. Use one of the 50-mm KPX082AR.14's. This lens approximately matches the f/number of the scattering cell aperture. The X-position of this lens is the most important parameter in optimizing the signal. Mount the lens on one of the translation stages. In this way, its X-position can be adjusted sensitively and reproducibly. A collimated beam is desired, so the lens should be placed one focal length away from the sample. Continue to use the solution of polystyrene microspheres in the sample location. You will be able to see the scattered light. Image it onto a white card. Adjust the Y-position of the lens to make a collimated beam. Adjust the X- and Z-positions of the lens so that the beam is centered about the spectrometer entrance aperture.

The focussing lens may be in place already from a previous experiment. If not, mount a 75-mm KPX088 one focal length from the slit. This is also a critical lens – use a translation stage. Adjust the X- and Z-positions so that the light falls on the center of the spectrometer entrance slit. Adjust the Y-position so that the beam has its tightest focus at the slit.

Finally, place the supernotch filter in the collimated beam a few inches upstream of the focussing lens. Adjust the angle of the filter relative to the beam to minimize transmitted light. Note that a halo of green light passes the supernotch for certain angles. Block this with one of the adjustable circular apertures.

This is the rough setup. To optimize it, observe the vibrational line of mineral oil which is red-shifted by approximately 3000 cm^{-1} . This is a strong signal; hopefully it will be easy to find with the alignment as-is. Use a fairly small slit width (50 microns or less). Check that the signal is optimized by carefully tweaking the XYZ positions of the collimating and focusing lenses. Get a sense for how far the lenses have to translate in order to optimize or lose the signal, especially in the X-direction. If you have to hunt for the hydrogen signal, you will

want to know what range of parameters it is reasonable to search over. Finally, minimize the laser-line light entering the spectrometer by making fine adjustments of the angle of the supernotch filter. For hydrogen, you may wish to set the grating angle so that the laser line falls just off the CCD array.

Having optimized the mineral oil signal, next try for hydrogen. Remove the mineral oil and put in the hydrogen sample cell. Ask the faculty or staff to help you with the gas-handling system. You will have to subtract background to see the signal. A background signal means the detected light level when the hydrogen gas is pumped out of the sample cell. Which noise component dominates the background? Use a very large slit width at first (~500 micrometer). Exposures on the order of ten seconds will be needed.

In principle, the signal is detectable with the setup described. Two refinements are worth considering:

- Before leaving the mineral oil, change the CCD binning and look at the image (not the spectrum). Set the binning parameters to ignore rows of pixels where no light is falling. This increases the signal to noise ratio by eliminating dark counts from those pixels.
- A beam expander may be placed in the laser beam upstream of the half inch mirror. This makes a tighter focus in the scattering cell, but it increases the precision with which the mirror and the laser-focus lens must be aligned.

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- This page was last modified on 30 January 2013, at 16:02.