Hydrogen Balmer Series High Resolution Spectroscopy : the Discovery of Deuterium

Physics 122 Lab

Contents

The Balmer Series in Hydrogen and Deuterium

Introduction:

You will be repeating an experiment that won the Nobel Prize. First, here's some background. In 1885 a Swiss schoolteacher named Johannes Balmer observed that the wavelengths of the visible spectral lines of the hydrogen atom, known then to have the simplest spectrum in the periodic table, could be expressed very accurately by the simple formula

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad n = 3,4,5,\dots \qquad \text{Eqn A}$$

where R is equal to 109,678 cm^{-1}. Not only did Balmer correctly describe the sequence of lines which carries his name, but he also suggested that other sequences of spectral lines could be found which would correspond to wavelengths predicted by the same equation with the 2^2 replaced by 1^2, 3^2, 4^2, etc. Subsequent investigations in the far ultraviolet and infrared regions confirmed his predictions with remarkable accuracy.

The simplicity of the hydrogen spectrum is due to the fact that it contains only one electron, and that the potential felt by the electron is described precisely by Coulomb's law. In quantum mechanical terms, the energy levels of the hydrogen atom depend only upon the eigenvalues of the radial part of the wave function, not the angular parts describing the atom's angular momentum. This Coulomb degeneracy disappears in atoms containing more than one electron, where the nuclear potential felt by an electron is partially screened by the other electrons.

The hydrogen atom is the simplest quantum-mechanical system. It consists of an electron bound, due to the Coulomb force, to a proton. It is characteristic of bound quantum-mechanical systems that their total energy cannot have any value, but that the system is found in one of a discrete set of energy levels, or states. Transitions of the system between these states may occur. Such transitions must satisfy the basic conservation laws of electric charge, energy, momentum, angular momentum, and the other relevant symmetries of nature.

Transition from a higher energy state to a state with less energy can occur for an isolated system, and the larger the probability for this transition, the shorter the "lifetime" of that excited state. During such spontaneous transitions of a quantum-mechanical system to a lower energy state, a quantum of radiation, or one or more particles, can be emitted, which will carry away the energy lost by the system (after recoil effects have been taken into account). In the presence of a radiation field the quantum-mechanical system can either gain energy from the field and change into a state with higher energy, or lose energy to the field and revert to a lower energy state. For all quantum-mechanical systems there exists a lowest energy state, the *ground state*.

By observing the quanta of radiation emitted during such transitions, we gain information on the energy levels involved. The typical example is optical spectroscopy, which consists of the accurate determination of the energy of the light quanta emitted by atoms. Infrared spectroscopy deals mainly with the quanta emitted by molecules, nuclear spectroscopy with the quanta emitted in nuclear transitions, and so on. In nuclei, however, the separation between energy levels is much larger, so that the emitted quanta of electromagnetic radiation lie in the gamma ray region; thus different techniques are employed for detection and measurement of their energy. It is also very common for nuclei to decay from one energy state to another by the emission of an electron and neutrino (beta decay) and for certain heavier nuclei by the emission of a helium nucleus (alpha particle). Similar processes take place in the interactions or decay of the elementary particles. The idea of energy levels and their structure for the hydrogen atom was first introduced by Niels Bohr in 1913. However, a complete theoretical interpretation had to wait until the introduction of the Schrodinger equation in 1926. Even then, for theory to agree with observation it is necessary to include additional small effects such as the fine and hyperfine structure, relativistic motion, and other higher order corrections. These corrections are derived using the theory of quantum electrodynamics (QED) so that today we can theoretically calculate the energy levels of the hydrogen atom to the amazing accuracy of 1 part in 10^{11}.

Bohr theory:

We will use the Bohr theory to predict the hydrogen energy levels, because it is so simple, even though it assigns the incorrect angular momentum to the states. The postulates of the Bohr theory are (a) that the electron is bound in a circular orbit around the nucleus such that the angular momentum is quantized in integral units of Planck's constant (divided by 2π); namely, $pr = mvr = n(h/2\pi) = n\hbar$ and (b) that the electron in this orbit does not radiate energy, unless a transition to a different orbit occurs. We can then calculate the radii of these orbits and the total energy of the system, potential plus kinetic energy of the electron. The attractive force between the electron (charge $-e$) and the proton (charge $+e$) or a nucleus (of charge $+Ze$) is the Coulomb force, which is set equal to the centripetal force.

The total energy of the electron is

$$E = T + V$$

$$= \frac{1}{2}mv^2 - \frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} \tag{1}$$

Here m, v, and $-e$ are the electron's mass, velocity, and electric charge, $+Ze$ is the charge on the nucleus, and r is the "orbital radius" of the electron[1]. The potential energy, of course, is just the attractive Coulomb potential between the electron and the nucleus. We can relate the velocity v to the other variables by using $F = ma$, where F is the Coulomb force and a is the centripetal acceleration. That is

$$\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r^2} = m\frac{v^2}{r} \tag{2}$$

which implies that

$$v^2 = \frac{1}{m}\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} \tag{3}$$

If we introduce this result into Eq. (1) we obtain

$$E = \frac{1}{2}\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} - \frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} = -\frac{1}{2}\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} = -\frac{1}{2}|V|. \tag{4}$$

At this point we can impose the Bohr quantization condition

$$r = n\frac{\hbar}{mv} \tag{5}$$

to eliminate v in Eq. (3). Here n is the principal quantum number. We obtain

$$\frac{n^2\hbar^2}{m^2r^2} = \frac{1}{m}\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{r} \tag{6}$$

or

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[1]We assume that the nucleus is infinitely heavy.

$$\frac{1}{r} = \frac{m}{n^2 \mathrm{h}^2} \frac{1}{4\pi\varepsilon_0} Ze^2. \tag{7}$$

Inserting this result in Eq. (4) we find for the total energy

$$E_n = -\left[\frac{mZ^2 e^4}{2(4\pi\varepsilon_0 \mathrm{h}^2)}\right]\frac{1}{n^2}. \tag{8}$$

For the hydrogen atom where $Z = 1$, the expression in brackets in Eq. (8) equals 13.6 eV. This is the energy required to take an electron in the ground state (n = 1) and separate it from the nucleus completely ($E = 0$). We refer to it as the binding energy of the hydrogen atom. It is customary to introduce the Rydberg constant (wave number) through

$$E_n = -hcR_\infty \frac{1}{n^2} \tag{9}$$

where

$$R_\infty = 10973731.534 m^{-1} \tag{10}$$

and thus

$$E_1 = -13.6057 eV. \tag{11}$$

Furthermore, from Eq. (1.11) we can write for the radius of the orbits in hydrogen

$$r_n = n^2 a_\infty \tag{12}$$

with

$$a_\infty = \frac{\mathrm{h}^2}{m} \frac{4\pi\varepsilon_0}{e^2} = 0.5291772 \times 10^{-10} m \tag{13}$$
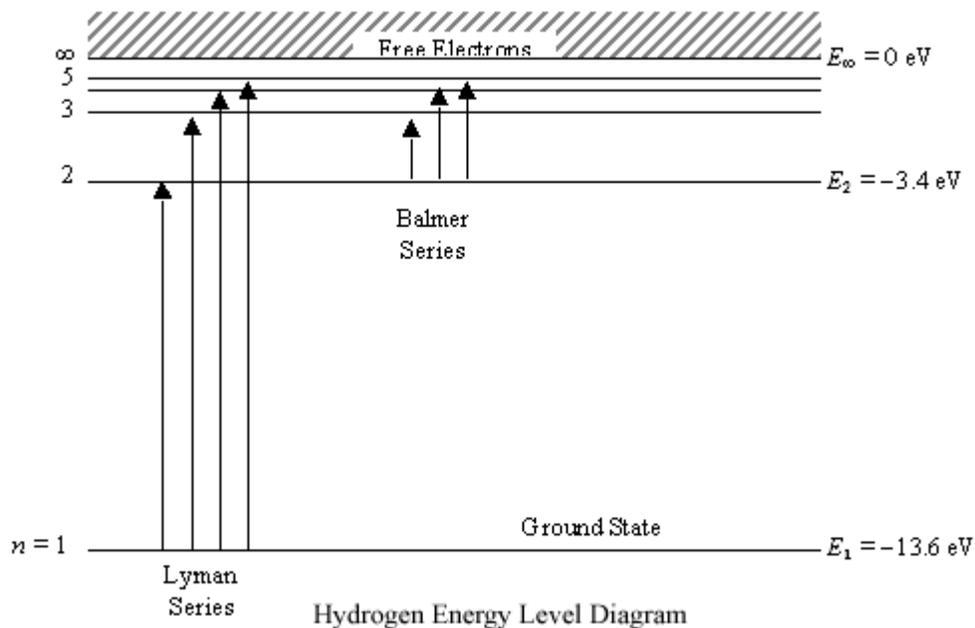
called the Bohr radius.

Figure 1. Energy-level diagram of the hydrogen atom according to the simple Bohr theory.

The energy levels of the hydrogen atom that we derived can be represented by Fig. 1. However, the lines observed in the spectrum correspond to transitions between these levels; this is shown in Fig. 2, where arrows have been drawn for all possible transitions. The energy of a line is given by

$$\Delta E_{if} = hcR_\infty \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \qquad (14)$$

where the subscripts i and f stand for initial and final state, respectively.

Since the frequency of the radiation is connected to the energy of each quantum through

$$E = h\nu$$

one finds that

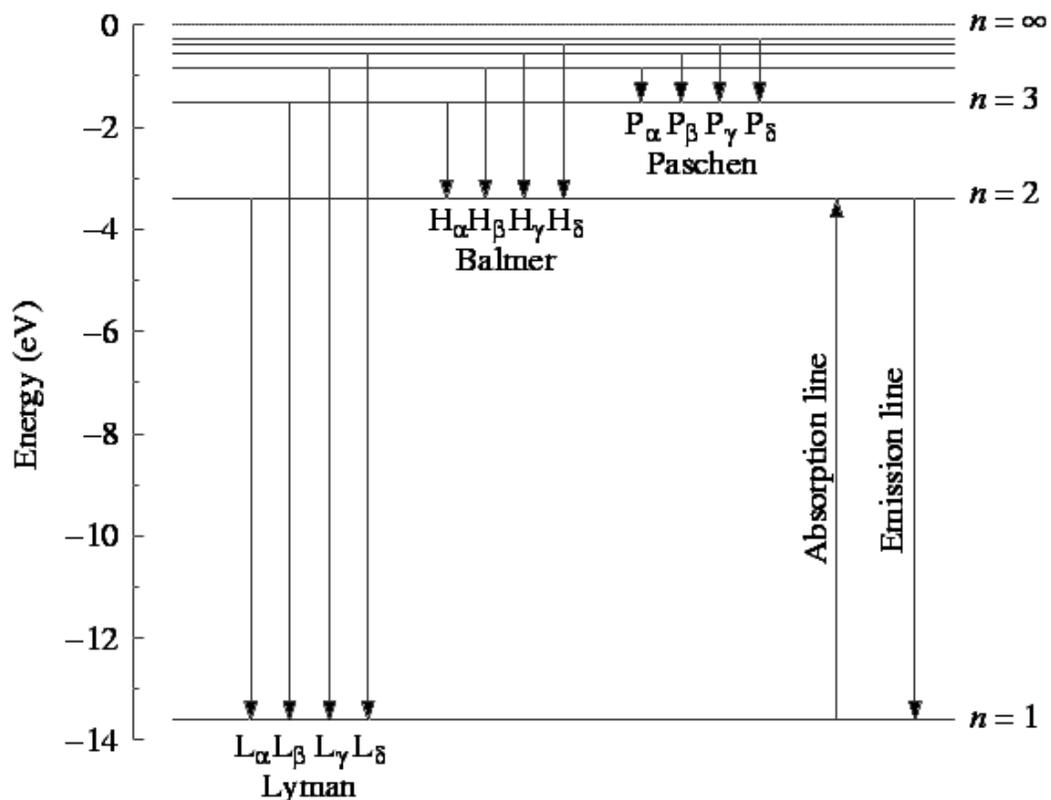$$\frac{1}{\lambda} = \frac{\nu}{c} = \frac{E}{hc}$$

Figure 2. Transitions between the energy levels of a hydrogen atom. The lines L_α, L_β, etc., belong to the Lyman series, B_α, B_β, etc., to the Balmer series, and P_α, P_β, etc., to the Paschen series, and so forth.

and

$$\frac{1}{\lambda_{if}} = R_\infty \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \tag{15}$$

Indeed, the simple expression of Eq. (15) is verified by experiment to a high degree of accuracy.

From Eq. (14) (or from Fig. 1) we note that the spectral lines of hydrogen will form groups depending on the final state of the transition, and that within these groups many common regularities will exist; for example, in the notation of Fig. 1

$$v(L_\beta) - v(L_\alpha) = v(B_\alpha). \tag{16}$$

If $n_f = 1$, then

$$\lambda_{i1} = 91.1 \left(\frac{n_i^2}{n_i^2 - 1} \right) nm \qquad n_i \geq 2 \tag{17}$$

and all lines fall in the far ultraviolet; they form the (so-called) Lyman series. Correspondingly if $n_f = 2$, then

$$\lambda_{i2} = 364.4 \left(\frac{n_i^2}{n_i^2 - 4} \right) nm \qquad n_i \geq 3 \tag{18}$$

and all lines fall in the visible part of the spectrum, forming the Balmer series. For $n_f = 3$ the series is named after Paschen and falls in the infrared.

More advanced:

A quantum description of the hydrogen atom starts with the form of the potential and kinetic energies of the bound electron and proton:

$$P.E. = V = -\frac{e^2}{4\pi\varepsilon_0 r}$$

$$K.E. = T = \frac{p_e^2}{2m_e} + \frac{p_n^2}{2m_n}$$

In terms of reduced coordinates, ignoring center-of-mass motion, the kinetic energy can be expressed as

$$T = \frac{p^2}{2m_r} = \frac{p_r^2}{2m_r} + \frac{L^2}{2m_r r^2}$$

Where

$$\vec{p} = m_r \dot{\vec{r}}$$

$$m_r = \frac{m_e m_n}{m_{e+m_n}} \quad \text{(the reduced mass)}$$

$$p_r = m_r \dot{r}$$

$$\vec{L} = \vec{r} x \vec{p}$$

So the Hamiltonian is

$$H = T + V = \frac{p_r^2}{2m_r} + \frac{L^2}{2m_r r^2} - \frac{e^2}{4\pi\varepsilon_0 r}$$

The Schrödinger equation for the hydrogen atom is:

$$H\psi = E\psi$$

Or:

$$\frac{1}{2m_r}\left(p_r^2 + \frac{L^2}{r^2}\right)\psi - \frac{e^2}{4\pi\varepsilon_0 r}\psi = E\psi$$

This equation can be simplified somewhat by examining the symmetries of this problem. Because the Coulomb potential is a central field (a function of r only), angular momentum is a constant of the motion and the hydrogen wave function should be an eigenfunction of both L^2 and L_z. In spherical coordinates, the eigenfunctions of L^2 and L_z alone are the spherical harmonics: $Y_{lm}(\theta,\varphi) = const. \times e^{im\varphi} P_l^m(\theta)$, where $P_l^m(\theta)$ s an associated Legendre function and the constant is determined by normalization. The eigenvalue of the operator L^2 acting on $Y_{lm}(\theta,\varphi)$ is $\mathrm{h}^2 l(l+1)$.

Because p_r operates on r alone, if we now write the hydrogen wave function as a product of a radial function and a spherical harmonic,

$$\psi(r,\theta,\phi) = R(r)Y_{lm}(\theta,\phi),$$

the Schrödinger equation reduces to a differential equation in r alone:

$$\frac{1}{2m_r}\left(p_r^2 + \frac{\mathrm{h}^2 l(l+1)}{r^2}\right)R(r) - \frac{e^2}{4\pi\varepsilon_0 r}R(r) = ER(r)$$

or, writing out p_r^2 explicitly,

$$\frac{1}{2m_r}\left(\frac{1}{r^2}\frac{d}{dr}\left[r^2\frac{dR}{dr}\right]\right) + \frac{\mathrm{h}^2 l(l+1)}{2m_r r^2}R - \frac{e^2}{4\pi\varepsilon_0 r}R = ER$$

Bound states correspond to values of $E < 0$. Solutions to this radial equation exist only for discrete values of E given by (see, for example, Saxon, Q.M., sec. 9.5):

$$E_n = -\frac{e^4 m_r}{8\varepsilon_0^2 \mathrm{h}^2 n^2} \quad for \quad n > l \qquad (19)$$

where n, the radial quantum number, is an integer greater than l. The radial function R is equal to

$$R(r) = e^{-\frac{r}{na_0}}\left(\frac{2r}{na_0}\right)^l L\frac{2l+1}{n+l}\left(\tfrac{2r}{na_0}\right) \times const.$$

where

$$a_0 = \frac{4\pi\varepsilon_0 \mathrm{h}^2}{m_r e^2} = 0.529\,\overset{\mathrm{o}}{\mathrm{A}}$$

is the <u>Bohr radius</u> of hydrogen, and $L_{n+l}^{2l+1}(x)$ is an associated Laguerre polynomial.

A photon emitted by an atom must have an energy $h\nu$ equal to the <u>difference</u> between two energy levels. Because the frequencies ν of photons emitted by a hydrogen atom in an excited state are equal to c/λ, the energies E_n of Eq. (19) provide a theoretical explanation of Balmer's empirical formula:

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad\qquad (20)$$

The constant R is seen to be $1/hc$ times the coefficient of $1/n^2$- in Eq. (19), or

$$R = \frac{e^4 m_r}{8\varepsilon_0^2 h^3 c} = 1.096776 \times 10^5 \; cm^{-1}$$

and is called the Rydberg constant for hydrogen. (The constant R $_\infty$ shown in tables of universal physical constants assumes the nuclear mass m_n is infinite.) An energy level diagram of the hydrogen atom is shown in Fig. 1 with transitions corresponding to the Balmer, Lyman (2^2 replaced by 1^2 in Eq. (20)), and Paschen (2^2 replaced by 3^2) series.

Further refinements to the quantum description of hydrogen include the hyperfine coupling between the nuclear and electron spins, and relativistic effects (the Lamb shift). When these corrections are added to the treatment above, the energy levels of hydrogen can be predicted with an accuracy exceeding one part in 10^8.

Experiment on the Hydrogen + Deuterium Spectrum

A. GENERAL

Measurements of the frequency of the radiation emitted by an excited hydrogen atom are based on either interference, as when a plane grating is used, or variation with wavelength of the refractive index of certain media, as when prism spectrometers are used. Prism spectrometers are obviously limited to wavelength regions for which they are able to transmit the radiation; for example, in the infrared, special fluoride or sodium chloride prisms and lenses are used; in the ultraviolet, the optical elements are made of quartz. Also, the sensitivity of the detectors varies with wavelength, so that different types are used in each case (thermopile, photographic emulsion, phototube, etc.).

In this laboratory a high resolution Czerny Turner monochromator is used. You will need to understand how a diffraction grating works and how a spectrograph works, before you undertake this experiment. This instrument is a variant of the ordinary reflection grating spectrometer. READ AND EXPLORE: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/gratcal.html   Also read the "related material" on the 122 web page for this experiment. Then read Parkinson's article at the end of this lab manual.   The Czerny Turner monochromator's prime virtue is that its combined mechanical and optical arrangement yields a nearly linear relationship between the mechanical translation of the adjustment screw (measured on the 4 digit counter) and the wavelength transmitted by the instrument. Hence, if one experimentally establishes this relationship using known wavelengths, it is possible to determine unknown wavelengths with reasonably high accuracy. The graph which displays the relationship between micrometer readings and wavelength is known as a *dispersion curve*. In order to provide visual identification of the known wavelengths which are used to calibrate this instrument, a high intensity mercury arc light source is provided with the equipment. The intensity of this source is sufficiently high that one is able to observe the color of light reaching the exit slit. In this manner it is possible to obtain a coarse determination of each point necessary to determine the dispersion curve before obtaining the exact point electronically. The following tabulation of known prominent **mercury lines** is given to calibrate the instrument.

Yellow (doublet)	5791×10^{-10}m.	Blue	4358×10^{-10}
Yellow	5770×10^{-10}m.	Violet	4078×10^{-10}m
Green	5461×10^{-10}m.	Violet	4047×10^{-10}m
Blue-Green (weak)	4916×10^{-10}m.	Ultraviolet	3663×10^{-10}m
		Ultraviolet	3650×10^{-10}m

Once a dispersion curve is prepared, it is possible to scan manually and motor-driven through the visible region of the hydrogen spectrum and determine the wavelength of those lines comprising the Balmer series. Note: The wavelengths listed in most tables are given for dry air at a pressure of 760

mm Hg. However, any theoretical calculation such as Eq. (A) predicts the vacuum wavelengths. The refractive index of air at STP is n_{air} = 1.00029.

B. Procedure

For convenience, you need to establish the relation between the "wavelength" displayed on the spectrograph counter mechanical readout and the actual wavelength. Prepare a least-squares dispersion curve for the Czerny-Turner monochromator using known mercury wavelengths. Once this is known, the measurements can be made on the first four or five transitions of the Balmer series, which lie in the visible region. Test Eq. (A) and obtain the Rydberg constant. Note that

$$\frac{1}{\lambda} = R_H \left(\frac{1}{4} - \frac{1}{n^2} \right)$$

so that from least squares,

$$R_H = \frac{\sum \rho_i^2}{\sum \lambda_i \rho_i}$$

where

$$\rho_i = \frac{4n_i^2}{n_i^2 - 4}$$

Obtain both R_H and R_D, the Rydberg constants for hydrogen and deuterium. From the difference between, R_H and R_D which is most accurately obtained from a single determination of the fine-structure splitting between the red Balmer α lines for the two isotopes, obtain the mass ratio of the isotopes. This will require using the narrow 15μ slits. (Please do not attempt to adjust the slit jaws.) For observing this doublet in the early thirties, Harold Urey received the Nobel prize [see the Related Links for the fascinating story].

Warning: The discharge tubes require the use of high voltage. Necessarily, caution must be observed to prevent physical contact with the electrical connections. In addition, the mercury source emits light in the near ultraviolet, which is harmful to the human eye. Consequently, avoid looking directly at the source.

Warning: The slit assemblies have a preferred orientation! When you set up the monochromator (spectrograph), be sure that both of the slits are the same size and that they are oriented with the slit jaws pointed out from the monochromator – otherwise they slit assemblies will not fully nest in their slots.

A recorded trace of the Hydrogen spectrum using a motor driven Czerny-Turner monochromator. Principal lines of the Balmer Series are indicated.
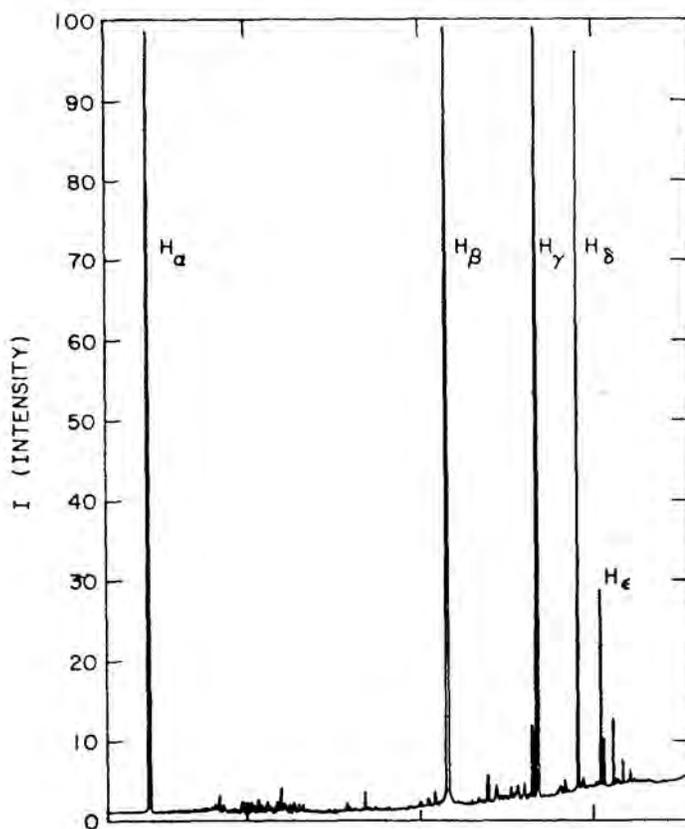
GENERAL GUIDE

Equipment for the experiment is shown below
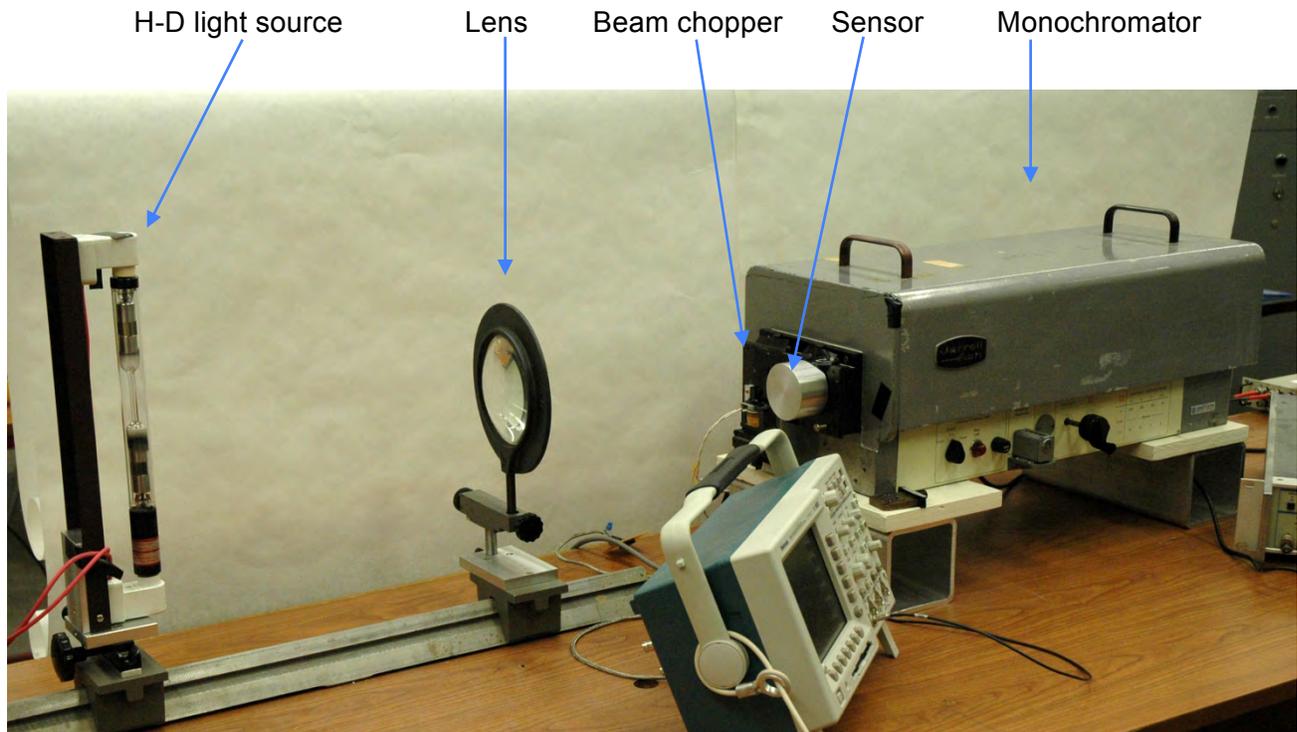
In the upper left is Hydrogen light source. Light is focused by the lens into the inlet slit on the left end of the monochromator and passes back through the exit slit into the aluminum box housing the photodiode light sensor. The sensor output is amplified and sent to the lock-in amplifier, off the image to the right.

The Mercury light source is a self contained unit. This source is used as a standard to obtain data for the creation of a dispersion curve to correct for wavelength errors in the monochromator readings. Caution; the mercury source emits light in the near ultraviolet, which is harmful to the human eye. Consequently, avoid looking directly at the source.

The Hydrogen-Deuterium light source is used with an external high voltage (5000 VAC) power supply. All electrical contact points are insulated, but care should be exercised in its use, and the power supply should always be turned off before handling the source lamp. This source will be used for taking the actual experimental data. **Be sure to turn on a fan aimed at the lamp.** Otherwise the tube will overheat and the line emission intensity will drop.
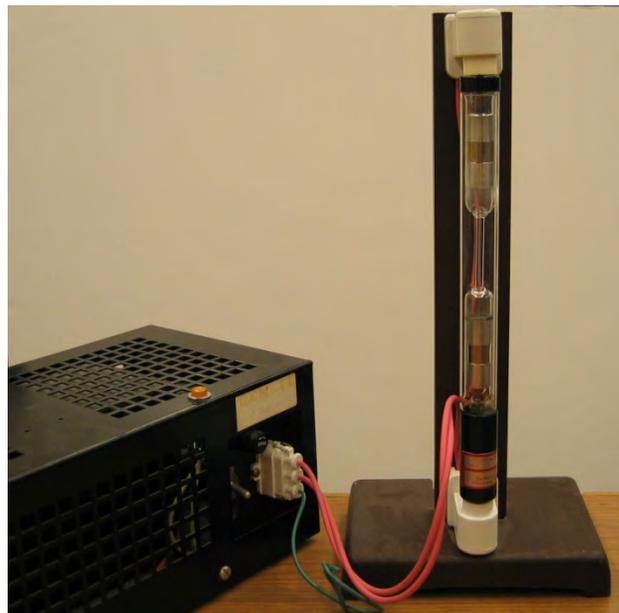
The experiment uses a Czerny-Turner grating monochromator made by Jerrell Ash.


Scan motor control   Wavelength readout   Speed ranges and manual scan

The optical path: light from the source, focused by a lens at A entering through the inlet slit at B and reflecting off of mirror C forming the parallel beam to the grating D then on to mirror E where only the selected wavelength light goes through the exit slit F and reaches the light sensor at G. Be careful when setting up the external optics A that you match the required beam divergence (B-C).
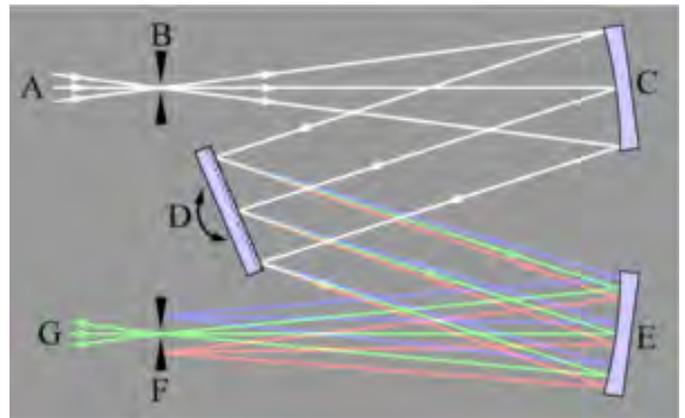

After exiting the lens at A, light passes by the chopper (which is alternately on and off the front of the slit), through the opening in the slit housing and through the slit. After passing through the optics, and diffracting off the grating, the light of a particular wavelength comes to a focus at the exit slit and then exits into the sensor housing where it is photo-converted into electrons, amplified, and this voltage is sent to the lock-in amp (see below.)
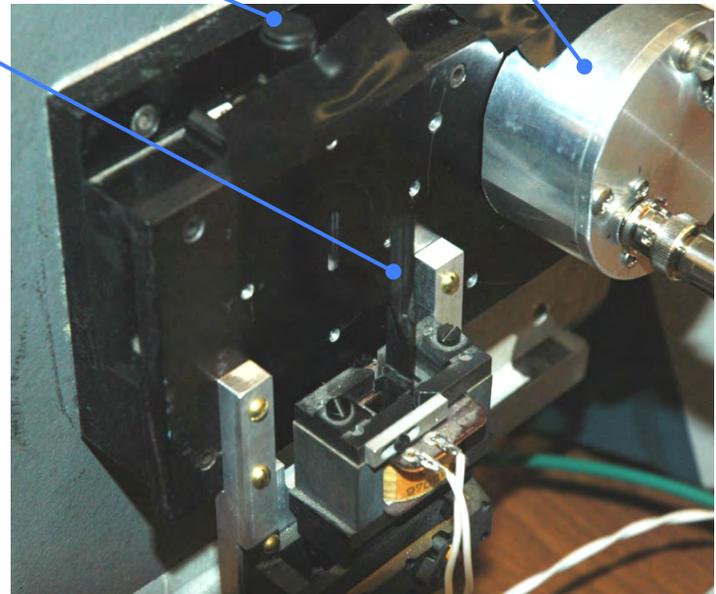
The chopper in the inlet slit path is used to chop the light, on and off, moving the photodiode output "signal" from nearly zero frequency up to the chopper frequency where the amplifier is less noisy -- allowing more sensitive readings. We recently replaced this with a rotating chopper wheel. The Lock-in Amplifier takes the output of the sensor, bandpass filters it passing AC signals near the beam chopping frequency (~20 Hz), multiplies that signal times the reference sine wave from the chopper, low-pass filters the product (averaging for selectable time constants) and then displays it on the front panel meter. See discussion and photos below. ***Show in your lab book mathematically how this low pass product of signals increases the signal-to-noise ratio.***
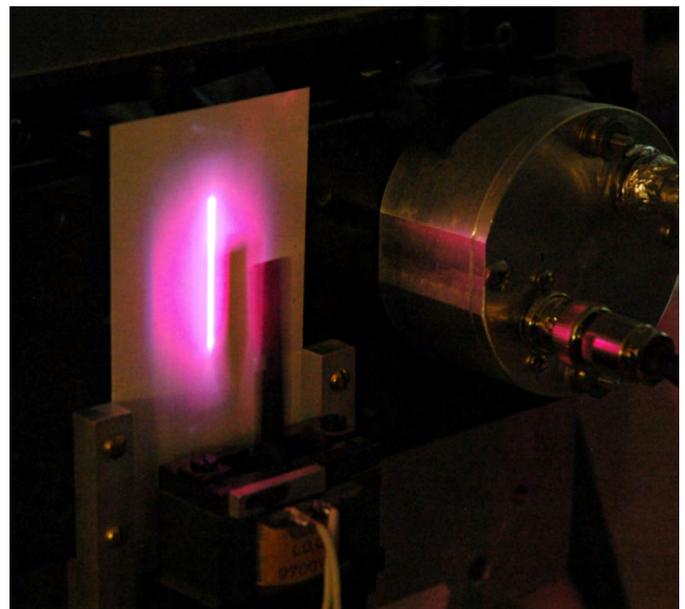
USEFUL HINTS

Determining the Dispersion curve

The mechanical digital readout on the monochromator is fairly accurate, but the reading may be off by a few Angstroms, and the error will vary across the full range, due to a number of factors. This is a form of *systematic error.* Before taking data you must calibrate this offset error vs wavelength. A source with emission lines at known wavelengths can be scanned and the data used to calibrate the monochromator readout. The differences between the known line wavelengths and the measured wavelengths on the monochomator readout can be used to generate what is called a dispersion curve which will show how error in the device readings are dispersed about the ideal linear curve. This curve can be used to correct wavelength data taken on subsequent runs with the system. Note this is purely for your convenience in finding the HD lines, since your measurement will be the *DIFFERENCE* in wavelength between the H and D lines! For our standard, we will use a mercury source. Below are listed the 9 prominent mercury lines that you should find during a scan.

Yellow (doublet)	5791×10^{-10}m.	Blue	4358×10^{-10}
Yellow	5770×10^{-10}m.	Violet	4078×10^{-10}m
Green	5461×10^{-10}m.	Violet	4047×10^{-10}m
Blue-Green (weak)	4916×10^{-10}m.	Ultraviolet	3663×10^{-10}m
		Ultraviolet	3650×10^{-10}m

A simple, projected grating, line spectrum from the Hg source shows the two yellow lines, the green and the blue line along with a faint violet 4045×10^{-10}m line. The other lines are too dim to be seen in the photo, but can be found by the monochromator. The lines will all be strong enough to be detected by the photocell. The Hg spectrum with wavelengths indicated in Angstroms is shown at bottom of page. You are calibrating your HD experiment, so you must use the same 15µm slits!

Because of mechanical back-lash in the gears, scan only in the direction of increasing wavelength. When tuning by hand you can arrange this by first tuning until you find the line, then back tracking to shorter wavelengths and then tuning slowly and carefully to longer wavelength to the peak.
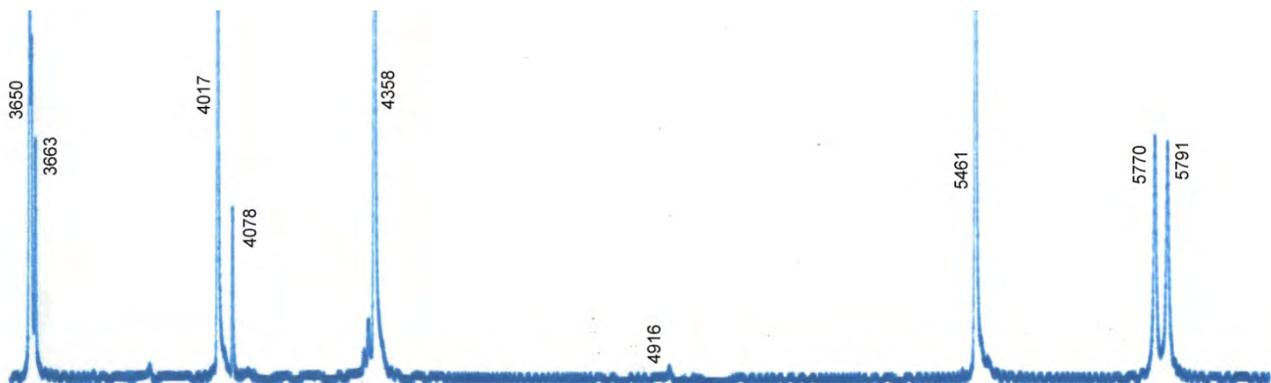
There are both 15μm and 130μm slits with the monochromator. You must first align the optics to maximize the light through the spectrograph. To get maximum light initially, we suggest you place the 130 μm slits into the slit housing (*slits oriented outwards*!) and align the source and lens to focus on the inlet slit and project light onto the first mirror. Be sure there is a coarse slit covering the exit hole in the *source lamp enclosure*. Turn on the Hg source lamp and wait a minute for it to warm up.

In order to see where the light lands inside, place a piece of white paper (a business card works well) in front of the slit housing, behind the chopper reed, and move the lens and light source to focus the vertical light beam on the paper's surface. Remove the paper and check to see that light is entering the slit.

Once you have achieved optimal alignment using the wide slit you can probably go ahead and set up for the high spectral resolution required for the HD scan. The increased resolution necessary will require using the narrow 15μ slits rather than the 130μ slits. **Explain why?** The 130μ slits can be lifted out of the slit housing and the 15μ slits dropped in place. Beware that the slit holders have a special orientation! (<u>Do not attempt to adjust the slit jaws</u>.) If optical alignment is not good enough for the lock-in amplifier to produce a useful signal of about <u>500 millivolts</u>, you will have to make a more accurate alignment of the light path. This is always the case.

To make a better alignment, lift the cover from the monochromator and place a white card in front of the first mirror. Replace the cover and prop up the slit end with the "special tool" shown in the photo. Now turn off the room lights (after checking with others in the room) and adjust the lens and source for the maximum amount of light on the card. Remove the card (past experience has proven that the system will not operate correctly if the card is left in place ;) and replace the monochromator cover.

At this point you should connect the scope to the same signal that is going into the lock-in amplifier so that you can see the waveform. Note that it is not a perfect sine or triangle wave at the chopper frequency of ~20 Hz, but instead has an additional component at 120 Hz. Can you think of why? Hint: turn off the chopper at see what happens. Is it coming from the Hg lamp source? **Explain what's going on.**

Peak up the optical alignment by maximizing the signal amplitude on the scope as you adjust the xyz position of the source and optics.
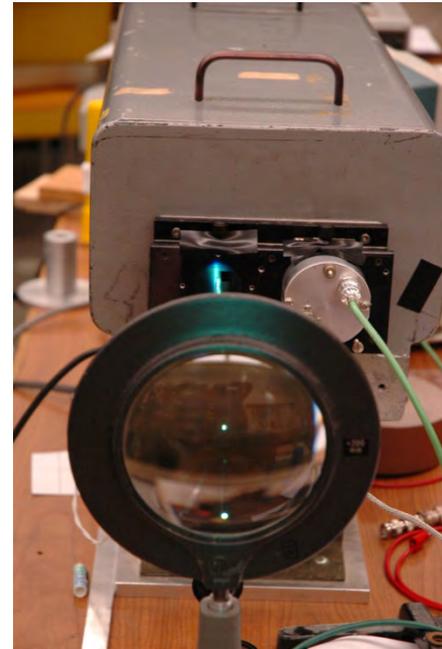
The monochromator control panel is shown below. Scanning can be done by either motor driven or manual (hand operated) methods. To the far left of the panel is the motor control. Actual motor control consists of Stop, Longer wavelength, and shorter wavelength scan directions. If the drive mechanism reaches its operational limits, it will stop and the scan limit lamp will light. The wavelength meter is a simple mechanical meter that displays Angstroms. The right side of the panel has the speed select and manual scan control. Speed ranges and manual control are selected by detented positions of the push/pull control shafts as called out on the chart.

Scanning arm movement is done by way of a lead screw and nut driven through a spur gear reducer mechanism. The push/pull shafts on the panel engage the appropriate gears for the selected speed. The picture here shows the somewhat fragile mechanism with a number of bronze gears. These are straight cut spur gears with no special tooth design to allow meshing them easily. Changing the speeds can be difficult at times. Do not use force; seek help if gear selection causes problems. Do not change speeds with the motor running. With the Hi-Lo shift in the middle position, the scan speed knob is used for manual scanning. The lead screw and nut will have some dead space when the rotation of the lead screw is reversed. This is called "back lash." There is a back lash compensation mechanism included, but it is not perfect. The wavelength readout for a given line will be slightly different when scanning towards *longer* wavelengths that it will be scanning in the *shorter* wavelength direction. The readout could vary by as much as 2 or 3 Angstroms due to backlash. It is best to take all data while scanning in the *same direction*.
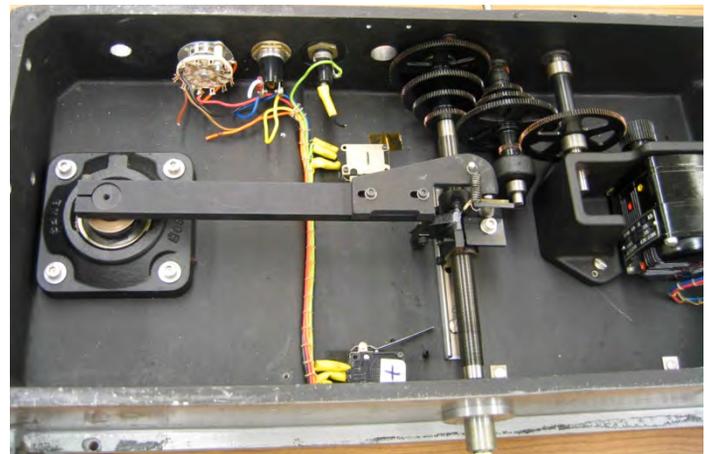

The easiest way to do a scan through a line or doublet is to run the monochromator to the short wavelength end of a narrow wavelength band spanning the line or doublet, beyond the first spectral line of interest and then scan back in the opposite (increasing wavelength) direction. You can experiment with the various power and manual scan speeds to find out what works best for you.

However, for your calibration using the Hg tube, we recommend manual (in one direction, increasing wavelength) scans in the vicinity of the known Hg emission lines. Then at the peak of the emission line read the wavelength reading on the mechanical counter to fractional angstroms.

Since you are chopping the light beam at ~20 Hz, the actual signal out of the monochromator (see it on the oscilloscope!) is shown on the meter on the front of the SRS SR530 lock-in amplifier.

With no light into the monochromator, the lock-in amplifier should be set to read zero. As lines are found while scanning, the amplifier gain should be set to avoid overload. The maximum reading on the amplifier meter coincides with the peak of the line being scanned. Finally, you will have to experiment with the phase offset of each of the lock-ins, to maximize the signal from any source.
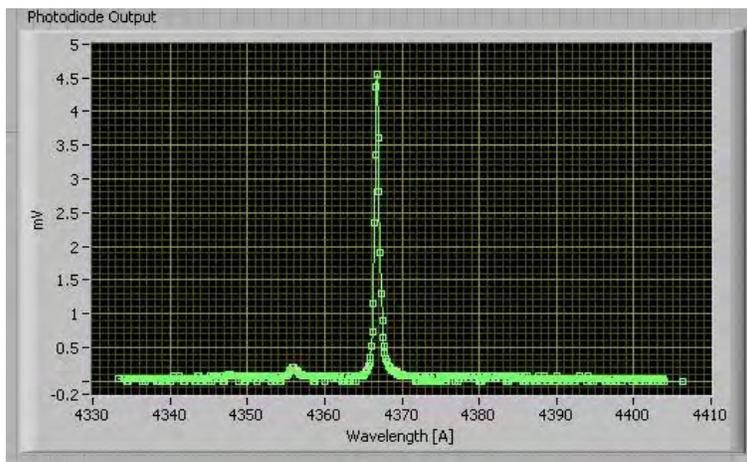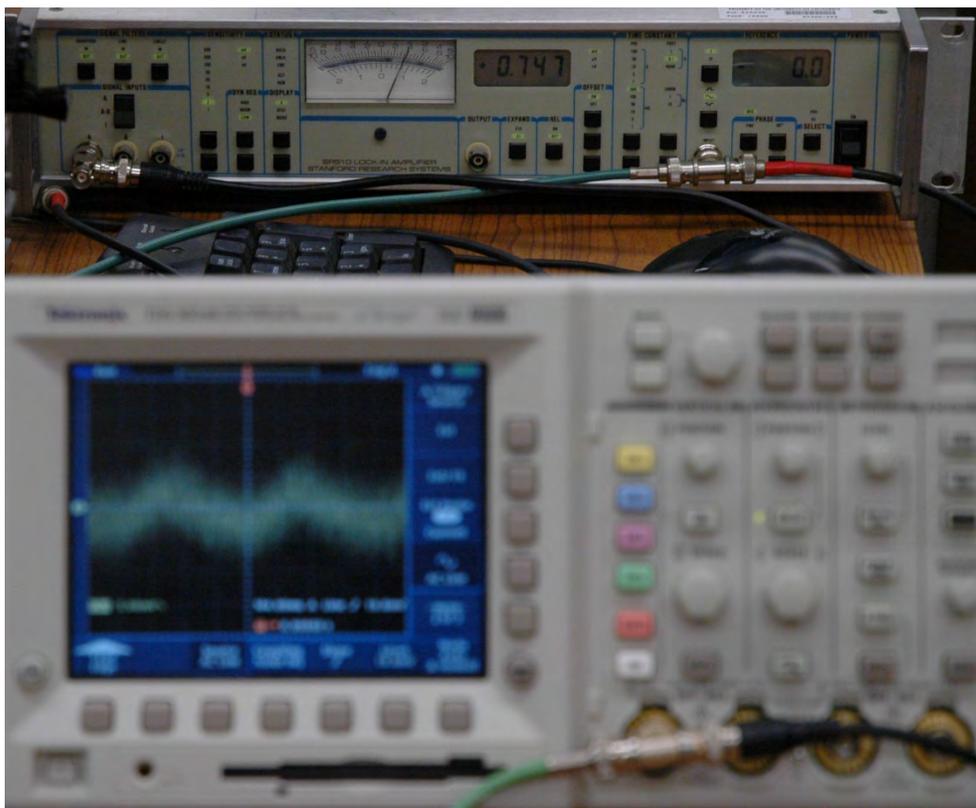
Using the 15µ slits, manually scan *towards increasing wavelength* along the monochrometer's range noting the wavelengths where the line peaks occur. Take this data and match it to the known line wavelengths to create the dispersion curve for the monochromator. Our test run for both scan directions provided the data below with dispersion values and chart – note the effect of back-lash in the gears. Your data may look different due to periodic maintenance of the monochromator.

Known	Experimental values		Dispersion values	
	Going Up	Going Down	Going Up	Going Down
3650	3637	3640	13	10
3663	3650	3652	13	11
4047	4032	4034	15	13
4078	4064	4066	14	12
4358	4344	4347	14	11
4916	4907	4909	9	7
5461	5461	5463	0	-2
5770	5776	5778	-6	-8
5791	5798	5800	-7	-9

Monochromator Dispersion Curve
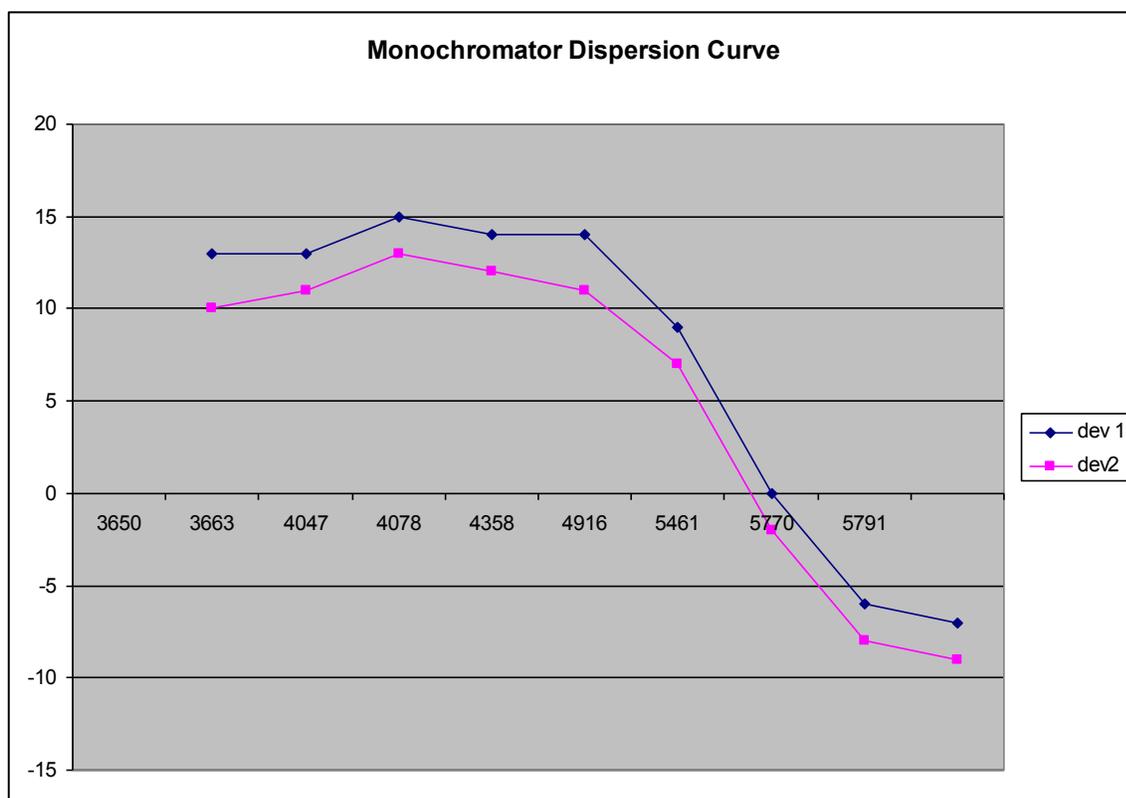
Determining the Balmer Series lines

Once a dispersion curve is prepared, it is possible to scan manually and motor-driven through the visible region of the hydrogen and deuterium spectrum and determine the wavelength of those lines comprising the Balmer series. Note: The wavelengths listed in most tables are given for dry air at a pressure of 760 mm Hg. However, any theoretical calculation such as Eq. (3) predicts the vacuum wavelengths. The refractive index of air at STP is n_{air} = 1.00029.

Scanning is done in the same way that was used to determine the dispersion curve. The increased resolution necessary will require using the narrow 15μ slits rather than the 130μ slits. The 130μ slits can be lifted out of the slit housing and the 15μ slits dropped in place. (Please do not attempt to adjust the slit jaws.) For observing this doublet in the mid-thirties, Harold Urey received the Nobel prize [see the links on the 122 web page].

Warning: The hydrogen-deuterium discharge tube requires the use of high voltage. Necessarily, caution must be observed to prevent physical contact with the electrical connections.

Replace the Hg source with the H-D source. _Turn on a fan pointed at the source lamp._ Turn on the source and align the optics as was done before. Keep accurate records of your calibration work in your lab book: If you have been very careful to use the optical track, taking notes where the lens and source should be in all dimensions, then you will not have to start at "square zero." You should be able to get over 400 microvolts on the 6561 Angstrom Hydrogen line with 15μ slits.
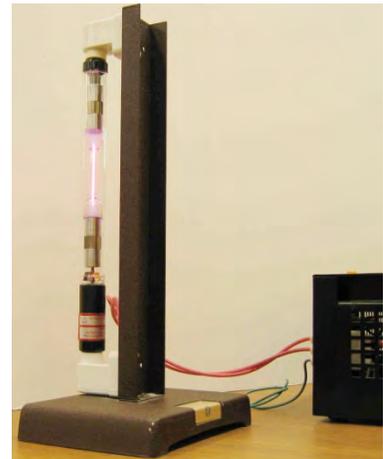
The combination of the much lower intensity H-D source and the smaller 15μ slits allows much less light to reach the exit slit and the photodiode sensor. Use the dispersion curve to correct the wavelength values. The source contains both Hydrogen and Deuterium, so the Balmer Series lines for both will be found. H and D Balmer lines are close together, but the monochromator can resolve them with the 15μ slits. **Read about resolving power in Melissinos and the useful posting on grating physics on the 122 web page for this experiment and the link on p10 of this Guide.**

The spectral scan below shows two of the Balmer Series lines for Hydrogen and Deuterium.
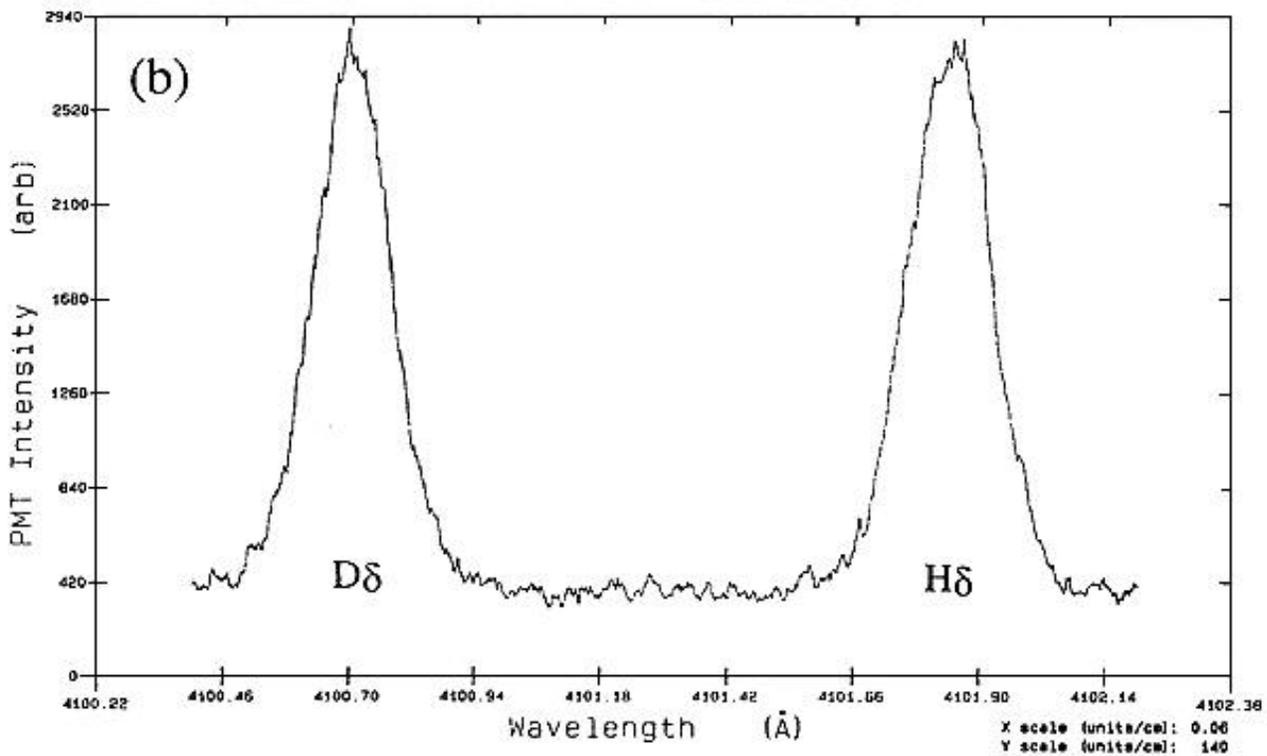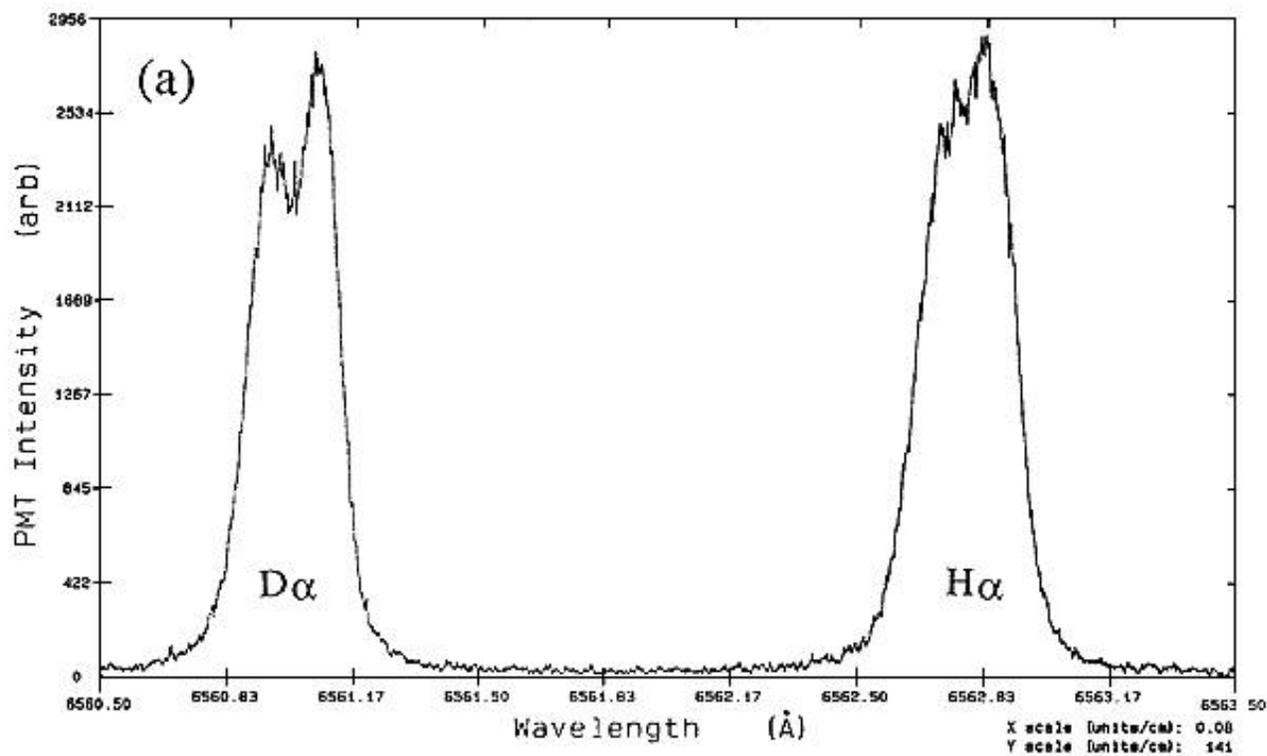
Appendix

References:

*Richtmyer, Kennard, and Cooper, "Introduction to Modern Physics", Chapters 9 and 14 (general)

*Herzberg, "Atomic Spectra and Atomis structure", pp. 10-26 (general)

*Jenkins and White, "Fundamentals of Optics", pp. 320-344 (grating theory)

*Kayser, "Tabelle der Schwingungszahlen", (to convert λ_{air} into λ_{vac})

*Stranathan, "The Particles of Modern Physics", pp. 212-228 (general and wavelengths)

*Any manual in optics (spectrometer adjustments)

*White, "Introduction to Atomic Spectra", pp. 132-9, 418-436

*Williams, Phys. Rev. 54, 558, 1938 (Experimental results)

*Lamb and Rutherford, "Fine Structure of the Hydrogen Atom", Part I, Phys. Rev. 79, 549, 1950 (Verification of the Lamb shift --- a classic paper)

Textbooks:

Preston & Dietz, "The Art of Experimental Physics" (Wiley, 1991) pp210-218

Melissinos & Napolitano, "Experiments in Modern Physics"

GLASS INSTRUMENTS INC.

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OPERATING INSTRUCTIONS

GAS DISCHARGE TUBES

GLASS INSTRUMENTS PART NUMBER: 7000 SERIES

1.   INTRODUCTION

Gas Discharge Tubes concentrate a gaseous discharge in a narrow capillary
tube to radiate a brilliant line source of light. Three types of tubes
are available: Balmer, High Intensity, and Quartz. Filling gases include
Argon, Neon, Krypton, Xenon, Mercury, Helium, water vapor (to produce atomic
hydrogen spectrum), and heavy-water vapor (to produce atomic hydrogen and
deuterium spectra). These last two gas-filled tubes are called Balmer Tubes
because they emit the Balmer lines of hydrogen at high intensities with
low background and because they have long operating lifetimes. The table
below identifies individual tubes.

TABLE 1

TYPE OF TUBE	TYPE OF GAS	PART NO.
Balmer	Hyd.-Deuterium	7005
	Hydrogen	7010
High Intensity	Argon	7015
	Neon	7020
	Krypton	7025
	Xenon	7030
Quartz	Argon	7035
	Neon	7040
	Krypton	7045
	Xenon	7050
	Mercury	7055
	Helium	7060

Any of the Gas Discharge Tubes listed in Table 1 can be energized by the
electrical output from a standard luminous-sign transformer producing 5000
volts at 0.06 amperes.

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2. SPECIFICATIONS

Nominal Operating Requirements: Voltage   5000 Volts
                                  Current   0.06 Amperes AC

Tube Dimensions: Outer Diameter   1 inch (25.4 mm)
                   Length   12 inches (305 mm)

Capillary Dimensions: Diameter   0.04 inches (1 mm)
                        Length   1.97 inches (50 mm)

3. DESCRIPTION

The Balmer and high intensity discharge tubes consist of glass tubing
envelopes which enclose a Vycor electrode shield and a capillary tube.
Each tube is filled with a highly purified gas. Electrical connectors are
standard, single contact caps, located on either end of the tube.

The quartz tubes have no outside glass envelope so that in operation,
they radiate at high intensity throughout the entire visible and ultra-
violet spectrum of the gas. The use of quartz extends the temperature range
over which they may be operated without damage. The light output of the
various tubes differs because of the relative intensities of the various
spectral lines. Quartz tubes may be ordered with any gas listed in Table 1,
except water and heavy-water vapors.

The Pyrex jacketed tubes produce the entire visible spectrum of the filling
gas. They are available filled with any gas listed in Table 1 except
mercury vapor.

The Balmer Tubes produce a simple, easily analyzed spectrum. The light is
emitted from single atoms of hydrogen which are formed in the dissociation
of water by discharge, rather than from molecular ions or more complicated
atoms. Any molecular hydrogen that may form is removed from the discharge
by the special trapping cartridge in the electrode. This ensures high
intensity lines with low background emission for longer tube life.

In the case of the heavy-water tube, both hydrogen and deuterium atoms
contribute to the light being emitted at slightly different wave lengths.
This difference, the so-called "isotopic shift", can be detected with an
Interferometer.

4. OPERATION

The tubes can be operated in any position. Balmer tubes operate best in a
vertical position with the black-metal, cylindrical, end-cap down. Forced air
cooling is not required unless the tubes are operated in an enclosure.
Overheating of the tubes is indicated by the appearance of sodium lines in
the spectrum.

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If desired, the tubes may be operated at a higher current than 0.06 amperes, but in this case it may be necessary to limit the period of operation to prevent overheating. Operating at higher currents may be necessary for Krypton and Xenon tubes for higher intensity because their voltage drops are lower than the other gases.

The Balmer tubes operate continuously without cooling or other precautions as long as they are mounted vertically in the open. Always position the tube with the water vapor supply cartridge, contained in the black cylindrical cap, at the bottom. If these tubes are to be operated in a housing or in some other position, it may be necessary to provide forced air cooling for the water vapor supply cartridge in order to maintain the proper pressure. High pressure and overheating are indicated by a flickering, deep pink, discharge with very little glow on the electrodes. Low pressure and insufficient heating are indicated by a whitish flickering glow which covers much of the electrodes. Increase the current or enclose the tube in a housing to maintain the proper glow.

A buildup of the concentration of molecular hydrogen may sometimes occur, especially after many short operating periods. When this occurs the overall background will increase in the blue and violet range obscuring those lines and suppressing the oxygen lines as well. Should this condition occur, allow the lamp to operate continuously for several hours so that the electrode temperature will remain high enough and for a long enough period of time for all the molecular hydrogen to be reconverted to water vapor.

The mercury vapor tube may, when new, require a short warm-up time to reach the proper operating pressure. Before operating this tube, be sure to dislodge any droplets of mercury that may be stuck in the capillary tube.

Warning: Ultraviolet radiation can be very harmful to the eyes. Do not look at the mercury discharge except through a suitable protective filter.

FIG. 1   WIRING DIAGRAM OF A TYPICAL POWER SUPPLY

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