

II: Experimental Atomic Spectroscopy

I. References

Condon & Shortley, *The Theory of Atomic Spectra*, (London: Cambridge University Press, 1967), pages 112-148.

Griffiths, *Introduction to Quantum Mechanics*, (Prentice-Hall, 1995) pp. 133-144, 239-244.

Eisberg, *Fundamentals of Modern Physics*, (New York: John Wiley & Sons, 1961), pages 110-137, 418-425.

Harrison, Lord and Loofbourow, *Particle Spectroscopy*, (New York: Prentice Hall, 1948) pages 228-233.

White, *Introduction to Atomic Spectra*, (New York: McGraw-Hill, 1934) pages 1-41.

Melissinos, *Experiments in Modern Physics*, (New York: Academic, 1966) pages 43-46.

Jenkins & White, *Fundamentals of Optics*, (New York: McGraw-Hill, 1976) pages 328-350.

II. Preparatory Questions

(must be answered in lab book before experiment is started and signed by instructor or TA)

- A. What direct, qualitative measurements are you going to make in this experiment?
- B. Does measurement of the wavelength of one line determine an energy state?
- C. What is the value of the finite nuclear mass correction factor for a positron and electron circulating about each other?

III. Purpose

The purpose of this lab is to demonstrate the validity of Bohr's theory of the atom from measurements of the line spectra of mercury, hydrogen, deuterium, and sodium. This experiment is also an introduction to spectroscopic apparatus and techniques.

IV. Measurements to be Reported

- A. The Rydberg constant as determined from measurements of the hydrogen spectrum.
- B. The ratio M_D/M_H as determined by measurements of the hydrogen-deuterium isotope shift.

- C. The quantum defects, S, P, and D for the sodium atom, as determined from measurements of the sodium spectrum.

V. Introduction

Spectroscopy is the analysis of radiation into its components by means of dispersion. In optical spectroscopy the wavelength spectrum of light emitted by various sources is obtained from dispersion by a prism or diffraction grating. A remarkable feature of the spectra of the elements is their discontinuity. The light emitted by atoms is concentrated at a finite number of wavelengths. It has been observed that each element has a characteristic spectrum, and measurements of the wavelengths of the spectral lines constitute a great part of the experimental basis for theories of atomic structure.

In this laboratory you will measure line spectra using a scanning monochromator. This gives an absolute reading of the wavelengths of the spectral lines. The spectrum of mercury (a well known spectrum) is first analyzed to familiarize you with the apparatus and assure that the monochromator is indeed accurate. You will then measure the spectrum of hydrogen, the splitting of the hydrogen deuterium lines, and the spectrum of sodium to find the Rydberg constant, the ratio of hydrogen to deuterium mass, and the quantum defects associated with sodium (Na).

VI. Theory

A. The Bohr Theory of the Hydrogen Atom

In 1913 Bohr proposed a model of the hydrogen atom which correctly predicted the observed lines in the spectrum of light emitted by hydrogen. The theory is a simple application of classical mechanics to a point electron and nucleus where the attraction is assumed to be the classical Coulomb force. Two additional assumptions, which were unusual for the time, were that:

The orbital angular momentum of the electron is quantized; it exists only in integral multiples of $h/2\pi$, h being Planck's constant.

The radiation properties of the electron do not follow classical electrodynamics. Instead, radiation is emitted only when the electron undergoes a discontinuous transition to a different, allowed orbit. The frequency of the radiation is equal to the change in energy divided by Planck's constant ($\nu = \Delta E/h$).

A prediction of the Bohr model, derived in most elementary physics texts, is that the allowed energy states of the hydrogen atom are given by

$$E = \frac{-2\pi^2 m e^4}{n^2 h^2} \quad \text{II-1}$$

in which m is the mass of the electron, e the electron's charge, and n is any positive integer. From this and the Einstein relation between the energy and the frequency ($E = h\nu = hc/\lambda$), one obtains an expression for the wavelength λ , of the light emitted in a transition between the i^{th} and j^{th} energy states:

$$\frac{1}{\lambda} = R_{\infty} \left[\frac{1}{i^2} - \frac{1}{j^2} \right] \quad \text{II-2}$$

Here i and j are positive integers for which $j > i$, R_{∞} is the Rydberg constant

$$R_{\infty} = \left[\frac{2\pi^2 m e^4}{c h^3} \right] \quad \text{II-3}$$

and c is the velocity of light. Note that the derivation assumes that the mass of the nucleus is infinite in comparison with the mass of the electron, or the reduced mass is equal to the mass of the electron.

$$\mu = \frac{m_e M_N}{m_e + M_N} \approx m_e \quad \text{II-4}$$

M_N is the nuclear mass and m_e is the electron mass. This is not a particularly good approximation for hydrogen.

One obvious test of the theory is a comparison of the Rydberg constant calculated from Eq. II-3 with that determined from wavelength measurements via Eq. II-2. Another test is to determine whether or not the measured wavelength spectrum has the line distribution predicted by Eq. II-2.

The series of lines obtained from Eq. II-2 for $i = 2$, and $j = 3, 4, \dots, \infty$ is called the Balmer series. Most of these lines lie in the visible light region, so they can be measured with an optical spectrograph. The wavelengths of some of these lines are listed in Appendix I to this Experiment. The transition from $j=3$ to $i=2$ is the α line, $j=4$ to $i=2$ is β etc.

The Bohr model assumes that electrons move in well-defined orbits. It has been observed, however, that the electron does not obey all the laws of classical mechanics. The application of quantum mechanics to atomic problems has shown that the concept of an atomic electron orbit is not really valid. Nonetheless, the Bohr model still correctly predicts the energy levels of hydrogen, and its simple picture of atomic structure is a close approximation to the more complicated quantum mechanical theory.

B. The Effect of Finite Nuclear Mass

We have assumed until now that the nucleus is infinitely massive. The correction for finite nuclear mass is obtained by replacing the electron mass, m , in Eq. II-1 and Eq. II-3 by the “reduced mass”, i.e., μ , Eq. II-4. For hydrogen $M_H = 1836 m_e$. The correction is very small, yet noticeable. The effect can be used, though, to observe nuclear isotopes. You will observe the spectra of hydrogen and deuterium; the hydrogen nucleus consists of a proton and the deuterium nucleus consists of a proton and a neutron. The difference between spectra of the two is, according to Bohr theory, due only to the nuclear mass difference. Substituting the reduced mass for hydrogen and deuterium into Eq. II-3 we get

$$R_H = R_{\infty} \left[\frac{M_H}{m_e + M_H} \right] \quad \text{and} \quad R_D = R_{\infty} \left[\frac{M_D}{m_e + M_D} \right]$$

Using the Taylor expansion we can obtain

$$\frac{R_D}{R_H} = \frac{M_D}{M_H} \left[\frac{m_e + M_H}{m_e + M_D} \right] \approx 1 + \frac{m_e}{M_H} - \frac{m_e}{M_D} \quad \text{II-5}$$

A measurement of R_D and R_H , together with the known values of m_e and M_H , determines the ratio M_D/M_H . Likewise if we use Eq. II-2 with the reduced masses and know the absolute wavelength and the splitting of the lines due to the mass difference we can also get a value for the mass ratio.

$$\frac{\lambda_D - \lambda_H}{\lambda_H} = \frac{m_e}{M_H} \left[\frac{M_H}{M_D} - 1 \right] \quad \text{II-6}$$

We will use the monochromator to find these wavelengths and determine the mass ratio; the true ratio should be approximately 2/1.

C. The Bohr Model of Alkali Atoms

The Bohr model is applicable in principle to any one-electron atom. The alkali atoms, in many of their energy states, closely resemble one-electron atoms. They consist of an inert electron core (a set of filled subshells) plus one active electron that circulates outside the core. The screen of the positive nuclear charge by the core electrons causes the active electron to “see” an effective charge of approximately $e(Z-1)$.

The Bohr model is applied to alkali atoms by absorbing the screening effects into the quantum number, and re-writing Eq. II-1 for the n th energy level, as

$$E = \frac{-2\pi^2 m e^4}{n'^2 h^2}$$

where $n' = (n - \mu)$, with n still an integer. The correction factor μ is called the “quantum defect”. It has been found experimentally (e.g, see Eisberg, p. 420) that there are series of energy states over which the value of μ remains approximately constant. A set of energy states having the same angular momentum will have the same quantum defect. This gives rise to several hydrogen-like series of spectral lines. The wavelengths of the lines are obtained by re-writing Eq. II-2 as

$$\frac{1}{\lambda} = R_\infty \left[\frac{1}{(i - \mu_1)^2} - \frac{1}{(j - \mu_2)^2} \right]. \quad \text{II-7}$$

in which μ_1 and μ_2 are two different quantum defects.

In the optical spectrum of sodium, for example, there are three or four prominent series which, historically, were identified by their appearance as “sharp,” “principal,” “diffuse,” and “fundamental”. With a large enough dispersion it could be noted that the lines were either doublets or triplets with separation of, at most, a few Angstroms.

For sodium ($Z = 11$) the first two subshells are filled and the one “optically active” electron is in the $n = 3$ subshell. However, the prediction of quantum mechanics beyond the Bohr model is that there are two more quantum numbers, P and m_P ($P = 0, 1, \dots, n-1$; $m_P = 0, \pm 1, \dots,$

$\pm P$) for a given n which lead to the same eigenvalue. There is a certain amount of degeneracy. An additional quantum number m_s is needed to describe the electron spin. For the alkali “one-electron” atoms the spin-orbit coupling produces an appreciable splitting of all but the $P = 0$ lines with a separation which increases with Z but for a given atom decreases with increasing n . The relevant quantum numbers when this effect is included become n, P, j and m_j , where j is associated with the total angular momentum of the atom and the electron (the sum of orbital and spin angular momentum of the electron) and m_j with the z component of this total angular momentum.

It is suggested that you review some of the background necessary for an understanding of the spectral characteristics of “hydrogen like” atoms (e.g. see Eisberg, pp. 418-425). At minimum, you should know how to interpret the energy level diagram of an alkali atom. There are inevitably several columns of energy levels given, instead of one as for hydrogen, since each value of P corresponds to a different energy state for a given n . The columns are labelled S, P, D, F corresponding to $P = 0, 1, 2, 3$ (where the initials correspond to the historical designation of the several series of spectra). A preceding superscript (e.g., 2P) indicates the two possible spin states for the single “optically active” electron. A following subscript indicates the values of the quantum number j that can only assume a value of $P+1/2$ or $P-1/2$ for a “one-electron” atom. Because of spin-orbit coupling, the energy of the $P+1/2$ level is higher than for the $P-1/2$ level. Thus the $^2P_{3/2}$ state has more energy than the $^2P_{1/2}$ state; i.e., it is less tightly bound. An energy level is completely identified by these quantum numbers as $n^{2S+1}P_j$. Thus the ground state of the sodium atom is $3^2S_{1/2}$.

If sodium atoms are excited to the various higher levels, transitions take place to return the electrons ultimately to the ground state. However, only those transitions occur in which the quantum number P changes by one (electric dipole radiation). The historically identified series are those in which transitions are made to the lowest possible n state.

Sharp	$n^2S \rightarrow n_0^2P$	doublet
Principal	$n^2P \rightarrow n_0^2S$	doublet
Diffuse	$n^2D \rightarrow n_0^2P$	triplet
Fundamental	$n^2F \rightarrow n_0^2D$	triplet

Except for the last series, $n_0 = 3$. When energetically allowed, n may also be 3. The strongest line in the sodium spectrum is the doublet of the principal series $3^2P_{1/2,3/2} \rightarrow 3^2S_{1/2}$.

For all but the principal and sharp series, it might be expected that a quartet of lines would be seen rather than a doublet. However, another selection rule that is obeyed is that $\Delta j = 0, \pm 1$ (the photon carries off only one unit of angular momentum). Thus, those lines of the diffuse (and fundamental) transitions are seen as triplets since a transition such as $^2D_{5/2} \rightarrow ^2P_{1/2}$ does not occur.

As a final note on the doublets, those that result from a transition from singlet states to a doublet (e.g., the Sharp series) would be expected to have a constant energy separation. Those arising from a doublet to a singlet state would have a decreasing separation with increasing n since the energy separation decreases with increasing n .

These are minor points to the purpose of the experiment, that of determining approximate values of the quantum defects which are different for each P value but do not vary appreciably with n . Neglecting the spin-orbit splitting the transitions are

$$\begin{array}{ll}
 \text{Sharp} & \frac{1}{\lambda} = R_{\infty} \left[\frac{1}{(3-P)^2} - \frac{1}{(n-S)^2} \right] \quad n > 3 \\
 \text{Principal} & \frac{1}{\lambda} = R_{\infty} \left[\frac{1}{(3-S)^2} - \frac{1}{(n-P)^2} \right] \quad n \geq 3 \\
 \text{Diffuse} & \frac{1}{\lambda} = R_{\infty} \left[\frac{1}{(3-P)^2} - \frac{1}{(n-D)^2} \right] \quad n \geq 3 \\
 \text{Fundamental} & \frac{1}{\lambda} = R_{\infty} \left[\frac{1}{(3-D)^2} - \frac{1}{(n-F)^2} \right] \quad n > 3
 \end{array}$$

where S, P, D, F are now used as the quantum defects.

VII. Experimental Equipment

The experimental apparatus can be thought of as consisting of three separate subsystems: (1) light sources, (2) monochromator-microprocessor unit and (3) computerized data acquisition and analysis system. A brief description on each follows. For more details on the equipment, the manuals should be consulted (located in filing cabinet in Room 3210).

1. Light Source

The experimental station is equipped with a mercury lamp, a hydrogen-deuterium lamp, and a sodium lamp. Each lamp is clearly marked and is powered by its own power supply. The experiment uses no focusing of the light sources; however, if you wish to investigate the effect on the experiment with focusing, lenses can be made available. However, all lines of interest can be seen without focusing.

NOTE: The sodium and mercury lamps are strong sources of ultraviolet radiation and should not be viewed directly. A black cloth is provided and can be used to block unwanted light.

2. Monochromator-Microprocessor

This experiment uses a SA Instruments HR-320 spectrograph/monochromator, an SA 1020-MS Microprocessor scan system and a Products for Research photomultiplier tube as the scanning monochromator to measure the wavelengths of the light emitted by the different lamps.

3. Computer System

A computer system is used to automatically digitize and store the photomultiplier output.

A. Monochromator

The laboratory is equipped with a HR-320 scanning monochromator (schematic in Fig. II-1). A photomultiplier tube and housing are mounted on the side of the unit to detect the light. The signal is taken off the anode of the PM tube and sent to a picoammeter which puts out a voltage which is proportional to the current.

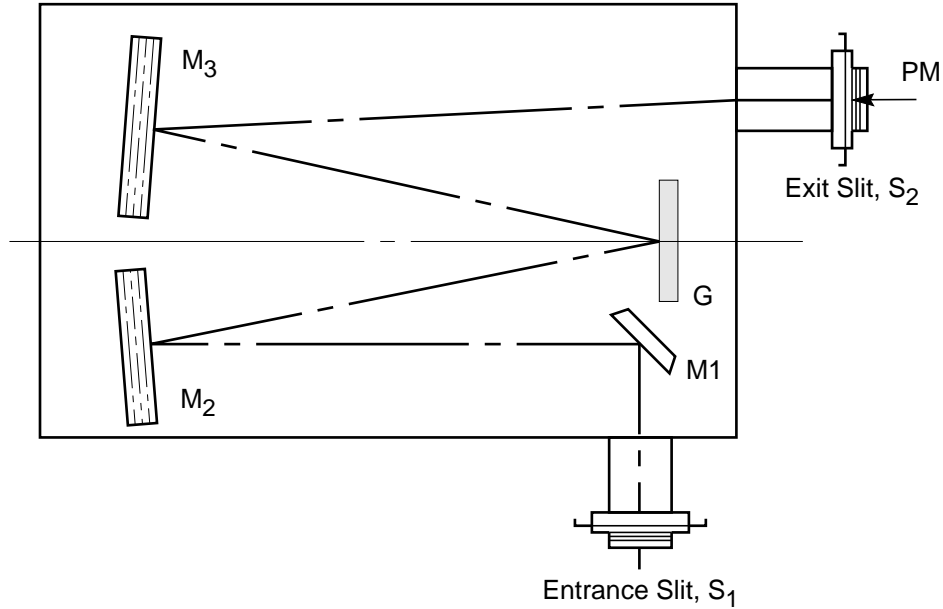


Figure II-1

The light beam enters the monochromator through an adjustable slit S_1 . The beam is reflected by the collimated mirror M_2 that renders it parallel and directs it toward the grating G . The grating is dispersive because different wavelengths are reflected at different angles. Thus, the grating diffracts the light and sends a particular narrow band of wavelengths onto mirror M_3 that focuses an image of the entrance slit onto the exit slit S_2 . Wavelength scanning at the exit slit plane is accomplished by rotation of the grating. The light is detected at the exit slit S_2 by a photomultiplier tube.

The grating diffracts the incoming light according to the formula (refer to Fig. II-2)

$$\sin \alpha + \sin \beta = \frac{m\lambda}{d} \quad \text{II-8}$$

If 2ϕ is the angle between the incident and diffracted wave, and θ is the angle between the axis of symmetry XX' of the unit and the line perpendicular to the grating, the formula can be rewritten as:

$$\lambda = \frac{2d}{m} \cos \phi \sin \theta \quad \text{II-9}$$

This formula is derived using $(\beta - \alpha) = 2\phi$, $(\beta + \alpha) = 2\theta$, and $2\sin A \cos B = \sin(A+B) + \sin(A-B)$ and expanding. This is just a mathematical trick to simplify the formula. If the angles of

incidence and diffraction are fixed, then a value of the angle θ will give us a value of the wavelength.

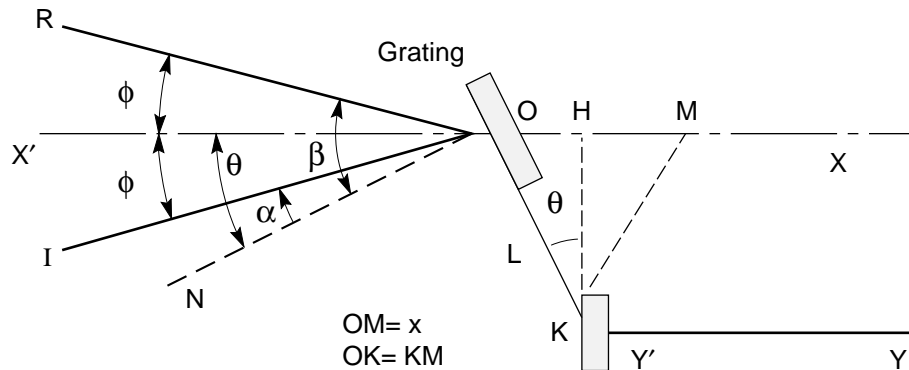


Figure II-2

where α : angle of incidence measured with respect
 β : angle of diffraction to the normal to the grating
 d : grating spacing (reciprocal of lines per unit length)
 m : order (0,1,2,...)
 λ : wavelength of light

Assuming that there are two equal lengths OK and KM such that point O is on the rotational axis of the grating, OK is parallel to the grating plane and M moves along the monochromator axis of symmetry $X'X$, it can be seen that

$$\sin \theta = \frac{x}{2L}$$

hence the wavelength is given by

$$\lambda = (d / mL)x \cos \phi$$

Mechanically, point K rests on a plane which moves along line $Y'Y$ parallel to $X'X$, such that y is the location of K along $Y'Y$. A constant of proportionality exists between x and y . It therefore suffices to know the value of y to identify the wavelength.

The HR-320 has no manual control of the wavelengths; instead wavelength scanning is accomplished by the use of a stepping motor controlled by a microprocessor unit. There is a dial (located on the side of the monochromator housing) which gives a direct reading proportional to the wavelength in angstroms. This dial reading is used to calibrate the microprocessor unit. The monochromator dial is factory-calibrated for a 1200 line/mm grating. However, there is an 1800 line/mm grating on this machine; therefore, the actual wavelength is calculated as $(1200 / 1800)\lambda_{\text{dial}}$. The wavelength can be swept at a rate

adjustable from 1 to 1800^{*1} Å /min. The smallest increment that can be read is then 0.2^{*} Å on the dial (0.14 Å real).

The monochromator is equipped with variable slits at the entrance and exit ports. These slits should be adjusted according to the needs of the experiment. Keep in mind that the width of these slits determines the resolution of the device. They are precisely tooled pieces and are very delicate, so care should be taken when adjusting them.

The photomultiplier tube is mounted on the side of the monochromator housing in a protective casing. Do not remove this casing. When light falls onto the photo-multiplier tube (consult Experiment VII for details on the working of the tube) a detectable current is produced at the anode. This tube is run at a negative high voltage (approximately 1000 volts). **DO NOT EXCEED 1200 VOLTS.** The output of the anode is fed to a picoammeter that then outputs a signal proportional to the anode current.

VIII. Procedure

The procedure will be to scan the spectrum of a source with the monochromator, and sample the output of its photomultiplier tube with the computer. Then the data acquired with the computer can be studied and printed for further analysis or display (or analyzed with a program called ANALYSIS).

A. Connections:

Connections are made from the photomultiplier tube to the Pico-ammeter and to the Lab Pro in the following way:

1. Connect the output of the photomultiplier tube to the input of the Pico-ammeter, Keithley model number 485. Set that instrument to the 20 microA scale.
2. Connect the Lab Pro channel 1 input to the Pico-ammeter analog output (Located on the back of the Pico-ammeter).
3. Connect the Lab Pro channel 2 input to the Trigger Out connector on the microprocessor Scan controller.

B. Slit adjustments

There are two slits associated with the monochromator: the input slit between the light source and the monochromator, and the output slit between the monochromator and the photomultiplier tube. Their adjustment is critical. NOTE THAT THE UPPER DIAL UNITS ARE 1 MICRON/DIVISION, THE LOWER DIAL UNITS ARE 50 MICRONS PER DIVISION. Take a look at the manuals in the lab for further information.

1. **The input slit:** An initial setting may be 5 microns. You may want to close it some (perhaps to 3 microns) to sharpen the line peaks. Note that the micrometer with which the slit width is adjusted does not stop turning when the slit is closed. Watch the slit open and close as you turn the micrometer.

¹ Refers to the wavelength reading on the monochromator dial. Dial readings will be indicated by a * next to the wavelength, the actual wavelength is 2/3 this value.

2. **The output slit:** That slit has two adjustments: the width and the height. The initial width setting may be 5 micron. You may want to close it some (perhaps to 3 microns) to sharpen the line peaks. The height of the slit can be changed if changes in the output of the photomultiplier tube are desired to better match the input sensitivity of the computer sampling. It is recommended that the slider be all the way out to allow full exposure to the photomultiplier.

Get acquainted with the setup and the equipment. Make sure all connections are properly made and turn on the power to the equipment. Initialize the microprocessor so it reads the same wavelength as the dial. Set the upper and lower limits to the desired wavelengths and adjust the sweep speed to suit your needs.

The first spectrum that you will collect is mercury. The mercury spectrum is very well known; a few of the stronger lines are given in Appendix I to this experiment. You should be able to resolve all of these lines with this equipment. Use this spectrum to become familiar with the equipment, then check the accuracy of the monochromator and adjust the monochromator for the best possible resolution by adjusting the variable slit widths.

Turn on the mercury lamp and place it directly in front of the entrance slit. Do not view the mercury lamp directly as it is a strong source of UV light. Scan the spectrum about ± 100 Å about the 4358.4 line (6540 Å on the dial). This is one of the more intense lines. As the wavelengths are scanned you should notice the current changing on the picoammeter as different lines are passed. If the current remains constant, you need to check the equipment. A constant current could be caused by numerous things: the high voltage to the phototube could be off, the shutters at the exit port could be closed, the picoammeter scale might not be sensitive enough, the variable slits could be closed or not open wide enough, the light source might not be shining on the slit. If the system is working, check the resolution and see how it varies with slit width. When the slit widths are decided, then use a scale on the picoammeter that will not overload it when the 4358 Å line is at its maximum. Do not use the picoammeter in the AUTO scale. This will cause the output to vary with what particular scale it is presently on and very confusing data will be obtained.

You should now be ready to record the mercury spectrum. Record the entire spectrum of Hg (2536 to 6149 Å) at a sweep speed of 900 Å/min. A monochromator speed of 900 Å/min will insure that the total sampling time is not too long. You should now calculate the corresponding total time the scan will take (it may run into several minutes). This information is essential in a later step of setting the data collection length of Logger Pro.

Computer acquisition of the spectrum

You are now ready to run the computer program “LoggerPro” which will permit you to record the output of the phototube signal.

1. Select the folder on the computer desktop labeled Lab_Pro_Templates. This folder contains Logger Pro templates designed for the Phys 405 lab experiments. Selecting one of these templates starts the program Logger Pro and loads the setup information for the experiment selected.
2. The range settings of the Pico-ammeter must be selected as appropriate for the input reading. Special attention should be noted to these ranges as they can have an effect on the values of the analog output signal.

3. For this experiment, it is suggested that you use a sampling rate of greater than 120 samples (measurements) per second. If you are close to 60 samples/second, you'll get a beating effect between the 60-Hz driven atomic lightsource and the sample rate.
4. The data collection length should be selected so that the total length of the sampling should equal the total time of the scan, as estimated above.

C. The following information is stored in the Logger Pro template.

1. The Lab Pro will collect data from 2 analog channels.
2. Channel 1 is set to collect data from the Pico-ammeter and display this data in the table and on the graph.
3. Channel 2 is set to trigger the data collection. The trigger that initiates the taking of data will be provided by the Microprocessor scan controller. The trigger data is not displayed.
4. The Data Collection sampling rate is set to 50 samples (measurements) per second. You should change this to greater than 120 samples/second.
5. The Data Collection Length has been set to 250 seconds. This will require changes as the time of scans for the different light source change the data collection length.

Determine the wavelengths of all the more intense lines from the spectrum obtained. How close are these measured lines to the values given in Appendix I of this Experiment? How accurate is your determination of the wavelengths?

Next, place the H-D lamp in front of the entrance slit. Record the entire spectrum (3645.6 to 6562.8 Å). How many lines can you observe? The intensity of the lines decreases with decreasing λ for hydrogen and deuterium. Is the splitting of the lines noticeable? Determine the splitting of all the stronger lines (6562.8, 4861.3, 4340.5, and 4101.1). If necessary, make separate sweeps of about 10 Å around each line at 100* Å/min.

Find the wavelengths of the observed lines for hydrogen and deuterium and their associated measurement errors. Make plots of $1/\lambda$ vs. $1/j^2$. From these plots determine the Rydberg constant for hydrogen and deuterium and verify that $i = 2$ for these data. From the value of the Rydberg constants find a value of the mass ratio of H to D. Measure the splitting and the wavelengths of the lines. From the value of the splitting and the wavelengths determine the hydrogen-deuterium mass ratio. Which of the values of mass ratio is more accurate? Why?

Finally, replace the H-D lamp by the Na lamp. Record the entire spectrum (2593- 6160 Å) of sodium. Can you notice the splitting of the lines into doublets and triplets? Adjust the sweep times (and slit widths if necessary) so that you can see the doublets and triplets and record the spectrum showing clearly the splitting of these lines. Identify the wavelengths of these lines. Use the value of $R_\infty = 109737.15 \text{ cm}^{-1}$ to determine the quantum defects for the sharp, principal and diffuse series. The S, P, and D lines can be identified using the figure in Appendix II of this experiment. The approximate values of the quantum defects are $S = 1.35$, $P = 0.86$, $D = 0.01$. (Set $D = 0$ to solve the necessary equations for S and P if you do not have access to Mathematica.)

IX. Questions (These questions are to be answered in the experimental write-up.)

- A.** How well do your data fit a straight line when $1/\lambda$ is plotted against $1/j^2$? What are the major sources of error in the measurement of λ ?
- B.** What is the approximate error in your determination of M_D/M_H ? Justify your answer. Justify the approximation in Eq. II-5. How would you improve the measurement?
- C.** Explain briefly why certain of the sodium lines are split into doublets. (Consult a book on modern physics.)

APPENDIX I

Mercury Spectrum	
Wavelength	Intensity
6149.5	weak (red)
5790.7	strong (yellow)
5769.6	strong (yellow)
5460.7	strong (green)
4358.4	very strong (blue)
4347.5	strong
4339.2	medium
4077.8	strong (violet)
4046.6	very strong
3906.4	weak
3663.3	
3662.9	strong
3654.	strong
3650.2	strong
3341.5	medium
3131.8	
3131.6	strong
3125.7	medium
2536.5	Very very strong

Hydrogen Spectrum	
Wavelength	Intensity
H _α 6562.8	(red)
H _β 4861.3	(turquoise)
H _γ 4340.5	(blue)
H _δ 4101.7	(violet)
3970.1	
3889.1	
3835.4	
3797.9	
Series limit 3645.6	
The intensity of the Balmer line series decreases continuously from H _α	

Wavelengths of sodium lines (only the stronger lines are listed):			
$\lambda[\text{\AA}]$			
6160.73	5149.09	4664.86	2853.03
6154.21	4982.87	4545.22	2852.83
5895.93	4978.61	4541.67	2680.44
5889.95	4751.89	4497.72	2680.34
5688.22	4748.02	4494.27	2593.93
5682.67	4668.60	3302.94	2593.82
5153.65		3302.34	

APPENDIX II

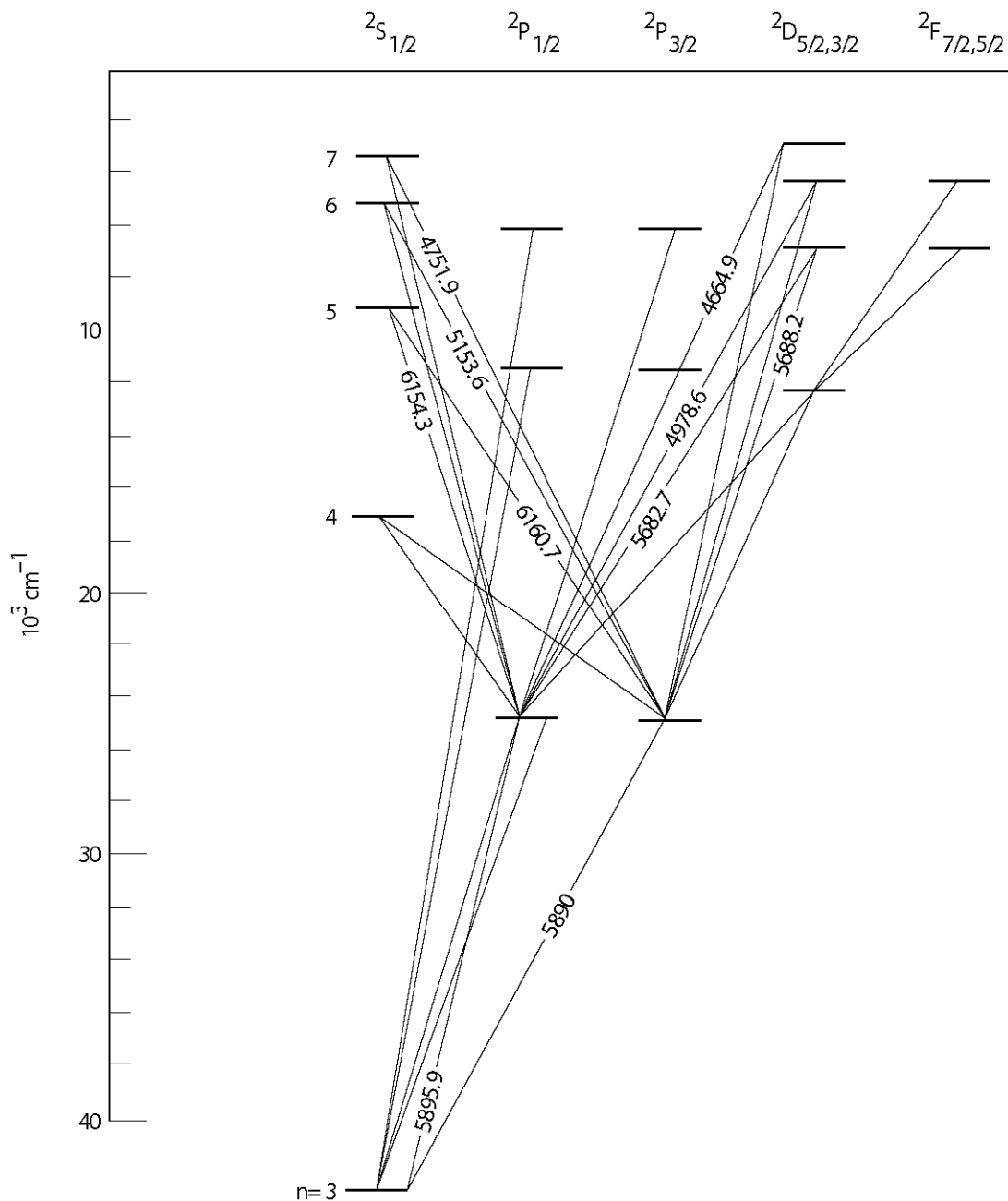


Figure II-3

The “allowed” transitions between the energy levels of sodium. The wavelengths in Angstroms of some of the principal lines are indicated. Note that the P states have now been shown in two columns, one referred to as $P_{1/2}$ the other as $P_{3/2}$: the small difference between their energy levels is the “fine structure”. (from *Experiments in Modern Physics*, by Melissinos)

APPENDIX III

Microprocessor Instructions

A picture of the microprocessor unit is shown in Fig. II-4. This microprocessor is used extensively for the data-taking so familiarize yourself well with its working. The microprocessor will control all the wavelength sweep times allowing for the wavelengths to be swept at a speed varying from 1* to 1800* Å/min. A brief description of its features is given below. Numbers refer to Fig. II-4.

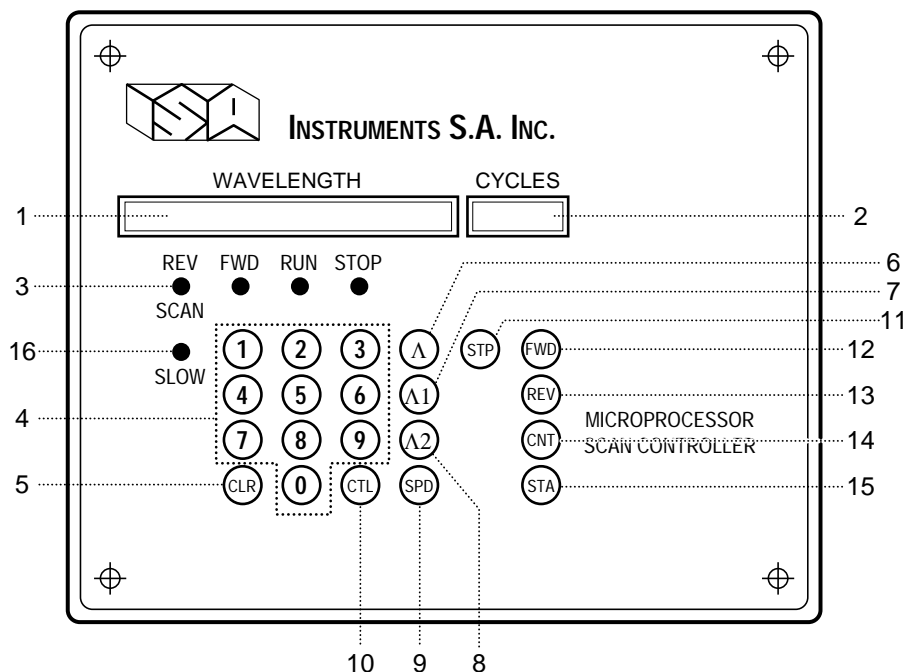


Figure II-4 Microprocessor display

1. **LED wavelength display** -- This digital display performs two functions. During scanning, it indicates the current wavelength. When any of the keys $\Delta 1$, $\Delta 2$, Δ , SPD, or CYL are pressed, the value of the appropriate register is displayed.
2. **LED "Cycles" display** -- This digital display indicates the number of cycles remaining to be scanned during cyclic or repetitive scanning.
3. **LED Function Lights** -- These four LEDs indicate the status of the scan in progress. "FWD" and "REV" indicate the direction the scan is proceeding in, forward or reverse. "RUN" and "STOP" indicate whether the micro is in the scan or stop modes. (The "STOP" light will be lit whenever the controller is in the "backlash correction" mode even though the motor is still running.)
4. **Numerical Keys** -- These keys, numbered 0 to 9, are used for entering values into the microprocessor's memory.

5. **“CLR” Key** -- This key clears the individual register that is punched directly preceding the use of the “CLR” key. This key should be used whenever you wish to enter data into a register. For example, if you wish to clear the current wavelength in register 1, press Λ 1 the “CLR”.
6. **Λ Key** -- This key enables the user to initialize the controller to read the same wavelength as the monochromator. Data should be entered in the format 00000.0, with the numbers moving across the display to the left as each digit is punched in. For example, the monochromator dial reads 3645.6 Å. Press Λ , then CLR then the keys 3, 6, 4, 5, 6. If the digit after the decimal point is to be a zero it must be keyed in to hold the decimal point.
7. **Λ 1 Key** -- This key allows data to be entered in the Λ 1 register, this register functions as the lower wavelength limit in the scan range. Digits should be entered in the same manner used for the Λ key.
8. **Λ 2 Key** -- This key allows data to be entered in the Λ 2 register. This register functions as the upper wavelength limit in the scan range.
9. **SPD Key** -- This key enters the desired scan speed into the register. The maximum speed allowed is 1800* Å/min. Keying in larger numbers will default to 1800* Å/min. Data should be entered in the following format: SPD, CLR, speed, no decimal points.
10. **CYL Key** -- The CYL key allows the user to enter the desired number of scans for repetitive or cyclic scanning into the register. Maximum allowable cycles is 99. You will make single scans.
11. **STP** -- This key will cause the system to stop, after first performing a backlash correction. This will cause the system to appear to run after the STP has been pushed. The system will return to the exact wavelength that it was at when the STP was pushed.
12. **FWD** -- The “Forward” key causes the system to scan in the direction of increasing wavelength at the preselected speed. When Λ is less than Λ 2, the system will proceed to Λ 2 then stop.
13. **REV** -- The “Reverse” key causes the system to scan in the direction of decreasing wavelength, at the speed selected by the “Scan/Slow” switch. If Λ is greater than Λ 1, the system will proceed to Λ and then stop.
14. **CNT** -- The “Continue” key allows a scan that was interrupted by use of the “STP” key to be continued where it left off.
15. **STA** -- The “Start” key begins cyclic or repetitive scanning. Scanning will take place in the forward direction at the preselected speed until Λ 2 is reached, and then return to Λ 1 at either the scan or slow speed, depending upon the position of the Scan/Slow switch. Each time the Λ 1 is reached the number of cycles remaining will be decremented by 1, until no scans remain to be done.
16. **Scan/Slew Switch** -- This switch selects the speed for the reverse direction scan. In the slew position, the reverse speed is 1800 Å/min. In the scan position, the reverse speed is the same as the user programmed forward speed.
17. **ON/OFF Switch** -- This controls the power to the microprocessor and is located on the back of the microprocessor unit.

Each time the microprocessor is turned off all registers are cleared and have to be reset. The following is an example of setting up the system. Suppose the mono-chromator dial reads 3145.5* Å and you wish to scan from 2000* to 5000* Å at a speed of 600* Å/min. This is the procedure you follow.

Operation	Display	Comments
1. Turn on system	0	
2. Press Λ , CLR	0	clears Λ register
3. Press, 3,1,4,5,5	3145.5	Initializes Λ register
4. Press $\Lambda 1$, CLR	0	clears $\Lambda 1$ register
5. Press 2,0,0,0,0	2000.0	sets $\Lambda 1$ register
6. Press $\Lambda 2$, CLR	0	clears $\Lambda 2$ register
7. Press 5,0,0,0,0	5000.0	sets $\Lambda 2$ register
8. Press SPD, CLR	0	clears SPD register
9. Press 600	600	sets sweep speed
10. Put SCAN/SLEW switch to SLEW		sets reverse speed
11. Press REV	Starts at 3145.5. Goes to 2000.0 at 1800 Å/min	
12. Press FWD	Updates current Λ . Scans at 600 Å/min to 5000.0 and then stops	