

MODERN PHYSICS LABORATORY

INTRODUCTORY NOTES **Spring 2009**

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Welcome to Modern Physics Laboratory. We hope the course will teach you new skills, but we also hope you will have some fun in a relatively informal setting. The syllabus is rather lengthy but **READ IT THOROUGHLY**; it's all important stuff. It describes the course and gives you some notes on important topics such as keeping lab books and writing scientific articles. The sections in the syllabus are as follows:

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GOALS

Modern Physics Laboratory will give you the opportunity to learn about doing experimental physics. By working through experiments chosen from several sub-fields, we hope you will gain experience in some of the techniques of scientific research and learn some new physics along the way. The issue at hand is not to merely mimic old experiments, but rather to have a chance to explore physical phenomena in a laboratory setting, making careful measurements, and drawing your *own* conclusions about the models and theories which are supposed to describe these phenomena.

COURSE REQUIREMENTS

Each student will perform three experiments. During class periods, you will actually make measurements, do data analysis, and discuss your work with the instructors. Background reading, further analysis, and report preparation will be done outside of class hours. By the last lab period of any experiment, all data analysis must be finished and conclusions must be drawn. When class sessions on one experiment are complete, the student immediately begins the next experiment.

Experiments - including set up, measurements, and data analysis - will be worked on by pairs of students. However, each individual is expected to turn in an independently-written lab notebook and article. While you should work on all data analysis and drawing of conclusions with your partner, articles should be written independently.

Given the number of effective lab days in the semester, each experiment will take about 8 sessions. However, the actual end of an experiment will be mutually agreed upon by the student and the instructor. Attendance for two full lab periods each week is required. Sessions must be scheduled to make up all absences. Extra time in the lab may also prove useful. Students must get their third written report done by the last day of classes, the latest due date for class work that University regulations allow. Oral presentations may be scheduled during finals week in lieu of a final exam.

Four steps will occur at the end of each experiment:

1. *Before* the last lab session, each student prepares a written statement of his/her conclusions and gives explicit references to the graphs, data tables, and calculated results that support those conclusions.
2. *During* the last lab session, the student and the instructor will have a close-out meeting to discuss the conclusions drawn from the experiment. Your ability to identify valid conclusions of your measurements and defend the supporting evidence will count toward your grade.
3. On the third weekday after that close-out discussion, the student will turn in a 1.5 to 2 page, detailed outline of the article. It must describe what will be included in the paper and indicate the conclusions drawn from completed data analysis. This outline forces you to organize your results, sharpen your conclusions, and fill in any needed analysis which you find lacking as you refine your thoughts. The outline has more to do with organizing and completing your scientific thinking than preparing to write a paper.
4. A formal written report, better described as a scientific article, on each experiment is due as specified by the instructor after the last lab session. A completed checklist itemizing the minimum requirements for structural issues must be attached. Also hand in your lab notebook and any earlier report(s) you did.

Scientific papers must be typed and printed out in single-column single-sided double-spaced format. Figures and graphs should be done using a computer, but need not be elaborate artistic creations. Comments on previous articles and notebooks should be carefully considered in preparing subsequent articles. Follow-through on the comments made on previous written reports will be important in evaluating your later work.

For one of the three experiments, both a written and an oral report will be required. We will try to give you preference as to which experiment you want to present orally. Scheduling oral reports at the end of the semester may entail use of time during the final exam period. The oral report will consist of a 40 minute presentation in the style of a scientific seminar, and a 30 minute question and answer period.

PROGRESS REPORTS AND BRIEF ORAL REPORTS

During the course of experiments, progress reports are required. Once a week, a short progress report summarizing the past week's work must appear in the lab book. These reports help you take a bird's eye view of your experiment and track your progress.

Twice during the semester, each student will give a 7 minute oral presentation to the class discussing his/her progress or describing a particular aspect of the experiment. These are typical of reports you would make in a professional setting. They will give you practice in important communication skills. These "short" talks will be not be graded, but will give you crucial experience for organizing your "long" seminar-style talk at the end of the semester.

RECITATION

In addition to the laboratory periods, there will be one lecture hour per week on Tuesday at 8:30 AM, in room Doherty Hall A200. We will discuss a number of topics relevant to experimental physics including: keeping lab books, communication techniques, and statistical treatment of experimental data. This part of the course is intended to be very applied and pragmatic. Student participation is **REQUIRED**. Several pencil-and-paper homework assignments will be made during recitations. There will be a weekly open-book quiz on material from the previous week. Some of the material covered discusses simple procedures to be used in your work. Other material is more complex. Most of the material is not found in the texts, so you must take notes and pay attention in class. You will be expected to incorporate all subject matter covered in these lectures into your reports and lab work, and you will be graded on how well you accomplish this. Failure to incorporate the simple procedural material and turn in all summaries will result in a significant decrease in your grade!

GRADING

For each experiment, your grade will have three components. The first 50% is based on all aspects of the lab work, including performance of the experiment, quality of the data, data analysis, conclusions, and all substantive contents of the final paper. Written communication skill as demonstrated in the articles will account for 25% of the grade. The content of the lab book and proper documentation techniques will account for the final 25% of the grade.

The first experiment counts for 20% of your overall grade; the second experiment counts 25%, and the third experiment 30%. Your long seminar-style talk provides 15%. The last 10% of the grade will be determined by recitation participation, including doing the assignments, the short talks, and quiz performance.

If you don't keep on schedule with data analysis, outlines, and reports, one experiment starts rolling on top of the next and hope of learning from the course is lost. The pace increases during the semester, so be forewarned. Penalties will be assessed for late work.

GENERAL COMMENTS

Key points we want to stress throughout the course:

1. Come to the lab prepared in advance. Read the handouts and answer the exercise questions contained therein. Study the physical principles behind each.
2. It is equally important to keep up with data analysis as the experiment proceeds. Some of this may be done during the lab and some outside of lab. Don't wait until after the experiment is over to start to work on the data!
3. Keeping good lab books is an essential part of the work. As will be discussed, this means much more than merely taking down tables of numbers.
4. A sophisticated approach to the comparison of experimental results with theory and/or previous experiments is also very important. It is not enough to say "they agree" or "they disagree". Rather, valid scientific conclusions are: "they agree well" or "they disagree badly" or something in between. Make the comparison quantitative.
5. Conclusions are important. Many students (as well as some professionals) write excellent articles but shortchange stating their scientific conclusions. Give them their proper due!
6. The essence of experimental physics is to maintain the closest possible contact with the physical phenomena occurring. Observe what's happening. Note carefully what you see and your ideas about those direct observations. Make preliminary graphs or sketches which reflect what you see as closely as possible. Don't let instrumentation and computers take over, preventing your eyes and brain from connecting with the actual experiment.

REQUIRED AND RESERVE BOOKS

We strongly suggest that you purchase these books, especially the first one:

- 1) *Data Reduction and Error Analysis for the Physical Sciences*, Philip R. Bevington and D. Keith Robinson, 3rd Edition, (McGraw-Hill, 2003) ; (A few copies of this book are available to borrow in the lab.)
- 2) *Experiments in Modern Physics 2nd Ed.*, Adrian C. Melissinos & Jim Napolitano (Academic Press, 2003); (A few copies of this book are available to borrow in the lab.)

The following books are on reserve in the E&S Library. These contain useful discussions of many aspects of the experiments and are mentioned in the write-ups for each experiment.

Bevington	Data Reduction and Error Analysis	519 B5713d
Cranshaw	Mössbauer Spectroscopy and its Applications	537.5352M913
Cullity	Elements of X-ray Diffraction	537.53 C96e2
Eisberg	Quantum Physics of Atoms, Molecules	530.12 E362q
Frauenfelder	Mössbauer Effect	535.3 F84m
Herzberg	Infrared and Raman Spectra of Polyatomic Molecules	539.1H58v.2
Hughes	Muon Physics	539.721 M97
Kittel	Introduction to Solid State Physics	530.41K62i6
Melissinos	Experiments in Modern Physics	530.28 M52e
Pake	Paramagnetic Resonance	538 P15p
Pake	The Physical Principles of Electron Paramagnetic Resonance	538.3 P15p
Paudler	Nuclear Magnetic Resonance	538.3 P32n
Pecora	Dynamic Light Scattering	535.84 B52d
Piepmeyer	Analytical Applications of Lasers	543.085 A532
Richtmyer	Introduction to Modern Physics	530R53a5
Schumacher	Magnetic Resonance	538.3 S39i
Segre	Nuclei and Particles	539.7 S45N2
Shoemaker	Experiments in Physical Chemistry	541.072s55e6
Siegbahn	Alpha, Beta and Gamma Ray Spectroscopy	535.84 S57a v.1&2

Slichter	Principles of Magnetic Resonance	539.1 S63p3
Taylor	Precision Measurement and Fundamental Constants II	QC1 65 no. 617
Thorndike	Mesons: A Summary of Experiment Facts	539.7T49M
Weissenberg	Muons	539.721 W43m
Wertheim	Mössbauer Effect: Principles and Applications	535.3 W49m
Wertheim	Mössbauer Effect Reprints	539.752 A51m
Wilson	Introduction to Scientific Research	507.2 W74i
Wilson	Molecular Vibrations	535.84W74ma
	Handbuch der Physik	530.8 H23 v.44

LAB BOOKS

(Further details on lab books can be found in an accompanying handout. Follow all directions in both that handout and the following paragraphs.)

In a research setting, laboratory notebooks are an important, complete record of the scientific work which has been done. They serve several purposes: (1) they allow the experimenter to have a complete record of the results so that he/she can reach conclusions and, where necessary, precisely reproduce experimental conditions; (2) they allow another trained scientist to reproduce the recorded experiments or build on them; and (3) when necessary, they may serve as a legal record of the temporal evolution of ideas and technical developments. Since this is a difficult but essential skill to develop, you are required to keep a notebook which is a complete record of your experimental progress. It should be a bound book so no pages can fall out. Entries should be made in ink; and, if needed, material may be neatly crossed out. You never know when you may change your mind and want those original notes. Record everything in your notebook; never use scratch paper or a separate pad. A record of what seems to be small side calculations may be needed later in tracking down an error or a surprising conclusion. You may consider the lab handout as an “instruction manual” that is available to the reader. Make reference (citing page and paragraph) to it if it saves you from rewriting words that already appear in the handout. However, if you do something the least bit different, you must record that in your notebook. Data analysis also belongs in the notebook. And unless they are completely unwieldy, preliminary computer output as well as graphs made on separate graph paper should be attached permanently to the book. Because of all this note taking, some pages will be messy; however, since this book is meant as a meaningful record don't let things get out of hand. When needed, annotations should make clear what the entries are. Portions of the book where data analysis is performed or thoughts summarized should be presented so that any trained scientist can understand the record. Don't be intimidated, just write down your ideas in simple, clear phrases; pretty sentences come later in the final reports.

The lab book should contain:

1. A plan of the day, including figures where appropriate. It is best to write the plan before class whenever possible. One good idea is to write the plan of the next class period's experimental work at the end of the current lab period, when what needs to be done is fresh in your mind.
2. A sketch of the experimental setup. Usually it is best to make the drawing in schematic or "block" form rather than an artistic perspective drawing of the setup as it actually appears in the laboratory. Sometimes it is relevant to indicate the physical layout as well. Dimensions to set the scale should be included.

3. Tables of data with errors (uncertainties) and units fully noted. If you can, keep more than a significant number of figures in all numbers. The time to concern yourself with the number of significant figures to quote is at the end, when the errors, both statistical and systematic, are estimated. In quoting results and associated errors, use the proper number format so that the error agrees with the number. Units and errors are essential parts of numerical results. Good practice is to use two significant figures of error, such as 0.2345 ± 0.0067 .
4. Plots of the data as they are being taken. If the results are unexpected or look unreasonable, you can look for the reason there in the laboratory rather than back in your room, when it is too late to take corrective action. Feel free to plot data *by hand* using a pencil and ruler!
5. Calculations that reduce the raw data to experimental results. This includes calculations of errors, with thorough consideration of propagating and estimating errors.
6. Observations of events that may be relevant, or may not be, but whose effects on the experiment are not necessarily clear to you at the time. Example: room temperature affects the calibration of some instruments.
7. Numerical comparisons of your results to what is expected, as well as comments and conclusions about your results and possible sources of systematic error.
8. Your weekly progress reports.

A final note: Keeping a lab book is an art that must be learned. It requires self-discipline. We expect that you will improve the quality of your lab book as the semester proceeds, and we require that it be submitted along with the scientific article. When the lab book and article are returned to you, look through both for instructor comments and questions.

Even though all experiments will be done with a partner, it is necessary to keep separate and independent records. That may seem to slow progress, but reliance on a partner's lab book for things not written in your own can be a thin reed to lean upon during article-writing time. The instructors will not expect to find in one partner's book what is missing from the other's. However, partners' lab books will be compared by the instructors at report-reading time to clarify what was done.

SCIENTIFIC ARTICLES

(Further details on written and oral reports can be found in an accompanying handout. Follow all directions in both that handout and the following paragraphs.)

Scientific discovery is useless unless it is communicated in a clear, concise, convincing manner. In this course, you will have a chance to communicate your results in written and oral form. The written report is a complete discussion of the experiment, independent of the lab book. It must stand alone. Think of writing a 'scientific article' suitable for publication rather than the kind of 'lab report' in which you simply answer the questions given in the handout for each experiment. Consider that the reader is a physicist who understands the scientific principles involved but who has not done the experiment. The article should not contain every detail recorded in the lab book but should convey why you did the experiment and what your conclusions were. Your descriptions of the experimental procedures, resulting data, and analysis techniques are there to convince the reader that your conclusions are based on sound scientific method and reasoning. Every detail of procedures need not appear, and chronological records of

your work are usually not appropriate. The article should be written so that the reader has a clear idea of what you did, why you did it, your conclusions, and how your results support or differ from those expected from a particular theory or from earlier related measurements. In outline, it should contain the following:

1. **Abstract.** It is a concise description (200 words or less) of the essential purpose of the experiment, the experimental technique used and your conclusions. These conclusions should include numerical results if they are not too lengthy and their quantitative comparison to accepted values. Typically you write the abstract last.
2. **Introduction.** Describe the motivation of the experiment. What do you expect to learn? Avoid listing goals such as "become a better person" or "learn something about how to do this type of experiment." Those may indeed be goals, but they have no place in a formal report, which must identify physical results that you wish to obtain and must relate those results to a larger context. Some discussion of theory and general physical background is appropriate, but do not repeat extensive details of the theory or derivations that are included in the handouts or standard references. A brief reference to the experimental technique used is also appropriate.
3. **Apparatus and Procedures.** Discuss the overall procedure for doing the experiment. Describe the apparatus and the role of each nontrivial element of it. A carefully-done block diagram of relevant aspects of the apparatus should be included. Discuss, when relevant, the precision of the apparatus. Discuss how many of a given type of measurement were made, and why. If there were alternative approaches, contrast them to your own, particularly if yours was both innovative and, in your opinion, better. The procedure discussion should *not* be a chronology of what you did.
4. **Results.** This section may contain samples of the raw data, typically in graphical form. Tables of results may also be included if they are not too extensive. You should mention here if data were discarded because of faulty procedure or setup. You should have computer-drawn graphs and values of derived quantities with units, with the proper number of significant figures, and proper estimates of precision. Do not include all step-by-step calculations, but make clear how they were done. Include a full quantitative discussion of how your estimates of precision are achieved. Remember that experimental uncertainty (error) has to do with factors internal to your own experiment such as the precision of meters, reproducibility of readings, statistical errors, systematic errors, and the like.

Quantitative comparison of your results to theory or to an accepted value of the quantity in question should also be included in this section. The difference between your result and the accepted value IS NOT the error in the experiment. Rather, this difference, considered in the light of the experimental error, is a measure of the degree of *agreement* between your experiment and the theoretical or accepted value. As the semester continues, the subject of proper treatment of experimental errors will be discussed in the lecture hour, so your discussions will be expected to be more complete as spring nears.

Appropriate graphs of your experimental data are essential. While tables of numbers may often be necessary, they are rarely sufficient to convey to the reader the significance of your results. A picture is worth a thousand words. Similarly, a carefully drawn graph conveys far more information than endless tables of numbers. All points on the graph should have experimentally-justified error bars indicated for the dependent variable, and, where appropriate, for the independent variable as well. Where appropriate, straight lines or curves

fit to the data should also be shown. Graphs are to be computer generated, even if you plotted the raw data by hand in your log book. The graphs in your reports will be judged on how well they represent the data rather than on how fancy they are.

The Results section is the place for a discussion of the uncertainties (error) in the experiment. In general, there may be other sources of error than the ones accounted for in your quoted experimental error, particularly if that error is obtained solely from statistical analysis of the data. The existence of other sources of error may be indicated by a disagreement between your results and a previous experiment, or the prediction of theory. Do the best you can to suggest what these other sources are and what their *quantitative* effect on your results might be.

5. **Conclusions.** Do not make any 'new' claims here that were not discussed in the previous section. The conclusions are what you've been aiming at from the beginning. **DO NOT SLIGHT THIS SECTION. GIVE IT ITS FULL DUE!** After all, it is the culmination of a lot of hard work, and the world is waiting to find out what you have learned from it all.

In the Conclusions section, summarize the results, quantitatively (even though that means repeating previous statements) and qualitatively if that is appropriate. This section is important, but a proper form is hard to prescribe. An instructor in a hurry may well look here first, so use care in this section. Scientists, who are often too busy to read all that they should, may read just the introduction and conclusion of a journal article. Thus, the basic message of the work must be clear from just these sections. In a mere lab report, suggestions for a better experiment or better procedure are often made at the end, but this should not dominate this section of a scientific paper. *Warning:* Do not make statements here that your previous sections do not support.

EXPERIMENT DESCRIPTIONS

The following are brief descriptions of the Modern Physics Laboratory experiments in operation for this semester. It is intended as an aid in selecting experiments.

Chaos

Purpose: To study the chaotic behavior of a forced vibrating beam in a double-well potential.

One of the hot fields of physics is also one of its oldest: classical mechanics. It is now possible to make some progress in studying the behavior of the vast majority of mechanical systems, those that obey non-linear differential equations. The system studied in this experiment approximates the forced Duffing oscillator. In this experiment the student investigates the parameters of the "pseudo" potential in the Duffing equation approximation, takes data on a PC, and analyzes the fractal dimension of the natural Poincaré section of the motion. As an interesting side light, students will also study the fractal dimensions of pieces of wire and of aluminum foil squeezed into spherical balls.

Characterization: Many new concepts and sidelights to investigate. Experiment requires care and patience in taking data. This experiment takes longer than average.

Compton Effect

Purpose: To measure the Compton effect in aluminum, i.e. the energy shift of gamma rays scattered from atomic electrons as a function of scattering angle, and the angular dependence of the differential cross section for Compton scattering.

The source of gamma rays is a long lived gamma emitter; detection is with a NaI scintillation crystal gamma ray detector and a multichannel analyzer. This experiment provides experience in measuring gamma ray energies accurately. Measurement of the gamma ray energy as a function of scattering angle is straightforward. The second part, measurement of the angular dependence of the differential cross-section, is more difficult. Care and thoughtful analysis are required to get a reasonable measurement of the differential cross section to compare to the Klein-Nishina formula.

Characterization: Though small scale, this experiment embodies many of the major components of a modern high energy physics scattering experiment. High precision agreement between differential cross sections and the Klein-Nishina formula is not to be expected.

Cosmic Ray Muons

Purpose: To measure the lifetime for muon beta-decay and to measure the flux of cosmic ray muons at sea level.

Muons generated in the upper atmosphere are incident on the earth's surface with a sizable flux. The apparatus detects those muons that stop in a plastic scintillator, marking first the time at which they enter, then the time at which the decay product produces a signal. The events accumulate at the rate of roughly five per minute, so that enough can be counted in a day to produce a decay curve that yields the lifetime. Final data should be taken for several days. The student gets experience in aligning the electronics of a typical coincidence experiment, and in doing statistical analysis of a decay curve with typical counter experiment random background.

Characterization: Medium length experiment. It is possible to get excellent answer for muon lifetime.

Electron Spin Resonance (out of service during Spring 2009)

Purpose: To observe the ESR of several paramagnetic samples, including the free radical DPPH, the paramagnetic salts CuSO_4 , $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, and MnCl_2 , and solutions of various concentrations of MnCl_2 in water. Students will determine some of the parameters of the resonances, such as g-value and line width, and will learn their meaning in terms of the ionic surroundings of the paramagnetic ions in the crystal and, for MnCl_2 , in dilute solution in water. They will also learn the operation of a simple ESR Spectrometer.

The source of microwave radiation is a 9 GHz klystron, attached to various pieces of waveguide apparatus. The samples are placed in a cavity in the magnetic field of a Varian benchtop magnet. The field is swept through the value for which the Larmor frequency of precession of the electron spins is equal to the klystron frequency. The resultant absorption of microwave power from the cavity by the spin system is detected, and either displayed on the oscilloscope or recorded on a chart recorder. The theory of this experiment involves learning about the effects of electrostatic crystalline fields on the motion of electrons in d-shells of the transition elements Cu and Mn. The structure of the resonance of the Mn sample provides an interesting puzzle for the student to work out.

Characterization: New concepts, both in experimental equipment and condensed matter physics. Average length, straightforward experiment.

Light Scattering

Purpose: To measure the size of small colloidal particles using dynamic light scattering.

The intensity of light scattered by microscopic spheres suspended in water fluctuates because of the motion of the scattering particles, which are undergoing Brownian motion. The time dependence of these fluctuations is analyzed to extract the particle size. The Einstein relation between viscosity and the diffusion constant is used to get the final result. This experiment uses a He-Ne gas laser as a light source, a photomultiplier to detect the scattered light, a storage scope to collect and display the data, and a PC for final storage and analysis.

Characterization: Substantial new concepts both in the theory and in understanding how the apparatus works. Taking data is straightforward if somewhat lengthy. Rewards efficiency in taking and simultaneously analyzing data.

Magnetic Susceptibility

Purpose: To measure the paramagnetic susceptibility of three paramagnetic salts by the Gouy balance technique. Students may also examine the magnetic response of a metal and a high temperature superconductor.

The Gouy balance method measures the force on a cylindrical sample of the salt in a magnetic field gradient, using a sensitive balance. By measuring at room and liquid nitrogen temperatures, one obtains for both samples the Curie constant, and the Curie-Weiss or Neel constant for each salt. From the Curie constant one obtains the effective magnetic moment of the magnetic spins in each sample. There is a close connection between the underlying physics of this experiment and the ESR experiment.

Characterization: Relatively short, straight-forward experiment.

Mössbauer Effect

Purpose: To observe the Mössbauer effect of recoilless emission and absorption of nuclear gamma rays. The energy-level splitting known as the Zeeman effect is studied along the way.

The experiment makes use of the 14.4keV gamma rays from nuclear transitions in ^{57}Fe , using a radioactive source of ^{57}Co embedded in Cu and four distinct iron rich absorption samples, to demonstrate internal magnetic field splitting, electric quadrupole splitting, and the nuclear isomer shift. The source speed is varied using a standard linear velocity sweep, and the Doppler-shifted 14.4 keV gamma rays are detected with a proportional counter. The student adjusts a discriminator to exclude as much as possible counts from all but the 14.4 keV gammas. The positions and widths of the Mössbauer lines are analyzed off-line. The Heisenberg Uncertainty Principle is also probed using the measured width of the 14.4 keV gamma ray line and the known lifetime for its emission.

Characterization: Longer length. Concepts: Doppler shifted gamma rays, recoilless gamma-ray emission and absorption, and internal electric and magnetic fields at nuclear sites in solids. The Zeeman effect at the nuclear level. Seeing line width broadening and absorption saturation.

Neutron Activation Analysis

Purpose: To determine the content of materials by examining the unique signature of their gamma ray emission spectra and their lifetimes following nuclear absorption of thermal neutrons.

The experiment uses a weak source of neutrons moderated by paraffin in a small barrel to activate the samples. Only the instructors have access to this source. The students calibrate the NaI crystal scintillator and pulse-height analyzer with gamma sources of known energy, much as is done in the Compton effect experiment, and then examine the activated gamma spectra and lifetimes of the excited states of both known and unknown samples. Also, the thermal neutron flux can be determined from the gamma ray yield.

Characterization: Straightforward experiment of average length. Introduces counting statistics and develops familiarity with isotopes across the periodic table.

Optical Pumping

Purpose: To observe and measure the hyperfine levels in atomic rubidium vapor using a technique which manipulates the quantum levels populated by the atomic electrons.

Rubidium energy levels are manipulated by placing them in external magnetic fields. Transitions between levels are stimulated by shining light through the vapor. Measurements are made of the g-factors characterizing two isotopes of Rubidium. The local magnetic field of the Earth can be measured with high precision. Learn about atomic spectroscopy. Spin precession (“Rabi oscillations”) can be observed and interpreted. The physics of the Zeeman effect and magnetic resonance are both contained in this experiment.

Characterization: Average-to-long experiment. It exemplifies several aspects of atomic spectroscopy involving angular momentum states. Several experimental techniques used are fundamental to many other atomic and optical physics experiments.

Nuclear Magnetic Resonance

Purpose: To observe and measure relaxation times of proton NMR in glycerin and water solutions of inorganic salts by using the pulsed spin-echo technique.

The student learns about the formation of the free induction decay and the spin echo in NMR experiments and the definitions of the longitudinal and transverse relaxation times (T_1 and T_2) in these samples. Several pulse sequences will be introduced and used.

Characterization: Concepts of spin precession, RF pulsing, and spin-echoes will be learned. It is the foundation for modern MR Imaging technology. May take longer than average.

Raman Spectroscopy

Purpose: To explore molecular vibrations using Raman scattering.

The atoms in molecules oscillate about their equilibrium positions. We use the inelastic scattering of light from these oscillations, Raman scattering, to probe the symmetry and strength of the bonding within the molecule. Raman scattering is a key research tool in physics and chemistry.

Characterization: Students learn about chemical bonding, molecules as harmonic oscillators, and the interaction of light with molecules. They will have the opportunity to use a Raman spectrometer of the same type as is found in a modern research laboratory.

Thermal Lensing

Purpose: To study the nonlinear optical process, thermal lensing, and use it to determine the optical absorption length of an extremely weakly absorbing liquid.

When a laser beam passes through a medium, it locally heats the medium along the beam. This heating causes the index of refraction to change locally, and the medium to act as a diverging lens. With proper arrangement of the optics, this effect -- called thermal lensing or thermal blooming -- can be detected even if the heating is very small.

Characterization: The student will use concepts in classical optics but will also observe many phenomena unique to optical propagation of laser beams.

X-ray Diffraction

Purpose: To determine lattice constants and other structural details of a number of different crystalline and non-crystalline materials by means of Bragg diffraction.

Students will learn the various types of cubic symmetry and the effect of structure factors on the spectrum of Bragg peaks. Samples include various alkali-halide compounds, metals, and other materials, selected according to the students' interest. Methods include both Laue photography and powder diffractometry. The emphasis of the experiment may be more heavily on the physics of x-ray diffraction or on crystallographic techniques, and will be tailored according to the students' interest.

Characterization: Average to longer-than-average, depending on the options chosen by the students. There are some new concepts not covered in the usual introduction to X-rays and Bragg scattering in 33-211. Radiation safety training is required before students can begin work on this experiment. See instructor for details.

The Zeeman Effect

Purpose: To observe the Zeeman Effect in an isotope of cadmium emitting light in a discharge tube and to use the results to make a quantitative determination of the splitting of a particular spectral line as a function of magnetic field, measure the g-factor of the electron, and understand the atomic structure for the transitions involved.

The experiment uses a Fabry-Perot interferometer. Students who have not had optics should study the theory of this device. The interferometer is a variable spacing type, with small spacing changes produced by piezoelectric crystals. The object of this experiment is to measure the Zeeman splitting as a function of magnetic field. This is done by measuring the fields at which interference patterns from different transitions overlap for each of several Fabry-Perot plate spacings.

Characterization: Experiment of average length. It will strongly reinforce understanding of level-splitting of atomic transitions due to external perturbations.