

**This is the information sheet for the last time I taught this class.
The class this summer (2012) will be very similar, if not identical.**

Course Information for Physics 575 Winter Quarter 2009

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Brief course description: Condensed matter and atomic experimental physics, including: classical and modern state-of-the-art experimental methods, experimental design and philosophy, the intellectual content and excitement of experimental physics, and the current frontiers.

Required Text: There will not be a formal textbook for this course. Instead we will use a set of lab binders. There is one binder for each experiment. Each one contains a wide variety of information for that lab.

Each binder starts at the introductory level---similar to that of Scientific American or Physics Today. Next it moves to the physics textbook level. Finally it moves to physics journals. You don't have to read the entire binder !!! In fact, there will be more material than you can easily read. The binders are intended to serve as comprehensive references that you can consult as you do the lab---especially as you write your lab report.

Grading: There will not be any exams in this course. Your grade will be based on your lab report grades.

How to get the most out of this class

What happens during the various meeting of each lab?

There will be four meetings for each lab, the goals of the first lab meeting are for you:

(1) to get familiar with the equipment---i.e., you should play with it for a while to make sure that you really know how it works!!!

And once you do....then,

(2) to take some data quickly, so that you can go away and analyze it before the next meetings. Only by taking some data, and by analyzing it before you write your lab report, can you be sure that you have decent meaningful data worth writing up!!!

What's with all the reading?

If you have looked through your thicklab binder, you're probably thinking: "He can't possibly expect us to read all this?!?" If you are, you are correct! I don't expect anyone to read everything in any of the binders! So, why have I given you "too much" material? The material that I've given you is a rather complete reference manual that would be a good start if you wanted to work seriously on one of these experiments. I'm going to give you some very specific recommendations for the pieces that I think everyone must/should read, and then I'm going to explain briefly what all the rest of it is, so everyone can read the bits and pieces that they find particularly interesting. Since you may, or may not, be able to get your hands on a book or article from the library that helps you with the lab, I'm giving you the best things I've found for the students after teaching the course numerous times. If you find something better, please let me know!!! In particular, there are lots of new lab resources on the internet that I have not yet located/identified.

So please do not mess up your copy of the binder, and please return at the same time that you turn in your lab report!!!

Your fellow students are counting on you to keep it clean and to return it on time, and you are counting on them!!! You may xerox anything you want to keep out of the binder, but you must return the original material to the binder.

The first lab meeting:

(1) **Read** at least one of the articles in the introductory section---so that you will have some understanding of, and feeling for, the physics behind the lab, before jump in!

Read the one page list of goals for the lab---so you will have some idea of what to do!

Teach the next group how to do the lab that you did the previous cycle.

(2) Of course, there will be things that you do not understand about each lab, and you won't have time to figure them all out before starting the lab! So make a **list of questions**, e.g., about the physics behind the lab, about the equipment used in the lab, about the experimental procedure for the lab, about the error analysis for the lab, about the best experimental art used in the lab, etc. The group teaching you (and Diedrich and I) will be glad to try to answer these questions.

The second lab meeting:

(1) Quickly **analyze** the data that you took during the first meeting, and think about the lab and your analyzed results: Are there things you need to figure out before you can take your "publication quality" data? Do you have a clear plan for what you need to measure, and exactly how you are going to do it?

(2) You will probably find it very useful to re-read some of the prelab reading, and to browse through the other material---for example, to start to understand how to do the analysis!

(3) Make a list of **questions** that you want to ask during the second meeting. Again, the group teaching you (and Diedrich and I) will be glad to try to answer these questions.

The third lab meeting:

Well, one idea for the third meetings is for you to try to do something creative!!! It will work out best if we talk during the before hand about what you'd like to do during the third meeting. The other important things for you to do during the third meeting are:

1) Ask your teaching groups (and Diedrich and I) to answer your questions at that point.

2) If you have analyzed some of your data, ask your teaching group (and Diedrich and I) to help you understand and interpret it. You can do this anytime before you turn in your lab report....

The fourth lab meeting:

1) Get your teaching group to give you their minilecture on the physics of the lab.

2) Finish analyzing your data so that your teaching group (or Diedrich or I) can check it for clarity and veracity.

After each lab....doing your lab report!!!

You must prepare a brief written lab report and turn it in on (or before) the due date! I will be glad to try to answer the additional questions that you will inevitably discover as you try to write your lab report. The reason that I'm asking you to write a lab report on each lab, is that I know you'll learn a lot more if you have to write it down and turn it in!!! **I want you to learn as much as you can about physics in general, and about experimental physics in particular, during this class!!! What I really want to see from your lab reports is that you've learned some physics by doing the lab and by writing it up.**

Learning is the most important thing in this class; clarity, simplicity, and quality are the next most important things!!!

You don't need to write a long report; I'm much more interested in quality than quantity! As noted above, I want you to learn as much as possible while doing the write up! I am interested in your ideas, thoughts, and suggestions about these experiments; please do not simply copy descriptions line-by-line, word-by-word from some book or article. However, I do want you to learn the facts....and I know that one good way for you to learn the facts is for you to write them down in your own words by following and working through one (or several) of the standard discussions!

Here are some suggestions about some of the things that you might want to discuss in your lab report:

- (1) What is the most important physics behind the lab?
I really want you to learn the physics---that it is the most important thing!!!
- (2) Briefly describe the equipment used in the lab.
I really want you to learn what the hardware does!
- (3) What did you do during the lab?
Please tell me the important canned things, but I also want to hear the unusual things!
- (4) What did you find?
Crystal clear, short, and sweet, is fine for this one!
- (5) Describe your error analysis
You don't need to do a formal error analysis, but you should explain how well you trust your results, and why! Also, what don't you trust, and why?
- (6) What was the most artistic thing about the lab?
What did you find particularly beautiful, elegant, and artistic about the physics behind the experiment and/or about the experimental physics?
- (7) What did you learn about the physics behind the lab?
What didn't you know before the lab that you know now?
- (8) What did you learn about experimental physics?
What didn't you know before the lab that you know now?

There's no maximum or minimum limit on the number of pages....the best lab reports typically contain 4-8 pages of text. Please explain your ideas about some of the 8 topics above. Summary plots, pictures, and figures are also very important components of a good report! Please turn in a copy of your data!

I want to hear your thoughts, impressions, and ideas!!! I do not want you to simply regurgitate standard textbook material!!! Translate the words and ideas in the books and articles into your words and your ideas---i.e., LEARN IT!!!

Teaching Methodology

We will use the same teaching methodology that medical schools traditionally use:

Watch One---You will watch the previous group show you how to do the experiment.

Do One---You will do the experiment with help as needed from the previous group.

Teach One---You will teach the next group how to do the experiment.

The previous group will be available to help you understand the experiment and to do it successfully---so, if you get stuck, please ask them for help. That will help them learn. You, in turn, will teach the next group both how to do the experiment and how to understand the physics.

You will discover that one of the very best ways to really learn something well is to teach it !!!

The Physics 575 Experiments

The Physics of Noise:

Noise 1: Shot Noise and Johnson Noise---You will learn how shot noise is due to the quantization of electrons and you will use it to measure the charge of the electron. You will learn how Johnson noise is due to the thermal fluctuations of the electrons and you will use it to measure Boltzmann's constant. For a given current at a fixed temperature, these two noise sources determine the best you can possibly do, and they therefore have very profound implications not only for experimental physics but for all technology!!!

Robert Millikan received the 1923 Nobel Prize in Physics "for his work on the elementary charge of electricity and on the photoelectric effect."

Noise 2: How to Hear a Hummingbird in a Hurricane---You will learn about the three primary experimental tools that we have for recovering small signals buried in noise: lock-in amplifiers, signal averagers, and spectrum analyzers. You will also learn how they work and how they improve the signal-to-noise ratio.

The Physics of Resonance:

NMR 1: CW Nuclear Magnetic Resonance---You will learn Edward Purcell's quantum mechanical description of NMR and you will learn Felix Bloch's classical description using Newton's equations and Maxwell's equations. You will measure the gyromagnetic ratio of the proton and you will make a high-precision measurement of the ratio of the g-factor of the proton to that of the fluorine-19 nucleus.

Felix Bloch and Edward Purcell received the 1952 Nobel Prize in Physics was awarded to "for their discovery of new methods for nuclear magnetic precision measurements and discoveries in connection therewith".

NMR 2: Pulsed Nuclear Magnetic Resonance---You will become a spin doctor---you will be able to prepare a large number of nuclear spins in a specific quantum state and to watch their time evolution.. You will learn how to measure T1 and T2 using spin echo techniques and you will measure them for a variety of samples.

Richard Ernst received the 1991 Nobel Prize in Chemistry "for his contributions to the methodology of nuclear magnetic resonance (NMR) spectroscopy."

Kurt Wutrich received the 2002 Nobel Prize in Chemistry "for his work to make NMR applicable for detailed studies of large molecules like proteins has given us new tools for investigations of the processes that constitute life."

Paul Lauterbur and Peter Mansfield received the Nobel Prize in Physiology or Medicine for 2003 "for their discoveries concerning magnetic resonance imaging"

SPR: Surface Plasmon Resonance---You will learn how many-body systems can often be described extremely well in terms of quasi-particles. Surface plasmon quasi-particles are the quantized collective oscillations of the photons and the electrons at the surface of a metal or semiconductor. You will learn how surface plasmons can be described in terms of Maxwell's equations. You will also learn the connection between the complex-valued dielectric constant and the complex-valued index of refraction.

The Physics of Diffraction and Interference:

Diffraction---You will learn about the physics of diffraction. You will measure and calculate the diffraction patterns for one- and two-dimensional crystals. You will learn about the 17 space groups in two-dimensions and you will learn how and why crystallography works.

Max von Laue received the 1914 Nobel Prize in Physics "for his discovery of the diffraction of x-rays by crystals." *

W.H. Bragg and W.L. Bragg received the 1915 Nobel Prize in Physics "in recognition of their services in promoting the investigation of crystal structures by means of X-rays." *

Interferometry---You will learn about the physics of interference. You will learn how Fabry-Perot interferometers work and why they are an essential ingredient of lasers. You will learn how Michelson interferometers work, and how they were used to do the Michelson-Morley experiment. You will learn how superconducting quantum interference devices (squids) work, and you will use one to measure the magnetic flux quantum.

Albert Michelson received the 1907 Nobel Prize "for his optical precision instruments and metrological investigations carried out with their aid."

Brian Josephson received the 1973 Nobel Prize in Physics "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as Josephson effects".

The Experimental Road to Quantum Mechanics:

Franck-Hertz Experiment---You will repeat the first experiment that used a probe other than photons to prove that the energy levels of atoms are quantized. This experiment provided crucial evidence that atoms have quantized energy levels.

James Franck and Gustav Hertz received the 1925 Nobel Prize in Physics "for their discovery of the laws governing the impact of an electron upon an atom."

Compton Scattering---You will repeat the first experiment that demonstrated the particle nature of photons. "After some preliminary work, he found an experimental method that gave results which were as exact as they were astonishing. Compton deduced a new kind of corpuscular theory, with which all experimental results showed perfect agreement within the limits of experimental error."

Arthur Compton received the 1927 Nobel Prize in Physics "for the discovery of the phenomenon named after him the Compton effect."

Moseley's Law and the X-Ray Spectra of Atoms---You will measure and calculate the x-ray emission lines of multi-electron atoms. You will learn how Moseley used x-ray fluorescence to correct the initial mistakes in Mendeleev's periodic table. You will learn how x-ray fluorescence is used to detect the elemental composition of unknown samples here on Earth and on Mars.

Charles Barkla received the 1917 Nobel Prize in Physics "for his discovery of the characteristic Roentgen radiation of the elements."

Hanle Effect---You will measure the Hanle effect in mercury, and you will learn about level crossing spectroscopy. Wilhelm Hanle discovered this effect, and wrote his thesis about it overnight. His experiment forced us to revise the old quantum theory to include the quantum superposition of degenerate states. For a very long time, Hanle's method was our only doppler-free way to measure atomic lifetimes.

The Experimental Road to the Laser:

Optical Pumping---You will measure the optical pumping of rubidium-85 and rubidium-87, and you will understand how this marvelous effect can be used to build fantastic magnetometers, atomic clocks, masers and lasers. Optical pumping was crucial for the development of the laser.

Alfred Kastler received the 1966 Nobel Prize in Physics “for the discovery and development of optical methods for studying Hertzian resonance in atoms.”

The Microwave Spectrum of Ammonia---You will measure the frequencies of the tunneling of the nitrogen atom through the hydrogen triangle. You will learn the physics of the quantum mechanical double-well which governs this problem, and which is so important in many other physical systems.

Charles Townes received the 1964 Nobel Prize in Physics “for fundamental work in the field of quantum electronics which has led to the construction of oscillators and amplifiers based on the maser-laser principle.”

* There have been 22 more Nobel Prize Laureates honored for their contributions to diffraction and crystallography:

1936 Debye
1937 Davisson and Thomson
1962 Perutz, Kendrew, Wilkins, Watson, and Crick
1964 Hodgkin
1976 Lipscomb
1985 Hauptman and Karle
1982 Klug
1986 Ruska, Roher, and Binnig
1988 Deisenhofer, Huber, and Michel
1994 Brockhouse and Shull
1997 Walker
2006 Kornberg

NMR-1

Your primary goals for this lab are:

- 1) To determine the gyromagnetic ratio γ of the proton using the measured resonance frequency f at a single value of the magnetic field B_0 , via $\gamma = f / B_0$.
- 2) To make a more precise measurement of the gyromagnetic ratio of the proton by measuring the resonance frequencies over a range of magnetic fields, and then using the slope of the resonance frequency versus magnetic field plot to determine γ . To understand why this provides a more precise determination. You should also check the effect of including the point at the origin, i.e., the point ($f=0$, $B_0=0$), on your result.
- 3) To determine the g-factor of the proton from your measured value of γ , and especially understand the physical meaning of the g-factor. Why is the g-factor of the electron so close to 2, and why is the g-factor of the proton so far from 2?
- 4) To make a precise measurement of the ratio of the g-factor of the proton to the g-factor of the fluorine-19 nucleus. Please note that Parts 1, 2 and 3 above, are limited by the accuracy of the Hall effect gaussmeter---which is only good to several percent. However, since this part (Part 4) measures the ratio of the resonance frequencies (which are accurate parts in ten million), this measurement of the ratio is much more precise than Parts 1-3.
- 5) To understand Edward Purcell's quantum mechanical description of NMR---including both absorption and emission
- 6) To understand Felix Bloch's classical description (i.e., using Newton's equations and Maxwell's equations)---including both absorption and emission.
- 7) To understand the relationship between Bloch's picture and Purcell's picture.

Day One: Learn how to take data, and take a preliminary set of data for the resonant frequency of protons, $f(\text{protons})$, versus the applied magnetic field.

Day Two: Take final data sets for $f(\text{protons})$ and $f(\text{fluorine})$ versus the applied magnetic field, and for $f(\text{protons})$ versus $f(\text{fluorine})$.

Day Three: Analyze your data. What value do you obtain for the g-factor of protons? How does this compare to the literature value? What value do you obtain for the g-factor of fluorine-19? How does this compare to the literature value? What value do you obtain for the ratio $[f(\text{proton}) / f(\text{fluorine})]$? How does this value compare with the literature value?

NMR-2

Your primary goals for this lab are:

- 1) To understand how to measure T2 using spin echo techniques via the A=90 degree and single B=180 degree pulse sequence.
- 2) To understand how to measure T2 using spin echo techniques via the A=90 degree and multiple B=180 degree pulse sequence.
- 3) To understand how to measure T1 using pulse techniques via the A=180 degree and single B=90 degree pulse sequence. {Why can't we apply multiple B pulses?}
- 4) To measure T1 and T2 for mineral oil using the three techniques above.
- 5) To measure T1 and T2 for the protons in water versus the concentration of copper sulfate ions in the solution.
- 6) If you want to, you can do something creative on the third day---for example, you could measure T1 and or T2 for a sample, or samples, of your choice. Some potential candidates include vaseline, paraffin, alcohol, a different paramagnetic solution,

Day One: First, learn about the apparatus, and then learn how to prepare specific spin states and to use them to measure the characteristic decay times by doing items 1 through 4 above.

Day Two: Measure T1 and T2 for the protons in water as a function of the concentration of copper sulfate ions in solution (item 5 above).

Day Three: Analyze your data. Plot T1 and T2 versus the logarithm of the copper sulfate concentration. How do your measured T1 and T2 values behave? Can you explain why? Explain the simple physics which governs T1 and T2.

Noise-1

Your primary goals for this lab are:

- 1) To measure the Johnson noise versus resistance for a series of resistors (0.2, 2, 20, 200, 2000 Ω) and to use your measurements to calculate the “quantum of information”, which is also known as Boltzmann’s constant k_B . Also to measure the Johnson noise versus temperature (i.e., 300 versus 77 Kelvin) for a 20 Ω resistor.
- 2) To measure the Shot noise produced by a temperature-limited vacuum tube diode versus the dc current flowing through the tube, and to use your measurements to determine the “quantum of charge”, which is also known as the magnitude of the charge of the electron e .
- 3) To accomplish items 1 and 2 above, you will need to learn how to measure the frequency response of the experimental apparatus---which is not ideal due to the effects of the stray capacitance and due to the limited frequency response of the preamplifier. You will also need to learn how to correct for the noise which comes from the preamplifier and from the spectrum analyzer.
- 4) To understand the physics of Johnson noise, and the close connection between Johnson noise and black body radiation, and to understand how the Johnson noise can be used to measure Boltzmann’s constant.
- 5) To understand the physics of Shot noise, and to understand how it can be used to measure the charge of the electron.

Day One: Learn how to take data using the spectrum analyzer, and then take a quick set of Johnson noise data.

Day Two: Take final sets of Johnson noise data and of Shot noise data.

Day Three: Analyze your noise data to obtain e and k_B . How do your values compare to the literature values for these quantities?

Noise-2

Your primary goals for this lab are:

- 1) To understand the three primary experimental tools that we have for recovering small signals buried in noise, and to learn how the signal-to-noise ratio improves with the signal processing they provide.
- 2) To understand signal averagers.
- 3) To understand lock-in amplifiers.
- 4) To understand spectrum analyzers.

Day One: Measure the improvement in the signal-to-noise ratio produced by signal averaging. Set up the signal generator to produce a 1 volt rms noise output. Connect this to the input of the signal averager. Measure the rms noise after signal averaging versus N the number of samples in the average. Plot the rms noise at the output of the signal averager versus N for $N = 1, 2, 4, 8, 16, 32, 64, 128, 256,$ and 512 samples, and compare your measured values with the theoretically predicted results.

Determine the smallest electronic signal that you can detect buried in 1 volt rms noise using the signal averager. Determine the smallest optical signal that you can detect using the signal averager.

Day Two: Measure the improvement in the signal-to-noise ratio produced by the lock-in amplifier. Set up the signal generator to produce a 1 volt rms noise output. Connect this to the input of the lock-in amplifier. Measure the rms noise at the output of the lock-in amplifier versus T the time constant of the lock-in. Plot the rms noise at the output of the lock-in amplifier versus T for $T = 0.01, 0.03, 0.1, 0.3, 1.0, 3.0$ and 10.0 seconds, and compare your measured values with the theoretically predicted results.

Determine the smallest electronic signal that you can detect buried in 1 volt rms noise using the lock-in amplifier. Determine the smallest optical signal that you can detect using the lock-in amplifier.

Day Three: Measure the improvement in the signal-to-noise ratio produced by spectrum analysis.

Determine the smallest electronic signal that you can detect buried in 1 volt rms noise using the spectrum analyzer. Determine the smallest optical signal that you can detect using the spectrum analyzer. Compare the vector and magnitude averaging features of the spectrum analyzer.

Interferometry Part A: Squids

Your primary goals for this lab are:

- 1) To observe the Meissner effect with a magnet and a chunk of high-temperature superconductor, and to understand the Meissner effect.
- 2) To measure the voltage versus current $\{V-I\}$, and the voltage versus magnetic flux $\{V-\Phi\}$ behavior of a superconducting quantum interference device (SQUID).
- 3) To make a crude measurement of the magnetic flux quantum Φ_0 from the periodic behavior of the SQUID that you measure via its $\{V-\Phi\}$ behavior. To understand the origin and meaning of the magnetic flux quantum.
- 3) To understand (and to be able to explain) the behavior you measure in terms of the simple quantum mechanics of two coupled Josephson junctions. You will actually see macroscopic quantum interference effects with your own eyes---because all of the superconducting electron pairs are described by the same macroscopic wavefunction! Please note that this interference is very similar to the usual double slit diffraction pattern, that the effect of the magnetic flux on the voltage across the SQUID is precisely analogous to the Aharonov-Bohm effect on the usual double slit experiment.
- 4) To use the Shapiro steps present in the ac Josephson effect to make a precise measurement of the magnetic flux quantum Φ_0 , and to understand how the quantization of charge and the quantization of the macroscopic wavefunction lead to this quantized magnetic flux quantum.
- 5) To understand (and to be able to explain) both the ac and the dc Josephson effects. To understand (and to be able to explain) how a SQUID works quantum mechanically, and how it can be used to make extremely precise measurements of extremely small voltages, currents, and magnetic fields.

Day One: Do the two versions of the Meissner effect, namely: (1) cool the superconductor and then put the magnet on it. (2) Put the magnet on the superconductor and then cool them both. How much work does the superconductor do when it lifts the magnet in part 2? Where does this energy come from? Measure the $\{V-I\}$ and $\{V-F\}$ curves for the Squid.

Interferometry Part B: Fabry-Perot

Your primary goals for this lab are:

- 1) To understand how Fabry-Perot interferometers work.
- 2) To understand the free spectral range and the finesse of a Fabry-Perot interferometer.
- 3) To understand how Fabry-Perot resonators are used to provide the feedback in laser oscillators, and why most lasers oscillate in multiple longitudinal modes.
- 4) To use a simple Fabry-Perot interferometer to measure the longitudinal mode spacing of several lasers.

Day One: Use the HeNe laser. First, set up the Fabry-Perot interferometer with a small mirror separation. Observe the interference pattern and measure the transmission versus the cavity separation. Then, set up the Fabry-Perot interferometer with a large mirror separation. Observe the interference pattern and measure the transmission versus the cavity separation. What is the optimum length of the measurement Fabry-Perot cavity with respect to the HeNe cavity---i.e., what happens when the two cavities have the same length?

Interferometry Part C: Michelson

Your primary goals for this lab are:

- 1) To understand how Michelson interferometers work.
- 2) To learn how to use Michelson interferometers to measure optical interferograms and learn how to determine the optical spectrum from the interferogram.
- 3) To measure the optical interferograms for a HeNe laser, a semiconductor laser, a white light source, and the green line of mercury.
- 4) To understand the original Michelson-Morley experiment.
- 5) To read Albert Michelson's Nobel Prize Lecture.

Day One: First learn how to do so, and then measure the interferograms for the laser. Measure the interferograms for the white light source and for the mercury line. What are your measured coherence lengths for each light source?

Surface Plasmon Resonance

Your primary goals for this lab are:

- 1) To measure the reflectivity versus incidence angle of a silver film in the ATR (attenuated total reflection) geometry at two HeNe laser wavelengths (i.e., red and green), and to understand the measured reflectivity in terms of the excitation of surface plasmons in the silver film.
- 2) To understand that many-body systems can often be described extremely well in terms of quasi-particles. In this case, the collective oscillations of the electron gas at the surface of the silver sample can be described very well in terms of surface plasmon quasi-particles. Of course, the most famous example is the collective excitations of the atomic vibrations in the lattice, which can be described very well in terms of phonon quasi-particles. Plasmons and phonons aren't really particles---they are collective excitations of the electron gas and of the lattice, respectively---but they are described very well in terms of quantum mechanical "particle-waves" called quasi-particles which allow us to express the conservation of energy and momentum in a very simple fashion.
- 3) To understand how surface plasmons can be described in terms of Maxwell's equations.
- 4) To see how these reflectivity curves depend on the real and imaginary components of the complex valued dielectric constant, and on the thickness, of the silver film.
- 5) To understand the connection between the complex valued dielectric constant and the complex valued index of refraction, and to understand how these two quantities are related to the reflection and the absorption of light by the silver film.

Day 1: Learn how to take data, and then measure the SPR curve. Calculate the SPR curve. Change the real part of the complex dielectric constant, the imaginary part of the complex dielectric constant, and the thickness of the silver film in the analysis program and document how each one changes the SPR curve.

The Franck-Hertz Experiment

Your primary goals for this lab are:

- 1) To study, and to understand, the Franck-Hertz effect for mercury and for neon.
- 2) To understand how and why the Franck-Hertz experiment was so crucial to the early development of quantum mechanics.
- 3) To see the Franck-Hertz bands in the neon tube, and to understand how and why the bands depend on the applied voltage as they do.
- 4) To measure the Franck-Hertz current versus voltage curves for the neon tube. For the neon tube, the filament current should be set to ~ 250 mA.
- 5) To measure the Franck-Hertz current versus voltage curves for the mercury tube. For the mercury tube, the filament current should be set to ~ 215 mA and the heater variac should be set to ~ 65 volts so that the temperature inside the oven is ~ 160 C.
- 4) To learn how to use a lock-in amplifier to take the derivatives of the mercury Franck-Hertz signal.
- 5) To learn how the lock-in amplifier takes the derivatives, and to understand how these derivatives reveal subtle features which are not apparent in the original signal.
- 6) To read James Franck's Nobel Prize Lecture.

Day One: Measure the Franck-Hertz current versus voltage curves for the neon tube and for the mercury tube. Study the evolution of the Franck-Hertz patterns in the neon tube versus the applied voltage.

Day Two: Measure the first derivative and the second derivative of the tube current versus the applied voltage for the mercury tube.

Day Three: Analyze your data. What value do you obtain for the ionization energy for neon? What value do you obtain for the ionization energy for mercury? How do your measured ionization energies compare with the literature values? Estimate the uncertainty of each of your measured ionization energies.

Microwave Spectroscopy of Ammonia

Your primary goals for this lab are:

- 1) To measure some of the microwave absorption lines in ammonia vapor which are produced by the inversion transition in ammonia.
- 2) To understand the inversion transition in ammonia---which occurs because the nitrogen atom tunnels through the hydrogen triangle---in terms of the quantum mechanical normal modes of the two-well system.
- 3) To understand the origin of the inversion transition in terms of the symmetric and anti-symmetric wavefunctions of the two-well system.
- 4) To understand the dependence of the inversion transition frequencies on the rotational quantum numbers J and K.
- 5) To understand how the interaction of the nuclear electric quadrupole moment of the nitrogen with the electric field gradient of the molecule produces the observed hyperfine splitting.
- 6) To read Charles Townes' Nobel Prize Lecture.

Day One: Measure the resonance frequencies for the most strongly absorbing lines of ammonia. Try to measure some of the weakly absorbing lines.

Day Two: Measure the resonance frequencies and the frequency splittings for some of the electric quadrupole split absorption lines. Measure some of the weakly absorbing lines. Measure the fwhm (full width at half maximum) of the resonant absorption frequency for one of the strongly absorbing lines versus the pressure of the ammonia.

Day Three: Analyze your data. What resonance frequencies did you observe and what are their J and K values? What quadrupole frequency splittings did you observe and what are their J and K values? How do your measured resonance frequencies compare with the literature values? How do your measured quadrupole frequency splittings compare with the literature values? Estimate the uncertainties of your measured resonance frequencies and of your measured splittings. Compare the pressure dependence of your measured fwhm with the theoretical prediction for collisional broadening. How well do they agree?

Optical Pumping of Rubidium

Your primary goals for this lab are:

- 1) To measure the resonance frequencies for rubidium 85 and for rubidium 87 in the earth magnetic field and to measure the earth's magnetic field using the Hall probe.
- 2) To calculate the "experimental" gyromagnetic ratios for these two isotopes from your measurements. The "experimental" gyromagnetic ratios are the ratios of the measured frequency to the measured (via the Hall probe) magnetic field for rubidium 85 and for rubidium 87.
- 3) To calculate the theoretically predicted values of the resonant frequencies, and to compare them with your measured values. Also compare the ratio of your theoretically predicted frequencies with the ratio of your measured frequencies.
- 4) To understand light induced transparency and optical pumping.
- 5) To understand how optically pumped rubidium can be used to make a very precise magnetometer, and to understand how much more accurate your rubidium magnetometer than your Hall effect magnetometer.
- 6) To understand how and why optical pumping is crucial to the operation of many lasers
- 7) To read Alfred Kastner's Nobel Prize Lecture.

Day One: Measure the earth's magnetic field with the Hall probe. Measure the resonance frequencies for rubidium 85 and 87 in the earth's magnetic field. Calculate your measured gyromagnetic ratios, and compare them with the literature values. How well do they agree?

Day Two: Repeat your measurements done on Day 1. Do you obtain exactly the same values? Do you obtain the same values within the uncertainties? What is the dominant source of uncertainty in your measurements?

Day Three: Analyze your data. What resonance frequencies did you obtain for rubidium 85 and 87. Convert your measured frequencies into magnetic fields. How do the values of the magnetic field you measured with the rubidium magnetometer compare with the value(s) you measured with the Hall probe? Which magnetometer do you trust? How do your measured resonance frequencies compare with the literature values? Predict the ratios of the rubidium 85 frequency to the rubidium 87 frequency; note that this ratio does not depend on the value of the applied magnetic field. How well does the ratio of your measured frequencies agree with the theoretically predicted value?

Moseley's X-Ray Fluorescence Law

Your primary goals for this lab are:

- 1) To measure the x-ray fluorescence spectra for the nine known samples. The atomic number Z for these nine samples is known.
- 2) To make Moseley plots of your experimental results for the nine known samples. Plot the square root of the channel number versus the Z of the sample. Make Moseley plots for all of the observed lines (i.e., $K\alpha_1$, $K\alpha_2$, $K\beta_1$, $K\beta_2$, $L\alpha_1$, $L\alpha_2$, $L\beta_1$, $L\beta_2$,).
- 3) To measure the x-ray fluorescence spectra for the six unknown samples, and to use your measurements to determine the atomic numbers of these unknowns.
- 4) To understand Moseley's Law.
- 5) To understand how and why Moseley's work was essential to the development of the periodic table.
- 6) To understand how x-ray fluorescence is used for non-destructive elemental analysis for samples containing only parts per million of the element in question.
- 7) To read the biographical information about Henry Moseley.

Day One: Measure the pulse height spectra for the nine standards, and make the associated Moseley plots.

Day Two: Measure the pulse height spectra for the six unknowns. Assign the Z of each unknown sample using your Moseley plots for the nine known samples.

Day Three: Analyze your data and compare your results with the literature values. Make Moseley plots for the literature values of the x-ray fluorescence energies for your nine knowns and six "now known" unknowns---i.e., plot the square root of the photon energy versus the Z of the sample. Also, convert your measurements from channel numbers into kiloelectronvolts. How well do your values for the photon energies agree with the literature values? How well can you assign the atomic number of your unknowns---i.e., what is the uncertainty in your Z values for the unknowns?

The Hanle Effect

Your primary goals for this lab are:

- 1) To measure the atomic excited-state lifetime of the 3P_1 state in mercury using the Hanle Effect.
- 2) To understand how and why the Hanle Effect works.
- 3) To understand how the Hanle Effect provides Doppler-free spectroscopy.
- 4) In particular, to understand why Hanle's experiment **required** the inclusion of energy eigenstate superposition in quantum mechanics.
- 5) To understand how Hanle's method has been generalized to the method called level-crossing spectroscopy. The Hanle effect is the special case of level-crossing spectroscopy at zero applied magnetic field.
- 6) To read Hanle's description of his experiment.

Day One: Measure the Hanle effect in mercury. What effect does the earth's field have on your measurements? Turn off the compensating field to find out. Understand the classical explanation of the Hanle effect.

Day Two: Repeat your measurements. Understand the quantum mechanical explanation of the Hanle effect.

Day Three: Analyze your data and compare your results with the literature values.

How well does your measured lifetime agree with the literature value? How well does your measured lineshape agree with the predicted lineshape?

Diffraction (old version needs revision)

Your primary goals for this lab are:

1) To measure Planck's constant by measuring the diffraction of optical photons from two "optical crystals" (triangular and rectangular) with known lattice spacings. You will determine the wavelength λ of the photons by measuring the diffracted angles and then using the grating equation $\lambda = d \sin \Theta$. Here d is the spacing between the lines in the grating, and Θ is the angle between the incoming and the outgoing photons.

2) To measure Planck's constant by measuring the diffraction of electrons from two thin crystals (graphite and aluminum) with known lattice spacings. You will determine the wavelength λ of the electrons by measuring the diffracted angles and then using Bragg's law $\lambda = 2 d \sin \theta$. Here d is the spacing between the Bragg planes, and θ is one half of the angle between the incoming and the outgoing electrons. So, $\Theta = (2\theta)$, or equivalently $(\Theta/2) = \theta$. N.B., for small scattering angles $\theta \sim \sin \theta$ and $\Theta \sim \sin \Theta$, and, consequently, the grating equation $\lambda = d \sin \Theta = d \sin (2\theta) = d (2\theta) = 2d\theta$ and Bragg's law $\lambda = 2 d \sin \theta = 2d\theta$ predict the same value of λ .

You will use your λ measurements to determine Planck's constant using de Broglie's law $\lambda = h/p$. So, you will also need the momentum. You will calculate the momentum p of the particles from their energy. For electrons you will use $p^2 = 2mE$ where $E = eV$. Here m is the mass of the electron, E is its kinetic energy and V is the acceleration voltage. You will use the voltmeter on the front of the electron diffraction apparatus to measure V . For photons you will use $p = E/c$.

3) And especially to understand, as Feynman put it, **the quantum mechanical way**:

"As time went on, there was a growing confusion about how these things really behaved---waves or particles, particles or waves? Everything looked like both. This confusion was resolved in 1925 or 1926 with the advent of the correct equations for quantum mechanics. Now we know how the electrons and light behave. But what can I call it? If I say that they behave like particles, I give the wrong impression; also if I say that they behave like waves. They behave in their own inimitable way, which technically could be called the quantum mechanical way. They behave in a way which is like nothing you have ever seen before. Your experience with things that you have seen is incomplete. The behavior of things on a very tiny scale is simply different. An atom does not behave like a weight hanging on a spring and oscillating. Nor does it behave like a miniature representation of the solar system with little planets going around in orbits. Nor does it appear somewhat like a cloud or fog of some sort surrounding the nucleus. It behaves like nothing you have ever seen before. There is one simplification at least. Electrons behave in this respect in exactly the same way as photons; they are both screwy, but in exactly the same way."

From *The Character of Physical Law* (1965)

4) To understand crystallography in terms of the convolution theorem---and to learn the Fourier transform of a few letters of the alphabet. To understand a crystal as a reservoir of discrete momenta due to the discrete translational symmetry of the crystal---and thereby acquire a very physical view of the reciprocal lattice in terms of the crystal momentum. The diffracted photon has a different momentum than the incident photon; the momentum required to change the photon's momentum comes from the crystal. The crystal is a reservoir of discrete momenta and the set of values of these vector momenta are the set of reciprocal lattice points.

5) To understand the origin and the utility of missing reflections. Since aluminum has a face centered cubic lattice, its diffraction pattern has fewer reflections than a simple cubic crystal. The pattern of missing reflections allows us to immediately distinguish between the different possible crystal types---in this case between simple cubic, face-centered cubic and body-centered cubic.

Day One: Obtain your photon diffraction data, by recording the optical diffraction pattern (1) for the triangular optical crystal, and (2) for the rectangular optical crystal. The easiest way to record the optical diffraction pattern is to trace it onto a sheet of white paper which you have taped onto the optical screen. This screen should be placed near the end of the table which is far away from the laser and the optical crystal should be placed close to the laser. Since you want to measure the angles of the diffracted beams, you will also need to know the distance between the optical crystal and the screen--so, be sure to measure it!

For the triangular optical crystal (Slide 3d) the spacings between its grating lines are given by $d^2 = (3/4) a^2 [h^2 + k^2 + hk]^{-1}$. For the rectangular optical crystal (Slide 7a) the spacings between its grating lines are given by $d^{-2} = [(h^2 / a^2) + (k^2 / b^2)]$. The energy of the red photons ($\lambda = 6328 \text{ \AA}$) emitted by the HeNe laser is 1.9595 eV.

Day Two: Obtain your electron diffraction data by recording the electron diffraction pattern (1) for the graphite crystal, and (2) for the aluminum crystal. The easiest way to record the electron diffraction pattern is to trace it onto a piece of an overhead transparency which you have taped onto the display. Since you want to measure the angles of the diffracted beams, you will need the distance between the crystal and the screen--this distance is 18.06 cm.

For the graphite crystal, the d-spacings are given by $d^{-2} = (4/3) a^{-2} [h^2 + k^2 + hk] + c^{-2} l^2$ and the hexagonal lattice constants $a = 2.4613 \text{ \AA}$ and $c = 6.7080 \text{ \AA}$. The graphite Bragg reflections that you measure have $l = 0$. For the face-centered cubic aluminum crystal, the d-spacings are given by $d^2 = a^2 [h^2 + k^2 + l^2]^{-1}$ and the cubic lattice constant $a = 4.0497 \text{ \AA}$.

Day Three: Analyze your data. What values do you obtain for Planck's constant from your measurements? Estimate the errors in your measured values and compare your values with the literature values---specifically, do the values you measure agree with the literature values within the experimental errors? (They Should!!!) To estimate the errors in your values of Planck's constant, you will need to estimate the errors in your λ measurements and the errors in your momentum values. Which measurement---photon or electron---gave you the best result? Why?

About Lab Reports

Your grade will be based on five written lab reports. I will be glad to answer the additional physics questions that you will inevitably discover as you write your lab reports. I am requiring you to write lab reports, *in your own words*, because I know that you will learn more physics that way.

I want to see how well you learned the physics. I do not want you to simply copy information line-by-line, word-by-word from some book, article, or the internet. I want you to learn the established facts---and I know that the best way for you to learn them is for you to write them down in your own words.

Here is what I want to see in your lab report:

(1) What did you do during the lab?

Please summarize the important canned things, but I also want to hear about the unusual things.

(2) What did you find?

Crystal clear, short and sweet, is best for this one.

(3) What does it mean?

What is the most important physics behind the lab? I really want you to learn the physics---both the experimental physics and the underlying theory. As I see it: Theorists make new theories, sometimes before the experiments, but often after. Experimentalists do new experiments. The sum total of our current understanding of the underlying physics was discovered by both and it belongs equally to both. It is very sad that it is no longer possible to be both.

(4) How well did your measurements turn out?

You do not need to do a formal error analysis, but you should explain how much you trust your results, and why. Also, explain what do not you trust, and why.

(5) What was the most artistic thing about the lab?

What did you find particularly beautiful, elegant and artistic about the experiment? Both about the experimental physics and about the underlying physics.

(6) What did you learn?

What do you know now that you did not know before?

I want you to learn as much as possible. Show me what you learned!

There is no maximum or minimum limit on the number of pages---the best lab reports typically contain 6-12 pages of text including figures. Summary plots, pictures, and figures are very important. A good picture is worth a thousand words and a good equation is worth a thousand figures. Please turn in a copy of your data.

Again I just want to be able to see how much physics you learned from doing the lab and writing the lab report. I do not want you to simply regurgitate standard textbook material. Translate the physics into your own words and especially into your own understanding.

Teaching Methodology

We will use the same teaching methodology that medical schools traditionally use:

Watch One

You will watch the previous group show you how to do the experiment.

Do One

You will do the experiment with help as needed from the previous group.

Teach One

You will teach the next group how to do the experiment, and you will be available to help them do it successfully.

If you get stuck, please ask the previous group for help. That will help them learn.

You will discover that one of the very best ways to really learn something well is to teach it !!!

What's with all the reading?

If you have looked through your thick lab binder, you're probably thinking: "He can't possibly expect us to read all this?!" If you are, you are correct! I don't expect anyone to read everything in any of the binders! So, why have I given you "too much" material?

The material that I've given you is a rather complete reference manual that would be a good start if you wanted to work seriously on one of these experiments. I will be happy to give you specific recommendations for the pieces that I think you should read.

Since all of you would not be able to get your hands on the best books or articles from the library, I'm giving you the best things that I have found for my students after teaching the course numerous times.

If you find something better, please let me know!!! In particular, there are lots of good new lab resources on the internet that I have not yet located/identified.

Here is an older version written when I was much younger, much more energetic and extremely enthusiastic---and used way too many exclamation points!!!!!!

You must prepare a written lab report. I will glad to try to answer the additional questions that you will inevitably discover as you write your lab report. The reason that I'm asking you to write a lab report on each lab, is that know you'll learn a lot more if you have to write it down and turn it in!!! I want you to learn as much as you can about physics!!! What I really want to see from your lab reports is that you've learned a lot of physics by doing the lab and by writing it up.

Learning is the most important thing in this class; clarity, simplicity, and quality are the next most important things!!!

You don't need to write a long report; I'm much more interested in quality than quantity! As noted above, I want you to learn as much as possible while doing the write up! I am interested in your ideas, thoughts, and suggestions about these experiments; please do not simply copy descriptions line-by-line, word-by-word from some book or article. However, want you to learn the facts....and I know that one good way for you to learn the facts is for you to write them down in your own words by following and working through one (or several) of the standard discussions!

Here are some suggestions about some of the things that you might want to discuss in your lab report:

- (1) What is the most important physics behind the lab?
I really want you to learn the physics---that it is the most important thing!!!
- (2) Briefly describe the equipment used in the lab.
I really want you to learn what the hardware does!
- (3) What did you do during the lab?
Please tell me the important canned things, but I also want to hear the unusual things!
- (4) What did you find?
Crystal clear, short, and sweet, is fine for this one!
- (5) Describe your error analysis
You don't need to do a formal error analysis, but you should explain how well you trust your results, and why! Also, what don't you trust, and why?
- (6) What was the most artistic thing about the lab?
What did you find particularly beautiful, elegant, and artistic about the physics behind the experiment and/or about the experimental physics?
- (7) What did you learn about the physics behind the lab?
What didn't you know before the lab that you know now?
- (8) What did you learn about experimental physics?
What didn't you know before the lab that you know now?

There's no maximum or minimum limit on the number of pages....the best lab reports typically contain 6-12 pages of text. Summary plots, pictures, figures, and equations are extremely important components of a good report! Please turn in a copy of your data!

Again I want to hear your thoughts, impressions, and ideas!!! I do not want you to simply regurgitate standard textbook material!!! Translate the words and ideas in the books and articles into your own understanding expressed in your own words.

In other terms, in the simplest possible terms, learn the physics and show me that you have learned it. That's all.