

## Physics 441/442 Advanced Laboratory – Fall 2009

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**Lab:** 4268 and 4288 PRL  
Official class hours: Mon, Tue, Thu - 1:00 pm – 5:00 pm  
The lab is OPEN for your use during working hours except when other classes are in session: M-F 9:00 am – 5:00 pm

**Course URL:** <http://instructor.physics.lsa.umich.edu/adv-labs/>

**WARNING:** Physics 441/442 is an evolving course that will continue to undergo changes from one semester to the next. Please read this handout carefully.

### A. Course Goals:

This course is a hands-on survey of the experimental foundations of modern physics. Some of the goals of this course are:

- 1) To allow you to reproduce and understand the experimental results that are the underpinnings of modern physics.
- 2) To provide you with an opportunity to develop critical writing skills and understand how to effectively present your scientific work to a larger audience.
- 3) To familiarize you with experimental techniques employed in contemporary research and industrial laboratories.
- 4) To give you a survey, via experiment, of many of the sub-fields of modern physics, and the pertinent experimental issues in each.
- 5) To expose you to the realities of the laboratory experience, where things don't always work, where the issues are not always clear, and where progress depends on perseverance, ingenuity, and judgment.
- 6) To learn and appreciate the ethical and social issues that are involved in scientific research. These include the handling of proprietary information, respect for colleagues and adherence to high standards of honesty in reporting scientific results.

You should be prepared for a fundamental difference in difficulty and philosophy between this course and preceding physics labs. This is going to be a "problem solving" experience, as distinct from a "cook-book" laboratory. You may have to teach yourself how to use and calibrate many different kinds of test equipment. You may have to search for weak signals in

the presence of noise. You may have to use statistical techniques to extract results from ambiguous data sets. Your success with the experiments, and with the course, will depend on the dedication and initiative that you apply to solving whatever puzzles arise. This is simply part of the reality and joy of the experimental method.

## B. Requirements:

The Advanced Physics Laboratory currently offers ~25 possible experiments. You will choose and perform 4 experiments each semester. New students will begin with the Radioactivity experiment, which provides experience with analyzing statistical data, and performing error analysis. Your choice of the remaining experiments gives you the opportunity to develop a specific focus, for example the physics of materials (Hall effect, superconductivity, electron microscope), atomic spectra (spectroscopy, saturated absorption, optical pumping), particle physics (gamma ray spectroscopy, muon lifetime, positron annihilation). Your overall Advanced Lab experimental program, to be designed in consultation with the instructors, must include at least one experiment from each of the categories listed in Section C. Some suggested programs are given in Appendix 1. You will need to propose a program of experiments, in writing, not later than September 28, 2009.

- 1) We strongly recommend that you work in partnerships, but each person must maintain their own notebook and must submit their own oral and written reports.
- 2) You must keep a laboratory notebook, which will be examined at regular intervals. Some discussion of what goes into a good notebook is given in Appendix 2.
- 3) You are required to write a written report (~ 6 pages) describing each of the four experiments you complete this semester. The first of these reports will be submitted to the instructor for special consideration. After review, it will be discussed with you with specific suggestions for improvements after which you will be asked to rewrite it and submit it for a final grade. At the end of the semester, you will be asked to give an oral presentation with a poster display to the entire class based on one of the experiments that you found particularly interesting. Each lab report is due according to the schedule given in Table I below. Late papers will be penalized at the rate of one letter grade per week. To keep track of your progress, we request that you sign in at every class meeting and indicate the experiment that you are currently working on.

	Monday class	Tuesday class	Thursday class
First report	October 12, 2009	October 6, 2009	October 8, 2009
Second report	November 2, 2009	October 27, 2009	October 29, 2009
Third report	November 23, 2009	November 17, 2009	November 19, 2009
Fourth report	December 14, 2009	December 8, 2009	December 10, 2009

Table I. Lab report due dates for Fall 2009

- 4) Many of the experiments available in this class invoke subtle physical concepts. To make sure that these ideas are reasonably appreciated, a short meeting must be scheduled after each lab report has been returned. The purpose of this meeting is to

talk about the physics involved as well as various aspects of the written report. The intent of these meetings is not to grill the victim but help make sure that the basic principles have been understood. However, failure to arrange such meetings will be penalized.

- 5) One problem that plagues most research is isolating critical issues from the complexity of the overall experimental environment. You will be expected to write a half-page summary of what you have accomplished at the end of each class period and submit it to the course instructor via E-mail before the end of the day. Even though the work is generally done by pairs of people, a separate report is required from each of you. Failure to submit such reports in a timely fashion will be reflected in the class participation score that is used to evaluate your final course grade.
- 6) The Physics Department does not offer a course in statistical methods although this is a critical component of any serious scientific work. Four lectures on this subject will be provided in the first few weeks of class.
- 7) One aspect of physics research that is not usually covered in the classroom is issues of responsibility and behavior in the conduct of research. We have found that this is quite a bit more difficult to present than the cut-and-dried subject matter of the physical sciences. For this semester, a one-hour lecture will be presented with the title of “The Ethical Physicist”. It will try to cover the basic rules of conduct regarding the honest reporting of data, fair attribution of credit, proper handling of proprietary information and, finally, some discussion of the sometimes contradictory aims of various participants in scientific research. As a formal assignment, you are requested to read a book that discusses the scientific enterprise and describe your impressions with the lead instructor.

### **C. The Experimental Catalog**

We list here the currently available experiments, sorted into the three major sub-fields of physics. Note that some experiments show up in more than one sub-field category.

#### **I. Atomic, Molecular, and Optical Physics**

- a. Atomic and Molecular Spectroscopy
- b. Zeeman Effect
- c. Optical Pumping
- d. Doppler-free Spectroscopy
- e. Faraday Effect
- f. Nuclear Magnetic Resonance
- g. Photoelectric Effect
- h. Franck-Hertz Experiment
- i. X-rays: Spectroscopy, Absorption, Moseley’s Law
- j. Magneto-Optical Trap
- k. Raman Spectroscopy
- l. Planck blackbody distribution and the solar photosphere temperature

## II. Nuclear and Particle Physics

- a. Radioactivity
- b. Quadrupole Mass Spectrometer
- c. Nuclear Magnetic Resonance
- d. Gamma-ray Spectroscopy
- e. Positron-Electron Annihilation
- f. Muon Lifetime
- g. Compton Scattering

## III. Solid State Physics and Materials

- a. Electron Microscope
- b. Hall Effect
- c. High Temperature Superconductors
- d. Ferroelectricity and Phase Transitions
- e. Electron Diffraction
- f. Atomic Force Microscopy

## IV. In various stages of development...

- a. Triboelectricity (X-rays from Scotch Tape)
- b. Chaotic oscillator (double pendulum)
- c. Rutherford scattering
- d. Electron-positron pair production

(Underlined: some of the more straightforward, basic experiments)

## D. Logistics

The official class times are Monday, Tuesday or Thursday afternoons from 1 to 5 pm. However, getting the most out of this course may require more hours than class times allow, so the Advanced Physics laboratory rooms are open from 9:00 am to 5:00 pm each weekday for your use.

You will generally work with a partner, and you are encouraged to work this out in whatever permanent or impermanent arrangements that you like. However, oral reports and written reports are required separately from each person.

Handouts for most experiments are available in the lab room. Online versions of most of these are available. The handouts are continuously evolving and never quite seem to keep up with the apparatus. The handouts generally contain a listing of references, a historical introduction, a description of the method, an outline of the analyses and explicit questions. The handouts should be considered a **lowest order guide** to the experiment, and you will find it useful to consult other references such as textbooks, recommended journal articles, and other on-line resources.

There will be occasional brief introductions concerning the fundamental material; however, you are expected to be familiar enough with the basic concepts of data manipulation, measuring

devices, computers, electronics, etc., that you can learn what ever else you need on the job. This is obviously a goal of the course. A number of manuals and reference books are available in the lab. Use them. However, note that you are not expected to know *a priori* how to work all the gadgets, and you should **ASK** if you have any questions about anything.

Computers: We have adopted a Windows/XP-based system in the Lab. You can save the data to a flash drive, or E-mail it to your own computer, and analyze the data using spreadsheets and data analysis programs. Microsoft Excel, Origin, Igor, and a number of other utilities are available. Although this course does not cover programming, you are encouraged to learn how to use IDL, Mathematica, and MATLAB since these are much more powerful tools for scientific computation. (My personal enthusiasm for Origin or Igor is extremely weak – CWA.)

In general, you are free to employ the available equipment as desired, particularly to improve the quality of your data or make additional measurements. Be independent and have fun. However, be courteous to the other users, observe safety procedures, and also please support the integrity of the lab. Don't leave the lab unattended with equipment lying around. Clean up after you are done for the day.

**NOTE: SAFETY IS EXTREMELY IMPORTANT! If in doubt, about the operation of any piece of equipment or apparatus, PLEASE ASK!**

The most attractive feature of science is the joy of pursuing questions that go beyond the immediate goals. You are strongly encouraged to think about the experiments you are performing and imagine additional issues worth exploring. The instructors for this course will try their best to accommodate such ideas if the resources are available and you are willing to put in the work.

## Appendix 1. Your 441/442 Sequence

The requirements are designed to give you flexibility in designing a "sequence" which reflects your interests in physics. After completing the required first experiment (Radioactivity) you may design a sequence built around a sub-field, as in examples (a-c) below, or you may wish to emphasize a certain way of doing experiments, as in example (d). Your program should be discussed with and approved by the instructor. Note that there is frequently a best order in which to do things, for instance Atomic Spectroscopy before the Zeeman effect; your program should reflect this. You are required to hand in a list of the experiments you intend to do after the second week of class.

### Examples of Sequences

(a). "Atomic Physics".

Here is a two-semester sequence which emphasizes mainstream atomic physics, while also satisfying the distribution requirement.

Photoelectric Effect  
Atomic and Molecular Spectroscopy  
Zeeman Effect  
Nuclear Magnetic Resonance  
Quadrupole Mass Spectrometer  
X-ray spectroscopy  
**Focus: Optical Pumping,  
Doppler-free Spectroscopy**

(b). "Nuclear/High Energy Physics".

A two-semester sequence illustrating techniques in experimental nuclear and high energy physics.

Mass Spectrometer  
Alpha-ray Spectroscopy  
Positron Annihilation  
Atomic and Molecular Spectroscopy  
Photoelectric Effect  
X-ray spectroscopy  
Nuclear Magnetic Resonance  
**Focus: Muon Lifetime  
Gamma-ray spectroscopy**

(c). "Condensed Matter Physics".

Here is a two-semester sequence which emphasizes techniques and principles in Condensed Matter Physics.

Photoelectric Effect  
Electron Diffraction  
Electron Microscope  
Ferroelectrics and Phase Transitions  
Rutherford Scattering  
X-ray Spectroscopy  
**Focus: Hall Effect  
High  $T_c$  Superconductors**

(d). "Forensic Physics".

Emphasizing techniques that can be applied to learn about a sample: a novel material, a residual gas, rocks on Mars, the intergalactic magnetic field, etc.

Electron Diffraction  
Atomic & Molecular Spectroscopy  
Alpha-ray Spectroscopy  
Nuclear Magnetic Resonance  
Mass Spectrometer  
X-ray Diffraction  
Doppler-free Spectroscopy  
**Focus: Electron Microscope  
Gamma-ray spectroscopy**

## Appendix 2: Keeping a Laboratory Notebook

Keeping a detailed laboratory notebook, or 'log book' is an essential part of experimental physics. Students taking Physics 441/442 are expected to record their laboratory procedures and observations during the course of their experiments. You will be required to turn in your log book from time to time, and some of the experiments you do will be graded solely on what you have written in your log book. We have made available some sample copies of laboratory logs maintained by professional research scientists, including some that recorded famous discoveries.

What goes into a useful laboratory log? - the answer is basically everything. Write down, in an informal 1<sup>st</sup>-person narrative style, what you did step-by-step, include sketches of the apparatus, wiring diagrams, etc., note the relevant experimental conditions and record any unusual events that might affect the experimental data, like someone accidentally turning on a light when your experiment was supposed to be done in a darkened room.

The following are some guidelines on how to write an effective log of your experiments:

- Always try to write the log as you are doing the experiment, not in the evening after you leave the lab. The purpose of such a log is to help you, the experimenter, to recall at a later date exactly how the experiment was performed, what the precise experimental conditions were, and to note any unusual events that might impact the analysis of the experimental data. Its value is in the details, which you will not remember later.
- Experimental data and observations are recorded in the log and should be accompanied by sufficiently detailed notes so that you could reproduce the data, if so required. You can never write too much in the lab book. Also note that you should never erase or delete material. Mistakes in the lab book should have a single line or "X" through them.
- If you are taking data by hand (rather than using a computer data acquisition interface), record your data in the log book, making sure to clearly label the different columns of data with the quantity that is being measured, including the units of measurement
- It is a good idea to make some rough plots or charts of the data as you are recording them, or immediately after, to help you decide if the data is valid and to detect problems with the apparatus. The square grid pattern on which all good lab books are printed is useful for this purpose. These rough plots are also useful in deciding if you need to take data at finer intervals so as not to miss some important behavior. It's also a good idea to do a rough, order of magnitude, calculation of the results at this point to check if everything is going as expected. If not, at least you won't have wasted the whole afternoon because of some artifact you haven't taken care of.

Professional scientists and engineers routinely maintain detailed log books of their experiments. In industry, these records are used as legal documents to substantiate claims of original discoveries and subsequent patent rights. In the research lab, many a Nobel Prize has been won based on unexpected findings that were first recorded in a log book as an odd-ball observation and later found to be important. The results in this class probably won't get you a trip to Stockholm, but we are going to get you into the habit of keeping a good experimental log book so you will be ready when that 'eureka' moment arrives.

### Appendix 3. Lab Reports

The formal lab reports are intended to present, in final and concise form, your experimental motivation, results, and conclusions, and why the reader should have faith in your results. Describe the physics and the apparatus, show your data, and describe your data analysis. Long derivations, discussions, etc. should be avoided unless relevant, and often it is adequate simply to give references. A good report will include demonstration that the nature and size of the relevant uncertainties are understood, that your apparatus is well calibrated, and that your measurement is generally robust. Final results should be clearly indicated in tabular, and where appropriate, graphical, form, and their significance should be discussed.

It is usually appropriate to compare the results obtained with "accepted" or known values. You will not be penalized for obtaining a "wrong" answer provided valid procedures were used, but in such a case you should also provide some more detailed discussion of uncertainties and at least make an attempt to understand the nature of the problem.

A model outline is provided below. You do not have to adhere to this form, as long as you cover the main points of the content.

**Title**, date, name, lab partner.

**Brief introduction** describing the purpose and physics of the experiment.

**Description of the experimental technique**, with emphasis on special features, problems involved, etc. Include schematic diagrams, sketches or photographs of the experimental setup.

**Presentation of data**, discussing any relevant details about experimental conditions during data taking and handling of data sets, etc.

**Analysis of data.** Here, you should present a logical and understandable description of how you reduced, analyzed, and extracted physics from the data. Outline carefully, step-by-step, including sample calculations and plots, how you obtained your final result. The final result is often given in the form:

$$A = x \pm \Delta x \text{ units} \quad \text{or} \quad A = x(1 \pm \varepsilon) \text{ units}$$

where  $x$  is the numerical value of your result,  $\Delta x$  is the standard deviation (uncertainty) and  $\varepsilon = \Delta x/x$  is the relative standard deviation. An error analysis explaining the sources of systematic errors and statistical uncertainty of the final result should be an integral part of this analysis.

**Discussion of the significance of the results.** Compare your results with theoretical predictions or accepted values. Reference the source of the latter.

**Answer the specific questions** that are usually included in the handout.

Finally, **reference** any source material used.



## Texts and References

A number of references are on reserve in the Science Library, or on the shelf in the lab. If you can't find a specific title, ask one of the instructors.

For general background on experimental physics, including many of our experiments:

- G. Trigg, *Landmark Experiments in Twentieth Century Physics*.
- B. Kramer, *The Art of Measurement*.
- P. Cutler and A. Lucas, *Quantum Metrology and Fundamental Physical Constants*.

General textbooks relevant to most of the experiments in the Lab:

- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*.
- H. Haken and W. Wolf, *The Physics of Atoms and Quanta*.

There are not many good books that could serve as a single text for an experimental course. The following can be very useful. Melissinos has complete treatments of lots of the experiments. Mark is clear, but his style is quaint.

- H. Mark and N. Olson, *Experiments in Modern Physics*.
- A. Melissinos & J. Napolitano, *Experiments in Modern Physics*.

Some good books on specifics:

- J. Hollas, *Modern Spectroscopy*.
- S. Svanberg, *Atomic and Molecular Spectroscopy*.
- O. Svelto, *Principles of Lasers*.
- S. Sze, *Semiconductor Devices, Physics, and Technology*.
- H. P. Myers, *Introductory Solid State Physics*.

In my own research, I have found many of the following books useful. I have also added a few titles that are more recent, etc. (CWA)

Statistics:

*Probability and Statistics in Experimental Physics*, Byron P. Roe

*Kendall's Advanced Theory of Statistics: 3-Volume Set*, Alan Stuart, Keith Ord, Steven Arnold, Anthony O'Hagan, Jonathan Forster

*Statistical methods in experimental physics*, W. T. Eadie, D. Drijard, F. E. James, M. Roos, B. Sadoulet

*Statistical Methods in Experimental Physics: 2nd Edition*, Frederick James

*Statistics for Nuclear and Particle Physicists*, Louis Lyons

*Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences*, R. J. Barlow

*How to Lie With Statistics*, Darrell Huff, Irving Geis

Electronic Techniques:

*The Art of Electronics*, Paul Horowitz, Winfield Hill

Computational Techniques:

*The Art of Computer Programming, Volumes 1-3 Boxed Set (2nd Edition)*, Donald E. Knuth

*Numerical Recipes 3rd Edition: The Art of Scientific Computing*, William H. Press, Saul A. Teukolsky, William T. Vetterling, Brian P. Flannery

*Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, Milton Abramowitz, Irene A. Stegun, P. M. Morse (foreword)

Graphics:

*The Visual Display of Quantitative Information, 2nd edition*, Edward R. Tufte

*The Cognitive Style of PowerPoint: Pitching Out Corrupts Within, Second Edition*, Edward R. Tufte

Computational Environments:

*EXCEL*, Microsoft Corporation

*IDL*, ITT Corporation

*Mathematica*, Wolfram Research, Inc.

*MATLAB*, The MathWorks, Inc.

And finally, the Web, used responsibly and with some caution, is a wonderful resource for many of the topics in this lab. For the values of fundamental constants, the following is particularly recommended:

<http://physics.nist.gov/cuu/Constants/index.html>

**Books about scientific research as a career**

Broad, William, *Star Warriors*

Kirshner, Robert P., *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos*

Djerassi, Carl, *Cantor's Dilemma*

Dürrenmatt, Fredrich, *The Physicists*

Dyson, Freeman, *The Scientist as Rebel*

Feynman, Richard P., *The Pleasure of Finding Things Out*

Frayn, Michael, *Copenhagen*

Goodman, Allegra, *Intuition*

Grinnell, Fredrick, *The Scientific Attitude (Second Edition)*

Kevles, Daniel J., *The Baltimore Case: A Trial of Politics, Science, and Character*

Levin, Janna, *How the Universe Got Its Spots: Diary of a Finite Time in a Finite Space*

Sobel, Dava, *Galileo's Daughter*

Watson, James D., *The Double Helix, A Personal Account of the Discovery of the Structure of DNA*

Consult with instructors about other possibilities.

### **Poetry for geeks**

Hein, Piet, *Grooks 1, Grooks 2, Grooks 3, Grooks 4*