Physics 326 - Advanced Physics Laboratory   Fall 2011

Instructor

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Office hours: M 10-11, Tu 11-12, Th 10-11, F 10-11, or by appointment
If the above hours are not convenient, feel free to email me or phone me to set up a specific meeting time.

Our course materials, including assignments, schedules and supporting materials, will be posted on the course website at p326.org You are expected to read your email regularly to stay in touch with course developments.

Introduction

The main purpose of this course is to develop your abilities as an experimenter, i.e., your ability to design, execute, and analyze the results of significant experiments. For some, it will be a natural prelude to doing experimental research as a senior, or an aid to research performed concurrently. For others, it may be the sole experience in independent laboratory work at Haverford or Bryn Mawr. The experiments themselves will also enable you to deepen your knowledge of some areas of physics.

Part of the process of learning to do experimental physics is skill development; for this reason in the first part of the semester, we will have a series of classes devoted to the experimental methods which are used most widely in experimental physics:

-- Aspects of basic electronics, including the use of test equipment
-- Low noise measurement techniques
-- Using computers as laboratory instrumentation tools
-- Optics (including control and manipulation of polarization, beam shaping, and photon counting)
-- Designing experimental equipment (including making up machine drawings)
-- Planning of experiments (including performing preliminary calculations and simulations)
-- Analyzing experimental data
-- Effective use of journals and other library resources
-- Writing a scientific paper

Another part of becoming a capable and self-reliant experimenter can only be learned from doing difficult and relatively unscripted experiments. In the later part of the course, you will perform an experiment from the list below or designed by you in consultation with the instructor. All of these experiments are a step up in complexity and expertise from a course like Haverford’s Physics 212 lab, and are designed to teach you interesting physics and important experimental (and problem-solving) skills. As a result, they are less scripted than sophomore lab experiments and you will play more of a role in figuring out how to measure and analyze the relevant data (and for that matter, figuring out what to measure!) They emphasize different combinations of experimental methods, so you can develop skills that are of particular interest to you if you wish. Experience shows that no matter which project you do, you will find your own abilities growing as you struggle to understand nature’s secrets. All experiments will be performed together with a lab partner. This simulates actual research, where most work is done in collaboration.

Prerequisite

You should have completed introductory quantum mechanics, Physics 214b or equivalent, including the accompanying lab, Physics 212, or equivalent. It is sometimes possible to waive these requirements, with consent of the instructor.

Format and Class Meetings

The course will meet Monday and Friday afternoons, 1:15-4 p.m OR Tuesday and Thursday 1:00-3:45, both sections in KINSC H106. This is a hands-on course, in which you will mostly learn by doing. Therefore, your attendance is expected at all class meetings. However, I realize that unavoidable conflicts may arise once or twice during the semester. If you will not be present at a scheduled lab or lecture time, you must let me know in advance and make up the time in agreement with your lab partner. All absences for athletic reasons must must scheduled in the first two weeks.

You will need to spend additional time reading, planning, writing, and working on your experiments in order to complete them on schedule. You should allocate about 12 hours per week to this course. There may be several weeks during the semester when the time required may exceed this estimate. (This is good practice for research!)

Course Requirements

a. There will be weekly homework assignments during the first two thirds of the semester.
b. Communication of results to a wide audience is an essential part of being a scientist. To hone your skills in this area, you will write one paper, co-write a second paper (together with your lab partner), and (again together with your partner) prepare and present a short talk. For the Johnson Noise experiment, you will write a short report (4-5 pages plus figures and references). For your test of Bell's inequalities, you will co-write another short report (4-5 pages plus figures and references) with your partner. Both papers are to be in the format of scientific papers; more information about paper formats can be found in the course lab manual. You will be evaluated both on the quality of your experimentation, and on the quality of your papers (depth of understanding; writing effectiveness). For the more independent experiment done in the last part of the semester, you and your partner will prepare and present a 20-minute talk, which will be delivered to your classmates.
c. There will be a one hour midterm exam covering the lecture material from the first two thirds of the semester.

Grading & Late Policy

The course grade will be computed as follows:
15% Problem sets
10% Short notebook style reports on labs at beginning of semester
15% Midterm exam
20% Report and performance on Johnson Noise project
20% Report and performance on Quantum Entanglement project
20% Talk, and performance on independent project
While this represents the weighing for computing the initial pass at a grade, I will factor in significantly improvement and growth in your performance as the semester proceeds, as well as your overall classroom performance in the labs (including attendance and involvement in each project.) Thus, you will be rewarded for your lab performance as a whole, rather than just the paper reporting that you turn in.

You may have two free one-week extensions for any late work. Send me an email or note if you are using a free extension for a particular assignment. You may receive an extension for an exam only with a Dean's excuse. Get in touch with me if you are suffering from an illness that requires you to miss class or coursework for any significant length of time.

Experiments

a. Johnson Noise (to be done by everyone)

Any object which has electrical resistance generates a small noise voltage, called the "Johnson noise", and given by $V_n = \sqrt{4k_B TRB}$ where V_n is the rms noise voltage, T is the absolute temperature, R is the resistance of the object, and B is the measurement bandwidth. This formula is remarkable, since the V_n does not depend on the material or shape of the object, nor on the number or type of charge carriers, nor on the measurement frequency (only the bandwidth). You will learn how to use a commercial low-noise, general purpose amplifier to amplify the Johnson noise, then program a computer and data acquisition board to measure and analyze it. You will be able to measure the value of the Boltzmann constant, and verify the material, temperature, and bandwidth dependencies predicted by the formula.

b. Quantum Entanglement and Bell's Inequalities (to be done by everyone)

Quantum entanglement is one of the central mysteries of quantum mechanics. You will prepare a system of two photons, well separated from each other, that are in an entangled state, which is a superposition of both photons having horizontal polarization and both photons having vertical polarization. If the polarization of one photon is measured and found to be horizontal, you immediately know that the other photon must also have horiztontal polarization. However, if the polarization of the first photon is measured and found to be vertical, you immediately know that the polarization of the other photon is also vertical. The state of the other photon is determined *instantaneously* when you measure the first photon; you will show on a homework problem that this does not violate the restriction from special relativity that information cannot travel faster than the speed of light. You will show experimentally that the state of the photons was not determined before the measurement was made, by showing that a version of Bell's inequality is violated.

c. Possible experiments for the independent project

While you are working on the Johnson Noise experiment, you should select and plan for your independent project. You may continue working with the same partner or change – it's up to you.

In this part of the course, you will be operating more like a research scientist, in that many of the important experimental decisions have not been made in advance. You may need to: order materials, design and/or construct apparatus, convince a "funding agency" (the physics department) that a certain piece of equipment should be purchased, determine the actual experimental objectives, etc.

If you wish, you may propose your own idea for the second project, in consultation with me. If you are interested in this avenue, you should start getting organized ASAP, since we may need to order some equipment or materials which could take weeks to arrive, or may need to get the machinist going on making something. If you already have an idea of what you want to work on, consult with me soon. If you are interested in designing your own project, but don't really have any solid ideas yet, you might look in the American Journal of Physics (back issues are in the physics lounge), in Scientific American, or in such journals as Physical Review Letters and Physical Review, Nature, Science, and the Journal of Applied Physics. It is frequently possible to replicate in a scaled-down version something which has only recently been accomplished in a research laboratory; often you will get ideas for original experiments you would like to try by reading someone else's account of research. We have a modest budget for buying new equipment, and can often find what is needed either here, at BMC, or at Penn. Be forewarned that, if you choose this avenue, it is unlikely that you will be able to complete the project, because of time constraints. However, these experiences can be very satisfying and instructive if you put in a substantial effort.

A more usual choice is to perform one of the experiments listed below. Some of these have already been tried and gotten working (more or less) at Haverford. However, do not imagine that those projects will require any less effort than an experiment of your own design. Typically, you will need to do considerable work on upgrading of equipment and/or procedures.

1. *Detailed exploration of transmission electron microscopy.* In Transmission Electron Microscopy (TEM), an electron beam passes through a very thin sample. Images can be formed either by shadowgraph (thick or high atomic number areas of the sample block the electrons more effectively) or by electron diffraction. The highest performance TEMs can image individual atoms. Haverford recently purchased a TEM, which cannot quite achieve that level, but is still very impressive. In this module, you will delve deeply into the principles and practice of transmission TEM, including the physics of how the electron beam is created and focused, how it interacts with the sample, the principle imaging modes, and the effects of accelerating voltage on the image.

2. *Electron beam lithography.* To fabricate structures smaller than 100 nm, and also to fabricate the master masks used for photolithography, scientists and engineers use electron beam lithography (EBL). Haverford has recently purchased a Scanning Electron Microscope (SEM), which can be used both to image nanostructures and to create them using EBL. You will learn how to use the SEM for imaging, and then use EBL to define a nanoscale pattern of your choice. For example, you might choose to create a an electrode pattern which could be used for studies of the electrical properties of macromolecules or self-assembled nanostructures, or to create a pattern that might be of interest for the study of plasmonics, or simply to create a picture or logo. After preparing your substrate in the SEM, you will develop it, metalize it in our vacuum evaporator, and finally use the electron microscope to image the results.

3. *MRI / NMR* Nuclear Magnetic Resonance is a tremendously important technique for analysis of chemical compounds and for medical imaging. However, it also has many applications in cutting-edge physics research, including studies of the behavior of gas molecules adsorbed on surfaces, and three-dimensional imaging of fluid flows. We have recently purchased a self-contained experimental apparatus for teaching more about these techniques, and it can operate in a number of different modes. Eventually, this may be used in physics 211, but it has been our experience in the past that it works best to have 326 students try things out first, as there are always surprising challenges to be overcome. You will refine a set of instructions made by a previous pair of 326 students, and evaluate whether it is realistic to attempt this experiment in 211.

4. *Microfluidics* Recently, techniques of photolithography have been applied to creating miniature chemical laboratories on silicon chips. It is hoped that these will find applications for example in sensitive detection of trace chemicals and pathogens. You might choose to duplicate a published experiment, or even to attempt to extend what is known about such microfluidic systems to even smaller size scales.

5. *Extended Atomic Force Microscopy* We have a Digital Instruments Atomic Force Microscope which can perform either imaging or force measurements on a variety of samples, either in air or in solution. Possible investigations might include measuring rupture forces between complementary strands of DNA, imaging of biological specimens, nanofabrication using the AFM, investigating the mechanical properties of gels, imaging of magnetic domains (using a magnetized tip), using the AFM tip as a movable gate electrode for probing electronic devices, etc.

6. *Chaos in electrical circuits.* The behavior of a particle in a two-well potential with external forcing can be surprisingly complicated; it includes essentially unpredictable chaotic motion. The best way to study these phenomena is to use a nonlinear electronic circuit that simulates the mechanical system. The circuit is to be constructed using operational amplifiers, and is interfaced to a laboratory computer using sample-and-hold circuits and an A/D converter. This is an excellent way to improve your electronics skills and to learn about nonlinear dynamics and the use of laboratory computers.

7. *Quantized conductance in nanocontacts.* In general, construction of nanoscale electronic circuits is a challenging exercise requiring specialized equipment. However, it's possible to see quantum mechanical effects on conductance in a simple circuit consisting of small-scale contacts established between two gold wires brought into loose contact. This lab allows you to use sensitive low-noise electronic measurements to see the consequences of quantum mechanics for such systems, which result in quantization of the conducting properties of these systems. Because this experiment has not previously been done at Haverford, you should undertake it with the expectation that there will be significant equipment challenges and some annoying delays. However, these can provide a great learning experience.

8. *Muon Physics* This sequence of experiments gives you experience with particle detectors and allows you to explore the physics of an exotic fundamental particle naturally produced by cosmic ray showers. You will use muon detection to demonstrate relativistic time dilation; this will require a road trip, so that you can make measurements at several different altitudes.

9. *Nanotube fabrication and characterization* Carbon nanotubes are revolutionizing many aspects of materials science. These tubes, from I to 100 nm in diameter, and with lengths up to a few microns, have much higher current-carrying capacity, thermal conductivity, and tensile strength than any other material. They can be made to contain relatively large quantities of gas, and may well serve as a useful way to store hydrogen for fuel-cell-powered vehicles. Nanotubes are already in commercial use for highly efficient light bulbs (so far sold only in Japan), and will likely soon be used to produce flat screen displays. Both these applications are based on the excellent ability of nanotubes to serve as electron emitters under high electric fields. Because of their small diameter and chemical properties, nanotubes also make excellent probes for atomic force microscopy (AFM). Nanotubes also exhibit a variety of interesting basic physics effects, including novel electrical conductivity. In this experiment, you will grow carbon nanotubes using a chemical vapor deposition process in which growth is initiated by tiny metal catalyst particles. Depending on your interests, you might then investigate the growth process itself, or perform measurements of the electrical properties of the nanotubes.

10. *Laser spectroscopy and atomic physics.* Spectroscopy of extraordinarily high frequency resolution can be achieved with laser sources. It is even possible to suppress the effects of Doppler broadening (due to atomic motion), so that the very small spectral splittings due to the interaction of the electrons with the nuclear magnetic moments ("hyperfine structure") can be resolved. In this experiment you will make sensitive optical measurements on samples, including an atomic Rb vapor (see Atom trap above), using a tunable diode laser source, and a computer for data acquisition.

Honor Code.

The instructor values Haverford's honor code for the integrity it fosters and the pedagogical flexibility it affords. I expect your cooperation in respecting the following guidelines. Please request clarification whenever necessary.

- You may seek assistance from the instructor, consult other written sources, and work with your fellow students in doing the "group" homework problems. However, you must write up your own solutions. (You may use the group’s effort, e.g. on the blackboard, as a guide, but you must not simply copy from this. Rather, use it as a reminder, and work out the logic and math on your own again as you write up your own version.

- You may consult with the instructor and consult other written sources in working the "individual" problems.

- Solutions to the written exercises will be made available shortly after the assignments are due. If you are using one of your “free” extensions, you may not consult the solutions.

- You should work alone on the take-home exam and refer only to your page(s) of notes. You are expected to follow all other instructions given on the exams.

- Extensions on taking exams can only be granted with a Dean's excuse. (If you will have trouble taking an exam on a particular for any reason, consult with the instructor in advance as soon as possible. There is some flexibility in rescheduling exams for the entire class.)