Case Western Reserve University Department of Physics
Research Experiences for Undergraduates
Summer 2010 Descriptions of Research Project

Students interested in applying for the summer program can peruse the list of projects below that we anticipate will be available for the summer of 2010. Completion of a first year physics course sequence is a prerequisite for all projects. Projects 8, 10, and 13, have additional prerequisites, as noted in the project descriptions.

Project 1: Optical and electrical properties of carbon nanomaterials (project advisor Jie Shan) Carbon is one of the most widespread and versatile elements. With the latest exciting discovery of fullerenes, carbon nananotubes and graphene, carbon nanomaterials have attracted significant interest among the scientific community. These materials, with their unique electronic structures and physical properties, are also of potential importance for electronic and optoelectronic applications such as transistors, sensors and solar cells. In this project, the REU student will be involved in the fabrication and characterization of the optical and electrical properties of carbon nanomaterials. The student will study the effects of quantum confinement, surfaces and interfaces on these properties, and gain expertise in some important optical characterization techniques such as absorption, photoluminescence and nonlinear optical spectroscopy.

Project 2: Solar Energy (project advisor Kenneth Singer) Solar cells are optical devices that absorb light and produce electricity through certain photoelectric processes. Light absorption normally depends only on the thickness of the material and the intrinsic absorption parameter (per unit length) of the material. However, effective absorption can be adjusted by locating the solar device in an optical cavity. Such a cavity effectively slows light down and alters the absorption spectrum leading to higher absorption per unit thickness. This, in turn, can affect how the generated electric current is collected at the electrodes. In this project, the optical cavity effect on absorption and photoelectric properties of polymer photovoltaic materials for solar conversion will be modeled and measured. The project involves making thin film photovoltaic devices including deposition of electrodes, spin coating of the polymer film and thermal treatment. The subsequent films will be evaluated as optical absorbers and photoelectric materials. The experiments will be compared with the modeling.

Project 3: Optical switching (project advisor Kenneth Singer) As computers become faster and faster, the ability to transmit large amounts of data even short distances becomes an important issue. One approach is to use short-range optical fiber communication, which may require the ability to switch light, that is, the build the optical equivalent of a transistor. We will be exploring new organic/polymeric materials for this purpose. We are especially interested in using slow light to enhance the optical switching effect in these materials. This requires building the material into an optical cavity. In this project, optical cavity effects on the optical properties of optical switching materials will be investigated. The effects will be modeled using an optical transfer matrix simulation program in our laboratory. Then, thin film cavities will be constructed using vacuum deposition of conductors and spin coating of polymer switching materials. The optical spectra and switching properties will be studied and compared to the modeling results.

Project 4: Synthesis and Characterization of Novel Nitride Semiconductors (project advisor Kathleen Kash) The family of semiconductors composed of gallium nitride, aluminum nitride, and indium nitride has become increasingly more important for the lighting industry. It provides the bright blue light emitting diodes that are used, for example, in those large, bright, three-color highway billboard displays, and may, with tremendous energy savings, even replace the incandescent light bulb. Zinc germanium nitride, zinc silicon nitride, and zinc tin nitride are members of a closely related family of semiconductors on which there has been very little research; in fact, no one has yet reported growing zinc tin nitride. Yet there is reason to expect that these materials may be superior to their better-understood counterparts for some important applications. The REU student's project will be to do experiments in the synthesis of one of these new materials, and will also gain expertise in some important characterization techniques. These include scanning electron microscopy for measuring the elemental composition and imaging the material (on the size scale of tens of nanometers), and x ray diffraction to measure the crystal structure. Depending on the particular project, the student may also learn how to do photolithography to make patterned substrates for growing the material in wire and dot structures.

Project 5: Gate-all-around Nanowire Transistor (project advisor Xuan Gao) Living in an age of information technology, we continuously confront the ubiquitous demand of faster and more powerful electronic devices for computing and storage. This need is being addressed by inventing smaller, higher performance and novel devices. The state-of-the-art transistors in the semiconductor industry have already reached the sub-100nm length scale, where it is essential and challenging to maintain the gate coupling efficiency. In this project, we will explore a few means to employ a wrap-around-gate on nanowire transistors (with diameters as small as 10 nanometers). Such a gate-all-around nanowire transistor may pave a way towards sub-100nm logic devices with high gate coupling efficiency. The student working on this project will obtain hands-on experience in microfabrication, including doing photolithography and metal deposition, investigate using either metals or conductive polymer electrolytes as the gate material, and characterize the electrical performance of the devices.

Project 6: Liquid Crystals (project advisor Charles Rosenblatt) Liquid crystals are a branch of "soft condensed matter," a classification that includes colloids, polymers, and gels. Liquid crystals have large electric, magnetic, and mechanical responses, and have both practical applications (for instance, in liquid crystal displays) and are also of fundamental scientific importance in areas such as phase transitions, pattern formation and topology, and molecular interactions. In our laboratory we study electro- and magneto-optic properties of liquid crystals, their phases and phase transitions, interactions with surfaces, symmetry properties, and their use in device applications. In this REU project the student will use an atomic force microscope to scribe nanoscopic patterns on substrates that impose liquid crystal alignment on the nanometer length scale. In particular, we have developed a method to mechanically generate surface chirality, i.e., breaking of mirror symmetry in two dimensions, at the nanoscale, which gives rise to many fascinating phenomena. [As an example, the letter "F" is chiral in 2D, meaning that it cannot be rotated into its mirror image when confined to a plane, whereas the letter "E" is not chiral]. The student will create 2D chirality in the substrate and investigate the resulting electric polarization induced in the liquid crystal right at the surface. The student will have the opportunity to prepare samples and to use several scanning probe microscope techniques, including atomic force microscopy and near field scanning optical microscopy, as well as electrooptic probes that measure the liquid crystal's temporal response to an applied electric field.

Project 7: Dark matter detection and xenon purification in the LUX detector program (project advisors Tom Shutt and Dan Akerib) One of the great mysteries of cosmology and astrophysics today is the presence of the mysterious "dark matter" – stuff that appears to permeate the cosmos and makes itself known through its gravitational effects, but which can't be directly seen through conventional astronomical techniques owing to its electric neutrality. As particle astrophysicists, we are carrying out a sequence of experiments using liquid xenon to test a specific dark matter hypothesis, that dark matter is composed of slow-moving Weakly Interacting Massive Particles, or WIMPs. If this hypothesis is correct, then WIMPs could be found locally in the Milky Way with Earth-based detectors. Since their signals are seldom and small, highly specialized detectors are needed to look for their occasional collisions with the detector's atomic nuclei. We are developing a sequence of experiments based on liquid xenon, one of the noble gases, which require that the xenon be extremely pure. Weare concerned about two different types of impurities. First, trace amounts of radioactive krypton, another noble gas, would give a background that's hard to distinguish from WIMP scatters. Second, trace amounts of electronegative impurities attenuate the signal before it can be measured. The REU student could extend our demonstrated technique of using activated charcoal gas-chromatography to study how to separate krypton at a faster rate, or develop techniques of flowing xenon in the liquid state (170 K) through chambers that capture electronegative impurities. Both developments are critical expanding our current 300-kg LUX detector to larger follow-up experiments with detector masses at the ton and 10-ton scales.

Project 8: Computer Modeling of Proton-Conducting Membranes (project advisor Philip Taylor) This work is aimed at elucidating the nature of proton transport in ionomer membranes by means of a combination of analytical theory and molecular modeling. There are two broad thrusts. The first of these is directed towards understanding the equilibrium structure of Nafion, which is a typical membrane material used, for example, in fuel cells. The second thrust is concerned with the transport of protons through a membrane of this type. The research on structure will proceed by building on existing work, but with the introduction of some novel techniques, among which is a hybrid Molecular Dynamics--Monte Carlo approach. This method permits rapid computations by temporarily decoupling the motion of the hydrophilic polar side chains from that of the hydrophobic backbone. The work on transport of protons in Nafion-like membranes will also involve a combination of theory and simulation. Atomistic molecular-dynamics simulations will be employed to determine some of the characteristic parameters for the diffusion of protons in hydrated membranes. These results will be used in a theoretical model of nonlinear diffusion to predict transport coefficients. Undergraduates with some experience in computing have been very successful in this research program. The tools we use include various combinations of packaged programs like "Materials Studio", which are comparatively quick to learn, and programs that the students write themselves using Mathematica or one of the common programming languages.

Project 9: Equilibrium shape of a dielectric droplet in an electric field (project advisor Philip Taylor) The equilibrium shape of a dielectric droplet in a uniform electric field is determined by the competition between the effects of surface tension and of the dielectric contribution to the free energy. The surface tension favors a spherical shape for the droplet, as this corresponds to the minimum surface area, while the effects of the electric field are to elongate the droplet into a needle-shaped form. To find the equilibrium shape reached by a droplet in the presence of these two forces is a challenging problem that has been studied for over a century, but has resisted an exact solution. We do, however, know that the droplet develops pointed ends at a certain critical field. In this project we will solve numerically the equations that determine the shape of the droplet in order to investigate the nature of the transition from smooth to pointed ends as the electric field is increased. The results of this calculation will have significance for the design of ink-jet printers, the electrospinning of polymers, and electrically switchable privacy windows.

Project 10: Effective mass approximation for shallow point defects (project advisor Walter Lambrecht) Impurities or point defects in semiconductors with energy levels close to the band edges are called shallow defects. In the simplest form of the so-called effective mass approximation, they have defect levels like the hydrogen atom but with rescaled energies. However, for acceptors, the extension of this model requires one to solve a set of coupled differential equations resulting from the degeneracy of the valence band maximum. The goal of this project is to develop a variational approach to do this. While in the past this has been done using perturbation theory which heavily relied on symmetry, modern computers should allow us to deal with this problem numerically. Ultimately, we also wish to explore the use of central cell corrections to the potential obtained from first-principles calculations. This project requires a student with good working knowledge of quantum mechanics and an interest and skills in computer programming.

Project 11: Experimental astrophysics using Cherenkov light detectors (project advisor Corbin Covault): The High Energy Astrophysics group is developing a new optical detector system to measure the astrophysical properties of the highest energy cosmic rays. Our work is part of a larger effort to study the fundamental nature of cosmic rays: What are cosmic rays made of? Where in the Universe are cosmic rays coming from? Our group works with the Pierre Auger Cosmic Ray Observatory, a new experiment to measure the largest energy cosmic rays. For this summer project, the student will work to develop a prototype optical detector system that is being considered for future deployment as part of the Auger Observatory. The work requires fabrication, testing, calibration, astrophysical observations of cosmic rays using the new detector system, and data analysis. The work will be done collaboratively with other members of the HEA group.

Project 12: Experimental Light Detectors and the Search for Extraterrestrial Intelligence (project advisor Corbin Covault) The High Energy Astrophysics group specializes in the detection of gamma-rays and cosmic rays from astrophysical sources. These same experimental techniques can be exploited for a new effort in the Search for Extraterrestrial Intelligence (SETI). In principle, an advanced civilization that wished to communicate across interstellar distances might find optical signaling processes using rapid-pulsed lasers quite attractive. If such light pulses are arriving at the Earth, we can detect them with a large-area light detector and fast coincidence electronics. For this summer project, the student will work to develop an new detector system that will serve as a prototype for a new kind of Optical SETI experiment. The work requires fabrication, testing, optical calibration, astrophysical observations using the new detector system, and data analysis. The work will be done collaboratively with other members of the HEA group.

Project 13: Testing quantum mechanics (project advisor Harsh Mathur) Quantum physics is the language in terms of which the fundamental laws of nature are expressed. It is the basis of our theoretical understanding of matter and light, and has led to the discovery of phenomena such as semiconductor electronic bands, lasers and superconductivity that are of immense practical importance. The fundamental principles of quantum physics were discovered in the 1920s but it remains of great interest to test their validity. For example, the basic equations of quantum physics are linear but recently Steven Weinberg showed that it was possible to modify the basic laws to allow non-linear equations. The linearity of quantum mechanics can be tested by experiments that probe the interaction of light with atoms and low-temperature condensates of atoms; such experiments are ongoing. The purpose of this project is to model and optimize the design of such experiments. To this end the student will analyze simple models in terms of conventional and non-linear quantum mechanics. Background in matrix algebra and differential equations at the level of introductory college courses is a necessary pre-requisite. An introduction to quantum mechanics at the level of a modern physics course is helpful but not essential.