Department of Physics & Astronomy

Projects for undergraduate students

Students interested in participating in research should contact mentors directly. Financial support to qualified students might be possible.

Mentor: Charles Liu (Charles.Liu@csi.cuny.edu)

Galaxy Evolution Studies with the Vera Rubin Observatory

The Vera Rubin Observatory obtains more than one trillion pixels of astronomical data during each night of observation, and the data has been made publicly available free of charge through research platforms funded in large part by the National Science Foundation and the U.S. Department of Energy. Students can search for galaxies with unusual star formation histories (unlike our Milky Way galaxy, which has a rather typical history) to examine the aging process of galaxies, which comprise the fundamental matter concentrations throughout the universe, and the growth of supermassive black holes over cosmic time.

Mentor: Kalani Hetti (Kalani.Hettiarachchilage@csi.cuny.edu)

Project 1: Computational investigation to predict new functional materials with exotic properties

The discovery of topological insulators and Dirac semimetals has opened new avenues for research in condensed matter physics and materials science. Those materials have potential applications in the field of electronics and quantum computing. The robustness of surface states in topological insulators makes them promising candidates for spintronics and quantum information. We use density functional theory (DFT) studies on selected intermetallic crystal systems by using Quantum espresso and Wien2k packages. Since DFT solves the Schrodinger equations self consistently, the eigen values and eigen functions of self-consistent calculation can be used to describe the quantum mechanical wave functions of the electron in the system which will be used to calculate numerous physical properties including electron density, total energy, band structure, phonon spectrum, formation energy, magnetic properties, elastic properties, optical properties and transport properties, etc. We are using Quantum Espresso package available in Access XSEDE machines received by supercomputing grant.

Through this project, students develop knowledge of materials and their physical properties, their significance, and the predictions made by theoretical calculations. The project also introduces students to supercomputing, data transfer techniques, basic coding, and data analysis. The final goal is predicting optimal materials for future device applications. We propose an investigation of topological materials, transition metals, magnetic semiconductors, doped systems with transition metal/rare earth ions by using high performance computational resources.

Project 2: Quantum Computing - Quantum Education and Simulation with IBM-Qiskit

As the field rapidly evolves, effective education and accessible simulation tools are essential for developing a skilled quantum workforce. In recent times, quantum computing has become mainstream, mainly due to freely available quantum computer platforms such as IBM Qiskit. However, the understanding of quantum computing among the general population and college students is still at a very low level. Also, some have a distorted view of quantum computing with a wrong view of quantum nature. This is because the quantum nature is very different from the classical world we see and live in. Quantum computing represents a transformative paradigm in computation, leveraging principles of quantum mechanics such as superposition and entanglement to solve problems beyond the capabilities of classical computers.

It is very important that the young generation be educated about quantum science. This project is based on quantum education and quantum computing with IBM Qiskit. We will began with classical computing concepts like bits, gates, and circuits then study basic quantum physics principles. Core topics like qubits, gates, and the Bloch sphere will be explored using vectors/linear algebra. Then we can use it for math modeling, while Qiskit and IBM Q Composer enabled circuit simulations. Algorithms like teleportation, phase estimation, variational algorithms were implemented to demonstrate real-world applications. The final goal of the project is to investigate the electronic structure of a simple molecule such as H_2.

Mentor: Gustavo Machado Monteiro (Gustavo.Monteiro@csi.cuny.edu)

Active Matter: Collective Motion, Active Gels, and Chiral Flows Beyond Equilibrium

Active matter is a relatively new area of physics that studies systems whose individual components continuously consume energy and inject it into their surroundings. Because of this constant energy input, these systems can spontaneously organize into large-scale motion and structures, such as flows, vortices, contractile networks, or coordinated movement; even without external forcing. Examples include bacterial suspensions that form swirling patterns, synthetic self-propelled particles that flock together, and actomyosin networks that contract and generate internal stress. Unlike conventional fluid systems, which relax to equilibrium once external forces are removed, active systems remain intrinsically out of equilibrium. Many active systems also exhibit *chirality*, breaking left-right and time-reversal symmetries, which can lead to persistent rotations, spiral patterns, or circular motion not seen in passive fluids.

This project is primarily theoretical and examines how microscopic propulsion and motor-generated stresses lead to emergent fluid-like behavior. Students will explore simplified models of self-propelled particles, artificial swimmers (active Brownian particles), actomyosin active gels and contractile instabilities, and chiral active matter with rotational flows. The work emphasizes analytical modeling and stability analysis, with some numerical calculations or basic simulations to explore solutions and visualize behavior. Students will develop skills in mathematical modeling, non-equilibrium physics, and computational methods, while gaining insight into collective dynamics that connect physics with chemistry (reaction-driven motion), biology (cell motility and muscle contraction), and engineering (design of smart materials).

Mentor: Vadim Oganesyan (Vadim.Oganesyan@csi.cuny.edu)

Flow equations for solving complex linear and nonlinear algebra problems

Much progress in science and technology relies on ready availability of efficient numerical linear algebra libraries such as BLAS+LAPACK. These packages usually produce numerically exact solutions, which may be neither required nor desirable in situations where input data is noisy and/or only partially available, as is the case of typical linear regression applications. Such practical obstacles are handled with so-called “regularization” approaches (e.g. ridge regression). Alternatively, it is known how to recast most (all?) matrix algebra problems as a dynamical systems, i.e. matrix ODE of the form $\dot{v} = M[v]$, where the problem is entirely specified by matrix M, which is generally nonlinear in the “state” of the system v which dynamically evolves towards the solution as we integrate these coupled ODE. The limit of $t \to \infty$ often corresponds to overfitting or kinds of defective solution. The goal of this project is to explore optimal stopping criteria that would allow producing robust solutions by integrating up until a time $t_{optimal}$, possibly at reduced computational cost. These methods have been explored the context of exact diagonalization (by F. Wegner), recurrent neural networks (by Saxe etal), and many others. Firm grasp of basic linear algebra (vectors, matrices, matrix-vector multiplication, also singular value decomposition and diagonalization) are required in addition to coding fluency.

Suggested reading: 1) Wegner’s own talk; 2) Flow equations for deep linear NNs

Mentor: Anshel Gorokhovsky (Anshel.Gorokhovsky@csi.cuny.edu)

Experimental methods in Laser and Optical technology

This Project introduces main experimental research methods of Laser and Optical science and technology. It includes the following subsections (flexible, based on available equipment and the student background):

a) Familiarity with physical principles and techniques of gas, semiconductor and DPSS lasers. Laser light properties.

b) Acousto-optic effects, acoustic waves, Bragg diffraction and acousto-optic modulators.

c) Optical Fabri-Pero spectral analyzer and spectra of multi and single frequency lasers. Spectra of non-modulated and modulated laser light.

d) Familiarity with Michelson Interferometer and a modification project to include the photodetection capabilities.

e) Polarized light, Malus’ Law, linear and circular polarization, birefringence in crystals and stress induced birefringence, 3D Cinema.

Mentor: Anatoly Kuklov (Anatoly.Kuklov@csi.cuny.edu)

Collective states of excitons and photons in engineered lattices of micro-resonators.

Optical systems are at the focus of modern communication and computation technologies. Various aspects of them cannot be studied using analytical methods. In many cases analytical approaches to studying strong interaction of light with materials produce wrong results. In these situations computational methods play a central role. One of such methods is classical and quantum Monte Carlo. In this project students will learn basics of the methods and apply them, first, to simplified systems and, then, to a more involved situations. Access to the CUNY High Performance Computing Center is available.

Mentor: Li Ge (li.ge@csi.cuny.edu)

Color flattening and purification by wave localization in the spectral synthetic dimension

Can you tell crimson from scarlet? Although we normally divide the visible light into seven different colors (red, orange, yellow, etc.), they collectively cover a spectrum over 400 nanometers in wavelength. Using a high-quality laser, a specific color can be realized nowadays with a precision down to 10^{-9} nanometer. In other words, one can define at least 4×10^{11} different colors! Treating each color as an artificial “atom,” one can link them together to form an extremely long “molecule” that extends along the wavelength axis, which is an example of a synthetic dimension. When this molecule is flat, meaning that it has a little bit of all the colors, a broad spectrum of light is formed (imagine solar light). But just like in spatial dimensions, molecules are not flat in general, and their bends correspond to peaks in our synthetic dimension, i.e., purified colors. In this project, we will explore theoretically how to couple a large number of such color “atoms,” by modulating the gain medium inside a laser periodically in time. Furthermore, we will identify ways to achieve a broad spectrum (color flattening) versus sharp spectral lines (color purification) by using different modulation functions and the wave localization mechanism.

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