

Optimization of patterned gold-assisted exfoliation for monolayer transition metal dichalcogenides

Alexander M. Recce

Mentors: James Hone, Keith C. Schwab, and Simon Yoon

Mechanical exfoliation yields high quality, research-grade 2D transition metal dichalcogenide (TMD) crystals; however, Scotch-tape exfoliation produces flakes of unpredictable size and position. We demonstrate a gold-assisted exfoliation approach that leverages Au-TMD adhesion to yield large-area, uniform monolayers. Using a patterned lithographic template with exposed SiO₂ regions, the hybrid gold substrate exfoliates flakes with high yield and predetermined geometry. To optimize the template geometry, we identify geometries that minimize mechanical deformation by assessing wrinkle formation by shape with a U-Net-based density-estimation pipeline. MoS₂ flakes are exfoliated on the hybrid gold substrate and stacked with polycarbonate-based dry pickup to produce zero-angle, artificial 3R-MoS₂ samples with thicknesses of 3 layers (L), 5L, and 10L. Measuring polarized second-harmonic generation (SHG) in regions of 1L to 5L indicated six-lobed angular responses and aligned crystallographic orientations. SHG intensity increased with layer count, with 41.8 times the monolayer response at 5L. A and B exciton resonances appeared in energy-dependent SHG spectra, but no interlayer exciton peak was found. However, there appeared some increased SHG intensity near the interlayer exciton energy range. Together, hybrid-gold tape facilitates reliable stacking of TMD monolayers at desired twist angles, enabling scalable assembly of 2D systems with modifiable structure and electronic properties.

Characterizing thermohaline convection in polluted white dwarfs using 3D hydrodynamical simulations

Marcus N. King

Mentors: James W. Fuller and Jose Rafael Fuentes

Recent surveys have revealed a large white dwarf population with evidence of polluting exoplanetary material in their atmospheres. Given stellar conditions, these materials should have very short gravitational sedimentation timescales, indicating ongoing accretion from debris disks onto the stellar envelope. In the envelope, this drives thermohaline (fingering) convection. Improved characterization of these materials requires a quantitative understanding of this mixing process. Recent work has established analytic solutions for thermohaline-unstable convection zone propagation within stellar interiors. We computationally verify these solutions via a series of 3D Boussinesq hydrodynamic simulations with varying initial conditions and fluid parameters, using the Dedalus code. We focus on the dynamics of this physical system in unmixed and premixed simulations. We find both model dynamics supporting analytical assumptions within previous work, and we also see a strong coupling between $h(t)$ and $X_s(t)$ in each case, supported by calculated power laws. These results demonstrate that the time-dependent propagation of the thermohaline-unstable front, coupled with surface heavy element abundance, may provide insights into the accretion history of these polluted white dwarfs.

Characterization and optimization of Kinetic Inductance Phonon-Mediated (KIPM) detectors for low-threshold dark matter direct detection

Jonathan X. Hu

Mentor: Sunil Golwala

Current dark matter searches have focused on the direct detection of Weakly Interacting Massive Particles (WIMPs) with masses above 1 GeV, whose expected recoil energies lie in the keV regime. These experiments have reached unprecedented sensitivities in the high mass range but have not yet observed WIMP signals, motivating a shift of attention toward sub-GeV dark matter candidates. Phonon-based detectors are a promising technology for resolving the eV and sub-eV energy depositions expected from low-mass dark matter interactions. Kinetic Inductance Phonon-Mediated (KIPM) detectors use superconducting microwave resonators coupled to a target substrate to sense the phonons generated by energy depositions within it. However, the energy resolution of current

KIPM detectors is limited primarily by amplifier noise in the readout chain. Kinetic Inductance Traveling Wave Parametric Amplifiers (KI-TWPAs) exploit the nonlinear kinetic inductance of a superconducting transmission line to transfer power from a strong pump tone to a weak signal tone, amplifying the signal parametrically. Their high gain and near quantum-limited added noise can therefore be used to suppress the readout noise and improve the energy resolution of KIPM detectors. In this work, we set up a new cryogenic testing environment in which KIPM detectors and KI-TWPAs can be operated, and we measure the gain and noise of the KI-TWPA. In addition, current models of KIPM detector pulses are largely phenomenological. We therefore work to develop physical models of these pulses based on phonon recycling and quasiparticle pair-breaking mechanisms in order to better understand the detector response. Together, these efforts can help guide improvements in the energy resolution and performance of future KIPM detectors for low-threshold dark matter detection.

Studying the quantum kinetic evolution of neutrinos

Olivia J. Xu

Mentors: Chad Kishimoto and Ryan B. Patterson

In a hot and dense neutrino gas, the evolution of neutrino flavor is described by the coherent growth of quantum phase and a simultaneous scattering-induced destruction of phase. This quantum kinetic evolution is driven by neutrino-neutrino and neutrino-antineutrino interactions, producing non-linear phenomena that could reflect neutrino flavor conversion in the early universe. Using self-consistent solutions to the Quantum Kinetic Equation—a quantum master equation for the evolution of a distribution of neutrinos, we analyze the evolution of initially out-of-equilibrium neutrino distributions to discuss the synchronized flavor oscillations in a purely coherent solution, the path to equilibrium in a purely kinetic solution, and how the quantum kinetic evolution of the neutrinos relates to these behaviors and emergent behavior from the interplay of both. In this project, we aim to describe the interplay between the coherent quantum phase and the scattering-induced decoherence. By exploring the evolution of out-of-equilibrium neutrino distributions, we hope to describe emergent phenomena like those found in the early universe.

Sub-cycle quantum control of Hubbard excitons in a Mott insulator

John M. Sullivan

Mentors: Matteo Mitrano and Nai-Chang Yeh

Quantum control of strongly correlated systems is a central goal of quantum materials research because it offers the potential to unlock highly advantageous emergent behaviors. We investigate the use of coherent dressing with periodic non-resonant fields to achieve quantum control of bound holon-doublon pairs, called Hubbard excitons, in the one-dimensional Mott insulator Sr₂CuO₃. We utilize a mid-infrared terahertz (THz) pump field in the 4 THz range and sub-picosecond resonant third-harmonic generation (THG) probing to perform measurements, advancing on prior mid-infrared THz work with the aim of inducing Autler-Townes splitting, Rabi oscillations, and coherent remapping of wavefunction trajectories across the Bloch sphere.

Spectator-error-free two-qubit gates for fluxonium qubits using a dual-mode coupler

Shuhul Mujoo

Mentors: William D. Oliver, David Hsieh, and Miguel Moreira

Superconducting quantum computers promise to solve complex problems, but they require highly accurate operations on pairs of quantum bits (qubits). The fluxonium is a promising qubit due to its long coherence times, yet building fast, high-quality two-qubit operations for it remains difficult. A leading approach links qubits through an intermediate circuit element called a coupler. However, these operations frequently suffer from spectator errors, meaning they are disturbed by the states of nearby idle qubits. This interference ultimately limits how large a processor can grow. This project develops a two-qubit operation that eliminates this error using a coupler with two adjustable modes. The second mode provides the precise control needed to suppress disturbances from neighboring qubits while preserving the main operation. To implement this, we simulate the coupled circuit to identify specific

settings where unwanted coupling cancels. Experimentally, we built specialized readout and control tools: a measurement that reads three qubit states simultaneously to flag leakage errors, and a calibration that corrects magnetic-flux crosstalk to steer the coupler reliably. Ongoing work focuses on calibrating the operation and measuring how effectively it suppresses spectator errors.

Development of a standalone scintillation detector kit for muon and gamma detection

Samikshya Mahapatra

Mentor: Ryan B. Patterson

Scintillation detectors are one of the most fundamental particle detectors and are essential for scientific discovery, but the few existing educational kits conceal their electronic components and the physics behind detection, preventing students from fully understanding the detection process. Here, we develop an easily reproducible, standalone scintillation detector kit to help students actively engage with particle detection principles and circuit design. The system uses easily sourced plastic or thallium-doped cesium iodide scintillators coupled with silicon photomultipliers, powered by USB power supplies. Throughout the development process, various amplifier, comparator, and counter configurations were designed and tested to optimize the signal readout. To verify particle interactions, particularly from cosmic muons, a stacked scintillator arrangement was implemented to accurately measure coincidence signals. Additionally, noise reduction techniques, such as RC filters and electromagnetic shielding, were integrated to improve the signal-to-noise ratio. Results demonstrate successful amplification of silicon photomultiplier signals and reliable detection of muon coincidence events. Two versions of the system have been developed based on the energy range to be studied. These results confirm the viability of a transparent and accessible detector design, providing a practical educational kit that allows students to construct their own independent particle detector to measure naturally occurring radiation.

Modeling and design of scalable qubits through a novel semiclassical framework for nondispersive fluxonium readout

Ram Sivaraman

Mentors: Gil Refael, Jacob Steiner, Nina del Ser, and Yinan Chen

Fast, high-fidelity readout of superconducting qubits is a foundational requirement for scalable quantum computation. In this work, we consider a fluxonium qubit coupled to a readout cavity. Fluxonium is designed to have unevenly spaced energy levels to prevent leakage into non-computational states. Conventional fluxonium readout techniques operate in the dispersive regime, which limits their readout speed. To overcome this, our research explores a nondispersive readout regime, where measurement times are significantly reduced. The challenge is that nondispersive readout creates rapid energy transfer between the qubit and cavity, risking computational leakage and the destruction of quantum non-demolition properties. We aim to find physical design parameters that minimize this leakage. To do so, we investigate semiclassical approximations for the quantum dynamics of the qubit-cavity system. Using non-perturbative two-dimensional Floquet theory, we provide a novel framework for evaluating nondispersive fluxonium dynamics under arbitrarily strong charge and flux drives. This approach circumvents divergences in time-dependent perturbation theory, allowing for the calculation of exact leakage probabilities into non-computational states. Minimizing this leakage provides a foundation for scalable fluxonium qubit design, which will incorporate modeling environmental damping, optimizing drive parameters, comparing the current semiclassical approach with purely quantum numerics, and preserving qubit coherence during rapid measurement.

Experimental characterization and simulation of nanopore ion beams for single-molecule mass spectrometry

Kensuke Shimojo

Mentor: Michael L. Roukes

This project investigates a nanopore ion field emission platform for high-sensitivity mass spectrometry and its eventual integration with a micro-electrostatic ion trap for single-molecule analysis. While conventional electrospray ionization relies on droplet evaporation, Coulomb fission in a background gas, and a differential vacuum setup, a nanopore source emits ions directly from solution into high vacuum. This approach can drastically reduce ion losses, yielding potential for single molecule mass spectrometry, a powerful tool in proteomics as low-abundance proteins can play essential roles in biology. The short-term goal of this work is to characterize the spatial profile of the unfocused ion beam emitted from a glass capillary nanopore using a microchannel plate detector and to establish a COMSOL model for predicting ion trajectories through electrostatic optics. Progress to date includes setting up a high-vacuum chamber, developing a compact emitter-chamber and load-lock design, and creating a simple COMSOL simulation of a divergent ion beam passing through an Einzel lens. The current simulation explores how lens voltage influences beam focusing and provides a foundation for later models incorporating more realistic ion masses, charge states, kinetic energies, and electrode geometries. These experimental and computational efforts will shape the design of an ion source and trap interface capable of efficiently coupling the nanopore emitter to a single-ion mass sensor. Forthcoming results will be discussed.