Research program proposal

New paths for topological phases, controlling ergodicity, and quantum hardware design

My research lies at the interface between condensed matter theory and quantum information science. I am especially interested in how quantum technologies can afford us a deeper understanding of yet undiscovered forms of quantum matter. I am excited to engage in this research with a team of students and collaborators that support the mission of the Department of Physics and the Institut Quantique at the University of Sherbrooke.

Past research

Topological and Non-Ergodic Quantum Matter: Throughout my career, I have sought to understand the interplay between topology, ergodicity, and symmetry in novel forms of quantum matter, particularly in systems with strong disorder, interactions, and external driving. This effort led me to discover a new type of disorder-induced topological phase transition (since corroborated experimentally) and to uncover the mechanism that makes spatial-symmetry-protected topological phases robust against disorder. I also discovered new quantum scars in Rydberg-atom quantum simulators, showed their robustness against disorder, and found that periodically driven phases exhibit quantized non-adiabatic Berry phases. A common thread has been my deep interest in quantum entanglement, using it to understand thermalization and proposing new entanglement measures to characterize topological and disordered systems.

Quantum hardware design: My work in quantum hardware design is motivated by the goal of enabling access to new regimes of quantum dynamics and quantum matter. I have designed dynamical Floquet qubits with enhanced resilience to decoherence, investigated new regimes of Josephson junction arrays to understand array modes and explore new qubit architectures, and contributed to the analysis of unexpected resonant transitions in transmons as well as to a computer-aided framework for modeling general superconducting circuits.

Experimental collaborations: I have collaborated with experimentalists on several projects. I proposed a history-dependent mechanism for vortex transport in Josephson junction arrays with the group of Professor Nadya Mason (Dean at the University of Chicago). I also studied the distribution of vortices and supercurrents in 2D superconducting island arrays in response to local magnetic probes with the groups of Professor Nadya Mason and Kathryn A. Moler (Stanford University).

Proposed Research Program

My research program lies at the interface of theoretical quantum materials research and quantum information science and engineering, focused on three interconnected thrusts:

Thrust 1. Topology from Inhomogeneity: A New Path for Quantum Matter

My research will investigate a new paradigm: topological phases that require the loss of translational invariance, challenging the view that treats inhomogeneity as detrimental. I have preliminary evidence for a class of such phases arising from strategically localized wave functions. These unconventional phases fall outside existing classifications, necessitating new theoretical tools (such as real-space topological invariants and topological markers) to capture their unique topological and real-space response properties. This program offers a vast scope for exploring new physics across 1D, 2D, and 3D systems, including the effects of interactions, disorder, and external drives, and has the potential to open a new field of topological matter. Since arriving at the University of Illinois at Chicago (UIC), I have studied a notion of entanglement density that provides position-resolved information about entanglement, offering a promising tool for analyzing these new topological phases.

Thrust 2. Arresting Ergodicity: Emergence of Order with Local Driving

My research will develop new strategies for realizing non-equilibrium quantum phenomena by investigating how local periodic driving can arrest thermalization. I will develop a real-space picture of how many-body systems become non-ergodic, moving beyond traditional ingredients like disorder or kinematic constraints. Drawing inspiration from dynamical decoupling (DD) protocols and my Floquet qubit studies, we will use DD to spatially control thermalization. While DD is typically used for decoherence, my program will apply it to inhibit local degrees of freedom from thermalizing, providing a new route to engineer non-ergodic and inhomogeneous quantum states.

Thrust 3. Designing Quantum Hardware: Processors and Batteries

This research will bridge our theoretical work with two key applications in quantum hardware:

- **Scaled-up Superconducting Quantum Processors:** At UIC, I am investigating unwanted ergodic dynamics caused by crosstalk in scaled-up processors. Applying insights from **Thrust 2**, we will design novel superconducting qubit and coupler architectures to suppress these errors. We will also leverage **Thrust 1** to explore more exotic possibilities, such as localizing excitations via engineered topological states. Since arriving at UIC, I have been investigating properties of protected superconducting qubits with my PhD student as well as the role of ergodicity in scaled-up quantum processors.
- **Non-equilibrium Quantum Batteries:** We will leverage our understanding of unconventional topology from **Thrust 1** to design new charging protocols, harnessing the energy transport properties of these phases. Insights from **Thrust 2** will aid in controlling the battery's charging process by studying quantum batteries in non-equilibrium systems. At UIC, I have obtained preliminary results with a student using quantum scars for this purpose.

I am particularly excited to bring this three-thrust research program to the University of Sherbrooke, given the Institut Quantique's unique strengths. **Thrusts 1 and 2** would integrate naturally with the existing efforts in topological materials and quantum magnets (such as the groups of Ion Garate, Maia Garcia Vergniory), while my research on quantum technologies in **Thrust 3** offers strong collaborative potential with the IQ's teams in quantum information (such as the group of Alexandre Blais).

External funding experience and goals

I am committed to securing financial support for my research group. My grant writing experience includes serving as a Co-PI on a seed-funded project within a DOE quantum center and making extensive contributions to a multi-PI DOE grant on atomic quantum simulators. I am currently preparing an NSF proposal as PI on designing superconducting quantum processors. This background positions me to pursue research support through NSERC Discovery and CIFAR programs, and to explore CFI opportunities when specialized computational infrastructure is required.

Mentoring experience and goals

My mentoring philosophy, developed from my experience with several undergraduate and graduate students, centers on supportive, personalized guidance. I aim to build a cohesive research group of approximately four members, ensuring I can dedicate ample time to each student. Students will choose projects aligned with their interests, fostering genuine excitement for their research. I will implement a peer-mentoring structure in which senior students assist junior members to effectively transfer knowledge, build collaborative experience, and strengthen the entire group.