Research Experience

Master's Research Thesis

My quantum condensed matter Master's research thesis is an analytical and computational search for supersolidity in ultracold atomic gases. A supersolid is an exotic state of matter that is simultaneously crystalline (breaking translational symmetry) and superfluid (breaking global U(1) gauge symmetry). More formally, it is said to possess both diagonal and off-diagonal long-range order, and can be thought of as a phase of matter in which every constituent atom is part of the solid and superfluid simultaneously. First theoretically proposed in the 1970s in solid ^{4}He, focus has since shifted to ultracold atomic systems, in which the interaction parameters can be artificially engineered and finely tuned. Current theoretical models for supersolidity rely on the addition of a perturbative beyond mean field term to prevent the collapse of the condensate. We have developed analytical models of varying complexity and subsquently modelled them numerically in an effort to prevent the need for this often nonphysical beyond mean field term, investigating different types of interaction between single component Bose gases as well as mixtures. Our analysis extracts experimentally relevant observables: density profiles, condensate fractions, excitation spectra, and phase diagrams, validated using linearised Bogoliubov analysis and the comparison of conserved quantities.

The majority of the research involved in this project requires the simulation of advanced many-body quantum mechanical systems in Python to solve Gross-Pitaevskii equations. Example modules used in this programming include numPy, sciPy, matplotlib, torchGPE, pyGPE, as well as the Imperial College London high-performance computing centre, requiring advanced understanding of scientific programming techniques for accuracy and subsequent optimisation for speed.

We use simulated noise models to investigate how the initial phase space affects the ground state and evolution of our supersolid models.

Our current research goals include:

• Demonstrate numerically accessible supersolid regimes in single-component and binary dipolar gases.

• Search for Moiré-pattern supersolidity in binary Bose–Bose mixtures and characterise its dynamical stability.

• Investigate and discuss the implications of a supersaturated supersolid state

• Analyse potential coherence benefits by computing decoherence-sensitive observables (mode lifetimes, phase diffusion) and assessing whether ordered phases offer mechanisms relevant to state encoding.

Research Applications

Beyond the new abilities to probe fundamental physics with new exotic states of matter, supersolids possess many applications. There is a pressing need for fault-tolerant qubit modalities in the current climate of quantum computing; the long-range coherence inherent in the definition of a supersolid paired with its ordered structure could help reduce decoherence in a supersolid qubit system. We

seek to investigate such applications if the available time and resources permit it. My expertise in quantum information theory, as well as my intimate knowledge of quantum error correction (QEC) protocols, existing superconducting qubit design and quantum algorithm design make me well suited to investigate such applications.

Relevance to FTQC

My background in quantum information theory and hands-on experience with quantum error correction tools (Stim, Crumble, detailed on CV) position me to bridge many-body physics and fault-tolerant ideas. During my university studies I have had a direct education in cavity quantum eletrodynamics in my quantum optics module, as well as a full theoretical education in QEC and quantum algorithm design in the quantum information course. This course also investigated example algorithms in quantum communication and quantum cryptography, the classical versions of which I was familiar with due to my A-Level studies in computer science. Additionally, I have direct experience in programming neutral atom systems at the laser pulse level in Python, using Pasqal's Pulser.