EE4902 Mini-project Research statement

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Forrays into Disordered systems, the XY and the Clock model

The quantum clock and XY model play a crucial role in the study of superconducting systems. For instance, the physics of a Josephson Junction Network (JJN) can be modeled via the quantum XY model, and in a similar vein, circulating current phases that purportedly arise in High-temperature superconductors are modeled by a variant of the quantum clock model. In its bare-bones version, both the quantum XY model and the clock model are described by a lattice of spins with nearest neighbor interactions, with spins possessing either continuous symmetry (quantum XY model) or discrete symmetry (quantum clock model). Furthermore, the phases and phase transition in these quantum many-body systems have been very well understood: For instance, it is well known that the quantum XY model hosts a transition from a topologically ordered phase wherein the correlation functions decay as a power-law to a disordered phase. The key element that distinguishes the two phases in these systems is the structure of the topological defects or vortices in the system. In the ordered phase, the topological defects are bound into vortex-antivortex pairs; in the disordered phase, these defects are un-bound. Surprisingly, it is now established that even the quantum clock model hosts an emergent vortex-driven topological phase even though the underlying spins lack continuous symmetry.

Over the last several years, JJNs have become one of the front-runners in experimentally realizable architectures for quantum computations. At their heart, these architectures are deeply concerned with the control and manipulations of vortices in such JJNs. Now, The problem that presents itself in the study of realistic quantum systems is the presence of impurities (or disorder) that always present themselves as a remnant of the manufacturing process. Such impurities are known to drastically impact the phases and phase transitions of quantum many-body systems. It also leads to exotic phenomena in quantum condensed matter systems such as the quantum Griffiths phase and the Infinite randomness fixed points. Thus, with a view toward the control and manipulation of vortices in an experimentally realizable quantum system, we will study the disordered XY model, with particular emphasis on the dynamics of the topological defects in these systems. More specifically, this project aims to explore the interplay of disorder and vortex physics on the quench dynamics (response to sudden changes in parameters and the nature of defects caused therein) of the system. One of the crucial aspects that we will investigate numerically is how the rate of defect production is controlled by the critical exponents of the equilibrium transition from the disordered phase to the topologically ordered phase. A crucial question in this context is whether a simple Kibble-Zurek type scaling theory captures the defect production rate. We would also like to study whether the defect production rate shows a cross-over behavior as a function of disorder, as is well established for equilibrium thermodynamic observables in the case of disordered thermodynamic observables.

We aim to study these questions analytically using a Strong Disorder Renormalization Group procedure backed with numerical techniques that can simulate time-dependent Hamiltonians (QuTip). Finally, it is well known that the quantum to classical mapping states that the disordered quantum XY model is equivalent to a classical (thermal) XY model with correlated line impurities. Using this result, we would like to investigate whether certain thermal quench protocols in classical systems with correlated impurities could be mapped to equivalent quench protocols in quantum systems.