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Microscopy of correlations at a non-equilibrium phase transition

Abstract

One of the distinguishing achievements of physics has been the ability to describe the Universe based upon underlying microscopic principles. When there are many participating objects being governed by these microscopic principles, the resultant behavior often harbors emergent collective phenomena that may not be obviously related to the microscopic description. Phase transitions, quantum or classical, are a canonical example of such celebrated many-body phenomena that have been understood in equilibrium through a successful framework of thermodynamic constraints, statistical ensembles, and a growth of system-wide correlations at the transition[134,93]. However, a new class of non-equilibrium quantum phase transitions has recently emerged with behavior that is not captured by this traditional framework. In the case of isolated quantum systems, the transition occurs among excited eigenstates and requires knowledge of the structure of these individual eigenstates in the quantum system[108,170,156,5,66]. Understanding what drives such a phase transition requires a deeper microscopic knowledge of the role of correlations at the transition.

The use of ultracold atoms in optical lattices have paved the way for faithfully realizing quantum phase transitions[58,24,23,17,148,94]. In particular, the advent of the quantum gas microscope realized a system that was highly controllable and provides microscopic access to the many-bodied wave func-

tions[55,15]. All experiments presented in this thesis use such a quantum gas microscope architecture where a quantum degenerate gas of ^{87}Rb is used to probe the behavior of non-equilibrium quantum systems in one spatial dimension.

This thesis will briefly discuss some studies of entanglement in equilibrium quantum phase transitions near the ground state of the system. The first experiment directly measures the second-order Rényi entanglement entropy that develops as a small Bose-Hubbard system transitions from a Mott insulator to a superfluid[76]. This is followed by a brief study of measuring entanglement growth at the transition in the transverse Ising model.

These studies progress to the investigation of two particular non-equilibrium quantum phases and their transition into one another: quantum thermalization and many-body localization. We investigate the development of entanglement entropy that mimics thermodynamic entropy for an isolated quantum system which locally thermalizes under its own unitary dynamics[83]. We then investigate the only known robust exception to this thermalizing behavior by studying the onset of many-body localization due to disorder. We observe the breakdown of thermalization in this phase and the logarithmically slow growth of entanglement throughout the system that identifies localization in an interacting, many-body system[98]. Lastly, we investigate the role of correlations in the critical dynamics that emerge at high-orders where the system transitions from thermalizing behavior to many-body localization[130].