論文の内容の要旨

Quantum Many-Body Physics in Open Systems: Measurement and Strong Correlations

（開放系における量子多体物理：測定と強相関効果）

氏名　蘆田　祐人

This Thesis studies the fundamental aspects of many-body physics in quantum systems open to an external world. The last two decades have witnessed remarkable developments in studies of in- and out-of-equilibrium many-body physics of closed quantum systems, as mainly motivated by experimental advances in atomic, molecular and optical (AMO) physics. Meanwhile, recent developments have allowed one to *measure* and *manipulate* many-body systems at the single-quantum level, thus revolutionizing our approach to many-body physics. At such ultimate resolution, the measurement backaction, which is the fundamental effect acted by an external observer, becomes significant. Moreover, microscopic manipulation capabilities of many-body systems have realized quantum systems strongly correlated with an external environment. These remarkable advances thus point to a new arena of many-body physics that is *open* to an external world, in which interactions with an external observer or an environment play a major role. The research of this Thesis is devoted to addressing the question of how the ability to measure and manipulate single quanta can create a new frontier of many-body physics beyond the conventional paradigm of closed systems.

In the first part of this Thesis (Chapters 3-4), we study the influences of measurement backaction from an external observer on quantum critical phenomena and out-of-equilibrium many-body dynamics. In the second part of this Thesis (Chapters 5-6), we reveal in- and out-of-equilibrium physics of quantum systems strongly correlated with an external environment, where the entanglement between the system and the environment plays an essential role. In the following paragraphs, we provide the backgrounds and specific details about the results provided in each part of this Thesis.

The first part of this Thesis is devoted to elucidating how the influences of measurement backaction from an external observer trigger new types of many-body phenomena that have no analogues in closed systems. The time evolution of an isolated quantum system is described by a single Hermitian operator, i.e., the Hamiltonian. In contrast, under continuous observation, the dynamics becomes intrinsically nonunitary due to the measurement backaction and is characterized not only by the Hamiltonian but also by a measurement process. Recent revolutionary developments in AMO physics, especially realizations of the technique known as quantum gas microscopy, have enabled one to measure quantum many-body systems at the single-atom precision, where the measurement backaction is expected to be significant. Moreover, further developments of *in-situ* imaging techniques of quantum gases will allow one to perform a nondestructive, real-time monitoring of the many-body dynamics. The aim of the first part of this Thesis is to show how one can utilize these revolutionary techniques to reveal previously unexplored effects of measurements on many-body physics.

To achieve this aim, we focus on two fundamental aspects of many-body physics, namely, *quantum critical phenomena* and *out-of-equilibrium dynamics*. In Chapter 3, we analyze an effective non-Hermitian Hamiltonian that governs the nonunitary evolution under continuous observation and elucidate the influence of measurement backaction on quantum criticality. We first consider universal low-energy behavior of one-dimensional quantum many-body systems and identify two possible types of relevant non-Hermitian perturbations to them. We show how they significantly alter the underlying critical phenomena and phase transitions beyond the conventional paradigms of the Tomonaga-Luttinger liquid theory and the Berezinskii-Kosterlitz-Thouless transition. We then study the influence of measurement backaction on quantum phase transitions in higher dimensions by analyzing the superfluid-to-Mott insulator transition in the Bose-Hubbard model as a concrete example. In Chapter 4, we discuss out-of-equilibrium dynamics influenced by measurement backaction. Specifically, we present three theoretical frameworks to describe the dynamics of quantum many-body systems under continuous observation and apply them to particular models to elucidate the underlying physics. Firstly, we formulate a class of many-body dynamics conditioned on measurement outcomes, which we term as the full-counting dynamics, and address propagation of correlations and that of information through many-body systems under measurement backaction. We apply the formalism to an exactly solvable model and show that, by harnessing backaction due to observation of individual quanta, correlations can propagate beyond the Lieb-Robinson bound at the cost of the probabilistic nature of quantum measurement. Secondly, we formulate the thermalization and heating dynamics in generic many-body systems under measurements. Combining the eigenstate thermalization hypothesis with quantum measurement theory, we extend the framework of quantum thermalization to open many-body systems, where we consider couplings of quantum systems to generic Markovian environments permitted by quantum measurements and engineered dissipations. This gives yet another insight into why thermodynamics emerges so universally in our world. Finally, we formulate the diffusive dynamics under a minimally destructive spatial observation. We derive a diffusive stochastic time-evolution equation to describe the dynamics of indistinguishable particles by taking the limit of weak-spatial resolution and strong atom-light coupling. We apply the general theory to a minimal example of two-particle systems and demonstrate that the measurement backaction qualitatively alters the underlying dynamics depending on the distinguishability of particles.

The second part of this Thesis is devoted to revealing in- and out-of-equilibrium many-body physics in quantum systems that are strongly correlated with an external environment, where the entanglement between the system and the environment plays a central role. In such situations, the strong system-bath correlations invalidate the Born-Markov approximation. We thus need to explicitly take into account the degrees of freedom of the environment rather than eliminating them as done in the master-equation approach. We focus on quantum impurity as the most fundamental paradigm of such a strongly correlated open quantum system. Historically, the physics of quantum impurity has originally been studied in the context of solid-state materials. The two most fundamental concepts developed there are the Kondo-singlet state, which is the many-body bound state formed by a localized spin impurity and the fermionic environment, and the polaron, which is a quasiparticle excitation formed by a mobile impurity dressed by surrounding phonon excitations. A broad class of problems that correspond to quantum impurity correlated with an external environment have been at the forefront of many subfields in physics. For instance, they have proven crucial to understanding thermodynamic properties of strongly correlated solid-state materials, and decoherence and transport phenomena of nanodevices such as quantum dots and Nitrogen-vacancy center that are promising candidates for future quantum information technology. They also lie at the heart of powerful numerical methods such as the dynamical mean-field theory. The physics of a quantum impurity has recently attracted renewed interests owing to experimental developments of microscopic manipulation capabilities in ultracold gases, molecular electronics, carbon nanotubes, and nanodevices such as quantum dots. While equilibrium properties of a quantum impurity are well established, these new techniques motivate a surge of studies in an out-of-equilibrium regime which is still an area of active research with many open questions. The aim of the second part of this Thesis is to elucidate the role of strong correlations in the prototypical open quantum systems for both in- and out-of-equilibrium regimes.

To achieve this aim, we develop a versatile and efficient theoretical approach to solving generic quantum spin-impurity problems in and out of equilibrium and apply it to reveal previously unexplored types of nonequilibrium many-body dynamics in Chapter 5. A quantum impurity in a nonequilibrium regime has been previously analyzed by a number of theoretical approaches. In spite of the rich theoretical toolbox, analysis of the long-time dynamics remains very challenging. Previous approaches become increasingly costly at long times due to, for instance, artifacts of the logarithmic discretization in Wilson's numerical renormalization group or large entanglement in the time-evolved state. Another difficulty is to extend the previous approaches to generic spin-impurity models beyond the simplest Kondo models. These major challenges motivate a study to develop a new theoretical approach to quantum impurity systems. To overcome the challenges, we introduce new canonical transformations that can completely decouple the impurity and the environmental degrees of freedom. We achieve this by employing the parity symmetry hidden in the total Hamiltonian of spin-impurity models. We combine the transformation with the fermionic Gaussian states and introduce a family of variational many-body wavefunctions that can efficiently encode strong impurity-environment correlations. We benchmark our approach by demonstrating its successful application to the anisotropic and two-lead Kondo models and also by comparing it to results obtained by other methods such as the matrix-product state ansatz and the Bethe ansatz. We apply our method to reveal new types of out-of-equilibrium many-body dynamics that are difficult to study in the previous approaches. We propose a possible experiment in ultracold gases to test the predicted spatiotemporal dynamics by using quantum gas microscopy. We also extend our approach to a bosonic environment and apply it to study the strongly correlated system of spinful Rydberg molecules, which has been realized in state-of-the-art experiments. In Chapter 6, we analyze out-of-equilibrium physics of yet another fundamental class of a quantum impurity, that is, a mobile spinless impurity known as polaron. As a concrete physical system, we study an impurity atom strongly interacting with a two-component Bose-Einstein condensate mimicking a synthetic magnetic environment. We show how the Ramsey interference technique acting on the environment can be used to directly measure novel out-of-equilibrium dynamics of magnetic polarons beyond the conventional paradigm of solid-state physics. We also discuss a concrete experimental realization in ultracold gases to test our theroetical results.

In summary, the results obtained in this Thesis should serve as pivotal roles in understanding many-body physics of quantum systems open to an external world, and are applicable to experimental systems in AMO physics, quantum information science and condensed matter physics.