Nonequilibrium Quantum Statistical Mechanics
RIKEN Hakubi Research Team（2021）
Team Leader: Ryusuke Hamazaki (D.Sci.)

(0) Research field
CPR Subcommittee: Physics

Keywords: Nonequilibrium science, statistical mechanics, quantum dynamics, information theory, many-body systems

(1) Long-term goal of laboratory and research background

Microscopic physics, such as quantum mechanics, and macroscopic physics, such as thermodynamics, have developed independently and succeeded in describing each of the scales. Since macroscopic systems are composed of microscopic ingredients, it seems that statistical mechanics can be understood from quantum mechanics. However, the gap between these two principles is still large. Recent experimental developments of artificial quantum systems, represented by ultracold atomic systems, have enabled us to control microscopic quantum dynamics with high precision and observe emergent many-body phenomena. This means that we can now test foundation of statistical mechanics in laboratory.

The main goal of our research team is to understand macroscopic nonequilibrium phenomena from the microscopic theory of quantum mechanics. One of the specific goals is to explore basic theories for understanding and controlling abundant nonequilibrium phenomena that can appear in isolated and open quantum many-body systems, realized in artificial quantum systems such as ultracold atoms. We also aim to understand the fundamental theory of non-equilibrium statistical mechanics, in light of its relation to information theory and statistics. Furthermore, we attempt to contribute to the interdisciplinary field such as condensed matter physics and biology through non-equilibrium science.

(2) Current research activities (FY2021) and plan (until Mar. 2025)

(A) Discovery of an exceptional dynamical quantum phase transition

Equilibrium phase transitions are characterized by the singularity of the free energy. Recently, it has been discovered that the "dynamical free energy," defined using time instead of temperature, can have singularities. This "dynamical quantum phase transition" has attracted attention since it can extend the concept of phase transition to finite time, but mechanisms of this phenomenon are still not well understood.

In this study, we proposed a new mechanism for the dynamical quantum phase transition in unitary periodically driven systems, which we call the "exceptional point-like dynamical quantum phase transition." This transition involves strong singularities that cannot exist in equilibrium dynamical free energy, divergence of the correlation length with respect to a quantity called the generalized correlation, and oscillatory long-range order of it. We first pointed out that when the original periodically driven system satisfies certain parameter conditions, we obtain a non-unitary operator with anti-unitary symmetry using a transformation called the space-time duality. We then showed that when this hidden anti-unitary symmetry is spontaneously broken (i.e., the eigenstates are no longer invariant under the symmetry transformation), a spectral singularity called an exceptional point occurs, causing a dynamical phase transition in the original model.

(B) Effects of long-range interactions and dynamical constraints on thermalization

The phenomenon of thermalization of isolated quantum many-body systems, which is closely related to the foundation of statistical mechanics, has attracted much attention in recent years due to the experimental development of artificial quantum systems. It is known that relaxation to thermal equilibrium for long times is justified by the eigenstate thermalization hypothesis (ETH), which states that every energy eigenstate of the system itself is indistinguishable from the thermal state. Last fiscal year, we showed numerically that the ETH holds with probability 1 when the locally interacting many-body system is picked up randomly, which has been published this year. This indicates the universality of ETH in locally interacting systems. In this year, we further focused on two issues: what happens when long-range interactions are present, and whether we can find exceptions of thermalization in simple systems even with local interactions.

In the former problem, we assumed that the interaction decays algebraically with distance, and showed numerically that if the power of the decay is above a certain value, the ETH and thermalization are still established with probability 1. On the other hand, when the power is below that value, the finite size effect increases, and it is not possible to determine whether the ETH holds. This result implies that the range of the interaction affects the validity of the ETH.

In the latter problem, we found that in the most basic quantum many-body spin system, i.e., the high-dimensional transverse-field Ising model, ETH and thermalization are no longer valid in the limit of weak transverse fields. We showed that this is because the dynamics of spins is dynamically constrained in this limit. Such a constraint was shown to lead to the Hilbert space fragmentation, a recently proposed mechanism that prohibits thermalization in isolated quantum many-body systems.

(C) Discovery of universal dynamical scaling in disordered quantum many-body systems

Last year we showed for the first time that the Family-Vicsek scaling (a universal scaling law for surface growth in classical systems) appears in the nonequilibrium dynamics of particle fluctuations in quantum systems. While this suggests a universal law for relaxation of quantum many-body systems, it has been unclear what kind of universality class exists for such dynamics.

In this fiscal year, we showed that the Family-Vicsek scaling appears in disordered Fermionic many-body systems, where a new universality class that does not exist in classical systems appears. We also showed that similar dynamical scaling appears not only in the particle fluctuations but also in the entanglement entropy of the system (which is a quantity that characterizes entanglement, a unique quantity in quantum systems).

Future plan

In the next and subsequent fiscal years, we will continue to deepen this year's research. We also pursue the universality of non-equilibrium many-body systems, especially open quantum systems, and search for controlling methods for such systems. Specifically, we will extend important concepts in isolated quantum systems, such as the above-mentioned Hilbert-space fragmentation, to open quantum systems. We explore and classify concepts such as equilibration and thermalization in open systems. We will discuss how various non-equilibrium classes of such open systems are obtained and controlled. In this context, we will also consider the relationship between non-equilibrium open systems and different fields such as information theory, control theory, and computational-complexity theory, and attempt to integrate them. As another direction, we aim to construct a rigorous theory of non-equilibrium statistical mechanics for many-body systems. For example, we will explore the time required for quantum many-body transitions and the cost of controlling them.

(3) Members

(Team Leader) Ryusuke Hamazaki, **(Assistant)** Kaori Fukaya

(4) Representative research achievements

1. Atsuki Yoshinaga, Hideaki Hakoshima, Takashi Imoto, Yuichiro Matsuzaki, and Ryusuke Hamazaki,
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2. Ryusuke Hamazaki,
Nat. Commun. 12, 1-7 (2021).

3. Kazuya Fujimoto, Ryusuke Hamazaki, and Yuki Kawaguchi,
Phys. Rev. Lett. 127, 090601 (2021).

4. Taiki Haga, Masaya Nakagawa, Ryusuke Hamazaki and Masahito Ueda,
Phys. Rev. Lett, 127, 070402 (2021).

5. Shoki Sugimoto, Ryusuke Hamazaki, and Masahito Ueda,
Phys. Rev. Lett. 126, 120602 (2021).

Laboratory Homepage
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https://www.riken.jp/en/research/labs/hakubi/h_nonequil_qtm_stat_mech/index.html