

Nonequilibrium Quantum Statistical Mechanics
RIKEN Hakubi Research Team (2024)
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(0) Research field

CPR Subcommittee: Physics

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(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 (FY2024) and plan

(A) Measurement-induced spectral transitions

It has recently been discovered that quantum many-body systems subject to measurements exhibit a novel dynamical entanglement transition arising from the competition between unitary dynamics, which enhances entanglement, and quantum measurements, which suppress it. In contrast, in quantum phase transitions of isolated systems, entanglement transitions are generally accompanied by spectral transitions between gapless and gapped phases in the eigenvalue spectrum of the Hamiltonian. This raises the natural question of whether measurement-induced entanglement transitions also involve corresponding spectral transitions. However, because measurement processes involve randomness originating from fluctuations of measurement outcomes, a conventional spectrum cannot be utilized. By employing Lyapunov analysis, a method traditionally used in classical chaos, we demonstrated for the first time that the measurement-induced entanglement transition indeed accompanies a spectral transition from a gapless to a gapped phase [1].

(B) Speed limits to fluctuation dynamics

Among various approaches to nonequilibrium statistical physics, speed limits, which are rigorous inequalities constraining nonequilibrium transitions, play an important role. While recent previous studies have focused on speed limits for expectation values of physical observables, Ref. [2] established a universal bound on fluctuations of observables; it states that “the speed of growth of fluctuations cannot exceed the fluctuations of the velocity observable.” Furthermore, we found a new trade-off relation showing that expectation values and fluctuations of an observable cannot be simultaneously large. These results apply to classical stochastic processes, classical and quantum hydrodynamics, and quantum unitary dynamics. It is also useful for quantum many-body systems, where many conventional speed limits fail. Applying these speed limits, we also derived upper bounds on the time evolution of the entanglement entropy in free-fermionic systems.

(C) Exact construction of thermal eigenstates

Quantum states in thermal equilibrium are often called thermal states, and thermal energy eigenstates play an important role in the context of, e.g., thermalization of isolated quantum many-body systems. In these studies, the existence of thermal eigenstates has been theoretically assumed, but no examples of their construction have been found. Reference [3] discovered examples of spin models having a thermal eigenstate that can be written down analytically. We also rigorously proved that the state is thermal and that the model is nonintegrable. Until that time, the construction of eigenstates has been limited to low-entanglement states such as ground states and many-body scar states, or integrable systems. However, this result is significant in that the eigenstates are volume-law entangled and the models are nonintegrable.

(D) Quantum spin and heat transport by near a magnonic critical point

Heat and spin transport mediated by magnons in ferromagnets has been actively investigated in recent years in the field of solid-state spintronics, which aims at developing low-power-consumption devices. However, magnon transport in solid ferromagnets is usually studied under strong magnetic fields, where magnons behave as a classical Boltzmann gas, and thus, how Bose-Einstein statistics of magnons affect transport efficiencies of spin and heat remains unexplored. To address this issue, Ref. [3] proposed quantum simulation of tunneling magnon transport using ultracold atomic systems with high controllability of effective magnetic fields. Furthermore, by employing the nonequilibrium Green's function method, Ref. [4] revealed a divergent enhancement of the spin conductance arising from the Bose statistics and criticality of magnons. The highly efficient spin-transport mechanism uncovered in this study, which stems from the quantum nature of magnons, provides new guiding principles for the design of solid-state spintronic devices and opens new avenues for both fundamental science and engineering applications in spin transport.

(E) Kinetically constrained models constructed from dissipative quantum dynamics

In Ref. [5], we investigated how to simulate quantum kinetically constrained models using open quantum many-body systems. Quantum kinetically constrained models have recently attracted significant attention as a class of systems exhibiting exotic dynamical behavior. However, existing models have been studied primarily in the context of effective Hamiltonians for isolated systems. Using the general framework of decoherence-free subspaces in open quantum systems, we showed that such quantum systems can generically realize models with even stronger kinetic constraints. We also discussed concrete applications of this approach.

Future plan

Since the above Lyapunov analysis is expected to be applicable to other measurement-induced phenomena and open quantum systems, we will continue to further develop this line of research. In addition, in connection with the speed-limit results, we will pursue rigorous evaluations of their implications for thermodynamics. This includes speeding up work-extraction processes and elucidating potential advantages of thermodynamic processes governed by quantum mechanics.

(3) Members

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(Assistant) Masae Takano,
(Postdoctoral Researcher) Somnath Maity
(Postdoctoral Researcher) Yuta Sekino
(Postdoctoral Researcher) Shoki Sugimoto,
(Special Postdoctoral Researcher) Yuuya Chiba
(Junior Research Associate) Hisanori Oshima

(4) Representative research achievements

1. Ken Mochizuki and Ryusuke Hamazaki,
Measurement-Induced Spectral Transition,
[Phys. Rev. Lett. 134, 010410 \(2025\)](#). [[arXiv:2406.18234](#)]

2. Ryusuke Hamazaki
Speed limits to fluctuation dynamics,
[Communications Physics volume 7, Article number: 361 \(2024\).](#)
3. Yuuya Chiba and Yasushi Yoneta,
Exact Thermal Eigenstates of Nonintegrable Spin Chains at Infinite Temperature,
[Phys. Rev. Lett. 133, 170404 \(2024\)](#)
4. Yuta Sekino, Yuya Ominato, Hiroyuki Tajima, Shun Uchino, and Mamoru Matsuo,
Thermomagnetic Anomalies by Magnonic Criticality in Ultracold Atomic Transport,
[Phys. Rev. Lett. 133, 163402 \(2024\).](#) [[arXiv:2312.04280](#)]
5. Somnath Maity and Ryusuke Hamazaki,
Kinetically constrained models constructed from dissipative quantum dynamics,
[Phys. Rev. B 110, 014301 \(2024\).](#) [[arXiv:2301.07290](#)]

Laboratory Homepage

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https://www.riken.jp/research/labs/hakubi/h_nonequil_qtm_stat_mech/