Nonequilibrium Quantum Statistical Mechanics
RIKEN Hakubi Research Team（2020）
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(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 (FY2020) and plan (until Mar. 2025)

(A) Discovery of an unconventional relation between spectral gap and dynamics

There was a conventional wisdom that the relaxation time of the dynamics of a system can be estimated by the inverse of the spectral gap of the generator of the dynamics. We have (i) made this relation a rigorous oone for constrained dynamics systems and (ii) found a violation of the relation under the skin effect.

Regarding (i), when a sufficiently large energy gap is present in a quantum system, the effective physics can be approximated by a low-energy theory. This effective theory can also approximate the dynamics of the system, but errors eventually accumulate with time and the approximation becomes worse. We find a universal rigorous upper bound on the error for such constrained dynamics as a function of the inverse of the spectral gap of the generator. This is the first result that mathematically guarantees the validity of constrained dynamics. Regarding (ii), it was previously believed that the relaxation time of the dynamics described by the Lindblad equation, one of the fundamental equations for quantum open systems, is the inverse of the spectral gap of the Lindblad operator. We have shown that the phenomenon called the skin effect, which has recently attracted attention in non-Hermitian systems, also occurs in Lindblad systems, and that the relation between the spectral gap and the relaxation time change when it occurs.

(B) Discovery of the universality for the relaxation of isolated quantum systems

Thermalization of isolated quantum many-body systems is a topic that has attracted great attention owing to the recent experimental development of cold atomic gases, etc., and is also closely related to the foundation of statistical mechanics. In particular, we have studied the universality of the non-equilibrium dynamics of such isolated systems.

As a first topic, we show numerically that the eigenstate thermalization hypothesis (ETH) is universally valid for realistic systems. The ETH states that the energy eigenstate of the system itself is indistinguishable from the thermal equilibrium state, and provides sufficient conditions for thermalization after a long time. Although the ETH has been numerical verified for individual systems, the question of how universally the ETH holds for realistic systems is non-trivial. We consider a system with random local interactions, which is expected to characterize a realistic system, and show numerically that ETH holds for most of those samples.

Universality can also appear for the relaxation dynamics before complete thermalization. We show that the Family-Vicsek scaling, which is well known in the context of surface growth in classical stochastic processes, can also appear as density fluctuations of quantum many-body systems.

(C) Theoretical discovery on random matrices describing open quantum systems

Dyson classified Hermitian random matrices, which describe isolated quantum systems, into three symmetry classes in light of time-reversal symmetry and showed that this classification leads to three different universality classes of local spectral statistics such as level-spacing distributions (Dyson's threefold way). On the other hand, for non-Hermitian random matrices describing open quantum systems, the universality of local spectral statistics does not vary irrespective of the presence of time-reversal symmetry, and therefore only one universality class was known. We thus focus on the fact that the complex conjugation and transposition operations are inequivalent in non-Hermitian systems. We then succeed in showing that a new universal level-spacing distribution emerges in the class of random matrices with respect to the symmetry for the transposition operation, which corresponds to the threefold way in non-Hermitian matrices.

Future plan

From the next fiscal year, we will deepen the research conducted in this year and further pursue the universality of non-equilibrium many-body systems, particularly quantum open systems. Specifically, we will extend the concepts that are known to be important in isolated systems, such as many-body localization, to open systems, and explore the concept of quantum chaos in open systems. This is also related to the themes (A) and (C) above. Another research target is to study the universality of thermalization dynamics of isolated systems and its exceptions. For example, we are currently investigating how the universality of the aforementioned Family-Vicsek scaling is affected by disorder and particle species, and searching for exceptional systems in which the ETH is violated. In addition, in (A), the timescale describing nonequilibrium dynamics is evaluated in view of its relation to the spectral gap. In recent years, such a speed limit for few-body systems has been advanced in relation to information theory. From next fiscal year, we will extend the information-theoretic speed limit to many-body systems, and try to integrate nonequilibrium statistical mechanics, many-body theory, and information theory.

(3) Members

(RIKEN Hakubi Team Leader)
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(4) Representative research achievements

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2. Zongping Gong, Nobuyuki Yoshioka, Naoyuki Shibata, and Ryusuke Hamazaki, Phys. Rev. Lett. 124, 210606 (2020).
3. Kazuya Fujimoto, Ryusuke Hamazaki, and Yuki Kawaguchi, Phys. Rev. Lett. 124, 210604 (2020).
4. Ryusuke Hamazaki, Kohei Kawabata, Naoto Kura and Masahito Ueda, Phys. Rev. Research, 2, 023286 (2020).
5. Xiao Chai, Di Lao, Kazuya Fujimoto, Ryusuke Hamazaki, Masahito Ueda, and Chandra Raman, Phys. Rev. Lett. 125, 030402 (2020).[Selected as Editor's Suggestion, Featured in Physics]

Laboratory Homepage

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