論文の内容の要旨

Many-body effect on quantum transport in superconducting circuits

（超伝導回路における量子輸送と多体効果）

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Recently, the term “quantum computer” is often heard even in daily life. The idea was proposed 40 years ago by R. P. Feynman for solving quantum problems that are notoriously hard to solve using classical computers. Undoubtedly, his idea has become one of the grand challenges in 21st-century science. Now, 40 years after the original idea has been proposed, the quantum computer is beginning to be realized in various platforms, e.g., superconducting circuits, semiconductors, cold atoms, or optical lattices. Particularly, a superconducting circuit is considered one of the prominent candidates for the realization of quantum computers because of their high degree of freedom for designing. While it is an ideal physical system for realizing quantum bits (qubits), it remains several problems such as decoherence due to the surrounding environments and disorder in circuit elements, which may degrade performance of quantum computation. In this thesis, however, we promote the opposite direction. Namely, we focus on the “bad” situation for the quantum computer as a quantum simulator for fundamental physics. By changing the perspective above, the superconducting circuit turns into an ideal platform to investigate many-body effects, quantum phase transition, localization, and quantum heat transport with the help of its high feasibility and controllability.

In this thesis, we investigate three problems on superconducting circuits. First, we consider a quantum phase transition in the sub-Ohmic spin-boson model, which describes single superconducting qubit coupled to a transmission line. We investigate how quantum critical phenomena appear through the microwave scattering off this circuit. By performing the quantum Monte Carlo simulation, we find signatures of the quantum phase transition and the Fermi-liquid-like behavior in the frequency dependence in the reflection loss, $1-|r(\omega)|^2$. These frequency dependences depend on the exponent s of the spectral density of excitations in the environment and show power law with $1-s$ and $1+s$ for the quantum critical regime and the delocalized regime, the latter of which is characterized by the Fermi-liquid-like feature through the Shiba-Korringa relation, respectively (see Fig. 1). Moreover, by introducing RLC transmission lines with spatial-dependent circuit elements, as an environment, we propose a way to realize the sub-Ohmic spin-boson model with arbitrary exponent s of the spectral density.

Second, we study the transmission properties through a disordered Josephson-junction chain. This circuit is not only useful for application as a superinductor but also suitable study many-body effects due to the Coulomb interaction and disorder. The interplay of these effects induces a superconductor-insulator transition. We focus on the deep insulating phase, in which the problem is reduced to the competition between the elasticity and pinning effect. By performing numerical calculation, we find a signature the collective

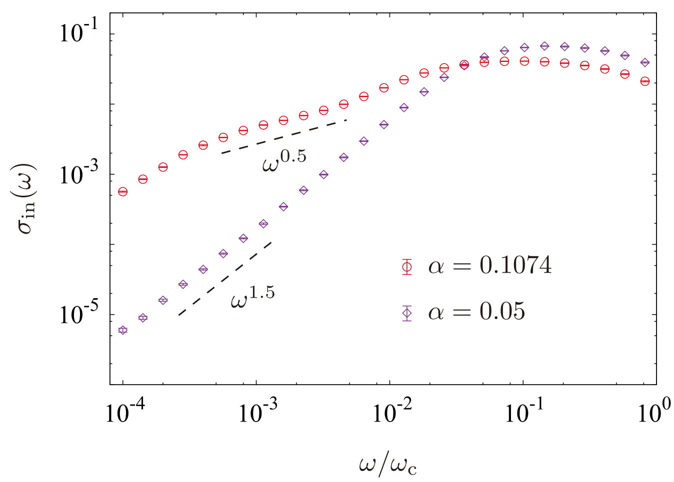

Fig. 1: The reflection loss as a function of the frequency for $s=0.5$. Plots are calculated by the quantum Monte Carlo simulation for $\alpha=0.1074$ (being at the critical point) and 0.05 (being in the delocalized phase).

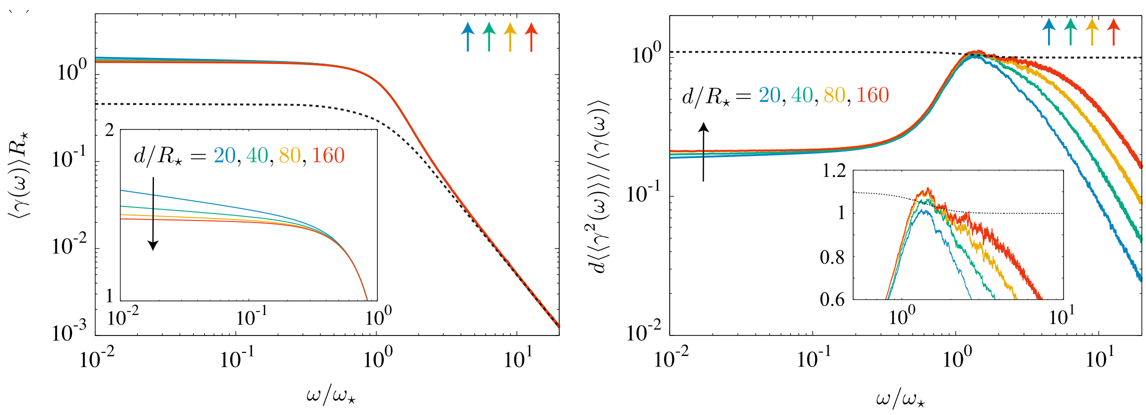

Fig. 2: The mean (left panel) and relative variance (right panel) of the Lyapunov exponent $\gamma(\omega) = -1/(2d)\ln T(\omega)$ as a function of the frequency for various chain length $d/R_\star = 20, 40, 80,$ and 160, where $R_\star$ is the Larkin length. The dotted lines in both panels represents the model with the Gaussian white-noise disorder.

pinning effect in the frequency dependence of the transmission in the whole frequency regime. For the high-frequency regime, although the pinning effect was expected to be neglected, we find that the pinning-induced disorder remains and affects the forward scattering length. On the other hand, for the low-frequency regime, by performing brute-force numerical calculations, we could gather the numerical pieces of the important quantities (the transmission, the Lyapunov exponent, and the reflection phase) and clarify the universality of the scattering property. Moreover, by compared with the well-known model with the Gaussian white-noise disorder, we clarify that the collective pining effect plays the important role in order to reproduce our result, as shown in Fig. 2 for the mean and the relative variance for the Lyapunov exponent.

Finally, we study quantum heat transport through an assembly consisting of a superconducting qubit embedded between superconducting harmonic resonators. This assembly is described by the quantum Rabi model, which is a typical multi-level system. By mapping the Ohmic dissipative quantum Rabi model into the spin-boson model with the structured bath and using the non-perturbative approximation, the noninteracting-blip approximation (NIBA), we discover a two-peak structure of the linear thermal conductance as a function temperature in the ultra-strong coupling regime (see Fig. 3) and find that this characteristic transport behavior comes from the fact that there are multiple levels in the assembly. Moreover, we show that the linear thermal conductance is sensitive to controllable parameters, which is expected to be advantageous for applying to quantum heat devices.

The results obtained in this thesis provide concrete foundation for further research on physics of superconducting circuits. We expect that all the results obtained in this thesis will be observed in near future.

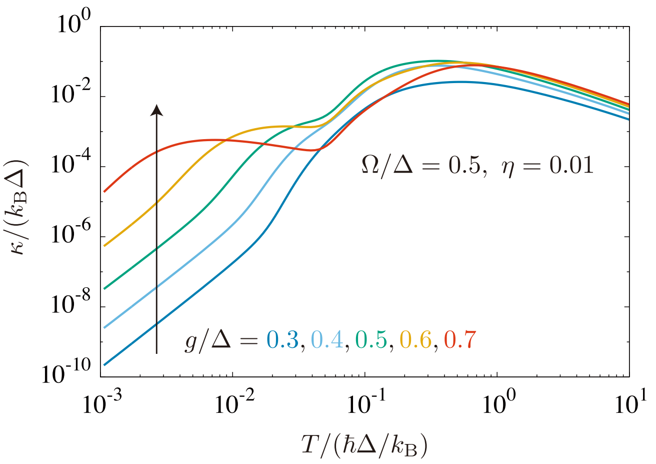

Fig. 3: The temperature dependence of the linear thermal conductance $\kappa(T)$ for small dissipation $\eta = 0.01$ and various coupling strengths $g/\Delta = 0.3, 0.4, 0.5, 0.6$, and 0.7, where Δ is the tunneling amplitude of the superconducting qubit. As the natural frequency Ω of the harmonic resonator increases, the two-peak structure is developed.