論文の内容の要旨

Nonequilibrium current fluctuation in interacting mesoscopic systems

（相互作用のあるメゾスコピック系における非平衡電流揺らぎ）

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Current fluctuation in mesoscopic conductors is of increasing importance along with the development of nanotechnology. As the current fluctuation essentially reflects a correlation of particles, it has been utilized to elucidate the properties of the fundamental excitation in the system. Owing to the great advance in measurement techniques, it becomes realistic to characterize the nonequilibrium transport in mesoscopic conductors by distribution of the current. The current distribution provides exclusive information on microscopic transport processes in the mesoscopic conductors. It has also been extensively studied to elucidate the fundamental aspects of the nonequilibrium statistical physics.

In this thesis, we focus on two important topics of the current fluctuation in interacting systems: (i) a detection scheme of the current distribution in a mesoscopic conductor and (ii) renormalization effect on current noise through an interacting mesoscopic system. The difficulty of analyzing the fluctuation in interacting systems arises from the absence of a systematic framework. We utilize a path integral approach based on the Keldysh formalism to provide microscopic understanding of the current fluctuation.

Detection scheme of current distribution in a mesoscopic conductor

The fundamental question as to the full counting statistics is whether and how it can be detected in a realistic measurement. There have been various theoretical proposals to detect the current fluctuation in the mesoscopic conductors. Supported by the rapid development of on-chip devices, the subject on the measurement of the full counting statistics is no longer just a theoretical matter. In the classical tunneling regime, it becomes possible to experimentally determine the distribution of current through the system to quantitatively address the fundamental relations in the nonequilibrium statistical physics such as the fluctuation theorem. The experimental verification of the fluctuation theorem is also in progress in coherent quantum conductors.

The first purpose of this thesis is to investigate a realistic and comprehensive detection scheme of the current distribution by using a simple LC circuit. In previous works, the explicit relations between the cumulants of the current distribution and those of the detector LC circuit have been clarified only for the first three cumulants. However, it is

still an open question whether and how the LC circuit can characterize all the cumulants of the current. In addition, the detailed analysis of the dynamics of the detector circuit is indispensable to achieve a good agreement between the theoretical predictions and the experimental results.

In this thesis, we establish the relations between all the higher order cumulants of the current fluctuation and those of the detector degrees of freedom in the classical and quasi-classical regimes. We consider the simple problem of determining the current distribution through a quantum point contact (QPC) by using an inductively coupled LC circuit as a detector. We use a critical assumption that the characteristic time scale of the detector is much slower than that of the QPC. With the aid of the quasi-stationary approximation, we can obtain a stochastic picture in which the flux through the detector circuit is perturbed by non-Gaussian noise generated by the current through the QPC: Instantaneous current through the QPC generates non-Gaussian fluctuation in the circuit. In the classical limit, the detector can be considered as a stochastic particle driven by the thermal and the non-Gaussian noise. Moreover, the quantum nature of the dissipative circuit becomes relevant as well at low temperatures.

In order to incorporate the thermal, non-Gaussian, and quantum noise in the detector circuit, we use a stochastic path integral approach. Based on this, we derive the formula to infer the current distribution in the mesoscopic conductor from the steady-state probability density function of the degrees of freedom in the detector circuit in the classical-quantum crossover regime. This indicates that there is a one-to-one correspondence between the distribution of the current and the detector even in the presence of the weak quantum fluctuation. It is also numerically clarified that the effect of the quantum fluctuation in the detector circuit becomes significant at sufficiently low temperatures to correctly estimate the current distribution.

Renormalization effect on current noise in a charge-fluctuating quantum dot

Remarkable advance in nanotechnology enables us to investigate the nonlinear transport in interacting systems. Among mesoscopic conductors, quantum dot systems offer an ideal arena to study nonequilibrium transport of interacting fermions. One of the most prominent many-body effects in the quantum dot system is the strong renormalization of the transmission between the quantum dot and the reservoirs due to their capacitive coupling. The quantum dot in this charge-fluctuating regime is described by the interacting resonant level model (IRLM). As a consequence of the renormalization effect, the I-V characteristic in the IRLM shows universal power-law behavior in the scaling regime, where the lead bandwidth is much larger than any other energy scale. The exponent of the power-law decay in the nonlinear regime is dependent on the strength of the two-body interaction.

The second purpose of this thesis is to elucidate the renormalization effect on the current noise in the charge-fluctuating quantum dot system. Although much is known about the current, little work has been done on the current noise in the IRLM. Recently, important insights for the noise were gained at a special parameter point where the model has self-duality. The analysis on the shot noise using field-theoretic techniques and the density matrix renormalization group method indicates that the quasi-particles with the effective charge $e^* = 2e$ are formed at the self-dual point. This is in clear contrast to the noninteracting limit $e^* = e$. However, the bias voltage V dependence of the current noise of the IRLM remains unclear away from the self-dual point. In addition, finite temperature effects were so far not investigated.

In this thesis, we develop a nonequilibrium functional renormalization group (FRG) scheme to investigate the current fluctuation in wide parameter regions which previous works could not have addressed. In contrast to the current which is solely determined by the self-energy, the computation of the current noise requires the current vertex function. We start with the lowest order truncation with respect to the two-particle interaction u to derive and solve the flow equation of the current vertex function. The simple lowest order approximation allows a unified picture of the current noise through the IRLM in the wide parameter regions including the case without the particle-hole symmetry and at finite temperatures.

In the scaling limit, the current noise calculated in plain perturbation theory is plagued by an artificial divergence, which is one of the major obstacles to go deep in the scaling regime. We find that the divergence originates from the vertex function which enters in the vertex correction to the current noise. Our FRG method removes the divergence at the particle-hole symmetric point, allowing a reliable analysis in the deep scaling limit. In this regime, the current noise shows a power-law decay with u-dependent exponent at high bias voltages $V \gg T_K$, where T_K is the characteristic energy scale of the IRLM. This is a manifestation of the renormalization effect in the nonequilibrium situation. The finite temperature effect on the current noise is also incorporated in consistent with the fluctuation dissipation theorem. We also analyze the effective charge in the weak coupling regime. It is found that the effective charge is only modified to second or higher order in the two-particle interaction.

In the absence of the particle-hole symmetry, a severe leading order divergence is found in the plain perturbation theory when the chemical potential of the lead is aligned with the energy level ϵ of the quantum dot. This divergence is consistently replaced by $\mathcal{O}(u^2)$ one, which is out of control in our lowest order approximation. Although the remaining order u^2 divergence prohibits us to go deep in the scaling limit, we obtain reliable results near the scaling limit. We find that the current noise robustly shows a power-law decay for $\max\{V, \epsilon\} \gg T_K$.