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（博士課程）
Doctoral Program

# 論 文 要 約

DISSERTATION OUTLINE

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| 系・コース：<br>Department of, Graduate major in | 物理学<br>物理学 | 系<br>コース | 申請学位（専攻分野）：<br>Academic Degree Requested | 博士<br>Doctor of | （ 理学 ） |
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要旨
Dissertation Outline


Recently, open quantum systems have been extensively investigated with the experimental developments such as cold atomic systems and we observed their interesting phenomena caused by boundary couplings. Though the analytical understandings of open quantum systems are generally difficult due to boundary couplings, exact solutions of the open quantum systems in the steady state have been obtained for one-dimensional case in the formulation of quantum master equation. However, still many problems remain to be studied such as fluctuation properties and finite temperature effects in the steady state. In the transient regime, the understandings have been limited with numerical calculation and there are few exact results because we need the full spectrum of the time-evolutional operator including effects of boundary couplings.

In this thesis, to analytically understand effects of boundary couplings on open quantum systems, we rigorously investigate the one-dimensional open tight-binding model with N sites coupled to two reservoirs on its edges with the nonequilibrium Green function method. We achieved two facts. First we obtain exact expressions of the mean physical quantities in the steady state and in the transient regime. For the steady state and the symmetric bias voltage case, we analytically obtain an exact expression of the electron density. From the expression, we show that a special state called superradiance state, which has been known in previous studies with the formulation of non-hermitian matrix, does not affect the qualitative behavior of the electron density in absolute zero temperature case. It is interesting because the superradiance state actually exists but it does not affect the qualitative behavior of the electron density in the settings. In addition, we prove that the phase transition which has been observed for the isolated tight-binding model also exists in our open case. The result is important because it is known that the boundary couplings can affect the exponent of the phase transition in isolated case but this does not hold in our open tight-binding model. For the asymmetric bias voltage case, where the steady current exists, we derive exact expressions of the steady current and the electron density on the edges with finite temperature effects(Fig. 1). Our approach is different from the matrix product state used in the previous study with the quantum master equation, where the author derived the exact expression of the current in the absolute zero temperature or high temperature limit. From the expression, we show that the steady current vanishes in the thermodynamic limit $N \to \infty$. This result is different from that of the zero temperature case where the current does not depend on the total number of the sites N and therefore transport is ballistic. In addition, from the exact expression we show that the superradiance transition vanishes for the finite temperature case. Therefore, we find that the superradiance transition is purely a result of quantum effects caused by the boundaries.

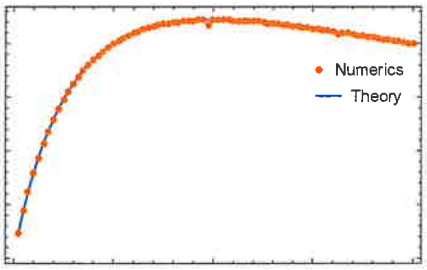


Fig.1 Comparison of the exact solution of the steady current with the numerical result for absolute zero temperature case and several boundary couplings. We can see good agreement between the analytical and numerical results.

In the transient regime, we derive an expression of the time-dependent electron density at absolute zero temperature in the limit $N \to \infty$. We analytically show that several interesting behaviors exist in transient regime. We prove that a two-step decay appears in the relaxation process purely caused by open boundaries(Fig. 2). From the analytical expression, we understand that at the time when the decay occurs electrons reach the site from the reservoirs. The value of the electron density after the first decay is determined by the on-site energy and the site index which we focus on. In addition, we see that the dependence of speed of convergence on boundary coupling qualitatively changes at a certain value of the boundary parameters where the superradiance states appear(Fig. 3). We analytically prove that the behavior is caused by an exponential term which only appears when there are superradiance states.

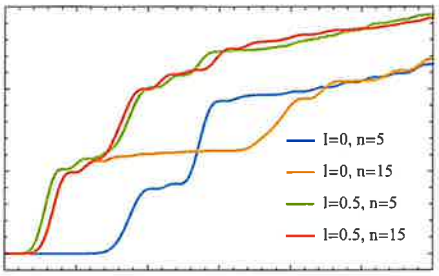


Fig. 2 Behavior of time-dependent electron density for several couplings and the site index. We can see that the two-step decay exists in all cases.

Second, we study the fluctuation properties of the open tight-binding model in the steady state and in the transient regime. In the steady state, we investigate the cumulant generating function of the integrated current in the steady state. As a result, we prove that the superradiance transition can appear in all the cumulants. In the transient regime, we study the current correlation function between the two reservoirs at the same time. By rigorously study a formal expression of the current correlation function derived in a previous study with the nonequilibrium Green function method, we find that the current correlation function expresses phase information. We numerically find that the dependence of the correlation on the boundary parameter changes when superradiance state appears. We also study effects of finite temperature. We find that the current correlation becomes weaker by increasing the temperature. We can understood this behavior by the fact that the phase information in the current correlation would vanish for high temperature case.

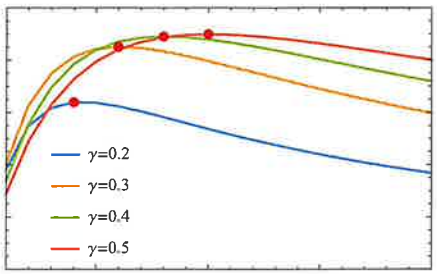


Fig. 3 Behavior of the electron density at a certain time and the right boundary couplings. We change the couplings between the sites and can see that the peak changes with the coupling between the sites. Actually, the superradiance transition occurs at the peaks.