論文の内容の要旨

Theory of Quantum Thermoelectricity with High Efficiency and High Power
(高効率高パワーの量子熱電効果の理論)

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Thermoelectric devices convert heat into electric power, which may contribute to solving the energy problem in modern society. Although many researchers have been working on it, the efficiency of thermoelectric devices is still low for practical use. Thanks to the recent development of nanotechnology, thermoelectricity in quantum systems named quantum thermoelectricity attracts increasing interest. Since quantum thermoelectricity is a vast unexplored field, there still is much room to find a highly efficient thermoelectric device. Moreover, the power as well as the efficiency has recently attracted more attention because it is also important for practical applications. In the present thesis, we investigate quantum thermoelectricity with a high efficiency and a high power in the linear-response regime both for a symmetric and an asymmetric linear-response matrices.

We first review nonequilibrium thermodynamics in the linear-response regime called the linear irreversible thermodynamics in Chapter 2. Only with Onsager's reciprocal theorem and the second law of thermodynamics, we prove that the upper limit of the maximum efficiency is the Carnot efficiency. For a symmetric linear-response matrix, we show that we obtain zero power at the Carnot efficiency. We also show that the efficiency at the maximum power is bounded by the universal value, a half of the Carnot efficiency called the Curzon-Ahlborn bound. For an asymmetric linear-response matrix, surprisingly, the second law of thermodynamics does not prohibit the Carnot efficiency with a finite power. We also give an example of the linear-response coefficients in the framework of the Landauer-Büttiker formula with two reservoirs, in which we find that we obtain a symmetric linear-response matrix even though there is a magnetic field. We will consider how to obtain an asymmetric matrix in Chapter 4.

In Chapter 3, we consider how to enhance the maximum efficiency and the efficiency at the maximum power for a symmetric linear-response matrix, both of which are described by a single parameter called the figure of merit. After representing familiar transport coefficients, such as the electric conductivity, the Seebeck coefficient, and the thermal conductivity, in terms of the linear-response coefficients, we focus on the Seebeck coefficient to enhance the figure of merit, whose high value requires breaking the electron-hole symmetry. We consider one of the candidates for a high Seebeck coefficient, namely thermoelectricity near Anderson localization transitions. For a single mobility edge, after we correct and extend previous studies, we consider corrections to the leading power-law singularity in the zero-temperature conductivity. We also investigate a finite-size effect on the thermoelectric coefficients. Although the Seebeck coefficient decreases with decreasing size, the figure of merit, first decreases but then increases as the size decreases. We finally study thermoelectricity in systems with a pair of localization edges, the ubiquitous situation in random systems near the centers of electronic energy bands. As the two thresholds approach each other, the Seebeck coefficient and the figure of merit increase significantly.

In Chapter 4, we investigate the possibility of the Carnot efficiency with a finite power for an asymmetric linear-response matrix using thermoelectricity in mesoscopic transport systems. We first review attempts in the realm of the Landauer-Büttiker formula, in which it was proved that we cannot obtain the Carnot efficiency with a finite power because of a strong bound of the linear-response coefficient from the unitarity of the scattering matrix. However, little is known for the cases to which we cannot apply the Landauer-Büttiker formula. We consider the model of quantum thermoelectricity with an electron-phonon interaction under a magnetic field, to which we cannot apply the formula. We obtain the following two results: We first find that we cannot reach the Carnot efficiency with a finite power for energy-independent space-symmetric resonant widths. We next find that the maximum efficiency and the efficiency at the maximum power for delivering electric power using heat supply from a phonon bath can be high. We finally consider a general 3×3 asymmetric linear-response matrix and clarify the conditions for the Carnot efficiency with a finite power, which our specific model does not satisfy.

Finally, we summarize the thesis and give possible future works in Chapter 5. We believe that a breakthrough of thermoelectricity will come from the quantum world. The idea from basic physics may produce a good and interesting thermoelectricity, which attracts much attention. Seeking quantum thermoelectricity may contribute not only to applied physics, but also to our interest as to what quantum is and how it affects the real world.