Summary of thesis: Non-Equilibrium Quantum Spin Transport Theory Based on Schwinger-Keldysh Formalism

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In this thesis, we microscopically investigate the non-equilibrium quantum transport phenomena of magnetization on the basis of the Schwinger-Keldysh formalism. In particular, we clarify the microscopic mechanism for the generation of the spin currents in metals and insulators.

Firstly, we reformulate the spin pumping theory on the basis of the Schwinger-Keldysh formalism, which can explicitly treat the system out of equilibrium at finite temperatures, and construct the microscopic quantum theory. Spin pumping is the experimentally established method for the generation of the spin currents and the spin-pumping system is defined as the junction between the non-magnetic metal and the ferromagnet under the applied microwave. Although the spin pumping phenomenon is well understood at the level of the semi-classical theory [1], to microscopically describe the phenomenon has been an urgent issue in order to capture the quantum-mechanical features. To obtain the deep understanding of spin pumping beyond the semi-classical treatment, we microscopically describe the non-equilibrium spin-flip process arising from quantum effects at the interface, where the exchange interaction between the conduction electrons and the magnons works, and quantum-mechanically analyze spin pumping on the basis of the spin continuity equation of the conduction electrons [2]. Then, we microscopically reveal the quantum-mechanical mechanism; we show that spin pumping is characterized by the spin relaxation torque (SRT), which breaks the spin conservation law of the conduction electrons, and find that all the informations about the quantum-mechanical spin-flip processes and the applied microwave are captured by the SRT. As the result, the net pumped spin current, which can be regarded as the non-linear response to the applied microwaves (i.e. quantum fluctuations), is represented only in terms of the SRT. The resultant distinction between our quantum theory and the preceding semi-classical one is also clarified. In addition, we theoretically predict that spin pumping is generated also by the electron spin resonance as well as the usual method via the ferromagnetic resonance. This theoretical prediction is the significant milestone to show the validity of our quantum theory.

After that, motivated by the breakthrough of the experimental techniques using the microwave pumping method [3], we show that the quasi-equilibrium Bose-Einstein condensation (BEC) of magnons occurs also in the spin-pumping systems. Then, we construct a magnon BEC theory where the thermalization processes, which work as a bridge between the magnon pumping driven by microwaves and the resultant quasi-equilibrium magnon BEC, are phenomenologically taken into account.

Finally, as the synthesis of our works, we utilize magnons in BEC and construct a microscopic theory on the transport of magnons in BEC; the Josephson effect in magnon BEC through the quantum-mechanical phase called the Aharonov-Casher (A-C) phase. We consider the junction in which two ferromagnetic insulators consisting of magnons BEC are weakly connected to each other. Then, we clarify the contribution of the A-C phase, which is just a special case of the geometric phase called the Berry's phase, to the Josephson spin current in the ferromagnetic junction. Even in the absence of the chemical potential difference, the A-C phase which satisfies a condition generates the transverse Josephson spin current carried by magnons in BEC. In this sense, the Josephson effect can be regarded as the macroscopic quantum phenomenon analogous to the magnon Hall effect.

Magnon BEC is a macroscopic state with quantum coherence and is robust against the loss of information. In addition, remarkably, the quasi-equilibrium magnon BEC can be experimentally produced at room temperature by using the microwave pumping method. That is, we have no need to cool the samples, which is in sharp contrast to the original Josephson effects in superconductors. These are the strong points of our method. On top of this, the A-C phase is characterized by the applied electric field, which is under our control. Then, by using the method we propose in this thesis, the first observation of the Josephson effect in magnon BEC is now possible. Thus, we can theoretically open a new door to experimentally exploring the spin current in the ferromagnetic insulators.

References;

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