Observation of spin-space mesoscopic transport with ultracold atomic gases

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Recent years have witnessed a great success in quantum simulation with ultracold atomic gases. Owing to unprecedented controllability of the quantum systems, ultracold atomic gases allow us to investigate regimes of quantum many-body physics in which other physical systems have yet to reach. Nowadays, research topics discussed with ultracold atomic gases cover ones associated with diverse fields in physics ranging from condensed matter physics to particle and nuclear physics, and astrophysics.

One of the rising topics in ultracold atomic gases is quantum transport occurring in a mesoscopic system. Historically, a mesoscopic system has been discussed in condensed matter physics since 80's when the fine processing technology in semiconductors was established. As quantum nature becomes significant in a submicron scale, a mesoscopic system becomes a sensitive probe to observe interesting quantum transport phenomena that do not appear in a macroscopic system, including measurements of conductance quantization and current noise. Since realizations of two-terminal transport systems in 2012, a variety of mesoscopic transport phenomena have also been examined in ultracold atomic gases.

Recently, Prof. Takahashi's group at Kyoto University realized a two-orbital optical lattice system with Yb atoms where singlet ($^1S_0$) and triplet ($^3P_0$) states of Yb atoms are simultaneously loaded on a two-dimensional optical lattice making a two-dimensional array of one-dimensional tubes. In addition, by applying a state-dependent optical lattice along the one-dimensional tubes, one can realize a situation that the singlet state of Yb atoms is itinerant whilst the triplet state of those is spatially localized. As a result, one makes a one-dimensional system in which itinerant particles interact with localized impurities.

In collaboration with Prof. Takahashi's group and Prof. Nishida at Tokyo Tech, we harnessed such a one-dimensional system to demonstrate mesoscopic spin transport phenomena [1]. As was theoretically discussed in [2], the key idea is that nuclear spin degrees of freedom in each Yb atom and couplings between nuclear spins can respectively be regarded as reservoirs and tunnel couplings in a mesoscopic system. Then, spin relaxation phenomena in our system are directly associated with multi-terminal mesoscopic transport phenomena.

To implement a mesoscopic system that consists of macroscopic reservoirs and few conduction channels, we prepared Yb atomic gases such that the number of the itinerant singlet state is considerably larger than that of the localized triplet state. Then, the spin relaxation via localized impurities occurs by controlling an interaction between itinerant and impurity atoms and by inducing a (nuclear) spin rotation. Here, the former and latter can be realized by means of the orbital Feshbach resonance and the Raman pulse, respectively. Finally, the spin relaxation phenomenon that originates from the spin rotational symmetry is measured through a damping of the Rabi oscillation from which one can extract transport characteristics.

Figure 1 is the resultant current-bias characteristic that has been extracted from the spin relaxation between two components in the nuclear spin. The characteristic clearly obeys Ohm's law in that the current is proportional to an applied

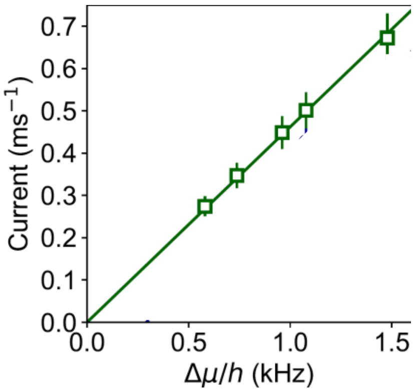

Fig. 1 Current-bias ($\Delta\mu$) characteristic extracted from relaxation of the Rabi oscillation. Squares are experimental data and solid curve is the theoretical prediction obeying Ohm's law.

chemical potential bias. What is especially important here is that the observed Ohmic response is well described by the celebrated Landauer formula that describes mesoscopic transport phenomena of noninteracting particles. The agreement between experiment and theory is a smoking gun of the correspondence between spin relaxation and mesoscopic transport phenomena.

The spin-space mesoscopic transport phenomena explored in this work have a couple of advantages. First, it is relatively easy to realize more than or equal to three terminal transport systems. Indeed, for the first time in ultracold atomic gases, we confirmed three-terminal transport phenomena (Fig. 2). In addition, we note that there is an interatomic interaction between reservoirs in spin-space transport. Since such an interaction is absent in the conventional mesoscopic systems, one can realize nontrivial transport phenomena that have not been explored [2]. Finally, a precision measurement in spin-space transport is also promising. For instance, measurements of full counting statistics in currents are allowed by combining an Yb quantum-gas microscope technique.

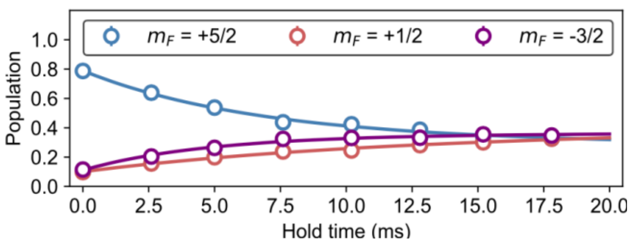

Fig. 1 Result in three terminals. The population of each nuclear-spin component decays over time, which implies that the total system approaches to equilibrium via three-terminal transport.

References
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