Kondo Transport under Steady-State Nonequilibrium Conditions

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Challenging problems are always encountered in various fields of theoretical physics; however, theorists somehow overcome the stumbling blocks. One of the unsolved problems in condensed matter physics is that of Kondo transport in a mesoscopic quantum impurity system under steady-state nonequilibrium conditions. The conventional Kondo problem is a well-known topic since the 1960's. Its equilibrium properties were clarified by the numerical renormalization group method in the early 1970's. The steady-state Kondo problem has been an interesting issue since 1998, when the Kondo phenomenon was clarified in a quantum-dot-single-electron transistor. In this mesoscopic Kondo system, one may apply a source-drain bias, a gate voltage, and a magnetic field. This experimental variety provides us with new types of Kondo phenomena that are quite different from those seen in the 1960's. Interestingly, in 1998, the mesoscopic Kondo phenomenon was also observed in an adsorbed magnetized atom on a metallic substrate by measuring the differential conductance dI/dV, where I and V denote the current and source-drain bias, respectively. In fact, the steady-state Kondo phenomenon was observed in a quantum point contact before 1998. However, the origin of the zero-bias peak in a quantum point contact is still under debate. It may belong to the category of a mesoscopic Kondo system.

It is not surprising that the dI/dV line shape for a sample with strong electron correlation is not fully understood. Examples involve doped and multilayer graphenes as well as high-Tc superconductors and the abovementioned systems. Furthermore, the dI/dV line shape does not reflect the sample density of states if a strong electron correlation is involved in tunneling. In this case, the structure of the dI/dV line shape is governed by the local density of states for the entire system. Hence, the basic physics for understanding the dI/dV line shapes of quantum impurity systems must be provided by solving the steady-state Kondo problem, which as yet remains unsolved.

The dI/dV line shapes of the abovementioned systems share the same structure, i.e., a zero-bias peak and two side peaks located at an energy much smaller than the Coulomb peak (quantum point contact). In some cases, the zero-bias peak is suppressed and pseudo-gap-like structures are observed (in scanning tunneling spectroscopy); further, the two side peaks are so close that the three coherent peaks appear as a single zero-bias peak (quantum-dot-single-electron transistor). The peaks in the tunneling conductance of these systems are obtained from resonant tunneling. The zero-bias peak is obviously formed by the resonant tunneling of a singlet through the Fermi level and the two side peaks are also formed by the resonant tunneling of a singlet through a certain coherent tunneling level located away from the Fermi level. Hence, the question that arises is that of the origin of this extra coherent tunneling level. Several studies have been performed on the two-reservoir Anderson impurity model under steady-state nonequilibrium conditions. However, the extra tunneling levels have not been identified and the dI/dV line shapes of the abovementioned systems are not explained by these studies.

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The key to finding these extra tunneling levels may be in the effect of the source-drain bias. The difference between the equilibrium and the steady-state nonequilibrium states is that in the latter, back-tunneling of a singlet is prohibited if no quasiparticle excitation is involved, whereas in the former, a singlet tunnels back and forth with equal probability. The prohibition of singlet back-tunneling makes it possible to describe the dynamics in a significantly reduced Liouville space in which the basis vectors that are used for singlet back-tunneling are neglected. Backward movement of an electron under source-drain bias is allowed only for the spin exchange of the singlet. This restriction gives bias-independent local density of states and the differential conductance is given by a single term, i.e., the derivative of local density of states over source-drain bias vanishes.

In the reduced Liouville space, the spectral function is expressed as a 5X5 matrix, which yields five tunneling levels: three coherent and two incoherent. One coherent tunneling level is at the Fermi level and the remaining two are symmetrically located away from the Fermi level. The two incoherent tunneling levels result in two broad Coulomb peaks. The zero-bias peak is suppressed in case of asymmetry in coherent or incoherent dynamics on the left and right sides of the mediating Kondo impurity. Our theoretical dI/dV line shapes for the various systems mentioned above fit the experimental data quite well. In conclusion, an understanding of Kondo transport under steady-state nonequilibrium conditions is just around the corner.