# Theory of the Nonequilibrium Kondo Effect in a Quantum Dot


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Recently it has been established that the Kondo effect is relevant to the transport property through the quantum dot. Clearly the new feature of the Kondo transport compared with the usual Kondo effect of magnetic impurities is the nonequilibrium nature, since the current is measured with a finite bias voltage.

Theoretical study of the nonequilibrium Kondo effect is based on the Keldysh formalism. In order to treat the correlation effect one possible method is the perturbation theory with respect to the Coulomb interaction $U$ in the dot [1]. According to this method the Kondo resonance is simply suppressed and does not show any particular structure in the nonequilibrium situation. Concerning the equilibrium Kondo problem it is well known that the second order perturbation theory gives remarkably good results[2]. However, it is not clear whether the second order perturbation theory works well in the nonequilibrium conditions. Actually the non-crossing approximation (NCA) has predicted the double peak structure at chemical potentials of both leads[3]. This result was obtained also by other approaches, the equation of motion[3], a real-time diagrammatic formulation[4] and scaling method[5]. Moreover the splitting of the Kondo peak was successfully observed by introducing a potential difference in the source lead[6]. These are favorable results for the splitting of the Kondo resonance by a finite bias voltage.

However it is not clear how the effects of the double peak structure, if it is true, appear in the differential conductance. Moreover concerning often used the NCA it is well known that the analyticity is broken in the low temperature limit. Thus one cannot discuss the conductance in the unitary limit by the NCA. It is clearly necessary to study the nonequilibrium Kondo effects by a better theoretical approach.

We develop a theory of quantum transport through a dot under finite voltage by using the perturbation theory up to the fourth order of $U$ based on the Keldysh formalism. We show that a single Kondo peak splits into double peaks when the voltage exceeds the Kondo temperature, $eV > k_B T_K$, which leads to the appearance of the new peak in conductance in addition to the zero-bias peak. Possible relevance of the new peak to the 0.7 conductance anomaly observed in quantum point contact is also discussed.


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