Charge and Spin Transfer in a Quantum Dot Coupled to a Mesoscopic Ring

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Coherent electron transfer between two sub-regions in a hybrid mesoscopic structure drastically influences the physical properties of the system. We consider an hybrid system composed of a quantum dot tunnel-coupled to a mesoscopic Aharonov-Bohm (AB) ring. Coupling between the two sub-regions accompanies charge transfer and spin flip, which modifies significantly the characteristics of the coherent electronic motion. In particular, it will be interesting to study the influence of the charge/spin fluctuations on the persistent current (PC) circulating the ring.

First, we discuss the effect of coherent charge transfer of a quantum dot coupled to a perfect one-dimensional (1D) AB ring (see Fig.1). For simplicity, we consider a single (spinless) impurity energy ε_0 for the QD coupled to the ring with its hoping strength Γ', and neglect the spin degree of freedom [1] . A pure 1D ring of N spinless electrons exhibits the PC being either diamagnetic or paramagnetic depending on the number of electrons being odd or even [2]. The half-amplitude of the AB oscillation I_0 for a perfect 1D ring is given by $I_0 = ev_F/L$, where v_F and L denote the Fermi velocity and the length of the ring, respectively. We concentrate on the ratio of the PC (I) to I_0 which indicates the modification of the PC provided by the charge transfer.

It is shown, for $\varepsilon_0 = 0$, that I/I_0 approaches zero with the power law of $(\delta/\Gamma')^2$, where δ represents the energy level spacing of the ring. The suppression of the current can be understood in terms of the charge fluctuation between the ring and the QD. It can also be considered to be equivalent to the behavior of the conductance in the corresponding open system [3] where the conductance becomes zero if the average occupation number of the QD equals to 1/2.

On the other hand, the role of the spin fluctuations in the same geometry of the QD + ring is strikingly different [4]. By using an Anderson impurity model and the variational treatment, we show that the Kondo effect gives rise to the scaling behavior of the PC as a function of δ/Γ' in the limit where charge fluctuation is suppressed. In contrast to the case of charge transfer, the coherent spin flip does not provide the complete suppression of the PC. It is shown that the PC of N electron system (I^N) is even equivalent to that of the ideal ring with the same number of electrons, in the continuum limit ($\delta/\Gamma' \to 0$). This conclusion is consistent with the exact Bethe ansatz result [5].

Our finding is very important since it implies, in general, that the behavior of the PC does not have correspondence with the conductance in the corresponding open system. In the 1D open system with a side-attached quantum dot, the conductance is completely suppressed in the Kondo limit [3]. We discuss why there is no such a correspondence in the Kondo systems, while it exists in a noninteracting systems. It is argued that this anomalous behavior must be related to the strongly correlated nature of the ground state, or to the separation of the charge and the spin degrees of freedom.

References

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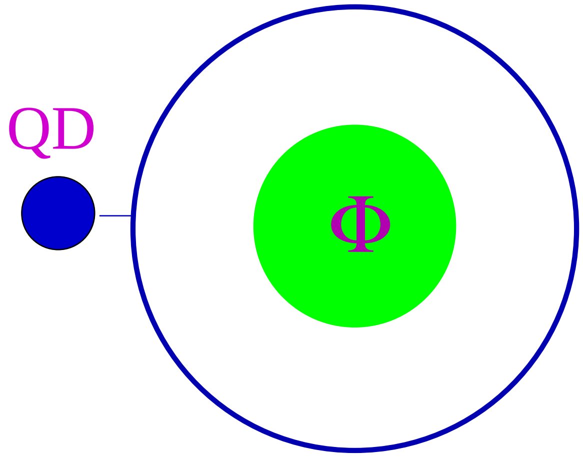

Figure 1: Schematic diagram of the hybrid quantum dot - Aharonov-Bohm Ring.

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