Aharonov-Bohm oscillations of electrical and thermal properties of a quantum dot ring geometry

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We investigate Aharonov-Bohm oscillations of the electrical current through a strongly correlated quantum dot embedded in an arbitrary scattering geometry in the linear and nonlinear regime. We also study the temperature and flux dependence of the thermopower S and find that it changes sign with temperature. At the temperature where $S(T_0) = 0$, the thermal properties are strongly flux dependent as compared to the electrical conductance.

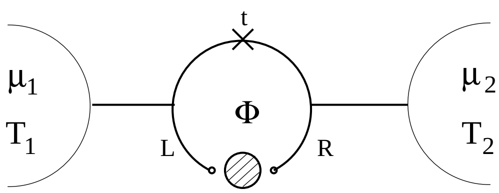

Figure 1: Geometry of the ring connected to reservoirs 1 and 2. The ring is connected to a quantum dot via high tunneling barriers. Φ is the flux penetrating the ring.

Recent experiments by Yacoby *et al.* [1] have renewed a theoretical interest in phase-sensitive transport [2], particularly in interacting systems. The flux dependence of the conductance of the system shown schematically in Fig. 1 was studied both in the linear and nonlinear regime [3, 4]. Since also the thermal properties of interacting quantum dots have been investigated experimentally in the past [5], it is necessary to understand the phase-sensitivity of quantities like the thermopower. While thermal effects in noninteracting systems have been studied in, e.g., Ref. [6], in this paper we concentrate on Aharonov-Bohm-type effects in the interacting case.

Although our formalism can be applied to an arbitrary scattering geometry [4], we will concentrate on the two-terminal configuration shown in Fig. 1. We assume that the upper arm of the ring is characterized by a transmission amplitude $t \ll 1$ (weak transmission), while the quantum dot in the lower arm contains one M-fold degenerate energy level ϵ_d which can be adjusted by varying a gate voltage. In the present paper we will treat the case of interacting electrons only, $M = 2$. The tunneling rate to the quantum dot is denoted by , . The total current between the reservoirs can be expressed in the notation of [4] as

$$I_\alpha = I_\alpha^{(0)} + \frac{e}{h} Re \sum_\sigma \sum_{\beta\gamma} \int dE \times s^\dagger_{\alpha\beta}\, s_{\alpha\gamma}\, A_{\gamma\beta}\, (\frac{i}{2} G^<_\sigma + i f_\beta G^R_\sigma) \,, \quad (1)$$

where $I_\alpha^{(0)}$ is the current without the dot (given by the usual Landauer-Büttiker formula), the matrices s and A describe the geometry of the system, i.e., the scattering properties of the system without the dot. The Green's functions $G^<$ and G^R contain the correlation effects caused by the interactions on the quantum dot [7]. The temperatures and chemical potentials of the reservoirs β enter via the Fermi functions f_β. In the linear response regime one has $I = G(\mu_1 - \mu_2)/e - B(T_1 - T_2)$ which defines the conductance G and the thermopower via $S = -B/G$.

We will now present the results obtained by evaluating Eq. 1. In Fig. 2 we show an example of the gate voltage dependence of the kinetic properties. Both quantities exhibit a pronounced resonance structure and, in particular, the thermopower changes sign. In Fig. 3 the temperature dependence of the thermopower is shown. In a certain range

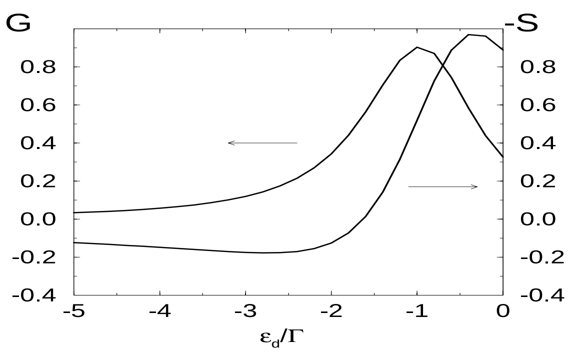

Figure 2: Conductance G and thermopower S as a function of level position ϵ_d. $\Phi = 0$, $T = 0.1$, , $t = 0.02$. G is given in units of e^2/h, S in units of k_B/e.

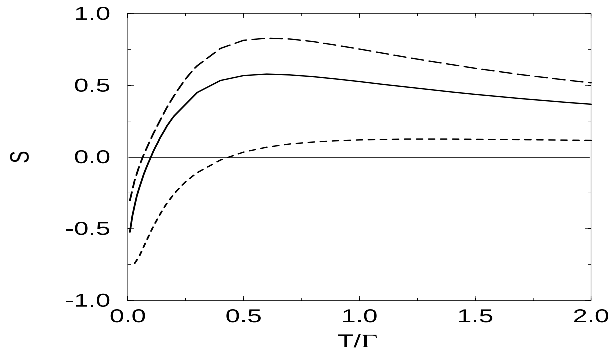

Figure 3: Temperature dependence of thermopower for $\epsilon_d = -2$, (dotted), -1.5, (solid), $-$, (dashed). $\Phi = 0$, $t = 0.02$.

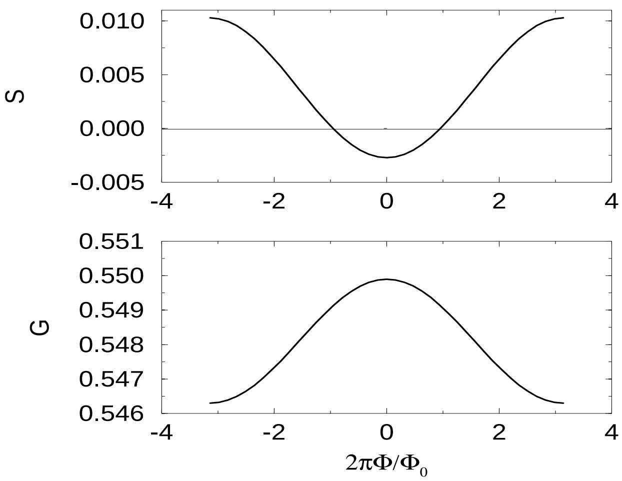

Figure 4: Thermopower (upper plot) and conductance (lower plot) as a function of magnetic flux threading the ring. $\epsilon_d = -1.62$, , $T = 0.1$, , $t = 0.02$.

of gate voltages the thermopower changes sign as a function of temperature. In the present case this behavior can be attributed to the Kondo-like structure of the spectral function. In fact, the model we use to describe the strongly interacting quantum dot is equivalent to an Anderson model ([7] and references therein).

The magnetic field dependence close to the resonance is shown in Fig. 4. In accordance with the Onsager principle, both quantities are even functions of the applied flux Φ. The Aharonov-Bohm oscillations of the conductance are clearly pronounced, however they are rather weak ($\delta G \sim te^2/h$) in comparison with the huge background value $G \sim e^2/h$. In contrast, the thermopower also exhibits Aharonov-Bohm-type oscillations, and the value of the latter in a certain range of parameters exceeds the background value. This means that the thermoelectric effects change sign as a function of a magnetic field, for the temperature and the gate voltage being fixed.

In conclusion, we have investigated the conductance and the thermopower of a quantum dot embedded in the ring. We have discovered that the thermopower is extremely sensitive to the external conditions, and, in particular, can change sign as a function of magnetic flux. We suggest that the experimental studies of the thermopower can provide an important information about the structure of the spectral function.

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