

Aharonov–Bohm interferometry with the T-shaped capacitively coupled quantum dots in the orbital Kondo regime

D. KRYCHOWSKI, S. LIPÍŃSKI*

Institute of Molecular Physics, Polish Academy of Sciences,
M. Smoluchowskiego 17, 60-179 Poznań, Poland

The magnetic field dependence of coherent transport through a pair of wires attached to two Aharonov–Bohm rings with embedded double dots is considered. The double dots are electrostatically coupled. The many-body problem is studied within the mean field slave boson approach and complementarily by the method of equation of motion in the limit of infinite intra and finite or infinite interdot Coulomb interactions.

Key words: *quantum dot; Aharonov–Bohm ring; Kondo effect; Fano effect*

1. Introduction

There is currently a great interest in phase coherence effects in nanoscopic systems due to their potential applications in quantum computers [1]. At present, various Aharonov–Bohm (AB) rings with embedded quantum dots in the arms have been fabricated, and quantum interference effects have been examined [2]. In these systems, the interplay of strong correlations and interference [3–5] attracts special attention. In the present paper, we discuss capacitively coupled AB interferometers containing double quantum dots (DQDs). This system enables us to manipulate each of the interferometers separately and to examine Coulomb-induced transfer of AB oscillations between the rings. The Kondo effect in strongly electrostatically coupled dots has two possible sources: the spin and orbital degeneracies. For vanishing Zeeman splitting at the dots, the transmission is a periodic function of the enclosed magnetic fluxes. For the broken spin degeneracy, the ideal periodicity is perturbed and the spin polarization of conductance is observed.

*Corresponding author, e-mail: lipinski@ifmpan.poznan.pl

2. Model

We study a pair of capacitively coupled double dots embedded in AB rings and side-attached to quantum wires. Each of the DQDs consists of an open dot (OQD) contacted by the leads and the “interacting” dot (IQD) (see the diagram in the inset to Fig. 1). The corresponding Hamiltonian reads:

$$H = \sum_{k\alpha j\sigma} \varepsilon_{k\alpha j\sigma} c_{k\alpha j\sigma}^\dagger c_{k\alpha j\sigma} + \sum_{j\sigma} \varepsilon_0 c_{j\sigma}^\dagger c_{j\sigma} + \sum_{j\sigma} \varepsilon_{j\sigma} d_{j\sigma}^\dagger d_{j\sigma} + \sum_j U_0 n_{j\uparrow} n_{j\downarrow} \\ + \sum_{\sigma\sigma'} U n_{1\sigma} n_{2\sigma'} + \sum_{k\alpha j\sigma} t (c_{k\alpha j\sigma}^\dagger c_{j\sigma} + c.c.) + \sum_{k\alpha j\sigma} t' (e^{i\varphi_j/2} c_{j\sigma}^\dagger d_{j\sigma} + e^{-i\varphi_j/2} c_{j\sigma}^\dagger d_{j\sigma} + c.c.) \quad (1)$$

where $\varepsilon_{j\sigma} = \varepsilon_d + g\mu_B\sigma h_j$ and h_j denotes local magnetic field at the dot j (we set $|e|=\mu_B=1$). The first term of Eq. (1) describes electrons in the electrodes, the second and third represent the OQDs and IQDs, the next two terms account for intra- (U_0) and intercouleomb (U) interactions ($n_{j\sigma} = d_{j\sigma} + d_{j\sigma}^\dagger$), and the last two terms describe tunneling to the leads and interdot IQD-OQD tunneling. The effect of the magnetic flux Φ is included by introducing the Peierls phase factors $e^{\pm i\varphi/2}$ ($\varphi = 2\pi\Phi/\Phi_0$, where Φ_0 is the magnetic flux quantum hc/e). The intradot charging energy is assumed to be strong ($U_0 \rightarrow \infty$) and we discuss the two opposite limits of weak ($U \sim \Gamma$) and strong ($U \rightarrow \infty$) interdot interaction. Γ denotes the level broadening

$$\Gamma = \pi t_0^2 \sum_{k\alpha\sigma} \delta(\varepsilon - \varepsilon_{k\alpha\sigma})$$

hereafter taken as a unit of energy. The currents flowing through the wires can be expressed in terms of the transmissions through the open dots [6]:

$$I_{j\sigma} = \frac{e^2}{\hbar} \frac{\Gamma}{2} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} (f_{jL}(\omega) - f_{jR}(\omega)) \text{Im}[G_{j\sigma,j\sigma}^{OQD}(\omega)] \quad (2)$$

where $G_{j\sigma,j\sigma}^{OQD}$ denotes the Green function of the open dot and f_{jr} are the Fermi distribution functions of the electrodes. The Green functions are determined by the mean field slave boson approach (SBMFA) [7]. The corresponding functions for the open and interacting dots are:

$$G_{j\sigma,j\sigma}^{OQD}(\omega) = \frac{1}{\omega - \varepsilon_0 + i\Gamma} \left(1 + \frac{|t'|^2 (2 + 2\cos[\varphi_j]) b_j^2 G_{j\sigma,j\sigma}^{IQD}(\omega)}{\omega - \varepsilon_0 + i\Gamma} \right) \quad (3)$$

$$G_{j\sigma,j\sigma}^{IQD}(\omega) = \frac{1}{\omega - \varepsilon_{j\sigma} - \frac{|t'|^2 (2 + 2\cos[\varphi_j]) b_j^2}{\omega - \varepsilon_0 + i\Gamma}} \quad (4)$$

where b_j denote mean values of the auxiliary boson fields. In the following, we use SBMFA to discuss only the limit of the vanishing Zeeman splitting at the dots, in

which case the use of two auxiliary fields is sufficient. To get an insight into the mixed valence range and the case of lifting of the spin degeneracy at the dots, we complement the calculations by the equation of motion treatment (EOM) using the decoupling procedure proposed by Lacroix [8].

3. Numerical results and discussion

Strong dot–dot interaction ($U \rightarrow \infty$). In this case, only one electron is accommodated in the system of coupled dots, i.e. $\langle n_1 + n_2 \rangle \approx 1$. The transmission is strongly affected by the interference between the ballistic channels of the wires and the Kondo resonant channels from IQDs.

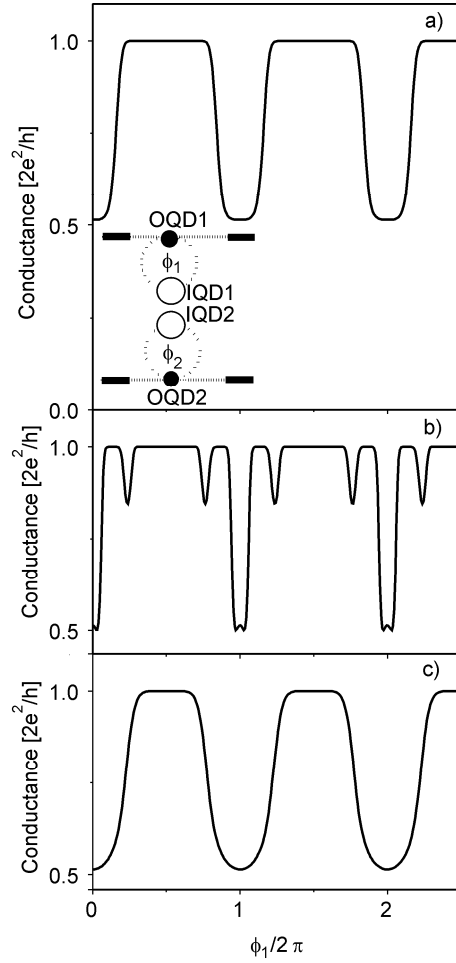


Fig. 1. AB oscillations of the upper circuit in the limit $U \rightarrow \infty$ for the cases of: a) equal magnetic fluxes $\phi_1 = \phi_2$, b) different fluxes $\phi_1/\phi_2 = 1/4$, c) the flux is applied to only one ring $\phi_2 = 0$, in this case conductance of the lower circuit is presented. The calculations were performed within SBMFA for $\varepsilon_0 = 0$, $\varepsilon_d = -3$ and half the bandwidth $D = 50$. The system is depicted in the inset

For the symmetrically coupled identical DQDs near the 0 flux [$\phi \approx 0 \pmod{2\pi}$], the spin and charge degrees of freedom are totally entangled and the Fermi liquid

ground state with $SU(4)$ symmetry is realized (phase shift $\delta_{j\sigma} = \pi/4$). In consequence of a destructive interference, a half-reflection is observed (anti-Kondo resonance). Figure 1 presents the influence of the applied magnetic fluxes. We discuss first the spin degenerate case ($h_j = 0$). Figure 1a shows the conductance oscillations for equal phases $\varphi_1 = \varphi_2$. Although $SU(4)$ symmetry is preserved, the flux strongly influences both the interference and the Kondo resonance leading to a modification of transmission probability through the system near the Fermi level. While increasing the flux, the destructive interference is replaced by a constructive one and the conductance reaches the unitary limit and then drops again for $\varphi \approx 2\pi$.

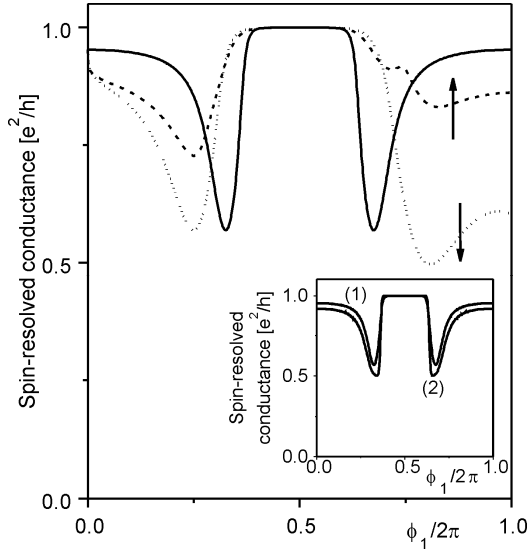


Fig. 2. Spin dependent AB oscillations for equal fluxes $\varphi_1 = \varphi_2$ and equal local magnetic fields at the IQDs $h_1 = h_2 = \alpha\varphi_1$, $\alpha = 0.125$ (dashed and dotted lines) compared with the case $\alpha = 0$ (solid lines). $\varepsilon_d = -0.9$ and the rest of parameters as in. Calculations were performed by the EOM method. The inset represents a comparison of the EOM results (line (1)) with SBMFA (line (2)) calculations

For different fluxes $\varphi_1 \neq \varphi_2$, the orbital degeneracy is broken. Figure 1b ($\varphi_1/\varphi_2 = 1/4$) presents an example of the two-period oscillations of conductance and Fig. 1c illustrates the Coulomb induced AB oscillations (oscillations observed also in the ring, where no magnetic flux is applied, $\varphi_2 = 0$). Figure 2 shows how the flux dependence of conductance changes in the mixed valence (MV) range and what are the consequences of lifting the spin degeneracy ($h_j \neq 0$). Concerning the former aspect, the conductance for $\varphi \approx 0$ is strongly enhanced compared to the Kondo regime and it is due to a much smaller effect of the destructive interference with a Kondo-like resonant channel. In this intermediate range, the resonance is deformed, broadened, lowered and shifted towards higher energies. The initial decrease of conductance is clearly observed in a wide range of the flux. It reflects the fact that the resonance is not centred at the Fermi level. Breaking of the spin degeneracy results in perturbing the periodicity of AB oscillations and conductance becomes spin dependent (Fig. 2). For some values of the flux, the spin polarization of conductance is significant, which can be used for spin filtering. The results for the nonvanishing Zeeman splitting are presented for the case when the local fields are equal to the homogenous field

$h = \Phi/(\pi r^2)$. For the radii of the rings $r_1 = r_2 = 20$ nm, the first quasi-period of AB oscillations ($\varphi = 1$) is reached for $h_0 = 0.125$, which for typical values of $F \approx 0.1$ – 0.5 meV [9] gives h_0 lying in the range (0.03–0.15) T.

Weak dot–dot interaction. The two IQDs are both singly occupied in this case $\langle n_1 \rangle = \langle n_2 \rangle \approx 1$ and behave as separate Kondo impurities. Fano-like suppression of the Kondo-mediated conductance for vanishing fluxes results in an almost perfect reflection, which is a consequence of a $\pi/2$ phase shift characteristic for $SU(2)$ symmetry of the ground state. In Figure 3, we present the evolution of the Coulomb induced AB oscillations with the increase of interdot interaction.

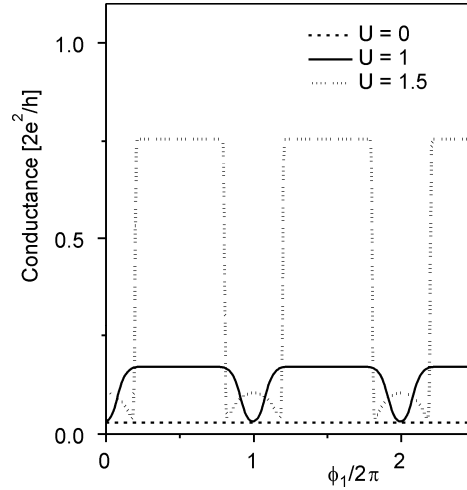


Fig. 3. AB oscillations in the limit of weak interdot interaction for the circuit with no directly applied magnetic flux ($\varphi_2 = 0$) (SBMFA)

Summarizing, the present paper provides a picture of combined influence of interference, the Kondo effect and interdot interactions on transport through a system of coupled quantum dots in the presence of applied magnetic fluxes.

References

- [1] DI VINCENZO D.P., *Science*, 270 (1995), 255.
- [2] KOBAYASHI K., AIKAWA H., KASUMOTO S., IYE Y., *Phys. Rev. Lett.*, 85 (2002), 256806.
- [3] BULKA B.R., STEFAŃSKI P., *Phys. Rev. Lett.*, 86 (2001), 5128.
- [4] LOPEZ R., SANCHEZ D., LEE M., CHOI M.S., SIMON P., LE HUR K., *Phys. Rev., B*, 71 (2005), 115312.
- [5] TANAKA Y., KAWAKAMI N., *J. Phys. Soc. Jpn.*, 75 (2006) 015004.
- [6] MEIER Y., WINGREEN N.S., LEE P.A., *Phys. Rev. Lett.*, 70 (1993), 2601.
- [7] COLEMAN P., *Phys. Rev. B*, 29 (1984), 3035.
- [8] LACROIX C., *J. Phys. F, Met. Phys.*, 11 (1981), 2389.
- [9] GERLAND U., VON DELFT J., COSTI T.A., OREG Y., *Phys. Rev. Lett.*, 84 (2000), 3710.

Received 7 May 2006

Revised 1 September 2006