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Antiresonance and decoupling in electronic transport through parallel-coupled quantum-dot structures with laterally-coupled Majorana zero modes

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ABSTRACT

We theoretically investigate the electronic transport through a parallel-coupled multi-quantum-dot system, in which the terminal dots of a one-dimensional quantum-dot chain are embodied in the two arms of an Aharonov–Bohm interferometer. It is found that in the structures of odd(even) dots, all their even(odd) molecular states have opportunities to decouple from the leads, and in this process antiresonance occurs which are accordant with the odd(even)-numbered eigenenergies of the sub-molecule without terminal dots. Next when Majorana zero modes are introduced to couple laterally to the terminal dots, the antiresonance and decoupling phenomena still co-exist in the quantum transport process. Such a result can be helpful in understanding the special influence of Majorana zero mode on the electronic transport through quantum-dot systems.

1. Introduction

Majorana modes in solid states have attracted a great deal of attention due to their fundamental interest and potential application for the fault-tolerant quantum computation. During the past years, different groups have proposed various ways to realize unpaired Majorana bound state (MBS), such as in a vortex core in a p-wave superconductor [1–6] or superfluid [7,8]. Recently, it has been reported that MBSs can be realized at the ends of a one-dimensional p-wave superconductor for which the proposed system is a semiconductor nanowire with Rashba spin-orbit interaction to which both a magnetic field and proximity-induced s-wave pairing are added [9–12]. More recently, experiments have been continuously improved for searching the MBSs, and the signs of MBS have also become clear [13–15]. This exactly means that MBSs can be constructed in solid states, and that its application becomes more feasible.

Transport property is an important aspect for describing the application probability of one quasiparticle. And then, researchers designed various circuits to investigate the transport properties of MBS. Moreover, it is considered to couple laterally to the QD systems to observe the quantifiable influence of the MBS on the electron transport process. As a consequence, some interesting results have been reported. For example, when the QD system is noninteracting and in the resonant-tunneling regime, the MBS modifies the conductance through the QD by inducing the sharp decrease of the conductance by a factor of $\frac{1}{2}$ [16,17]. For the QD in the Kondo regime, the QD-MBS coupling induces the new Kondo physics and reduces the conductance plateau by exactly a factor $\frac{3}{4}$ [18]. Besides in the double-QD structures, the crossed Andreev reflection [19] and nonlocal entanglement [20] induced by the MBSs are show interesting behaviors.

QDs are well-known for the characteristics that they can couple to form the QD-molecule systems. In comparison with the single-QD systems, QD molecules present more intricate quantum transport behaviors, because of the tunable structure parameters and abundant quantum interference mechanisms. For instance, in the T-shaped QD-molecule structures, the antiresonance points in transmission spectrum are related to the molecular states of the laterally-coupled sub-molecule [21–23]. In QD-ring structures, abundant decoupling phenomenon will come into being, which is significant for the electron manipulation. The influence of MBS on the resonant tunneling and Kondo physics motivates us to think about its role in modulating other transport results, such as the antiresonance and decoupling mecha-

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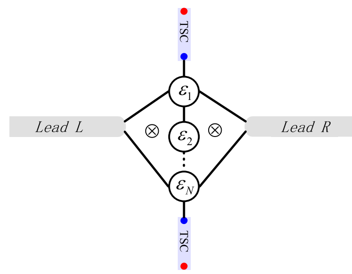

Fig. 1. Schematic diagram of one parallel-coupled multi-QD setup with laterally-coupled Majorana zero modes, where the terminal QDs couple to two leads. The terminal QDs are also connected with Majorana zero modes. The couplings between the terminal QDs and the leads are defined by $\mathcal{V}_{\alpha j}$ ($\alpha \in L, R$ and $j = 1, N$). In addition, local magnetic flux is supposed to thread such a quantum ring.

nisms. Therefore, in the present work we consider one parallel-coupled QD structure, in which the terminal QDs of a one-dimensional QD chain are embodied in the two arms of an Aharonov–Bohm interferometer. In such a system, all the even(odd) molecular states can decouple from the leads for odd(even)-QD structures, accompanied by occurrence of antiresonance which are related to the eigenenergies of the sub-molecule without terminal QDs. Our purpose is to investigate the influence of the QD-MBS coupling on this phenomenon. What's interesting is that when Majorana zero modes are introduced to couple laterally to the terminal QDs, the antiresonance and decoupling phenomena survive, moreover, they are independent of the increase of the QD-MBS coupling.

2. Theoretical model

The electronic transport structure is illustrated in Fig. 1. In such a structure, each terminal QD of one QD chain is coupled to one MBS, respectively. The Hamiltonian of this system can be written as $H = H_0 + H_D + H_M + H_{MD} + H_T$. The first term is the Hamiltonian for the two normal metallic leads, which takes the form as

$$H_0 = \sum_{\alpha k} \varepsilon_{\alpha k} c^\dagger_{\alpha k} c_{\alpha k}. \tag{1}$$

$c^\dagger_{\alpha k}$ ($c_{\alpha k}$) is an operator to create (annihilate) an electron of the continuous state $|k\rangle$ in the lead-α ($\alpha \in L, R$). $\varepsilon_{\alpha k}$ is the corresponding single-particle energy. The second term is the Hamiltonian for the QD molecule. It is described as

$$H_D = \sum_{j=1}^{N} \varepsilon_j d^\dagger_j d_j + \sum_{j=1}^{N-1} t_j d^\dagger_j d_{j+1} + \text{H.c.} \tag{2}$$

$d^\dagger_j$ (d_j) is the creation (annihilation) operator of electron in QD-j. ε_j denotes the electron level in the corresponding QD, and t_j denotes the tunneling between the two neighboring QDs. Note that since the QD structure is noninteracting, we in this paper neglect the spin index. Next, H_M is the Hamiltonian of the Majorana bound states. In this work, we would like to adopt its low-energy effective form, for clarifying its-induced leading physics. And then, H_M reads [24]

$$H_M = i\epsilon_U \eta_{U1}\eta_{U2} + i\epsilon_D \eta_{D1}\eta_{D2}. \tag{3}$$

Each term describes the paired MBSs generated at the ends of the nanowire and coupled to each other by an energy $\epsilon_{U(D)} \sim e^{-l_{U(D)}/\xi}$, with $l_{U(D)}$ the wire length and ξ the superconducting coherence length. The following term describes the tunnel coupling between QD-1 (and QD-N) and the nearby MBS, which is given by

$$H_{MD} = (\lambda_U d_1 - \lambda^*_U d^\dagger_1)\eta_{U1} + (\lambda_D d_N - \lambda^*_D d^\dagger_N)\eta_{D1}. \tag{4}$$

$\lambda_{U(D)}$ is the coupling coefficient between QD-1 (QD-N) and the MBS. Finally, H_T represents the coupling between the QD molecule and the metallic leads

$$H_T = \sum_{\alpha k} \mathcal{V}_{\alpha 1} d^\dagger_1 c_{\alpha k} + \sum_{\alpha k} \mathcal{V}_{\alpha N} d^\dagger_N c_{\alpha k} + \text{H.c.} \tag{5}$$

$\mathcal{V}_{\alpha j}$ is the tunneling element between QD-j and lead-α. Due to the existence of one quantum ring, local magnetic flux can be introduced through the ring to adjust the quantum interference that governs the electronic transport, due to its-induced Aharonov–Bohm effect. Under the symmetric gauge, the QD-lead coupling coefficients can be taken to be $\mathcal{V}_{L1} = \mathcal{V}^*_{RN} = \mathcal{V}_0 e^{i\phi/4}$ and $\mathcal{V}^*_{LN} = \mathcal{V}_{R1} = \mathcal{V}_0 e^{i\phi/4}$ [25]. Here ϕ is the magnetic-flux phase factor, which obeys the relationship of $\phi = 2\pi \frac{\Phi}{\phi_0}$ with Φ being the magnetic flux and $\phi_0 = h/e$ the magnetic flux quantum.

In Fig. 1, we consider that $\mu_L = \varepsilon_F + \frac{eV}{2}$ and $\mu_R = \varepsilon_F - \frac{eV}{2}$ (μ_α is the chemical potential of lead-α, and ε_F is the Fermi level in the case of $V = 0$ which can be assumed to be zero), and their difference will drive the electron transport. Note that in the presence of MBSs, this structure is actually a three-terminal system. Thus, the current of lead-L and lead-R should be calculated, respectively, for completely clarifying the transport properties. The current in lead-α can be evaluated by various methods, such as the scattering matrix method and the nonequilibrium Green function technique [26]. We here employ the latter to discuss the transport behaviors. Via a straightforward derivation, we obtain the expression of the current in one lead:

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