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Full counting statistics in a serially coupled double quantum dot system with spin–orbit coupling

Qiang Wang [a], Hai-Bin Xue [b,*], Hai-Qing Xie [a]

[a] Department of Physics, Taiyuan Normal University, Taiyuan 030031, China
[b] College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, China

HIGHLIGHTS

- The quantum coherence dependence of FCS depends on the SOC-tuned hopping strength.
- The spin polarization rates determine the formation of super-Poissonian shot noise.
- The spin polarization rates and magnitude of magnetic field can induce a strong NDC.
- The obvious energy-level detuning dependence of FCS can reflect the magnitude of SOC.
- The dip position of the skewness can be used to qualitatively extract SOC strength.

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ABSTRACT

We study the full counting statistics of electron transport through a serially coupled double quantum dot (QD) system with spin–orbit coupling (SOC) weakly coupled to two electrodes. We demonstrate that the spin polarizations of the source and drain electrodes determine whether the shot noise maintains super-Poissonian distribution, and whether the sign transitions of the skewness from positive to negative values and of the kurtosis from negative to positive values take place. In particular, the interplay between the spin polarizations of the source and drain electrodes and the magnitude of the external magnetic field, can give rise to a gate-voltage-tunable strong negative differential conductance (NDC) and the shot noise in this NDC region is significantly enhanced. Importantly, for a given SOC parameter, the obvious variation of the high-order current cumulants as a function of the energy-level detuning in a certain range, especially the dip position of the Fano

* Corresponding author.
E-mail address: xuehaibin@tyut.edu.cn (H.-B. Xue).

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factor of the skewness can be used to qualitatively extract the information about the magnitude of the SOC.

1. Introduction

The full counting statistics (FCS) [1–3], which can yield all zero-frequency current cumulants of transferred-electron number, can well describe the electron tunneling through coupled quantum dot (QD) systems, and provide a powerful tool to reveal different transport mechanisms and the information on the quantum correlations, which are not accessible through the differential conductance and average current measurements. For instance, the FCS can be used to determine the intrinsic relaxation and decoherence times of spin states of QD systems [4], and to reveal the multistability (i.e., background charge configurations) of a QD system [5], and to detect the stabilized pure states of QD system under nonequilibrium conditions [6], and to observe Majorana bound states by the shift of the minimum points of both the shot noise and the skewness [7]. In particular, the high-order current cumulants can be proposed to identify the internal level structure of QD systems [8], and to qualitatively extract the information about the effective nuclear-spin magnetic field [9] and the quantum coherence in QD systems [10]; and the high-order factorial cumulants can be used to detected the interactions among the conduction electrons transport through coupled QD systems [11–13]. Moreover, the steady-state fluctuation theorem in coupled QD system [14,15] and the entropy fluctuation theorems in driven single orbital QD systems [16] can also be tested through electron counting statistics experiments [15]. Consequently, the FCS in coupled QD systems has attracted increasing attention both experimentally [17–25] as well as theoretically [26–48].

On the other hand, the controlled manipulation of spin degree of freedom in coupled QD systems is critical for their application in nanoelectronic and spintronic devices. Particularly, the spin–orbit coupling (SOC) provides an electrical way to detect and manipulate of the spin degree of freedom. However, most of the previous investigations on quantum transport in QD systems with SOC or spin-flip scattering were focused mainly on the average current [49–51] or the shot noise [52–55]. The influence of the SOC on the FCS of coupled QD systems has received little attention. Especially, extracting the information about the magnitude of the SOC from the FCS in a coupled QD system with SOC has not yet been revealed.

In this work, we study the FCS of electron transport through a serially coupled double QD system with Rashba SOC, and then discuss the feasibility of extracting information about the magnitude of the SOC from the FCS. This paper is organized as follows. In Section 2, we present the Hamiltonian of a serially coupled double QD system with SOC weakly coupled to two electrodes and introduce the particle-number-resolved quantum master equation employed to study the FCS. In Section 3, we discuss the influences of the magnitude of the spin–orbit coupling, the quantum coherence, the spin polarization rates of the two electrodes, the magnitude of the external magnetic field, and the energy-level detuning on the FCS, and analyze the condition of extracting information about the SOC parameter from the FCS. Finally, in Section 4, a summary is presented.

2. Model and method

2.1. Hamiltonian of the double QD system weakly coupled to two electrodes

The Hamiltonian for the serially coupled double QD system with Rashba SOC weakly coupled to two electrodes is written as

$$H_{\text{total}} = H_{\text{dot}} + H_{\text{electrodes}} + H_{\text{T}}. \quad (1)$$