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Decoherence of the Kondo singlet caused by Fano resonance

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Abstract. We investigate the structure of an Aharonov-Bohm interferometer with a quantum dot coupling to left and right electrodes. By employing cluster expansions, the equations of motion of Green's functions are transformed into the corresponding equation of motion of connected Green's functions, which provides a truncation scheme. With this method under the Lacroix's truncation approximation, we show that Fano resonance causes a decoherence of the Kondo singlet.

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Key words: cluster expansions, Kondo singlet, Fano resonance, Lacroix's truncation approximation

1 Introduction

Decoherence has been a hot subject over the past two decades [1–5]. The Kondo singlet has been studied for more than three decades [6] and the observations [7, 8] of quantum effects of electron wave functions in quantum dot systems have opened a new approach for the study of the Kondo singlet. The Kondo singlet of the quantum dot system leads to an increase of conductance of the mesoscopic system in the Kondo regime at the characteristic Kondo temperature when a localized spin of the quantum dot is screened into singlet, which provides a new channel for the mesoscopic current. Many aspects of the Kondo singlet of the quantum dot systems have been investigated in detail in recent two decades such as magnetic flux effects, temperature dependence properties, and phase evolution [9–11]; from the Kondo regime to the mixed-valence regime [12]; from equilibrium properties to non-equilibrium properties [13].

The Fano resonance, come from interference of discrete and continuum level [14], is a ubiquitous phenomenon observed in different systems. In recent years, the interest

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in the Fano resonance has been renewed because two well-known experiments. One is the scanning tunneling microscope(STM) experiment [15] designed to study the Kondo singlet, in which the tunneling spectra manifest themselves as Fano resonance that is determined by two interfering paths — Kondo resonance serves as the discrete resonant scattering path and the conduction band does as the continuum nonresonant channel modified by broadened impurity level [16]. The other is the structure of an Aharonov-Bohm interferometer (ABI) adding a quantum dot(QD) [17], in which Fano resonance has been observed in conductance through the ABI+QD structure but the nature of the nonresonant path has not yet been fully clarified [18].

The Kondo singlet and the Fano resonance can coexist in the ABI+QD structure and in the STM system [19]. However the resonant and the nonresonant paths that induce the Fano resonance can't be detached spatially in the STM system, that is disadvantageous for us to investigate the properties of the nonresonant path. The ABI+QD structure has an advantage in which the resonant and the nonresonant paths can be separated spatially [20]. Both the Kondo singlet and the Fano resonance can be simultaneously builded in ABI+QD structure when the dot level is adjusted to Kondo regime and the temperature is lower than Kondo temperature [21,22]. It is an interesting question how do the Fano resonance and the Kondo singlet interplay when both appear simultaneously in ABI+QD structure?

In previous studies [23,24] attention has been paid to the evolution of the Fano and the Kondo singlets with the variation of the temperature and the relative position of the dot level; the interact between the Fano state and the Kondo state is not discussed by authors. But it is an inescapable issue how the Fano resonance and the Kondo singlet interplay when the Fano state and the Kondo state is simultaneously builded in ABI+QD structure. Through a numerical simulation we find that the building of Fano state suppresses the amplitude of Kondo resonance, and a possible explanation is that Fano resonance causes a decoherence of the Kondo singlet.

The ABI+QD structure can be modeled by the following Hamiltonian [25,26]:

$$\begin{aligned} H = & \sum_{\alpha k\sigma} \varepsilon_{\alpha k} C^{\dagger}_{\alpha k\sigma} C_{\alpha k\sigma} + \sum_{\sigma} \varepsilon_{d\sigma} d^{\dagger}_{\sigma} d_{\sigma} + \frac{U}{2} \sum_{\sigma} n_{\sigma} n_{\bar{\sigma}} \\ & + \sum_{\alpha k\sigma} (V_{\alpha} d^{\dagger}_{\sigma} C_{\alpha k\sigma} + V^{*}_{\alpha} C^{\dagger}_{\alpha k\sigma} d_{\sigma}) \\ & + \sum_{kk'\sigma} (T_{LR} C^{\dagger}_{Lk\sigma} C_{Rk'\sigma} + T^{*}_{LR} C^{\dagger}_{Rk'\sigma} C_{Lk\sigma}), \end{aligned} \tag{1}$$

where $\alpha = L, R$ denotes the left or right electrode, and $\sigma = \uparrow, \downarrow$ denotes the spin up or down.

The model is solved by employing the equation of motion method of Green's function. And the hierarchy of equations of motion is truncated under the Lacroix's approximation [27,28]. After a lengthy but direct algebra calculation, in the limit of $U \to \infty$, the