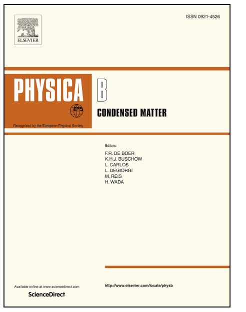
Accepted Manuscript



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PII: S0921-4526(18)30227-8

DOI: 10.1016/j.physb.2018.03.029

Reference: PHYSB 310790

To appear in: *Physica B: Physics of Condensed Matter*

Received Date: 14 November 2017

Revised Date: 13 March 2018

Accepted Date: 14 March 2018

Please cite this article as: C.-I. Kim, C.-J. Kang, M.-I. Choe, P.-I. Lyu, J.-K. Ahn, C.-S. Yun, Influence of electron-phonon interaction on quantum phase transition in the triple quantum dots coupled to pseudo-gap Fermi system, *Physica B: Physics of Condensed Matter* (2018), doi: 10.1016/j.physb.2018.03.029.

Physica B
journal homepage: www.elsevier.com

Influence of electron-phonon interaction on quantum phase transition in the triple quantum dots coupled to pseudo-gap Fermi system

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ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online

Keywords:
Triple quantum dots
Quantum phase transition
Power-law pseudo-gap
Electron-phonon interaction

ABSTRACT

We investigate the triple quantum dots with triangular geometry, in which one of the dots (embedded dot) is coupled to pseudo-gap Fermi system and electrons in the dot interact with a local phonon mode. The model, which we treat using the analytical argument and the numerical renormalization group, exhibits the quantum phase transition between ferromagnetically-coupled local moment phase and antiferromagnetically-coupled strong coupling phase depending upon electron-phonon coupling. We restrict our discussion to the case that inter-dot exchange couplings are much smaller than the Kondo temperature for the embedded dot. Since Fermi system has the density of states dependent on energy in power-law fashion, the embedded dot retains an unscreened spin degree of freedom even in Kondo regime. For the coupling to such Fermi system, the simultaneous increase of electron-phonon coupling and pseudo-gap exponent has the contrary effects on the quantum phase transition depending upon inter-dot couplings.

1. Introduction

Triangular triple quantum dot, which is one of the multi-dot systems, has intensively been studied in condensed matter physics because of its simple geometry [1-5]. One of the interesting features of this system is the quantum phase transition (QPT) between ferromagnetically-coupled local moment (FLM) phase and antiferromagnetically-coupled strong coupling (AFSC) phase in the case that inter-dot tunnel-couplings are much smaller than Coulomb repulsion [6-9].

In general, such QPT is based on two mechanisms; one is the case with $J >> T_K$ (J is the exchange coupling between embedded dot and side dot, and T_K is the temperature at which the local spin on embedded dot is Kondo-screened). In this case, the QPT is due to triangular symmetry breaking in the isolated triple quantum dots (TQD) [6, 7]. If $J >> J'$ (J' is the exchange coupling between side dots), then odd-parity doublet state is a ground state, thereby the whole system being in FLM. In contrast, if $J << J'$, even-parity doublet state is a ground state and the whole system is in AFSC. It is important to note that the coupling to the Fermi system causes only Kondo screening, but does not change largely the internal spin entanglement in isolated TQD. On the other hand, in the case $J << T_K$, there appears RKKY-type (indirect exchange) interaction between side dots mediated by Kondo singlet state. Therefore, the QPT is due to the competition between RKKY-type and direct exchange interactions [8, 9]. In such competition, if RKKY-type interaction (direct exchange interaction) prevails, the stable spin triplet (singlet) state is formed between side dots and the whole system is in FLM (AFSC).

Considering a single quantum dot coupled to ordinary Fermi system (e.g. metallic electrode) in the Kondo regime, it is often a very good approximation to replace the conduction density of states (DOS) by a constant. Then, the local spin on the dot undergoes the complete screening by spin density of Fermi system for an arbitrary hybridization width Γ ($0 < \Gamma << U$) [10]. The DOS in Fermi system is, however, effectively not a constant but dependent on energy. Such systems are, for example, heavy-fermion and cuprate unconventional superconductors [11, 12], zero-gap bulk semiconductors [13], and various (quasi-)two-dimensional systems such as graphite [14, 15] and graphene [16]. Since the DOS is dependent on energy in power-law fashion $\rho(\varepsilon) \propto |\varepsilon|^r$ (r is pseudo-gap exponent) for these materials [17, 18], we can no longer take it as a constant in dealing with the essential Kondo screening around Fermi energy. When a single quantum dot is coupled to Fermi system with power-law pseudo-gap (or pseudo-gap Fermi system), then Kondo screening depends upon hybridization width. In other words, Kondo screening occurs only for width Γ larger than non-zero critical hybridization width Γ_c and the local spin on the dot is not screened completely but partially. In this state, there remains an unscreened spin degree of freedom on the embedded dot. At the particle-hole symmetric point, the critical hybridization width Γ_c, for $0 < r < 0.5$, increases with pseudo-gap exponent, furthermore, $\Gamma_c \to \infty$ for $r \geq 0.5$ [19, 20].