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Transverse spin fluctuations in metallic quantum dots

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Abstract

We present a full fledged quantum mechanical treatment of the interplay between the charge and spin zero mode interactions in quantum dots. Transverse spin fluctuations are shown to suppress the Coulomb blockade and give rise to non-monotonic behavior of tunneling DoS as one approaches the Stoner instability. We discuss both transport through a quantum dot and the dynamic magnetic susceptibility of the latter.

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The importance of electron–electron interactions is emphasized in low-dimensional conductors. In one-dimension interactions in the charge and spin channels are separable. Considering zero-dimensional quantum dots (QDs) taken in the metallic regime with its internal dimensionless conductance $g \gg 1$, the "Universal Hamiltonian" [1,2] scheme provides a framework to study the leading interaction modes: zero-mode interactions in the charge (H_C), spin (H_S) and Cooper (H_{BCS}) channels:

$$H = \sum_{\alpha,\sigma} \varepsilon_\alpha a^\dagger_{\alpha,\sigma} a_{\alpha,\sigma} + H_C + H_S + H_{\mathrm{BCS}}. \quad (1)$$

Here α denotes a single-particle orbital state with spin projection σ. While this Hamiltonian is simple, the physics involved is not at all trivial. The charge channel interaction $H_C = E_c(n - N_0)^2$ leads to the phenomenon of the Coulomb blockade (CB). Here $E_c = e^2/2C$ is a charging energy, $n = \sum_\alpha a^\dagger_{\alpha,\sigma} a_{\alpha,\sigma}$ the number operator; N_0 stands for a positive background charge tuned to a Coulomb valley. The exchange interaction $H_S = -J(\mathbf{S})^2$ with $\mathbf{S}_{\sigma\sigma'} \equiv \frac{1}{2}\sum_\alpha a^\dagger_{\alpha,\sigma} \sigma_{\sigma\sigma'} a_{\alpha,\sigma'}$ leads to Stoner instability, which, in mesoscopic systems as opposed to bulk, is modified [1]. The last term $H_{\mathrm{BCS}} = \lambda_{\mathrm{BCS}} T^\dagger T$ with $T = \sum_\alpha a_{\alpha\uparrow} a_{\alpha\downarrow}$ leads to the superconducting instability provided that $\lambda_{\mathrm{BCS}} < 0$. Superconducting correlations are suppressed by magnetic field and thus do not exist for Gaussian Unitary Ensemble (GUE). Discarding both Cooper and spin-orbit interaction channels, the description of the metallic QD allows for only two other channels, namely charge and spin. In a recent theoretical study [3] the effect of the spin channel on Coulomb peaks has been analyzed employing a master equation in the classical limit. In this paper we report the full fledged quantum mechanical treatment of the interplay between the charge and the spin zero mode interactions in quantum dots. The non-perturbative effects of zero-mode charge interaction (e.g. zero-bias anomaly [4]) are described in terms of the propagation of gauge bosons ($U(1)$ gauge field) [5]. Here we adopt similar ideas to account for spin fluctuations described by the non-abelian $SU(2)$ group.

We introduce easy axis anisotropy $H_S \to -J\left[(S^z)^2 + \varepsilon\left((S^x)^2 + S^y)^2\right)\right]$, where $\varepsilon = J_\perp/J_\parallel < 1$. In this case the spin rotation symmetry is reduced to $SO(2)$. We will treat the terms of transverse and longitudinal (Ising) fluctuations independently. The Euclidian action for the model (1) is given by

$$S = \int_0^\beta \left[\sum_{\alpha\sigma} \bar{\psi}_{\alpha\sigma}(\tau)[\partial_\tau + \mu]\psi_{\alpha\sigma}(\tau) - H \right] \mathrm{d}\tau. \quad (2)$$

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Here ψ stand for Grassmann variables describing electrons in the dot. Employing a Hubbard–Stratonovich transformation with the bosonic fields ϕ (for charge) and Φ (for spin) we obtain the action which includes terms quadratic in Ψ, ϕ and Φ. The gauge transformation [5,6] allows to integrate out all non-zero Fourier components of fields ϕ and Φ^z which stand for the Coulomb and longitudinal spin fluctuations respectively. The zero modes of these fields are accounted by corresponding winding numbers [7]. In the spirit of [5], the interaction of electrons with the finite-frequency charge and longitudinal modes (ϕ_n, Φ^z_n) may be interpreted in terms of a gauge boson dressing the electron propagator. The *exact* electronic GF in the absence of transverse fluctuations ($\varepsilon = 0$) is given by $G_{\alpha,\sigma}(\tau_i - \tau_f) = G^{[0]}_{\alpha,\sigma}(\tau_i - \tau_f, \mu)\mathrm{e}^{-S_\parallel(\tau_i-\tau_f)}$ [5]. Here $S_\parallel(\tau) = (E_c - (J/4))(|\tau| - (\tau^2/\beta))$. The exchange interaction effectively modifies the charging energy. For long-range interaction this correction is small $E_c/J \sim (k_F L)^{d-1} \gg 1$ [2] (L is a linear size of the d-dimensional confined electron gas, k_F is a Fermi momentum), while for contact interaction $E_c - J/4 = 0$.

The transverse fluctuations are taken into account perturbatively assuming $\varepsilon < 1$. The transverse correlator is considered in Gaussian approximation (Δ is the mean level spacing)

$$\langle \Phi^+(\tau_1)\Phi^-(\tau_2)\rangle = \frac{J}{2}\delta(\tau_1 - \tau_2) + \frac{\varepsilon J^2}{2\beta(\Delta - \varepsilon J)}. \tag{3}$$

Corrections due to spin transverse fluctuations are incorporated into the transverse gauge factor $F_\perp(\tau, \varepsilon)$

$$G(\tau) = G_0(\tau)\mathrm{e}^{-S_\parallel(\tau)}F_\perp(\tau, \varepsilon). \tag{4}$$

We show that away from the Stoner instability [6], $F_\perp$ is dominated by the "white noise" term of Eq. (3), while in the vicinity of this point it is the second (singular Stoner) term in (3) which dominates. We have computed the temperature and energy dependence of the TDoS for various values of ε (see Fig. 1). The non-monotonic behavior of tunneling DoS as one approaches the Stoner instability is attributed to effects of the transverse spin fluctuations.

The longitudinal susceptibility (χ^{zz}) is *not* affected by the gauge bosons. By contrast, χ^{+-} acquires the Φ^z dependent gauge factor. The condition $T > \Delta$ allows us to evaluate the path integral in the Gaussian approximation. One finds to leading order in ε

$$\chi^{zz}(\tau) = \frac{\chi_0}{1 - J\chi_0}, \quad \chi^{+-}(\tau) = \frac{\varepsilon\chi_0 \mathrm{e}^{J\tau}}{1 - \varepsilon J\chi_0}, \tag{5}$$

where $\chi_0 = 1/\Delta$. The above susceptibilities are given as function of τ. χ^{zz} (5) diverges at the thermodynamic Stoner instability point, while χ^{+-} remains finite. Notwithstanding, the static transverse susceptibility is enhanced by the gauge fluctuations. The dynamic behavior (including relaxation processes) and the ε corrections to $\chi^{\mu\nu}$ will be discussed elsewhere.

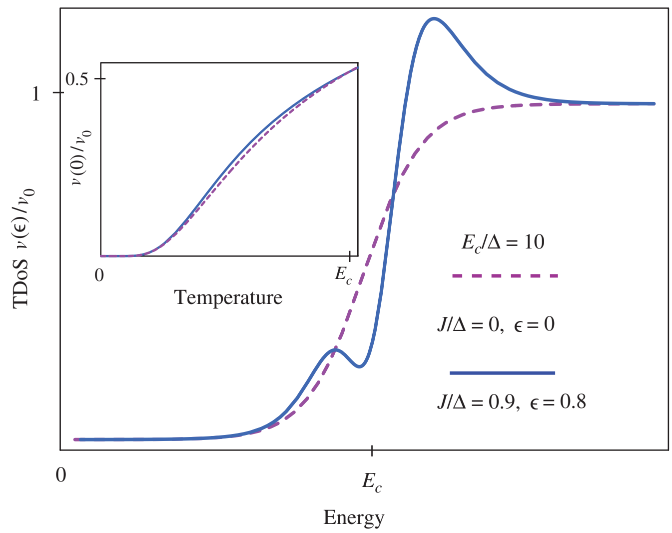

Fig. 1. The spin-normalized tunneling density of states shown as function of energy. Insert: TDoS at Fermi level as function of temperature.

We investigate influence of spin and charge zero-mode interactions on the TDoS and the susceptibilities. Longitudinal spin fluctuations suppress the CB and the static longitudinal susceptibility is greatly enhanced near the Stoner instability. Transverse fluctuations generally tend to suppress the CB, but also contain a term which dominates the dynamics near the Stoner instability and *enhances* the CB. The transverse susceptibility will be enhanced as well.

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