Phase separation and tunnelling magnetoresistance in manganites

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Abstract

A simple model for manganites is considered. It takes into account both the Coulomb repulsion between electrons and the essential magnetic interactions. The phase diagram of this model, which contains two regions of small-scale phase separation, is constructed. The tunnelling magnetoresistance for the phase-separated state is calculated. The effects of Coulomb blockade and spin-assistant tunnelling are taken into account.

Key words: manganites; phase separation; charge ordering; spin-assistant tunnelling; magnetoresistance.

1. Introduction

An interplay between charge and spin ordering on one hand and phase-separation on the other has attracted a significant attention of theorists in connection with the physics of high-T_c superconductors and manganites.

In the present paper, we consider this interplay in manganites on the basis of a simple model, which takes into account both the Coulomb repulsion of electrons on neighboring sites and essential magnetic interactions.

2. Theoretical model and phase diagram

The Hamiltonian of the model has a form:

$$\hat{H} = -t \sum_{<i,\,j>\,\sigma} c^{+}_{i\,\sigma} c_{j\,\sigma} + V \sum_{<i,\,j>} n_i n_j - \\ -J_H \sum_{i} \boldsymbol{S}_i \boldsymbol{\sigma}_i + J \sum_{<i,\,j>} \boldsymbol{S}_i \boldsymbol{S}_j, \qquad (1)$$

where V is the Coulomb repulsion on neighboring sites, J_H is on-site FM exchange, J is the AFM Heisenberg exchange. We consider this model in a physically reasonable strong-coupling limit:

$$J_H S > V > W > JS^2, \qquad (2)$$

where $W = 2zt$ is a bandwidth.

In this limit, a homogeneous charge-ordered (CO) state has a negative compressibility for all densities of electrons $n \neq 1/2$ [1]. Hence our system is unstable towards phase separation away from $n = 1/2$. We analyze the simplest version of phase-separated state with small metallic FM droplets in an insulating CO and AFM matrix.

The energy of this state reads:

$$E = -tn_d \left(z - \frac{\pi^2 a^2}{R^2} \right) + zJS^2 \frac{4}{3}\pi \left(\frac{R}{a} \right)^3 n_d - \\ - \left(zJS^2 + \frac{2zt^2}{3V} \right) \left[1 - \frac{4}{3}\pi \left(\frac{R}{a} \right)^3 n_d \right], \qquad (3)$$

where R is the radius of a spherical droplet, n_d is the droplet concentration, a is the lattice constant. Minimization of the energy (3) with respect to the radius yields:

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$$\frac{R}{a} \sim \left(\frac{t}{V} + \frac{JS^2}{t}\right)^{-1/5}. \tag{4}$$

As a result, taking into account also a tendency towards phase separation at small densities, we come to the following phase diagram [1,2]:

- at $0 < n < (JS^2/t)^{3/5}$, it corresponds to phase separation into a FM metal embedded in an AFM insulating matrix.
- at $(JS^2/t)^{3/5} < n < (t/V + JS^2/t)$, the system is a FM metal.
- finally, at $(t/V + JS^2/t) < n < 1/2$, we have phase separation in the form of FM metallic droplets inside an AFM charge-ordered matrix.

This phase diagram is in a good qualitative agreement with many experimental results for real manganites [3–6].

3. Tunnelling magnetoresistance in a phase-separated state

It is reasonable to assume that a charge transport in a phase-separated state is dominated by electron transitions between the droplets. A creation of a two-electron droplet is associated with a Coulomb energy barrier $A \sim e^2/\varepsilon_0 a$. As a result for $A \gg k_B T$ a tunnelling conductivity reads [7]:

$$\sigma \sim \frac{\omega_0}{k_B T} \exp\left(-\frac{A}{2k_B T}\right). \tag{5}$$

A tunnelling magnetoresistance at low magnetic fields behaves as [8]:

$$MR(H) \sim \frac{H^2}{T^n}, \tag{6}$$

where n varies from 1 to 5 depending on parameters of the system.

In a strongly anisotropic case:

$$MR(H) \sim \frac{H^2 H_a}{T^5}, \tag{7}$$

where H_a is an effective field of anisotropy. Such a temperature behavior of magnetoresistance has been recently observed in phase-separated La-Pr manganites [9].

These results were obtained by taking into account the dependence of the droplet radius on the magnetic field and the effects of spin-assistant electron tunnelling. The latter are determined by the relative orientation between a spin of a tunnelling electron and a large magnetic moment of a FM droplet.

Note that a quadratic dependence of magnetoresistance on magnetic field is in agreement with experimental results [10,11].

At high magnetic fields the magnetoresistance at first goes to saturation and then increases exponentially:

$$MR(H) \sim \frac{JzS}{k_B T} \exp\left(\frac{AbH}{10 k_B T}\right), \tag{8}$$

where $b = \mu_b g / zJS$.

4. Conclusions

Summarizing, we constructed a phase diagram for manganites, which contains two extended regions of small-scale phase separation.

We also calculated a tunnelling magnetoresistance for a phase-separated state taking into account the effects of Coulomb blockade and spin-assistant electron tunnelling.

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