Non-Fermi behavior of the disorder electronic system

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Abstract

We showed that an electronic system with weak disorder considered in the finite-charge infinite U Hubbard model can present a non-Fermi behavior. The imaginary part of the self-energy has been calculated and a linear temperature dependence was obtained. This result is in agreement with the non-Fermi behavior observed at the insulator-metal crossover in La$_{2-x}$Sr$_x$CuO$_4$. 

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I. INTRODUCTION

The interplay between strongly correlated electron systems and disorder is still an open question. The most efficient method is to start from the weak disorder in the electronic system and to consider correlations using the renormalization group (RG) method\textsuperscript{1–3}. The main result of this method is prediction of the metal-insulator transition when the symmetry was broken by the interaction with impurities.

The problem was studied using infinite-U Hubbard model and the t-J model\textsuperscript{4–6}. The infinite dimension approach introduced by Metzner and Vollhardt\textsuperscript{7} has been applied by many authors\textsuperscript{8–10} (for a complete discussion see Ref. \textsuperscript{10}) and using RG method Si and Kotliar\textsuperscript{11} showed that in an extended Hubbard model the disorder can induce a non-Fermi behavior.

In this paper we will show that the weak disorder in the finite-charge infinite-U Hubbard model can induced a non-Fermi behavior for a two-dimensional (2D) electronic system close to the metal-insulator transition. The paper is organized as follows. In Sect. II we present the model. The self-energy of the electronic system is calculated in Sect. III and we show that linear temperature dependence may appear, which show a typical non-Fermi behavior. The relevance of our results for the explanation of the experimental results will be discussed in Sect. IV.

II. MODEL

We consider an electronic system with weak disorder in the finite-charge infinite-U Hubbard model. The charge susceptibility has been calculated in\textsuperscript{6} as

\[
\chi_c(q, \omega) = \frac{N(0)NDq^2}{2[Dq^2A_0 + D\alpha q^4/k_B^4 - i\omega]}
\] (1)
where $N(0)$ is the density of state, $N$ is the orbital degeneracy, $D = v_F^2 \tau / 2$ is the diffusion coefficient, $A_0 = 1 - 2t_0N(0)$ (with $t_0$ the base kinetic energy), $\alpha = 3(Q/N)^2(m^8/m)^2/4$ with $Q$ the total charge and $k_F$ is the Fermi wave vector. For a filling $n_f$ ($m/m^* = 1 - n_f$) close to metal-insulator phase transition $q^4$ term, given by the quasiparticles interaction, is important and we will show that is essential in the behavior of the electronic system.

The effect of disorder will be considered as contained in the enhancement of the charge susceptibility and in order to analyze the effect of it on the energy of the electronic excitations we take the general form for the self-energy in one-loop approximation.

### III. SELF-ENERGY

The self-energy of the electrons due to the interaction of electrons with the charge fluctuations in the presence of disorder has the general form:

$$
\Sigma(p, \omega) = g^2 \int \frac{d^2q}{(2\pi)^2} \int^{\infty}_{-\infty} \frac{d\omega'}{2\pi} \left[ \coth \frac{\omega'}{2T} - \tanh \frac{\bar{\varepsilon}(p + q)}{2T} \right] \frac{I m \chi_c(q, \omega')}{\omega + \omega' - \bar{\varepsilon}(p + q) + i\alpha} 
$$

where $\bar{\varepsilon}(k) = k^2/2m - \mu$. An analytical calculation can be performed for the two dimensional case. Using the approximation

$$
\bar{\varepsilon}(p + q) \approx \bar{\varepsilon}(p) + vq \cos(\theta)
$$

and the identity

$$
\lim_{\alpha \to 0} \frac{1}{\omega - \bar{\varepsilon} + i\alpha} = \frac{1}{i} \int_{0}^{\infty} dt \exp [i(\omega - \bar{\varepsilon} + i\alpha)t] = \frac{1}{i} \int_{0}^{\infty} dt [\cos (\omega - \bar{\varepsilon})t + i \sin (\omega - \bar{\varepsilon})t]
$$

we write Eq. (2) as

$$
\Sigma''(p, \omega) = -\frac{g^2}{2\pi} \int_{0}^{\infty} dt \cos (\omega - \bar{\varepsilon})t \int^{\infty}_{-\infty} \frac{d\omega'}{2\pi} I m \chi_c(q, \omega') \coth \frac{\omega'}{2T} \int_{0}^{2\pi} \frac{d\theta}{2\pi} \exp [-ivqt \cos \theta]
$$
\[ \Sigma'(p, \omega) = \frac{g^2}{2\pi} \int_0^\infty dt \sin(\omega - \tilde{\varepsilon})t \int_0^\infty d\omega' \frac{2\pi}{2} \Im \chi_c(q, \omega') \coth \frac{\omega'}{2T} \int_0^{2\pi} \frac{d\theta}{2\pi} \exp \left[ -ivqt \cos \theta \right] \] (6)

These equations will be transformed if we perform the approximation \( \coth \omega/2T \approx 2T/\omega \) and in Eqs. (5)-(6) consider

\[ S_c = \int_\infty^{-\infty} d\omega' \frac{2\pi}{2} \Im \chi_c(q, \omega') \coth \frac{\omega'}{2T} \approx \frac{T}{\pi} \int_\infty^{-\infty} d\omega' \frac{Dq^2\chi_0}{(DA_0q^2 + D\alpha q^4/k_F^2)^2 + \omega'^2} = \frac{\chi_0 k_F^2}{\alpha} \frac{T}{\xi^{-2} + q^2} \] (7)

where

\[ \chi_0 = \frac{NN(0)}{2} \]

\[ \xi^{-2} = \frac{A_0 k_F^2}{\alpha} \] (8)

Using the exact formulas

\[ J_0(z) = \int_0^{2\pi} \frac{d\theta}{2\pi} \exp \left[ -iz \cos(\theta) \right] \] (9)

\[ K_0(kb) = \int_0^\infty dx \frac{x J_0(xb)}{x^2 + k^2} \] (10)

where \( J_0(x) \) and \( K_0(z) \) are the Bassel functions. The imaginary part of the self-energy given by Eq.(3) has the form

\[ \Sigma''(p, \omega) = -\frac{g^2 T}{2\alpha \pi} \int_0^\infty dt \cos \left[ (\omega - \tilde{\varepsilon}(p))t \right] K_0(v_F t \xi^{-1}) \] (11)

where \( v_F \) is the Fermi velocity. Performing the integral over \( t \) in Eq. (11) we obtain

\[ \Sigma''(p, \omega) = -\frac{g^2 \chi_0 k_F^2 \pi}{\alpha} \frac{T}{2 \sqrt{(\omega - \tilde{\varepsilon}(p))^2 + (v_F \xi)^{-2}}} \] (12)

In the approximation \( \omega - \tilde{\varepsilon}(p) \gg (v_F \xi)^{-1} \) from Eq. (12) we get
From Eq. (13) we can see that due to the coupling with the charge fluctuations the electronic excitations present a non-Fermi behavior, obtained also at $T = 0$ by Wang et al.\cite{4}, but was considered as a holon like propagation of the charge fluctuations. The result expressed by Eq. (13) has been obtained in the approximation $\omega \ll T$ and following the method proposed by Vilk and Tremblay\cite{12} (See Appendix D of Ref. 12 for an accurate discussion about the enhancement of the Fermi behavior in a non-Fermi behavior of electrons interacting with fluctuations).

An important approximation for this calculation is the existence of an energy scale for the charge fluctuations in the presence of weak disorder. More than that this energy scale characterized by a frequency $\omega_0$ has to satisfy the condition $\omega_0 \ll T$, because only the coupling of the electrons with low energy fluctuations gives a non-Fermi behavior. In this model we require because of the weak disorder, that $\varepsilon_F \tau = c$ has to be large. Then we can define $\omega_0 \simeq \tau^{-1} = c/\varepsilon_F$ and the condition $\omega_0 \ll T$ becomes $c \ll T \varepsilon_F$.

IV. DISCUSSION

We showed that a non-Fermi behavior may appear by the coupling of electrons in the presence of disorder to the charge fluctuations. Such a mechanism was also proposed for the coupling of electrons with two-dimensional spin fluctuations\cite{13,14}. The coupling between electrons and fluctuations near the quantum critical point has been also proposed\cite{15,16} as the explanation for the non-Fermi behavior of the electronic system and it seems to be an
appropriate mechanism in the heavy fermion systems.

Our model can be a good explanation for the experimental data obtained by Boebinger et al. on La$_{2-x}$Sr$_x$CuO$_4$ which present a linear dependence of the temperature at the insulator-metal crossover. Recently a similar behavior has been observed for Pr$_{2-x}$Ce$_x$CuO$_4$ (this is an electron-doped system) at low temperature.
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