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Memory matrix theory of the dc resistivity of a disordered antiferromagnetic metal with an effective composite operator

Hermann Freire

Instituto de Física, Universidade Federal de Goiás, 74.001-970, Goiânia-GO, Brazil

HIGHLIGHTS

- The memory matrix approach is implemented for a spin-fermion model with disorder.
- A composite operator is included in the corresponding SDW quantum critical theory.
- The dc resistivity of the emergent strange metal phase in the model is calculated.
- This theory is consistent with experimental data of important correlated materials.

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ABSTRACT

We perform the calculation of the dc resistivity as a function of temperature of the "strange-metal" state that emerges in the vicinity of a spin-density-wave phase transition in the presence of weak disorder. This scenario is relevant to the phenomenology of many important correlated materials, such as, e.g., the pnictides, the heavy-fermion compounds and the cuprates. To accomplish this task, we implement the memory-matrix approach that allows the calculation of the transport coefficients of the model beyond the quasiparticle paradigm. Our computation is also inspired by the $\epsilon = 3 - d$ expansion in a hot-spot model embedded in d-space dimensions recently put forth by Sur and Lee (2015), in which they find a new low-energy non-Fermi liquid fixed point that is perturbatively accessible near three dimensions. As a consequence, we are able to establish here the temperature and doping dependence of the electrical resistivity at intermediate temperatures of a two-dimensional disordered antiferromagnetic metallic model with a composite operator that couples the order-parameter fluctuations to the entire Fermi surface. We argue that our present

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E-mail address: hermann_freire@ufg.br.

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theory provides a good basis in order to unify the experimental transport data, e.g., in the cuprates and the pnictide superconductors, within a wide range of doping regimes.

1. Introduction

The ubiquitous "strange-metal" phase that appears in the cuprate superconductors near optimal doping [1–3], the iron-based superconductors [4,5], and heavy fermions compounds [6], to name a few, is probably the most outstanding challenge in the field of strongly correlated systems and quantum criticality. This metallic phase displays a universal linear-in-T resistivity at intermediate temperatures. Since this phase clearly possesses no well-defined quasiparticle excitations at low energies, it represents a universal example of a non-Fermi liquid state that emerges in those correlated materials. Notwithstanding this fact, the underlying microscopic mechanism of such a state remains largely unknown up to this date [7,8]. One problem associated with this conundrum is related to the issue that it is very difficult, from a theoretical viewpoint, to write down a fairly "realistic" model that describes a highly resistive metallic state with no quasiparticles whose momentum relaxation mechanism yields $\rho \sim T^{\alpha}$, such that $\alpha < 2$. By contrast, conventional metals are normally described by the paradigmatic Landau's Fermi liquid theory, in which the resistivity follows the well-known scaling relation $\rho \sim T^2$ due to both umklapp scattering and disorder.

In this respect, a prominent theoretical proposal to describe a "strange-metal" phase consists of assuming the existence of a quantum critical point [9,10] (QCP) at $T = 0$ that is responsible for generating such a state at finite temperatures [11,12]. Experimental results in many compounds are by now quite numerous and provide a strong support to this perspective. Interesting possibilities of quantum critical points include spin-density-wave [13–17] (SDW), charge-density-wave [18,19] (CDW), pair-density-wave [20–24] (PDW), onset of various nematic orders [25], loop-current orders [26,27], fractionalized phases [28], preformed excitonic pairs [29], among many others (see, e.g., [30]). We note in passing that recently an evidence of a novel PDW phase in the cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+x}$ has been given by Hamidian et al. [31] using scanned Josephson tunneling microscopy, which was in fact anticipated by the microscopic theories in Refs. [23,24]. In the present work, we shall focus only on the question of a SDW quantum phase transition underlying the phase diagram of a given correlated material in order to assess specifically what is the corresponding effect on the dc electrical resistivity as a function of doping of the adjacent metallic phases of the system at intermediate temperatures.

The study of the SDW quantum criticality has quite a long history in the field (see, e.g., [13–16,32,33]), but we will not detail all those works here. In this description, the microscopic mechanism of the Cooper pair formation is associated with the exchange of short-range antiferromagnetic spin-density-wave (SDW) fluctuations [32], which can be enhanced in the vicinity of a SDW quantum critical point. From a numerical viewpoint, it has been recently established [34] via a sign-problem-free Quantum Monte Carlo approach that the paradigmatic spin-fermion model, originally proposed by Abanov and Chubukov [13], indeed describes a high-T_c dome-shaped superconducting phase with the correct d-wave symmetry, in agreement with the experimental situation. Despite this statement, we note that in the underdoped regime of the hole-doped cuprates it has been argued [35,36] that the spin-fermion model must be altered to account for the non-double occupancy constraint that should be enforced for this case. From a weak-to-moderate coupling perspective, many analytical works have pointed out that the Abanov–Chubukov spin-fermion model essentially flows to strong-coupling at low energies [15], and one has to be very careful in devising new approximate perturbative schemes to calculate its physical properties. In this sense, an ingenious proposal consists of the $\epsilon = 3 - d$ expansion within a hot-spot model embedded in d-space dimensions recently developed by Sur and Lee [37]. Interestingly, they obtain in their work a stable non-Fermi liquid fixed point at low energies that is perturbatively controlled near three spatial dimensions.

Transport calculations of the two-dimensional spin-fermion model are also of interest and have been performed by several researchers in the field [38–44]. Since it has become increasingly clear in