



HAL
open science

Spin-charge gauge compositeness of electron in HTS: Hints from metal-insulator crossover and entropy behavior

P.A. Marchetti, A. Ambrosetti, Z.B. Su, Lianbo Yu

► **To cite this version:**

P.A. Marchetti, A. Ambrosetti, Z.B. Su, Lianbo Yu. Spin-charge gauge compositeness of electron in HTS: Hints from metal-insulator crossover and entropy behavior. *Journal of Physics and Chemistry of Solids*, 2009, 69 (12), pp.3277. 10.1016/j.jpcs.2008.06.066 . hal-00601176

HAL Id: hal-00601176

<https://hal.science/hal-00601176>

Submitted on 17 Jun 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

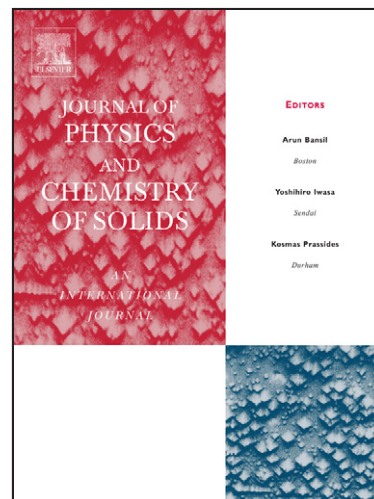
Author's Accepted Manuscript

Spin-charge gauge compositeness of electron in HTS:
Hints from metal-insulator crossover and entropy
behavior

P.A. Marchetti, A. Ambrosetti, Z.B. Su, L. Yu

PII: S0022-3697(08)00297-7
DOI: doi:10.1016/j.jpcs.2008.06.066
Reference: PCS 5600

To appear in: *Journal of Physics and
Chemistry of Solids*



www.elsevier.com/locate/jpcs

Cite this article as: P.A. Marchetti, A. Ambrosetti, Z.B. Su and L. Yu, Spin-charge gauge compositeness of electron in HTS: Hints from metal-insulator crossover and entropy behavior, *Journal of Physics and Chemistry of Solids* (2008), doi:10.1016/j.jpcs.2008.06.066

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting galley proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Spin-charge gauge compositeness of electron in HTS: Hints from metal-insulator crossover and entropy behavior

P.A. Marchetti

Dipartimento di Fisica “G. Galilei”, INFN, I-35131 Padova, Italy

A. Ambrosetti

Dipartimento di Fisica, I-38100, Trento, Italy

Z.B. Su

Institute of Theoretical Physics, Chinese Academy of Sciences, 100080 Beijing, China

L. Yu

*Institute of Physics and Institute of Theoretical Physics,
Chinese Academy of Sciences, 100080 Beijing, China*

(Dated: June 23, 2008)

We show that the coexistence of Fermi arcs and metal-insulator crossover of the in-plane resistivity can give a hint of a peculiar “gauge compositeness” of the electron in hole-doped high T_c cuprates and a similar hint also comes from the negative intercept at $T = 0$ of the electronic entropy extrapolated from moderate temperatures in the “pseudogap phase”. An implementation of this “compositeness” within the spin-charge gauge approach is outlined and is employed to discuss the above phenomena.

PACS numbers: 71.10.Hf, 71.27.+a, 74.25.Fy, 74.25.Gz

HINTS OF “GAUGE COMPOSITENESS”

We point out two experimental phenomena which suggest, or at least are fully compatible with, a peculiar “compositeness” of the low-energy electron excitation of hole-doped high T_c cuprates. This “composite” structure should involve a gapful bosonic constituent and a gapless fermionic constituent, one carrying spin and the other charge, together with a gauge interaction binding them into a resonance. Such a construction is accomplished in particular in the spin-charge gauge approach, developed by us in recent years [1].

The relevant phenomena are:

1) The metal-insulator crossover (MIC) found in the in-plane resistivity decreasing T in heavily underdoped samples, in particular of LSCO and YBCO [2], [3], and in underdoped samples of a variety of cuprates in the presence of a strong magnetic field suppressing superconductivity [4].

2) The negative intercept at $T = 0$ of the electronic entropy S extrapolated from moderate temperatures in the “pseudogap phase” (PG) [5].

Let us explain why these phenomena suggest a “spin-charge gauge compositeness” of the electron.

We start from the MIC. Often this crossover is attributed to disorder-induced localization. However, this interpretation is at odds with the following facts: i) The adiabaticity suggests that MIC with and without magnetic field have the same origin. Including higher doping samples exhibiting MIC, denoting with ℓ the mean free path, $k_F\ell$ at MIC ranges from 0.1 to 10, *i.e.* from far below to far above the Ioffe-Regel limit $k_F\ell \approx 1$,

which should characterize a MIC due to disorder localization. ii) In LSCO and YBCO samples with $a - b$ in-plane anisotropy the MIC temperature of ρ_a is different from that of ρ_b [6] contradicting the “unique” localization temperature, characteristic of the standard theory of localization. iii) It has been observed a universality of suitably normalized resistivity, ρ_n , in terms of T/T^* [3] [7], where T^* can be identified as the PG temperature. If MIC is intrinsic to the cuprate physics, as follows from the above considerations, it is rather difficult in conventional Fermi-liquid-like theories to reconcile an insulating (semiconducting) behavior of the resistivity with the presence of a Fermi surface (FS), or better Fermi arcs, as detected by ARPES [8]. In fact, the appearance of Fermi arcs suggests the presence of a gapless fermionic excitation, which should produce a metallic in-plane resistivity ρ . The coexistence of FS and insulating behavior of ρ is instead easily accommodated in a slave-particle gauge theory which implies a “gauge compositeness” of the electron. In these approaches, due to the gauge string binding together fermionic and bosonic constituents of the “electron”, the velocity of the electron resonance determining the conductivity is dominated by the slowest constituent (Ioffe-Larkin rule [9]). Since the fermionic constituent shows a metallic behavior, exhibiting a FS, the electron resonance has a metallic/insulating behavior if the bosonic constituent does. Furthermore if the dominant contribution is due to the bosonic constituent, it can explain both the insensitivity to details of the FS allowing universality and the negligible effect of non-magnetic impurities affecting only the fermionic constituent (following an original intuition by Anderson [10]).

Let us turn to the negative intercept of the extrapolated electronic entropy. A negative intercept suggests a negative contribution to entropy of a “constraint field” reducing the low-energy degrees of freedom. Such a negative contribution naturally arises in a slave-particle gauge approach from the scalar component of the gauge field in two dimensions (in the Coulomb gauge) which does not carry dynamical degrees of freedom[11]. The approximate linear in T behavior of S is consistent with a standard Fermi-liquid contribution and thus can be attributed to the fermionic constituent of the “electron”. Ultimately the presence of the gauge field is due to the Gutzwiller projection coming from the strong on-site Coulomb repulsion, hence it should be responsible for the “compositeness”.

IMPLEMENTATION IN THE SPIN-CHARGE GAUGE APPROACH

We now outline how the above ideas are actually implemented in the spin-charge gauge approach. In this approach the (approximate) model Hamiltonian for the CuO layers in high T_c cuprates is given by the 2D t - J model on a square lattice. The global symmetries of the t - J model corresponding to the $SU(2)$ -spin-rotation and $U(1)$ -charge groups are gauged, *i.e.* one converting them into local symmetries by coupling the fermion of the model to a spin ($SU(2)$) and a charge ($U(1)$)(Chern-Simons) gauge fields, carrying no dynamical degrees of freedom, thus obtaining an equivalent model. A good feature of introducing these gauge fields is that they allow a more flexible treatment of charge and spin responses within a spin-charge decomposition scheme. At the end they will disappear from the game due to a kind of Mean Field treatment, but leaving behind sign of their presence crucial for the low-energy physics, as outlined below. The Gutzwiller projection permits to apply to the fermion of the so obtained gauged t - J model the spin-charge decomposition: One rewrites it as a product of a charged spinless holon and a spin 1/2 neutral spinon (actually via a semionic decomposition [12], [13]). An additional “slave particle” gauge field appears for a correct counting of degrees of freedom. Therefore, treating in “mean-field” the spin and charge gauge fields, the basic dynamical fields of the approach are:

1) Fermionic holons with a finite FS, dressed by spin vortices originating from the spin gauge field, with Fermi momenta $k_F \sim \delta$ in PG and $\sim 1 - \delta$ in the “strange-metal phase” (SM) at higher T or δ , where δ denotes the doping concentration. This change is a remnant of the charge gauge field, which introduces a π flux in PG, thus reducing the Fermi momenta via Hofstadter mechanism. A direct evidence of this small FS might come from a recent experiment on Shubnikov-de Haas oscillations[14].

2) Antiferromagnetic (AF) bosonic spinons with a gap

$Jm \sim J\sqrt{\delta|\ln\delta|}$ due to the interaction with the spin vortices, consistent with AF correlation length at small δ derived from neutron experiments [15].

3) Slave-particle gauge fluctuations (in the normal state) dominated by the Reizer singularity [16], due to the finite FS of holons, with an anomalous skin momentum scale $Q \sim (T/t)^{1/3}k_F^{2/3}$. For the appearance of Reizer singularity the presence of a gap for spinons is crucial, because gapless spinons would condense at low T thus gapping the gauge field through the Anderson-Higgs mechanism. Gauge fluctuations renormalize holon and spinon lifetimes, renormalizing in particular m to $M = (m^2 + ick_F T/t)^{1/2}$ in PG. They further bind together spinon-antispinon into a magnon resonance, and holon-spinon into an electron resonance in a momentum slab Q around the FS, with inverse life-time $\Gamma \sim \Im M$ in PG, $TQ/(tm^2)$ in SM. In PG one has a further reduction of the spectral weight of the electron resonance outside the magnetic Brillouin zone, which bears some resemblance with the appearance of Fermi arcs.

To summarize, in this approach the electron exhibits a “spin-charge gauge compositeness” with the fermionic constituent given by the spinless holon and the bosonic constituent given by the bosonic spin 1/2 spinon.

Let us explain how one recovers the MIC. The in-plane resistivity is calculated via the Ioffe-Larkin addition rule: $\rho = \rho_s + \rho_h$, where ρ_s is the resistivity of the spinon-gauge subsystem and ρ_h of the holon-gauge subsystem. ρ is dominated by the spinon-gauge scattering and in PG

$$\rho \sim \rho_s \sim \frac{|M|^{1/2}}{\sin(\arg \frac{M}{2})}.$$

This formula shows that the spinon gap m combined with the diffusion $\sim T$ caused by the gauge fluctuations is able to reproduce the MIC. For $m^2 \gg ck_F T/t$ one finds $\rho \sim T^{-1}$, insulating due to dominating short range AF order. For $m^2 < ck_F T/t$ one finds $\rho \sim T^\alpha$, $\alpha \sim 1/4$ metallic, due to dominating diffusion. The above equation implies the universality of the normalized resistivity $\rho_n = (\rho(T) - \rho(T_{MIC})) / (\rho(T^*) - \rho(T_{MIC}))$ as a function of $T/T^* \sim (k_F T)/(tm^2)$. Since in PG $k_F \sim \delta$ and $m^2 \sim |\delta \ln \delta|$, one obtains a slow decrease of $T/T^* \sim T/(|t \ln \delta|)$. Here T^* can be identified as the temperature of the inflection point in ρ and T_{MIC} of the minimum. The shape of the universal curve derived above agrees semi-quantitatively with the experimental observations [17]. Furthermore the structure of M produces an approximate T^2 behaviour of ρ immediately above the MIC [18], as found experimentally in lightly doped LSCO [19].

Let us turn now to the electronic entropy S . In the spin-charge gauge approach S is the sum of four terms: the contribution of free spinons, S_s , of free holons, S_h and the fully renormalized contribution of transverse and scalar gauge fluctuations, S_\perp, S_0 [20]. The spinons are

massive and thus $S_s \simeq 0$ for T lower than the spinon gap (few hundreds K). The holons are described by a Fermi Liquid, therefore the standard result applies: $S_h \sim m_h T$ with m_h the holon mass $\sim k_F$, thus $S_h \sim \delta T$ in PG. S_\perp and S_0 are estimated using the (approximate) fully renormalized retarded Green function of the gauge field, following [21] and obtaining: $S_\perp \approx Q_0^2 \sim T^{2/3}$ and $S_0 \approx -\frac{\Lambda}{v_F} T + \frac{1}{v_F^2} T^2$ with $\Lambda \sim J$, an UV cutoff. One can see that the scalar contribution contains a negative term, as discussed in general terms above. In this approach the approximately linear behavior of S is basically due to the holons, renormalized by gauge fluctuations. The increase of the slope of S at low δ and its saturation at higher T or δ found experimentally [5] are due to the transition from $m_h \sim \delta$ characteristic of PG to $m_h \sim 1 - \delta$ characteristic of SM. The negative intercept is due to the negative scalar gauge contribution and it appears in PG due to the “effective” rather small Fermi temperature, a consequence of the π -flux characteristic of a 2D system, suppressing the positive S_\perp contribution. The experimentally observed upturn in S/T or γ [5] decreasing T at very low T and above T^* are due to the contribution of transverse gauge fluctuations, respectively in PG and in SM. These enhancements of entropy are due to the presence of the gapless transverse gauge mode.

To conclude, we have shown that the “gauge compositeness” of the low-energy electron excitation appearing in the spin-charge gauge approach to the t - J model is able to explain the very unusual phenomena of metal-insulator crossover and negative intercept of electronic entropy, including a number of peculiar experimentally observed features.

therein.

- [2] H. Takagi *et al.*, Phys. Rev. Lett. **69**, 2975 (1992).
- [3] B. Wuyts *et al.*, Phys. Rev. B **53**, 9418 (1996).
- [4] Y. Ando *et al.*, Phys. Rev. Lett. **75**, 4662 (1995); G.S. Boebinger *et al.*, Phys. Rev. Lett. **77**, 5417 (1996); P. Fournier *et al.*, Phys. Rev. Lett. **81**, 4720 (1998); S. Ono *et al.*, Phys. Rev. Lett. **85**, 638 (2000).
- [5] J.W. Loram *et al.*, Phys. Rev. Lett. **71**, 1740 (1993); J. W. Loram *et al.*, Physica C **235-240**, 134 (1994); J.W. Loram *et al.*, J. Phys. Chem. Solids **59**, 10 (1998).
- [6] Y. Ando, K. Segawa, S. Komiya, and A.N. Lavrov, Phys. Rev. Lett. **88**, 137005 (2002); M. Dumm, D. N. Basov, S. Komiya, and Y. Ando, Phys. Rev. Lett. **91**, 077004 (2003).
- [7] Z. Konstantinovic *et al.*, Physica C **341**, 859 (2000).
- [8] A. Damascelli, Z. Hussain, and Z.X. Shen, Rev. Mod. Phys. **75**, 473 (2003).
- [9] L. Ioffe and A. Larkin, Phys. Rev. B **39**, 8988 (1989).
- [10] P.W. Anderson, “The Theory of Superconductivity in the High-Tc Cuprates”, Princeton University Press, 1997.
- [11] R. Hlubina, W. O. Putikka, T. M. Rice, and D. V. Khveshchenko Phys. Rev. B **46**, 11224 (1992).
- [12] J. Fröhlich and P.A. Marchetti, Phys. Rev. B **46**, 6535 (1992).
- [13] P.A. Marchetti, Z.B. Su, L. Yu, Phys. Rev. B **58**, 5808 (1998).
- [14] N. Doiron-Leyraud *et al.*, Nature **447**, 565 (2007).
- [15] B. Keimer *et al.*, Phys. Rev. B **46**, 14034 (1992).
- [16] M. Reizer, Phys. Rev. B **39**, 1602 (1989); **40**, 11571 (1989).
- [17] P.A. Marchetti, L. De Leo, G. Orso, Z.B. Su and L. Yu, Phys. Rev. B **69**, 024527 (2004).
- [18] P.A. Marchetti, Z.B. Su, L. Yu, to appear in Physica C: Superconductivity doi:10.1016/j.physc.2007.03.383.
- [19] Y. Ando *et al.*, Phys. Rev. Lett. **92**, 197001 (2004).
- [20] P.A. Marchetti and A. Ambrosetti, in preparation.
- [21] A.M. Tselik, “Quantum Field Theory in Condensed Matter Physics”, Cambridge University Press, 1995.

[1] For a review see: P.A. Marchetti, Z.B. Su, L. Yu, J. Phys: Condens Matter **19**, 125212 (2007) and references