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ARTICLE

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Non-Fermi-liquid *d*-wave metal phase of strongly interacting electrons

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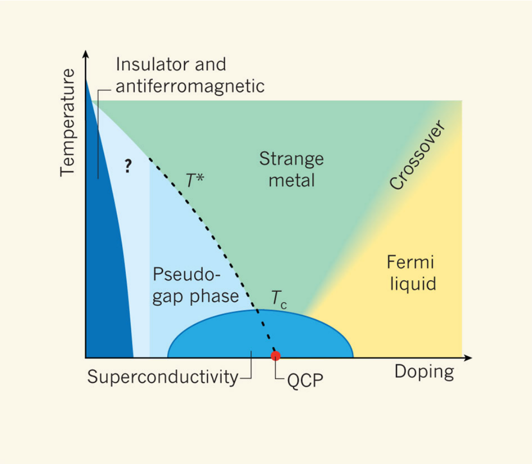
Developing a theoretical framework for conducting electronic fluids qualitatively distinct from those described by Landau's Fermi-liquid theory is of central importance to many outstanding problems in condensed matter physics. One such problem is that, above the transition temperature and near optimal doping, high-transition-temperature copper-oxide superconductors exhibit 'strange metal' behaviour that is inconsistent with being a traditional Landau Fermi liquid. Indeed, a microscopic theory of a strange-metal quantum phase could shed new light on the interesting low-temperature behaviour in the pseudogap regime and on the *d*-wave superconductor itself. Here we present a theory for a specific example of a strange metal—the '*d*-wave metal'. Using variational wavefunctions, gauge theoretic arguments, and ultimately large-scale density matrix renormalization group calculations, we show that this remarkable quantum phase is the ground state of a reasonable microscopic Hamiltonian—the usual t-J model with electron kinetic energy t and two-spin exchange J supplemented with a frustrated electron 'ring-exchange' term, which we here examine extensively on the square lattice two-leg ladder. These findings constitute an explicit theoretical example of a genuine non-Fermi-liquid metal existing as the ground state of a realistic model.

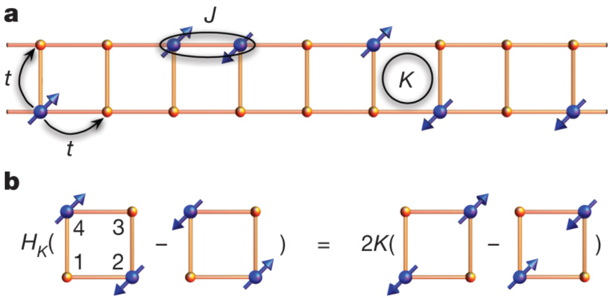
Motivation



Chandra Varma, Nature 468, 184-185 (11 November 2010)

- Anisotropic resistivity ρ: effective 2D description
- $\rho \propto T$ in contrast to $\rho \propto T^2$ for Fermi liquid
- violation of Luttingers volume theorem
- different experiments: different total amount of charge carriers
- ...

t-j-K model



$$H = H_{tJ} + H_K$$

$$H_{tJ} = -t \sum_{\langle i,j \rangle, s=\uparrow\downarrow} \left(c^\dagger_{is} c_{js} + c^\dagger_{js} c_{is} \right) + J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

$$H_K = 2K \sum_{\square} \left(S^\dagger_{13} S_{24} + S^\dagger_{24} S_{14} \right)$$

$$S^\dagger_{ij} = \frac{1}{\sqrt{2}} \left(c^\dagger_{i\uparrow} c^\dagger_{j\downarrow} - c^\dagger_{i\downarrow} c^\dagger_{j\uparrow} \right)$$

slave-boson technique for d-wave metal

- electron operator can be written as product of charge carrying slave boson (chargon) and spin-half fermionic spinon

$$c_s(\mathbf{r}) = b(\mathbf{r}) f_s(\mathbf{r})$$

- $b(\mathbf{r})$ is given by a d-wave Bose-metal wavefunction
- $f_s(\mathbf{r})$ is given by a Slater determinant
- Use a constraint so the Hilbert space does not change size:

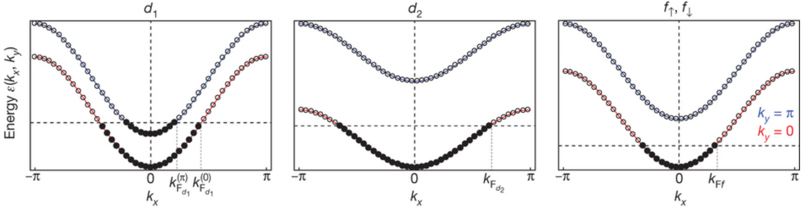
$$b^\dagger(\mathbf{r}) b(\mathbf{r}) = \sum_s f_s^\dagger(\mathbf{r}) f_s(\mathbf{r}) = \sum_s c_s^\dagger(\mathbf{r}) c_s(\mathbf{r}) = n_e(\mathbf{r})$$

- This is achieved by strongly coupling $b(\mathbf{r})$ and $f_s(\mathbf{r})$ via an emergent gauge field
- The Bose-metal itself consists of two fermionic slave particles (partons) $b(\mathbf{r}) = d_1(\mathbf{r}) d_2(\mathbf{r})$ coupled via a gauge field to implement the constraint:

$$d_1^\dagger(\mathbf{r}) d_1(\mathbf{r}) = d_2^\dagger(\mathbf{r}) d_2(\mathbf{r}) = b^\dagger(\mathbf{r}) b(\mathbf{r})$$

Mean-field solution

- Project 2D system on quasi-1D ladder geometry. In this case a two-leg ladder with up to $L_x = 48$ sites in length and electron density $\rho = 1/3$.
- in mean-field approximation: 5 1D gapless modes



- Because of the constraints: $k_{Fd1}^{(0)} + k_{Fd1}^{(\pi)} = k_{Fd2} = 2k_{Ff} = 2\pi\rho$

Gauge theory description + solution using bosonization

- Kinetic energy density (linearized) in the parton language:

$$h_{kinetic} = \sum_{k_y=0,\pi} \sum_{P=R/L} P v_{d1}^{(k_y)} d_{1P}^{(k_y)\dagger}(-i\partial_x) d_{1P}^{(k_y)} + \sum_{P=R/L} P v_{d2} d_{2P}^{\dagger}(-i\partial_x) d_{2P} + \sum_{s=\uparrow,\downarrow} \sum_{P=R/L} P v_f f_{sP}^{\dagger}(-i\partial_x) f_{sP}$$

- Bosonize the fields:

$$d_{1P}^{(0)} = \eta_{d_1^{(0)}} e^{i\left(\varphi_{d_1^{(0)}} + P\theta_{d_1^{(0)}}\right)}, \ldots$$

- Bosonize the interaction terms as well

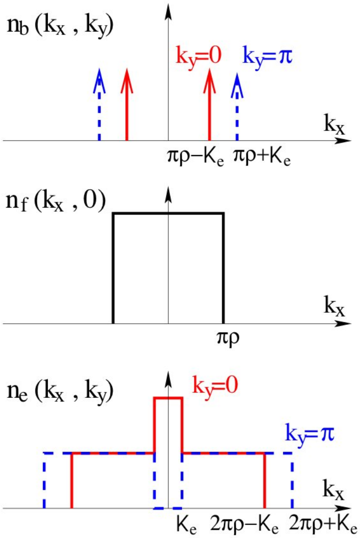
$$h_{int,4d_1} = \omega \left[d_{1R}^{(0)\dagger} d_{1L}^{(0)\dagger} d_{1L}^{(\pi)} d_{1R}^{(\pi)} + H.c. \right] = 2\omega \cos\left[2\sqrt{2}\varphi_{d1-}\right]$$

$$h_{int,4f} = -u \left(f_R^{\dagger} \frac{\vec{\sigma}}{2} f_R \right) \cdot \left(f_L^{\dagger} \frac{\vec{\sigma}}{2} f_L \right) = \frac{u^z}{8\pi^2} \left[(\partial_x \varphi_{f\sigma})^2 - (\partial_x \theta_{f\sigma})^2 \right] + u^{\perp} \cos(2\sqrt{2}\theta_{f\sigma})$$

- After bosonization, the constraint is simply: $\theta_{d1}^{(0)} + \theta_{d1}^{(\pi)} = \theta_{d2} = \theta_{f\uparrow} + \theta_{f\downarrow}$
- perform an orthonormal transformation on the θ and φ fields:

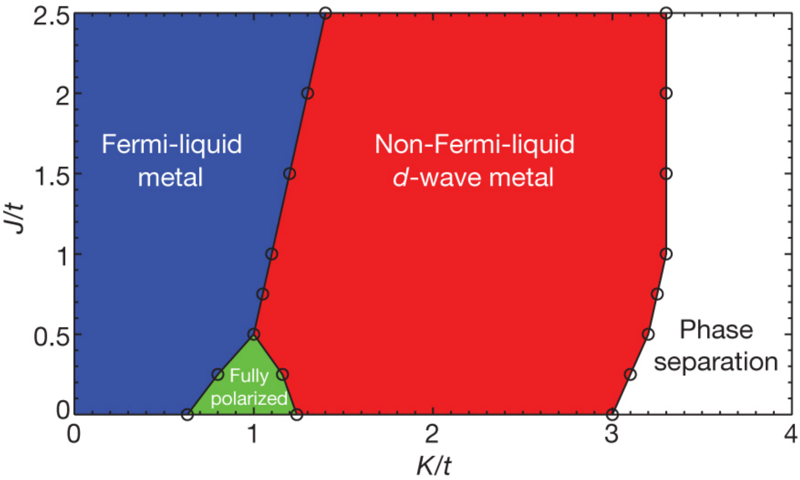
$$
\begin{aligned}
\theta_{f\sigma} &= \frac{1}{\sqrt{2}}(\theta_{f\uparrow} - \theta_{f\downarrow}) \\
\theta_{d1-} &= \frac{1}{\sqrt{2}}(\theta_{d1}^{(0)} - \theta_{d1}^{(\pi)}) \\
\theta_{\rho tot} &= \frac{1}{2\sqrt{2}}(\theta_{f\uparrow} + \theta_{f\downarrow} + \theta_{d1}^{(0)} + \theta_{d1}^{(\pi)} + 2\theta_{d2}) \\
\theta_a &= \frac{1}{\sqrt{3}}(\theta_{d1}^{(0)} + \theta_{d1}^{(\pi)} - \theta_{d2}) \\
\theta_A &= \frac{\sqrt{3}}{2\sqrt{2}}\left(\theta_{f\uparrow} + \theta_{f\downarrow} - \frac{\theta_{d1}^{(0)} + \theta_{d1}^{(\pi)} + 2\theta_{d2}}{3}\right)
\end{aligned}
$$

- Gauge field fluctuations render the θ_a, θ_A fields massive: only 3 modes remain



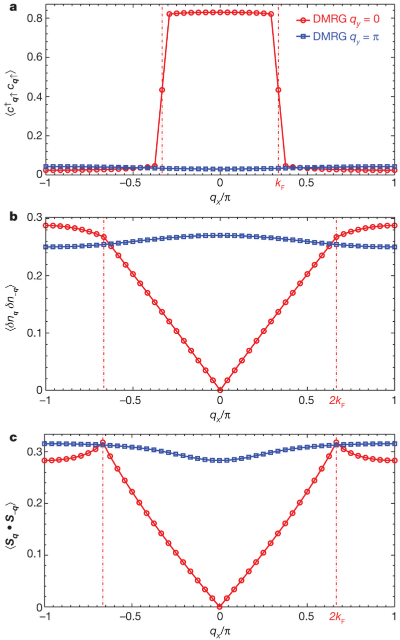
$$K_e = \pm\left(k_{Fd1}^{(0,\pi)} - \pi\rho\right)$$

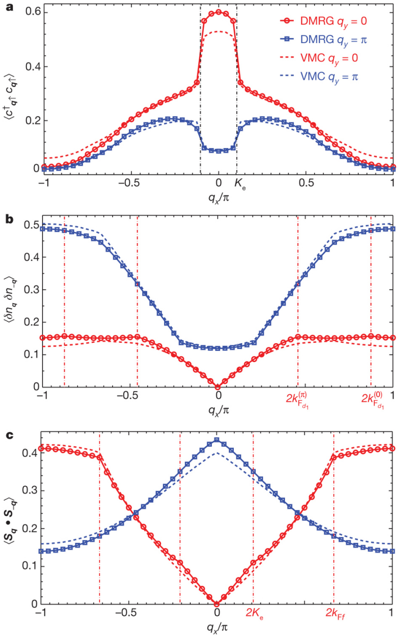
DMRG phase diagram



Measured correlation functions: $\langle c^{\dagger}_{\mathbf{q}s} c_{\mathbf{q}s} \rangle$, $\langle \delta n_{\mathbf{q}} \delta n_{-\mathbf{q}} \rangle$, $\langle \mathbf{S}_{\mathbf{q}} \cdot \mathbf{S}_{-\mathbf{q}} \rangle$

DMRG expectation values





Conclusion

- A two-leg ladder model to describe the strange metal phase is introduced
- It shows strong non-Fermi-liquid behaviour
- The model is to some extend analytically accessible using slave-boson technique and bosonization
- The two-leg ladder d-wave metal is extendable to systems with more legs.
- The d-wave symmetry of its metallic phase suggests that there may be incipient d-wave superconductivity