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Various ordered states in a 2D interacting electron system close to an electronic topological transition

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Abstract

We consider a 2D electron system on a square lattice with hopping beyond nearest neighbors. The existence of the quantum critical point associated with an electronic topological transition in the noninteracting system results in density wave (DW) and high-temperature d-wave superconducting (dSC) instabilities in the presence of an exchange interaction J. We analyse different DW ordering such as isotropic Spin DW (SDW), d-wave SDW, isotropic Charge DW (CDW) and d-wave CDW. The coexistence of dSC and SDW orders leads necessarily to the existence of a third order which is a π triplet superconducting (PTS) order. A new phase diagram with a mixed phase of SDW, dSC and PTS order is found. The theory is applied to high-T_c cuprates.

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A strong opinion exists in the physical community that the anomalous properties of high-T_c cuprates can reflect the existence of some hidden quantum critical point (QCP). It has been suggested recently [1,2] that such a QCP could be due to an electronic topological transition (ETT) in a 2D system. As was shown, the existence of this QCP results in DW and dSC instabilities of the normal state. In the present paper we study DW states of different natures and the mixed state with both DW and dSC ordering.

The starting point is a 2D model of interacting fermions on a square lattice with hopping between nearest (t) and next nearest (t') neighbors (while $t'/t < 0$ which corresponds to the situation experimentally observed [3])

$$H = \sum_k \varepsilon_k c^+_{k\sigma} c_{k\sigma} + \sum_i U n_{i\uparrow} n_{i\downarrow} + \sum_{\langle i,j \rangle} \left[J^z \boldsymbol{S}^z_i \boldsymbol{S}^z_j + J^{\perp} \boldsymbol{S}^+_i \boldsymbol{S}^-_j + \frac{b}{4} n_i n_j \right], \quad (1)$$

where $n_i = n_{i\uparrow} + n_{i\downarrow}$ ($n_{i\sigma} = c^+_{i\sigma} c_{i\sigma}$) and $\boldsymbol{S}_i = c^+_{i\alpha} \sigma_{\alpha\beta} c_{i\beta}$ are the charge and spin densities. The Fermi surface (FS) of noninteracting quasiparticles with the dispersion law $\varepsilon_k = -2t(\cos k_x + \cos k_y) - 4t' \cos k_x \cos k_y$ changes from closed to open at the critical doping x_c resulting in the 2D ETT which is at the origin of two types of instabilities: dSC and DW. Calculations show that the superconducting temperature is highest at x_c, thus the regimes $x < x_c$ and $x > x_c$ could be seen, respectively, as underdoped and overdoped. The shape of the FS in the underdoped regime favors the DW instabilities with the antiferromagnetic wave vector $\boldsymbol{Q} = (\pi, \pi)$. The DW order parameter is $\psi_k = \langle c^+_{k+Q\uparrow} c_{k\uparrow} \pm c^+_{k+Q\downarrow} c_{k\downarrow} \rangle$. On the one hand, it could be of the spin (−) or charge (+) type and on the other, it could be isotropic or have a certain dependence on $\boldsymbol{k}$. The $\boldsymbol{k}$-dependent case corresponds to the so-called unconventional DW order which was considered for example in Ref. [4] (see also Ref. [5]). Below, we consider four different types of DW order: isotropic spin or charge density wave (SDW or CDW), d-wave spin or charge density wave (dSDW or dCDW). For all of them the spectrum is given by

$$E^{\pm}_k = \frac{\varepsilon_k + \varepsilon_{k+Q}}{2} \pm \sqrt{\left(\frac{\varepsilon_k - \varepsilon_{k+Q}}{2} \right)^2 + \Delta^2_k} \quad (2)$$

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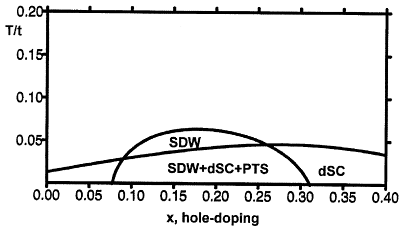

Fig. 1. Phase diagram for $t/J = 1.5$ and $t'/t = -0.3$. T is the temperature. The ordered SDW phase starting from the QCP at $x = x_c$ develops toward the underdoped region. Its size increases with increasing J and eventually leans out the superconducting phase as in this figure. SDW and dSC result in a mixed phase where PTS order is also present.

with $\Delta_k = \Delta_0$ for SDW and CDW orders, and $\Delta_k = \Delta_0[\cos k_x - \cos k_y]$ for dSDW and dCDW orders. The effective coupling constants are given respectively, by

$$g_{\mathrm{SDW}} = 2U + 2J^z, \quad g_{\mathrm{dSDW}} = b + J^z - 2J^{\perp},$$

$$g_{\mathrm{CDW}} = -2U + 2b, \quad g_{\mathrm{dCDW}} = b + J^z + 2J^{\perp}.$$

In the case of the t–J model ($J^z = J^{\perp} = -b$ and $U = 0$) which we use below to describe the high-T_c cuprates, only two instabilities, dCDW and SDW, are possible, being determined by equal effective constants, $g_{\mathrm{SDW}} = g_{\mathrm{dCDW}}$.

On the second stage we write a set of coupled equations for different order parameters. We show that the mixed state with both SC and DW order parameters is favorable in the underdoped regime at low temperature (see Fig. 1). Moreover, the coexistence of DW and dSC order parameters results in the appearance of a third ordering. In the case when DW order is of the isotropic SDW type[2] this third order parameter (π triplet superconducting [6,7] (PTS) one) is related to the π operator introduced in the framework of the SO(5) theory which creates triplet Cooper pairs with total momentum $\boldsymbol{Q}$. The resulting phase diagram is shown in Fig. 1 for the t–J model with realistic parameters for high-T_c cuprates.

Notice that the pure DW order develops in the region where the pseudogap behavior in the normal state is experimentally observed, see e.g. Ref. [3]. The admixture of SDW order in the dSC state could be responsible for the anomalous spin dynamics observed by neutron scattering inside the superconducting phase. If the dSC order is suppressed, the underdoped regime could be insulating due to the DW order while the overdoped one will remain metallic in good agreement with experiment [8] where superconductivity is suppressed by a pulsed magnetic field.

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