Pomeranchuk Instability as Order Competing with Superconductivity

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Abstract

We study the large *xy* anisotropy of magnetic excitations observed for $YBa_2Cu_3O_y$ with y=6.45, 6.6, and 6.85. We show that the delicate interplay among the Pomeranchuk instability, superconductivity, and a lattice anisotropy plays an integral role to understand the observed anisotropy of magnetic excitations. The Pomeranchuk instability can be a key ingredient as an order competing with superconductivity in cuprates.

Key words: cuprates, competing order, magnetic excitations, nematic order, Pomeranchuk instability, Fermi surface, *t*-*J* model

1. Introduction

The interplay of antiferromagnetism and superconductivity was a central subject of cuprate superconductors. Recently, it was recognized that besides antiferromagnetism there appear to exist other orders competing with superconductivity, such as spin-charge stripes, staggered flux, *d*-density wave, and *d*-wave Fermi surface deformations (*d*FSD). In particular, the *d*FSD is distinguished from the other orders in the sense that it is an instability at $\mathbf{q} = 0$ while the others are generated by electron-electron interactions with large momentum transfer near $\mathbf{q} = (\pi, \pi)$. The *d*FSD instability leads to spontaneous symmetry breaking of the Fermi surface and breaks the point-group symmetry of the underlying lattice. The *d*FSD is frequently referred to a *d*-wave Pomenranchuk instability or electronic nematic order.

The *t*-*J*[1, 2, 3] and Hubbard[4] models, which are believed to be the microscopic models for cuprates, show the tendency of the *d*FSD instability. The *d*FSD competes with singlet pairing, which may prevail over the *d*FSD instability. However even in such a case, fluctuations of the *d*FSD may survive. This is indeed the case in the slave-boson analysis of the *t*-*J* model. It was shown that sizable fluctuations of the *d*FSD appear as a collective mode in the superconducting state[5] as well as a *soft* band structure in the sense that the band becomes very susceptible to a small *xy* anisotropy such as coming from a lattice structure[1].

In this paper, we argue the importance of delicate interplay among the *d*FSD, superconductivity, and a lattice anisotropy for cuprate superconductors through studying the anisotropy of magnetic excitations recently observed for $YBa_2Cu_3O_y$ ($YBCO_y$) with $y = 6.45$[6], 6.6[7, 8], and 6.85[7]. Both the *d*FSD and singlet pairing are generated by the J term in the *t*-*J* model. We include both effects and employ the slave-boson scheme of the *t*-*J* model. We then compute the dynamical magnetic susceptibility in the renormalized random phase approximation (RPA). Since a comprehensive theoretical analysis for $YBCO_y$ with $y = 6.85$ and 6.6 is presented in Ref. [9] and that for $YBCO_{6.45}$ in Ref. [10], we emphasize obtained insights into the physics of high-temperature superconductivity in this paper.

2. Study on $YBCO_y$ with $y = 6.85$ and 6.6

$YBCO_y$ has an orthorhombic crystal structure for $y \geq 6.4$, for which inelastic neutron scattering measurements were performed[7, 8]. Because of the presence of a *xy* anisotropy of the lattice, it is not surprising that the magnetic excitations exhibit an anisotropy. The crucial feature of the experimental observation was that the anisotropy exhibits a characteristic temperature dependence: the anisotropy is enhanced with decreasing temperature to become most pronounced around the onset of superconductivity or pseudogap, and is suppressed at lower temperatures. Furthermore, the anisotropy is more pronounced at lower doping.

It is difficult to interpret these data just coming from the orthorhombicity of the lattice, which is almost temperature independent and is decreased at lower doping, implying the importance of electron-electron correlations. In fact, the analysis of the *t*-*J* model[1, 3] predicted that a small *xy* band anisotropy can be strongly renormalized by the underlying *d*FSD fluctuations. In particular, in the slave-boson analysis[1], it was shown that the resulting anisotropy is enhanced with decreasing temperature to become most pronounced at the onset of singlet pairing and is decreased at lower temperature because of the competition with singlet pairing. The impact of this feature on magnetic excitations was comprehensively studied in the slave-boson scheme by computing the dynamical magnetic susceptibility in the renormalized RPA[9]. Obtained spectra revealed the same characteristic temperature and doping dependence as the experimental observation[7, 8]. Moreover, the theoretical results also reproduced well-known properties of magnetic excitations in YBCO: doping dependence of the magnetic resonance energy, the so-called hourglass-shaped dispersion traced by the strong intensity of the spectrum, and the incommensurate magnetic fluctuations realized only in a singlet pairing state. This agreement suggests not only the validity of the slave-boson analysis of the t-J model to understand magnetic excitations in cuprate superconductors, but also the importance of the dFSD correlations as an order competing with superconductivity.

3. Study on $YBCO_{6.45}$

The above insight is based on agreement with the experimental data for optimally doped ($y = 6.85$)[7] and underdoped ($y = 6.6$)[7, 8] $YBCO_y$. It could be natural to expect a similar result in a more underdoped region. However, the experimental data[6] for $YBCO_{6.45}$ revealed that magnetic excitations changed drastically. First, the anisotropy of magnetic excitations was not pronounced around the onset temperature of superconductivity or pseudogap, but instead was increased monotonously with decreasing temperature and saturated at low temperature. Second, no impact of superconductivity on magnetic excitations was observed, which is qualitatively different from the usual observation, namely the strong suppression of low energy magnetic excitations in the superconducting state and the emergence of the magnetic resonance peak at a moderate energy. The peculiar observations in $YBCO_{6.45}$ cannot be captured even qualitatively in the slave-boson analysis of the t-J model, implying something not included in the slave-boson theory happens in the strongly underdoped region. Our idea is that strong dFSD fluctuations become dominant in the strongly underdoped region and suppress singlet pairing substantially[10]. In order to test this idea, we considered the limiting case of zero amplitude of singlet pairing in the slave-boson analysis of the t-J model. This phenomenological prescription turned out to capture the most salient features observed in $YBCO_{6.45}$: the strongly enhanced anisotropy of magnetic excitations at low temperature and the enhanced spectral weight at low energy. This agreement suggests that singlet pairing is strongly suppressed by dFSD correlations in the strongly underdoped YBCO.

4. Conclusions and discussions

Taking these theoretical results[9, 10] obtained in the slave-boson scheme of the t-J model into account, we propose the phase diagram shown in Fig. 1. The d-wave resonating-valence-bond (RVB) phase is described by spinons' singlet pairing with d-wave symmetry, which is interpreted as the pseudogap in cuprates. The observation of the relatively large anisotropy of magnetic excitations in $YBCO_{6.85}$[7] and $YBCO_{6.6}$[7, 8] and its characteristic temperature dependence suggest that there are sizable dFSD correlations hidden in a large part of the phase diagram, which drive a large response of electronic band anisotropy to a small external anisotropy. The strength of the dFSD fluctuations grows at lower doping. In particular, for $YBCO_{6.45}$[6] the effect of dFSD fluctuations becomes so strong that the dRVB state is suppressed substantially. This suppression does not necessarily indicate the suppression of the pseudogap, since strong fluctuations of the dFSD also

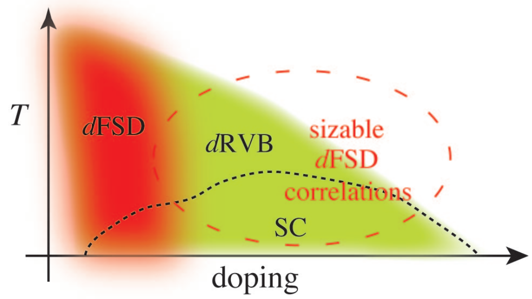

Figure 1: (Color online) Phase diagram in the plane of carrier density and temperature. SC is the superconducting state below a dashed line; dRVB is the d-wave resonating-valence-bond state where spinons form singlet pairing with d-wave symmetry. Sizable dFSD fluctuations are present in a large part of the phase diagram including the dRVB and SC state, and become stronger at lower doping. In a very low doping region, the effect of the dFSD becomes so strong that the dRVB is strongly suppressed.

contribute to the pseudogap in the sense that life time of quasiparticles around $(\pi, 0)$ and $(0, \pi)$ are strongly reduced while not along the direction $(0, 0) - (\pi, \pi)$[11].

While the phase diagram in Fig. 1 is based on the study of YBCO, we expect that the presence of sizable fluctuations of the dFSD and its enhancement at lower doping are generic features of cuprates, which is indeed supported by the analysis of the t-J model[1, 2, 3]. It would be a subtle issue whether the dFSD fluctuations in turn suppress the dRVB substantially in the strongly underdoped region in general. It is therefore worth developing the phenomenological study of Ref. [10] to be a more microscopic analysis.

The importance of strong dFSD correlations in cuprates was also emphasized in a scenario of a quantum phase transition into the dFSD state in the strongly underdoped region[12, 13]. In this scenario, the dFSD instability was assumed deeply inside the d-wave superconducting state while we have proposed the importance of competition of the dFSD and singlet pairing, and the substantial suppression of the latter to understand the magnetic excitations in $YBCO_{6.45}$.

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