Theory of the in-plane anisotropy of magnetic excitations in YBa$_2$Cu$_3$O$_{6+y}$

Hiroyuki Yamase and Walter Metzner
Max-Planck-Institute for Solid State Research, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

Abstract

A pronounced $xy$-anisotropy was observed in recent neutron scattering experiments for magnetic excitations in untwinned YBa$_2$Cu$_3$O$_{6+y}$ (YBCO). The small anisotropy of the bare band structure due to the orthorhombic crystal symmetry seems to be enhanced by correlation effects. A natural possibility is that the system is close to a Pomeranchuk instability associated with a $d$-wave Fermi surface deformation ($d$FSD). We investigate this possibility in the bilayer $t$-$J$ model within a self-consistent slave-boson mean-field theory. We show that the $d$FSD correlations drive a pronounced $xy$-anisotropy of magnetic excitations at low doping and at relatively high temperatures, providing a scenario for the observed $xy$-anisotropy in optimally doped as well as underdoped YBCO, including the pseudogap phase.

Key words: magnetic excitation, Y-based cuprates, Fermi surface

PACS: 74.25.Ha, 74.72.Bk, 74.20.Mn, 71.10.Fd

The interpretation of neutron scattering data for high-$T_c$ cuprates within a spin-charge stripe scenario has attracted much interest\cite{1}. It predicts a satellite signal at either $q = (\pi, \pi \pm 2\pi \eta_y)$ or $(\pi \pm 2\pi \eta_x, \pi)$, depending on the direction of the stripes. Recently Hinkov et al.\cite{2} performed neutron scattering experiments for untwinned YBa$_2$Cu$_3$O$_{6+y}$ to check this scenario. The untwinned crystals are purely orthorhombic and thus it is expected that the stripe direction is determined uniquely by the orthorhombicity, leading to only one satellite signal. However, they observed two satellite signals at both $q = (\pi, \pi \pm 2\pi \eta_y)$ and $(\pi \pm 2\pi \eta_x, \pi)$, with $\eta_x \neq \eta_y$ and different intensity, and concluded that the stripe scenario did not work. Then how can we understand this $xy$-anisotropy of magnetic excitations? Our scenario is that it comes from electron correlation effects associated with a $d$-wave Fermi surface deformation ($d$FSD).

The $d$FSD was first discussed in the $t$-$J$\cite{3} and the Hubbard\cite{4} model: the Fermi surface expands along the $k_x$ direction and shrinks along the $k_y$ direction, or vice versa. The $d$FSD is driven by forward scattering interactions of quasi-particles (Pomeranchuk instability). The $d$FSD competes with the $d$-wave superconductivity ($d$SC). In the slave-boson mean-field analysis of the $t$-$J$ model\cite{3}, the dominant instability is the $d$SC and the spontaneous $d$FSD does not occur. However, the system still has appreciable $d$FSD correlations, which yield an enhanced anisotropy of a renormalized band structure in the presence of an external anisotropy such as orthorhombicity of a lattice\cite{3}.

We explore this $d$FSD correlation effect and compute magnetic excitations in the bilayer $t$-$J$ model in the slave-boson mean-field scheme with a small $xy$-anisotropy in $t$ and $J$. The magnetic excitations contain the even and the odd channel. Comprehensive results for the odd channel as well as our detailed formalism are presented in Ref.\cite{5}. We focus on the even channel in this paper and take the same model parameters as in Ref.\cite{5}.
Fig. 1. (Color online) $\mathbf{q}$ maps of magnetic excitation spectra for a sequence of $\delta$ for $T = 0.01J$ and $\omega = 0.30J$ in the even channel; 5%(10%) anisotropy is introduced in $(J)$; the right-hand panels show a bare anisotropy effect, namely without $dFSD$ correlations; $\mathbf{q}$ is scanned in $0.6\pi \leq q_x, q_y \leq 1.4\pi$ except for the panels for $\delta = 0.20$ where $0.5\pi \leq q_x, q_y \leq 1.5\pi$.

$q$ maps of magnetic excitation spectra are shown in Fig. 1 for a sequence of hole-doping rates $\delta$ at low $T$. The left-hand panels are self-consistent results while the right-hand panels are corresponding non-self-consistent results where $dFSD$ correlations are switched off, keeping just the bare input anisotropy. The strong spectral weight forms a diamond shaped distribution around $q = (\pi, \pi)$ with prominent weight at $q = (\pi, \pi \pm 2\pi\eta_y)$ and $(\pi \pm 2\pi\eta_x, \pi)$. A robust measure of the anisotropy of magnetic excitations is given by $\Delta\eta = \eta_x - \eta_y$ [5]. Although the input anisotropy is fixed, we can read off appreciable $\delta$ dependence of $\Delta\eta$ from Fig. 1. In particular, the bare anisotropy effect (right-hand panels) becomes less effective for lower $\delta$, where an almost isotropic distribution is seen. The $dFSD$ correlations, on the other hand, enhance the bare anisotropy effect and yield a sizable anisotropy even for low $\delta$.

The importance of the $dFSD$ correlations appears also in the $T$ dependence. The diamond shaped distribution at low $T$ (Fig. 1) is rather robust against $T$ although the spectral weight around $\mathbf{q} = (\pi, \pi)$ increases with $T$. Such spectral weight finally becomes dominant [Fig. 2(a)] and a pronounced $xy$-anisotropy appears. Figure 2 shows a comparison between results including $dFSD$ correlations (left-hand panels) and results based on the bare anisotropy only (right-hand panels), for a sequence of $T$. We see that $dFSD$ correlations drive a pronounced anisotropy for temperatures around $T_{RVB}$ (corresponding to the pseudogap temperature) while they become less effective for higher $T$.

We have seen that the $dFSD$ correlations lead to a pronounced anisotropy of magnetic excitations at low $\delta$ and at relatively high $T$, which are common features in both the odd[5] and the even channel. Anisotropic magnetic excitations are observed in YBa$_2$Cu$_3$O$_{6.6}$[2] and YBa$_2$Cu$_3$O$_{6.5}$[6], and in the pseudogap phase[2]. These data can not be understood by the bare anisotropy effect only (see right-hand panels in Figs. 1 and 2), implying the importance of $dFSD$ correlations.

References

[1] J. M. Tranquada et al., Nature 375 (1995) 561.
[2] V. Hinkov et al., Nature 430 (2004) 650; V. Hinkov et al., cond-mat/0601048
[3] H. Yamase and H. Kohno, J. Phys. Soc. Jpn. 69 (2000) 332; 69 (2000) 2151.
[4] C. J. Halboth and W. Metzner, Phys. Rev. Lett. 85 (2000) 5162.
[5] H. Yamase and W. Metzner, Phys. Rev. B 73 (2006) 214517.
[6] C. Stock et al. Phys. Rev. B 69 (2004) 14502.