Spin-orbit coupling in the superconducting phase and DDW states of high-T<sub>c</sub> cuprates

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Received 16 October 2009 / Received in final form 9 April 2010
Published online 24 June 2010 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 2010

Abstract. The effects of the spin-orbit coupling are considered for the high T<sub>c</sub> cuprates with asymmetric superconducting gap (SC) and the d-density wave (DDW) phase due to its vital role in the experimental determination of the DDW state. Experiments predict an anisotropy in the DSC gap where |Δ(0, π)| > |Δ(π, 0)| and the gap node deviates from the diagonal direction towards the k<sub>x</sub> axis. Measurements also demonstrate DDW to be a possible candidate for the pseudogap in the underdoped phase. Due to the spin-orbit (SO) coupling in the low temperature orthorhombic (LTO) phase, the phase diagram of the cuprates suffers a change due to the modification of the T<sup>c</sup> value, the temperature characteristic of pseudogap, although T<sub>c</sub> remains unaltered. Moreover, for a more generalized SO coupling, the DDW gap decreases with the angle but has no effect on the SC gap. We calculate the density of states in the various regimes of doping for the mixed SC+DDW states in the underdoped (UD) phase, SC state in the overdoped phase and also the DDW state in the UD phase and compare them with various theoretical and experimental works. The temperature dependence of the specific heat does not exhibit any qualitative change due to the SO coupling.

1 Introduction

A fundamental aspect in the field of high temperature superconductors is the presence of a competing order in the underdoped regime leading to the explanation for a superconducting dome and a possible scenario for the pseudogap characterized by the depletion of the density of states. Recently, various experimental works critically examining the behavior of specific heat [1,2], photoemission [3,4], tunneling [5,6] and optical conductivity [7,8] have predicted the existence of two competing energy gaps, a pseudogap and the superconducting gap. A series of works have led to the proposal of a d-density wave order (DDW) [9–18] scenario as a possible candidate for pseudogap where the particle hole pair of the same orientation form the condensate. The DDW states break parity as well as translational, rotational and time inversion symmetry. Due to a spin fluctuation is stronger at (π+δ, π) direction than at (π, π) direction, the orthorhombic structure of the YBCO superconductors with asymmetric CuO-chain layer has a profound effect on the superconducting properties as is evident from the experimental work of Basov et al. [21] who observed a 50% anisotropy in the penetration depths of α and β directions. Apart from the penetration depth results various other experiments measuring infrared and optical conductivity and dc resistivity have also found large anisotropies along the two directions which suggest that substantial currents are carried along the chains. Hence, the physics in the CuO chains becomes an essential feature in the process of understanding the cuprates. Recently the angle-resolved phase-sensitive experiments by Kirtley et al. [22] show that |Δ(0, π)|/|Δ(π, 0)| ~ 1.2 and the gap nodes shift by about 3° away from the diagonal direction towards the k<sub>x</sub> axis whereas the electron tunneling experiment [23] demonstrates a shift of 5° towards the k<sub>y</sub> axis. Moreover, the inelastic neutron scattering experiments and the spin dynamics experiments also support the anisotropy in the superconducting (SC) gap. The inelastic neutron scattering experiments in detwinned YBCO samples demonstrated that the incommensurated peak of spin fluctuation is stronger at (π+δ, π) direction than at (π, π) direction. Furthermore, the superconducting gap (SC) was shown to be a mixture of d<sub>x²−y²</sub>, an extended

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s, and an isotropic s-wave order parameter, essential for the existence of the anisotropy in the gap magnitude between \((0, \pi)\) and \((\pi, 0)\) points. Henceforth, the theoretical calculations need to incorporate the anisotropy observed in the experimental results. The above mixture has been considered recently [24] to study the spin susceptibility and the spectral function of electrons. An admixture of the \(d_{x^2-y^2}\) and s-wave states has already been thoroughly studied [25–27] in the orthorhombic lattice, where the subdominant s wave had been considered to be the extended or the isotropic order parameter based on the experimental results [28,29]. This kind of gap function exhibits a shift in the node but does not show the anisotropy in the values at \((\pi, 0)\) and \((0, \pi)\). Moreover, depending on the phase between the \(d\)- and the s-wave, a second jump of the specific heat has been observed due to the vanishing of the s and d-wave components at different temperatures. The non-observance of the second jump, along with the anisotropy in the gap magnitude at \((0, \pi)\) and \((\pi, 0)\), also the shift in the gap node can only be taken into account considering the isotropic s wave along with dominant \(d_{x^2-y^2}\) and a subdominant extended s wave [30].

The quasiparticle density of states (DOS) is discussed in the framework of the presence of pseudogap along with the anisotropic superconducting gap. The single-particle density of states exhibits explicitly the anisotropic pairing symmetry and many of the physical observables can be best understood in terms of the DOS. The STM measurements are able to provide unique explanation about the short distance electronic structure of these materials which is a powerful technique based on the concept of quantum tunneling. Apart from the symmetry of the gap the presence or absence of the DDW state can also be settled through STM measurements. Recently, this method has been successfully utilized in the pseudogap regime for \(T > T_c\). The DDW state creates a circulating current arising only in the lines of the nesting vector \((\mu, \nu)\). In the simple case, the SO coupling term plays the role of the staggered spin flux with the magnitude along the [110] direction. In the generalized case we consider the values of \(1\), \(2\), and \(3\) for \(\mu\) and \(\nu\) at half filling, while it takes negative values away from half filling and with the introduction of the second nearest neighbor interaction. The \(d\)-density wave and the superconducting gaps are given by \(W\) and \(\Delta_k\) respectively. \(\mathcal{V}_{DG}\) and \(\mathcal{V}_{SC}\) are the pairing interactions for the density wave and superconducting channels respectively. \(\phi_k = (\cos k_x - \cos k_y)\) represents the nesting function which determines the symmetry of the DDW order parameter. The SO coupling parameter \(\lambda_{ij}\) is determined by the lattice symmetries [32,33] as already considered in reference [19]. It shows a staggered pattern given by \(\lambda_{i,i+x} = (-1)^{i_x+i_y}(\lambda_1, \lambda_2, 0), \lambda_{i,i+y} = (-1)^{i_x+i_y}(−\lambda_2, −\lambda_1, 0)\) [34].

In the first instance we choose a simple model where \(\lambda_1 = \lambda_2 = \lambda / \sqrt{2}\). Later, we choose a more generalized and a realistic \(\lambda_{ij}\). In the simple case, the SO coupling term plays the role of the staggered spin flux with the quantization axis along the [110] direction. In the generalized case we consider the values of \(\lambda_{1,2}\) to be \(\lambda = \lambda \cos \theta\) and \(\lambda = \lambda \sin \theta\) where \(\theta\) lies between \(0^\circ\) and \(90^\circ\).

The Hamiltonian with the respective lattice symmetries in the above two cases can be written as

\[
H = \sum_{k,\sigma}(c_{k,\sigma}c_{k,\sigma} + \text{h.c.}) + 2i \sum_{k,\sigma,\alpha,\beta,\pm} c_{k,\sigma}^{\dagger} \lambda_{\alpha,\beta} f_{\pm,\pm}(k) \sigma_{\alpha,\beta} c_{k,\sigma} + \text{h.c.,}
\]

where \(\lambda_{\alpha,\beta}\) is the nesting vector for wavevector \(k\) and spin \(\sigma\). \(W, \Delta_k\) are the DDW and SC gaps respectively. \(\mathcal{V}_{DG}\) and \(\mathcal{V}_{SC}\) are the pairing interactions for the density wave and superconducting channels respectively. \(\phi_k = (\cos k_x - \cos k_y)\) represents the nesting function which determines the symmetry of the DDW order parameter. The SO coupling parameter \(\lambda_{ij}\) is determined by the lattice symmetries [32,33] as already considered in reference [19]. It shows a staggered pattern given by \(\lambda_{i,i+x} = (-1)^{i_x+i_y}(\lambda_1, \lambda_2, 0), \lambda_{i,i+y} = (-1)^{i_x+i_y}(−\lambda_2, −\lambda_1, 0)\) [34].

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