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BSCCO Superconductors: Hole-Like Fermi Surface and Doping Dependence of the Gap Function

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We use the gradient of the energy-integrated angle resolved photoemission (ARPES) intensity in order to define precisely the Fermi surface (FS) in BSCCO superconductors. We show that, independent of the photon energy, the FS is a hole barrel centered at (π,π). Then, the superconducting gap along the FS is precisely determined from ARPES measurements on overdoped and underdoped samples of Bi2212. As the doping decreases, the maximum gap increases, but the slope of the gap near the nodes decreases. Though consistent with d-wave symmetry, the gap with underdoping cannot be fit by the simple $cos(k_x) - cos(k_y)$ form. A comparison of our ARPES results with available penetration depth data indicates that the renormalization of the linear T suppression of the superfluid density at low temperatures due to quasiparticle excitations around the d-wave nodes is large and doping dependent.

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1. INTRODUCTION

In high temperature superconductors, well-defined quasiparticle excitations exist only in the superconducting state,[1] where a description in terms of superfluid Fermi liquid (FL) theory should be appropriate.[2] In FL theory, the quasiparticles are characterized by a renormalized Fermi velocity v_F, and their residual interactions described by Landau parameters, which manifest themselves through a renormalization of various response functions such as the superfluid density $\rho_s(0)$. In this paper we examine whether the slope of the superfluid density at low temperatures, $d\rho_s/dT$, is affected by interactions or not, and what the relation of its renormalization is to that of $\rho_s(0)$.

To address these issues we use the unique capability of ARPES to directly measure the Fermi wavevector k_F, velocity v_F, and the superconducting gap anisotropy near the node, from which we can estimate the slope of $\rho_s(T)$ assuming non-interacting quasiparticles. Comparing this with the actual value obtained by penetration depth experiments leads to a direct estimate of the renormalization due to quasiparticle interactions. This is done by exploiting the relation[3]

$$\left|\frac{d\rho_s}{dT}(T=0)\right| \propto \left|\frac{d}{dT}\left(\frac{1}{\lambda^2}\right)\right| = A\beta^2\frac{v_F k_F}{v_\Delta}. \tag{1}$$

where λ is the penetration depth, and A is a doping-independent constant.[4] ARPES is used to determine the three parameters at the node: the Fermi velocity v_F, the Fermi wavevector k_F, and the slope of the superconducting gap $v_\Delta = 1/2|d\Delta/d\phi|(\phi = \pi/4)$, where ϕ is the Fermi surface angle. The only unknown in Eq. 1 is the renormalization factor β due to quasiparticle interactions.

2. HOLE-LIKE FERMI SURFACE

In order to reliably measure the k-dependence of the gap function, one has to define accuratly the Fermi surface. In high T_c superconductors this is not a trivial task since these materials are strongly correlated, and do not show well defined quasiparticles in the normal state. Additional complications arise due to strong k-dependence of the matrix elements or the presence of strong superlattice images.[5] Nevertheless, the FS can be identified by looking at the energy integrated ARPES intensity $I(\mathbf{k}) = M(\mathbf{k})n(\mathbf{k})$. Here, $M(\mathbf{k})$ is the k-dependent matrix element and $n(\mathbf{k})$ the momentum occupation. We further define the normalized gradient $|d_{\mathbf{k}}I(\mathbf{k})|/I(\mathbf{k})$, which is a very useful tool to determine the FS.[6] In order to avoid complications due to the presence of superlattice images[5] we have investigated lead-doped

Bi2201 samples. Figures 1a) and 1c) show the measured $I(\mathbf{k})$ around $(\pi, 0)$ at 22 eV and 28 eV photon energy, respectively. One observes that the intensity maximum strongly depends on the incident photon energy. At 28 eV there is a large intensity drop around $(\pi, 0)$, due to matrix elements effects, which makes it difficult to define the FS. Fig. 1b,d show the corresponding $|d_{\mathbf{k}}I(\mathbf{k})|/I(\mathbf{k})$. The FS crossings are defined by the regions of maximum gradients (clearest in Fig. 1b,d). This method unambiguously shows that the FS is centered around (π, π) and is photon energy independent, in contradiction with the conclusions that the FS is centered around Γ as recently obtained from ARPES measurements performed at 33 eV photon energy.[7] We do believe[8] that matrix element effects and the presence of umklapp bands are responsible for the inferred FS crossing along the $(0, 0) - (\pi, 0)$ direction.[7]

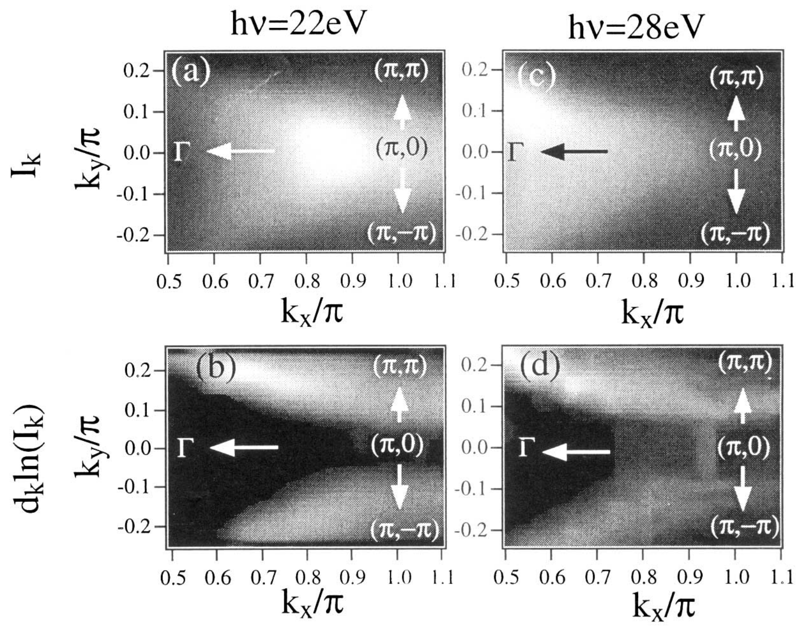

Fig. 1. a,c) $I(\mathbf{k})$ obtained at 22 eV and 28 eV, respectively. b,d) Corresponding normalized gradients.

3. DOPING DEPENDENCE OF THE GAP

Once the FS crossing has been determined it is possible to measure the k-dependence of the gap function. Fig. 2a shows ARPES data at T=15 K for an underdoped Bi2212 $75K - T_c$ (UD75K) sample at different Fermi surface (FS) angles. From the shift of spectral weight away from E_F, one clearly sees an anisotropic gap, which is maximal near the $(\pi, 0)$ point ($\phi = 0$) and zero near the (π, π) direction ($\phi = 45°$). For comparison we also plot (dashed line) in Fig. 2a ARPES spectra from an overdoped $87K - T_c$ (OD87K) sample at two points on the FS. We immediately see that the UD sample has a larger maximum gap (at $\phi = 0$) than the OD one, but it has a smaller gap at the corresponding point ($\phi = 38$ degrees) near the node. Thus the raw data directly give evidence for an interesting change in gap anisotropy with doping. The resulting angular dependence of the gap is plotted in Fig. 1b,c for an OD87K and an UD75K sample, respectively.

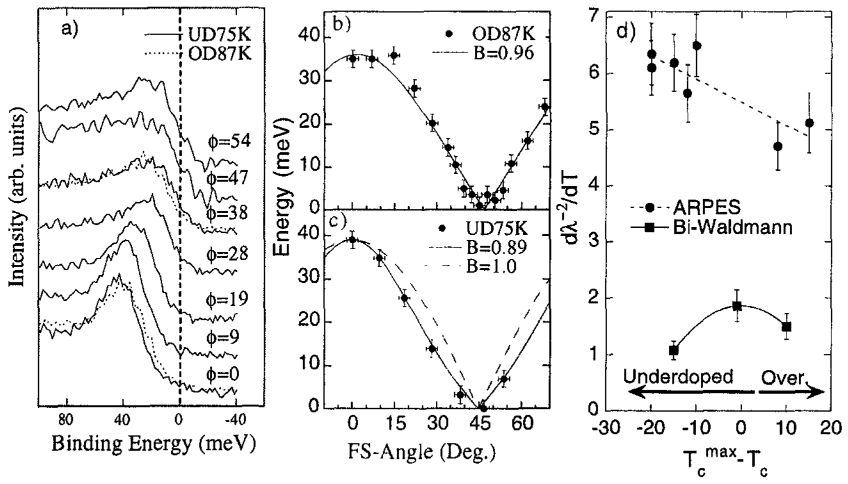

Fig. 2. a) ARPES Spectra of OD87K and UD75K samples. b,c) Δ_k for OD87K and UD75K samples. The solid line represents the best fit as described in the text. d) $|d\lambda^{-2}/dT|$ estimated from ARPES ($\beta = 1$) (circles) and penetration depth measurements in Bi2212 (squares).

To quantify this flattening around the nodes, we have used the following expression to fit the gap: $\Delta_k = \Delta_{max}[B\cos(2\phi) + (1 - B)\cos(6\phi)]$ with $0 \leq B \leq 1$, where B is determined for each data set. Note that $\cos(6\phi)$ is the next harmonic consistent with d-wave symmetry and represents next nearest neighbour interactions. We find (see Fig. 2b,c) that while the overdoped data sets are consistent with $B \approx 1$, the parameter B decreases significantly in the underdoped regime. Our data suggest that the change in the gap function with underdoping (increase of the $\cos(6\phi)$ term) is related to an increase in the range of the pairing interaction.

We now return to Eq. 1. It is known from previous ARPES measurements that the band dispersion along $(0,0)-(\pi,\pi)$ and k_F along this direction are almost doping independent.[9,10] Using ARPES inputs, together with the strongly doping dependent v_Δ, we can estimate the slope $|d\lambda^{-2}/dT|$ in the case of non-interacting quasiparticles ($\beta = 1$) and compare our results to London penetration depth data obtained on Bi2212.[11] Fig. 1d shows that the slope $d\rho_s/dT$ obtained from penetration depth data *decreases* with underdoping, in opposition with the trend deduced from a theory with non-interacting quasiparticles ($\beta = 1$) using ARPES input (circles). From our results, it is clear that the renormalization factor β is considerably smaller than unity and doping dependent, a conclusion different from that inferred earlier.[3,12]

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