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Incommensurate, dispersive, density of states modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

Scanning tunneling spectroscopy of $Bi_2Sr_2CaCu_2O_{8+\delta}$ reveals weak, incommensurate, spatial modulations in the tunneling conductance. When images of these energy-dependent modulations are Fourier analyzed the dispersion of their wave vectors can be determined. Comparison of the dispersions with angle-resolved photoemission indicates that quasiparticle interference, due to elastic scattering between specific regions of the Fermi surface, provides a consistent explanation for the conductance modulations.
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Keywords: Quasiparticle interference; Scanning tunneling microscopy; $Bi_2Sr_2CaCu_2O_{8+\delta}$

1. Introduction

The widely accepted model for low-energy physics of the cuprate superconductors relies on the concept of quasiparticles. These quasiparticles are the elementary electronic excitations above the superconducting energy gap which, in $Bi_2Sr_2CaCu_2O_{8+\delta}$, has four nodes [1]. The scattering of these quasiparticles with each other and the crystal determine a great deal of the low-energy physics of these materials. When the scattering occurs between two states it produces oscillations in the norm of a quasiparticle's wave function with wavelength $\lambda = 2\pi/q$, where q is the scattering vector. These oscillations should be observable as spatial modulations in the tunneling conductance detectable by scanning tunneling microscopy [2]. Here we describe the study of these conductance oscillations in $Bi_2Sr_2CaCu_2O_{8+\delta}$.

2. Experimental

We use TSZ grown single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with T_c ranging from 78 K underdoped (UD) to 85 K overdoped (OD). Cleaving the sample in cryogenic ultra-high vacuum reveals the BiO plane. On these surfaces we measure the local differential tunneling conductance ($G = \mathrm{d}I/\mathrm{d}V$) as a function of position (x, y) with atomic resolution. Because $G \propto \mathrm{LDOS}(V)$, where V is the sample bias voltage and $\mathrm{LDOS}(V)$ is the local density of states, this results in a two-dimensional map of the LDOS at each energy. Fourier transforms of these LDOS maps reveal $\bar{q}$ with the $\bar{q}$-vectors of the LDOS modulations.

3. Results

Fig. 1 shows a typical FT(LDOS) taken at 16 meV on an UD sample with $T_c = 78$ K. A total of nine features dominate the image. The largest central peak results from short wave vector disorder with $\lambda > 10a_0$ will not

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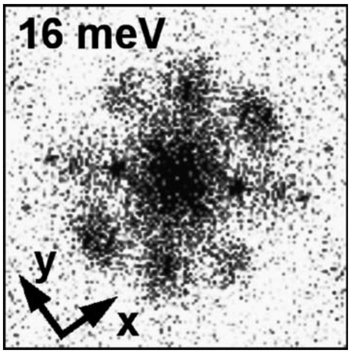

Fig. 1. Typical FT(LDOS) taken at 16 mV on the 78 K UD sample. The Cu–O bond directions are along the x and y axes. The $(\pi, 0)$ align with these axes while the (π, π) are aligned (45° to them).

be discussed further. Next, one can see four peaks whose $\bar{q}$-vectors are oriented towards the $(\pm\pi, 0)$ or $(0, \pm\pi)$ (i.e. oriented along the x and y axes with the Cu–O bonds). Finally, an additional four peaks are present in the $(\pm\pi, \pm\pi)$ (45° to the Cu–O direction). At each energy these sets of peaks, along (π, π) or $(\pi, 0)$, are located the same distance from the origin and can be described by two wave vectors: $q_{\pi,\pi}$ and $q_{\pi,0}$ respectively.

The locations of $q_{\pi,\pi}$ and $q_{\pi,0}$ as a function of energy (E) for several different dopings are shown in Fig. 2. The different classes of q's evolve in different characteristic ways. The $q_{\pi,\pi}$ (open symbols) move from high wave vector far from the Fermi energy E_F and move towards lower q at lower energies. The other four points, $q_{\pi,0}$

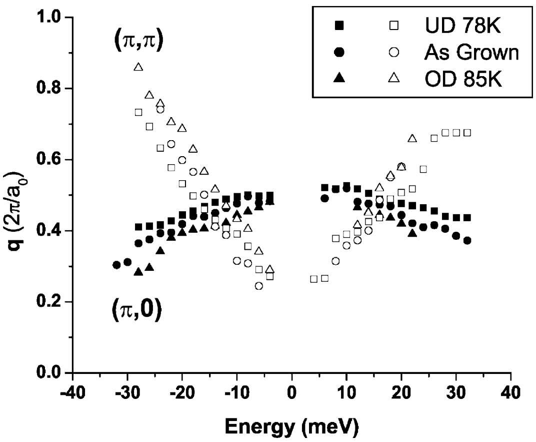

Fig. 2. Dispersion of the discussed modulations for several dopings. Filled symbols are (π, π) and the open ones are $(\pi, 0)$ and $(0, \pi)$. The different shapes correspond to different dopings, for UD, "As Grown", and OD.

have a finite wave vector at E_F and disperse inward (shorter q) until they merge with the inhomogeneity peak at higher energy.

To model these phenomena [3] we use the normal state Fermi surface (FS) and the superconducting gap $\Delta(\bar{k})$ as studied by ARPES [1,4–7]. At any energy ($E = eV$) we expect the eight regions in $\bar{k}$-space above the FS with the lowest energy (i.e. $E = \Delta(\bar{k}_{FS})$ excitations to be the dominate contributors of DOS(E). If we take two q's that connect these "bright-spots" along the $(\pi, 0)$ and (π, π) directions and plot their dispersion we find excellent agreement with these data.

4. Conclusion

We conclude that (1) quasiparticle band-structure effects play the primary role in LDOS modulation effects in $Bi_2Sr_2CaCu_2O_{8+\delta}$, (2) the relationship between the relatively strong "checkerboard" modulations around the vortex core [8] and the modulations in zero-field discussed here and in [9,10] has yet to be determined, and (3) since quasiparticle scattering between high joint-DOS regions of k-space is here shown to be a mechanism for incommensurate, dispersive, spatial modulations of the superconducting electronic structure, renewed exploration of such a scattering-related explanation for other incommensurate magnetic phenomena [11–14] in the cuprates may be appropriate.

Acknowledgements

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