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Vortex-induced quasi-particle 'checkerboard' in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

Scanning tunneling microscopy is used to image the additional quasi-particle states generated by quantized vortices in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$. They exhibit a Cu–O bond oriented 'checkerboard' pattern, with $(4.2 \pm 0.4)a_0$ periodicity and $\sim$30 Å decay length.

Keywords: High-T_c superconductivity; Vortices; Scanning tunneling microscopy; Electronic density of states; $Bi_2Sr_2CaCu_2O_{8+\delta}$

1. Introduction

The phase diagram of the high temperature superconductors (HTSCs) consists of well-known antiferromagnetic and superconducting regions, as well as several unidentified regions, where theory has predicted a variety of candidate phases. Determining which phases actually exist is a key experimental challenge. Because the suppression of superconductivity inside vortices can allow an alternate magnetic or electronic ordered state to appear there, much theoretical and experimental attention has focused on the behavior of HTSC materials in magnetic fields.

Theories predict that a phase transition into a magnetic ordered state can occur where superconductivity is weakened by a vortex, and localized magnetic order of wavelength λ will generate spatial modulations in the quasi-particle density of states with wavelength $\lambda/2$. For additional discussion of alternate vortex-induced phases in HTSCs, see [1].

Spin properties of HTSCs in a magnetic field have been measured by neutron scattering. In $La_{2-x}Sr_xCuO_4$, a magnetic field induces both spin-fluctuations [2] and static spin order [3] with spatial periodicity $8a_0$ along the Cu–O bond directions. In La_2CuO_{4+y}, static spin ordering with the same $8a_0$ periodicity increases with increasing field [4].

2. Experimental

To look for magnetic field induced effects, we study $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals which are slightly overdoped with $T_c = 89$ K. We use a scanning tunneling microscope [5] to acquire maps of the local density of states $\mathrm{LDOS}(E, x, y, B)$ in 1 meV energy increments for several different field strengths in the exact same 560 Å field of view.

To focus preferentially on B field effects, we define

$$S_{E_1}^{E_2}(x, y, B) = \sum_{E_1}^{E_2} [\mathrm{LDOS}(E, x, y, B) - \mathrm{LDOS}(E, x, y, 0)]\, \mathrm{d}E$$

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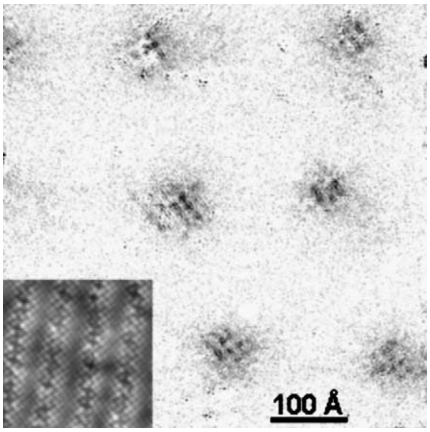

Fig. 1. Map of $S_1^{12}(x, y, 5)$: seven vortices are evident as the darker regions of dimension ~100 Å with an internal 'checkerboard' pattern. The inset shows a topographic image of the BiO plane at 2× magnification. The atomically resolved square lattice and the supermodulation at 45° are evident.

which represents the integral of B-induced spectral density between the energies E_1 and E_2 at each location (x, y). In $Bi_2Sr_2CaCu_2O_{8+\delta}$, these states have broad resonances around ±7 meV [6], so $S_{\pm 1}^{\pm 12}(x, y, B)$ maps the spectral strength under their peaks.

Fig. 1 shows an image of $S_1^{12}(x, y, 5)$ for a field of view containing seven vortices. Each vortex displays a 'checkerboard' pattern in the integrated LDOS, oriented along the Cu–O bonds, whose direction can be seen in the topographic inset. We have observed vortex-induced modulations with the same periodicity and orientation on multiple samples and in multiple B fields.

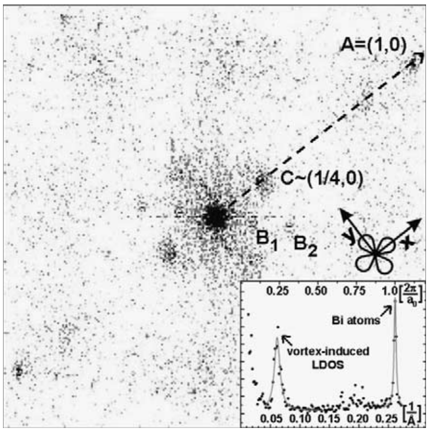

Fig. 2. Power spectrum of the field of view shown in Fig. 1. The atomic periodicity is detected at the four points labeled by A, which by definition are at $(0, \pm 1)$ and $(\pm 1, 0)$ in units of $2\pi/a_0$. The harmonics of the supermodulation are labeled B_1 and B_2. The signature of the vortex-induced LDOS appears at four k-space points labeled by C. The inset shows a linecut along the dashed line, with Lorentzian fits to the k-space locations of the vortex-induced LDOS and the atomic signature.

We show in Fig. 2 the power spectrum of $S_1^{12}(x, y, 5)$. Most importantly, $PS[S_1^{12}(x, y, 5)]$ shows peaks at the four k-space points labeled by C, which correspond to the spatial structure of the vortex-induced quasi-particle states. We fit a Lorentzian to $PS[S_1^{12}(x, y, 5)]$ at each of these k-space bright spots. We find that the vortex-induced spectral intensity occurs at a k-space radius 0.062 $Å^{-1}$ with width $\sigma = 0.011 \pm 0.002$ $Å^{-1}$. Equivalently, the vortex-induced 'checkerboard' has real space periodicity $(4.2 \pm 0.4)a_0$.

3. Results and discussion

Theories predict that an SDW of periodicity λ will have an associated CDW of periodicity $\lambda/2$ (see discussion in [1]), so one may be tempted to connect the $8a_0$ periodic spin modulations [2–4] with the $4a_0$ periodic LDOS modulations. However, recent STM results on $Bi_2Sr_2CaCu_2O_{8+\delta}$ [7,8] in zero magnetic field have shown new LDOS modulations, some of which appear similar to the vortex-induced 'checkerboard', but whose wave-vectors disperse with energy. These LDOS modulations may be explained by quasi-particle interference due to the shape of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ Fermi surface, without reference to alternate phases. In addition, $B = 0$ T neutron scattering experiments have shown that the incommensurate spin fluctuations in $YBa_2Cu_3O_{6+x}$ also disperse with energy [9].

The question remains how to interrelate the $B = 0$ T dispersing spin fluctuations in $YBa_2Cu_3O_{6+x}$ [9] and LDOS modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [8], and also the high magnetic field spin order in $La_{2-x}Sr_xCuO_4$ [2,3] and La_2CuO_{4+y} [4] and the LDOS modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ reported here. We are aware of no experiments to date which look for dispersing spin or LDOS order in magnetic fields. Therefore, further experiments are required to determine the connection between all these phenomena.

Acknowledgements

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