Four-fold structure of vortex core states in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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We present a detailed study of vortex core spectroscopy in slightly overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ using a low temperature scanning tunneling microscope. Inside the vortex core we observe a four-fold symmetric modulation of the local density of states with an energy-independent period of $(4.3\pm0.3)a_0$. Furthermore we demonstrate that this square modulation is related to the vortex core states which are located at \(\pm6\) meV. Since the core-state energy is proportional to the superconducting gap magnitude \(\Delta_p\), our results strongly suggest the existence of a direct relation between the superconducting state and the local electronic modulations in the vortex core.

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The high-temperature superconductors are characterized by an unconventional temperature-doping phase diagram, which is the object of numerous studies focusing in particular on the nature of the pseudogap and superconducting states. However, in spite of this effort the microscopic origin of superconductivity in these materials is still not understood. A promising approach to investigate the superconducting states is to study the electronic properties of the vortex cores. Scanning tunneling microscopy (STM) observations of vortex cores were first carried out on NbSe$_2$. The behavior of the tunneling conductance, which measures the local density of states (LDOS), was found to agree with the prediction by Caroli et al., that a band of localized states develops in the cores. The subsequent observation of vortices in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) gave a surprising result: contrary to the observations in NbSe$_2$, the vortex-core spectra showed two peaks staying at a constant energy irrespective of the distance to the vortex center, as if the vortex would contain only two localized states instead of a whole band. Following this, several groups investigated theoretically the vortex core in a \(d\)-wave superconductor, leading to the conclusion that the spectra observed in YBCO cannot be explained in the framework of the BCS theory and that an extension of this theory is necessary at the very least.

The STM study of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) uncovered another property of the vortex-core spectra: they display the low temperature pseudogap. Subsequently it was found that the two localized states are also present in this compound, and that the states seen in YBCO and in Bi2212 have a common characteristic, appearing at an energy of about \(0.3\Delta_p\), where \(\Delta_p\) is the position of the coherence peaks in the superconducting state.

Hoffman et al. observed a spatial modulation of the low energy tunneling conductance in the vortex cores having a period of about \(4a_0\). Later, it was found that similar modulations also appear in the absence of magnetic field. Hoffman et al. noticed that the wavelength of these modulations disperse with energy and it was proposed that the effect can be understood in terms of quasiparticle interference due to scattering on impurities and other inhomogeneities. However, some of the periodic modulations reported by Howald et al. did not disperse in energy, and an explanation in terms of static stripes was put forward. More recently, Vereshchin et al. studied the spatial dependence of the tunneling conductance in the pseudogap phase. They observed an incommensurate square lattice with period \((4.7\pm0.2)a_0\). The modulations observed above \(T_c\) do not disperse and it was thus concluded that they are different from the interference modulations seen in the superconducting state. A non-dispersing square pattern was also reported at low temperatures in strongly underdoped Bi2212 and Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ (NCCOC), which are characterized by pseudogap-like spectra. Thus there is considerable evidence that a square pattern with a non-dispersing wavelength is associated with the pseudogap, whereas in the superconducting state one observes predominantly dispersing modulations, presumably due to quasiparticle interference.

In this letter we report a detailed study of the LDOS modulation inside the vortex core. We confirm the early observations by Hoffman et al., but our measurements show in addition that this modulation does not disperse with energy, like the ones observed in the pseudogap phase. We further demonstrate that this square modulation is linked to the localized vortex-core state, and we thereby establish a direct relation between the vortex core electronic modulations and the superconducting state.

Our STM measurements were performed on a Bi2212 single crystal grown by the travelling solvent flux zone method and annealed in 500°C under 15 bar oxygen.

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pressure. After annealing we measured $T_{c,\text{onset}} = 88$ K ($\Delta T_c = 4$ K) by ac-susceptibility. The relatively flat background slope of the conductance spectra, as well as the magnitude of the superconducting gap $\Delta_p$, indicate that the sample is slightly overdoped. In the region studied, we observe an average gap $\Delta_p = 25.2$ meV with a standard deviation $\sigma = 4$ meV. This gap distribution is consistent with the observed superconducting transition width.

We performed the measurements with a home-built STM [17] under ultrahigh vacuum. The sample was cleaved in situ at room temperature before cooling and applying the magnetic field and the tunnel junction was made between the (001) sample surface and an electrochemically etched Iridium tip. All data presented here was acquired at 2 K, first at zero field and then at 6 T.

In Fig. 1a, we show a topographic scan at zero field which clearly resolves the atomic lattice of the BiO top layer, as well as the characteristic supermodulation running along the (1,1) direction. Figure 1b is a conductance map at $V = -15$ mV, which was acquired in the same area simultaneously with the topographic image. The Fourier transform (FT) shown in Fig. 1c reveals four peaks corresponding to the Bi lattice and several peaks due to the supermodulation and its harmonics running along the $(\pi, \pi)$ direction. In contrast to earlier reports [10, 11, 12], we do not observe quasiparticle interference peaks in zero field, presumably because of the absence of sufficiently strong scattering centers. The red circles in the inset of Fig. 1c indicate the positions where the peaks of a $4a_0 \times 4a_0$ period would be expected are indicated in red in the inset.

FIG. 1: (a) $16 \times 16$ nm$^2$ topographic image of Bi2212 showing the atomic lattice on the BiO plane. The atomic corrugation is 2 Å. The image was acquired at a bias voltage $V = 0.6$ V and a tunnel current $I = 0.8$ nA. (b) $dI/dV$ conductance map in the same area at $V = -15$ mV, zero field and $T = 2$ K. (c) Absolute value of the Fourier transform of (b). $a^*$ and $b^*$ are the reciprocal vectors of the atomic lattice with modulus $2\pi/a_0$.

In Fig. 2a, we show a conductance map at $V = -25$ mV which clearly displays the location of the vortex core. Its size and irregular shape are consistent with previous studies [13, 14]. In Fig. 2b, we present a conductance map at $V = +6$ mV which corresponds to the energy of the core state. Inside the core one can observe a striking square pattern formed by four bright regions, similar to the observations by Hoffman et al. [9].

In order to quantitatively analyze these structures we performed the FT of conductance maps at several energies. In Fig. 2c we show the FT obtained at $V = +9.6$ mV. In addition to the peaks corresponding to the atomic lattice, we observe two clear structures. First we see four peaks at $q_1 \simeq 0.25\pi/a_0$ corresponding to an incommensurate period of $(4.3 \pm 0.3)a_0$ oriented parallel to the CuO bond direction. These maxima are clearly visible in all LDOS-FT taken between 4 and 12 mV, and between $-8$ and $-12$ mV. We note that their intensity at negative bias (occupied states) is $\sim 2/3$ smaller than at positive bias (empty states). Second we see two maxima at $q_2 \simeq 0.75\pi/a_0$ which only appear along the $(\pm \pi, 0)$ direction. Looking closer, one can observe that the quartet of $q_1$ peaks is slightly rotated with respect to the atomic lattice, while the two $q_2$ peaks are not.

To clearly identify which signal in the real-space conductance map of Fig. 2a originates from the $q_1$ peaks, we show in Fig. 2d the filtered inverse FT. We selected a region in $q$-space containing the four $q_1$ peaks (see inset). The inverse FT exhibits four bright regions at the corners of a square which clearly correspond to the pattern observed in the raw data. We thus demonstrate that the low energy structure in the vortex core shown in Fig. 2a is indeed at the origin of the four $q_1$ peaks.

We now address the spatial variation of the LDOS inside the vortex core. In Fig. 3, we indicate 27 circular areas, each of containing 21 pixels of our spectroscopic
The inset shows the filter applied to the image acquired at circles with radii \( q \). The maxima of the square pattern are again seen in curve C taken on and at increasing distance from the center. The strongest alent by the four-fold symmetry (same color in Fig. 3a) to an average of spectra taken in circles which are equiv-spectrum of the central circle, the curves B–F correspond sation of this data. Whereas A again shows the average fourfold pattern. In Fig. 3d we show a different represen-tation reflects the spatial variation of the localized states. In order to investigate this further and extract the most robust features we have averaged spectra inside each circle along the trace indicated by the arrow in Fig. 3a. Figure 3c shows the average spectra of each circle along the \( \pi,0 \) direction. The core states appear clearly in the two circles located \( \pi,0 \) and \( \pi,\pi \) respectively and G’ was taken at point G, at a distance of 3.4 nm from the center of the square pattern. Whereas G’ is similar to the zero field spectrum, A’ and C’ differ in a remarkable manner. The core states appear very distinct in spectrum C’, which is at one maximum of the fourfold pattern, but in A’ there is hardly any signature of the core states. Thus it appears that the square pattern reflects the spatial variation of the localized states. In order to investigate this further and extract the most robust features we have averaged spectra inside each circle of Fig. 3c. Figure 3d: shows the average spectra of each circle along the trace indicated by the arrow in Fig. 3c. The core states appear clearly in the two circles located on the maxima of the square pattern (red). At the center A, only a weak signature of the localized states is seen, and this signature disappears when moving outside the fourfold pattern. In Fig. 3e we show a different representation of this data. Whereas A again shows the average spectrum of the central circle, the curves B–F correspond to an average of spectra taken in circles which are equivalent by the four-fold symmetry (same color in Fig. 3c) and at increasing distance from the center. The strongest signature of core states is again seen in curve C taken on the maxima of the square pattern.

We therefore conclude that the vortex-core states are closely related to the square pattern. In Fig. 3, we plot a cut in the Fourier transform along the \( \pi,0 \) direction at several energies. The peak at \( q_1 \) corresponding to the \( 4a_0 \)-period does not disperse with energy within the error margins of our measurement. While a weak dispersion towards longer wavelengths cannot be excluded given our present resolution, this possible dispersion would be in the opposite sense than the one observed along \( (\pi,0) \) in the superconducting state and attributed to quasiparticle interference. We also remind that the peak at \( q_2 \) corresponding to a wavelength of \( (4/3)a_0 \) is present in the \( (\pi,0) \) direction, but not in the \( (0,\pi) \) direction.

Figure 3d shows the intensities of the three dominant peaks as a function of energy. The intensity of the \( q_1 \) peak has a clear maximum at the energy of the localized state and increases again when approaching 20 meV. In fact this curve mimics the local density of states measured at the four maxima of the square pattern (Fig. 3f, curve C).

Comparing our results with the observations of Ver-shinin et al. in the pseudogap state above \( T_c \), we find that the ordering in the vortex core is very similar to the ordering in the pseudogap state. The basic structure is a non-dispersing square modulation in the Cu-O bond direction. The period \( (4.3 \pm 0.3)a_0 \) in the vortex core at 2 K is slightly smaller than the period \( (4.7 \pm 0.2)a_0 \) in

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FIG. 2: (a) 8.7 \( \times \) 8.7 nm\(^2\) conductance map at \( V = -25 \) mV. The inset shows the simultaneously acquired topography at the same scale as the underlying conductance map. (b) Conductance map in the same area as (a) at \( V = +6 \) mV. (c) FT image at \( V = +9.6 \) mV. (d) Filtered inverse FT image. The inset shows the filter applied to the image acquired at \( V = +6 \) mV and which selects the region between the two circles with radii \( q[2\pi/a_0] \sim 0.17 \) and \( 0.32 \).

FIG. 3: (a) Central region of Fig. 2d. Each circle contains 21 pixels. (b) Spectra taken at the core center (A’), on a maximum of the square pattern (C’) and outside the core (G’). (c) Spectra averaged in the 7 circles along the arrow in (a); For clarity, the spectra were shifted vertically by 0.4 nS. (d) Spectra averaged over the four-fold symmetry equivalent circles, drawn with identical color in (a); The spectra are offset vertically by 0.3 nS.
FIG. 4: (a) Tunneling conductance at energies between 0 and +16 meV measured along $(\pi, 0)$. (b) FT intensity of $q_0 = 2\pi/a_0$, corresponding to the atomic lattice, $q_1 \approx 0.25(2\pi/a_0)$ corresponding to the square pattern in the vortex core, and $q_2 \approx 0.75(2\pi/a_0)$ which only appears along the $(\pm \pi, 0)$ directions. The intensities where measured on the peaks indicated in Fig. 2.

the pseudogap state at 100 K. In the pseudogap state, the intensity of the peak in the FT was found to be largest and energy independent below 20 meV, whereas we find an energy dependence resembling the tunnel conductance. This discrepancy may be due to temperature broadening at 100 K. Another difference is that we find a $(4/3)a_0$ modulation in one direction. Such ordering was also seen by Hanaguri et al. [15] at low temperature in Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ with a main period of $4a_0$.

In this paper we evidence that the amplitude of the vortex core states has a four-fold structure directly reflecting the modulation observed in the vortex core. Since these states appear at an energy proportional to the gap $\Delta_\rho$, our results connect the superconducting state to the electronic modulation. We further find that the four-fold modulation has the same behaviour as in the pseudogap phase [13], what could be expected since the vortex cores display the pseudogap [9]. The relation between the pseudogap and the superconducting state has been the topic of many theoretical studies possibly leading to spatially modulated structures [19]. In particular, several authors have proposed that a pair density wave (PDW) is at the origin of the observed structures [21]. In the context of our study this model is attractive, since we establish a clear link between the superconducting state, the pseudogap and the square pattern in the vortex core. Within the PDW picture, this suggests that the localized states at $E \approx 0.3\Delta_\rho$ correspond to the lowest pair breaking excitations of the PDW. The relation between the localized states and the square pattern thus sets a critical test for these theories.

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