Unusual dependence of vortex core states on the superconducting gap in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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We present a scanning tunneling spectroscopy study on quasiparticle states in vortex cores in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. The energy of the observed vortex core states shows an approximately linear scaling with the superconducting gap in the region just outside the core. This clearly distinguishes them from conventional localized core states, and is a signature of the mechanism responsible for their discrete appearance in high-temperature superconductors. The energy scaling of the vortex core states also suggests a common nature of vortex cores in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ and YBa$_2$Cu$_3$O$_{7-\delta}$. Finally, the observed vortex core states do not show any dependence on the applied magnetic field in the range from 1 to 6 T.

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In conventional, s-wave superconductors, the suppression of the order parameter in a vortex core creates a potential well for low-energy quasiparticles, leading to the formation of localized states [1–3]. On the contrary, if the superconducting order parameter has nodes in it – as for $d_{x^2-y^2}$ symmetry in high-temperature superconductors (HTS) – one expects the low-energy quasiparticles in a vortex to be extended along the nodes of the gap function, so to be delocalized. This would result in a broad peak at the Fermi level in the quasiparticle local density of states (LDOS) of a vortex core [4–6]. In this light, the observation of discrete vortex core states in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) [7] and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) [8] by scanning tunneling spectroscopy (STS) has come as a complete surprise. As a result, the nature of these states has been subject of increasing theoretical study [9–12,14] leading to a range of possible scenarios for explaining the experimental data. The need for understanding of the electronic structure of the vortices in HTSs has become even more pressing because of the antiferromagnetic fluctuations recently observed in vortex cores in La$_{2-x}$Sr$_x$CuO$_4$ [17].

To our knowledge, the most direct way to access the electronic structure of a vortex core is by using a scanning tunneling microscope (STM). In a typical experimental set-up for studying vortex cores in HTSs (as well as in this study), the STM tip and tunneling direction are perpendicular to the CuO$_2$ planes. The quasiparticle excitation spectrum then follows from the $dI/dV$ tunneling spectra [18]. Experiments on HTSs have revealed the following characteristics of vortex cores. In YBCO the vortex core states appear as two clearly distinct, sub-gap excitations, which do not disperse on moving out of the vortex core, but rather transform into weak shoulders in the superconducting spectra (and sometimes also observed at zero magnetic field) [9]. In BSCCO the vortex core spectra reveal a remarkable resemblance to the pseudogap spectra observed above the critical temperature $T_c$ [9]. In addition, vortex core states appear as weak shoulders in this pseudogap, do not change in energy as a function of increasing distance from the vortex core [3] (contrary to the vortex core states in conventional superconductors [3]), and decay over a characteristic length scale of about 20 Å [9]. Though quite irregular shapes can be observed due to vortex motion [20], the cores do no show any sign of the four-fold symmetry that may be expected for d-wave superconductors.

In this letter, we present new data on vortex cores in BSCCO, obtained with a low-temperature STM. Our main results can be summarized as follows. First, the energy of the vortex core states scales with the superconducting gap outside the core, clearly distinguishing these states from localized vortex states ($E \sim \Delta^2/E_F$) in conventional superconductors [9]. Since in BSCCO the superconducting gap scales with the oxygen doping level [21] [22], this directly gives the doping dependence of the vortex states as well. Second, the vortex core spectra do not show any significant dependence on the external magnetic field over a range from 1 to 6 T, which questions field-dependent scenarios for explaining the vortex core states.

A systematic study of vortex core spectra requires, apart from sufficient instrumental resolution, relatively high sample homogeneity. More precisely, in order to compare spectra inside a vortex core to those in the nearby superconducting region, (zero-field) spectral reproducibility over at least 100 Å is necessary. This condition can be met in BSCCO single crystals with transition widths $\Delta T_c \leq 1$ K (as measured by AC susceptibility). Most of the data presented here were obtained,
with magnetic field and tunneling direction perpendicular to the CuO$_2$ planes, on two different overdoped samples: (i) A sample with $T_c = 77.7$ K ($\Delta T_c = 0.4$ K), cooled down at 6 T, and after measurements at 6 T the field was reduced (at low temperature) to 4 and 1 T. (ii) A sample with $T_c = 77$ K ($\Delta T_c = 1$ K), zero-field cooled, measured at fields of subsequently 0, 6, 2, and 0 T. For the latter sample, lines of spectra in and near vortex cores, as well as vortex images as a function of field can be found in Refs. [8,20]. Some additional data were taken on two other overdoped samples with $T_c = 76.1$ K ($\Delta T_c = 0.3$ K), and on an optimally doped sample with $T_c = 87.4$ K ($\Delta T_c = 1.0$ K). Samples were cleaved in ultra-high vacuum environment (10$^{-9}$ mbar), shortly before cooling down STM and sample to 4.2 K in exchange gas ($\sim$ 10$^{-2}$ mbar helium). All measurements in this study were taken at 4.2 K. For further experimental details we refer to Refs. [27–29].

The quasiparticle LDOS at an energy $E = eV$ on the surface of the sample was obtained by measuring the differential tunneling conductance $dI/dV$ at sample bias $V$ as a function of position, using a lock-in technique. In homogeneous BSCCO samples, clearest vortex images were found by measuring the conductance at $V = -\Delta_p/e$, where $\Delta_p$ corresponded to the energy of the superconducting coherence peaks. We thus obtained maps of spots where superconductivity was suppressed. A comparison of the number of these spots per area to the magnetic flux scales for the bias voltage.

In Fig. 1 we show a map of vortex cores at 6 T (field cooled measurement), taken by measuring the conductivity $dI/dV$ at -30 mV, and normalized on its value at zero field, justified the identification as vortex cores [19,24].

FIG. 1. Image of vortex cores at 6 T (field cooled measurement), taken by measuring the conductivity $dI/dV$ at -30 mV, and normalized on its value at zero field.

In order to study the dependence of the vortex core spectra on the superconducting energy gap (taken as the energy of the coherence peaks $\Delta_p$), we measured vortex core spectra on different samples, and also made use of a certain inhomogeneity (on a scale larger than 100 Å) of some of the samples which we would characterize as moderately homogeneous. (In fact large-scale homogeneity has also been obtained, using an optimum oxygenation procedure.) $\Delta_p$ has also been obtained, using an optimum oxygenation procedure.

In Fig. 2(a) we show a map of vortex cores at 6 T. As can be verified directly, the number of vortices (30 ± 2) in Fig. 1 corresponds to the average flux crossing this area (29Φ$_0$) at 6 T. In general, the density of vortices scales with the magnetic field as one should expect. We do not observe any systematic change in the size and shape of the vortex cores for the different applied fields.

$dI/dV$ spectra were taken in and around several of the thus imaged vortex cores. Spectra along a 200 Å trace through a vortex core are shown in Fig. 2(a). The spectra discussed hereafter were obtained by averaging the spectra just outside the core [above and below in Fig. 2(a)] and the spectra well inside the core [in the middle of Fig. 2(a)], for the superconducting spectra and the typical vortex core spectra respectively. These averaged spectra can be found in Fig. 2(b-d), for a vortex core at 1 T and for one at 6 T in BSCCO, as well as for a vortex core in YBCO [7].

Compared to the superconducting state, the LDOS in the vortex cores seems considerably reduced, with loss of spectral weight near the Fermi level. The characteristics of the vortex spectra in BSCCO, asymmetric pseudogap with weak shoulders at low bias, do not show any dependence on the field strength. We neither observe, within the experimental resolution, any change (due to the magnetic field) in the spectra outside the vortex core. The spectra taken at different field strengths are in fact remarkably similar, both those inside, and those around vortices.

FIG. 2. (a) Spectra along a 200 Å trace through a vortex core in BSCCO at 1 T. The vortex core is about halfway the trace. The spectra have been offset for clarity. (b) Averaged spectrum in the centre of this core, and in its immediate vicinity (dashed line). The latter spectrum may appear a bit broad, since it is the average of several spectra with peaks at slightly different energies. (c) For a vortex core in BSCCO, at 6 T. (d) For a vortex core in YBCO at 6 T. Note the different scales for the bias voltage.
For a precise and consistent determination of the energies of the core states, the vortex core spectra were fitted with a fifth order polynomial over a range $0.6\Delta_p < eV < 1.5\Delta_p$, with the fits forced to go through the zero-bias conductance. These fits of the pseudogap background were subtracted from the vortex spectra, thus leaving the excess spectral weight related to vortex core states. For the vast majority of vortices, the core state energies as determined from the fitted and subtracted data fall within the error bars of the core state energies determined directly from the raw data (see the arrows in Fig. 4). The latter are less precise because the core states are partly hidden in the slope of the pseudogap. The results have been checked for robustness against variation of the fitting parameters and range, and have been plotted on a normalized energy scale in Fig. 3.

**FIG. 3.** Spectra of vortex core states obtained by subtracting a fitted background (see text) from the vortex core spectra, plotted with an energy scale normalized on the energy of the coherence peak $\Delta_p$ of spectra near the core. There is no significant variation in the spectra for different magnetic fields and $\Delta_p$.

These data confirm the independence of the vortex states on the magnetic field, and also show that their energy $E_{core}$ directly scales with the superconducting gap. This scaling comes out even more clearly when $E_{core}$ is plotted as a function of $\Delta_p$, for all measured vortices in different samples and at different fields, see Fig. 4. The dependence on $\Delta_p$ is certainly not quadratic, as one would expect for conventional localized states in vortex cores. It is roughly linear, passing through the origin, and with a slope of 0.28. We have checked that the energies extracted from the raw data, with a bit more scattering of the data and a slope of approximately 0.30, do show the same behavior. This linear behavior is an important result, since it proves that the vortex core states in BSCCO do not correspond to conventional localized states.

Since doping dependent tunneling experiments on BSCCO show a roughly linear dependence of $\Delta_p$ on oxygen doping, we can directly read the horizontal scale as the (local) hole doping of the BSCCO samples, going from overdoped to underdoped. This indicates that the electronic nature of the vortex cores remains the same for a considerable doping range.

**FIG. 4.** The energy of vortex core states $E_{core}$ as a function of the superconducting gap (the energy of the coherence peaks) $\Delta_p$. Plotted are data for different magnetic fields, and different BSCCO single crystals. At $\Delta_p = 17$ meV the value extracted from YBCO data. The straight line is a linear fit to all data points, forced to go through the origin, with a slope of 0.28. An unrestricted linear fit would cut the vertical axis at about 1 meV, the latter value also being the uncertainty of the offset.

In Fig. 4 we have also included data obtained on YBCO, for comparison. Though the vortex core states in YBCO appear much more pronounced than those in BSCCO (see Fig. 3), their energy scale shows a remarkable similarity, strongly suggesting a common origin. It is tempting, but rather speculative, to compare this to the energy scale of the antiferromagnetic fluctuations with an energy of $3 \sim 4$ meV, for a spin gap of 6.7 meV, as observed in La$_{2-x}$Sr$_x$CuO$_4$.

Our results, especially the linear scaling of $E_{core}$ with $\Delta_p$, rule out conventional localized states as an explanation for the vortex core states observed in HTSs (they would neither be consistent with the lack of dispersion as a function of position, see Fig. 4). Furthermore, they provide sufficient details to discuss other scenarios.

First of all, in a pure $d$-wave superconductor the vortex core states would appear as a broad zero-bias conductance peak, in clear disagreement with experiment. One may avoid this difficulty by supposing that the quasiparticle states from different vortex cores form bands, which would lead to the splitting of the zero-bias conductance peak into two different peaks. In that case, however, the energy gap between these peaks should depend on the magnetic field, which is inconsistent with the results presented above.

A possible explanation for the observed vortex core states is the symmetry breaking of the order parameter...
in the vicinity of a vortex core. This will lead to secondary (possibly imaginary) $d_{xy}$ or $s$ components of the order parameter, effectively blocking the nodes of the $\Delta_{x^2-y^2}$ gap function, and allowing localized states. Though in a simple BCS $d$-wave superconductor these components are too small to influence the spectra, they appear more important when the Coulomb interaction on the Cu sites is taken into account. Numerical calculations using the $t-J$ model estimate their size strongly doping dependent to be between 5 and 30% of the $\Delta_{x^2-y^2}$ order parameter. Our results imply that such a secondary component would scale with the $\Delta_{x^2-y^2}$ gap over a wide doping range and, contrary to what one should expect, would be independent of the magnetic field between 1 and 6 T.

In this context, one may ask whether the observed core states are directly related to the vortices, or are merely enhanced inside the cores. In the secondary order parameter scheme, the latter possibility would mean that this secondary component is also present at zero field. In fact, low-energy features similar to vortex core states (though considerably less pronounced) have been observed in the gap of YBCO at zero field, and interpreted as the signature of an additional $s$ or $d_{xy}$ component in the order parameter in overdoped YBCO.

The energy scaling and field independence of the core states naturally suggest another scenario, involving the pseudogap state. Keeping in mind that the pseudogap above $T_c$ (and in the vortex cores) scales with the superconducting gap as well, one can speculate that the presence of the pseudogap leads to a splitting of the BCS $d$-wave zero bias conductance peak. This idea has been elaborated in two very recent calculations, using the two-body Cooperon operator for modeling phase fluctuations and invoking spin-density wave order in the vortex cores. The pseudogap being much more dominant in BSCCO than in YBCO, it will suppress the low-energy core states in the former material much more than in the latter, in agreement with our observations.

In conclusion, we have measured vortex core quasiparticle states as a function of the superconducting gap and the magnetic field. Their energy dependence on the superconducting gap near the vortex core is approximately linear, with a slope of about 0.28. The vortex core states do not show any dependence on the applied magnetic field in the range from 1 to 6 T. Our results suggest a common origin for vortex core states in YBCO and BSCCO. The linear energy scaling of these states with the superconducting gap, the lack of any dispersion as a function of distance from the vortex core centre, and the suppression of LDOS in the core compared to the superconducting state further underline the non-BCS behavior of HTSs, and of their vortex cores in particular.

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