Linear and Field-Independent Relation between Vortex Core State Energy and Gap in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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We present a scanning tunneling spectroscopy study on quasiparticle states in vortex cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$. 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 $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $YBa_2Cu_3O_{7-\delta}$. Finally, these states do not show any dependence on the applied magnetic field between 1 and 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 (HTSs)—one expects the low-energy quasiparticles states 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 $YBa_2Cu_3O_{7-\delta}$ (YBCO) [7] and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) [8,9] by scanning tunneling spectroscopy has come as a complete surprise. As a result, the nature of these states has been the subject of increasing theoretical study [4–6,10–16], leading to a range of possible scenarios for explaining the experimental data. The need for an 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 $La_{2-x}Sr_xCuO_4$ [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, subgap 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) [7]. In BSCCO the vortex core spectra reveal a remarkable resemblance to the pseudogap spectra observed above the critical temperature T_c [19]. In recent extensive studies, benefiting from more stable tunneling conditions, vortex core states appear as weak shoulders in this pseudogap. They do not change in energy as a function of increasing distance from the vortex core center [8] (contrary to the vortex core states in conventional superconductors [2]), and they 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 not show the fourfold 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 ($E \propto \Delta^2/E_F$) in conventional superconductors [1]. Since in BSCCO the superconducting gap scales with the oxygen doping level [21–26], 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 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 and (ii) a sample with $T_c = 77$ K

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($\Delta T_c = 1$ 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 an ultrahigh vacuum environment (10^{-9} mbar), shortly before cooling down the STM and the sample to 4.2 K in exchange gas ($\sim 10^{-2}$ mbar helium). The magnetic field and tunneling direction were perpendicular to the CuO_2 planes [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, the clearest vortex images were found by measuring the conductance at $V = -\Delta_p/e$, where Δ_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 for different fields, as well as their disappearance at zero field, justified the identification as vortex cores [19,20].

In Fig. 1 we show such maps of vortex cores at 1 and 6 T. As can be verified directly, the number of vortices (30 ± 2) in Fig. 1(b) corresponds to the average flux crossing this area ($29\Phi_0$) 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 for the typical vortex core spectra, respectively. These averaged spectra can be found in Figs. 2(b)–2(d), for vortex cores at 1 and 6 T in BSCCO, as well as for a vortex core in YBCO [7]). More and similar spectroscopic information, of regions with larger gaps, can be found in Ref. [8]. 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 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.

In order to study the dependence of the vortex core spectra on the superconducting energy gap (taken as the energy of the coherence peaks Δ_p), we measured vortex cores on different samples and also made use of variations of the gap (inhomogeneity on a scale >100 Å) in some of the samples. (In fact, large-scale homogeneity has also been obtained, using an optimum oxygenation procedure.) Δ_p has been determined from the average of spectra around the vortex core. The error in this Δ_p quantifies the variation of the gap width, due to inhomogeneity, in the immediate neighborhood of the core (50–100 Å from its center). It was determined from traces of spectra as in Fig. 2.

The data can be represented more clearly by normalizing the (low-bias part of) the spectra to the pseudogap background. The latter was determined by a smooth fit that follows the general shape of the spectra, but excludes the

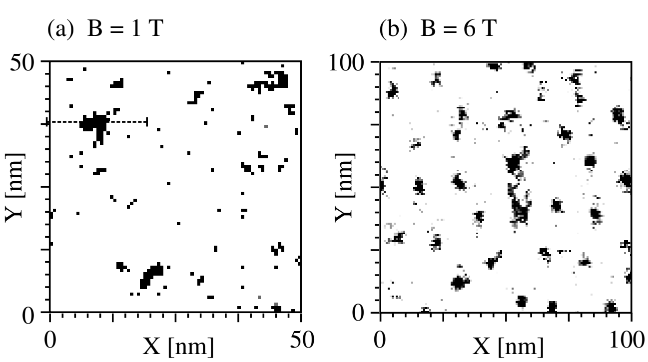

FIG. 1. Images of vortex cores at (a) 1 T and (b) 6 T (field cooled measurement; see text). (a) dI/dV at -40 mV, normalized to its value at -75 mV. The trace in Fig. 2 was taken at about (10, 38) nm. (b) dI/dV at -30 mV, normalized to its value at zero bias. Note the different scales in (a) and (b).

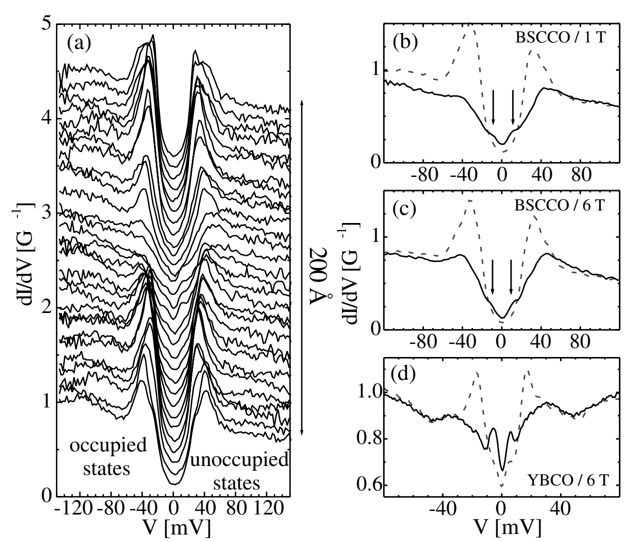

FIG. 2. (a) Spectra at 1 T along the 200 Å trace indicated in Fig. 1(a). The vortex core is in the center of the trace. The spectra have been offset for clarity, and V is the sample bias. (b) Averaged spectrum in the center of the core (solid line), and in its immediate vicinity (dashed line, superconducting gap). (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.

low-bias features. In practice this was achieved by a fifth order polynomial fit over a range $0.5\Delta_p < eV < 1.2\Delta_p$, forced to go through the zero-bias conductance. 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.

These data confirm the independence of the vortex states on the magnetic field and show that their energy $E_{\rm core}$ directly scales with the superconducting gap. This scaling comes out even more clearly when $E_{\rm core}$ [as determined from raw data, e.g., Fig. 3(a)] is plotted as a function of Δ_p in Fig. 4. The dependence on Δ_p is certainly not square-like, as one would expect for conventional localized states in vortex cores [1]. It is roughly linear, with a slope of 0.30, as determined from a linear fit through all BSCCO data and restricted to go through the origin ($\chi^2 = 0.19$, correlation coefficient $r = 0.81$). An unrestricted fit would cut the vertical axis at (1.5 ± 3.7 meV), for a slope of 0.26 (χ^2 and r the same as before, within the given precision). For comparison, a linear fit to $E_{\rm core}/\Delta_p$ as a function of Δ_p ($E_{\rm core} \propto \Delta_p^2$, through the origin) yields $\chi^2 = 0.55$, and a *negative* $r = -0.18$. This is an important result, because 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 Δ_p on oxygen doping [21–26], 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.

In Fig. 4 we have also included data obtained on YBCO, for comparison [7]. Though the vortex core states in YBCO appear much more pronounced than those in BSCCO (see Fig. 2), 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 3–4 meV, for a spin gap of 6.7 meV, as observed in $La_{2-x}Sr_xCuO_4$ [17]. A recent study of Pan *et al.* [9] indicated vortex core states in BSCCO at $E_{\rm core} = 7$ meV, for a gap of $\Delta_p = 32$ meV, on samples with transition widths of 4–5 K. Though the latter value implies that it may be difficult to obtain a uniform (at least over ~100 Å) Δ_p within error bars as indicated in Fig. 4, their results are consistent with our work (for a discussion on some small variations in the asymmetric pseudogap background, see Ref. [8]).

Our results, especially the linear scaling of $E_{\rm core}$ with Δ_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 of $E_{\rm core}$ as a function of position; see Fig. 2). 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 [4–6], in clear disagreement with experiment. One may argue 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 [10,11]. This will lead to secondary (possibly imaginary) d_{xy} or s components of the order parameter, effectively blocking the nodes of the $d_{x^2-y^2}$ gap function and allowing localized states [5]. Though in a simple BCS d-wave superconductor these components are too small to influence the spectra [6], they appear more important when the Coulomb interaction on

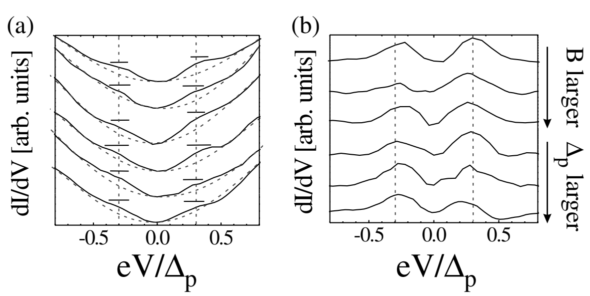

FIG. 3. (a) Vortex core spectra (solid lines) for different fields and gaps. From top to bottom: $B = 1, 2, 4, 6, 6$, and 6 T; $\Delta_p =$ (32 ± 2), (47 ± 5), (32 ± 1), (33 ± 2), (43 ± 2), and (52 ± 5) meV. The small horizontal lines indicate the errors in $E_{\rm core}$ used in Fig. 4. The vertical, dashed lines indicate $eV/\Delta_p = 0.3$, as follows for $E_{\rm core}$ from the fitting discussed below. (b) Normalized vortex core spectra, obtained by dividing the raw core spectra by fits to the pseudogap background [see text and dashed lines in (a)].

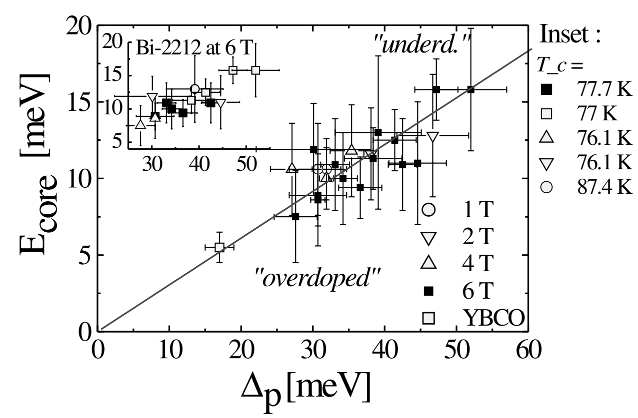

FIG. 4. The energy of vortex core states $E_{\rm core}$ as a function of the superconducting gap (the energy of the coherence peaks) Δ_p. Plotted are data for different magnetic fields and different BSCCO single crystals. At $\Delta_p = 17$ meV the value extracted from YBCO data. The straight line is a linear fit to all BSCCO data points, forced to go through the origin, with a slope of 0.30. In the inset again the BSCCO data at 6 T, distinguishing between the different samples (T_c).

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 [13,15]. 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 [6,16], would be independent of the magnetic field between 1 and 6 T.

The energy scaling and field independence of the core states suggest another possibility, which is yet to be explored in more detail. Keeping in mind that the pseudogap above T_c (and in the vortex cores) scales with the superconducting gap as well [22,25,26,30], one can speculate that the presence of the pseudogap leads to a splitting of the BCS d-wave zero bias conductance peak (ZBCP). Since the pseudogap does not fully suppress the spectral weight at low energy [19], it can leave some traces of the originally very pronounced ZBCP in the vortex core. This idea has been elaborated in two very recent calculations, using the two-body Cooperon operator for modeling phase fluctuations [31] and invoking spin-density wave order in the vortex cores [32]. 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 [31], in agreement with our observations (Fig. 2).

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 0.3. 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 variation (dispersion) of E_{core} as a function of distance from the vortex core center, 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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