Observation of the Low Temperature Pseudogap in the Vortex Cores of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Vortex cores in under- and overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ are studied by local probe tunneling spectroscopy. At the center of the cores, we find a gaplike structure at the Fermi level which scales with the superconducting gap, but no quasiparticle bound states. This low temperature pseudogap is intimately related to the superconducting gap and shows striking similarities with the normal state pseudogap measured above T_c. A possible interpretation is that both pseudogap structures reflect the same "normal" state containing phase incoherent excited pair states. [S0031-9007(98)05816-5]

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The understanding and description of the mechanism driving high temperature superconductivity is one of the major challenges in modern solid state physics. Since the experimental observation of this phenomenon in 1986, many models have been proposed. However, despite large efforts, the origin of high temperature superconductivity is still not known. What we know is that the superconducting state is built up of paired electron states and that there is strong evidence that at least in some of the compounds the pairing has a *d*-wave symmetry. A basic property of the classic BCS state of conventional superconductors is that the excited states are quasiparticles resulting from broken pairs. As a result, upon heating the pairs disappear simultaneously with the coherent superconducting state at T_c. This happens because the size of a pair given by the coherence length is much larger than the average distance between the pairs. In high temperature superconductors, the binding energy of a pair (Δ) is found to be much larger than in low temperature superconductors and, consequently, the coherence length ($\xi \sim 1/\Delta$) is approaching the average distance between the pairs. The question can, therefore, be raised if pairs can exist above T_c, either in the form of strong fluctuations or in the form of some kind of preexisting pairs [1]. The observation of a pseudogap above T_c [2,3] puts this question in a more acute form: Is this pseudogap a signature of such preexisting pairs or does it have a different origin?

In this Letter we address this question from a new perspective. We report here the first observation of vortices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) by the technique of scanning tunneling spectroscopy (STS). We focus, in particular, on the low temperature spectra inside the vortex cores, and we establish a direct connection between these spectra and the pseudogap observed above T_c. The samples investigated were oxygen underdoped ($T_c = 83.0$ K) and oxygen overdoped ($T_c = 74.3$ K) BSCCO single crystals similar to those we used for the temperature and doping dependence studies reported in Ref. [3]. Here we investigate these crystals at 4.2 K in a magnetic field applied perpendicular to the Cu-O layers. The tunneling spectroscopy is carried out using an Ir tip mounted perpendicularly to the (001) surface of BSCCO in a scanning tunneling microscope (STM). Experimental details are given in Refs. [4,5].

The tunneling microscope measures the local (quasiparticle) density of states (DOS) and the observation of vortices by STM is based on the fact that the local DOS is different inside and outside the vortex core. The first measurements of this type were performed by Hess *et al.* [6] on $NbSe_2$. More recently Maggio-Aprile *et al.* [7] reported the first STS observation of vortices on a high temperature superconductor, $YBa_2Cu_3O_7$ (YBCO). In spite of the excellent quality of the spectra obtained on BSCCO, it was so far not possible to observe the vortices on this material by STM. It turns out that the reason for this difficulty is that the spectra inside the vortices are, surprisingly, not very different from the zero field ones. In $NbSe_2$ [6,8] and YBCO [7], the sharpest vortex imaging contrast is obtained by mapping the conductivity at $+\Delta_p$ normalized to the conductivity at or near zero bias. However, the same procedure does not reveal any contrast in BSCCO. As will be clear from the spectra shown below, we have found that the sharpest contrast to map the vortex structure on BSCCO is obtained using the conductivity at a negative sample voltage $V = -\Delta_p/e$ to define the grey scale, where Δ_p is the peak position in the superconducting tunneling spectrum. In Fig. 1 we show such maps measured at 4.2 K in fields of 0 and 6 T. In the absence of a magnetic field, we find a uniform image reflecting the uniformity of the tunneling spectra over the surface. However, when a magnetic field is applied, dark areas corresponding to lower conductivity at $-\Delta_p$ appear in the image [Fig. 1(b)]. These areas do appear only when a magnetic field is applied, and their characteristic spectra are very different from those observed in degraded regions on the surface [5]. We, thus, identify them with the vortex cores. The vortices do not seem to arrange in a regular lattice. This is not unexpected since neutron studies have shown that the regular lattice disappears above an external field of 0.06 T even at low temperature [9]. However, the vortex density corresponds to the

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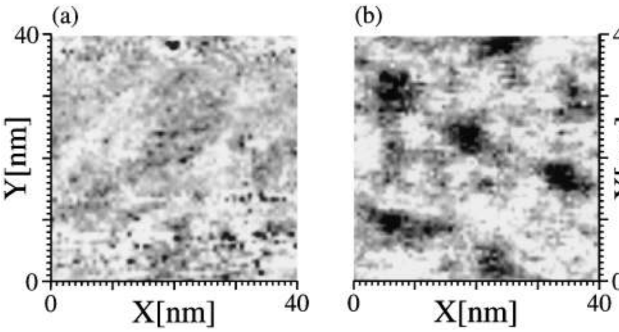

FIG. 1. STS maps of the conductance at $V = -\Delta_p/e$ at 4.2 K on overdoped BSCCO ($T_c = 74.3$ K); white and dark correspond to large and low conductance, respectively: (a) $B = 0$ T; (b) $B = 6$ T.

applied field, and their apparent diameter is consistent with the expected core size ($\sim 2\xi$).

Figure 2(a) shows a series of tunneling spectra taken at regular intervals along a 4.2 nm line starting at the center of a vortex and ending outside the core on BSCCO. As can be seen, when the tip enters the vortex core, the tunneling DOS becomes highly asymmetric. The peak at positive sample bias shifts towards a higher voltage, whereas the peak at negative sample bias just disappears simultaneously with the disappearance of the dip at $\approx -2\Delta_p$. Furthermore, at low bias, between the two peaks, the DOS does not change very much, and there is no sign of localized quasiparticle states inside the vortex cores as observed in $NbSe_2$ [6,8] and YBCO [7]. Many years ago, Caroli *et al.* [10] showed that there are localized quasiparticle states in a vortex core separated by an energy of the order Δ^2/E_F, with a minigap of the order Δ^2/E_F at the Fermi level. The pronounced zero bias peak observed by Hess *et al.* [6] at the center of a vortex core was identified as a signature of these low lying states. However, since the minigap in $NbSe_2$ is of the order of μeV, it was not possible to observe it directly. In contrast to the behavior of $NbSe_2$, the local DOS in the vortex core of YBCO shows split peaks at ± 5.5 meV, and these structures were interpreted as the signature of the first localized states with a minigap of 11 meV [7]. This interpretation implies that these vortex cores are in an extreme quantum limit which means that the size of the pairs in YBCO are of the order of the distance between the pairs. In Fig. 2(b) we show a series of spectra taken along a line going from the center of a vortex to a point in between the vortices in YBCO [7]. The comparison to the spectra in BSCCO is striking, although the zero bias conductivity in YBCO is much higher. There is hardly any difference in the low bias conductivity in BSCCO inside and outside the vortex cores, whereas in YBCO there is a clear signature of localized states. However, the behavior of the spectra around the peak positions $\pm\Delta_p$ looks very similar in the two compounds, and there may even be a similar asymmetry in this part of the spectrum at the vortex core in YBCO. Note that the energy scale in Figs. 2(a) and 2(b) differs by a factor of 2, reflecting the fact that the reduced gap $2\Delta_p/k_BT_c$ in BSCCO is typically a factor of 2 larger than the main peak position in YBCO.

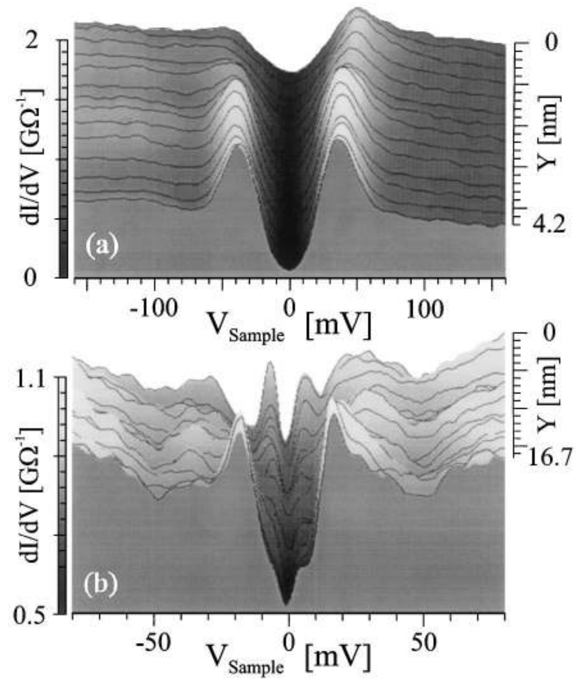

FIG. 2. Three dimensional view of tunneling spectra measured at equally spaced positions along a line extending from the center of a core ($Y = 0$) to a point located away from the vortices at 4.2 K and 6 T. (a) 4.2 nm trace on overdoped BSCCO ($T_c = 74.3$ K). (b) 16.7 nm trace on optimally doped YBCO ($T_c = 91$ K). Note the difference by a factor of 2 in the energy scales and the large zero bias conductance in YBCO.

There may be several reasons for the absence of quasiparticle states inside the vortex cores of BSCCO. One important fact is that the gap in BSCCO is larger than in YBCO, and based on the results of Caroli *et al.* [10], this would put the first localized state at a higher energy than in YBCO. Another element is the very probable *d*-wave character of the pair wave function in BSCCO. A vortex in a pure *d*-wave superconductor may possibly not contain any localized states as a consequence of the nodes in the gap function. This problem was investigated by Wang and MacDonald [11] who found that such a *d*-wave gives a zero bias peak in the vortex core spectra rather than the split peaks expected for an *s*-wave. However, we do not see any sign of a zero bias peak. If one takes into account that the pair wave function may have an *s*-wave component around a vortex even in an otherwise clean *d*-wave superconductor [12], one obtains split peaks [13] similar to what is observed in YBCO [7]. If BSCCO develops a similar component, we may understand the absence of a zero bias peak. In this case, the absence of the expected split peaks reflecting bound states at a higher energy below the gap may be due to the combination of the large gap values and the *d*-wave symmetry. However, neither of the above models explains the asymmetry of the structure inside the vortex core, nor explains why the peak at positive bias shifts continuously outwards as we approach the vortex center. Finally, one may argue that the crystals or their surfaces are approaching the dirty limit to explain the absence of quasiparticle states inside the vortex cores [14]. The difficulty with this argument is that there are a number of evidences, including the shape of the spectra we observe, that the superconducting gap in BSCCO has a *d*-wave symmetry. In this case we should have seen a reduced gap due to pairbreaking contrary to our observations. If BSCCO is, nevertheless, an *s*-wave superconductor, scattering should make it isotropic and we should have observed an *s*-like spectrum. Moreover, the dirty limit implies an extremely short mean free path [below 2 nm, see Fig. 2(a)], thus, we find this limit very unlikely.

A comparison with the temperature dependent measurements performed on similar single crystals [3] brings the vortex core spectroscopy on BSCCO into a different and exciting perspective. Indeed, the characteristic features of the pseudogap observed above T_c are precisely the ones we find for the DOS in the vortex core: Both the dip at $\approx -2\Delta_p$ and the peak at $-\Delta_p$ disappear, whereas, the peak at $+\Delta_p$ remains finite and shifts to a higher energy. The spatial dependence of the spectra at 4.2 K through a vortex core corresponds to the temperature dependence of the spectra in zero field through T_c as reported in Ref. [3], if appropriate thermal smearing is taken into account. Thus, we conclude that we are dealing here with the same pseudogap, and tunneling into the vortex core corresponds to a measure of the low temperature normal state DOS. To put this observation on more quantitative level, we compare in Fig. 3 the conductivity measured at the vortex center at 4.2 K and 6 T with the pseudogap measured above T_c in zero field. Figure 3(a) shows the spectra for the underdoped sample at 4.2 K inside and outside the vortex core, as well as the spectra observed in zero field at 88.7 and 98.6 K. The dotted curves are the 4.2 K vortex core spectra thermally smeared to 88.7 and 98.6 K, respectively. In Ref. [3] we found that the positive bias peak position shifts outwards over a finite temperature interval across T_c. At 88.7 K the peak position of the thermally smeared vortex core spectrum is slightly higher than the one actually measured at that temperature. However, at 98.6 K the peak in the spectrum above T_c has reached the same position as the smeared vortex core spectrum and the two spectra reflect basically the same shape. Figure 3(b) shows the same behavior for the overdoped sample. Thus, it appears that the local DOS measured at the vortex center is the normal state pseudogap structure and that the pseudogap structure measured above T_c is essentially the thermally smeared low temperature pseudogap structure. This implies that the pseudogap, like the superconducting gap seen by tunneling [3,15], is temperature independent. In Ref. [3] we concluded that the pseudogap scales with the superconducting gap as the doping is changed. Figure 3 clearly indicates that the same conclusion holds for the pseudogap seen in the vortex core: Comparing Figs. 3(a) and 3(b) one sees directly that the two gap structures scale with each other. Furthermore, from Fig. 2 it is clear that we do not have a situation where the superconducting peak at $+\Delta_p$ is simply reduced in intensity as one enters the vortex core and, thus, makes a higher energy peak appear. The two spectral features do clearly not coexist below T_c away from the vortex cores; the peak at $+\Delta_p$ really shifts towards a higher energy as was also found when the temperature is raised above T_c [3].

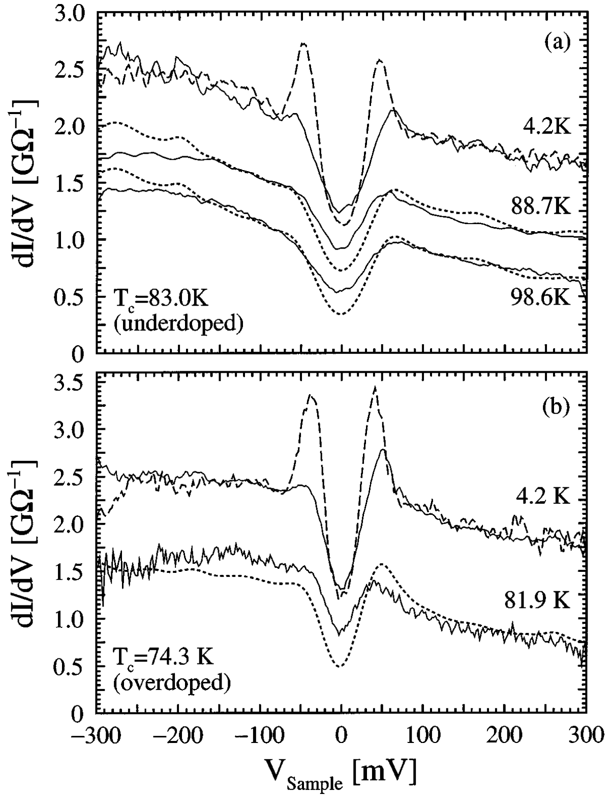

FIG. 3. Tunneling spectroscopy of BSCCO: The 4.2 K spectra were measured at 6 T at the center of a vortex core (solid line) and between vortices (dashed line). The spectra above T_c displayed as solid lines were measured in zero field and reflect the normal state pseudogap structure. The dotted curves were obtained by numerically smearing the spectra measured at the center of the cores at 4.2 K and 6 T to the temperature(s) indicated for each doping level. They illustrate the striking resemblance of the vortex core pseudogap and the normal state pseudogap. For clarity, the 4.2 K curves are offset by 1.0 $G\Omega^{-1}$ and the 88.7 K curves by 0.4 $G\Omega^{-1}$.

The striking correspondence of the vortex core spectra with the normal state pseudogap, the similarity of the low lying excitations inside and outside the vortex cores, as well as the temperature and doping dependence of the spectra reported in Ref. [3], have important consequences. If one would assume that the pseudogap had an origin different from superconductivity, for instance a charge density wave, then one would have to assume that superconductivity develops on top of a normal state spectrum with a gap of the same amplitude as the superconducting gap. Although this might happen, it would be difficult to understand why the two gaps follow each other closely as the doping is changed. One would normally expect the inverse to happen. It would also be necessary to explain why there is virtually no change of the low lying excitations as one goes from the normal (pseudogap) state to the superconducting state. Although one cannot exclude that some model, assuming the pseudogap to have an origin different from superconductivity, may explain all these facts, we are not aware of such models at this point. In any case, our results put serious constraints on such a model.

On the other hand, a picture involving some kind of preexisting pairs above T_c would be in agreement with our experiments if we anticipate that the energy to break such pairs is similar to the energy to create (two) quasiparticles in the superconducting state. Among the arguments in favor of this picture, we note first that the gap in BSCCO happens to be very large: For underdoped samples we find $2\Delta_p/k_B T_c = 10-12$. This suggests that at T_c the thermal energy may not be enough to break the pairs. Another important fact is that as the temperature is raised above T_c or as one moves across a vortex, the superconducting spectrum evolves in both cases smoothly into the pseudogap spectrum, with a superconducting gap being essentially the same as the pseudogap. Furthermore, the two gaps scale as the doping is changed. Note that if the pseudogap would merely reflect superconducting fluctuations, one would not expect the pseudogap to show up at low temperatures in the vortex cores. In order to understand why one would see the pseudogap in the vortex core, it is important to recall the absence of a signature of quasiparticle states inside the vortex core showing that the energy to create such quasiparticles may be very large. We, therefore, speculate that the normal core may be due to the presence of low lying excited pair states which are not phase coherent with the superconducting state around the vortices and are, thus, giving a spectral signature similar to the one from the pairs above T_c. Comparing these results with those obtained in YBCO [7], we believe that due to its larger gap, BSCCO may be an extreme case while YBCO may be an intermediate case between a more BCS-like (*d*-wave) superconductor and BSCCO. Evidence that the pairs are smaller in BSCCO than in YBCO is seen in Fig. 2. The size of the vortex, defined as the distance from the center to the point where the superconducting peaks at Δ_p are fully restored, is at least a factor of 2 larger in YBCO than in BSCCO, in agreement with the larger gap in BSCCO.

Concerning the asymmetry of the pseudogap spectra, we have pointed out earlier that the dip at $\approx -2\Delta_p$ in the superconducting spectra is asymmetric [5,16]. Indeed, no or only a faint [17] dip feature is seen near $+2\Delta_p$. Various explanations have been given for the existence of this dip. A particularly attractive explanation is that it is a result of (π, π) scattering of electrons in the vicinity of $(\pi, 0)$ and $(0, \pi)$ in the Brillouin zone [18]. The observed asymmetry would then arise from the asymmetry of this scattering when comparing occupied and unoccupied states around $(\pi, 0)$ and $(0, \pi)$. The asymmetry in the pseudogap spectra above T_c or in the vortex cores may possibly result from the same effect. In any case, it is a striking fact that as we go from the superconducting state to the pseudogap state, the spectrum evolves from nearly symmetric peaks, as expected in a BCS picture, to clearly asymmetric peaks. This asymmetry, thus, puts constraints on possible models for the pseudogap.

In summary, we have described first scanning tunneling spectroscopy studies of the vortex lattice in under- and overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. The striking result is that we observe no signature of quasiparticle bound states in the vortex cores, but instead we find a gap structure that has all the characteristics of the normal state pseudogap above T_c in zero field. We conclude that it is indeed the pseudogap at low temperature. Among possible interpretations, the one which appears most exciting is that both pseudogap structures reflect the same "normal" phase containing excited pairs instead of the quasiparticles inherent in the BCS theory.

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