Single superconducting energy scale in the electron-doped cuprate superconductor $Pr_{2-x}Ce_xCuO_{4-\delta}$

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The tunneling spectra of the electron-doped cuprate $Pr_{2-x}Ce_xCuO_{4-\delta}$ as a function of doping and temperature are reported. We find that the superconducting gap, Δ, shows a BCS-type temperature dependence even for extremely low carrier concentrations. Moreover, Δ follows the doping dependence of T_c, in strong contrast with tunneling studies of the hole-doped cuprates. From our results we conclude that there is a single superconducting energy scale in the electron-doped cuprates.

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In his pioneering experiment Giaever showed that when a simple metal and a classical superconductor are connected through an insulating barrier the tunneling conductance is proportional to the density of states in the superconducting electrode. He used this method to directly measure the energy gap, Δ, in various superconductors.[1] Giaever found that Δ drops to zero at the critical temperature T_c. In addition, for various materials Δ/kT_c is approximately constant as earlier predicted by Bardeen, Cooper, and Schrieffer (BCS). Their theory predicts a single energy scale that is both related to the onset of single-particle excitations (Δ) and the temperature, T_c, at which coherence is destroyed.[2]

In the hole-doped high T_c cuprates Renner *et al.*[3] showed that the spectra obtained by scanning tunneling spectroscopy exhibit no special temperature dependence at the temperature where macroscopic superconductivity, i.e., vanishing resistance and Meissner effect, ceases to exist. This behavior was interpreted as a signature of the pseudogap state, which can be detected in a variety of experiments.[4] The nature of this pseudogap and its relation to superconductivity are still a puzzle. It has been suggested that the pseudogap is precursor superconductivity,[5] a competing order parameter,[6] or a phenomenon related to the range of antiferromagnetic interactions.[7]

Deutscher[8] has pointed out that for the hole-doped cuprates there are two energy scales that merge together at high doping levels: the lower one, which follows T_c, is the phase-coherent energy scale, probed by Andreev-Saint-James reflections. The higher energy scale is related to single-particle excitations. It increases monotonically with decreasing doping. More recent contributions have confirmed Deutscher's observation of two energy scales for the hole-doped cuprates.[9–11]

The electron-doped and the hole-doped cuprates share many structural and electronic properties:[12] they both comprise copper oxygen planes, where *d*-wave superconductivity takes place.[13] The parent compounds are antiferromagnetic insulators, which become superconducting upon adding charge carriers (doping) in a dome-shaped region in the temperature-doping phase diagram. For the electron-doped cuprates the Fermi surface evolves from small electron pockets in the underdoped regime into a large holelike Fermi surface on the overdoped side.[14,15] For the hole-doped cuprates possible evidence for electron pockets were found in underdoped $YBa_2Cu_3O_{6.5}$ in quantum oscillation measurements.[16] Similar measurements on the overdoped side were interpreted in terms of large holelike Fermi surface.[17]

On the other hand, there are several differences between the two types of cuprates: while for the hole-doped side the antiferromagnetic phase disappears rapidly with doping, it is relatively extended on the electron-doped side, possibly persisting into the superconducting dome.[18,19] The temperature dependence of the resistivity well above T_c is very different for the hole-doped and the electron-doped cuprates.[12] Finally, possible existence of higher harmonics in the order parameter for the electron-doped superconductors has been reported by several groups.[20–22]

For the hole-doped cuprates the pseudogap and the superconducting gap coexist both in the doping and the momentum space, they intermix for many spectroscopic probes (an exception is Andreev-Saint-James reflections that are sensitive only to the superconducting state). The superconducting state may possibly be obscured by the pseudogap for underdoped samples for most momentum directions. By contrast, the superconducting gap is not obscured by the pseudogap for the electron-doped cuprates. Therefore, the superconducting gap in the electron-doped cuprates can be measured directly by tunneling spectroscopy.

We make use of the absence of a pseudogap phase in the electron-doped cuprates to directly measure the full doping and temperature dependence of the superconducting gap. We show that for these compounds there is a single superconducting energy scale, Δ, which follows the same doping dependence as T_c for the entire phase diagram, even for the heavily underdoped region (samples with T_c as low as 6 K). Assuming that the two types of cuprates share the same mechanism responsible for superconductivity, our results may imply that the pseudogap state in the hole-doped cuprates is a competing order to the superconducting one.

We fabricated superconductor/insulator/superconductor (SIS) junctions using $Pr_{2-x}Ce_xCuO_{4-\delta}$ (PCCO) and lead as described elsewhere.[22,23] The advantage of planar tunnel junctions is using the ability to measure the SIS tunneling conductance at various temperatures and magnetic fields without changing the properties of the junction. This is in

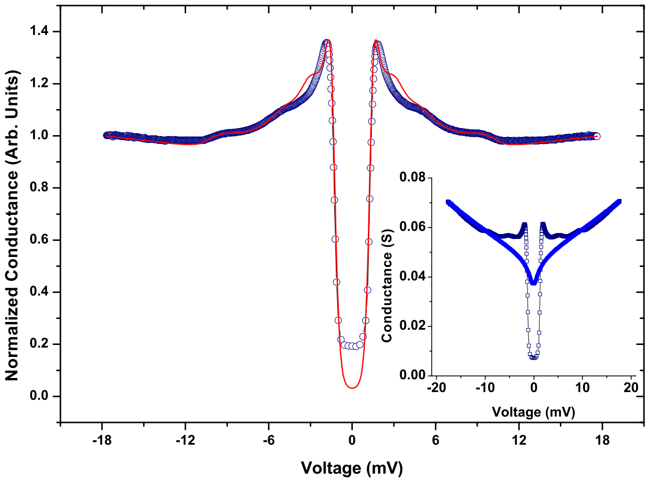

FIG. 1. (Color online) Tunneling spectra of heavily underdoped PCCO $x=0.125$ at $T=2$ K. The circles are the normalized data and the solid line is a fit (see text for detail) with $T_c=6.5\pm0.5$ K. We obtained $\Delta_{(max)}=1.5\pm0.3$ meV, $\Gamma=0.85\pm0.05$ meV, $Z=8$, $\theta_{(max)}=40°\pm10°$, $\mu_0H_{C2}=1.5\pm0.5$ T, and $2\Delta/K_BT_c=5.4\pm1.1$. Inset: a plot of the differential conductance at zero magnetic field (□) and at $\mu_0H=14$ T (△), which is used to normalize the data.

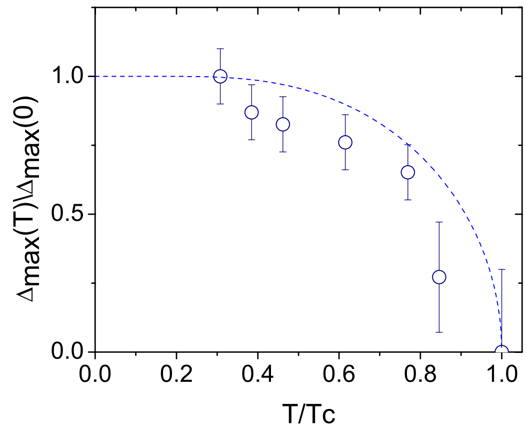

FIG. 2. (Color online) Reduced gap amplitude of the PCCO $x=0.125$ plotted as a function of the reduced temperature. The circles are the reduced gap amplitudes at different reduced temperatures as found from each fit. The dashed line is the BCS prediction.

strong contrast with scanning tunneling microscopy measurements, where a change in temperature or magnetic field may result in junction resistance variation due to its exponential dependence on tip-sample distance. At high magnetic fields, $\mu_0H=14$ T, superconductivity in the PCCO is muted and the normal state is revealed. This enables us to normalize the data as was done by Giaever.[1] This eliminates spurious barrier and normal-state effects. This procedure is impossible for the hole-doped cuprates due to its inaccessible upper critical field.

The conductance versus voltage for a typical underdoped $x=0.125$ junction is shown in Fig. 1. The strong phonon structure of the lead (at ±5 meV and at ±10 meV), and the relatively low conductance at zero bias are indicative of the high quality of the junctions. The inset of Fig. 1 presents the differential conductance as a function of voltage at zero field and at an applied field of 14 T. At high magnetic fields a small reduction in the zero-bias conductance is revealed. This behavior has been reported in other tunneling measurements on the electron-doped cuprates.[23–26]

We fit the data using a Blonder-Tinkham-Klapwijk[27] model extended for anisotropic order parameters.[28] We used a modified d-wave gap, which was suggested for the electron-doped cuprates.[21,29] This modified d-wave gap better fits the Raman,[21] angle-resolved photoemission spectroscopy (ARPES),[20] and tunneling[22] spectra. In this model the gap has a maxima away from the $(\pi,0)$ at an angle $\theta_{(max)}$. We used Z, Δ, $\theta_{(max)}$ and Γ as free parameters, with Z being the barrier strength and Γ being the lifetime broadening.[30] More detail on the fitting procedure are described elsewhere.[22]

We emphasize that the gap amplitude, which is the main focus of this contribution, is independent of the details of the order parameter chosen for the fit. The gap amplitude is determined predominantly by the energy at which the coherence peaks appear at low temperatures.

In Fig. 2 we show the temperature dependence of the gap maximum as found from fitting the tunneling spectra at various temperatures for the PCCO $x=0.125$ sample. We point out that all fitting parameters are determined at the lowest temperature, leaving the gap amplitude as the only temperature-dependent fitting parameter. For comparison the BCS prediction is shown. This result is similar to the temperature dependence reported for higher dopings.[22,31]

In Fig. 3 we present the obtained gap amplitude at low temperatures as a function of doping. This is the main result of this paper. We note that the gap decreases when decreasing the doping toward the underdoped regime.

Our result is in strong contrast with scanning tunneling spectroscopy data on the hole-doped cuprates.[32] To better understand the similarities and differences between the two types of cuprates we shall now discuss the various gap spectroscopies on the hole-doped cuprates, and compare their findings to our results on the electron-doped PCCO. Following Deutscher[8] and the recent ARPES measurements,[9] the various results fall into two classes: The first class of experi-

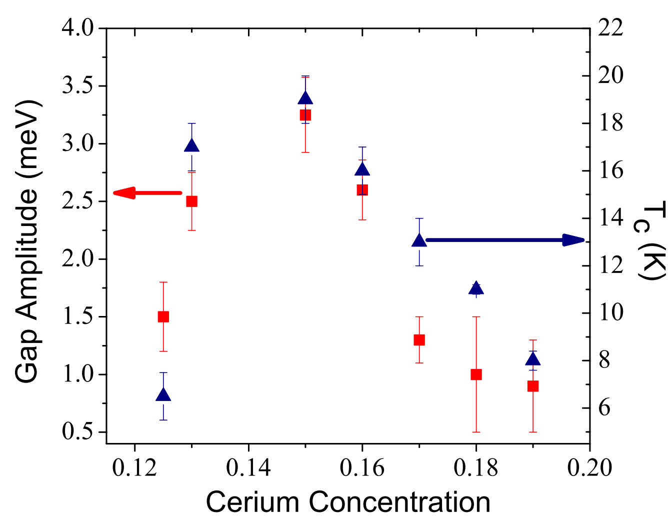

FIG. 3. (Color online) The obtained gap amplitude as a function of doping (□). The critical temperature as a function of doping (△).

ments includes probes that are mostly sensitive to $(\pi,0)$ or antinodal direction. The second class includes experiments that are sensitive to the nodal direction (π,π). Experiments that belong to the first class such as Raman scattering in the B_1g channel, most scanning tunneling spectroscopies and most angle-resolved photoemission spectroscopy experiments report a gap that increases with decreasing doping on the underdoped side. This is the **k** direction at which the pseudogap is maximal.[33] Scanning tunneling spectroscopy experiments in their common configuration, i.e., the tip being perpendicular to the CuO_2 plane, are mostly sensitive to the antinodal momentum direction. In this configuration, at zero bias one can tunnel only into the nodal direction in which the gap (and the pseudogap) is zero. As the energy is increased the momentum cone opens up and the measurement is dominated by momenta away from the nodal direction. For this reason the gap features in scanning tunneling spectroscopy arise mainly from the antinodal direction in the momentum space. It is, therefore, not surprising that for the hole-doped cuprates the gap amplitude measured by scanning tunneling spectroscopy increases with decreasing doping on the underdoped side,[32] as observed for all measurements that probe momenta along the antinodal direction. One should therefore bear in mind that for the hole-doped cuprates a measurement of the gap by tunneling or ARPES is not necessarily a measurement of the superconducting order parameter.

On the other hand Raman B_2g channel and the slope of the penetration depth as a function of temperature are both mostly sensitive to the nodal direction. Such nodal sensitive measurements show a gap that follows the doping dependence of T_c on the hole-doped side of the phase diagram.[8]

We can, therefore, conclude that for the hole-doped cuprates probes exciting single particles such as Raman scattering, angle-resolved photoemission spectroscopy, or tunneling can probe the superconducting gap depending on their momentum selectivity, i.e., the superconducting gap is observed for the nodal direction, while the pseudogap dominates for the antinodal one. This picture is consistent with recent ARPES measurements focusing on the nodal region of $Bi_2Sr_2CaCu_2O_{8+\delta}$.[9] Andreev-Saint-James reflections exhibit a similar doping dependence as the nodal sensitive probes, and can, therefore, be associated with the second class.[8]

Indeed, a tunneling study into the nodal direction of the hole-doped cuprate $YBa_2Cu_3O_{7-\delta}$ showed a gap that decreases with doping on the underdoped side.[34] This is consistent with the idea that when probing the nodal direction, one is sensitive solely to the superconducting energy gap. Such measurements that are sensitive to nodal momenta give similar doping dependence for the gap as Andreev-Saint James reflections that are only sensitive to the coherent state.

Our results in the electron-doped cuprates of an order parameter that follows a BCS temperature and doping dependence are, therefore, in line with nodal gap measurements in the hole-doped cuprates. This suggests that the energy scale relevant for superconductivity measured in our experiment by simple tunneling experiment is related to the nodal energy scale found in the hole-doped cuprates.

In summary, we present tunneling spectra measurements on lead/insulator/$Pr_{2-x}Ce_xCuO_{4-\delta}$ junctions over the entire doping range where superconductivity is observed in PCCO. From these spectra we extracted the gap amplitude for each doping and at various temperatures. Our results show a BCS-type temperature dependence for the superconducting gap even in the much underdoped regime. We show that the gap amplitude follows the doping dependence of the critical temperature T_c. This is in strong contrast with the celebrated doping dependence of the pseudogap for the hole-doped cuprates. Our results are, therefore, consistent with a single superconducting energy scale.

We can further assume that the hole-doped and electron-doped cuprates share the same mechanism for superconductivity. In addition, one can note that for the hole-doped cuprates the gap probed by Andreev-Saint-James reflections or by spectroscopy sensitive to the nodal direction follows the same doping dependence as our tunneling gap. We therefore conclude that for the hole-doped cuprates the nodal gap is related to superconductivity, while the pseudogap may be a competing order.

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