Andreev reflection in Au/La$_{2-x}$Sr$_x$CuO$_4$ point-contact junctions: separation between pseudogap and phase-coherence gap

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We made point-contact measurements with Au tips on La$_{2-x}$Sr$_x$CuO$_4$ samples with 0.08 $\leq x \leq 0.20$ to investigate the relationship between superconducting gap and pseudogap. We obtained junctions whose conductance curves presented typical Andreev reflection features at all temperatures from 4.2 K up to $T_c^A$ close to the bulk $T_c$. Their fit with the BTK-Tanaka-Kashiwaya model gives good results if a $(s+d)$-wave gap symmetry is used. The doping dependence of the low temperature dominant isotropic gap component $\Delta_c$ follows very well the $T_c$ vs. $x$ curve. These results support the separation between the superconducting (Andreev) gap and the pseudogap measured by angle-resolved photoemission spectroscopy (ARPES) and tunneling.

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The possibility of an experimental investigation of the relationship between superconducting gap and pseudogap in high-$T_c$ cuprates directly arises from the hypothesis, first suggested by G. Deutscher, of a really different nature of these two energy gaps. Nowadays the idea is becoming more and more accepted that the pseudogap is a property of the normal state, maybe a precursor of the opening of the superconducting gap which is due to the achievement of the phase coherence in the condensate. Thus, different spectroscopic tools can be used to detect them. Andreev reflection, being strictly related to the phase coherence, is a probe of the superconducting state and therefore can be used to measure the coherence gap. On the contrary, tunneling and angle-resolved photoemission spectroscopy (ARPES) are expected to be able to detect the energy gap in the quasiparticle excitation spectrum, even in the absence of phase coherence.

In the particular case of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), few experiments have been performed to investigate the Andreev gap, while some tunneling and ARPES evidences exist supporting a monotonical increase of the low-temperature gap amplitude at the decrease of doping.

In this paper we present a thorough study of the doping and temperature dependence of the superconducting gap in LSCO extracted from the conductance vs. voltage curves of point-contact junctions between Au tips and LSCO polycrystalline samples with six different Sr concentrations ranging from strongly underdoped ($x=0.08$) to slightly overdoped ($x=0.20$).

Details on the sample preparation are given elsewhere. The good quality of the LSCO samples was evidenced by XRD powder diffraction and EDS microprobe analysis. AC susceptibility and resistivity measurements gave bulk critical temperatures in good agreement with the standard curve of $T_c$ vs. $x$ for LSCO. The Au tip was obtained by electro-chemical etching with HNO$_3$+HCl of a 0.2 mm diameter Au wire.

Figure 1 shows some representative low-temperature $I$-$V$ characteristics (solid lines) obtained in samples with $x=0.08$ (a) and $x=0.12$ (b), together with the $dI/dV$ vs. $V$ curves (dashed lines).

Figure 2 reports an example of the low-temperature conductance curves (open circles) for the six values of $x$ here considered, normalized so that $dI/dV$=1 in the normal state, and vertically shifted for clarity.

These curves and all the others presented in the following were actually selected among a great number of data sets. We fixed selection criteria so as to ensure that the measurement was spectroscopically meaningful and that the result was not affected by spurious effects. In particular, we required the absence of any voltage-dependent heating effect and the thermal stability of the junction. In principle, comparing the conductance curves to those predicted by the BTK model provides by itself a good probe of the fulfillment of the ideal measurement conditions. Our experimental curves are indeed fairly similar to the ideal BTK ones obtained with a finite potential barrier, although their maximum value is less than that expected and the shape is not always compatible with a pure $s$-wave gap symmetry. The oscillations of $dI/dV$ at $|V| \geq 10$ mV are not “classic” as well, but are often observed in high-$T_c$ compounds.

The absence of heating effects is a key point of our discussion. As well known, point-contact measurements give reliable spectroscopic information provided that the contact radius $a$ is smaller than the mean free path $\ell$ in both materials (ballistic regime). Since any control on the contact dimension is impossible from the experimental point of view, one usually evaluates $a$ from the normal-state junction resistance $R_N$. In our case, the values of $R_N$ reported in Fig. 2 give 146Å $\leq a \leq$ 800Å, whereas the (evaluated) mean free path $\ell$ ranges from 40 to 70Å from underdoped to overdoped. These values...
FIG. 1: (a) An example of the $I$-$V$ characteristics of a point-contact junction between the Au tip and a LSCO sample with $x=0.08$ (solid line), together with the relevant $dI/dV$ vs. $V$ curve (dashed line). (b) The same as (a) but in the case of $x=0.12$.

FIG. 2: The normalized conductance curves (open circles) of Au/LSCO point-contact junctions for various doping levels (0.08 $\leq x \leq$ 0.2) at low temperature (4.22 K $\leq T \leq$ 5.61 K). The curves are vertically displaced for clarity. The solid lines represent the best-fit curves calculated by using the BTK-T-K model. The parameters of each theoretical curve are indicated in Table I.

FIG. 3: Qualitative doping dependence of the superconducting Andreev gap (solid circles) roughly evaluated as described in the text. The trend of the superconducting gap is compared to that of the tunneling gap reported in literature [1].

would rather indicate that the contact is in the thermal (Maxwell) regime, characterized by strong heating phenomena. Nevertheless, in the curves we chose the variation of the normal-state conductance with bias is very small and well within that expected in the ballistic regime [12]. The exceedingly low contact resistances are thus very likely to be due to the presence of several parallel ballistic contacts between sample and tip [13]. Anyway, there’s no doubt that the features shown in Fig.s 1 and 2 can only be produced by Andreev reflection at the S-N interface.

Even at a first glance, the curves in Fig. 2 show that the gap amplitude increases up to a maximum and then decreases again when one moves from underdoped to overdoped samples. The simplest way of evaluating the gap is to identify its edges with the positions of the conductance maxima. The resulting gap values are shown in Fig. 3 as a function of doping, together with those measured by tunneling [4]. The two measures almost coincide in the overdoped region, but differ more and more when the doping is reduced.

To investigate in greater detail the doping dependence of the Andreev gap, we compared the experimental curves to the theoretical ones predicted by the BTK-Tanaka-Kashiwaya model [14], in which we also introduced the quasiparticle lifetime broadening $\Gamma$. If one restricts the analysis to the low-temperature data of Fig. 2, different possible symmetries of the order parameter ($s$, $s+d$, $s+id$, anisotropic $s$) give curves which agree almost equally well with the experimental ones. Actually, no experimental probes sensible to the gap symmetry support an anisotropic $s$-wave symmetry in LSCO, and therefore we won’t consider it.

Further information about which gap symmetry is the most suitable for the fit can be found in the temperature dependence of the conductance curves. An example of this dependence for three different doping contents ($x =$
0.08 (a), $x = 0.10$ (b) and $x = 0.20$ (c)) is shown in Fig. 4, which actually reports for clarity only some of the curves we measured.

First of all, a result worth to mention is that the Andreev features always disappear at a temperature $T_c^\Delta$ close to the bulk $T_c$ or slightly lower. At $T > T_c^\Delta$, the conductance curves are identical to those expected in a N-N point-contact ballistic junction [12]. The fact that Andreev reflection gives no evidence of gap above $T_c^\Delta$ (N-N point-contact ballistic junction [12]). The fact that Andreev reflection gives no evidence of gap above $T_c^\Delta$ confirms that it measures the “true” superconducting gap, due to the phase coherence.

The information on the gap symmetry we were looking for can be obtained by fitting the conductance curves in the whole temperature range (from 4.2 K up to $T_c^\Delta$) with the BTK-T-K model. The free parameters, in the general case of mixed symmetry, are: the isotropic and anisotropic gap components ($\Delta_s$ and $\Delta_m$), the parameter $Z$ (proportional to the potential barrier height), the lifetime broadening $\Gamma$ and the angle $\alpha$ between the $a$ axis and the normal to the S-N interface [14] ($\alpha$ is unknown because our samples are polycrystalline). Actually, some constraints reduce the number of adjustable parameters. First, since $R_N$ changes very little with $T$, we assumed $Z$ to be constant and we extracted it from the fits in the various symmetries of the lowest-temperature curves. We obtained very low values of $Z$ ($\lesssim 0.3$), which make the choice of $\alpha$ have little influence on the values of $\Delta_s$ and $\Delta_m$ determined by the fit, independently of the symmetry used [14]. Therefore, we could choose $\alpha = 0$ without loss of generality. The remaining parameters $\Delta_{is}$, $\Delta_{im}$ and $\Gamma$ were varied in order to fit the data, but always keeping $\Gamma$ as small as possible.

A good agreement between the theoretical curves and the experimental data in the whole temperature range is only obtained if a ($s + d$)-wave gap symmetry is used [3]. This provides the missing information about the symmetry to be used for the fit at low temperature, and allows us to refine the rough evaluation of the doping dependence of the gap sketched in Fig. 3. The ($s + d$)-wave theoretical curves which best fit the low-temperature data in Fig. 2 are shown in the same figure as solid lines. The results are consistent with those obtained in LSCO by Deutscher et al. [2]. Although the general symmetry is $s + d$, for some values of $x$ the weight of the $d$ component is zero - that is, the actual symmetry is pure $s$-wave (but only at low temperature). In all cases the $s$-wave component is dominant and thus is the more representative one. Also notice that it is a very robust parameter, since its value would change very little if other gap symmetries were considered. Table I resumes all the values of the parameters related to the curves of Fig. 2.

In Fig. 5 the doping dependence of the low-temperature

![Figure 4: Temperature dependence of the normalized Andreev conductance in LSCO samples with $x = 0.08$ (a), $0.10$ (b) and $0.20$ (c).](image)

### Table I: Best-fit parameters and temperatures for the curves of Fig. 2.

| Doping | $T_c$ (K) | $\Delta_s$ (meV) | $\Delta_d$ (meV) | $\Gamma$ (meV) | $Z$ | $T_c^\Delta$ (K) | $2\Delta_s/k_B T_c^\Delta$ |
|--------|-----------|-----------------|-----------------|--------------|----|-----------------|-------------------|
| 0.08   | 4.22      | 3.4             | 2.5             | 0.19         | 0.20| 9.6             | 8.2               |
| 0.10   | 4.22      | 4.8             | 3.1             | 0.27         | 0.23| 25.3            | 4.4               |
| 0.12   | 4.22      | 5.6             | 0               | 0.92         | 0.18| 26.0            | 5.0               |
| 0.13   | 4.22      | 6.8             | 0               | 1.50         | 0.17| 29.1            | 5.4               |
| 0.15   | 4.65      | 6.8             | 0               | 0.44         | 0.08| 35.3            | 4.5               |
| 0.20   | 5.61      | 6.0             | 3.5             | 1.00         | 0.13| 27.9            | 5.0               |
FIG. 5: Doping dependence of the ARPES leading-edge shift (open circles, from Ref.[5]), of the tunneling gap (open squares, from Ref.[4]) and of our point-contact Andreev isotropic gap $\Delta_s$ (solid circles) in LSCO. The temperatures $T_{\Delta}^c$ at which the Andreev features disappear in our samples are also reported (up triangles) and compared to the $T_c$ vs $x$ curve from Ref.[8] (solid line).

$\Delta_s$ (solid circles) obtained from our fit is compared to those of the ARPES leading-edge shift (LE) recently determined in LSCO [5] (open circles) and of the gap determined by tunneling measurements (open squares) [4]. The doping dependence of the isotropic gap component $\Delta_s$ determined by the fit of our Andreev data confirms our previous evaluation. In fact, it follows surprisingly well the $T_c$ vs $x$ curve (thick solid line) [8]. On the contrary, both the ARPES LE and the tunneling gap increase monotonically at the decrease of $x$ and, in the underdoped region, reach values very larger than those of the superconducting gap. As a further support to our results, the Andreev gap almost coincides with the tunneling gap in overdoped samples.

In conclusion, we found that the gap measured by Andreev reflection spectroscopy in LSCO closes at $T_c$, and we obtained a spectroscopic information supporting a mixed $s + d$-wave symmetry for the order parameter in LSCO. Finally, we found that the doping dependence of the isotropic component of the low-temperature Andreev gap clearly follows the $T_c$ vs. $x$ curve, in contrast with both the tunneling gap and the ARPES LE.

In our opinion, these results support the separation between pseudogap and phase-coherence (superconducting) gap first claimed by Deutscher. Within this picture, the pseudogap is a property of the non-superconducting state of LSCO, independently of its origin. Although we make no hypothesis about the mechanisms which govern the opening of the pseudogap, our results are very well described by some models appeared in literature [13, 16].

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