



Observation of zero-bias tunneling conductance peak in underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-\delta}$

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Abstract

Scanning tunneling spectroscopy (STS) was performed on a -axis films of underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-\delta}$ ($x = 0.15, 0.125$), which were grown on LaSrAlO_4 substrates and ranged in T_c from 10 to 28 K. Pronounced zero-bias conductance peaks (ZBCP) with no detectable splitting were observed in the tunneling spectra at 4.2 K. These ZBCP closely resemble those seen by STS on optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals and films, and can be attributed to a predominantly d-wave pairing symmetry. Quantitative spectral analysis allows us to place a 5% upper limit on any out-of-phase subdominant order parameters, such as in the $d + is$ or $d + id'$ scenario. © 2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$; Pairing symmetry; Tunnel junctions spectroscopy; Zero-bias peak

Pairing symmetry has been central to the study of high-temperature superconductivity (HTSC) in the cuprates. It is now believed that most of the higher- T_c hole-doped cuprates have a $d_{x^2-y^2}$ pairing symmetry (for a recent review, see Tsuei [1]; also see van Harlingen [2]). To establish more closely the connection between the d-wave pairing and HTSC, it is important to determine whether the former persists in the lower- T_c hole-doped cuprates, such as $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-\delta}$ (LSCO), particularly away from optimal doping.

Tunneling spectroscopy has traditionally provided a sensitive measurement of the quasiparticle density of states. For a superconductor with d-wave pairing symmetry, recent studies have demonstrated that tunneling into the ab -plane is dominated by Andreev-bound resonance states, resulting in a zero-bias conductance peak (ZBCP) [3–7]. This work presents the first observation of tunneling ZBCP on slightly and highly underdoped a -axis LSCO films, with T_c ranging between 10 and 28 K. Quantitative spectral analysis allows us to place a 5% upper limit on the presence of any out-of-phase sub-

dominant order parameters, such as in the $d + is$ or $d + id'$ scenario [8,9].

The a -axis epitaxial films were grown by pulsed laser deposition on a -axis LaSrAlO_4 substrates. Details of the growth technique and sample characterization are given elsewhere [10]. The tunneling spectroscopy was taken at 4.2 K using a scanning tunneling microscope, with a Pt–Ir tip as counterelectrode [3,4]. The best spectral results were produced by first cleaning the films with Toluene. Junction impedances were $\approx 0.1 \text{ M}\Omega$.

Shown in Figs. 1(a) and (b) are the tunneling conductance data taken on the film samples with $x = 0.15$ ($T_c = 23 \text{ K}$) and $x = 0.125$ ($T_c = 15 \text{ K}$) respectively. The lower T_c is typical of a -axis films. A distinct ZBCP is seen in each of the spectra and, in the $x = 0.15$ case, flanked by a weak dip structure and a linear spectral background. The height of the ZBCP varied slightly on different places on each sample, though the width appeared rather invariant [11]. No splitting of the ZBCP was observed, to within the measurement resolution of $\approx 1 \text{ mV}$.

These ZBCP spectra closely resemble those seen by STS on optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) single crystals and films [3–5], and can be attributed to a predominantly d-wave pairing symmetry. To quantitatively

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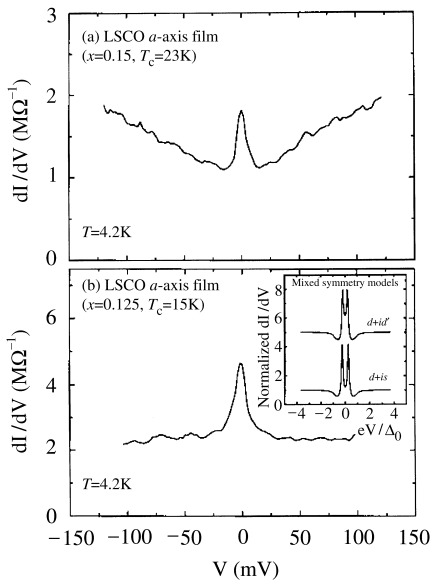


Fig. 1. Scanning tunneling spectroscopy data taken on LSCO *a*-axis films at 4.2 K for (a) $x = 0.15$, $T_c = 23$ K and (b) $x = 0.15$, $T_c = 15$ K. The inset in (b) gives the mixed symmetry spectral simulations showing the ZBCP splitting.

to assess the purity of the d-wave, we use the generalized Blonder, Tinkham and Klapwijk theory [12,13]. Shown in the inset of Fig. 1(b) are spectral simulations for the $d + is$ and $d + id'$ mixed symmetry scenarios, using the model parameters $Z = 1.5$, $\Delta_0 = 25$ meV, $s/d = 0.2$ and $d'/d = 0.2$ as described in Refs. [3,4] for comparison. It is clear that either of the out-of-phase subdominant order parameter would produce a ZBCP splitting by an amount corresponding to its magnitude. The absence of such splitting in our data indicates LSCO to have less

than 5% out-of-phase *s*- or *d*-wave relative to the predominant *d*-wave, in both the slightly and highly underdoped regimes. This is in disagreement with recent point-contact spectroscopy results suggesting either an $s + d$ or extended *s*-wave scenario for LSCO [14]. This is also in contrast to the observation of surface-induced time-reversal symmetry breaking on YBCO planar junctions [6], although the possibility for such broken symmetry in LSCO below 4.2 K or in a magnetic field cannot be ruled out. A systematic study of the ZBCP spectral variation is being undertaken to study if and how the *d*-wave pairing symmetry would vary across the entire phase diagram of temperature versus doping.

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