Nodeless Superconducting Phase Arising from a Strong ($\pi$, $\pi$) Antiferromagnetic Phase in the Infinite-Layer Electron-Doped Sr$_{1-x}$La$_x$CuO$_2$ Compound

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The asymmetry between electron and hole doping remains one of the central issues in high-temperature cuprate superconductivity, but our understanding of the electron-doped cuprates has been hampered by apparent discrepancies between the only two known families: $R$-Cu$_2$O$_2$ (RCCO), where $R$ is a trivalent rare-earth cation, Néel AF persists up to an electron doping of $x = 0.14$ [2,3] before $d$-wave SC sets in. On the other hand, studies of the only other known $n$-type family, $R$Ce$_{2-x}$Cu$_4$O$_8$ (SLCO), where $R$ is a trivalent rare-earth cation, Néel AF persists up to an electron doping of $x = 0.03$, with $d$-wave superconductivity (SC) following at higher doping levels. In the electron-doped ($n$-type) materials, however, the situation is less clear [1]. In the most studied $n$-type family, $R$Ce$_{2-x}$Cu$_4$O$_8$ (RCCO), where $R$ is a trivalent rare-earth cation, Néel AF persists up to an electron doping of $x = 0.03$, with $d$-wave superconductivity (SC) following at higher doping levels. In the electron-doped ($n$-type) materials, however, the situation is less clear [1].

In the hole-doped cuprates, it is well established that Néel antiferromagnetism (AF) is rapidly suppressed at a hole doping of $x = 0.03$, with $d$-wave superconductivity (SC) following at higher doping levels.

In order to establish a unified understanding of the electron-doped cuprates, we have synthesized epitaxially-stabilized thin films of SLCO [10,11] by oxide molecular-beam epitaxy and have probed their electronic structure in situ with high-resolution ARPES. Our results demonstrate not only that robust ($\pi$, $\pi$) AF is generic to the electron-doped cuprates, but that in SLCO the coupling of electrons to the AF is unusually strong, leading to a reconstruction of the Fermi surface (FS) in which the presumptive nodal hole pocket is pushed entirely below the Fermi energy ($E_F$). Removing the $d$-wave nodal states at $E_F$ from the normal state FS provides a natural mechanism for realizing nodeless SC without requiring a change in the symmetry of the order parameter away from $d$ wave.

SLCO possesses a number of favorable characteristics that make it an ideal candidate for the study of cuprate SC. First, the crystal structure of SLCO is comprised solely of flat CuO$_2$ planes separated by alkaline earth atoms and is devoid of chains, orthorhombic distortions, incommensurate superstructures, ordered vacancies, and other complications that abound among the other cuprate families. In addition, SLCO has the highest $T_c$ of all $n$-type cuprates, 43 K [13], and can also be hole doped to a $T_{c,max}$ of 110 K [14]. Finally, it lacks the large rare-earth magnetic moments present in RCCO, which have been shown to couple to the magnetism in the CuO$_2$ plane [15]. Epitaxial thin films of SLCO ($x = 0.10$) were grown on (110) GdScO$_3$ substrates using a Veeco GEN10 oxide molecular-beam epitaxy system [16]. Shuttered layer-by-layer deposition was performed in distilled O$_2$ at a background pressure of $1 \times 10^{-6}$ Torr and monitored with reflection high-energy electron diffraction. Immediately after growth, the films were oxygen reduced by vacuum annealing in the growth chamber and then transferred under ultra-high vacuum into the ARPES measurement...
chamber. Measurements were performed with a VG Scienta R4000 electron spectrometer and He-4α photons (21.2 eV) at a base temperature of 10 K. After ARPES, samples were characterized by x-ray diffraction, resistivity measurements using a Quantum Design Physical Properties Measurement System, x-ray absorption spectroscopy, and x-ray photoelectron spectroscopy.

In Fig. 1(a), we show a $k$-resolved map of spectral weight near $E_F$. A large circular Fermi surface centered at $(\pi, \pi)$, generic to all doped cuprates, is apparent. We extract Fermi wave vectors ($k_F$’s) by fitting maxima in the momentum distribution curves (MDCs) used to generate the map. After applying appropriate symmetry operations, the set of $k_F$’s are plotted as yellow points in the areas outside of the map. Also shown is a 2D tight-binding (TB) prediction for the FS. The parameters of the TB dispersion $(\mu, t, t', and t'')$ were generated by first constraining $\mu$ so that the electron filling was fixed at $x = 0.10$. Then $t'/t$ and $t''/t$ were varied to reproduce the shape of the FS predicted by band structure calculations (details can be found in the Supplemental Material in Ref. [17]). Finally, $t$ was adjusted to match the experimental high-energy dispersion in the nodal direction. The resulting TB parameters are $\mu = -6$ meV, $t = 215$ meV, $t' = -34$ meV, and $t'' = 43$ meV.

Assuming a quasi-2D FS, the experimentally determined $k_F$’s yield a Luttinger volume corresponding to $x = 0.09 \pm 0.02$, in agreement with the nominal doping level. Figures 1(b)–1(d) show a number of notable features of the data. First, the intensity is strongly modulated as a function of angle around the FS, a phenomenon originally observed in Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ [18]. Second, the location of spectral weight along the $(0, 0)$–$(\pi, \pi)$ nodal direction deviates significantly from the TB prediction, whereas the agreement is better in other areas of momentum space. Third, the MDC-derived nodal quasiparticle (QP) dispersion shows a clear upturn at a binding energy of about 40 meV.

To explain these features, we employ a simple model first proposed for the RCCO family [18–20] whereby electrons with wave vectors $k$ and $k + (\pi, \pi)$ are mixed via an off-diagonal matrix element $V_{\pi\pi}$. Despite the lack of explicit strong electron correlations, this model has been shown to be successful in reproducing the key low-energy features in the electronic structure of the RCCO family. The $V_{\pi\pi}$ term is assumed in this work to originate from static or slowly fluctuating AF. It could also arise from any sufficiently strong $(\pi, \pi)$ ordering, but the strong AF ordering in RCCO presents it as an obvious candidate. The term opens a gap of size $2|V_{\pi\pi}|$ at the intersection of the underlying band structure $e(k)$ with its image folded across the AF zone boundary $e'(k)$. The corresponding energies are

$$E \pm (k) = \frac{e(k) + e'(k)}{2} \pm \sqrt{\left(\frac{e(k) - e'(k)}{2}\right)^2 + |V_{\pi\pi}|^2}.$$

An illustration of this band structure is shown in Fig. 2(a). The gap results in so-called “hot spots” where spectral weight is dramatically suppressed, dividing the FS into two sheets: an electron pocket near the zone boundary at $(\pi, 0)$, and a hole pocket in the nodal region at $(\pi/2, \pi/2)$. This readily explains the observed intensity modulation displayed in Fig. 1(b).

For $V_{\pi\pi}$ sufficiently large (> 170 meV in our model), the nodal pocket is pushed entirely below $E_F$, leaving only an electron sheet around $(\pi, 0)$. Such behavior has been

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simulations of the model for V_{\pi\pi} > 170 meV, the nodal hole pocket is fully gapped. (b) Comparison of the experimental FS map and the simulation, neglecting final-state photoemission matrix elements. (c) Simulation of the experimental spectrum presented in Fig. 1(d). The white line shows the model's underlying band structure. (d) Nodal band dispersion, as determined by an MDC analysis. Dots are derived from the experimental data shown in Fig. 1(d) and the line is extracted from the simulation in panel (c) by an identical procedure.

reported for Sm_{1.86}Ce_{0.14}CuO_{4} [20] and Eu_{1.85}Ce_{0.15}CuO_{4} [21], and is consistent with our data. Figure 4(a) shows an AF-induced pseudogap in the energy distribution curve (EDC) at the node, and in Figs. 2(b)–2(d), we compare simulations of the model for V_{\pi\pi} = 190 meV with our data (details can be found in the Supplemental Material in Ref. [17]), where we find that a fully gapped nodal pocket is consistent with all of the other features of the data. The submergence of the nodal pocket shifts the near-E_{F} intensity toward (\pi/2, \pi/2), explaining the inconsistency highlighted in Fig. 1(c). Additionally, the upturn in the dispersion at 40 meV, as marked by the arrows in Figs. 1(d) and 2(d), is an artifact of the MDC analysis procedure in the presence of a gap and is commonly observed in other systems [22]; an identical MDC analysis of our simulation yields a similar upturn. If we revise our earlier Luttinger count assuming only small electron pockets in a folded zone (x vs 1 + x), we obtain a doping x = 0.10 ± 0.03, again consistent with our chemical composition.

The fact that in SLCO the Luttinger sum appears to agree using either the large hole pocket (1 + x) or small electron pocket (x) counting scheme reflects the fact that when using the 1 + x scheme, our MDC analysis still counts the nodal regions as forming part of the FS even though they are, in reality, gapped. In the absence of (\pi, \pi) order, this large circular contour would constitute the underlying FS with an area of 1 + x. This suggests that, at least for the purpose of counting the Luttinger volume, a simple mean-field spin-density-wave scenario appears to work for SLCO and the other electron-doped materials. This is in contrast with the hole-doped cuprates, where especially on the underdoped side there are major discrepancies in counting the doped carriers by ARPES using either an x or 1 – x picture [23]. This is likely related to the fact that in the most lightly electron-doped compounds, the low-energy states clearly form closed electron pockets around (\pi, 0), while in the lightly hole-doped materials, the contour of low-energy excitations appears to form a discontinuous "Fermi arc," which is more poorly understood and still a subject of debate. This suggests a fundamental difference between electron- and hole-doped cuprates, specifically in the nature of the FS and the integrity of states near (\pi, 0).

The ability to explain all experimental features using a simple model strongly suggests that the coupling of electrons to (\pi, \pi) order in SLCO results in a reconstructed FS that gaps the nodal pocket. This cuprate FS topology, comprised solely of small electron pockets, has been reported in numerous quantum oscillation measurements of YBa_{2}Cu_{3}O_{6+\delta} at high magnetic fields and may be relevant to those observations, particularly because such fields have been shown to stabilize AF [24,25].

By comparing the near-E_{F} spectral difference between the node and the hot spot, we can remove trivial temperature effects from the Fermi step and determine the temperature dependence due to the AF. Figure 3 shows this spectral difference as a function of temperature. Due to the presence of the AF gap, the intensity at the hot spot is dramatically reduced relative to the node over a 200 meV energy scale below E_{F}, and this suppression drops rapidly between 150 K and 250 K. Assuming that static AF order exists, this could be associated with the closing of the gap above the Néel transition. From our data, we estimate a characteristic transition temperature T^{*} = 220 ± 30 K. The similarity between our T^{*} and the Néel temperature T_{N} for other electron-doped cuprates suggests that the observed spectral change could arise from the Néel transition. We cannot, however, conclusively determine if the AF in SLCO is static or arises from fluctuating antecedent spin correlations.

Measurements of nonsuperconducting (as grown) Pr_{2-x}Ce_{x}CuO_{4} have shown a gapping of nodal states argued to arise from the presence of excess oxygen [26].
Our samples were oxygen reduced and confirmed to be superconducting by \textit{ex situ} transport measurements with \(T_c\)'s in the range 25 ± 5 K. In addition, in Fig. 4, measurements from two samples exhibiting clear SC gaps of \(\Delta = 1\text{–}2\text{ meV}\) on the electron pockets are shown, with the gap closing upon warming above \(T_c\). This gap value is consistent with RCCO, where \(\Delta = 2 \text{ meV}\) [27,28], and confirms that small gaps are generic to electron-doped cuprates. As argued above, the hole pocket does not possess strong coherent weight at \(E_F\) and thus exhibits only a trivial temperature dependence. The gapping of the hole pocket by AF therefore can naturally explain the numerous reports of fully gapped SC in SLCO [4–7] without needing to invoke a change in the symmetry of the order parameter from \(d\) to \(s\). This nodeless \(d\)-wave scenario has been proposed theoretically by Yuan \textit{et al.} [29] and Das \textit{et al.} [30], and coexisting AF and SC has been proposed theoretically by Sénéchal \textit{et al.} [31]. Because the momentum range spanned by the electron pockets is narrow, we do not observe any substantial gap anisotropy, nor can we unequivocally rule out the possibility of \(s\)-wave SC. A recent phase-sensitive measurement of SLCO, however, shows a \(d_{2s-\pi^2}\) symmetry of the SC order parameter [32]. Our results demonstrate that cuprate high-\(T_c\) SC can occur in a material with only electron-like carriers, coexistent AF, and without \(d\)-wave nodal QPs.

In conclusion, we have performed the first ARPES measurements on the infinite-layer cuprate \(\text{Sr}_{1-x}\text{La},\text{CuO}_2\). Based on the accuracy of our Luttinger count, the success of our simple model, and the observation of a SC gap at \((\pi, 0)\), we conclude that strong AF tendencies and SC coexist simultaneously and homogeneously in SLCO. Furthermore, the unusually strong coupling of electrons to \((\pi, \pi)\) AF results in a FS reconstruction comprised solely of electron-like carriers. SC is restricted only to electron pockets in SLCO, providing the first direct observation of high-\(T_c\) SC in a cuprate completely devoid of hole-like carriers, as recently proposed by theoretical calculations [29,30]. Furthermore, we have demonstrated that a gapping of the nodal states near \((\pi/2, \pi/2)\) by AF suppresses \(d\)-wave nodal QPs. This picture can provide a natural explanation of the earlier conflicting reports regarding the nature of SC in SLCO [4–9]. By performing the first direct measurements of the electronic structure of an \(n\)-type cuprate distinct from \(\text{Re}_{2-x}\text{Ce},\text{CuO}_4\), we have firmly established that robust AF and a small SC gap are intrinsic features of the electron-doped cuprates and not material specific.

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