Suppression of the antiferromagnetic pseudogap in the electron-doped high-temperature superconductor by protect annealing

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In the hole-doped cuprates, a small number of carriers suppresses antiferromagnetism and induces superconductivity. In the electron-doped cuprates, on the other hand, superconductivity appears only in a narrow window of high-doped Ce concentration after reduction annealing, and strong antiferromagnetic correlation persists in the superconducting phase. Recently, Pr1.3-La0.7Ce0.4CuO4 (PLCCO) bulk single crystals annealed by a protect annealing method showed a high critical temperature of around 27 K for small Ce content down to 0.05. Here, by angle-resolved photoemission spectroscopy measurements of PLCCO crystals, we observed a sharp quasi-particle peak on the entire Fermi surface without signature of an antiferromagnetic pseudogap unlike all the previous work, indicating a dramatic reduction of antiferromagnetic correlation length and/or of magnetic moments. The superconducting state was found to extend over a wide electron concentration range. The present results fundamentally challenge the long-standing picture on the electronic structure in the electron-doped regime.
Since the discovery of the cuprate high-temperature superconductors, one of the central issues has been the relationship between antiferromagnetic (AFM) order or AFM spin fluctuations and superconductivity. Starting from the AFM parent insulator, a small amount (~2%) of hole doping destroys the AFM ordering and superconductivity emerges. However, for the electron-doped high-temperature superconductors (e-HTSCs), the antiferromagnetism persists up to the optimum doping (~15%). In the underdoped region of e-HTSCs, a large pseudogap opens due to AFM order or AFM correlation as observed by optical measurements and scanning tunneling spectroscopy. Angle-resolved photoemission spectroscopy (ARPES) studies have shown that the pseudogap opens around the hot spots, namely, crossing points of the Fermi surface (FS) with the AFM Brillouin zone boundary in superconducting samples. A neutron scattering study has revealed that the AFM correlation length is of order ~10 lattice spacing in the superconducting phase, and the pseudogap in the ARPES spectra of the superconducting phase has been reproduced by assuming a similar AFM correlation length.

Since the discovery of the e-HTSCs, it has been well known that annealing in a reducing atmosphere is necessary to realize superconductivity. As-grown samples are non-superconducting and AFM. By annealing the AFM-phase shrinks, and superconductivity appears. Effects of annealing are still not fully understood on the microscopic level; a small amount of oxygen atoms at the apical oxygen site, which stabilize the AFM ordering, and/or those at the regular site (in the CuO2 plane or the LnO (Ln: rare earth) layer) are possibly removed by reduction annealing, while the discovery of secondary phase of Ln2O3, the AFM folding of the Fermi surface, namely, crossing points of the Fermi surface (FS) with the AFM Brillouin zone boundary in superconducting samples.

To study the effect of protect annealing on the electronic structure of PLCCO, we have performed ARPES measurements on single crystals of PLCCO with x = 0.10 under different annealing conditions (Methods section). For sufficiently annealed samples, a sharp quasi-particle (QP) peak was observed on the entire FS without signature of an AFM pseudogap unlike all the bands and increase the spectral intensity at Fermi level (E_F) but the AFM pseudogap has been seen in all the e-HTSCs from the underdoped to overdoped regions studied so far. Therefore, the AFM pseudogap has been regarded as a hallmark of the e-HTSCs and the relationship between antiferromagnetism and superconductivity has been considered as a more essential ingredient of the e-HTSCs than the hole-doped ones.

Figure 1 | Superconducting properties of PLCCO samples. (a) A typical phase diagram for a hole-doped cuprate La2−xSrxCuO4. The AFM, superconducting and spin-glass phases are denoted by AFM, SC and SG, respectively. (b) Critical temperatures (Tc’s) determined from the resistivity of PLCCO single crystals annealed by the conventional method reported by Sun et al. (open triangles). (c) Schematic description of the protect annealing method. (d) The same plot as a. (e) The same plot as b for protect-annealed single crystals reported by Adachi et al. (open circles, T. Adachi et al., unpublished). Tc was determined from magnetic susceptibility measurements. (f) Magnetic susceptibility of a protect-annealed PLCCO single crystal (x = 0.10) which shows the Tc of 27.0 K.

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previous studies, indicating dramatic reduction of AFM correlation length and/or of magnetic moments. By measuring the FS area, we also found that this superconducting state with suppressed antiferromagnetism was extended over a wide electron concentration range. The present study will call for a re-examination of the relationship between superconductivity and antiferromagnetism and of the phase diagram of the cuprate superconductors. Presented results for the annealed sample are those for annealed sample 1 with a $T_c$ of 27.0 K out of three protect-annealed superconducting samples unless otherwise stated.

**Results**

**Suppression of the AFM pseudogap.** Figure 1 shows the properties of the PLCCO samples. Although PLCCO with $x = 0.10$ did not show superconductivity in previous studies26 (Fig. 1b), samples protect-annealed as schematically described in Fig. 1c show high $T_c$ values as shown in Fig. 1e,f (For the superconducting properties, see Supplementary Fig. 1).

In Fig. 2a–c, FS mappings of as-grown, weakly annealed (non-superconducting) and annealed ($T_c = 27.0$ K) samples are shown. In the as-grown sample, the intensities are strongly suppressed around the hot spots due to the AFM order. The intensity partially recovers by the weak annealing, but the FS is still disconnected between the nodal and anti-nodal regions by the presence of the hot spots. This means that the weak annealing was not enough and the influence of AFM correlation still persists. However, in the sufficiently annealed sample, the suppressed intensities at the hot spots were fully recovered, and the entire FS became a continuous circular one. This very simple FS shape is very different from those reported in the previous studies on superconducting samples5, in which the intensity is suppressed at the hot spots like the weakly annealed sample reported in the present work. The change induced by the protect annealing is clear also in the band image plots (Fig. 2d–f), and corresponding energy distribution curves (EDCs; Fig. 2g–i) along the cuts through the node, the hot spot and the anti-node for each sample.

In Fig. 3a, EDCs are plotted along the FS for each sample. The as-grown and weakly annealed samples show a pseudogap between the node and the hot spot, and band splitting between

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**Figure 2** | ARPES spectra of PLCCO with and without protect annealing. (a–c) FS mappings of as-grown, weakly annealed and annealed samples, respectively. The intensity is integrated over $\pm 10$ meV of $E_F$. The suppressed intensities at the hot spots, the crossing points of the FS and the AFM Brillouin zone boundary, are fully recovered in the annealed sample. (d–f) Intensity plot in energy-momentum space for each sample along each cut indicated in a–c. (g–i) EDCs plotted for each cut. Blue EDCs are taken at $k_F$ positions. Peak positions are marked by vertical bars. The AFM pseudogap that is observed at the hot spots (cut 2) of the as-grown and weakly annealed samples is suppressed in the annealed sample.
QPs $\sim Z \text{Im} \Sigma_k (\epsilon)$, where $\Sigma_k (\epsilon)$ is the self-energy and $Z$ is the renormalization factor assumed to be constant in the low-energy region considered here, as a function of QP energy $\epsilon$, can be evaluated by multiplying the momentum distribution curve width $\Delta k$ by the Fermi velocity $v_F$ (Supplementary Note 1). Figure 4a shows thus obtained scattering rate $-Z \text{Im} \Sigma_k (\epsilon)$ of the annealed sample with $T_c = 27.2$ K (annealed sample 2) along the three cuts, those crossing the node, the hot spot and the anti-node (Cut 1, 2 and 3 in Fig. 2c). The dynamical (that is, energy-dependent) part of $-Z \text{Im} \Sigma_k (\epsilon)$ is also plotted at the bottom of Fig. 4a.

We consider two possibilities that the QP created by photoemission is scattered by excitations of electron–hole pairs, which commonly happens in metals, and AFM spin fluctuations. $\text{Im} \Sigma_k (\epsilon)$ for the particle–hole excitation at low temperatures is approximately given by

$$\text{Im} \Sigma_k (\epsilon = E_k < 0) \propto \sum_{q, \omega} \chi(q, \omega) \text{Im} \frac{f(E_{k+q})}{E_{k+q} - E_k - \omega + i\delta},$$

where $\chi(q, \omega) = \sum_k \frac{f(E_{k+q}) - f(E_k)}{E_{k+q} - E_k - \omega + i\delta}$ is the Lindhard function. Using equation (2) with $\omega_{\text{SF}} = 6$ meV deduced from the inelastic neutron scattering measurement of Pr$_{1-x}$La$_x$Ce$_2$CuO$_4$ (ref. 31), and the experimentally obtained band structure $\epsilon = E_k$ fitted to the tight-binding model (Supplementary Note 2), $\text{Im} \Sigma_k (\epsilon = E_k)$ can be calculated along the three cuts for different $\xi$ values (for the detail of the calculation, see Supplementary Note 1). The calculated $-\text{Im} \Sigma_k (\epsilon = E_k)$ for AFM spin fluctuations and particle–hole excitations are shown in Fig. 4b–d, e, respectively. AFM spin fluctuations with $\xi > 4a$ (a: in-plane lattice constant) yield strong scattering around the hot spot in the low-energy region because low energy AFM spin fluctuations scatter the QPs near one hot spot to another. However, when the correlation length is decreased to $\xi = 2a$, the scattering at the hot spot is no longer clear as is the case for the scattering by particle–hole excitations. Except for the energy-independent offset (the static part of the QP scattering rate) discussed below, the dynamical part of the QP scattering $-Z \text{Im} \Sigma_k (\epsilon) - Z \text{Im} \Sigma_k (\epsilon = 0)$, that is, the inelastic scattering of QPs is almost the same among the three cuts as shown in Fig. 4a, suggesting that the dynamical QP scattering in the protect-annealed sample arises from particle–hole excitations as well as from AFM spin fluctuations, if existed, with a short correlation length of $\xi \lesssim 2a$.

A calculation based on an AFM-phase fluctuation model$^9$ has also shown that if the correlation length is as small as $\xi \sim 2a$, an AFM pseudogap becomes invisible as in the spectra of the protect-annealed samples (Figs 2 and 3), while an AFM pseudogap opens for $\xi \gtrsim 4a$. The short AFM correlation length is consistent with $\mu$SR measurements on PLCCO single crystals with $x = 0.10$ (ref. 33). The rotation of muon spins was observed in as-grown samples, suggesting the existence of long-range AFM order, while in sufficiently protect-annealed samples only fast relaxation was observed, suggesting that AFM correlation is short-ranged. The reduction of the magnitude of the fluctuating spin moment would also contribute to the weakening of the AFM pseudogap. If the latter is the case, the AFM correlation length $\xi$ somewhat larger than $2a$ would still be consistent with the ARPES spectra. Thus the absence of AFM correlation

The hot spot and the anti-node. These features are explained by strong AFM correlation as reported in previous ARPES studies$^{4,5}$. Surprisingly, all of those features are absent in the annealed sample, and a sharp single QP peak is observed on the entire FS, indicating the suppression of AFM correlation.

The same EDCs are plotted in Fig. 3c, d with different intensity normalizations. According to the plot in Fig. 3c, where EDCs have been normalized to the intensity around $-0.4$ eV, one can see that the QP peak at $E_F$ on the entire FS is dramatically enhanced by the annealing. This growth of the QP spectral weight suggests that the scattering of the QPs by impurities or defects is also suppressed by the annealing. Figure 3d, where the EDCs have been normalized to the peak height, shows that the as-grown sample has a gap on the entire FS, consistent with the transport measurements showing an insulating behaviour$^{29}$, and that the gap closes by the annealing, consistent with a previous ARPES measurement reported by Richard et al.$^{17}$.

**Quasi-particle scattering rate.** Suppression of the AFM pseudogap around the hot spots enables us to investigate the low-energy physics on the entire FS. The scattering rate of the

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**Figure 3 | EDCs on the FS of PLCCO.** (a) EDCs of as-grown (red curves), weakly annealed (black curves) and annealed (blue curves) PLCCO samples along the FS (for $k_z$ positions, see the inset). Peak positions are denoted by vertical bars. (b) The same plot as a for overdoped Nd$_{2-x}$Ce$_x$CuO$_4$ ($x = 0.17$) annealed in a conventional method$^9$. (c, d) Evolution of EDC with $k_F$ as normalized to the intensity $\sim -0.4$ eV. This plot indicates that the spectral weight of the QP peak is dramatically enhanced by annealing. EDCs plotted in c are normalized to the intensity $\sim -0.4$ eV. This plot indicates that the spectral weight of the QP peak is dramatically enhanced by annealing. EDCs plotted in d are normalized to the peak height. By protect annealing, the gap/pseudogap closes on the entire FS. The momentum positions where the EDCs were taken are indicated in the inset in c. (e) EDCs on the FS of the annealed sample plotted without offsets. EDCs are normalized to the peak height after the EDC near $(\pi, \pi)$ was subtracted as a background. The inset shows the corresponding momentum positions.
signals in the protect-annealed samples indicates that AFM correlation length $\xi$ and/or the magnitude of the (fluctuating) local magnetic moments are dramatically reduced by the protect annealing.

As for the static part of the QP scattering rate $\Gamma_0 = - \text{ZIm } \Sigma_k (\epsilon)$, that is, the elastic-scattering rate of QPs, Fig. 4a indicates its enhancement near the anti-node. Note that the elastic scattering is caused by static disorder and should be added to the dynamical scattering, which vanishes at $\epsilon = 0$. In fact, Fig. 4f shows that $\Gamma_0$ obtained by fitting $- \text{ZIm } \Sigma_k (\epsilon)$ to a power law function $\Gamma_0 + A \epsilon^2$ (Supplementary Note 1) increases as one approaches the anti-node. Consistent with these data, the EDC width is also broader around the anti-node as one can see from Fig. 3e, suggesting stronger QP scattering in the anti-nodal region. This tendency has been widely observed in the hole-doped cuprates$^{34-37}$, suggesting common QP scattering mechanisms both in the hole- and electron-doped cuprates. As for the hole-doped cuprates, coupling with AFM fluctuations peaked at $(\pi, \pi)$ or scattering between van Hove singularities (for example, between $\phi = 90^\circ$ and $\phi = 0^\circ$)$^{39}$ have been proposed as a possible origin. In the case of e-HTSCs, however, the $(\pi, \pi)$ scattering mechanism is less effective because the wave vector connecting two anti-nodal parts of the FS are strongly deviated from $(\pi, \pi)$ because of the smaller radius of the FS compared with those of hole-doped cuprates (Fig. 4g). The van Hove singularity scenario is also difficult for e-HTSCs because the singularities lie well $(\sim 400\text{ meV})$ below $E_F$ as opposed to $(\sim 100\text{ meV})$ in the hole-doped cuprates. Alternatively, weak nesting between two anti-nodal parts of the FS around $(\pi, 0)$ could enhance elastic scattering of the QPs. If such scattering is strong, incipient charge instability may arise from this FS nesting (Fig. 4g). Recently, charge ordering with $q \sim (0.25\pi, 0)$ was indeed found both in hole- and electron-doped cuprates$^{40,41}$. As for the electron-doped cuprates, the $q$ vector is reported to connect either two anti-nodal points or hot spots, and hence it is possible that QPs are scattered between two anti-nodal regions connected by $q \sim (0.25\pi, 0)$ and the same scattering causes charge instability.

It is interesting to discuss the possible relevance of the present result to the superconductivity with much lower Ce concentration or even without Ce doping. For thin films and powdered samples of e-HTSCs$^{21-24}$, in those samples, superconductivity with $T_c$ as high as the present protect-annealed samples is achieved rather independently of the Ce concentration. Recently, it has been proposed using the local-density approximation combined with dynamical mean-field theory that the AFM long-ranged order is necessary to open a charge-transfer gap in the parent compound of e-HTSCs while Coulomb repulsion without AFM order is sufficient to open the gap in the hole-doped cuprates$^{42,43}$. In addition, it has been shown that, when protect-annealed, even extremely underdoped bulk single-crystalline PLLCO $(x = 0.05)$ becomes superconducting with $T_c$ values comparable to the present annealed samples (T. Adachi et al., unpublished. For the superconducting properties, see Supplementary Fig. 1).
**Carrier concentration.** The doped electron concentrations of the as-grown and weakly annealed samples estimated from the FS area, $n_{FS}$, were 0.131 and 0.130, both of which were not far from the nominal Ce concentration $x = 0.10$ (Supplementary Fig. 2 and Supplementary Note 2). On the other hand, the $n_{FS}$'s of the protect-annealed samples fell in the range from $n_{FS} = 0.118$ to 0.180, some of which are significantly larger than that expected from the nominal Ce concentration $x = 0.10$ (Supplementary Figs 2 and 3, Supplementary Table 1 and Supplementary Note 2). This is distinct from the results of the previous ARPES studies8,17 in which the FS area was reported to be consistent with Ce concentration. We note that carrier doping by annealing has also been implied by the systematic shift of the Néel temperature by annealing as observed in a neutron scattering study 44. In Fig. 5, the $T_c$ values of the protect-annealed samples are plotted against the electron concentration. For comparison, the values of $T_c$ of PLCCO and Pr$_{1-x}$LaCe$_x$CuO$_4$ single crystals annealed by the conventional method26,31,45, and those of the protect-annealed PLCCO single crystals (T. Adachi et al., unpublished). For the superconducting properties, see Fig. 1 and Supplementary Fig. 1), are also plotted with respect to the nominal Ce concentration $x$. In the previous studies, the $T_c$ rapidly decreases with increasing Ce concentration above $x \sim 0.11$. On the other hand, the present samples maintain high $T_c$ values compared with all the previous samples up to the highest $n_{FS}$ of 0.180 as shown in Fig. 5. This can be understood under the assumptions that Ce doping causes structural disorder and that high $T_c$ can be maintained if more electrons can be doped without increasing Ce concentration (beyond $x = 0.10$).

Although additional electrons are somehow doped in the course of annealing, the suppression of the AFM pseudogap cannot be accounted for only by the electron doping: as shown in Fig. 3b, while overdoped Nd$_{1.7}$Ce$_{0.3}$CuO$_4$ with $x = 0.17$ still clearly shows two peaks in its EDC around the hot spot due to AFM correlation19, such a spectral feature is absent in the present ARPES spectra of annealed sample 1 with $n_{FS} = 0.168$. Furthermore, while weakening of the AFM pseudogap with Ce doping in the previous studies was accompanied by a rapid degradation of superconductivity19,46, protect-annealed PLCCO ($x = 0.10$) shows $T_c$ as high as $\sim 27$ K despite the absence of the AFM pseudogap, calling for a re-examination of the relationship between superconductivity and antiferromagnetism in the e-HTSCs.

**Discussion**

Finally, we discuss possible origins of the excess electron doping determined by ARPES compared with the doped Ce content. In previous studies using inductively coupled plasma (ICP) and X-ray and neutron scattering5,16, Kang et al. detected that 3–3.5% of Cu were deficient in as-grown PLCCO ($x = 0.12$) and Pr$_{1-x}$LaCe$_x$CuO$_4$ ($x = 0.12$) samples and that an impurity phase of rare-earth oxides with $\sim 1.6$% volume fraction was present in annealed samples, concluding that the annealing repaired the Cu defects by creating the Ln$_2$O$_3$ impurity phase instead of removing apical oxygen. On the other hand, in the present samples, Cu deficiency was not detected before annealing by the ICP analysis within 1% accuracy. Furthermore, the impurity phase of rare-earth oxides was not detected after annealing by X-ray diffraction within the detection limit ($\sim 1\%$) and by scanning electron microscopy. Another difference from Kang et al.15,16 is that they reported an expansion of the c-axis parameter by annealing while we observed a decrease (12.284 and 12.256 Å before and after protect annealing, respectively) as observed in the previous studies by Radaelli et al.15 and Schultz et al.12 which supported the removal of apical oxygen by annealing. Taking all these into account, we conclude that the Cu-deficiency scenario15,16 is not applicable to the present protect-annealed PLCCO samples, and instead oxygen atoms may be removed by annealing from the apical sites11,12 and/or the regular (CuO$_2$-plane and/or LnO-layer) sites13 without producing the impurity phase. Therefore, additional electrons should have been introduced by oxygen removal from the regular site, that is, either from the CuO$_2$ planes or the LnO layers. Although one cannot further identify the position of the removed oxygen atoms at present, considering the relatively high $T_c$ of the protect-annealed sample, one can conclude that oxygen removal takes place at atomic sites which induce less disorder than Ce substitution.

In conclusion, we have performed ARPES measurements on protect-annealed PLCCO single crystals with Ce doping of $x = 0.10$ with varying annealing conditions. Sufficiently annealed samples showed a $T_c$ as high as 27.0 K and did not show any signature of AFM fluctuations or the AFM pseudogap, which has been observed in all the other e-HTSCs so far. While the scattering of QPs near $E_F$ by AFM correlation was not observed at the hot spot in the annealed samples, stronger scattering was observed in the anti-nodal region than in the nodal region, similar to the hole-doped cuprates. This suggests the existence of common scattering mechanisms both in the hole- and electron-doped cuprates although the $(\pi, \pi)$ scattering and the van Hove singularity mechanisms proposed for the hole-doped cuprates do not seem important for the electron-doped cuprates. The protect-annealed samples studied here showed almost the same values of...
$T_c$, whereas the actual electron concentration estimated from the FS area varied over a wide range. Thus the intrinsic electronic structure revealed by the present ARPES study will be of great importance to elucidate the mechanism of the high-temperature superconductivity.

Methods

Sample preparation. Single crystals of PLCCO with $x = 0.10$ were synthesized by the traveling–solvent floating–zone method. The composition of the as-grown crystal was determined to be Pr$_{1.17}$La$_{0.73}$Ce$_{0.10}$Cu$_{1.00}$O$_{4+yc}$ by the ICP method, by assuming that the content of Pr, La, Ce and Cu amounts to 3 atoms per f.u. Relative error for each element was ±0.01. Three kinds of samples were prepared: as-grown, weakly annealed and annealed samples, among which only the annealed ones showed superconductivity with the $T_c$ of 27.0 K (annealed sample 1). By protect annealing a bulk polycrystalline PLCCO sample, not shown here, the oxygen content was confirmed to be reduced by 0.03 ± 0.01 by isomotic titration. We also prepared two additional annealed samples with $T_c$ = 27.2 and 26.2 K (annealed samples 2 and 3, respectively). The weakly annealed samples were annealed at 650°C for 24 h, and the annealed samples at 800°C for 24 h. Bulk superconductivity in the annealed samples was confirmed by specific-heat measurements.

ARPES measurements. ARPES experiment was performed at beamline 28A of Photon Factory. The composition of the as-grown crystals was determined to be Pr$_{1.17}$La$_{0.73}$Ce$_{0.10}$Cu$_{1.00}$O$_{4+yc}$ prepared via a molten alkaline hydroxide route. Phys. C 471, 682–685 (2011). Takekatsu, T., Kato, M., Noji, T. & Koike, Y. Undoped and hole-doped superconductors $T_{\text{La}_{1-x} \text{Eu}_x \text{Sr}_2 \text{CuO}_4}$ ($x = 0$ and 0.05) prepared by solid-state reaction. Appl. Phys. Express 5, 073101 (2012).

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Author contributions
M.H., T.Y., H.S., L.C.C.A., K.Ok., D.O., K.S., M.T. and T.M. performed ARPES measurements with the assistance of H.K., K.On., H.A. and M.A., M.H. analysed the data and performed the calculations. Y.M., A.T., T.A. and Y.K. synthesized and characterized single crystals. M.H. and A.F. wrote the manuscript with suggestions by T.A., Y.K., T.Y., T.M. and all other coauthors. A.F. was responsible for overall project direction and planning.

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