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**Single-particle excitation gap in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$
studied by high-resolution angle-resolved photoemission**

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Abstract

We report angle-resolved photoemission spectroscopy on optimally-doped high- T_c superconductor $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ ($T_c = 37$ K) to elucidate the character of low-energy excitations in the superconducting state. We find a clear evidence for the emergence of a sharp superconducting quasiparticle peak below T_c together with opening of a superconducting gap at off-nodal region, while no signature of a quasiparticle peak is observed at $(\pi, 0)$. From the comparison of spectral lineshape and energy dispersion between the nodal and the off-nodal region, we conclude that there are two characteristic energy scales (70 and 20 meV) in the superconducting state of optimally-doped $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$.

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Introduction

After the discovery of high- T_c superconductivity in cuprates, intensive experimental and theoretical efforts have been made to clarify the mechanism of superconductivity and the origin of “glue” which binds two electrons (holes) to form Cooper pairs. Recent angle-resolved photoemission spectroscopy (ARPES) studies have revealed an anomalous behavior of low-energy single-particle excitations, known as a kink in the energy dispersion which shows a strong renormalization of band in the vicinity of E_F [1-13]. The kink has been regarded as a signature of the coupling between electrons and certain collective excitations (modes), and is observed along the nodal direction in almost all the hole-doped high- T_c cuprates at the energy of 50-80 meV. As for the

candidate of mode, the lattice vibrations (phonons) [1-3] and the spin excitations (magnons) have been proposed so far [8-13], but the clarification of the make is still controversial, mainly because the characteristic energy scale of phonons and spin excitations (magnetic resonance mode) are quite similar to each other. One of effective approaches to effectively distinguish two different candidates is to perform ARPES experiment on a compound having a lower T_c value than Bi2212 (maximum $T_c = 90$ K) which is most intensively studied so far, since the difference in T_c values may also change the characteristic energy scale in the superconducting state due to the difference in the size of superconducting gap. One of promising candidates to examine this possibility is $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) of which T_c is as high as 38 K. Previous ARPES studies on LSCO have been mainly performed above T_c and also along the nodal region [4-6], and there are few ARPES reports on detailed electronic states in the superconducting state in the off-nodal region where the d -wave superconducting gap opens.

In this paper, we report high-resolution ARPES results on optimally-doped $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ in the superconducting state to find an found evidence for two different kinks in the energy dispersion. The one is the nodal kink at 70 meV which is commonly seen in previous ARPES works on many hole-doped cuprates, and another is the off-nodal kink at 20 meV which appears only below T_c . This experimental result indicates the existence of at least two different types of characteristic low-energy excitations in optimally-doped LSCO.

Experiment

High-quality single crystals of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ ($T_c = 37$ K, optimally-doped) were grown by the traveling-solvent floating-zone method. ARPES measurements for $(\pi, 0)$ point and off-nodal region were performed using a SCIENTA SES-2002 spectrometer with a high-flux discharge lamp and a toroidal grating monochromator in Tohoku University. We used He I α resonance line (21.218 eV) to excite photoelectrons. The energy and angular resolutions were set at 6.5 meV and 0.2° , respectively. ARPES measurements for nodal cut were performed using a R4000 spectrometer at the U-4mNIM beamline in Synchrotron Radiation Center, Wisconsin, using photons with the energy of $h\nu = 18$ eV. The energy and angular resolutions were set at 10 meV and 0.5° , respectively. Clean surface for the ARPES measurement was obtained by *in situ* cleaving of crystal in an ultrahigh vacuum better than 4×10^{-11} Torr. The Fermi level (E_F) of the sample was referenced to that of a gold film evaporated onto the sample substrate. We have confirmed the experimental result being reproducible by measuring several samples.

Results and Discussion

Figs. 1 (a)-(c) show ARPES spectra of optimally-doped $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ ($T_c = 37$ K) measured in the superconducting state along (a) the nodal cut, (b) the off-nodal cut, and (c) the $(\pi, 0)$ -(π, π) cut. We also show the corresponding intensity plot as a

function of wave vector and binding energy [Figs. 1(d)-(f)]. Since the spectral intensity measured at He I α ($h\nu = 21.218$ eV) is significantly suppressed along the nodal cut due to the matrix-element effect, we measured nodal ARPES spectra in the second Brillouin zone (BZ) by using lower photon energy ($h\nu = 18$ eV) to enhance the spectral intensity. As clearly seen from Fig. 1(a), we find a highly dispersive band along the nodal cut which clearly cross E_F . This band shows a dispersion kink at around 50-80 meV [Fig. 1(d)] as reported previously [4-6]. Figure 1(b) shows ARPES spectra measured along the off-nodal cut as indicated by an arrow B in the right panel. A broad peak at ~ 100 meV gradually disperses toward the lower binding energy with approaching the Fermi wave vector (k_F). The peak in the very vicinity of E_F approaches E_F with approaching k_F , but never crosses E_F , and disperses back again toward higher binding energy after passing k_F , in contrast to the spectral behavior along the nodal direction (Fig. 1(a)). This behavior at the off-nodal cut is quite similar to that observed in Bi-based multilayered cuprates [14,15], demonstrating that the observed band at the off-nodal cut is attributed to the Bogoliubov quasiparticle band due to the occurrence of superconductivity. We also find from the intensity plot at the off-nodal cut [Fig. 1(e)] that the band dispersion shows an anomalous behavior which cannot be explained by the simple Bogoliubov quasiparticle picture; the band dispersion is not straight at higher energy but possesses a kink at 20 meV, which is much lower in energy than the nodal kink [Fig. 1(d)] and any other kinks observed previously [1-13]. We find that the off-nodal kink vanishes above T_c in contrast to the nodal kink. This implies that the

emergence of off-nodal kink is closely linked to the onset of superconductivity, while the nodal kink may not be directly related to the superconductivity. We note here that no evidence for the emergence of kink nor a sharp Bogoliubov quasiparticle peak has been found along the $(\pi, 0)$ - (π, π) cut, as seen in Figures 1(c) and (f). This point will be discussed later in more detail.

To quantitatively discuss the behavior of energy band dispersion, we plot in Fig. 2(a) the energy position of peak for three cuts A-C, determined by fitting the energy distribution curves (EDC). Along cut A, the energy dispersion shows a sudden change in the slope at 70 meV, showing a clear kink. Along cut B, we identify two peaks in the vicinity of E_F separated with respect to the 20-meV binding energy, although it is difficult to trace peaks in the energy region higher than 100 meV because of relatively large background as compared to the intensity of the main band. Since the observation of two peaks is not explained by the conventional Bogoliubov quasiparticle picture in the weak-coupling limit, this indicates the presence of strong electron-mode coupling at the off-nodal region in the superconducting state. Since the energy scale (~ 20 meV) is remarkably small as compare to the nodal kink (70 meV), it is suggested that the origin of kink is different between the nodal and the off-nodal region. As the origin of mode which electrons are couple to, the Longitudinal optimal (LO) breathing phonon and the B_{1g} buckling phonon have been proposed previously [1,3]. However, by considering the fact that the energies of these phonons are about 70 meV and 40 meV respectively, the off-nodal kink is hardly explained within the context of the coupling between electrons

and phonons. Furthermore, absence of 20-meV kink above T_c is not consistent with the phonon picture since we expect a small change in the phonon spectrum across T_c . We therefore think that the 20-meV kink is produced by the coupling of electrons with spin excitations. According to the recent inelastic neutron scattering experiment of $\text{La}_{1.82}\text{Sr}_{0.18}\text{CuO}_4$ [16], $\chi''(\omega)$ at incommensurate wave vectors below T_c shows a distinct peak at 9 meV. The authors explained the pile-up in $\chi''(\omega)$ in terms of the incommensurate magnetic resonance. According to the previous studies [17,18], the energy of the kink E_{kink} in the ARPES spectra in the superconducting state is described as $E_{\text{kink}} = \epsilon_{\text{max}}$, where ϵ_{max} is the mode energy and the maximum superconducting gap size, respectively. In the case of LSCO, E_{kink} and ϵ_{max} obtained from the ARPES experiment is 20 and 7-13 meV, respectively [19,20], therefore E_{kink} is 7-13 meV, in good agreement with the incommensurate magnetic-resonance energy repeated by the inelastic neutron scattering experiment. These experimental facts suggest that the 20-meV kink is created by the coupling of electrons with the incommensurate magnetic resonance.

Now we discuss momentum dependence of spectral lineshape in the superconducting state. As seen in Fig. 2(b), we observe a characteristic break (dip) in the ARPES spectrum at the k_F point along the nodal cut (cut A), while the dip is observed at 20 meV at the off-nodal k_F point (cut B). These energies well correspond to the characteristic energies of dispersion kink as discussed above, suggesting that the energy position of spectral break / dip is also determined by the characteristic energy scale of

the electron-mode coupling. Another interesting feature in Fig. 2(b) is the absence of a sharp peak around $(\pi, 0)$ point (cut C), in sharp contrast to the emergence of a sharp Bogoliubov quasiparticle peak at the off-nodal region (cut B). This observation is surprising since the previous ARPES studies in Bi2212 and Bi2223 [9,15] reported the existence of an intense sharp peak below T_c comparable to the peak at the off-nodal region. One of plausible explanation to why the peak is significantly weakened around $(\pi, 0)$ is the effect of strong inhomogeneity at the surface, which produces significant spatial variation in the superconducting gap size as observed in a tunneling experiment [21]. Another possibility is the presence of some kind of competing order which remarkably weakens the superconductivity around the antinodal region. Further systematic ARPES studies as a function of doping and temperature are necessary to elucidate the origin of anomalous broadening of spectral feature around $(\pi, 0)$ point.

Conclusion

We reported high-resolution ARPES results on $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ ($T_c = 37$ K). We found an evidence for the existence of two characteristic energy scales in the energy dispersion at the superconducting state, which are clearly separable in energy (70 and 20 meV respectively). We discussed the origin of these energy scales in terms of phonons and magnons, and concluded that the 20-meV energy scale is related to the coupling of electrons with the spin excitations.

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Figure captions

Fig. 1

ARPES spectra of optimally-doped $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ measured along (a) the nodal cut, (b) the off-nodal cut, and (c) the $(\pi, 0)$ - (π, π) cut as shown by arrows in the Brillouin zone (top panel). We set the temperature of the measurement at 20 K and 10 K, for nodal cut and other cuts, respectively. (d)-(f) Corresponding ARPES intensity plots as a function of wave vector and binding energy. Bright are correspond to the high spectral intensity.

Fig. 2

(a) Plots of peak positions in the energy distribution curves for three representative cuts. Peak position for the nodal cut has been determined after dividing the AREPS spectra by the Fermi-Dirac distribution function convoluted with an instrumental resolution. (b) ARPES spectra at Fermi vectors (k_F) measured at 10 K along the nodal, the off-nodal, and the $(\pi, 0)$ - (π, π) crossing point. Triangles show the position of spectral break / dip.

Figures

Figure 1

Figure 2