Low-energy spectroscopic mapping studies in optimally-doped Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$

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Abstract

We performed high-resolution scanning tunneling microscopy/spectroscopy on an optimally-doped Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ crystal with $T_c \approx 25$ K. The so-called “checkerboard” local-density-of-state modulation previously found in heavily underdoped regime also manifests in the spectroscopic map of the optimally-doped sample. In addition, spatially-inhomogeneous energy gap with peaks at the gap edges is observed below about 10 meV. The gap tends to be buried at elevated temperatures and correlates with the checkerboard modulation. These results suggest that the gap is related to superconductivity which coexists with the checkerboard modulation.

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1. Introduction

Recent scanning tunneling microscopy/spectroscopy (STM/STS) measurements on high-$T_c$ cuprates have revealed the “checkerboard” (CB) local-density-of-state (LDOS) modulations in the vortex core [1], above $T_c$ [2], and in heavily underdoped regime [3]. The CB modulation is often discussed in terms of the electronic order which competing/coexisting with superconductivity. However, the relation between CB and superconductivity is still unclear. Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ is an ideal material for CB research because it shows very clear CB modulation [3]. However, no clear superconducting signal was observed in the LDOS spectrum probably because the available samples were limited in the underdoped regime. Recent progress in sample preparation has allowed us to grow sizable optimally-doped crystals. In this article, we report on results of STM/STS measurements on optimally-doped Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ and discuss the possible coexistence of CB and superconductivity.

2. Experimental

Single crystals of optimally-doped Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$ with $T_c = 25$ K were grown by a flux method under high pressure [4]. STM/STS measurements were performed with a newly-developed ultra-high-vacuum very-low-temperature STM. Sample surface was prepared by in situ cleaving along (001) plane. Differential conductance $dI/dV$ spectrum, which is a measure of the LDOS, was taken at every pixel of the topographic STM image to make a spectroscopic map. Measurements were performed in the temperature range between 0.4 K and 20 K.
3. Results and discussion

Fig. 1 shows a constant-current STM image and a simultaneously acquired \(dI/dV\) map taken at energy \(E = +25\) meV. In underdoped samples, the CB modulation has been clearly observed around this energy [3]. It is obvious that the CB modulation is also observed in the present optimally-doped sample. Namely, the CB modulation is a robust feature in \(\text{Ca}_2-x\text{Na}_x\text{CuO}_2\text{Cl}_2\).

Typical tunneling spectrum shows V-shaped pseudo-gap, which characterizes the CB state, below \(|E| \sim 100\) meV [3]. To look for the spectroscopic evidence of superconductivity, we performed detailed low-energy spectroscopy inside of the pseudo-gap. We found that another gap opens below \(|E| \sim 10\) meV. The low-energy gap accompanies coherence-peak-like structures at the gap edges and reminds us of a superconducting gap.

The low-energy gap is spatially-inhomogeneous. To analyze the gap variation, we classify the gap according to its magnitude. As shown in Fig. 2a, smaller gap has sharper gap-edge peak. This behavior is similar to that for the superconducting gap of \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8\) [5]. Next we examined the temperature effect. Fig. 2b shows the temperature evolution of the spectrum taken at the position indicated in Fig. 1a. Thin solid line overlaid on the 20 K spectrum denotes the thermally broadened 0.4 K spectrum. It is clear that the observed 20 K spectrum is more broadened than expected. Although we could not go beyond the transition temperature \(T_c\), this result suggests that the gap is closing or buried toward \(T_c\). The same tendency is commonly observed over the field of view.

The observed temperature effect and the similarity between the low-energy gap and the superconducting gap of \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8\) strongly suggest that the low-energy gap in \(\text{Ca}_2-x\text{Na}_x\text{CuO}_2\text{Cl}_2\) is originated from superconductivity. The magnitude of the low-energy gap of \(\text{Ca}_2-x\text{Na}_x\text{CuO}_2\text{Cl}_2\) is about 1/3–1/4 of the superconducting gap of \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8\). This is naturally understood by considering the difference in \(T_c\).

Finally, we examined the spatial variation of the low-energy gap. We found that the gap is inhomogeneous but ubiquitous. Namely, superconductivity may coexist with the CB modulation. The gap-edge peak shows a wide variety of shapes. In the field of view shown in Fig. 1, 16\% of the spectra show no peak and 49\% of the spectra show single-sided peak either in the filled (8\%) or empty (41\%) states. The position where no peak is observed is always at the dark “perimeter” of the CB plaquette. Such a close correlation between the peak and CB indicates the interplay between superconductivity and the CB modulation.

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References