

# Electronic Structure of $\text{Sr}_{14-x}\text{Ca}_x\text{Cu}_{24}\text{O}_{41}$ Studied by Angle Resolved Photoemission Spectroscopy

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## INTRODUCTION

Through extensive studies in recent years, the  $\text{Sr}_{14-x}\text{Ca}_x\text{Cu}_{24}\text{O}_{41}$  system has provided the best opportunities to elucidate fundamental physical properties of hole-doped  $S=1/2$  spin ladders. Existence of a spin gap in two-leg ladders is confirmed by NMR and neutron diffraction measurements.[1,2] In the high-Ca doped samples, possibility of hole-pairing, which results in the one-dimensional (1D) charge transport along the ladders, is suggested by the optical reflectivity measurements [3]. Most importantly, superconductivity appears for high-Ca samples when pressure is applied [4]. These experimental observations are considered to be consistent with, or, at least, closely related, to the theoretical suggestions made on the spin ladders [5].

In spite of the accumulating experimental results, there are a lot of remaining issues yet to be clarified for understanding the physical properties of these systems. In order to understand the electronic structure, we have performed Fermi surface mapping by angle resolved photoemission spectroscopy. In this work, we have observed not only a clear 1D Fermi surface but also energy dispersion perpendicular to ladder direction.

## EXPERIMENT

The ARPES measurements were carried out at BL10.0.1.1 of the Advanced Light Source, using incident photons with an energy of 55.5 eV. We used a SCIENTA SES-200 spectrometer in angle mode. The total energy resolution was about 20 meV. We studied high quality single crystals of  $\text{Sr}_{14-x}\text{Ca}_x\text{Cu}_{24}\text{O}_{41}$  with  $x = 0$  and 11 grown by the traveling-solvent floating-zone method. Measurements were performed in ultra high vacuum of  $10^{-11}$  Torr at 150 and 20 K for  $x=0$  and  $x=11$  respectively. Clean sample surfaces were obtained by cleaving *in situ*. ARPES spectra have been measured along the plane that includes chain and ladder.

## RESULTS AND DISCUSSION

Figure 1 shows the second derivative of ARPES spectra along ladder direction. Red and blue spots correspond to a peak and dip feature in the ARPES spectra respectively. The feature seen at about  $-1$  eV is a chain band reflecting the periodicity along c-axis[6]. The dispersive feature shown by the blue part represents the ladder dispersion, because they agree with the periodicity caused by Cu-Cu distance in ladder direction. As shown in Fig. 1, the energy dispersion of  $x=11$  is about 0.2 eV higher than that of  $x=0$ . This indicates that the shift of the chemical potential is caused by the hole doping from chain to ladder induced by Ca doping. In the  $x=0$  spectra, the ladder derived feature represented by blue spot is observed in  $0.5 < k_z < 1.5$  while this feature is

absent in  $x=11$ . This “shadow band” feature may indicate that the electron correlation in  $x=0$  is stronger than in  $x=11$ [7], consistent with previous results.

New information has been obtained from two dimensional (2D) spectral weight mapping. Figure 2 shows the photoemission spectral weight plotted in the momentum space integrated near the Fermi level ( $E_F$ ). The integrated energy window is 400 and 200 meV for  $x=0$  and 11, respectively, considering that they have different gap size. Here, the unit of  $k_z$  and  $k_x$  are given by  $\pi/c$  and  $\pi/a$  respectively, where  $c$  and  $a$  are Cu-Cu distance along ladder direction and the inter ladder distance. The right panel shows the corresponding simulation derived from tight binding band calculations[8]. As shown in Fig. 2, we have observed spectral weight concentrated on the line  $k_z=0.5$ , which indicates the 1D nature of the system, consistent with the band calculation, although they have energy gap at  $E_F$  as shown in Fig. 1. There is a significant difference between the spectral weight mapping of  $x=0$  and 11. The spectral weight in  $x=11$  has strong intensity around  $k_x=+1$  and  $-1$ , which is in good agreement with a periodicity corresponding to inter ladder distance as seen in the band calculation. On the other hand, the spectral weight of  $x=0$  shows a concentration in  $|k_x|<1$ , which does not correspond to the inter ladder periodicity, suggesting the existence of extra periodicity in the electronic structure for  $x=0$ . One possibility is charge ordering as suggested by neutron diffraction[9], NQR[1], and optical measurement. From the modulation of the ARPES mapping, the periodicity of charge ordering is estimated to be  $\sim 8\text{\AA}$ . A corresponding scattering study to search for charge order is highly desired.

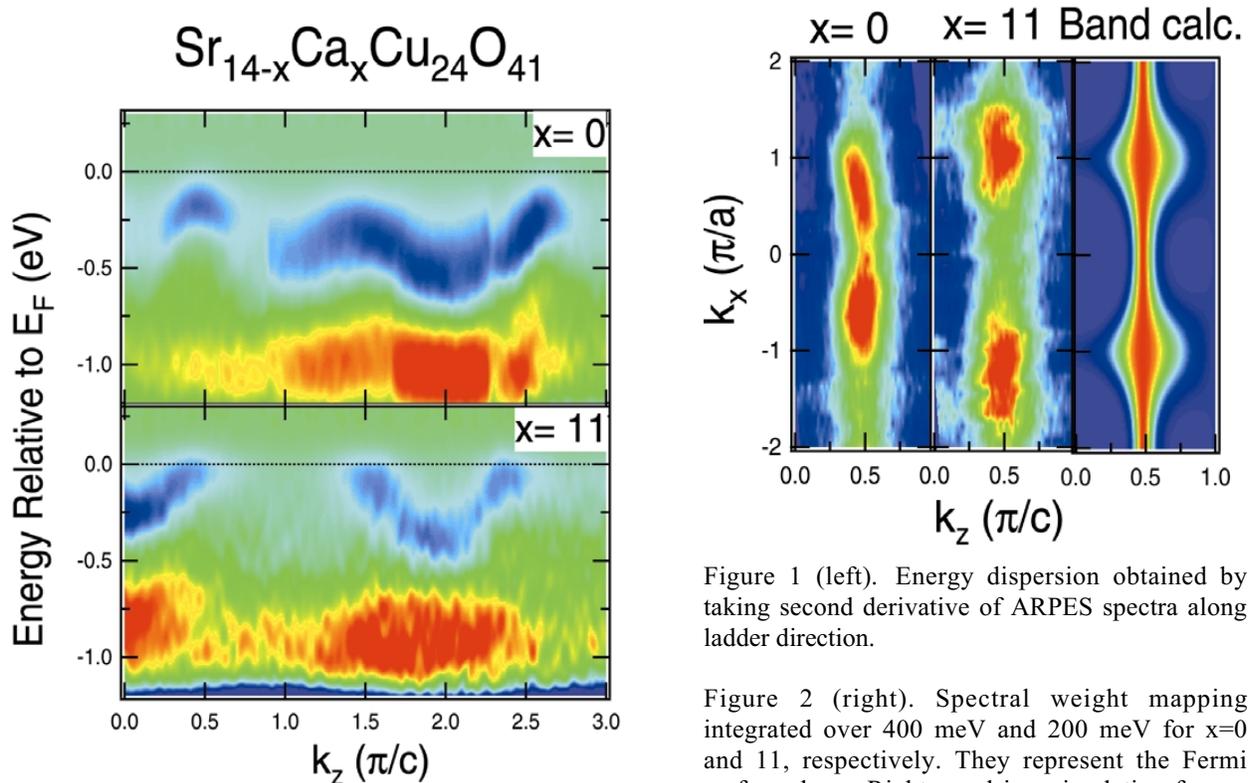


Figure 1 (left). Energy dispersion obtained by taking second derivative of ARPES spectra along ladder direction.

Figure 2 (right). Spectral weight mapping integrated over 400 meV and 200 meV for  $x=0$  and 11, respectively. They represent the Fermi surface shape. Right panel is a simulation from a band calculations[8].

## CONCLUSION

We have confirmed the one dimensional Fermi surface of the ladder band from the spectral weight mapping by ARPES, which is in agreement with band calculation results. Contrast to the prediction from the band calculation, in  $x=0$ , the spectral weight near  $E_F$  is concentrated in  $|k_x| < 1$ . This implies that charge ordering may occur in the ladder perpendicular direction.

## REFERENCES

- [1] M. Takigawa *et al.*, Phys. Rev. B **57**, 1124 (1998), K. Magishi *et al.*, Phys. Rev. B **57**, 11533 (1998), T. Imai *et al.*, Phys. Rev. Lett. **81**, 220 (1998).
- [2] R. S. Eccleston *et al.*, Phys. Rev. Lett. **81**, 1702 (1998).
- [3] B. Ruzicka *et al.*, Euro. Phys. J. **B6** (1998) 301, T. Osafune *et al.*, Phys. Rev. Lett. **82**, 1313 (1999).
- [4] M. Uehara *et al.*, J. Phys. Soc. Jpn. **65**, 2764 (1996).
- [5] for a review, see E. Dagotto and T. M. Rice, Science **271**, 618 (1996).
- [6] T. Takahashi *et al.*, Phys. Rev. B **56**, 7870 (1997).
- [7] T. Sato *et al.*, J. Phys. Chem. Solids **59**, 1912 (1998).
- [8] M. Arai and H. Tsunetsugu, Phys. Rev. B **56**, R4305 (1997).
- [9] M. Matsuda *et al.*, Phys. Rev. B **54**, 12199 (1996).

This work was supported by Technology Agency and the New Energy and Industrial Technology Development Organization (NEDO).

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