Raman Studies of Anisotropic Magnetic Excitations in Fluctuating Nematic Striped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ and the Comparison to Uniform $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$

S. Sugai · Y. Takayanagi · N. Hayamizu · Y. Sone · N. Nakagawa · T. Muroi

Received: date / Accepted: date

Abstract The mechanism of the high temperature hole-doped superconductivity was investigated by Raman scattering. The Raman selection rule is unique, so that anisotropic magnetic excitations in a fluctuating spin-charge stripe can be detected as if it is static. We use different Raman selection rules for two kinds of magnetic Raman scattering processes, two-magnon scattering and high-energy electronic scattering. In order to confirm the difference, the Raman spectra of striped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) and non-striped $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (NCCO) were compared. The main results in LSCO are (1) magnetic excitations are presented by individual energy dispersions for the $k_\parallel$ stripe and the $k_\perp$ stripe, (2) the charge transfer is allowed only in the direction perpendicular to the stripe. The direction is the same as the Burgers vector of an edge dislocation. Hence we assume that a charge moves together with the edge dislocation of the charge stripe. The superconducting coherence length is close to the inter-charge stripe distance at $x < 0.2$. Therefore we propose a model that superconducting pairs are formed in the edge dislocations. The binding energy is related to the stripe formation energy.

Keywords Pairing at edge dislocations · Anisotropic stripe excitations · Burgers vector · Raman scattering · LSCO · NCCO

1 Introduction

The spin-charge stripe structure $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ in the hole-doped high temperature superconducting cuprate has been intensively investigated, because it has a strong possibility to solve the superconducting mechanism. In the previous conference (Superstripes 2011) we presented the direct observation of individual $k_\parallel$ and $k_\perp$ stripe magnetic excitations in a fluctuating spin-charge stripe state utilizing high-energy Raman scattering. The advantage of Raman scattering is the unique selection rule which is determined by two Cartesian vectors parallel to the electric fields of incident and scattered light. If we chooses the electric field of incident light to one of the possible stripe direction and the electric field of scattered light to the other possible stripe direction, the observed spectra do not depend on the stripe direction, because Raman scattering is symmetric for the exchange of incident and scattered light. Using this technique we can observe the fluctuating stripe, as if it is static. Magnetic scattering arises from two mechanisms, two-magnon scattering and high-energy electronic scattering. The two mechanisms have
different symmetries [14]. Using the difference we disclosed the following results. (1) The magnetic excitations in the stripe state of LSCO are presented by the dispersions calculated by Seibold and Lorenzana [15, 16]. The energy of the $k\parallel$ stripe dispersion decreases together with the decrease of the high-energy intensity in the magnetic susceptibility. The separation of the dispersion curve in the $k\perp$ stripe is caused by the Brillouin zone folding due to the extended magnetic unit cell. (2) the electronic scattering spectra show only $k\perp$ stripe excitations, indicating that the carrier hopping is restricted to the perpendicular direction to the stripe.

In order to confirm the above analysis, we compared the Raman spectra of striped LSCO and non-striped electron-doped NCCO [17]. The experimental results certified the above analysis in LSCO. The restriction of the charge transfer direction is reminiscent of the Burgers vector of an edge dislocation. The edge dislocation easily slide in the Burgers vector direction which is perpendicular to an inserted half layer, giving ductility in metal. The carrier density dependent coherence length which gives the pair size is close to the inter-charge stripe distance at $x < 0.2$. It indicates that the charge moves together with the edge dislocation and the superconducting pairs are formed in the edge dislocations.

High energy magnetic Raman scattering has been reported in hole doped superconductors [18,19,20,21,22,23,24] and electron-doped superconductors [25,26,27]. Many of them reported only the $B_{1g}$ spectra, because the $B_{2g}$ spectra are two-magnon scattering inactive. The $B_{2g}$ high-energy electronic Raman spectra are very sensitive to the crystal surface condition. Only fresh cleaved surface gives the key structure, a hump from 1100 to 3100 cm$^{-1}$ in LSCO. The hump is scarcely reported except for a sign in the report by Machtoub [22]. The spectra in NCCO is sensitive to the oxygen reduction. We optimized the reduction condition to shorten the superconducting transition range less than 2 degree in the resistivity curve.

2 High-energy Raman spectra in striped LSCO and non-striped NCCO

Figure 1 shows the comparison of Raman spectra in LSCO and NCCO. The spectra in insulator are shown by black curves and those in metal by red curves. The high-energy $B_{1g}$ spectra show magnetic excitations caused by the two-magnon scattering process and the electronic scattering process, while the $B_{2g}$ spectra present magnetic excitations caused by the electronic scattering process only. In LSCO the $B_{1g}$ spectra represent $k\parallel$ and $k\perp$ stripe excitations and the $B_{2g}$ spectra only $k\perp$ stripe excitations. In LSCO the $B_{1g}$ magnetic scattering peak whose energy decreases with increasing $x$ is caused by the $k\parallel$ dispersion. The hump from 1100 cm$^{-1}$ to 3100 cm$^{-1}$ in the $B_{1g}$ and $B_{2g}$ spectra is caused by the $k\perp$ dispersion.

Each of $B_{1g}$ and $B_{2g}$ spectra in NCCO are almost the same as in LSCO at $x = 0$, because the magnetic scattering mechanism is only two-magnon scattering. However, the spectra in the metallic phase are very different. The black curve in Fig. 1(b) shows the scattering in as-grown insulating crystals and the red curve in oxygen reduced metallic crystals. The $B_{1g}$ peak energy in the as-grown crystal does not change even if Ce concentration increases to $x = 0.16$ where the reduced sample is a superconductor. It is noted that the $B_{2g}$ spectra change as Ce concentration increases regardless of as-grown or reduced. When the crystal becomes metal, the $B_{1g}$ spectra abruptly shift to high energy and change into nearly the same form as the $B_{2g}$ spectra. The isotropic charge transfer in the uniform spin lattice gives the same spectra in $B_{1g}$ and $B_{2g}$ symmetries. The peak energy can be interpreted by the theoretical model that an electron hops in a uniform antiferromagnetic spin lattice [23]. A hopping electron overturns the site spin, so that the motion of an electron can be approximated by the motion in the linear confining potential increasing with the path length. The transition energies between the discrete levels are 4800, 8200,... cm$^{-1}$ using $J = 0.3t$ and $t = 0.4eV$. The lowest transition energy coincides with the energy of the broad Raman peak in the metallic phase at $x = 0.14$.

Thus the Raman spectra in the metallic phase are very different by the existence or absence of the spin-charge stripe structure. The $B_{1g}$ two-magnon peak shifts to low energy in LSCO, as carrier density increases. On the other hand in NCCO it keeps the constant energy in the insulating phase even if Ce concentration increases and two-magnon peak disappears in the metallic phase. The $B_{2g}$ hump from 1100 to 3100 cm$^{-1}$ in LSCO which is assigned to the dispersion segment in the $k\perp$ stripe does not appear in NCCO. These experimental results certify our assignment that the $B_{2g}$ spectra in LSCO present the $k\perp$ stripe excitations.

3 Charge transfer united with the edge dislocation of the stripe in LSCO

The surprising result of the charge transfer only in the perpendicular direction to the stripe is reminiscent of an edge dislocation in metal. The edge dislocation easily slides perpendicularly to the inserted layer. Applying the properties of the edge dislocation to the stripe state, the experimental results are interpreted that carriers in
Raman studied of striped p- and uniform n-cuprates

Fig. 1 (color online) $B_{1g}$ and $B_{2g}$ Raman spectra in LSCO and NCCO. The spectra in the insulating phase is shown by the black curve and in the metallic phase by the red curve. The black spectra in NCCO were measured in as-grown crystals and the red spectra in reduced crystals. The two-magnon peak energies are shown by the dashed lines. The sharp peaks below 1400 cm$^{-1}$ in La$_2$CuO$_4$ are two-phonon peaks.

Figure 2(a) shows the single edge dislocation and Fig. 2(b) the looped edge dislocation [10]. The spin alignments at both sides of the charge stripe have opposite phases [5], so that the looped edge dislocation has lower energy [10]. The edge dislocation moves to right by displacing small parts of charge stripes at and near the edge indicated by the dashed segments. The density of the edge dislocation is assumed to increase with increasing the carrier density. As for the superconductivity in the stripe phase, the Bosonization of charge and spin dynamics in a one-dimensional conductor (Tomonaga-Luttinger liquid) was used [10,12]. However, the separation of the spin and charge degree of freedom has not been observed and the charge hopping in the looped edge dislocation is not a simple one-dimensional hopping. Therefore we suppose that the superconducting pairs are formed in the moving carriers at the edge dislocation. This model is supported by the carrier density dependent coherence length in the following.
4 Superconducting pairs formed in the edge dislocation

Figure 3(a) shows the carrier density dependence of the Ginzburg-Landau coherence length $\xi = \sqrt{\Phi_0/2\pi H_c^2}$ and the distance $d$ between charge stripes in LSCO, where $\Phi_0$ is the fluxoid quantum. The $d$ obtained from neutron scattering decreases from the insulator-metal transition point to $x = 1/8$ and then keeps constant at $x > 1/8$. The $\xi$ is close to $d$ from the insulator-metal transition point to $x \approx 0.2$ and then increases as $x$ increases. The increase of $\xi$ at $x > 0.2$ may be caused by the shortening of stripes by the increased edge dislocation density.

Figure 3(b) shows the coherence length $\xi$ of hole-doped LSCO and electron-doped NCCO and PCCO. The coherence lengths of NCCO and PCCO are sited on a single curve. The $\xi$ of NCCO and PCCO is much longer than that of LSCO. The coherence length $\xi = 22$ nm at $x = 0.17$ approaches $\xi = 38$ nm of Nb. The stronger the binding energy is, the shorter the coherence length is. The clear difference between the striped and the non-striped cuprates indicates that the superconducting mechanism is related to the stripe in the hole-doped cuprate and different in the electron-doped cuprate.

Thus the proximity between $\xi$ and $d$ in LSCO indicates that the pairing is formed in the moving edge dislocation. The coherence length of LSCO at $x < 0.2$ is only twice the inter-hole distance on the assumption that holes are uniformly distributed. Therefore the superconducting state is in the crossover regime between BCS (Bardeen-Cooper-Schrieffer) and BEC (Bose-Einstein condensation). It is like a bipolaron, but the binding energy is related to the stripe formation energy rather than the electron-phonon interaction energy and the charge transfer direction is restricted to one direction for each pair.

In summary two kinds of magnetic Raman scattering mechanisms in the stripe state is confirmed by comparing the spectra in LSCO and NCCO. The magnetic excitations in LSCO are expressed by the individual energy dispersions in the $k\parallel$ stripe and the $k \perp$ stripe. The charge transfer is restricted in the direction perpendicular to the stripe. This direction is the same as the Burgers vector of the edge dislocation. Hence the charge transfer is assumed to be united with the edge dislocation. We propose a model that the superconducting pairs are formed in the edge dislocations, because the coherence length is close to the distance between the charge stripes.

References

1. H. Yoshizawa, S. Mitsuda, H. Kitazawa, and K. Katsumata, J. Phys. Soc. Jpn., 57, 3686 (1988).
2. R. J. Birgeneau, Y. Endoh, K. Kakurai, Y. Hidaka, T. Murakami, M. A. Kastner, T. R. Thurston, G. Shirane, and K. Yamada, Phys. Rev. B 39, 2868 (1989).

3. A. Bianconi, N. L. Saini, A. Lanzara, M. Missori, T. Rossetti, H. Oyanagi, H. Yamaguchi, K. Oka, and T. Ito, Phys. Rev. Lett. 76, 3412 (1996).

4. N. L. Saini, H. Oyanagi, T. Ito, V. Scagnoli, M. Filippi, S. Agrestini, G. Campi, K. Oka, and A. Bianconi, Eur. Phys. J. B 36, 75 (2003).

5. J. M. TranquadaCB. J. SternllebCJ. D. AxeCY. Naka-
mura, and S. Uchida, Nature 375, 561 (1995).

6. K. Yamada, C. H. Lee, K. Kurahashi, J. Wada, S. Wakimoto, S. Ueki, K. Kimura, Y. Endoh, S. Hosoya, G. Shirane, R. J. Birgeneau, M. Greven, M. A. Kastner, and Y. J. Kim, Phys. Rev. B 57, 6165 (1998).

7. M. Matsuda, M. Fujita and K. Yamada, R. J. Birgeneau, Y. Endoh, and G. Shirane, Phys. Rev. B, 65, 134515 (2002).

8. J. M. Tranquada, H. Woo, T. G. Perring, H. Goka, G. D. Gu, G. Xu, M. Fujita, and K. Yamada, Nature 429, 534 (2004).

9. M. Matsuda, M. Fujita, S. Wakimoto, J. A. Fernandez-Baca, J. M. Tranquada, and K. Yamada, Phys. Rev. Lett. 101, 197001 (2008).

10. J. Zaanen, O. Y. Osman, H. V. Kruis, Z. Nussinov,and J. Tworzydlo, Philos. Mag. B 81, 1485 (2001).

11. S. A. Kivelson, I. P. Bindloss, E. Fradkin, V. Oganesyan, J. M. Tranquada, A. Kapitulnik, and C. Howald, Rev. Mod. Phys., 75, 1201 (2003).

12. J. Zaanen, Z. Nussinov, and S. I. Mukhin, Ann. Phys. (NY) 310, 181 (2004).

13. M. Vojta, Adv. Phys., 58, 699 (2009).

14. S. Sugai, Y. Tamai, Y. Takayanagi, N. Hayamizu, and T. Murai, J. Supercond. Nov. Magn. 25, 1393 (2012).

15. G. Seibold, and J. Lorenzana, Phys. Rev. B 73, 144515 (2006).

16. G. Seibold, and J. Lorenzana, Phys. Rev. B 80, 012509 (2009).

17. K. Yamada, K. Kurahashi, T. Uefuji, M. Fujita, S. Park, S.-H. Lee, and Y. Endoh, Phys. Rev. Lett. 90, 137004 (2003).

18. G. Blumberg, M. Kang, M. V. Klein, K. Kadowaki, C. Kendzior, Science, 278, 1427 (1997).

19. J. G. Naeni, J. C. Irwin,T. Sasagawa, Y. Togawa, and K. Kishio, Canadian J. Phys. 78, 483 (2000).

20. B. Nachumi, C. Kendziora, N. Ichikawa, Y. Nakamura, S. Uchida, Phys. Rev. B 65, 092504 (2002).

21. S. Sugai, H. Suzuki, Y. Takayanagi, T. Hosokawa, N. Hayamizu, Phys. Rev. B 68, 184504 (2003).

22. L. H. Machtoub, B. Keimer, and K. Yamada, Phys. Rev. Lett. 94, 107009 (2005).

23. L. Tassini, W. Prestel, A. Erb, M. Lambacher, R. Hackl, Phys. Rev. B 78, 020511(R) (2008).

24. B. Muschler, W. Prestel, L. Tassini, R. Hackl, M. Lambacher, A. Erb, S. Komiya, Y. Ando, D. C. Peets, W. N. Hardy, R. Liang, and D. A. Bonn, Eur. Phys. J. Special Topics 188, 131 (2010).

25. S. Sugai, Y. Hidaka, Phys. Rev. B 44, 809 (1991).

26. I. Tomeno,M. Yoshida, K. Ikeda, K. Tai, K. Takamuku, N. Koshizuka, S. Tanaka, K. Oka, and H. Unoki, Phys. Rev. B 43, 3009 (1991).

27. Y. Onose, Y. Taguchi, K. Ishizaka, Y. Tokura, Phys. Rev. B 69, 024504 (2004).

28. E. Manousakis, Phys. Rev. B 75, 035106 (2007).

29. Y. Wang, and H.-H. Wen, Europhys. Lett. 81, 57007 (2008).

30. H. H. Wen, H. P. Yang, S. L. Li, X. H. Zeng, A. A. Souki-
assian, W. D. Si, and X. X. Xi, Europhys. Lett. 64, 790 (2003).

31. M. M. Qazilbash, A. Koitzsch, B. S. Dennis, A. Gozar, Hamza Balci, C. A. Kendziora, R. L. Greene, and G. Blumberg, Phys. Rev. B 72, 214510 (2005).

32. A. S. Alexandrov, J. Ranninger, and S. Robaszkiewicz, Phys. Rev. B 33, 4526 (1986).