= −40 V) to the tunneling regime (V_g = 0 V) evident in Fig. 3 is a consequence of the changes in interface transparencies as a function of gate voltage. This conclusion is consistent with the expected properties of 0.3-μm ballistic (*13*) SWNTs, where changes in Fermi energy induced by typical gate voltages [for example, ~0.4 eV at V_g = −40 V (*12*)] are insufficient to alter the populations of electronic subbands. It is also in agreement with recent numerical results on how interface transparency depends on the Fermi energy in metallic nanotubes (*18*).

At temperatures down to 4.2 K, the qualitative picture in which either Andreev or tunneling processes dominate transport (*15*) works well. As the temperature is lowered further, new features appear that cannot be explained within this picture. Specifically, below ~4 K, a narrow peak in dV/dI emerges around zero bias, superimposed on the Andreev dip (Fig. 5A). This peak grows as the temperature is lowered, and by 40 mK dominates dV/dI measurements for almost all values of gate voltage, except for a few small intervals of V_g where a dip at zero bias can still be observed (Fig. 5B). No such peak is expected within a noninteracting picture. Similar low-temperature behavior of the differential resistance has been observed in two-dimensional electron gases connected to superconductors (*19, 20*), and has been tentatively attributed to electron-electron interactions (*21*). Electron-electron interaction may also explain the absence of subharmonic structure in dV/dI due to multiple Andreev reflections (*17*) as well as the absence of a supercurrent.

From this perspective, the recently reported observation by Kasumov *et al.* of a supercurrent in an individual SWNT sample as well as in SWNT ropes with superconducting contacts (*10*) is remarkable. It is particularly notable that the individual SWNT described in (*10*) had a higher normal-state resistance than in the present experiment [26 kilohms, compared to <18 kilohms (*22*)], which works against a proximity-induced supercurrent within a conventional picture. The experimental situation suggests that the basic physical mechanism responsible for a supercurrent in SWNT remains to be sorted out. The ability to control superconducting correlations in one dimension will greatly facilitate future study of this interesting phenomenon.

References and Notes

1. See D. Esteve, H. Pothier, S. Gueron, N. O. Birge, M. H. Devoret, in *Mesoscopic Electron Transport*, L. L. Sohn, L. P. Kouwenhoven, G. Schon, Eds. (Kluwer, Dordrecht, Netherlands, 1997), pp. 375–406; B. J. van Wees and H. Takayanagi, *ibid.*, pp. 469–501.
2. V. J. Emery, in *Highly Conducting One-Dimensional Solids*, J. T. Devresee, R. E. Evrard, V. E. van Doren, Eds. (Plenum, New York, 1979), pp. 247–303; J. Voit, *Rep. Prog. Phys.* **57**, 977 (1994).
3. S. Iijima, *Nature* **354**, 56 (1991); ______ and T. Ichihashi, *ibid.* **363**, 603 (1993).
4. S. J. Tans *et al.*, *ibid.* **386**, 474 (1997).
5. M. Bockrath *et al.*, *Science* **275**, 1922 (1997).
6. S. J. Tans, M. H. Devoret, R. J. A. Groenveld, C. Dekker, *Nature* **394**, 761 (1998).
7. D. H. Cobden, M. Bockrath, P. L. McEuen, A. G. Rinzler, R. E. Smalley, *Phys. Rev. Lett.* **81**, 681 (1998).
8. M. Bockrath *et al.*, *Nature* **397**, 598 (1999).
9. A. Bachtold *et al.*, *ibid.*, p. 673.
10. A. Yu. Kasumov *et al.*, *Science* **284**, 1508 (1999).
11. J. Kong, H. T. Soh, A. M. Cassell, C. F. Quate, H. Dai, *Nature* **395**, 878 (1998); T. H. Soh *et al.*, *Appl. Phys. Lett.* **75**, 627 (1999).
12. The capacitive coupling between the gate and the SWNTs can be estimated from the results of (*7*), which had a sample geometry essentially identical to ours. From those results, we infer that a change in gate voltage of 1 V corresponds to a change in Fermi energy of roughly 10 meV.
13. The present fabrication method yields low-resistance SWNTs over a broad range of tube lengths up to ~10 μm (A. F. Morpurgo *et al.*, unpublished data), with no apparent correlation between resistance and length. This suggests that electrons move ballistically in the tube, and that the measured resistance is dominated by the contacts.
14. M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, ed. 2, 1996).
15. G. E. Blonder, M. Tinkham, T. M. Klapwijk, *Phys. Rev. B* **25**, 4515 (1982).
16. A. F. Andreev, *Zh. Eksp. Teor. Fiz.* **46**, 1823 (1964) [*Sov. Phys. JETP* **19**, 1228 (1964)].
17. M. Octavio, M. Tinkham, G. E. Blonder, T. M. Klapwijk, *Phys. Rev. B* **27**, 6739 (1983).
18. A. Rochefort, F. Lesage, D. R. Salahub, P. Avouris, preprint available at http://xxx.lanl.gov/abs/cond-mat/9904083. See the discussion on page 2.
19. See, for instance, figure 3A in H. Takayanagi and T. Akazaki, *Physica B* **249–251**, 462 (1998); J. P. Heida, thesis, University of Groningen (1998).
20. S. G. den Hartog, thesis, University of Groningen (1998).
21. See (*20*); for a possible theoretical explanation of the observations made on two-dimensional electron gases, see Y. Oreg, P. W. Brouwer, B. D. Simons, A. Altland, *Phys. Rev. Lett.* **82**, 1269 (1999).
22. For instance, in sample 2, three SWNTs in parallel gave a low-temperature resistance of 6 kilohms, implying that at least one of the three tubes is below 18 kilohms. Similar values below 20 kilohms can be inferred for the other samples as well.

23. We thank B. J. van Wees for useful discussions, and N. Iosad and D. Wilms Floet for high-quality Nb sputtering. Supported by the NSF Presidential Faculty Fellowship program (grant DMR-9629180-1), the NSF Partnership for Nanotechnology program (grant ECS-9871947), the Stanford Center for Materials Research (an NSF-Materials Research Science and Engineering Center), the National Nanofabrication Users Network (funded by NSF grant ECS-9731294), the Camile Henry-Dreyfus Foundation, and the American Chemical Society.

9 June 1999; accepted 31 August 1999

Evidence for One-Dimensional Charge Transport in $La_{2-x-y}Nd_ySr_xCuO_4$

Takuya Noda, Hiroshi Eisaki, Shin-ichi Uchida

Doping dependences of the resistivity and the Hall coefficient are presented for neodymium-doped lanthanum strontium cuprate ($La_{1.4-x}Nd_{0.6}Sr_xCuO_4$) in the static spin-charge stripe ordered phase. For doping concentration $x \leq 1/8$, a rapid decrease in the magnitude of the Hall coefficient at low temperatures provides evidence for one-dimensional charge transport, whereas for $x > 1/8$, the Hall coefficient remains relatively large in the ordered phase. The results indicate a crossover from one- to two-dimensional charge transport taking place at $x = 1/8$.

The one-dimensional (1D) spin-charge density modulations in the two-dimensional (2D) CuO_2 planes, or stripe phase, was proposed by Tranquada *et al.* (*1*) to account for the anomalous behavior in $La_{2-x-y}Nd_ySr_xCuO_4$ (*2*), in which slight changes in the crystal structure lead to suppression of the superconductivity. Elastic neutron scattering experiments on $La_{2-x-y}Nd_ySr_xCuO_4$ (LNSCO) with x near the "magic number"—1/8—have demonstrated that the compound exhibits spin-charge order with the periodicity eight and four times that of the lattice unit cell, respectively (*1*). Similar spin-charge orders have been observed for other values of x (*3*), where the periodicity of the static spin correlation has almost the same x dependence as that observed in the incommensurate inelastic neutron scattering peaks in $La_{2-x}Sr_xCuO_4$ (LSCO) (*4*), suggesting that spin-charge modulations exist in superconducting LSCO. Furthermore, recent neutron-scattering experiments on $YBa_2Cu_3O_{7-y}$ (*5*) and $Bi_2Sr_2CaCu_2O_8$ (*6*) suggest that the stripe fluctuations may be inherent to the doped CuO_2 planes. The possibility of the formation of stripes had been discussed before these new findings (*7*) and it is proposed that the dynamic stripe fluctuation is a possible driving force for high-temperature superconductivity (HTSC) (*8*).

However, in spite of the accumulated interest, because of a lack of direct evidence for one-dimensionality, full consensus on the existence of spin-charge stripes has not been established. The difficulty is that the spin-charge stripes in the adjacent CuO_2 plane are directed by 90° to each other, as suggested from the neutron and x-ray scattering measurements (*1*,

Department of Superconductivity, The University of Tokyo, Tokyo 113-8656, Japan.

9), and what we see in the transport (*10, 11*), magnetic (*3*), and optical (*12*) measurements is essentially the average of the two orientations.

The Hall effect measurement has the ability to detect the 1D charge dynamics. When a sample is placed in a longitudinal electric field, E_x, and a transverse magnetic field, B_z, a transverse (Hall) electric field, E_y, is generated because of the carrier accumulation on one face of the sample. The Hall effect arises from finite off-diagonal conductivity σ_{xy}, with the Hall coefficient R_H defined as $R_H = E_y/j_xB_z = \rho_{yx}/B_z$, where $\rho_{yx} = \sigma_{xy}/(\sigma_{xx}\sigma_{yy} - \sigma_{xy}\sigma_{yx})$ ($\sigma_{xx} = j_x/E_x$, $\sigma_{yy} = j_y/E_y$; diagonal conductivity).

Considering a bundle of independent 1D strings, we should not expect any off-diagonal conductivity, as the carriers cannot hop to the adjacent strings. This would be the case if the stripes were really 1D in whichever direction they are oriented in each plane. Therefore, we might be able to obtain the direct evidence for or against 1D charge dynamics from the behavior of σ_{xy}.

Based on the above strategy, we have investigated the resistivity and the Hall coefficient of LNSCO single crystals as a function of doping concentration with $x = 0.10$, 0.12, 0.13, and 0.15. Single crystals of $La_{1.4-x}Nd_{0.6}Sr_xCuO_4$ were grown by the traveling-solvent floating zone method (*10*). In this study, we fixed Nd content to $y = 0.6$ instead of $y = 0.4$, the value frequently used in previous studies. For $y = 0.4$, the way the spin-charge orders develop with temperature has been extensively investigated by neutron scattering (*1, 3*), x-ray scattering (*9*), and ^{63}Cu nuclear quadrupole resonance (NQR) (*13*) measurements. From these measurements, the charge order for $x = 0.10$ and 0.12 appears at temperatures close to the structural-phase transition temperature (T_0) [low-temperature orthorhombic (LTO) − low-temperature tetragonal (LTT) for $x = 0.12$; LTO–*Pccn* (a space-group symmmetry) for $x = 0.10$] and that for $x = 0.15$ appears 10 K below T_0 (LTO–LTT). The LTT and *Pccn* structures favor the stripe order as they can pin down the vertical or horizontal stripe-type charge modulation. All the crystals investigated here show a transition to the LTT phase, so we can conclude that the $y = 0.6$ crystals have essentially the same spin-charge order. The advantage of studying $y = 0.6$ crystals is that we can avoid the possible complexity due to the different crystal structures for different values of x because for $x = 0.10$ the LTT phase appears only when y exceeds 0.4 (*14, 15*). Resistivity and the Hall coefficient measurements are done by the standard direct current six-probe method. The superconducting transition temperature (T_c) is estimated from a SQUID (superconductivity quantum interference device) measurement.

The in-plane resistivity ρ_{ab} (Fig. 1) for four Sr compositions exhibits a jump at doping-dependent temperature T_0 [74 K ($x = 0.10$), 78 K ($x = 0.12$), 80 K ($x = 0.13$), 84 K ($x = 0.15$)], in good agreement with previous results on polycrystalline samples (*11, 14*).

Above T_0, ρ_{ab} shows the same temperature (T) dependence as that of LSCO (*16*), indicating that the charge dynamics in LNSCO is essentially identical to that of Nd-free LSCO. Below T_0, increases of ρ_{ab} with lowering temperature, which are most evident for $x = 0.15$, discriminate the charge transport of the spin-charge-ordered phase from the normal phase of HTSC (*17*).

In spite of the change in the T dependence below T_0, it should be mentioned that ρ_{ab} in LNSCO shares a common behavior with that of LSCO. The jump in ρ_{ab} at T_0 is small—at most 5% of the value above T_0—and the magnitude of resistivity stays low, well below the critical value for the Anderson localization, which corresponds to $\rho_{ab} \approx 1.5$ mΩ cm in this case (*10*). Low resistivity in the charge-ordered phase is unique to cuprate and in dramatic contrast to other transition-metal oxides such as $La_{5/3}Sr_{1/3}NiO_4$ (*18*) and $Nd_{1/2}Sr_{1/2}MnO_3$ (*19*), which also exhibit stripe orders. In both cases, the increases in resistivity by several orders upon charge ordering means that the charge degrees of freedom are quenched because of the ordering. On the other hand, these results suggest that the charge excitations are nearly gapless in the spin-charge ordered state, consistent with the recent optical

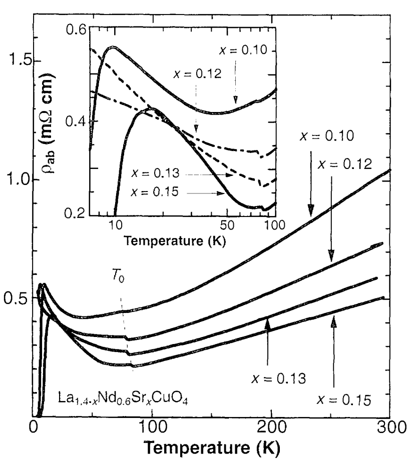
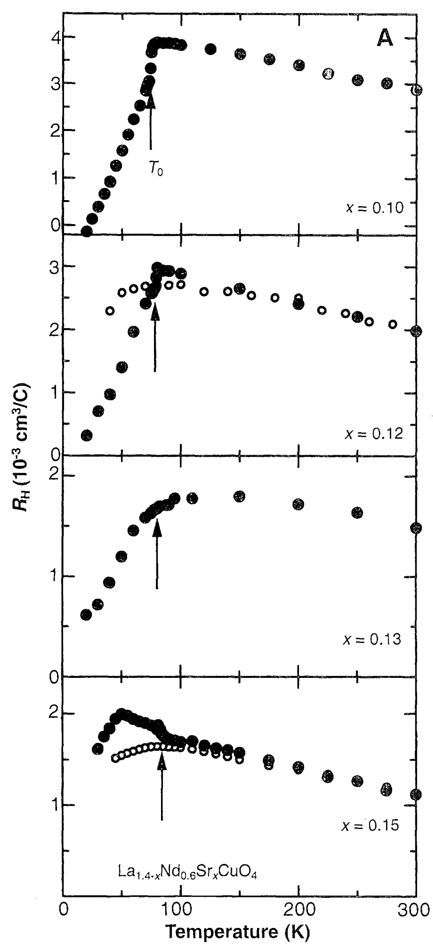


Fig. 1. Temperature dependence of in-plane resistivity (ρ_{ab}) of $La_{1.4-x}Nd_{0.6}Sr_xCuO_4$ with $x = 0.10$, 0.12, 0.13, and 0.15. (**Inset**) ρ_{ab} plotted on a logarithmic T scale. T_0 values of the samples are marked with a dashed line.



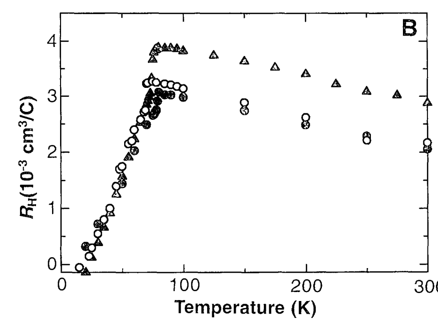


Fig. 2. (**A**) Temperature dependence of R_H for $x = 0.10$, 0.12, 0.13, and 0.15 (top to bottom) measured at a magnetic field (5 T) parallel to the c axis with the current along the CuO_2 plane. Arrows indicate T_0. For comparison, R_H values for LSCO for $x = 0.12$ and 0.15 are also plotted (open circles). (**B**) Temperature dependence of R_H for $x = 0.10$ (triangles) and 0.12 (closed circles) with $y = 0.6$ and for $x = 0.12$ with $y = 0.4$ (open circles).

reflectivity measurement (*12*). There is no appreciable difference in the optical conductivity in the far-infrared region between LNSCO and LSCO even below T_0.

Another similarity we find is nearly logarithmic T dependence of ρ_{ab} of LNSCO, which is seen for underdoped LSCO when its superconductivity is suppressed by strong magnetic fields (*20*). The similarity suggests that the carriers in the ordered phase have characteristics similar to those in LSCO with suppressed superconductivity.

The doping dependence of ρ_{ab} does not show any distinct behavior at $x = 1/8$ but monotonically changes with x. Indeed, a slope of logarithmic T dependence of ρ_{ab} increases with x. In this sense, 1/8 cannot be regarded as a singular point as far as the longitudinal charge transport is concerned (*11*).

Above T_0, R_H is almost the same as that for Nd-free compounds in both magnitude and T dependence (Fig. 2A). Below T_0, for $x \leq 1/8$, R_H shows a rapid decrease, after a small discontinuous drop at T_0, approaching zero at low temperatures. This decrease has nothing to do with superconductivity, because it takes place well above resistive T_c (*21*), and the values are independent of magnetic fields. Such a radical decrease of R_H was reported earlier for LNSCO with Nd = 0.4 and Sr = 0.12 (Fig. 2B) (*10*) and for polycrystals of $La_{1.875}Ba_{0.125}CuO_4$ (*22*). Thus, this behavior is characteristic of the spin-charge-ordered phase for $x \leq 1/8$.

For $x = 0.13$, with only a 1% increase of doping, R_H does not show such a remarkable change below T_0. The decrease of R_H below T_0 is gradual and R_H preserves finite values even at the lowest temperature. For $x = 0.15$, R_H continues to increase across T_0, which is opposite that for $x \leq 1/8$, ending up at a fairly large value, comparable with that at 200 K.

One may suppose that the decrease of R_H results from a change in the Fermi surface associated with the stripe order and an accidental cancelation between contributions from hole and electron surfaces. However, it is unlikely in this case because such a picture requires a subtle balance of the two contributions. Such a subtle balance would be easily lost by a weak perturbation, such as a change in x or y, which contradicts the robustness of these results against the change in x and y. As shown in Fig. 2B, the T dependence of R_H below T_0 is essentially the same for $x = 0.12$ with $y = 0.4$ and 0.6 as well as $x = 0.10$ with $y = 0.6$ (*10*).

To ensure that the decrease of R_H results from a disruption of transverse charge transport in the stripe phase, we calculate σ_{xx} and σ_{xy}; $\rho_{xx} = \rho_{yy}$ and $\rho_{xy} = -\rho_{yx}$ as the system has a fourfold symmetry within the x-y plane. We observe that $\rho_{xy}(B) \ll \rho_{xx}(B)$ and magnetoresistance is extremely small, with $[\rho_{xx}(B) - \rho_{xx}(B = 0)]/\rho_{xx}(B = 0) < 0.5\%$ at $B = 5$ T over the whole T range. Therefore, we can derive σ_{xx} and σ_{xy} from $\sigma_{xx}(B) = 1/\rho_{xx}(B) = 1/\rho_{ab}(B = 0)$ and $\sigma_{xy}(B) = R_H B/\rho_{ab}(B = 0)^2$. The T dependence of σ_{xx} and σ_{xy} for $x = 0.12$ are shown in Fig. 3, which indicates that σ_{xy} decreases approximately linearly in temperature below T_0, approaching to 0 as $T \to 0$. On the other hand, σ_{xx} keeps large values even at the lowest temperature. The reduction of σ_{xy} clearly demonstrates that the charge order causes suppression of the transverse motion of the carriers.

We can demonstrate the direct relationship between the reduction of σ_{xy} and the development of charge order. In the same figure, we overlay the intensity of the charge-order peak (I_c) observed in the x-ray diffraction for a crystal with $x = 0.12$ and $y = 0.4$ measured by Zimmermann *et al.* (*9*) after reasonable rescaling (*23*). Both quantities show essentially the same T dependence with each other. This is evidence that the suppression of σ_{xy} is due to the charge order.

The reduction of σ_{xy} seen for $x \leq 1/8$ is associated with suppression of the cyclotron motion due to confinement of carriers within 1D charge stripes (*24*). In contrast, σ_{xy} for $x = 0.13$ and 0.15 has finite values even at the lowest temperatures well below T_0, indicating that the charge transport for $x > 1/8$ sustains a 2D nature, as in the HTSCs. In this sense, the observed change when we go through 1/8 is a 1D-2D crossover. Strictly, a truly 1D state would be realized at the lowest temperature near $T = 0$ where σ_{xy} would vanish. Figure 3 indicates that the 1D state is not robust against increasing temperature, which strongly reflects the fluctuating nature of the charge stripes.

A question that follows is whether we can affiliate these experimental observations with the results of the scattering experiments (*2*–*4*). The low-energy magnetic scattering in LSCO, which is characterized by the 2D antiferromagnetic wave vector $Q_{AF} = (1/2,1/2)$, at very low doping, shifts to positions $(1/2 \pm \varepsilon, 1/2)$ and $(1/2, 1/2 \pm \varepsilon)$ incommensurate with the underlying lattice, with the linear relationship between ε and x ($\varepsilon \sim x$) for $0.05 < x \leq 1/8$. For $x > 1/8$, ε tends to saturate, keeping the value around 1/8. This relation of ε and x is followed exactly by the elastic peaks in LNSCO. That $x = 1/8$ is regarded as the crossover point in the spin dynamics of L(N)SCO indicated by these results is consistent with 1D-2D crossover in the charge dynamics.

According to the stripe picture, the incommensurability ε represents an interstripe distance of l, with the relation $l = a/2\varepsilon$ (where a is the in-plane lattice constant). At $x = 1/8$ the half-occupied charge stripes (one hole resides at every two Cu sites on the charge stripe) form a regular array with the interstripe spacing $4a$. The linear relationship between ε and x for $x \leq 1/8$ indicates that the interstripe distance is inversely proportional to the hole number and hence the occupancy of the holes within each charge stripe remains constant. In such a case, holes would be able to move along each stripe because they have a degree of freedom at the single-stripe level, although a charge-density-wave or spin-density-wave instability should dominate at $T = 0$ according to the conventional physics of 1D metals (*8*). On the other hand, hopping of holes between the charge stripes will be severely suppressed because the holes have to traverse the hole-depleted spin domains (*25*).

The saturation of ε for $x > 1/8$ indicates that the interstripe cannot be shorter than $4a$. Excess holes either should be accommodated into charge domains, which are already half-occupied, or should overflow into spin domains. In either case, each stripe can no longer be regular. Charge stripes would broaden and penetrate into spin domains or would be bent in order to put in all carriers (*26*). Then there might arise extra stripe pathways running along the perpendicular direction. All these effects would violate the one-dimensionality. As a result, holes become able to hop between charge stripes, thus making σ_{xy} and R_H finite (*27*).

Finally, we discuss the transport properties of the normal CuO_2 planes without static stripe order. We have pointed out that the longitudinal charge transport in the spin-charge-ordered phase is apparently different from that of the normal states of HTSC, but the differences are small. The magnitude of resistivity is nearly the same and a logarithmic increase of resistivity is also observed for LSCO when its superconductivity is suppressed by strong magnetic fields. In addition, a quasi-static spin-charge order has been observed in LSCO for $x \leq 1/8$ by the elastic neutron-scattering experiment (*28*) and more recently by the ^{63}Cu NQR measurement (*29*). All these results strongly suggest that the stripe order readily shows up in the normal state of lanthanum cuprates and hence the stripe

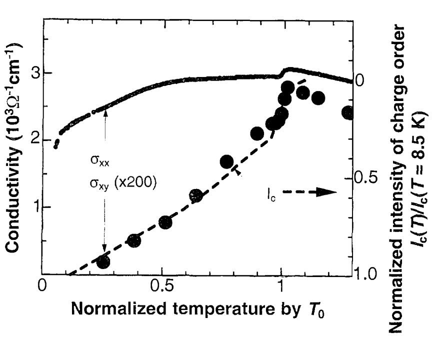


Fig. 3. Temperature dependence of σ_{xy} (closed circles) and σ_{xx} (dots) for $x = 0.12$ and $y = 0.6$. σ_{xy} is multiplied by 200 in this plot. The intensity of the charge satellite peaks (I_c) for $x = 0.12$ and $y = 0.4$ (dashed line) is superimposed on the σ_{xy} data. Note that I_c is plotted with the vertical axis upside down and temperature is normalized by T_0 ($T_0 = 78$ K for $x = 0.12$ and $y = 0.6$; $T_0 = 68$ K for $x = 0.12$ and $y = 0.4$).

fluctuation may play an important role in the low-energy charge and spin dynamics, at least in this class of high-T_c cuprates.

References and Notes

1. J. M. Tranquada, B. J. Stemlieb, J. D. Axe, Y. Nakamura, S. Uchida, *Nature* **375**, 561 (1995); J. M. Tranquada *et al.*, *Phys. Rev. B* **54**, 7489 (1996).
2. M. K. Crawford *et al.*, *Phys. Rev. B* **44**, 7749 (1991).
3. J. M. Tranquada *et al.*, *Phys. Rev. Lett.* **78**, 338 (1997); J. M. Tranquada, N. Ichikawa, S. Uchida, unpublished data.
4. S-W. Cheong *et al.*, *Phys. Rev. Lett.* **67**, 1791 (1991); T. E. Mason *et al.*, *ibid.* **71**, 919 (1993); K. Yamada *et al.*, *Phys. Rev. B* **57**, 6165 (1998).
5. H. A. Mook *et al.*, *Nature* **395**, 580 (1998).
6. H. A. Mook, F. Doğan, B. C. Chakoumakos, preprint available at http://xxx.lanl.gov/abs/cond-mat/9811100.
7. J. Zaanen and O. Gunnarsson, *Phys. Rev. B* **40**, 7391 (1989); K. Machida, *Phys. C* **158**, 192 (1989); V. J. Emery and S. A. Kivelson, *ibid.* **209**, 597 (1993).
8. A. H. Castro Neto, *Phys. Rev. Lett.* **78**, 3931 (1997); S. A. Kivelson, E. Fradkin, V. J. Emery, *Nature* **393**, 550 (1998).
9. M. v. Zimmermann *et al.*, *Europhys. Lett.* **41**, 629 (1998); T. Niemöller *et al.*, preprint available at http://xxx.lanl.gov/abs/cond-mat/9904383.
10. Y. Nakamura and S. Uchida, *Phys. Rev. B* **46**, 5841 (1992).
11. M. Hüker *et al.*, *J. Phys. Chem. Solids* **59**, 1821 (1998).
12. S. Tajima *et al.*, *ibid.*, p. 2015.
13. P. M. Singer, A. W. Hunt, T. Imai, preprint available at http://xxx.lanl.gov/abs/cond-mat/9906140.
14. B. Büchner, M. Breurer, A. Freimuth, A. P. Kampf, *Phys. Rev. Lett.* **73**, 1841 (1994).
15. Another advantage we have expected is that we may increase the stability (or pinning strength) of the spin-charge order by using more Nd. Also, we suspect that we have suppressed T_c more to enable the measurements of transport properties to be extended to lower temperatures.
16. Y. Nakamura and S. Uchida, *Phys. Rev. B* **47**, 8369 (1993).
17. As for the superconductivity in the ordered phase, T_c values for all values of x are less than 1.8 K, as estimated by magnetic susceptibility measurements. Apparent T_c at higher temperatures for $x = 0.10$ and $x = 0.15$ presumably comes from a slight inhomogeneity in Nd composition in a crystal.
18. S-W. Cheong *et al.*, *Phys. Rev. B* **49**, 7088 (1994).
19. H. Kuwahara *et al.*, *Science* **272**, 80 (1996).
20. Y. Ando, G. S. Boebinger, A. Passner, T. Kimura, K. Kishio, *Phys. Rev. Lett.* **75**, 4662 (1995); G. S. Boebinger *et al.*, *ibid.* **77**, 5417 (1996).
21. We could not reliably measure R_H at low temperatures because the measurement of R_H has been hindered by the small superconducting signal within the samples, which produces an extra voltage change caused by the magnetic field.
22. M. Sera *et al.*, *Solid State Commun.* **69**, 851 (1989).
23. Use of other data, such as those from neutron diffraction experiments, does not result in any difference in our analysis. In addition, the difference in Nd composition does not affect our conclusion; we reached the same conclusion with $y = 0.4$ data for σ_{xx} and σ_{xy}.
24. It should be noted that R_H is not a truly macroscopic measure of the one-dimensionality of the system. The disappearance of R_H would be realized if the length scale of the 1D segments was larger than the characteristic length scales for one-dimensionality, such as magnetic length or the mean free path.
25. We think longitudinal transport to the stripe direction is more conductive than transverse transport. However, we cannot rule out the possibility that charges are more mobile in the transverse direction (J. Zaanen, personal communication).
26. H. Eskes, O. Y. Osman, R. Grimberg, W. v. Saarloos, J. Zaanen, *Phys. Rev. B* **58**, 6963 (1998).
27. A similar picture is proposed and discussed theoretically in (8), where "dynamic" stripes, which interact with each other, are discussed.
28. T. Suzuki *et al.*, *Phys. Rev. B* **57**, 3229 (1998); H. Kimura *et al.*, *ibid.* **59**, 6517 (1999).
29. A. W. Hunt, P. M. Singer, K. R. Thurber, T. Imai, *Phys. Rev. Lett.* **82**, 4300 (1999).

30. Supported by a Grant-in-Aid for Scientific Research and a COE grant from the Ministry of Education, Japan. We acknowledge useful discussions with A. Fujimori, K. Hirota, N. Ichikawa, T. Imai, A. Ino, K. M. Kojima, A. Maeda, N. Nagaosa, S. Tajima, J. M. Tranquada, K. Yamada, and J. Zaanen.

19 May 1999; accepted 18 August 1999

One-Dimensional Electronic Structure and Suppression of *d*-Wave Node State in $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$

X. J. Zhou,[1,2] P. Bogdanov,[1] S. A. Kellar,[1] T. Noda,[3] H. Eisaki,[3] S. Uchida,[3] Z. Hussain,[2] Z.-X. Shen[1]*

Angle-resolved photoemission spectroscopy was carried out on $(La_{1.28}Nd_{0.6}Sr_{0.12})CuO_4$, a model system of the charge- and spin-ordered state, or stripe phase. The electronic structure contains characteristic features consistent with other cuprates, such as the flat band at low energy near the Brillouin zone face. However, the low-energy excitation near the expected *d*-wave node region is strongly suppressed. The frequency-integrated spectral weight is confined inside one-dimensional segments in the momentum space (defined by horizontal momenta $|k_x| = \pi/4$ and vertical momenta $|k_y| = \pi/4$), deviating strongly from the more rounded Fermi surface expected from band calculations. This departure from the two-dimensional Fermi surface persists to a very high energy scale. These results provide important information for establishing a theory to understand the charge and spin ordering in cuprates and their relation with high-temperature superconductivity.

The stripe phase (*1*, *2*), which has attracted considerable attention in connection with recent neutron-scattering data from Nd-substituted $(La_{1.48}Nd_{0.4}Sr_{0.12})CuO_4$ (Nd-LSCO) (*3*), represents a new paradigm for thinking about charge carriers in a solid. Unlike conventional metals in which the charge distribution is homogeneous, the stripe picture asserts that the charge carriers are segregated into one-dimensional (1D) domain walls. At the same time, the electronic spins in the domain between the walls order antiferromagnetically with a π phase shift across the domain wall. The possibility of charge segregation propensity and its implications on conduction as well as superconducting mechanism are at the heart of the current debate in high-temperature superconductivity research (*1–24*). Within the context of stripe picture, it is a formidable task to develop a theory describing the electronic structure that provides the microscopic foundation to understand the physical properties. The difficulty stems from the fact that our theoretical machineries are developed either in real space or in momentum (k) space. For an inhomogeneous system like the charge-ordered state, a hybrid description appears to be necessary. This is even more difficult when the strong many-body effects have to be taken into account. So far, little information about the electronic structure of the stripe phase is available. In this report, angle-resolved photoemission data are reported for Nd-LSCO, a model compound for which the evidence for spin and charge ordering is the strongest (*3*). We discuss these results both in terms of the k-space language, which is commonly used to describe the electronic structure of solids, and in terms of a hybrid of the real space and k-space picture. These results may provide a phenomenological foundation to build a comprehensive theory on the charge and spin ordering in cuprates and their relation with superconductivity.

Angle-resolved photoemission spectroscopy (ARPES) measures the single-particle spectral function $A(k, \omega)$ weighted by the photoionization cross section (*25*). Typical spectra of Nd-LSCO (Fig. 1) were sampled from the first and fourth quadrants of the Brillouin zone (BZ) at a temperature of 20 K (*26*). Although the spectra do not contain sharp peak structure, the data still show edge or cusplike structures with clear

[1]Department of Physics, Applied Physics and Stanford Synchrotron Radiation Laboratory, Stanford University, Stanford, CA 94305, USA. [2]Advanced Light Source, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA. [3]Department of Superconductivity, University of Tokyo, Yayoi 2-11-16, Bunkyo-ku, Tokyo 133, Japan.

*To whom correspondence should be addressed. E-mail: zxshen@stanford.edu

Evidence for One-Dimensional Charge Transport in La _{2-x-y} Nd_ySr_xCuO₄

Takuya Noda; Hiroshi Eisaki; Shin-ichi Uchida

Science, New Series, Vol. 286, No. 5438. (Oct. 8, 1999), pp. 265-268.

Stable URL:

http://links.jstor.org/sici?sici=0036-8075%2819991008%293%3A286%3A5438%3C265%3AEFOCTI%3E2.0.CO%3B2-8

References and Notes

[19] **Striction-Coupled Magnetoresistance in Perovskite-Type Manganese Oxides**

H. Kuwahara; Y. Tomioka; Y. Moritomo; A. Asamitsu; M. Kasai; R. Kumai; Y. Tokura

Science, New Series, Vol. 272, No. 5258. (Apr. 5, 1996), pp. 80-82.

Stable URL:

http://links.jstor.org/sici?sici=0036-8075%2819960405%293%3A272%3A5258%3C80%3ASMIPMO%3E2.0.CO%3B2-4