SPIN DENSITY WAVE ORDER IN THE SUPERCONDUCTING STATE OF La_2CuO_{4+Y}

In the high temperature (high-T_c) superconductors, the multiple roles played by the electrons continue to defy theoretical understanding. It appears that all high-T_c superconductors are based on structures with CuO_2 planes, in which the electrons on neighboring copper ions are strongly coupled magnetically. In systems based on La_2CuO_4, antiferromagnetism is a dominant feature of the phase diagram at low doping levels, and conventional itinerant-electron behavior dominates in the high doping regime. Intermediate doping levels are described by neither, but this is where the superconducting properties are optimal. In our experiments, we focus on the evolution of magnetic properties from the insulating antiferromagnet to the superconductor.

It is becoming increasingly apparent that incommensurate spin structures are universal to the high-T_c superconductors. Especially noteworthy is the observation of static incommensurate magnetic ordering coexisting with superconductivity in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ and recently in $La_{2-x}Sr_xCuO_4$ [1, 2]. Further experiments are needed to understand the coexistence of the incommensurate spin density waves (SDW) and superconductivity, the details of the spin structure, and the influence of pinning potentials.

A crystal of La_2CuO_{4+y} with a superconducting transition at $\approx$ 42 K was produced by doping pure La_2CuO_4 electrochemically with a large quantity of excess oxygen ($y \approx 0.12$). The superconducting shielding signal measured after cooling in zero field is shown in Fig. 1a. The transition is very sharp with an onset $T_c \approx 42$ K. Our initial characterization suggests that the crystal is a bulk superconductor with a hole concentration similar in density and homogeneity to that of $La_{2-x}Sr_xCuO_4$ crystals with $x \approx 0.15$.

At temperatures below the superconducting T_c, we observe elastic magnetic scattering at a quartet of incommensurate positions centered around (100), which is the Bragg position for the antiferromagnetism in the undoped insulator. Surprisingly, we find that the incommensurate wavevectors are not precisely along the Cu-O-Cu bond direction, but are rotated by about 3°.

In Fig. 2a we show elastic scans along the in-plane *h* direction through an incommensurate position for various temperatures using 5 meV neutrons. Below 42 K, the observed peaks are extremely sharp and are resolution-limited, while above 42 K

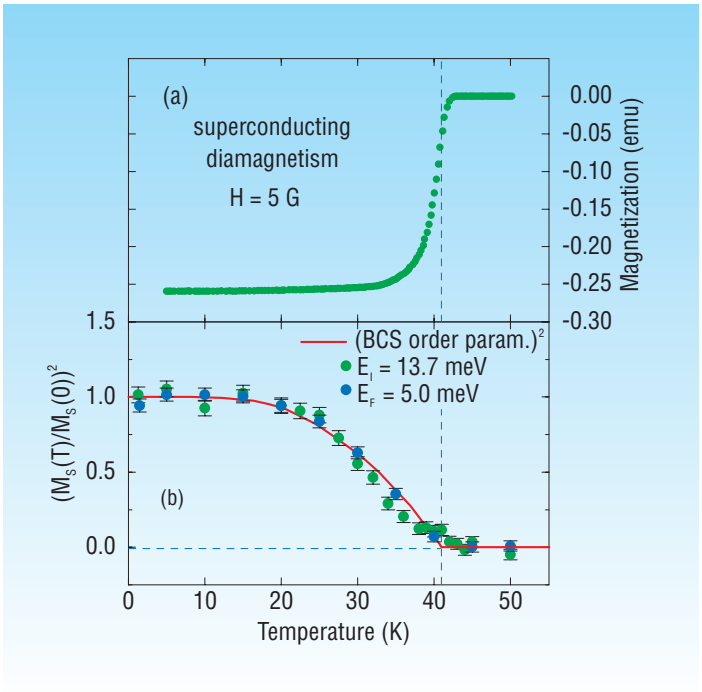

FIGURE 1. (a) Magnetic susceptibility measured after cooling in zero field. (b) Peak intensity of the incommensurate elastic scattering as a function of temperature. The measurement was performed with two different neutron energies of 13.7 meV and 5 meV. The solid line denotes the BCS superconducting order parameter squared, with a T_c of $\approx$ 41 K.

the peaks disappear. The solid lines in the figure are Gaussians convolved with the instrumental resolution which indicate that the in-plane static magnetic order is correlated over distances larger than 400 Å. From this, we conclude that static long-range magnetic order exists in the superconducting state of La_2CuO_{4+y}. Also, the SDW order is not specific to a tetragonal crystal structure as previously believed since this crystal is orthorhombic; it is a more general phenomenon.

We then investigated how the static spin arrangement is correlated between CuO_2 planes. The *l*-dependence of the incommensurate scattering is shown in Fig. 2b. The intensity modulation of both the (10*l*)- and (01*l*)-centered scattering is reminiscent of the spin structure of the undoped parent compound La_2CuO_4. The solid lines in both panels represent fits to Gaussian lineshapes convolved with the instrumental resolution, assuming a model for the stacking arrangement and spin direction identical to that of pure La_2CuO_4.

Y. S. Lee, R. J. Birgeneau, and M. A. Kastner
Department of Physics
Massachusetts Institute of Technology
Cambridge, MA 02139

Y. Endoh, S. Wakimoto, and K. Yamada
Department of Physics
Tohoku University
Aramaki Aoba
Sendai 980-77, Japan

R. W. Erwin and S.-H. Lee
NIST Center for Neutron Research
National Institute of Standards and Technology
Gaithersburg, MD 20899-8562

G. Shirane
Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

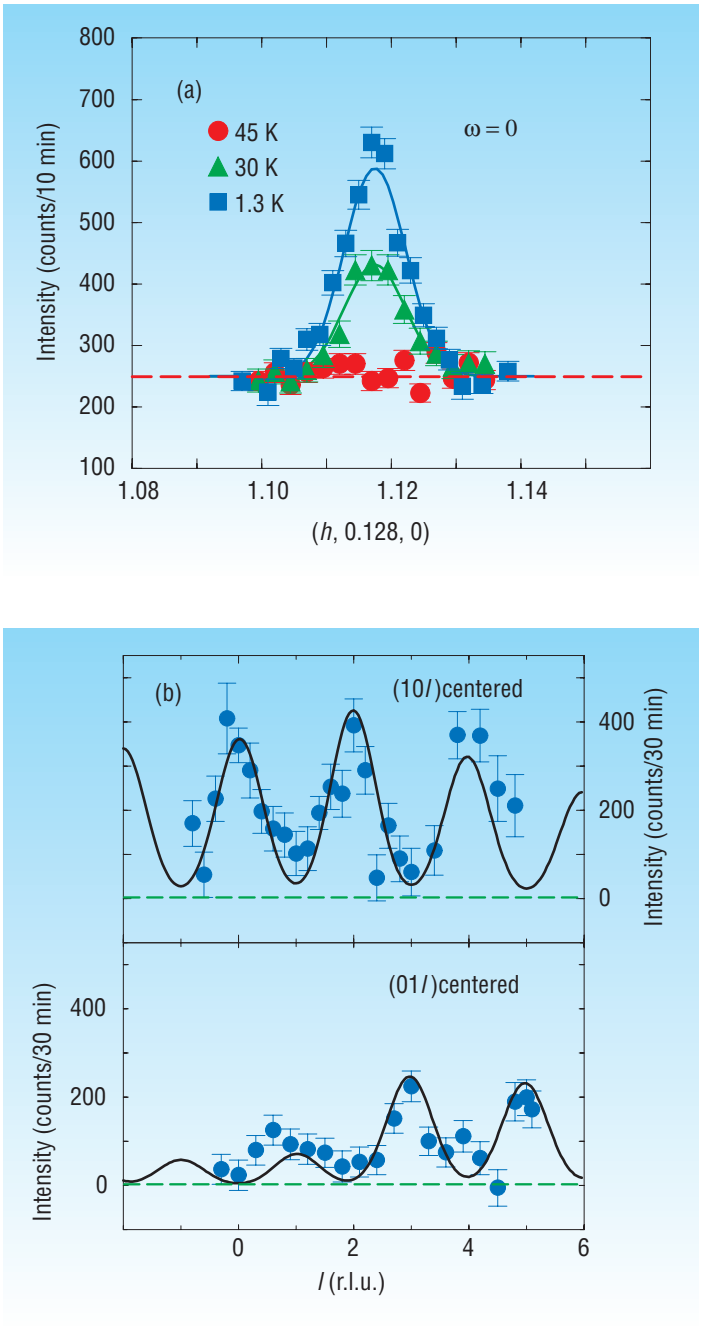

FIGURE 2. (a) Scans along the in-plane H direction over one of the incommensurate SDW peaks for various temperatures. (b) The top panel shows the *l*-dependence of the SDW scattering centered about the (10*l*) position. The bottom panel shows scattering centered about the (01*l*) position.

Here, the only free parameters are the width and a single overall intensity scale factor. The agreement is clearly satisfactory, with the fit indicating that the spins are correlated across ≈ 3 CuO_2 planes. We conclude that the stacking arrangement of the magnetically ordered planes in our La_2CuO_{4+y} sample follows that of undoped insulating La_2CuO_4, even though the magnetic order in the CuO_2 planes is incommensurate. This is the first direct evidence that the magnetism of the doped superconductor mimics the magnetism in the undoped insulator in such a specific way.

We show in Fig. 1b the peak intensity of the elastic signal as a function of temperature measured using both 13.7 meV and 5 meV neutrons. The fact that one obtains identical results for the temperature dependences of the intensities with these two different neutron energies and, concomitantly, energy resolutions indicates that the scattering is truly elastic. The intensity of the elastic scattering turns on at approximately the same transition temperature as superconductivity. Noting that the intensity of the magnetic scattering is proportional to the square of the magnetic order parameter, we plot the square of the BCS order parameter curve over the data using a T_c of ≈ 41 K. The agreement indicates that the magnetism exhibits mean field behavior just like conventional superconductivity. This is very surprising given the two dimensionality of the ordered magnetism. The size of the ordered moment is 0.15 μ_B, which is 25 % of the ordered moment in pure La_2CuO_4. Our results argue against an itinerant electron description of the incommensurate magnetism since it is difficult to see how a delocalized model can support interplanar spin correlations and choose the same preferred spin direction as in insulating La_2CuO_4. It appears that the spins are localized and ordered in this high temperature superconductor.

REFERENCES

[1] J. M. Tranquada et al., Phys. Rev. Lett. **78**, 338 (1997).
[2] H. Kimura et al., Phys. Rev. **B59**, 6517 (1999).