Superconducting Stripes

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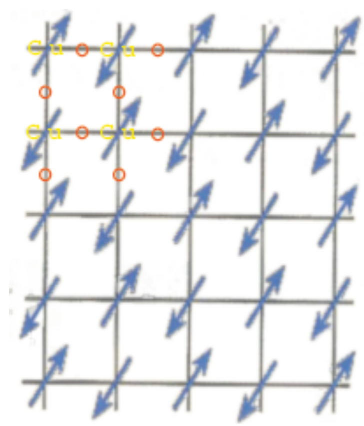
I. Introduction

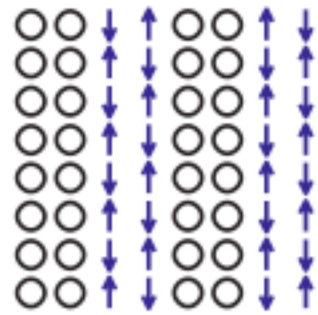
In 1972 Bardeen, Cooper, and Schrieffer shared the Nobel prize in physics for describing a mechanism of superconductivity. Their BCS theory describes the electron lattice interaction in which electrons form a bound state and are allowed to flow without resistance—provided the temperature is cool enough.

In 1986 the above theory was broken with the discovery of superconducting LBCO. This material, and many others that followed, broke the critical temperature (Tc) barrier predicted by BCS theory. The older, simpler superconducting compounds were called Type I superconductors while the newer high Tc ones were—rather unimaginatively—called Type II superconductors. This discovery launched a scientific renaissance that has spawned numerous new theories and models to explain Type II superconductivity. A few of these theories are: spin vortices, quenched phase disorder, s-waves, d-waves, spin density waves, and spin charge interactions.



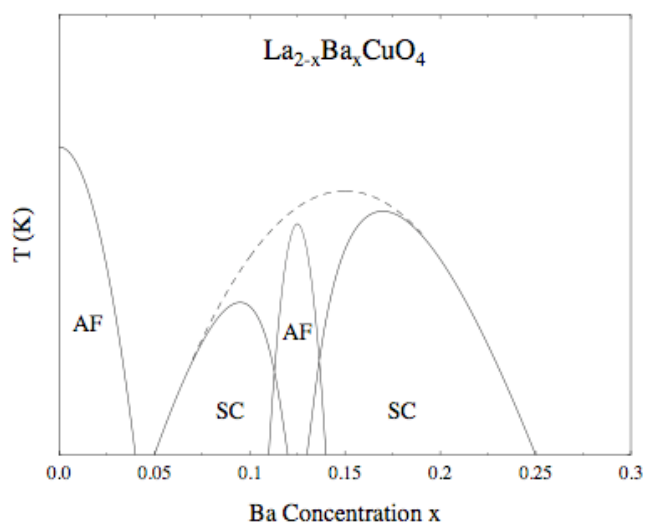
Cuprates are the family of superconducting compounds which dominate the high Tc scoreboard. They consist of copper oxide conduction planes (shown here) and a charge reservoirs. The chemical composition of the charge reservoir dopes the copper atoms into the Cu^{2+} or Cu^{3+} state which are spin ½ and spin zero respectively.

Antiferromagnetism, the alternating up down in the spin lattice, is induced by the spin-overlap integral and is the default state of the copper oxide conduction plane. However, one can optimize superconductivity by doping holes into the system. Of the geometries that have been tested, spin stripes appear to be the most promising. This optimization is accomplished through our ability to tweak the charge reservoir.



- **Stripes**

While some believe antiferromagnetism is important for superconductivity, others are baffled by its mysterious suppression at the doping concentration x = 1/8. (see phase diagram) This has been shown to be the result of *static* charge and spin ordered stripes which have lead many to question the relevance of charge inhomogeneity to superconductivity. *Dynamic* stripes might be present in the superconducting region, but this has been difficult to establish in the absence of a clear experimental signature. John Tranquada has done of series of experiments to test his hypothesis of the spin stripe phonon relationship for Type II superconductors.



BCS theory predicts that above a certain temperature the high energy phonons will destroy the electron-lattice correlations which allow Cooper pairs to propagate, but experimentally superconductivity indeed exists. Stripes might be the key to this conundrum despite their destructive effect at the x=1/8 doping concentration.

Imagine that one could shield a dimension of the conduction plane from the high energy lattice phonons. If this were the case then the Cooper pairs could still couple to the lattice through the low energy phonons along the shielded dimension while the destructive properties of the high energy phonons would be isolated to orthogonal dimensions—thus raising the Tc. Spin stripes could be this shielding mechanism (see Figure 1)

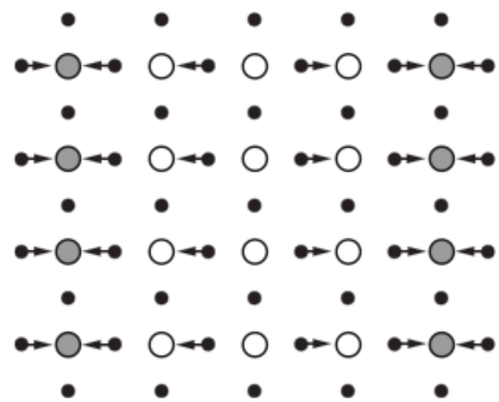
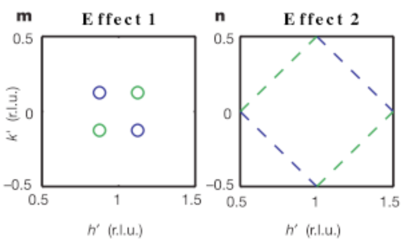


Figure 1 | Displacement pattern of the oxygen ions for the phonon with q = (0.25 0 0) propagating perpendicular to the stripes. Arrows represent atomic displacements. Large circles correspond to copper and small ones to oxygen. Open large circles represent hole-poor antiferromagnetic regions, while the filled circles represent the hole-rich lines.

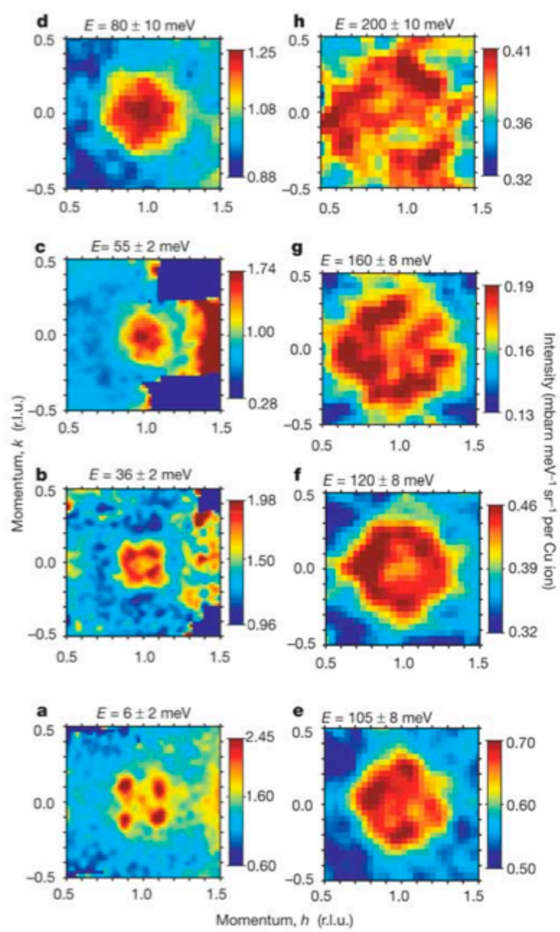
To test this theory we need to see what sort of stripes and phonons we have present. Unfortunately, spin structures are notoriously difficult to see, John Tranquada mentioned that it was like trying to look at a distant flag using a coke bottle for binoculars, and this comment was about the detectable static spin. Dynamic stripes, on the other hand, are not yet detectable through neutron scattering. We know of their existence, however, through the fingerprints they leave on magnetic excitations.

- **Neutron Scattering**

In order to detect spin features we must first understand the neutron scattering experiments which detect them. Inelastic neutron scattering is the tool of choice, for it probes through the charge reservoir into the conduction plane interacting with both the lattice phonons and copper's magnetic moment. The intensity of the beam is plotted as a function of the vector change in momentum for a given incoming neutron energy. This allows one to measure the momentum of the phonons and spin states, and is an effective index for both phonons and spins.



Here is a sketch of the two features to look for in the following constant energy slices of neutron data. The first effect comes from a disruption of the uniform antiferromagnetic background in the copper lattice it is evidenced by a neutron resonance peak centered at the point Q_{AF} = (½ , ½) in k-space (momentum space). The presence of spin stripes, however, splits the above point into four dots. Unfortunately the coordinates have been rotated for "ease of plotting," so the (½ , ½) doesn't match the axes.

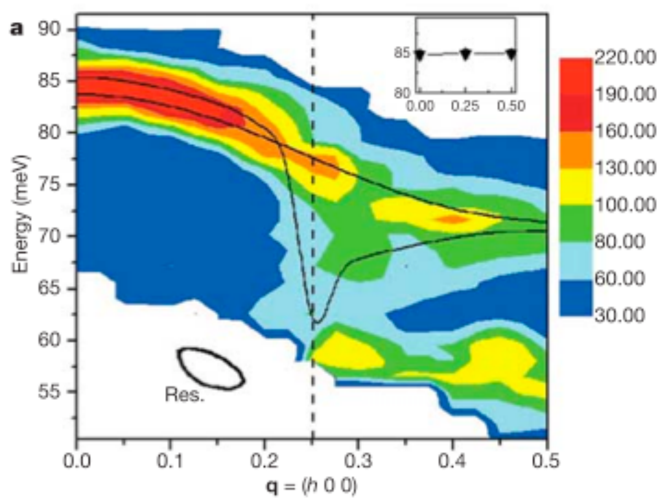


The second effect comes from the antiferromagnetic spin ladder which is susceptible to spin waves. Spin waves are periodic long range oscillations in the magnetic moment's orientation. Its signature pattern is a large diamond whose shape comes from the superposition of the Brillion Zones from the vertical and horizontal spin ladders.

It is instructive to compare the idealized cartoon above to the real data on the right. At 6meV one can plainly see the classic four dot signature of the stripes breaking the antiferromagnetic Q_{AF} = (½ , ½) vector. As the neutrons become more energetic the stripe's perturbation degenerates into the standard antiferromagnetic wavevector. As energy continues to increase the spin wave phenomenon becomes apparent. All of this evidence points to the existence of static stripes in YBCO (x = 1/8), otherwise the fluctuations wouldn't yield images which resemble the theoretical mode so closely.

- **The Dispersion Signature**

To further correlate stripes with superconductivity the phonon dispersion curves were analyzed in another neutron diffraction experiment done on LBCO (x = 1/8). The interesting anomaly is the drastic jump in the lower dispersion curve this as compared to the upper one, or as compared to the q = (h, h, 0) curve in the inset. A study was done comparing the dispersion curves of compounds known for their static stripes with compounds known for



One compound well known for its static stripes is La[2-x]Sr[x]CuO[4], figure 4a (see next page) shows its dispersion curves for four different doping values which correspond to un-doped x = 0, under doped x = 0.07, optimally doped x = 0.15, and over doped x = 0.30. One should note that the compounds which aren't close to the superconducting state have a large intensity peak which corresponds to one dispersion

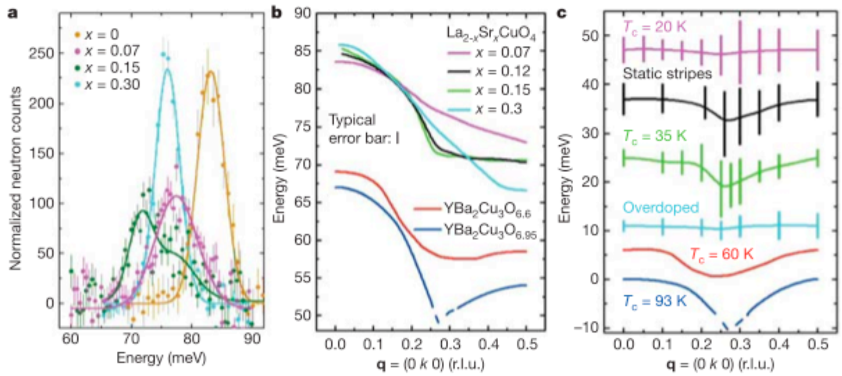


Figure 4 | **Correlation of the phonon anomaly with stripe order and superconductivity.** **a**, Comparison of energy scans taken at 10 K on $La_{2-x}Sr_xCuO_4$ at q = (0.25 0 0), after subtraction of linear background. Solid lines are guides to the eye; error bars represent ±1 s.d. The resolution was somewhat lower in the measurement on the $x = 0$ sample (L.P., W. Reichardt and A. Yu Rumiantsev, unpublished results), where Cu111, rather than Cu220, monochromator was used. **b**, Dispersion of the anomalous branch in $La_{2-x}Sr_xCuO_4$ ($x = 0.07$, 0.12 and 0.15) and the [010] bond-stretching branch along the chain direction in $YBa_2Cu_3O_{6.6}$ ($T_c = 66$ K)[18] and $YBa_2Cu_3O_{6.95}$ ($T_c = 93$ K)[19]. The $x = 0.12$ compound was $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. The curve for $YBa_2Cu_3O_{6.95}$ is only approximate, as the anomaly is so strong near **q** = (0 0.25 0) that there is no well defined peak there (see Fig. 1 in ref. 19). The difference in energies at **q** = 0 results from slightly different Cu–O bond lengths. Dashed blue line represents the region where the bond-stretching mode mixes with others and its precise energy cannot be established[21]. **c**, Difference between the downward cosine dispersion, fitted to the zone centre and the zone boundary for each sample, and the dispersions in **b**; vertical lines represent peak widths. For the $YBa_2Cu_3O_{6+x}$ data the width information is not available because the data were taken in the defocusing scattering geometry with relatively poor energy resolution. Curves are offset for clarity. Dashed blue line is the same as in **b**.

curve while both the optimal and near optimal doped intensity peaks are better fit by two Gaussians, for they represent two dispersion curves at a given energy.

In testing the following hypothesis, we are making the assumption that in the above graph the cosine like dispersion curve is normal and the other one is indicative of superconductivity. Fig 4b compares the dispersion curves from different concentrations of LSCO and YBCO. The key comparison is the deviation from the cosine like behavior of each curve and it's critical temperature as seen in Fig 4c. A secondary note is the similarity of the black curve (LNSCO which is also known for its static stripes) and green curves. This is evidence that stripes play a role in Type II superconductivity. A third note comes from examining the flat (hence cosine like) light blue curve of the non-superconducting, over-doped sample and noting that its intensity peaks which are near constant width (indicated by the vertical bars) which indicates a single dispersion curve. Superconducting activity along the q = (h, 0, 0) direction might be the cause of the anomalies

▪ Conclusion

In summary there are some promising indications that link spin stripes to superconductivity. The first piece of evidence is the spin stripe sheltered phonon which might use an old-fashioned BCS style electron lattice coupling to mitigate superconductivity. Second LBCO shows magnetic signs of both static stripes and spin ladders. Finally, LSCO, which also has pockets of static stripes and superconductivity in its phase diagram, exhibits a strong correlation between optimally doped superconductors, near optimally doped superconductors, and its static strip phase. The shared feature is the width of the neutron scattering peak which points to dual dispersion curves and the non-cosine like behavior of one of these dispersion curves. Superconducting stripes have a new claim as the mechanism of Type II superconductivity.

▪ Bibliography

1) Reznik et. al. “Electron-phonon coupling reflecting dynamic charge Inhomogeneity in copper oxide superconductors” Nature 440, pg 1170.
2) Tranquada et. al. “Quantum magnetic excitations from stripes in copper oxide superconductors” Nature 429, pg 534.