Striping in High T_c Superconductivity

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1 Introduction

Superconductivity has been an intriguing and puzzling topic in physics for nearly a century. However, a full theoretical understanding of this phenomenon is has proved elusive. While superconductivity is a very large field, we will briefly discuss only a specific property of certain superconductors and the theories associated with it.

Superconductivity was first discovered in 1911 by Heike Onnes with liquid-helium cooled mercury. It was not until 1950 that a phenomenological theory was developed to describe superconductivity by Ginzburg and Landau. The Ginzburg-Landau theory treats superconductivity as a phase-transition. Seven years later, Bardeen, Cooper and Schrieffer presented the first complete microscopic theory of superconductivity (BCS theory). As a very basic description, the BCS theory treats the superconducting current as a superfluid of Cooper pairs. Both theories merited the awarding of a Noble Prize.

In this paper we will focus on the phenomenon in the cuprate superconducting class of materials known as striping. Striping is a particular periodic ordering of the spins and charge in the solid's lattice. The property of striping in high-T_c superconductors is a newly researched and proving to be an exciting field. However, it is uncertain how this phenomenon affects superconductivity in cuprates.

2 Striping

2.1 Basics

We begin by discussing the very basics of what stripes are. In general, striping refers to 1-dimensional ordering of charge, magnetic spin, or both charge and magnetic spin on a 2-dimensional plane of a material [1]. The concept of stripes was first introduced by theorists in the 1990s, as part of an effort to explain how electrical and magnetic properties of superconducting materials interact [2] [3]. In a conventional metal, charge is distributed homogeneously. However, cuprates with the appropriate doping show segregation of charges and spin into 1D domain walls [1].

It is important to introduce two regimes in describing the electronic behaviour of materials. One regime is dominated by the kinetic energy of the system, and electrons behave as a Fermi liquid. In this case, electrons are excited above the Fermi surface where they then interact with each other as a system of delocalized quasi-particles. In this regime, many-body theory is needed to describe the interactions and mean-field calculations are often employed. Another regime is dominated by the potential energy. In this case, the Fermi liquid behaviour is frozen out and an electronic crystal results. While these two regimes seem straightforward, it is in the realm which neither kinetic nor potential energy dominate that stripes are found. The charge-spin ordering is neither a rigid lattice structure, nor a system of delocalized quasi-particles [1].

Cuprate ceramics have a 2-dimensional layered structure consisting of sheets of copper and oxygen, in between layers of a doping material such as yttrium and barium (in the case of $YBCO$) [2]. The spin orientations of the copper atoms arrange themselves in opposite orientations, creating a antiferromagnetic ordering. This pattern is known to hamper the long range movement of dopant free charges through the material. Striping tends to develop at low dopings, in the same regime as low a T_c and disappears at dopings coinciding with high a T_c [3]

When the dopant introduces holes as the free charge (which have no associated spin), they move in a frustrated fashion. The movement of the hole requires the rearrangement of spins, which comes with a high energy cost. In order to optimize the movement of the holes in the system, it was initially proposed that the holes oriented themselves together in 1D stripes on the copper-oxygen planes. These stripes allow the the holes to move along the single dimension without the energy required to move a spin. The regions in between the hole stripes are devoid of holes and contain the spins, arranged in an antiferromagnetic order [2]. This local electronic behaviour is, in actuality, quasi-one-dimensional. The Coulomb coupling between stripes falls off exponentially with distance [4]. The result is an anisotropic material which behaves as a metal in one direction, and an insulator in another [3].

2.2 Implications of Striping on Superconductivity

In the 1980s, cuprates became the focus of much research when it was discovered that these Mott insulating antiferromagnets become high-T_c superconductors with the appropriate doping [5]. However, at dopings below the superconducting level, cuprates demonstrate striping. These doping concentrations correspond to low T_c superconductivity, and thus it would appear that striping and superconductivity compete at some level [3].

Kivelson, et al. provide a review of the experimental detection of stripes, in which they touch upon the competition between superconductivity and stripe ordering. Figure 1 shows, qualitatively, the superconducting and stripe ordered phases of cuprates as a function of doping and temperature [5].

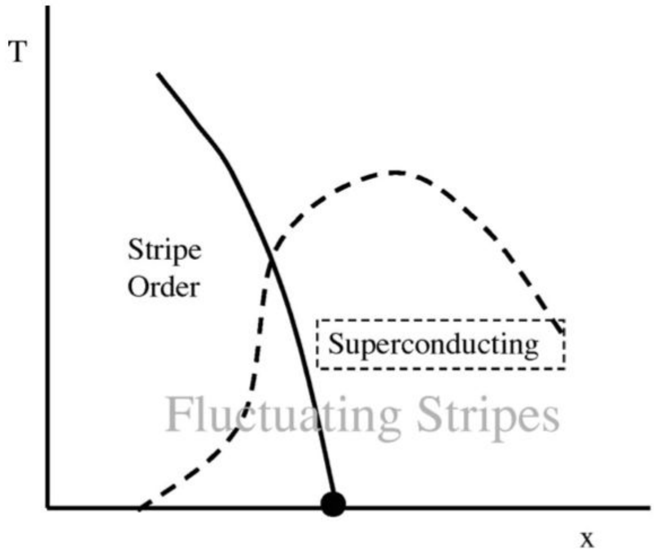

Figure 1: Qualitatively showing the suppression of stripe ordering as doping enters the superconducting pase [5].

As can be seen, the stripe ordered phase has little overlap with the superconducting phase. Yet some overlap does exist. What does this overlap indicate?

3 Experimental Findings

Striping initially proved elusive when it came to finding experimental evidence. Tranquada, at Brookhaven National Lab, believed that stripes were mobile in the lattice and thus it was difficult to resolve them experimentally [2]. With appropriate doping, Tranquada and his group hoped to immobilize the stripes sufficiently enough to obtain conclusive data. Their efforts proved successful by using a lanthanum-strontium copper oxide ceramic doped with neodymium. Neutron scattering tests showed alternating striping of magnetic spin and electric charge.

Neutron scattering is the method by which neutron-beam bombardment is used to image materials. The neutron has no intrinsic charge, and thus does not interact with the material via Coulomb attraction. However, the neutron is known to have a small intrinsic magnetic moment. For this reason, the neutron is able to penetrate deeply into the material, without being scattered by electrons. The neutron then scatters from magnetic interactions with the material. This allows neutrons to act as a very effective probe of materials' magnetic properties.

Upon using neutron scattering, Tranquada observed static stripe formation in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. A $\sim 0.1\ cm^3$ single crystal sample, kept at 11 K was studied via neutron diffraction using triple-axis spectrometers [6]. Tranquada observed diffraction peaks which correspond to Cu spin ordering shown in Figure 2. The data collected is shown in Figure 3.

Tranquada and his group also characterized these peak intensities in terms of the temperature of the sample. They found a strong increase in the peak intensity corresponding the magnetic stripes below a temperature of 3 K [6]. While the magnetic stripes appeared more sensitive to temperature dependencies, both types of ordering disappear before 70 K [6]. Figure 4 shows the peak intensities as a function of temperature.

After the initial findings of Tranquada, the group at Brookhaven moved forwarded in experimental investigation of stripes. One interesting finding relat-

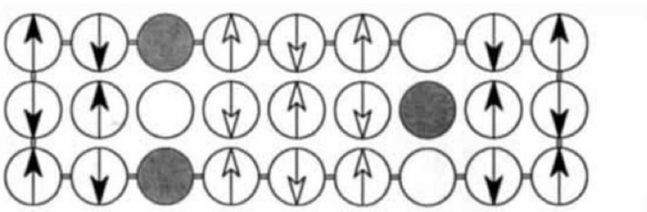

Figure 2: Schematic identifying the ordering of magnetic spin and charge in the cuprate lattice [6].

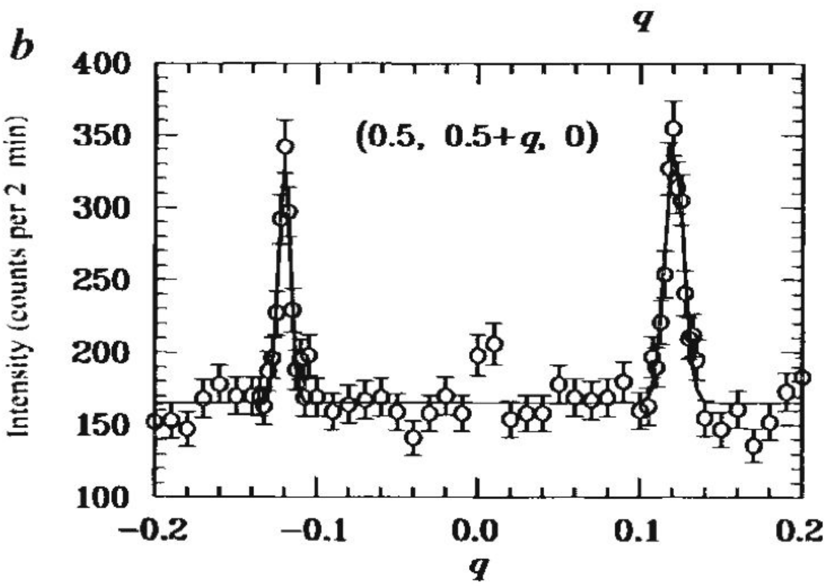

Figure 3: Neutron scattering data indicating magnetic spin stripe ordering. Peaks indicate the locations of the spins[6].

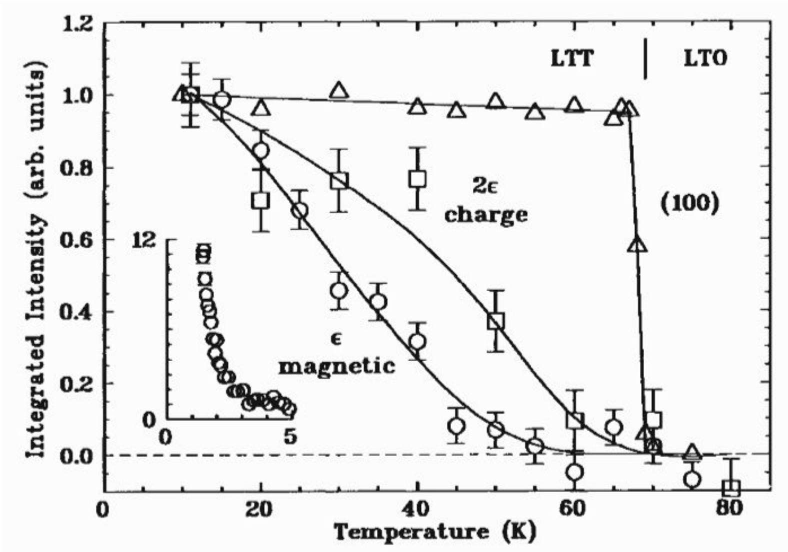

Figure 4: Data showing spin-ordering (see Figure 3) as a function of temperature [6].

ing stripes to superconductivity that was made using one of the most studied of cuprates: $La_{2-x}Ba_xCuO_4$. Results of four-probe resistivity measurements show that stripe order in $La_{2-x}Ba_xCuO_4$ frustrates the 3D superconductivity in the system, but not the 2D superconductivity. That is, with striping present resistivity measurements in the copper oxide plane show superconducting properties at appropriate temperatures. However, resistivity measurements out of the copper oxide plane do not [7].

Another interesting phenomenon surrounding the stripe ordering is that of magnetic spin incommensurability. Incommensurability is when the periodicity of the spins do not align with the periodicity of the underlying lattice. In the case of $La_{2-x}Ba_xCuO_4$, the spin is found to occur at a periodicity other than that of the antiferromagnetic lattice – (π, π) [8]. In the case of $YBa_2Cu_3O_{7-x}$, incommensurability is seen via neutron scattering after cooling, at temperatures above T_c [8]. Such results indicated that incommensurate spins are a common feature in cuprates, which is important in understanding of how antiferromagnetic spin structures and superconductivity relate [8].

Mohotalla, from the University of Connecticut, and his research group studied the phase separation in a cuprate similar to that studied by the initial experiment by Tranquada. However, instead of using a stripe-immobilized $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ sample, Mohotalla et al. uses a super oxygenated $La_{2-x}Sr_xCuO_{4+y}$ sample [9]. The excess oxygen raises the T_c to 40 K, which corresponds to the same temperature at which spin-charge order occurs [9]. In this system, Mohotalla document evidence that there is infact simultaneous phase separation such that part of the sample forms a high T_c superconductor and other portions form stripe ordered states where superconductivity is suppressed [9][10]. Figure 5 shows the phase diagram as observed by Mohotalla and his research group.

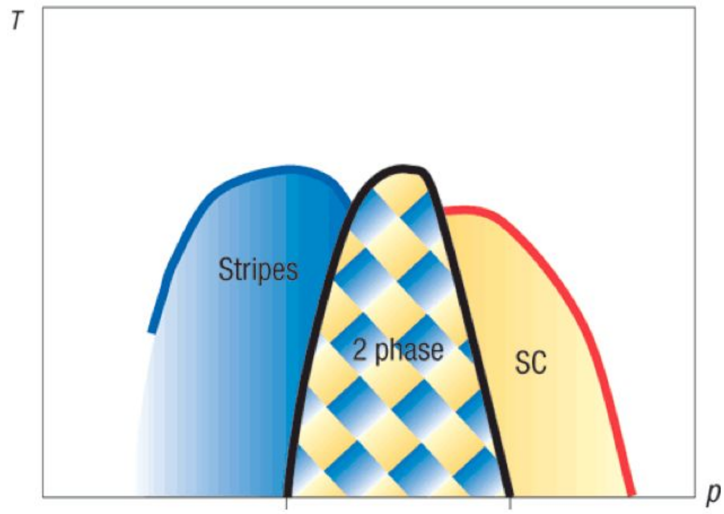

Figure 5: Demonstrating the combined striped-superconducting phases observed by Mohotalla [9].

The findings by Mohotalla et al. are indeed exciting as we attempt to better understand the superconductivity in cuprates. However, it is still not clear what role striping plays in this, or weather or not the mechanism for striping is helps or hinders superconductivity. The current state of the theory caues experimental research in striping and superconductivity to be crucial at this stage.

Yet what impact do the results of Tranquada, the Brookhaven group, and experimental evidence of 1D spin-charge ordering, have on the study of copper oxides and superconductivity? In Tranquada's own words, "[f]urther theoretical work would be required to [..]to understand whether and how they may be related to superconductivity" [6].

4 Conclusion

Cuprates are inherently an interesting set of materials, due to their high T_c as superconductors. However, the presence of this particular spin-charge ordering in them only increases their appeal. The anisotropic ordering of magnetic spins and holes into 1D stripes is an intriguing break of symmetry in the copper oxide plane. An while it has been shown to exist in a temperature and doping regime that is near that of the the cuprates' superconducting phase, it's connection to superconductivity proves elusive. It would appear from the works of Mohotalla and others that striping and superconductivity, while appearing simultaneously in a crystal, do not exist in the same region. This would indicate a significant competition between the superconducting phase and the stripe ordered phase. Unfortunately, a great deal of work remains to be done in order to fully understand the microscopic theory of this phenomenon, its underlying mechanism, and its implications on the mechanism of superconductivity in cuprates.

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