Research Interests and Plans

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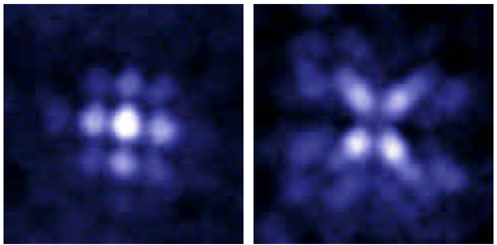
Research Interests

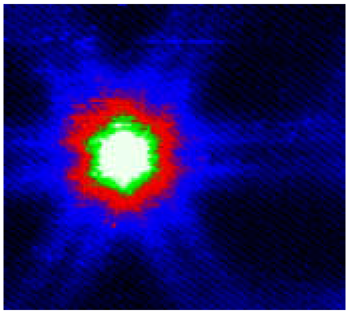
My main interests lie in nanoscale investigations of strongly correlated electron systems, such as high temperature superconductors (HTSC). In particular, I am interested in the fundamental question of how defects and disorder affect these systems, and the more practical question of what observations about these effects at the microscopic level can tell us about the macroscopic nature of these systems. As an example, impurities are known to have a strong effect on superconducting order in HTSC. To investigate this, I have studied the atomic scale effects of individual Zn and Ni impurities in the high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO)[1]. Maps of the position and energy dependence of impurity states (as shown here surrounding a Ni atom), tell us not only the type of scattering leading to these states (in the case of Ni, a combination of potential and magnetic), but also reveal the surprising fact that superconductivity actually coexists with the magnetic moment of a Ni atom while it is destroyed by the "magnetic hole" of a Zn atom. These results suggest that the superconducting mechanism may be magnetic in nature.


Energy dependent Ni impurity state wavefunctions

This is but one system in which local perturbations can reveal important information, and only one of several such perturbations that can yield interesting results. Below I outline several scientific questions I intend to pursue. I have also included some results from my previous studies, as evidence for the feasibility of the proposed research.

Research Plans

1. Magnetic vortices in exotic superconductors


A single magnetic vortex in $NbSe_2$

One fascinating perturbation to superconducting order is the magnetic vortex. Generated by the application of an external magnetic field, vortices penetrate a superconductor and generate, in the simplest case, columns of material where the superconducting order parameter is completely suppressed. However, even in conventional superconductors, vortices are filled with a large number of localized states. The spatial distribution for one such state in the conventional superconductor $NbSe_2$ is shown here. The shape and energy distribution of these states depend intricately on the symmetry of the superconducting order parameter.

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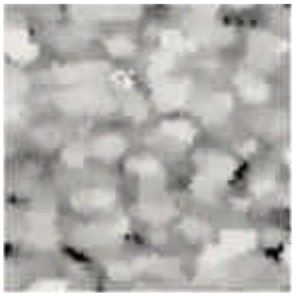
[1] E.W. Hudson, *et al.*, *Science* **285**, 88 (1999); S.H. Pan, *et al.*, *Nature* **403**, 746 (2000); E.W. Hudson, *et al., in preparation.*

Recently, two important questions about HTSC vortices have arisen that I propose to answer through STM studies. First, there have been predictions that several different types of vortices[2] will exist in HTSC, depending, for example, on whether the system is overdoped or underdoped[3]. Secondly, it has been experimentally observed that, in $La_{2-x}Sr_xCuO_4$, vortex-like excitations persist above T_C[4]. As these authors suggest, however, a more direct means of observing vortices is required to confirm their results. STM imaging of vortex bound states, such as I have previously done in optimally doped BSCCO at low temperatures[5], is an optimal technique for addressing both of these fundamental questions.

2. Nanoscale inhomogeneity and phase separation


Gap variations in BSCCO

Another aspect of strongly correlated electron systems which is recently gaining attention is the possibility of nanoscale phase separation. In the hole-doped manganese oxides, for example, phase separation has been predicted to, and indeed appears to, exist[6]. In this case, the ground state of the system, rather than being homogenous in charge density, instead segregates into regions which are hole rich and hole poor. In general, phase separation can manifest in regions of different magnetic ordering, (e.g. ferromagnetic (FM) and antiferromagnetic (AF)), in regions of different conducting properties, (e.g. superconducting and insulating), and in regions of different shapes and sizes, (e.g. droplets in an otherwise uniform sea or rod-like “stripes” that twist through the material like spaghetti[7]). I have recently observed segregation of different superconducting gap magnitudes in BSCCO[8], as shown above.

One difficulty in experimentally investigating phase separation is that in real space the separation often appears disordered. Thus scattering techniques, the cornerstone measurements for determining charge and magnetic order in condensed matter systems, can face intense problems in extracting this information. STM avoids this problem by working directly in real space, on length scales from angstroms to microns, and is ideally suited to search for such nanoscale inhomogeneity. I propose to do so in two systems which have attracted a great deal of experimental and theoretical attention. The first, $La_{1-x}Ca_xMnO_3$, is a colossal magnetoresistive (CMR) material, and has exhibited evidence of FM droplets in an AF state at low doping[6]. The second, $La_{2-x}Sr_xCuO_4$, is a HTSC that has shown charge striping when doped with Nd[9], and for which evidence of a stripe phase in the undoped material is beginning to appear[10]. Direct observation of phase separation in either of these systems would be a fundamental advance, leading to new understanding both in their individual fields (CMR or HTSC) and in the study of phase separation in general. It would also open the door to a number of related studies, such as the investigation of phase transitions into and out of these segregated phases.

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[2] P.A. Lee and X-G. Wen, cond-mat/0008419

[3] M. Franz and Z. Tesanovic, cond-mat/0002137

[4] Z.A. Xu, *et al.*, *Nature* **406**, 486 (2000).

[5] S.H. Pan, *et al.*, *Phys. Rev. Lett.* **85**, 1536 (2000).

[6] A. Moreo, S. Yunoki, E. Dagotto, *Science* **283**, 2034 (1999), and references therein.

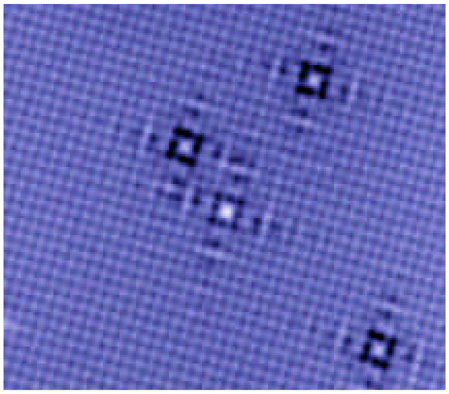
[7] V.J. Emery and S.A. Kivelson, *Physica C* **209**, 597 (1993).

[8] E.W. Hudson, *et al.*, *in preparation*.

[9] J.M. Tranquada, *et al.*, *Nature* **375**, 561 (1995).

[10] A.W. Hunt, *et al*,. *Phys. Rev. Lett.* **82**, 4300 (1999); A. Ino, *et al.*, *Phys. Rev. B* **62**, 4137 (2000).

3. The interplay of magnetism and superconductivity



Atomic resolution on Sr_2RuO_4, with impurities

Conventionally, magnetism and superconductivity have been considered mutually exclusive phenomena. Recently, however, a number of systems have begun to show that magnetism and superconductivity can actually be strongly related or even codependent phenomena. In some systems, magnetic and superconducting ordering are separated only by changes in temperature, pressure or doping. This is the case, for example, in the high temperature superconductors, which are doped from antiferromagnetically ordered parent materials, and in UGe_2, recently discovered to convert from a ferromagnetic to superconducting state when placed under pressure[11]. In other systems, such as $RuSr_2GdCu_2O_8$, superconductivity and magnetism coexist[12,13], apparently, however, by allowing distinct subsets of the electrons (for example, those residing in different atomic planes) to order differently. This is true in the extreme for Sr_2RuO_4, whose surface – pictured above – is suspected to be ferromagnetic even while the remainder of the crystal is superconducting.[14]

I propose to study the interplay between magnetism and superconductivity in this second class of materials. In particular I want to address the major outstanding question of how, locally, superconducting order is influenced by magnetic order. Using the ability of the STM to locate nanoscale defects, my students and I will study how the local destruction of magnetic order in one plane effects superconductivity in the next, and vice versa. The ability to locally destroy magnetic or superconducting order (or both) will provide us with a unique opportunity to study how this order recovers and thus insight into what creates it in the first place.

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[11] S.S. Saxena, *et al.*, *Nature* **406**, 587 (2000).
[12] J.W. Lynn, *et al.*, *Phys. Rev. B* **61**, 14964 (2000).
[13] W.E. Pickett, *et al.*, *Phys. Rev. Lett.* **83**, 3713 (1999).
[14] R. Matzdorf, *et al.*, *Science* **289**, 746 (2000).