Chapter 4

Vortex Checkerboard

There is no need to invoke alternative order parameters to explain observed DOS modulations in optimally doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. To continue the search for interesting alternative order parameters in BSCCO (which might manifest themselves as DOS modulations), we must search in other areas of the high-$T_c$ phase diagram. In this chapter, I will report on a search for alternative order parameters in BSCCO in high magnetic fields. The relationship of these studies to the phase diagram of BSCCO is shown in figure 4.1.

Scanning tunneling microscopy is used to image the additional quasiparticle states generated by quantized vortices in BSCCO. They exhibit a Cu-O bond oriented “checkerboard” pattern, with four unit cell ($\sim 4a_0$) periodicity and $\sim 30$ Å decay length. These electronic modulations may be related to the magnetic field-induced, $8a_0$ periodic, spin density modulations of decay length $\sim 70$ Å discovered in La$_{1.84}$Sr$_{0.16}$CuO$_4$.$^{65}$ One proposed explanation is a spin density wave localized surrounding each vortex core.$^{40}$ General theoretical principles predict that, in the cuprates, a localized spin modulation of wavelength $\lambda$ should be associated with a corresponding electronic modulation of wavelength $\lambda/2$,$^{33, 37, 35, 48, 39, 36}$ in good agreement with our observations.

4.1 Low-$T_c$ and Cuprate Vortex Phenomenology

In conventional s-wave type II superconductors, the superconducting order parameter is suppressed in the cores of quantized magnetic vortices, and recovers over a distance of about one coherence length $\xi$. Bound quasiparticle states can exist inside these cores$^{121}$ with lowest energy given approximately by $E \sim \Delta^2/2\varepsilon_F$, where $\varepsilon_F$ is the Fermi energy and $\Delta$ is the superconducting gap. Such “core” states at the Fermi energy were first imaged by
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Figure 4.1: A schematic phase diagram of Bi$_2$Sr$_2$CaCu$_2$O$_8+\delta$. The red arrow shows the direction in phase space covered in this chapter. Optimally doped samples are studied at $T = 4.2$ K, while the $B$-field is increased to 7 Tesla.

Hess et al. using low temperature STM.$^{122}$

A simple description of a vortex in an $s$-wave superconductor is a particle-in-a-box. In the vortex core, the superconducting order parameter is destroyed, so the quasiparticle has no binding energy and can exist freely. However, outside the vortex “box”, the unattached quasiparticle has energy $\Delta$ greater than it would have if joined into a Cooper pair. So we can think of the quasiparticle as sitting in a circular potential well of height $\Delta$ and radius $\xi$. No matter how shallow the well, there will exist at least one bound state, which will decay exponentially outside the box.$^{123}$

However, the cuprate superconductors have a $d_{x^2-y^2}$ order parameter. This means there are four gap nodes, which would imply that there are four holes in the walls of the vortex “box”. So we might expect that such a leaky box would contain only scattering states, which decay as a power law with distance. Indeed, initial theoretical efforts focused on the quantized vortex in an otherwise conventional BCS superconductor with $d_{x^2-y^2}$ symmetry.$^{124, 125, 126, 127, 128}$ These models included predictions that, because of the gap nodes, the local density of electronic states (LDOS) inside the core is strongly peaked at the Fermi level. This peak, which would appear in tunneling studies as a zero bias conductance peak (ZBCP), should display a four-fold symmetric “star shape” oriented toward the gap nodes, and decaying as a power law with distance.

Scanning tunneling microscopy studies of HTSC vortices have revealed a very different electronic structure from that predicted by the pure $d$-wave BCS models. Vortices
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Figure 4.2: Density of states spectra from (a) YBa$_2$Cu$_3$O$_{7-\delta}$ (from Maggio-Aprile et al.$^{129}$) and (b) Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (adapted from Pan et al.$^{131}$) Red traces show spectra inside the vortex cores, while black traces show spectra taken far from the vortices. In (b) we show also a spectrum at an intermediate distance (green trace), outside the vortex “core” but still clearly influenced by the vortex.

In YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) lack ZBCPs but exhibit additional quasiparticle states at $\pm 5.5$ meV,$^{129}$ whereas those in BSCCO also lack ZBCPs.$^{130}$ More recently, the additional quasiparticle states at BSCCO vortices were discovered at energies near $\pm 7$ meV.$^{131}$ Typical DOS spectra from BSCCO and YBCO vortex cores are shown in figure 4.2.

Thus, a common phenomenology for low energy quasiparticles associated with vortices is becoming apparent. Its features include:

1. The absence of ZBCP’s.
2. Low energy quasiparticle states at $\pm 5.5$ meV (YBCO) and $\pm 7$ meV (Bi-2212).
3. A radius for the actual vortex core (where the coherence peaks are absent) of $\sim 10$ Å.$^{131}$
4. A radius of up to $\sim 75$ Å within which these states are detected, and apparently decay exponentially.$^{131}$
5. The absence of a four-fold symmetric star-shaped LDOS.

In response to these discoveries, theorists began to play with the possibility that the superconducting order parameter has an additional component. For example, a smaller coexisting $s$ component or a $d_{xy}$ component would eliminate the gap nodes and could allow an exponentially decaying bound state to exist. However, these proposed components would have to have magnitude greater than the energy of the bound state (in order for it
to be bound). With bound states at 5.5 meV and 7 meV, the additional order parameter component would thus have magnitude at least 15-20% of the $d_{x^2-y^2}$ gap. It is unlikely that such a large order parameter of different symmetry could have escaped detection by other experimental methods such as ARPES.

So theorists turned to investigations of alternative, non-superconducting order parameters which may be competing with superconductivity, and may be able to appear where superconductivity is weakened or destroyed in and around the vortex core.

### 4.2 Theories of Alternative Ordered States

Theory indicates that the electronic structure of the cuprates is susceptible to transitions into a variety of ordered states as summarized in section 1.2.3.

Experimentally, antiferromagnetism (AF) and high temperature superconductivity (HTSC) occupy well known regions of the phase diagram, but outside these regions, several unidentified ordered states exist. For example, at low hole densities and above the superconducting transition temperature, the unidentified “pseudogap” state exhibits gapped electronic excitations. Other unidentified ordered states, both insulating and conducting, exist in magnetic fields sufficient to quench superconductivity.

Because the suppression of superconductivity inside a vortex core can allow one of the alternative ordered states to appear there, the electronic structure of HTSC vortices has attracted wide attention.

Zhang and Arovas et al. first focused attention on magnetic phenomena associated with HTSC vortices with proposals that a magnetic field induces antiferromagnetic order localized by the core. More generally, new theories describe vortex-induced electronic and magnetic phenomena when the anticipated effects of strong correlations and strong antiferromagnetic spin fluctuations are included. Common elements of their predictions include:

1. The proximity of a phase transition into a magnetic ordered state can be revealed when the superconductivity is weakened by the influence of a vortex.

2. The resulting magnetic order, either spin or orbital, will coexist with superconductivity in some region near the core.

3. This localized magnetic order will generate associated spatial modulations in the quasiparticle density of states.
4.3. EXPERIMENTAL EVIDENCE FOR ALTERNATIVE ORDERED STATES IN MAGNETIC FIELDS

Theoretical attention was first focused on the regions outside the core by a phenomenological model that proposed that the circulating supercurrents weaken the superconducting order parameter and allow the local appearance of a coexisting spin density wave (SDW) and HTSC phase\(^{40}\) surrounding the core. In a more recent model, which is an extension of Zhang\(^{38}\) and Arovas,\(^{135}\) the effective mass associated with spin fluctuations results in an AF localization length that might be substantially greater than the core radius.\(^{138}\) An associated appearance of charge density wave order was also predicted\(^{139}\) whose effects on the HTSC quasiparticles should be detectable in the regions surrounding the vortex core.\(^{40}\)

4.3 Experimental Evidence for Alternative Ordered States in Magnetic Fields

Other experimental information on the magnetic structure of HTSC vortices is available from inelastic and elastic neutron scattering on the lanthanum-copper-oxide family of high-\(T_c\) superconductors, and also nuclear magnetic resonance (NMR) studies on \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\).

4.3.1 Inelastic Neutron Scattering

Near optimum doping, some cuprates show strong inelastic neutron scattering (INS) peaks at the four \(\vec{k}\)-space points \((1/2 \pm \delta, 1/2)\) and \((1/2, 1/2 \pm \delta)\), where \(\delta \sim 1/8\) and \(\vec{k}\)-space distances are measured in units of \(2\pi/a_0\). This demonstrates the existence, in real space, of fluctuating magnetization density with spatial periodicity of \(8a_0\) oriented along the Cu-O bond directions, in the superconducting phase. The first evidence for field-induced fluctuating magnetic order in the cuprates came from INS experiments on optimally doped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) \((x=0.163)\) by Lake \textit{et al.}\(^{65}\) When \(\text{La}_{1.837}\text{Sr}_{0.163}\text{CuO}_4\) is cooled into the superconducting state, the scattering intensity at these characteristic \(\vec{k}\)-space locations disappears at energies below \(\sim 7\text{ meV}\), opening up a “spin gap.” Application of a 7.5 T magnetic field below 10 K causes the scattering intensity to reappear with strength almost equal to that in the normal state. These field-induced spin fluctuations have a spatial periodicity of \(8a_0\) and wavevector pointing along the Cu-O bond direction. Their magnetic coherence length \(L_M\) is at least \(20a_0\) although the vortex core diameter is only \(\sim 5a_0\). This implies that magnetic ordering is taking place in the region \textit{surrounding} the core.
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4.3.2 Nuclear Magnetic Resonance

NMR studies by Mitrović et al.\textsuperscript{72} explored the spatial distribution of magnetic fluctuations near the vortex core. NMR is used because $1/T_1$, the inverse spin-lattice relaxation time, is a measure of spin fluctuations, and the Larmor frequency of the probe nucleus is a measure of their locations relative to the vortex center. In near-optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ at $B = 13$ T, the $1/T_1$ of $^{17}$O rises rapidly as the core is approached, then diminishes inside the core. This experiment is consistent with vortex-induced spin fluctuations occurring outside the core.

Spatially resolved NMR is used by Kakuyanagi et al.\textsuperscript{140} to probe the magnetism in and around vortex cores of nearly optimally doped Tl$_2$Ba$_2$CuO$_{6+\delta}$ ($T_c = 85$ K). The NMR relaxation rate $1/T_1$ at the $^{205}$Tl site provides direct evidence that the antiferromagnetic (AF) spin correlation is significantly enhanced in the vortex core region. This AF enhancement near the Tl-2201 vortices is a factor of two orders of magnitude, compared with a factor of 2-3 in YBCO. In the core region, Cu spins show a local AF ordering with moments parallel to the CuO$_2$ planes and Néel temperature $T_N = 20$ K. Kakuyanagi implies that the AF enhancement extends some distance outside of the vortex core, but claims still that the AF vortex core competes with superconductivity.

4.3.3 Elastic Neutron Scattering

More recently, elastic neutron scattering experiments were performed on related compounds in the lanthanum-copper-oxide family of high-$T_c$ superconductors. While inelastic neutron scattering probes spin dynamics, elastic neutron scattering probes static spin order.

Studies by Khaykovich et al.\textsuperscript{68} on La$_2$CuO$_{4+y}$, found field-induced enhancement of elastic neutron scattering (ENS) intensity at these same incommensurate $k$-space locations, but with $L_M > 100a_0$. Thus, field-induced static AF order with $8a_0$ periodicity exists in this material. They were not able to perform measurements in fields above 9 T, but an extrapolation of the observed increase in static spin ordering to higher fields predicted that the whole area of the sample would be spin-ordered at an applied field well below $H_{c2}$, implying that static AF order and SC can coexist in the same area in La$_2$CuO$_{4+y}$.

A second elastic neutron scattering experiment was performed by Lake et al.\textsuperscript{46} on under-doped La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.10$). This experiment showed that static spin order was absent at temperatures $T > T_c$. But below $T_c$, static spin order increased with decreasing $T$ and with increasing applied field $H$. At $T = 2$ K and $H = 14.5$ T, the order has an in-plane correlation length of $\zeta > 400$ Å, which is much greater than the vortex core size, and greater
even than the vortex-vortex separation distance of 130 Å, implying again that AF and SC coexist at the same spatial location in underdoped LSCO. Perhaps most significantly, Lake showed that the square ordered moment per Cu site increased as \( M^2 H/H_c^2 \ln(H_c/H) \) (with \( M^2 = 0.12\mu_B^2 \) per Cu\(^{2+}\)), in excellent quantitative agreement with the coupled SDW + SC theory of Demler et al.\(^{40}\)

### 4.4 STM Vortex Data in Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\)

All of the neutron scattering and NMR data implies a coexisting magnetic order and superconductivity, but since none of these probes are real space probes, there is no direct picture of the two orders coexisting in the same location in the crystal. We need a real space probe like an STM to look for other types of ordering in superconducting regions of the crystal (i.e. regions outside the vortex core). All of the neutron scattering data indicates a spin order with periodicity \( 8a_0 \). We cannot look for spin order directly, but we expect a coupled charge order with period \( 4a_0 \).

To test for DOS modulations on these length scales, we need higher resolution maps of the vortices first imaged by Pan et al.\(^{131}\). For these experiments, I show data from two different crystals: (1) "As-grown" BSCCO crystals are generated by the floating zone method, are slightly overdoped with \( T_c = 89 \) K, and contain 0.5% substitution of Ni impurity atoms. (2) "As-grown" BSCCO crystals are generated by the floating zone method, are slightly underdoped with \( T_c = 84 \) K, and contain a nominal 0.6% substitution of Zn impurity atoms. Unprocessed topographies and DOS maps at the vortex state energy +7 meV are shown in figure 4.3.

The most detailed study of the vortices was made using the Ni-doped sample, which will be discussed in the remainder of this chapter. To study effects of the magnetic field \( B \) on the superconducting electronic structure, we first acquire zero-field maps of the differential tunneling conductance \( (g = dI/dV) \) measured at all locations \((x, y)\) in the field of view (FOV) of figure 4.3(b). Because LDOS\((E = eV) \propto g(V) \) where \( V \) is the sample bias voltage, this results in a two dimensional map of the local density of states LDOS\((E, x, y, B = 0) \). We acquire these LDOS maps at energies ranging from -12 meV to +12 meV in 1 meV increments. The \( B \) field is then ramped to its target value and, after any drift has stabilized, we re-measure the topograph with the same resolution. The FOV where the high-field LDOS measurements are to be made is then matched to that in figure 4.3(b) within 1 Å (\( \sim 0.25a_0 \)) by comparing characteristic topographic/spectroscopic features. Finally we acquire the LDOS maps, LDOS\((E, x, y, B \neq 0) \), at the same series of energies as the zero-field case.
4.4. STM VORTEX DATA IN Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

Figure 4.3: Raw data: topographies and density of states maps for two distinct samples. Panel (a) shows a topographic image of a 490 Å square area of Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. Panel (c) shows the DOS in the same area at +8 meV in an applied field $B = 7$ T. Panel (b) shows a topographic image of a 586 Å square area of Ni-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. Panel (d) shows the DOS in the same area at +7 meV in an applied field $B = 5$ T. In panels (a) and (b), the supermodulation (with wavelength $\sim 26$ Å) is clearly visible, at 45° to the Cu-O bond directions. In panels (c) and (d), schematics of the Brillouin zone show the $x$ and $y$ crystal axes (whose directions can also be discerned from the raw data in the topographies). In both DOS images (c) and (d), approximately 6 vortices can be seen, with a “checkerboard”-like pattern oriented along the $x$ and $y$ axes with approximately $4a_0$ periodicity. This checkerboard is qualitatively the same in two samples with very different types of impurities (and also in a nominally impurity-free sample, not shown here).
4.5 Analysis

We can clearly see the checkerboard ordering inside the vortices in the raw data in figures 4.3(c) and 4.3(d), but other effects (such as the impurity resonances) are distracting and inhibit our ability to obtain an accurate measure of the wavelength of the structure. So we employ several tricks:

1. Integrate the maps over all energies influenced by the vortices, so as to capture all the signal under the peak centered at 7 meV, rather than just the signal from the single energy 7 meV. This is demonstrated in figure 4.4.

2. Subtract the zero-field-integrated data from the field-integrated data, to remove effects from impurities and other inhomogeneities which don’t change with field. This is demonstrated in figure 4.5.

3. Take a Fourier transform to obtain an accurate measure of the wavelength. This is demonstrated in figure 4.6(a).

![Figure 4.4: The vortex-induced LDOS is centered at energy $E = 7$ meV, but has significant weight over a range of energies around 7 meV. We integrate over energies from 1 to 12 meV to maximize the vortex-induced signal.](image)

To focus preferentially on $B$ field effects, we define a new type of two dimensional map:

$$S_{E_1}^{E_2}(x, y, B) = \sum_{E_1}^{E_2} \left[ \text{LDOS}(E, x, y, B) - \text{LDOS}(E, x, y, 0) \right] dE$$  \hspace{1cm} (4.1)

which represents the integral of all additional spectral density induced by the $B$ field between the energies $E_1$ and $E_2$ at each location $(x, y)$. This technique of combined energy
integration and electronic background subtraction greatly enhances the signal-to-noise ratio of the vortex-induced states. In BSCCO, these states are broadly distributed in energy around $\pm 7$ meV, so $S^{\pm 12}(x, y, B)$ effectively maps the additional spectral strength under their peaks.

Figure 4.5: A map of $S^{12}(x, y, 5)$ showing the additional LDOS induced by the seven vortices. Each vortex is apparent as a “checkerboard” at 45° to the page orientation. Not all are identical, most likely due to the effects of electronic inhomogeneity. The units of $S^{12}(x, y, 5)$ are picoAmps because it represents $\sum dI/dV \cdot \Delta V$. In this energy range, the maximum integrated LDOS at a vortex is $\sim 3$ pA, as compared with the zero field integrated LDOS of $\sim 1$ pA. The latter is subtracted from the former to give a maximum contrast of $\sim 2$ pA. We also note that the integrated differential conductance between 0 mV and -200 mV is 200 pA because all measurements reported in this paper were obtained at a junction resistance of 1 GΩ set at a bias voltage of -200 mV.

Figure 4.5 is an image of $S^{12}(x, y, 5)$ measured in the FOV of figure 4.3(d). The locations of seven vortices are evident as the darker regions of dimension $\sim 100$ Å. Each vortex displays a spatial structure in the integrated LDOS consisting of a “checkerboard” pattern oriented along the Cu-O bonds. We have observed spatial structure with the same periodicity and orientation, in the vortex-induced LDOS on multiple samples and at fields ranging from 2 to 7 Tesla.

In all 35 vortices studied in detail, this spatial and energetic structure exists, but the “checkerboard” is more clearly resolved by the positive-bias peak. This energy asymmetry may be due to the asymmetric set-up condition of the STM which determines the tip height.
4.5. ANALYSIS

(a) Power spectrum data

(b) Power spectrum schematic

Figure 4.6: Fourier transform analysis of vortex-induced LDOS. (A) $\text{PS}[S_1^{12}(x, y, 5)]$, the two-dimensional power spectrum of the $S_1^{12}(x, y, 5)$ map shown in figure 4.5. The four points near the edges of the figure are the $\vec{k}$-space locations of the square Bi lattice. The vortex effects surround the $\vec{k} = 0$ point at the center of the figure. (B) A schematic of the $\text{PS}[S_1^{12}(x, y, 5)]$ shown in (A). Distances are measured in units of $2\pi/a_0$. Peaks due to the atoms at $(0, \pm 1)$ and $(\pm 1, 0)$ are labeled A. Peaks due to the supermodulation are observed at $B_1$ and $B_2$. The four peaks at $C_1$ and their companions at $C_2$ occur only in a magnetic field and represent the vortex-induced effects at $k$-space locations $(0, \pm 1/4)$ and $(\pm 1/4, 0)$ and $(0, \pm 3/4)$ and $(\pm 3/4, 0)$.

while imaging: the tip height is fixed by requiring the total tunneling current be 100 pA while the sample is biased at -100 mV, thus fixing the integral of the density of states out to -100 meV below the Fermi level. It’s possible that if the setup condition instead fixed the integrated density of states up to 100 meV above the Fermi level, we would see the vortex pattern more clearly at negative energies. (We have not yet carried out this experiment.)

We show the power spectrum from the two-dimensional Fourier transform of $S_1^{12}(x, y, 5)$, $\text{PS}[S_1^{12}(x, y, 5)] = |\text{FT}[S_1^{12}(x, y, 5)]|^2$, in figure 4.6(a) and a labeled schematic of these results in figure 4.6(b). In these $\vec{k}$-space images, the atomic periodicity is detected at the points labeled by A, which by definition are at $(0, \pm 1)$ and $(\pm 1, 0)$. The harmonics of the supermodulation are identified by the symbols $B_1$ and $B_2$. These features (A, $B_1$, and $B_2$) are observed in the Fourier transforms of all LDOS maps, independent of magnetic field, and they remain as a small background signal in $\text{PS}[S_1^{12}(x, y, 5)]$ because the zero-field and high-field LDOS images can only be matched to within 1 Å before subtraction. Most importantly, $\text{PS}[S_1^{12}(x, y, 5)]$ reveals new peaks at the four $\vec{k}$-space points which correspond to the spatial structure of the vortex-induced quasiparticle states. We label their locations C. No peaks of similar spectral weight exist at these points in the two-dimensional Fourier
Figure 4.7: A trace of $PS[S_{12}^{12}(x, y, 5)]$ along the dashed line in figure 4.6(b). The strength of the peak due to vortex-induced states is demonstrated, as is its location in the $\vec{k}$-space unit cell relative to the atomic locations. The spectrum along the line toward $(0,1)$ is equivalent but there is less spectral weight in the peak in $PS[S_{12}^{12}(x, y, 5)]$ at $(0,1/4)$. Note also the weaker peak at $\sim (0, 3/4)$.

To quantify these results, we fit a Lorentzian to $PS[S_{12}^{12}(x, y, 5)]$ at each of the four points labeled C in figure 4.6(b). We find that they occur at $k$-space radius $0.062 \text{ Å}^{-1}$ with width $\sigma = 0.011 \pm 0.002 \text{ Å}^{-1}$. Figure 4.7 shows the value of $PS[S_{12}^{12}(x, y, 5)]$ measured along the dashed line in figure 4.6(b). The central peak associated with long wavelength structure, the peak associated with the atoms, and the peak due to the vortex-induced quasiparticle states are all evident. The vortex-induced states identified by this means occur at $(\pm 1/4, 0)$ and $(0, \pm 1/4)$ to within the accuracy of the measurement. Equivalently, the “checkerboard” pattern evident in the LDOS has spatial periodicity $\sim 4a_0$ oriented along the Cu-O bonds. Furthermore, the width $\sigma$ of the Lorentzian yields a spatial correlation length for these LDOS oscillations of $L = (1/\pi \sigma) \approx 30 \pm 5 \text{ Å}$ (or $L \approx 7.8 \pm 1.3a_0$). This is substantially greater than the measured core radius. It appears in figures 4.3(d) and 4.6(a) that the LDOS oscillations have stronger spectral weight in one Cu-O direction than in the other. The ratio of amplitudes of $PS[S_{12}^{12}(x, y, 5)]$ between $(\pm 1/4, 0)$ and $(0, \pm 1/4)$ is approximately three. But this could be explained by an asymmetric tip.
4.6 Interpretation

How might our observation of $\sim 4a_0$ periodic $B$-field-induced electronic structure relate to the spin structure of the HTSC vortex?

4.6.1 Antiferromagnetic Vortex Core

The original suggestion of an AF insulating region inside the core cannot be tested directly by our techniques, although the Fermi-level LDOS measured there is low, as would be expected for an AF insulator. However, the structure we see has periodicity $\sim 4a_0$, so the vortex core must have some additional structure beyond a simple AF state with $2a_0$ periodicity.

4.6.2 Staggered Flux Phase

The staggered flux phase also cannot be directly tested via STM. But its predictions include a $2a_0$ periodic orbital magnetic order. Again, the structure we see has periodicity $\sim 4a_0$ so it cannot be explained by the SFP phase alone.

4.6.3 Stripes

Another possibility is that $8a_0$ periodic “stripes” are localized surrounding the core, but that two orthogonal configurations are apparent in the STM images because of fluctuations in a nematic stripe phase, or because of bilayer effects. This explanation gains some credibility from the fact that an $8a_0$ periodic spin structure is expected to be coupled to a half-wavelength $4a_0$ periodic charge structure, similar to what we observe.

4.6.4 Coexisting Spin Density Wave + Superconductivity

A more recent proposal is that when the HTSC order parameter near a vortex is weakened by circulating superflow, a coexisting SDW+HTSC phase appears, resulting in a local magnetic state $\mathbf{M}(r)$ surrounding the core. A second proposal is that the periodicity, orientation, and spatial extent of the vortex-induced $\mathbf{M}(r)$ are determined by the dispersion and wavevector of the pre-existing zero field AF fluctuations. In both cases, the $8a_0$ spatial periodicity of $\mathbf{M}(r)$ is not fully understood but is consistent with models of evolution of coupled spin and charge modulations in a doped antiferromagnetic Mott insulator.
Figure 4.8: (a) Superfluid velocity $v(x)$ rises and the HTSC order parameter $|\Psi(x)|$ falls as the core is approached. The periodicity of the spin density modulation deduced from INS is shown schematically as $M(x)$. The anticipated periodicity of the LDOS modulation due to such an $M(x)$ is shown schematically as LDOS$(x)$. (b) A schematic of the two-dimensional “checkerboard” of LDOS modulations that would exist at a circularly symmetric vortex core with an $8a_0$ spin modulation as modeled in (a). The dashed line shows the location of the $\sim 5a_0$ diameter vortex core. The dark regions represent higher intensity low energy LDOS due to the presence of a vortex. They are $2a_0$ wide and separated by $4a_0$. (c) The two dimensional autocorrelation of a region of $S^{12}(x,y,5)$ that contains one vortex. Its dimensions are scaled to match the scale of (a), and it is rotated relative to figure 4.3(d) so that the Cu-O bond directions are here horizontal and vertical.

Figure 4.8(a) shows a schematic of the superflow field and the magnetization $M(r)$ localized at the vortex. Almost all microscopic models predict that magnetic order localized near a vortex will create characteristic perturbations to the quasiparticle LDOS. In addition, general theoretical principles about coupled charge- and spin-density-wave order parameters indicate that spatial variations in $M(r)$ must have double the wavelength of any associated variations in the LDOS$(r)$. Thus, the perturbations to the LDOS$(r)$ near a vortex should have $4a_0$ periodicity and the same orientation and spatial extent as $M(r)$ as represented schematically in figure 4.8(a). In an LDOS image this would become apparent as a checkerboard pattern, shown schematically in figure 4.8(b). In figure 4.8(c), we show the autocorrelation of a region of figure 4.3(d) that contains one vortex, to display the spatial structure of the BSCCO vortex-induced LDOS. It is in good agreement with the quasiparticle response described by figures 4.8(a) and 4.8(b). Therefore, assuming equivalent vortex phenomena in LSCO, YBCO and BSCCO, the combined results from INS, ENS, NMR, and STM could lead to an internally consistent new picture for the electronic and magnetic structure of the HTSC vortex.
4.7 Further Questions

Unfortunately we are unable to distinguish between the various scenarios in the previous section. Some questions we would like to ask in future experiments to address these scenarios are summarized here.

4.7.1 One-Dimensionality

Some degree of one-dimensionality is evident in these incommensurate LDOS modulations because one Cu-O direction has stronger spectral intensity than the other by a factor of approximately two.

However, this could easily be caused by a tip effect. An asymmetric tip will blur the DOS in one direction, but may still allow very high resolution in the orthogonal direction. The best way to check for an asymmetric tip is to image an isolated impurity with high resolution. If it appears distorted, then it’s likely the tip is asymmetric. Another check is to look at the autocorrelation of an image: a double tip will show peaks in the autocorrelation at the length scale of the double tip.

Another possibility is that there is just so much disorder in the system (from at least 100 Ni atoms in the FOV, plus at least 10 other impurities of uncertain origin) that the pinning forces distort the vortices.

The best way to check for asymmetry would be to look at vortices far from impurities, with a tip which has been previously checked for asymmetry by imaging a single isolated impurity.

4.7.2 Dispersion

The vortex-induced modulations are the same orientation and a very similar wavelength to the \( \vec{q}_1 \) modulations discussed in the previous chapter. In fact, the wavelength of the \( \vec{q}_1 \) modulations disperses through the apparently static wavelength found here for the vortex modulations (although not at 7 meV). So we must ask, have we missed detecting a dispersion because we have integrated over the whole range of relevant energies from 1 meV to 12 meV?

The \( \vec{q}_1 \) peak disperses only weakly: from 0.22 to 0.25 of the Brillouin zone. In order to see this weak dispersion, we need \( \vec{q} \)-space resolution at least 1% of the Brillouin zone, which means we need a real field of view of size at least 100\( a_0 \approx 400 \) Å. But the vortices are only \( \sim 100 \) Å, which gives us a \( \vec{q} \)-space resolution \( \sim 4\% \) of the Brillouin zone. Even though
we have seven vortices in our field of view, our resolution is increased only by a factor of $\sim \sqrt{7} = 2.6$. This would likely not be enough to definitively measure a dispersion. The non-integrated vortex power spectrum, extracted along the line in figure 4.6(b), is shown in figure 4.9 for energies from 0 meV to 12 meV.

The search for a dispersion of the vortex resonance is so far inconclusive. One possibility to detect or rule out a dispersion in the future might come from imaging vortices in higher magnetic fields. If, as neutron scattering experiments imply, the magnetic-field induced ordering comprises a larger and larger fraction of the area as the field is increased, until the ordering covers the whole area, then it is possible that we could achieve more $\vec{k}$-space resolution in high fields. In the foreseeable future, the highest possible field for this type of slow, high-resolution STM measurement is approximately 15 T.

4.7.3 Charge Density Wave

One way to check for a charge density wave is to look for a spatial phase flip across the Fermi level $\varepsilon_F$. The data shown here are not sufficiently well-resolved to determine whether there is a phase flip. Spatial resolution is only 1 pixel per 2 Å, but also there are too many impurities influencing the pinning and making it difficult to see clearly.
More importantly, these data were taken only with a negative setup condition (requiring the total current to be constant at a fixed negative bias voltage). These data should be retaken at higher spatial resolution, and with both positive and negative setup conditions, ideally on a sample with fewer impurities, to resolve the question of the phase flip and test definitively for a charge density wave.

Matsuba et al.\textsuperscript{142} recently showed the first STM images of an ordered vortex lattice in BSCCO, which implies that their vortices are unpinned. Although their images are lower resolution, they do offer some support for the quasiparticle checkerboard we observed, and specifically for the increased strength and clarity of the positive-energy states. This is intriguing because they used an opposite setup condition: they required a constant current with a \textit{positive} bias of +0.5 V on the sample, instead of a \textit{negative} bias of -0.1 V as we used. Despite the opposite setup condition they also saw increased intensity for the positive-energy states. Before we draw any conclusions from this, we emphasize that the same group should measure both setup conditions in the same area of the same sample.

### 4.7.4 Field Dependence

The neutron scattering experiments all show an increase in spin ordering (both static order and fluctuating order, in different related compounds) on increasing applied $B$-field. It would be very useful to look at our vortex-induced DOS ordering as a function of applied $B$-field to see if it increases in strength with the same field dependence. STM is not a very reliable measure of absolute DOS amplitude, due to the tricky normalization procedure and related uncertainty of tip-sample separation. However, a careful study could be made of multiple fields on the same field of view with a few reliable impurity resonances to calibrate and cross-normalize the amplitude of maps taken at different field strengths. Or, the impurity resonances themselves may change with applied $B$-field, so another background signal might be needed instead for normalization. But as long as we can guard against a tip change while ramping the $B$-field, it seems likely that such a study is possible and will be very useful.

The Demler theory of coexisting spin density wave order plus superconductivity gives a clear quantitative prediction for the increase of SDW order with increasing applied $H$-field:

$$ M^2 \propto H / H_c \ln(H_c / H) $$  \hspace{1cm} (4.2)

Equation 4.2 governs spin ordering, but STM is sensitive to charge ordering. However, the two are predicted to be coupled, so we should do a careful study to look for an increase
in vortex-induced DOS modulations following equation 4.2. This would lend extra support to Lake’s finding\textsuperscript{92} that the static spin order obeys Demler’s prediction,\textsuperscript{40} and also give evidence to support the common assumption that the spin and charge order are coupled in the cuprates.

### 4.7.5 Doping Dependence

Ando and Boebinger have led experiments to investigate the transport properties of La$_{2-x}$Sr$_x$CuO$_4$, across a range of dopings $x$, in magnetic fields sufficient to quench superconductivity. They have found a significant crossover from unusual insulating behavior in underdoped,\textsuperscript{133} to conducting in overdoped,\textsuperscript{134} in very high magnetic fields.

We have so far investigated vortices in BSCCO samples only very close to optimally doped. It will be very important to look for differences in the induced order in further underdoped samples. If the induced order really is a charge density wave of some sort, we might expect it to be significantly enhanced in underdoped samples.

A recent experiment by Hoogenboom \textit{et al.}\textsuperscript{143} shows that the energy of the vortex-induced state varies systematically with the local gap in the neighborhood of the vortex. For larger local $\Delta$ (i.e. more underdoped) the vortex-induced resonance also has larger energy. However, the error bars on this study are large, and the import of the result is not clear, since the gap inhomogeneity has a length scale of $\sim 30$ Å while the vortex-induced resonances appear over a $\sim 100$ Å length scale, so the vortex-induced resonance may be influenced by several regions of very different local $\Delta$. It would be useful to look again at this result with a number of samples of wider variation in bulk doping.

### 4.8 Conclusion

The vortex-induced electronic structure has some superficial similarities to quasiparticle interference. Both display $\sim 4a_0$ periodic CuO bond-oriented order. At $\sim 7$ meV, the density of states pattern surrounding the vortex looks quite similar by eye to the quasiparticle interference density of states pattern filling all space in zero applied field at $\sim 10$–20 meV. However the vortex electronic structure is 10–100 times stronger than the quasiparticle interference. Also, while the zero-field quasiparticle interference varies with energy, the vortex electronic structure apparently doesn’t disperse, although we can’t know for sure from existing data. Furthermore, the quasiparticle interference shows 16 $\vec{q}$-space peaks, while the vortex structure shows only 4: $(1/4, 0)$, $(0, 1/4)$, $(3/4, 0)$, and $(0, 3/4)$. Since the
vortex electronic structure appears where we know the SC to be destroyed, it seems very likely that the vortex-induced electronic structure is evidence of another competing order. If so, it would be the first real-space image of a new periodic electronic state in the cuprates.

Independent of models of the vortex structure, the data reported here are important for several reasons. First, the $\sim 4a_0$ periodicity and register to the Cu-O bond directions of the vortex-induced LDOS are likely signatures of strong electronic correlations in the underlying lattice. Such a $4a_0$ periodicity in the electronic structure is a frequent prediction of coupled spin-charge order theories for the cuprates, but has not been previously observed in the quasiparticle spectrum of any HTSC system. This may be the first local glimpse into the structure of the mysterious “pseudogap” phase whose bulk properties are exhibited by all high temperature superconducting materials outside of the superconducting dome.