Journal of Low Temperature Physics, Vol. 131, Nos. 3/4, May 2003 (© 2003)

Electronic checkerboard pattern in striped racetrack domains: a consistent picture of recent neutron and STM experiments.

Brian Møller Andersen, Per Hedegård, and Henrik Bruus*

Ørsted Laboratory, Niels Bohr Institute for APG,
Universitetsparken 5, DK-2100 Copenhagen Ø, Denmark
**Mikroelektronik Centret, Technical University of Denmark, DK-2800 Lyngby*

We discuss recent elastic neutron scattering and scanning tunneling experiments on high-T_c cuprates exposed to an applied magnetic field. In particular we show that a physical picture consisting of antiferromagnetic vortex cores operating as pinning centers for surrounding stripes is qualitatively consistent with the neutron data provided the stripes have the usual antiphase modulation. Further, we calculate the electronic structure in such a region using a T-matrix method, and find a checkerboard interference pattern consistent with recent scanning tunneling experiments.

PACS numbers: 74.72.-h, 74.25.Ha, 74.25.Jb

Elastic neutron scattering results on $La_{2-x}Sr_xCuO_2$ (x=0.10) have shown that the intensity of the incommensurate peaks in the superconducting phase is considerably increased when a magnetic field of $H = 14.5T$ is applied perpendicular to the CuO_2 planes.[1] Spatially resolved nuclear magnetic resonance (NMR) experiments have shown strong evidence for antiferromagnetism in and around the vortex cores of near-optimally doped $YBa_2Cu_3O_{7-\delta}$[2] and $Tl_2Ba_2CuO_{6+\delta}$.[3] Furthermore, muon spin rotation measurements from the mixed state of $YBa_2Cu_3O_{6.50}$ find static antiferromagnetism in the cores.[4] Further evidence for coexistence of the two orders in and around vortex cores has come from scanning tunneling microscopy (STM) performed on the surface of $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+x}$.[5–7] Theoretically the discussion of competing order parameters in the doped Mott insulators has been a hot topic for over a decade. The SO(5) model was

0022-2291/03/0500-0281/0

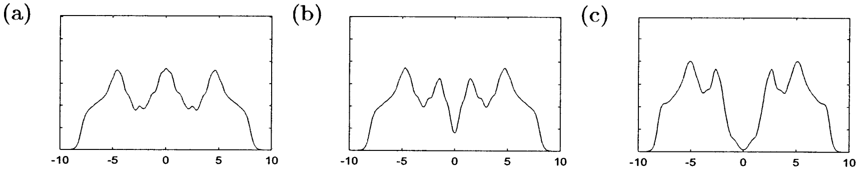

Fig. 1. LDOS in the vortex core; (a) for a pure d-wave superconducor, (b) including a magnetic order parameter that increases when approaching the core (applies to YBCO), (c) same as (b) but with increased magnetism in the core (BSCCO). The dashed line shows the bulk spectrum.

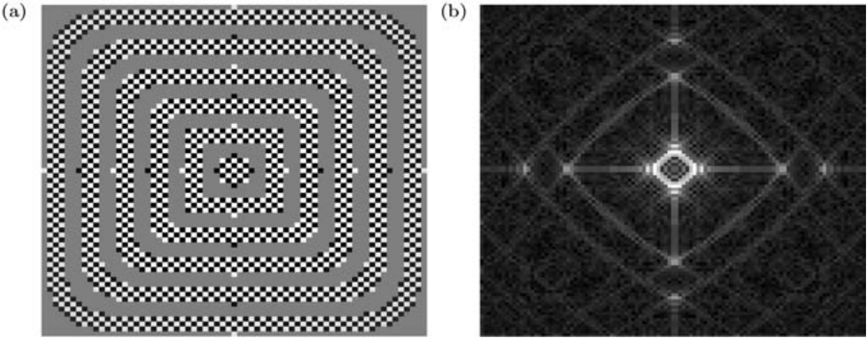

Fig. 2. a) The induced spin structure around the vortex cores. Black (white) represent spin up (down) and gray is the superconducting state. For clarity we have exaggerated the distance between adjacent magnetic domains. b) Fourier spectrum of the spin density order from a).

first to predict the existence of antiferromagnetic vortex cores[8] and to suggest several experiments to observe these anomalous cores.[9,10] Relaxing the strict SO(5) constraint between the antiferromagnetic and the superconducting sectors seem to be necessary to explain the large magnetic correlation observed in ref.1[11] and to explain the modest splitting of the zero bias conductance peak (ZBCP) expected in vortex cores of d-wave superconductors[12–14] (See figure 1). The splitting of the ZECP shown in Figure 1 is identical to the spin splitting of the zero energy Andreev bound states at a $\{110\}$ interface of an antiferromagnet and a $d_{x^2-y^2}$-wave superconductor.[15]

The physical picture we have in mind is presented in figure 2a. This is the ideal static picture of a real space version of an antiferromagnetic core (center) which has pinned a number of surrounding stripes. Without the applied magnetic field only impurities can produce a similar pinning effect of the fluctuating stripes. In addition to the creation of more pinning cen-

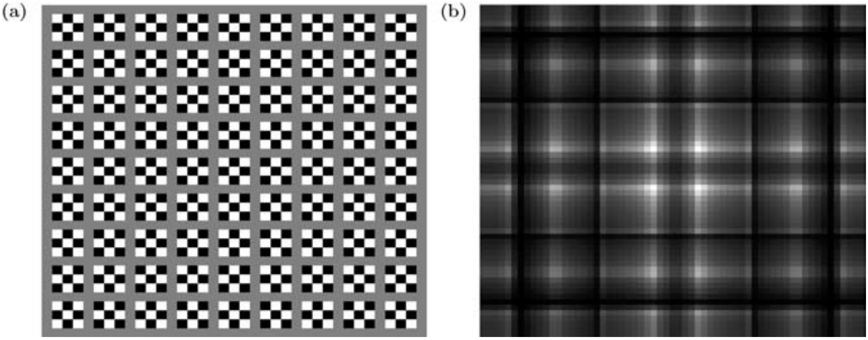

Fig. 3. a) Real space picture of the spin structure in a checkerboard geometry. Black (white) represent spin up (down) while gray is the superconducting state. Similarly to the ring structure above each island of antiferromagnetic spins can be seen to be out of phase with its nearest neighbor. b) Fourier spectrum of the checkerboard structure shown in a). Note that the four main incommensurate peaks are rotated 45 degrees relative to the Cu-O a-b axis.

ters when applying a magnetic field, the single site impurities are expected to pin much weaker than the large "impurities" created by the flux lines. This is qualitatively consistent with the measurements by Lake *et al.*[1] of the temperature dependence of the increased magnetic signal for different magnetic field strengths (Note figure 2 and 3 in ref. 1). The intention of the first part of this article is not to apply a specific model to explain the above experiments, but to use simple Fourier analysis to make a number of model independent observations. In our discussion we focus only on the competition between the ordered states and consider complications arising from coupling to low-lying nodal quasiparticles to be absent because of constraints from momentum conservation.

Both experimentally[16] and theoretically[17] we expect an antiphase modulation of the induced antiferromagnetic ring domains. Indeed as seen from figure 2b the related diffraction pattern is qualitatively consistent with the increased incommensurability observed in ref. 1!

Recently STM results have shown a checkerboard pattern of the local density of states (LDOS) around the vortex cores in slightly overdoped BSCCO.[7] Similar results obtained by Howald *et.al.*[18] without an applied magnetic field have been succesfully described in terms of interference from quasiparticle impurity scattering.[19] The LDOS modulation was found to have half the period of the spin density wave observed by neutron scattering (i.e. four lattice sites), and to be oriented along the crystal axes of the CuO_2 plane. Is

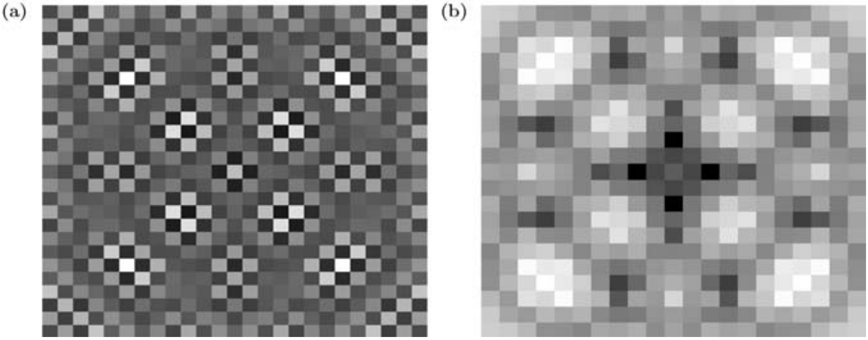

Fig. 4. a) LDOS modulations in a domain of super-elliptic antiferromagnetic racetracks (Figure 2). b) Smeared LDOS from a)

there a simple way to understand this electronic structure in terms of some static field induced spin texture? If we *assume*, naively, that the checkerboard charge density wave is intrinsic to the $\mathrm{CuO_2}$ planes (and not a bilayer effect) where it gives rise to a static spin density wave checkerboard pattern, what should an elastic neutron scattering experiment expect to find? To answer this question we need to investigate an idealized pattern like the one shown in figure 3a. Here we have also expected an antiphase order between the magnetic droplets. The Fourier spectrum of the checkerboard spin configuration is shown in figure 3b. Note the 45 degree rotation of the four main incommensurable peaks and the expected checkerboard pattern of the higher harmonics. This picture is clearly not appropriate for LSCO for doping levels close to $x = 0.10$. It is interesting that a rotation of the incommensurable peaks at low dopings ($x < 0.055$, close the insulator-superconductor phase transition) has been observed in LSCO.[20] Unfortunately there is no simple way to create an antiphase spin geometry without frustrating the spins at low dopings where droplets of charge in an antiferromagnetic background is the expected situation.[21] However, this might be possible in the highly overdoped regime where the droplets have been inverted to separate magnetic islands. In that case a 45 degree rotation of the incommensurable peaks would be consistent with a checkerboard pattern.

There is, however, a simple, consistent way to understand the racetrack spin structure of Figure 2 with the checkerboard STM results; namely through the formation of standing waves within the superconducting domains. Figure 4 shows the result of a full calculation which will be presented elsewhere.[22] Essentially we have embedded the perturbations from the spin structure shown in Figure 2 in an otherwise homogeneous $d_{x^2-y^2}$-wave superconductor and calculated the LDOS in the perturbed region. The figure is obtained after integrating over a small energy window (0-12 meV) and shows clearly that checkerboard interference patterns arise at these low energies due to interference effects. The checkerboard LDOS pattern is very robust with respect to variations in model parameters.[22]

In summary we discussed the phenomenology of a simple physical picture of pinning of stripes around vortex cores that are forced antiferromagnetic by an applied magnetic field. Contrary to commen belief the LDOS inside the cores are not inconsistent with insulating, magnetic cores. The induction of striped ring structures around the core seems from simple Fourier analysis to be consistent with the diffraction spectra observed on LSCO only if the stripes are out of phase with their neighbors in the usual sense.

In materials where a checkerboard spin pattern is relevant, we show that a 45 degree rotation of the main incommensurable peaks are to be expected contrary to the experiments on LSCO. Finally, the checkerboard LDOS by Hoffman *et.al.* arise from interference of standing waves around the vortices.

Acknowledgement: this work was supported by the Danish Natural Science Research Council through the Ole Rømer Grant No. 9600548.

REFERENCES

1. B. Lake *et.al.*, *Nature* **415**, 299 (2002).
2. V.F. Mitrovic *et.al.*, *Nature* **413**, 501 (2001).
3. K. Kakuyanagi, K. Kumagai, Y. Matsuda, M. Hasegawa, *condmat/0206362.*
4. R.I. Miller *et.al.* , *Phys. Rev. Lett.* **88**, 137002 (2002).
5. I. Maggio-Aprile *et.al.* Phys. Rev. Lett **75**, 2754 (1995); C. Renner, *et.al.*, *Phys. Rev. Lett.* **80**, 3606 (1998).
6. S.H. Pan *et.al*, *Phys. Rev. Lett.* **85**, 1536 (2000).
7. J.E. Hoffman *et.al.*, *Science* **295**, 466 (2002).
8. D.P. Arovas *et.al.* *Phys. Rev. Lett.* **79**, 2871 (1997).
9. H. Bruus *et.al*, *Phys. Rev. B* **59**, 4349 (1999).
10. B.M. Andersen, H. Bruus, P. Hedegård, *Phys. Rev. B* **61**, 6298 (2000).
11. J-P Hu, S-C. Zhang, *J. Phys. Chem. Solids.* (in press).
12. Y. Wang, A.H. MacDonald, *Phys. Rev. B* **52**, R3876 (1995).
13. The calculation leading to this LDOS is described elsewhere.[10] The cause of the splitting is equal to that suggested by Andersen *et al.*[10] and by Zhu *et al.*.[14]
14. J-X. Zhu, C.S. Ting *Phys. Rev. Lett.* **87**, 147002 (2001).
15. B.M. Andersen, P. Hedegård, *condmat/0206422.*
16. J.M. Tranquada *et.al*, *Nature* **375**, 561 (2002).
17. O. Zachar, S.A. Kivelson, V.J. Emery, *Phys. Rev. B* **57**, 1422 (1998).
18. C. Howald, H. Eisaki, N. Kaneko, A. Kapitulnik, *condmat/0201546.*
19. Q-H. Wang, D-H. Lee, *condmat/0205118.*
20. S. Wakimoto, G. Shirane, Y. Endoh, *et al.*, *Phys. Rev. B* **60**, R769 (1999).
21. M. Veilette *et.al*, *Phys. Rev. Lett.* **83**, 2413 (1999).
22. B.M. Andersen, P. Hedegård, (unpublished).