The Fourth State:

Attempts to identify the electronic ground state of lightly hole-doped Cuprates.

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The phase diagram of several hole-doped copper oxides shows four different electronic phases existing at zero temperature. Familiar among these are the antiferromagnetic Mott insulator (MI), high-T_c superconductor (HTSC), and metallic (M) phases. But in some cuprates at least, a fourth phase, of unknown identity, occurs at light doping along the zero temperature bound of the so-called 'pseudogap' (PG) regime[i]. When studied at relatively high temperatures (where there are powerful fluctuations of several different kinds) the PG regime is rich in peculiar phenomena but has proven impervious to attempts to identify which electronic phase dominates. In this discussion we hope, instead, to review available experimental information about the ground state (i.e. near zero temperature) of electronic phase(s) associated with this regime. Our purpose is to explore the question: "what is the identity of the fourth state in the cuprates".

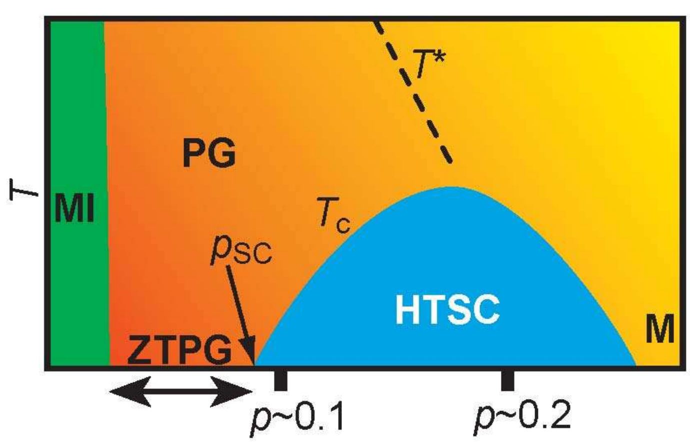

Fig. 1 Schematic phase diagram showing where 'fourth state' can exist.

We will review experimental results from nuclear magnetic resonance (NMR), angle resolved photoemission (ARPES), muon spin rotation, and transport. We will then present the first electronic structure imaging studies of a lightly hole-doped copper-oxide in the zero temperature pseudogap regime[ii]. Scanning tunneling spectroscopy at T<100mK is used to study $Ca_{2-x}Na_xCuO_2Cl_2$. We find that at energies $|E| > 100$ meV, electron extraction probabilities greatly exceeding those for injection. Such strong bias asymmetries in conductance have long been anticipated because, in a lightly hole-doped MI, the reservoir of states from which electrons can be extracted at negative sample-bias is determined by 1-*p,* while that of hole-states into which electrons can be injected at positive sample-bias is determined by *p* (where *p* is the number of holes per CuO_2). We find that for $|E| < 100$ meV, the $Ca_{2-x}Na_xCuO_2Cl_2$ spectrum exhibits a V-shaped energy gap centered on $E = 0$. States within this gap undergo intense spatial modulations, with the spatial correlations of a four CuO_2-unit-cell square 'checkerboard', independent of energy. Intricate atomic-scale electronic structure variations also exist within the 'checkerboard'. These data are consistent with an unanticipated crystalline electronic state existing in the zero temperature pseudogap regime of $Ca_{2-x}Na_xCuO_2Cl_2$. To complete this discussion, we will also introduce very recent atomic-resolution images of the spatial arrangements of deep filled states (which from ARPES are unperturbed by the doping process) in $Ca_{2-x}Na_xCuO_2Cl_2$.[iii]

Finally, we hope to initiate a discussion of how these experimental data are related to theoretical models for lightly doped copper-oxide Mott insulators including resonating valence bond superconductivity, gossamer superconductivity, staggered-flux phase, d-density wave phase, fractionalized spin liquids, valence-bond solids, stripes, and SO(5)-hole-pair crystals.

[i] Timusk, T. & Statt, B. ***Rep. Prog. Phys***. 62, 61-122 (1999).

[ii] T. Hanaguri, C. Lupien, Y. Kohsaka, D.-H. Lee, M. Azuma, M. Takano, H. Takagi, & J. C. Davis. Discovery of a 'Checkerboard' Electronic Crystal State in Lightly Hole-Doped $Ca_{2-x}Na_xCuO_2Cl_2$. To appear in ***Nature*** Aug. 2004.

[iii] In collaboration with C. Lupien (Cornell), Y. Kohsaka (Cornell/Tokyo), T. Hanaguri (RIKEN & Tokyo), D.-H. Lee (UC Berkeley), M. Azuma (Kyoto), M. Takano (Kyoto), and H. Takagi (RIKEN & Tokyo)