Competing Orders: speculations and interpretations

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- Three questions:
  - Are COs unavoidable in these materials?
  - Are COs responsible for the pseudo-gap regime?
    For the superconductivity itself?
  - Which if any competing orders are present at T=0 in an “ideal” system?
Preparing for the conference...
Competing Order means?

- At least local symmetry breaking (charge or spin or ?? ordering) in regions large enough and with slow enough dynamics (quasi-static) that they can be clearly identified
  - in the pseudo-gap region
  - in the T=0 normal state
  - in the SC state
    - bulk coexistence
    - in the vortex “cores”

- n.b. “resonance” or “soft mode” does not mean quasi-static local order. It means there is an excitation which could be made to induce local or global order, which is fairly long-lived.
Theoretical Reasons for CO

• Pseudo-gap seems to strengthen with under-doping
  - Luttinger theorem otherwise predicts large Fermi surface
  - Even “exotic” (RVB-type) scenarios seem to require a small Fermi surface if no CO at T=0

• Quantum-critical thinking
  - A continuous or nearly continuous QPT out of a superconductor should be described by a field theory of *quantum vortex unbinding*

  - Vortex Berry phases lead *inevitably* to CO in the proximate normal state

  - Believe this is true for any *(super-)*clean SC-N QPT provided the quasiparticle DOS remains vanishing at $E_F$ up to the QCP
  - Details of CO depend upon doping, pairing symmetry, some other parameters, but it is generally at a doping-dependent wavevector
  - Requires CO within range of zero-point motion of vortex core in SC state
Cause or Effect?

• Pseudo-gap is a *high energy* phenomena
  – If it is the cause, CO should be locally formed at comparable or higher temperature $T_{CO} > T^*$
  – Usually, expect $T_{CO}$ no more than 2-3 times actual critical temperature for CO, *unless*
    • frustrated – incommensurate/glassy charge order?
    • or: order occurs in *dilute*, disconnected *local regions*
  – Actual *critical temperatures* for identified COs are *low*
    • “observations” of CO at higher $T$ seem to be observing “soft mode” *excitations* characteristic of potential CO at lower $T$ (c.f. neutron resonance) - Vershinen *et al* STM?

• Conclude
  – If CO drives pseudo-gap, it must be frustrated or dilute
  - OR -
  – It is a consequence not the driving force behind the pseudo-gap
High Temperature Order?

• **Frustrated (charge?) order**
  - Charge order does seem much more robust when commensurate but…
  - Many properties seem to behave smoothly with doping
  - Would like to see clear signatures of local, even frustrated, charge ordering (glassiness?) at high temperatures - especially in cleanest YBCO materials (c.f. NQR/NMR in LSCO)
  - Naïve charge order could explain gap but not width near antinodes

• **Dilute order**
  - Coexistence of small but well-formed regions of CO state inside normal or SCing phase seems to require proximity to a *strong first order* transition (if disorder is weak) **Zhang SO(5)**
  - Why should coexistence occur over such a large region (the pseudo-gap) of phase space?
  - One possibility is Emery-Kivelson suggestion of phase separation
    - macroscopic neutrality forces spatial segregation
    - test: is charge density in CuO$_2$ plane actually inhomogeneous?
CO as a derivative phenomena?

• Implication: pseudo-gap is some more subtle “critical” state
  -RVB “algebraic spin liquid”/QED$_3$?  
  -Quantum critical “fan”? Of what QCP?

• What do we learn from observations of CO at lower energy/temperature?
  -Critical PG state must be “susceptible” to observed CO at low-T  
  -Conversely, PG state must be able to avoid CO if experiments find otherwise at low temperature.

• In “cleanest” cuprate ortho-series YBCO
  -low-T CO may be $\approx$ antiferromagnetic clusters (µSR, neutron)  
  -thermal and electrical transport indicate metallic non-SC state w/ WF violation?  
  -indications (3meV neutron resonance) of $\approx$ continuous onset of magnetic order

PG state should be susceptible to local and bulk magnetic order and (presumably) Fermi surface formation
Algebraic Spin Liquid?

n.b. I will presume to explain P. Anderson et al theory

- A predicted RVB state of \( \frac{1}{2} \)-filled t-J-like model
  - has power-law spin and density fluctuations of many types
  - “neutral fermions” with d-wave-like PG

- Proposal: PG is to be understood as governed by \( \frac{1}{2} \)-filled RVB Algebraic Spin Liquid (\( \approx \text{QED}_3 \))
  - Experimental trouble if AF state actually borders SC phase?

- Problems?
  - ASL may be intrinsically unstable
  - Doping is not negligible in PG regime
  - Not clear whether ASL can give rise to metal at \( T=0 \)
    (clearly only small Fermi surface possible if at all)
Deconfined Criticality

- RVB-states can be more robustly stabilized in quantum critical region.
- Could dSC-CO QCP be also deconfined? Seems very likely something like this can happen for d-wave SC.

Senthil et al, 2004 (LB, S. Sachdev)

Burkov et al, 2004 (doped dimer model)

Same QCP can describe transition to different non-SCing phases
Conclusions

• If CO is really a driver for the pseudo-gap, it probably must imply charge inhomogeneity at high temperature $T \sim T^*$. Large inhomogeneity at low T. Testable.

• Other possibility: pseudo-gap is some critical state, which should be *almost* stable, leading to observed CO at low T, near impurities, etc.

• RVB and its more recent incarnations at QCPs seem attractive candidates for such a state.
  – perhaps SC-CO QCP combines both physics in a natural way

• Main conclusion: recent experiments are amazing and CIAR is clearly playing a key role in advancing the field.