Near the Superconducting Edge: Spin Confinement and Central Modes

Bill Buyers
National Research Council, Chalk River, Canada

Program on Quantum Phase Transitions
Kavli Institute for Theoretical Physics,
Santa Barbara January 25, 2005

Collaborators:

National Research Council Chalk River Laboratories:
- Zin Tun
- Zahra Yamani

University of British Columbia:
- Ruixing Liang
- Darren Peets
- Doug Bonn
- Walter N. Hardy

University of Toronto:
- Chris Stock
- Bob J. Birgeneau
- Paul S. Clegg

ISIS:
- Chris D. Frost

Oxford:
- Roger Cowley
- Radu Coldea

Johns Hopkins
- Collin Broholm
**YBCO\textsubscript{6+x}**

No gap in normal *spin* response

Incommensurate spin modulations at low energy and resonance grow in for \( T < 2T_c \)

Chris Stock et al

PRB 69, 014502 ‘04

PRB 71, Jan 1 ‘05

---

**DISPERSION \( x=6.5 \)**

Wave vector increases with energy \( \omega = cq \) centred on \( Q_{AF} \)

No ‘silent’ \( q \)-band like \( x=6.85 \) – Pailhes weak Landau damping

The velocity of \( c=400 \text{ meV}\text{-Å} \)

is reduced to 60% of the insulator.

\( J// = 70 \text{ meV} \)

\( J \perp = 10 \text{ meV} \)
Resonance $\text{YBCO}_{6.5}$
$T_c=59\text{K}$

Has spin triplet symmetry (polarized neutrons)
- A particle-particle process seen via SC pairing?
- A particle-hole exciton below energies with Landau damping?
- Spin response pushed up by SC gap energy?
- Incoherence?

Resonance:
peak susceptibility
The resonance is $\sim 40\%$ preformed in the normal phase

Local pairs occur dynamically.

Pairs achieve coherence in the superconducting phase.
High energies:

MAPS of smoke rings: intersection with cone of spin excitations

isotropic for $33 < E < 110$ meV

On resonance 33 meV

Above resonance 77 meV

High-energy spin map in $\text{YBCO}_{6.5}$

Ridge of paramagnon velocity – from $(\pi, \pi)$

Resonance: Q-width same as for stripes below resonance
Incommensurate fluctuations: STM charge modulation is twice the spin matches nesting wave vector

For YBCO$_{6.5}$ ($T_c=59$ K), we plot from BSCCO Hoffmann, Science (2002)

$q_{\text{spin}} = Q_{59}/2$

$= 0.08$ rlu

At 12 meV we observe

$q_{\text{spin}} = 0.06$ rlu=$0.10$ Å$^{-1}$

$Q$ of BSCCO scaled by doping
$E$ scaled by resonance energy

See Christensen et al 0403439
for optimally doped LSCO

Neutron data from Stock et al 0408071
Spin squared couples to charge density via Landau or via antiphase domains

Ensures that $Q_{\text{spin}} = \frac{1}{2} Q_{\text{charge}}$

$(\pi + \delta_{\text{spin}}, \frac{1}{2})^2 = 2 \delta_{\text{spin}} = \delta_{\text{charge}}$

If $Q_{\text{charge}}$ follows spin then it is not a caliper of a Fermi surface dimension?

t-J model – linear in spin – quadratic in charge:

$$H = t \sum_{i,j(i)} (b_i + b_j^\dagger) h_i^\dagger h_j + \frac{1}{4} J \sum_{i,j(i)} (b_i^\dagger b_i + b_j^\dagger b_j + b_i b_j + b_i^\dagger b_j^\dagger)$$

Spin-charge coupling fails along (110)

q-STM expands with energy
q-neutron remains constant

Hence relation to STM is not generally valid
We find that checkerboards with a commensurate \((\pi, \pi)\) background are not low-energy states of t-J model and can only be stabilized with large external potentials.

White, Scalapino PRB 70, 220506(R) (2004)
**YBCO_{6.35}: Modified Lorentzian**

Resonance is overdamped with a relaxation rate \( \sim 2.5 \text{ meV} \sim 0.6 \text{ ps}^{-1} \)

---

**The resonance as soft mode**

The resonance is critical: it is *the soft-mode* at the superconducting phase boundary - but not the pairing boson.

It tracks \( T_c \sim (p-p_c)^{1/2} \)

not the doping, \( p \sim \delta \), nor ladder width

It drives the transition from superconductor to antiferromagnet.
A new lower energy scale: below damped resonance lies a Central mode: 30 times lower in energy & 150 times stronger.

Two energy scales:
- Central Peak
  - 0.08 meV
- Damped resonance
  - 2.5 meV
- Are they coupled?

YBCO$_{6.35}$: conserved total moment—sample is single-phase.

$$S (S + 1) = Z \chi \frac{1}{\pi} \int d\omega \int d^3 q [n(\omega) + 1] \chi''(q,\omega)$$

$$Z \chi \sim 0.5$$

Soft mode drives central mode

Full moment to 32 meV detected

6% expected for E<32 meV
Triplet spin fluctuations \( \chi^{xx} = \chi \) all \( x \), all \( \omega \)
\[ \therefore \text{holes cannot}\]
spins Schrainer Siggia
-Short-range in space
8 cells
-Slow in time

Spins behave as 3D coupled bilayers
Correlation length
\[ \xi_c = 8 \pm 2 \text{ Å} \sim 1 \text{ cell} \]
AF between planes
In-plane \( \xi_{xy} = 8 \) cells
\[ \therefore \text{Not Bragg LRO.} \]
- glass phase coexists with SC
Central peak grows as $T \to 0$ but $T_c(\rho, 0, T)$ is subcritical

Spin amplitude ignores $T_c$

Finite DOS at $\omega=0$ since $\xi$ finite $C_v(T), \rho(T), K(T)$?

Central peak $T, q$ & $\gamma(T)$

- strong spin
- weak SC response

- only $\gamma = \tau^{-1}$ senses $T_c$
$\omega/T$ Scaling: $I(\omega,T)/I(\omega,T=0) \sim \arctan (\omega/a_1T + (\omega/a_2T)^3 + \ldots)$

$T$ above and below $T_c=18$K $\omega<30$meV $T>T_c=59$ K $\omega<20$ meV farther from QCP?

\begin{align*}
\chi''(\omega,T)/\chi''(\omega,T=0) &= \arctan(0.9 (\omega/T) + 2.84 (\omega/T)^3) \\
\chi'(\omega,T) / \chi'(\omega,T=0) &\propto \arctan(1.1 (\omega/T))
\end{align*}

$\chi''(\omega/T)/\chi''(\omega,T=0)$

$\chi'(\omega,T)/\chi'(\omega,T=0)$

YBCO$_{6.35}$

YBCO$_{6.5}$

Spin response of soft mode driving a defect mode 
à la antiferroelectric SrTiO3
Halperin Varma '76

$\chi^{-1} = \omega_0^2 - \omega^2 - i \omega [\Gamma + \delta^2 / (\gamma - i \omega)]$

$\gamma << \omega_0$, $\Gamma$

$2$ K $\omega_0$=0.65 meV

$\gamma$=0.07 meV (0.8 K)

$\Gamma$=6.5 meV

Coupling $\delta$=3.0 meV
Slow hopping of driven “defect”
What is the slow object?

![Graph showing energy vs. temperature with different curves labeled w0 LHS, g_0=1/tau RHS, w_infl LHS, and g_CM RHS. The graph indicates central and soft modes with Tc/Topt=0.2 p=6%.]

**Guessed texture of spins and carriers**

- Superconducting fermion channels wrapping the spin clusters
- Glassy spins confined in antiphase islands

![Puzzle pieces representing the texture of spins and carriers with arrows indicating charge channel and labeled ~8 cells.]

Dr. Bill Buyers, National Research Council (KITP 1-25-05) Near the Superconducting Edge: Spin Confinement and Central Modes
Large islands of AF correlated spins (8×8) entirely turn over only very slowly.
As doping decreases the hopping rate slows – hence CM for p=6% not for 9%

Spins in adjacent islands are coupled through a frustrated (ferro) charge region (antiphase domains at large p)

Soft spin resonance has same symmetry as the central mode to which it transfers its weight - CM means non-zero spin DOS.

Holes break the spin rotation invariance- QCP to glass?

SC boundary is far from the critical AF point but SC coexists with a nearly critical glass phase. But farther from dome QPT!

---

**YBCO phase diagram**

**Low p:**
AF spin correlations suppress charge density up to a large pseudogap.

**Medium p:**
AF correlations suppressed by SC below SC spin gap χ(ω) ~ω q_inc; transfer up to E_res. SW above.

**Large p:** SF too weak to see below E_res
No D-density-wave peak at E=0 in YBCO nor a spin gap
Dynamic stripes at low energy signify spin-charge domains
Resonance is a fingerprint of SC d-wave DOS and shows that local pairs exist dynamically in the normal phase
At high energy the isotropic spin wave cone is recovered - it is well defined in q but overdamped in E
The approach to the antiferromagnetic insulator is driven by a soft-mode collapse of the resonance
No SC-AF coexistence: near the SC transition the spins are confined; AF LR-ordered state does not coincide with the SC boundary
Stripes and spin confinement show that spin-charge spatial separation takes place at medium and small doping
Separation contrasts with periodic spin-fermion theories

End of KITP talk.

The following are background and related slides.
Spin response and NMR in YBCO$_{6.5}$

- grows on cooling
- shows no pseudogap decrease below $T^*$ NMR
- is suppressed below $T_c$ by the superconducting order but only for $E < 16$ meV
- SC gap is $\approx 3.5T_c \approx 20$ meV
- pseudogap is $\approx 100$ meV (Norman)

Chain Oxygen Staging and Superstructures (YBCO$_{6+x}$):

**Ortho–I Phase:**

$x = 1.0$

**Ortho–II Phase:**

$x = 0.5$

**Ortho–III Phase:**

$x = 0.67$  *F-F-E*

$x = 0.33$  *F-E-E*

N. H. Andersen *et al.*

Oxygen order

- Ortho-II ordered (every second chains filled)
- Oxygen ordered (correlation length of 100 Angstroms)
- Detwinned (70% single domain)

Yamada Plot: $T_c \sim$ Incommensurability

- $T_c \sim \delta$ (Yamada et al.)
- A universal relation for YBCO and possibly all cuprates?
- Not for $\delta < \delta_c$, $p < p_c$
YBCO$_{6.5}$ Low-energy Excitations
(Gapless but Suppression at low temperatures)

![Graph showing $\chi''(Q, \omega) (\mu_B^2 / eV)$ vs. $E$ (meV).]

- $T=85$ K (Normal State)
- $T=15$ K (Superconducting State)
- $Q=(\pi, \pi)$

**Orbital currents?**

The form factor falls slowly like a local spin, not the fast $Q^{-4}$ falloff for plaquette currents.
The wave vector and intensity are the same in all directions in plane.

- A symmetric cone of spin excitations
- \( q \) opens with energy.

- Not a square pattern as for \( x=6.6 \) (Hayden)
- \( q \) fixed with energy

- Dispersion centred on \((\pi,\pi)\)
  as in Tranquada on LBCO 2004

**YBCO6.35**

Overdamped spin fluctuations at all momenta
Spin fluctuations in YBCO$_{6.35}$ emanating from the resonance at 33 meV

Muons: coexistence of AF and SC?

- Coexistence of magnetism and superconductivity

- Neutrons say no: no LRO

FIG. 3: Samples Y$_{8-24}$. a) magnetic transition temperatures (▲ from ωL, ◆ from $T_1^{-1}$) and SC critical temperature $T_c$, vs. hole concentration h; three samples show a distinct $T_N>T_f$. b) Muon volume fractions vs. h: AF (○, at $T=0$ K) and SC (▲, for $T_f\leq T\leq T_c$). c) Sketch of a stripe superconductor. d) SQUID susceptibility in YBa$_2$Cu$_3$O$_{6.97}$, Y$_{15}$ (h=0.70) and Y$_{20}$ (h=0.75): $H = 1$ Oe, FC (▲) and ZFC (●).