Spatially Inhomogeneous Magnetic Field Response in YBa$_2$Cu$_3$O$_y$ and La$_{2-x}$Sr$_x$CuO$_4$ Above $T_c$

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Discovery of High-$T_c$ Superconductivity

Time Magazine May 11, 1987

GM advertisement April, 2009
Transverse-Field $\mu$SR

Raw time spectrum

$\omega = \gamma_\mu B_{\text{local}}$
HiTime: World’s only high transverse-field (7 T) μSR spectrometer
The time evolution of the muon spin polarization is described by:

$$P(t) = G(t) \cos(\gamma_\mu B_\mu t + \phi)$$

where $G(t)$ is a relaxation function describing the envelope of the TF-μSR signal.
Magnetic field distribution of a vortex lattice

Asymmetry spectrum $A(t)=A_0 P(t)$ plotted in a rotating reference frame:

V$_3$Si

$H = 50$ kOe

$T = 3.8$ K

Fourier transform
Field-induced relaxation above $T_c$ in highly underdoped La-based containing static magnetism for $H = 0$.

A.T. Savici et al. PRL 95, 157001 (2005)

La$_{1.88}$Sr$_{0.12}$CuO$_4$ ($T_c = 28$ K)

- Two-component exponential decay for $T < 25$ K
- Single exponential decay for $T > 25$ K

Note: plots do not show behaviour of small exponential relaxation rate for $T < 25$ K

The LARGER exponential decay is due to field-induced magnetic order ➔
Observe two-component exponential relaxation function in $\text{La}_{1.855}\text{Sr}_{0.145}\text{CuO}_4$:

$$G(t) = [A_1 e^{-\Lambda t} + A_2 e^{-\lambda t}] \exp(-\Delta^2 t^2)$$

- nuclear dipoles
- unknown electronic moments

La2-xSrxCuO4

$H = 7 \text{T}$

$T = 2 \text{K}$

$T_c = 2 \text{K}$

Khaykovich et al. PRB 71, 220508(R) (2005)

J. Chang et al. PRB 78, 104525 (2008); PRL 102, 177006 (2009)
Field-induced spin-glass like magnetism

La$_{2-x}$Sr$_x$CuO$_4$ @ $T = 5$ K

appearance of low-field “tail”

JES et al. PRB 76, 064522 (2007)
Relaxation of TF-μSR Signal in La_{1.824}Sr_{0.176}CuO_{4} (T_c = 37.1 K) at H = 7T

\[ G(t) = \exp(-\Lambda t) \exp(-\Delta^2 t^2) \]

- \( \Lambda \neq 0 \) at \( T < T_c \) because of field inhomogeneity created by the formation of a vortex lattice
- \( \Lambda \neq 0 \) at \( T > T_c \). Why?
Relaxation of TF-μSR Signal in YBa$_2$Cu$_3$O$_{6.57}$ ($T_c = 62.5$ K) at $H = 7$ T

\[ G(t) = \exp[(-\Lambda t)^\beta] \exp(-\Delta^2 t^2) \]

nuclear dipoles

spatial field inhomogeneity ($\beta = 1$ at $T \geq 40$ K)
$T < T_c : \text{YBa}_2\text{Cu}_3\text{O}_y \, @ \, H = 0.5 \, \text{T}$

$H \rightarrow 0$

$1/\lambda_{ab}^2 \, (\mu\text{m}^{-2})$

$\rho(B)$

$B \, (\text{T})$

$y = 6.50$

$y = 6.95$

$6.75$

$6.95$

$\text{JES et al. PRB 76, 134518 (2007)}$
$T < T_c : \text{YBa}_2\text{Cu}_3\text{O}_y @ H = 7 \text{ T}$

$T = 2.3 \text{ K}$

- $y = 6.46, p = 0.089$
- $y = 6.67, p = 0.12$
- $y = 6.80, p = 0.141$

J.S. White et al. PRB 78, 174513 (2008)
$T < T_c : \text{YBa}_2\text{Cu}_3\text{O}_y @ H = 7 \text{ T}$

$T = 2.3 \text{ K}$

$\Lambda (\mu s^{-1})$

$T = 10 \text{ K}$

$1/\lambda_{ab}^2 (\mu m^{-2})$

$H \rightarrow 0$

JES et al. PRB 76, 134518 (2007)
$T > T_c : \text{YBa}_2\text{Cu}_3\text{O}_y @ H = 7 \text{ T}$

$T = 90 \text{ K}$

$y = 6.46 \quad p = 0.089$

$y = 6.67 \quad p = 0.12$

$y = 6.80 \quad p = 0.141$

$\Lambda (\mu \text{s}^{-1})$

$\Lambda (\mu \text{s}^{-1})$

$T = 90 \text{ K}$

$\text{Hole Doping, } p$

$\text{Hole Doping, } p$

JES et al. PRL 101, 117001 (2008)
Remnant copper moments (static or dynamic)?

Expect the following to occur:

- **Antiferromagnetic**
- **Superconducting**
- 1/8
- “stripes”
- $\Lambda$

![Diagram showing phase transitions and hole doping](image)

Graph showing $\Lambda$ (in $\mu s^{-1}$) vs. hole doping $p$ at different temperatures (90 K, 110 K, 150 K, 190 K, 210 K).

- $\Lambda$ varies with hole doping $p$.
- Temperature influences the phase transitions.
Is spatial field inhomogeneity above $T_c$ due to a 2D vortex liquid as inferred from the Nernst measurements?
μSR measurements of vortex solid-to-liquid transition

- Collapse of μSR line width at $T_m < T_c$
- μSR line width in vortex liquid phase decreases with increased $H$

Lee et al. PRL 75, 922 (1995)

JES, Brewer & Kiefl, RMP 72, 769 (2000)
$\Delta B \sim H$ at temperatures near and above $T_c$.

$\Delta B = 2\Lambda / \gamma_\mu$

La$_{1.834}$Sr$_{0.166}$CuO$_4$ ($T_c = 37.3$ K)

La$_{1.88}$Sr$_{0.12}$CuO$_4$ ($T_c = 28$ K)

A.T. Savici et al. PRL 95, 157001 (2005)

JES et al. PRL 101, 117001 (2008)
Experimental Signatures of Pairing Correlations above $T_c$

**Fluctuating Diamagnetism**
W.C. Lee et al. PRL 63, 1012 (1989)

![Graph showing fluctuating diamagnetism](image1)

**Residual Meissner effect**

![Graph showing residual Meissner effect](image2)

**Diamagnetism** (torque magnetometry)
Y. Wang et al. PRL 95, 247002 (2005)
Lu Li et al. EPL 72, 451 (2005)
Lu Li et al. arXiv:0906.1823

**Vortex-like Nernst signal**
Y. Wang et al. PRB 64, 224519 (2001)

![Graph showing vortex-like Nernst signal](image3)
Experimental Signatures of Spatially-Inhomogeneous Pairing Correlations above $T_c$

Weak magnetic domains of unknown origin in La$_{2-x}$Sr$_x$CuO$_4$ above $T_c$, identified from thermomagnetic hysteresis.

C. Panagopoulos et al. PRL 96, 047002 (2006)

Spatially-inhomogeneous pairing correlations in Bi$_2$Sr$_2$CaCu$_2$O$_{8+8}$ above $T_c$ observed by STM.

Field Dependence of Magnetization

- Static superconductivity far above $T_c$ unlikely, yet LF-$\mu$SR measurements show no evidence of dynamics
- Inhomogeneous field distribution consistent with distribution of *time-averaged local fields* associated with droplets of different $T_c$:

$$\Lambda = \delta(\langle B(t) \rangle - H)$$

Regions with local $T_c$ that exceed the bulk $T_c$

Geshkenbein, Ioffe & Millis

Zero-field $\mu$SR measurements

La$_{1.85}$Sr$_{0.15}$CuO$_4$

$G_x(t)$

Time ($\mu$s)

$T = 5$ K

$T = 100$ K

La$_{1.76}$Sr$_{0.24}$CuO$_4$

$G_x(t)$

Time ($\mu$s)

$T = 5$ K

$T = 100$ K

$\Rightarrow$ relaxation due solely to nuclear dipoles
Vortex Lattice in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

$\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$


$\text{La}_{1.80}\text{Sr}_{0.20}\text{CuO}_4$

$T < T_c \,: \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \; @ \; H \leq 0.2 \; T$

Superfluid density in overdoped regime

Drop of $\mu$SR linewidth in overdoped region explained by *phase separated* hole-poor superconducting and hole-rich normal fermion metal regions.

**Caution:** $\sigma$ is not solely dependent on $n_s$
$T < T_c : \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \, @ \, H = 7 \, \text{T}$

$T < T_c$ (and $p < 0.19$): La$_{1.834}$Sr$_{0.166}$CuO$_4$ @ $T = 5$ K
Disappearance of AF correlations approaching overdoped edge of the superconducting dome

S. Wakimoto et al., PRL 92, 217004 (2004); PRL 98, 247003 (2007)

Source of field inhomogeneity below $T_c @ H = 7$ T

La$_{2-x}$Sr$_x$CuO$_4$

$x < x_c$: linewidth dominated by field-induced quasi-static magnetism that diminishes with increasing $x$

$x > x_c$: linewidth dominated by the field inhomogeneity of the vortex lattice

$$G(t) = \exp\left[-(\Lambda t)^{\beta}\right]$$

La$_{1.85}$Sr$_{0.15}$CuO$_4$

$H = 7$ T

La$_{1.76}$Sr$_{0.24}$CuO$_4$

$H = 7$ T

$\Lambda$ (μs$^{-1}$)

β

$T_c(0)$
La$_{2-x}$Sr$_x$CuO$_4$ @ $H = 7$ T

$G(t) = \exp\left[-(\Lambda t)^\beta\right]$
La_{1.7}Sr_{0.3}CuO_4 (T_c = 0 K)


Consistent with increasing concentration of heavily-overdoped non-superconducting compound
Curie magnetism in heavily overdoped La_{2-x}Sr_xCuO_4

T. Nakano et al., PRB 49, 16000 (1994)
S. Wakimoto et al., PRB 72, 064521 (2005)

Proposed cause:
- Phase separation into hole-poor SC regions and hole-rich normal Fermi-liquid regions
  …but AF correlations diminished in heavily overdoped region
  …paramagnetic impurity phase inconsistent with different effect of Sr overdoping and Zn substitution (known to produce paramagnetic moments) on dynamic AF correlations
- Holes doped directly into Cu3d orbital (rather than O2p), producing free Cu spins and/or changing AF correlations between Cu spins
  …needs to be the case for more than ¼ of doped holes
Competing ferromagnetism?


La$_{2-x}$Sr$_x$CuO$_4$

Field stabilized FM?

$\Lambda$ (μS$^{-1}$) vs $x$

30 K, 35 K, 40 K, 50 K, 60 K, 80 K, 100 K

$X_1$, $X_2$, $X_c$

T$^*$

3D AF

DSC

$T_N$

$T$

0
$\Lambda (\mu s^{-1})$ vs. $x$ for $T = 40$ K.

La$_{2-x}$Sr$_x$CuO$_4$

@ $T = 110$ K
$H = 7$ T

Fluctuating SC vs. Growing FM?

C. Panagopoulos et al. PRL 96, 047002 (2006)
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