Three-Dimensionality of Field-Induced Magnetism in $La_{2-x}Sr_xCuO_4$

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Collaborators

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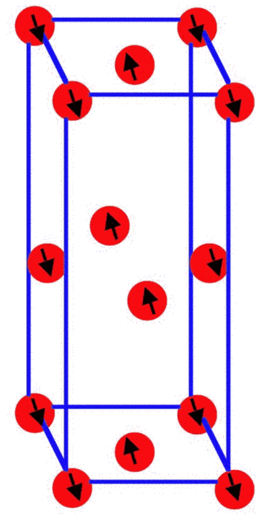
The Parent Compound La_2CuO_4

- Insulator
- Two-dimensional antiferromagnet
- T_N=325K
- Ordered moment is $0.5\mu_B/Cu^{2+}$



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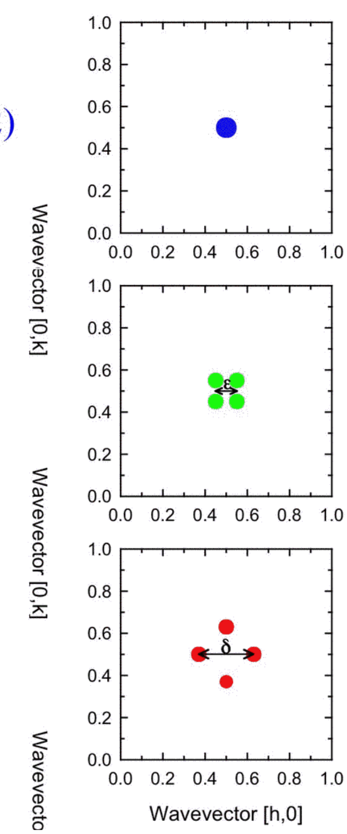
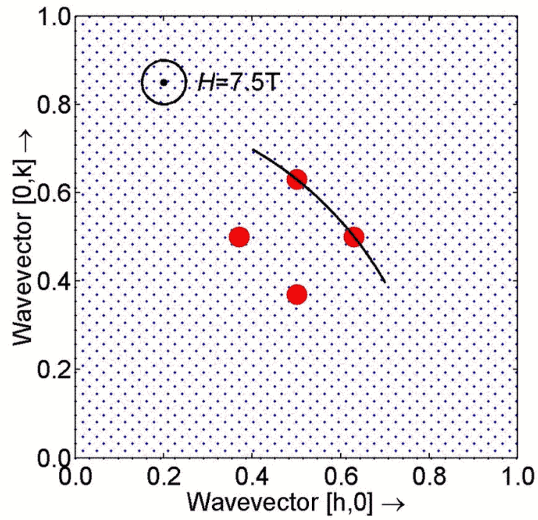
Magnetism in $La_{2-x}Sr_xCuO_4$

- Insulating Antiferromagnet (0.00<x<0.02)
  - Commensurate elastic magnetic order
  - T_N=325K, ordered moment is $0.5\mu_B/Cu^{2+}$
- Stripes/Spin-Glass (0.02<x<0.06)
  - 'diagonal' incommensurate magnetism,
  - elastic signal
- Superconductor (0.06<x<0.25)
  - 'parallel' incommensurate magnetism,
  - elastic signal (0.06<x<0.125)
  - inelastic signal (0.06<x<0.25)



$La_{2-x}Sr_xCuO_4$ in a Magnetic Field

- Type II superconductor
  - magnetic flux penetrates via vortices for $H_{c1}<H<H_{c2}$
- Vortices carrying one fluxon and form flux lattice
  - Eg For H=7.5T a_v=178Å
- Pair coherence length gives the size of the vortex cores
  - ξ=20Å



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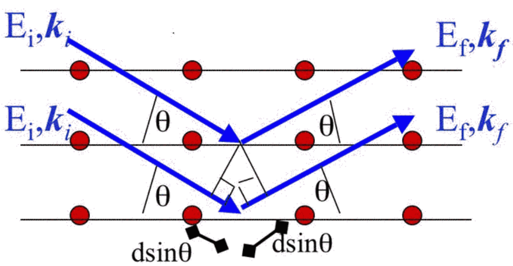
Neutron Scattering

Neutrons properties	spin-1/2	
	no charge	
Neutron with velocity v	de Broglie wavelength	$\lambda=h/mv$
	wavevector	$k=2\pi/\lambda$
	momentum	$\boldsymbol{p}=h\boldsymbol{k}$
	kinetic energy	E=mv/2=hk/2m
Neutron sources	Reactor	e.g. BER II (HMI)
	Spallation source (accelerator)	e.g. ISIS (U.K.), SNS (ORNL)

Elastic scattering
Bragg's Law - 2$d$sin=nλ



Inelastic scattering

Conservation of momentum
$\mathbf{q} = h\boldsymbol{k}_i + h\boldsymbol{k}_f$

Conservation of energy
$E=E_i-E_f$

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Outline

A magnetic field suppresses superconductivity and by investigating a cuprate superconductor in a magnetic field we should gain some insight into the ground state which would have appeared had superconductivity not intervened.

Optimally doped LSCO x=0.16 – probing in-plane magnetism

Underdoped LSCO x=0.10 – probing in-plane magnetism

Underdoped LSCO x=0.10 – probing 3D correlations

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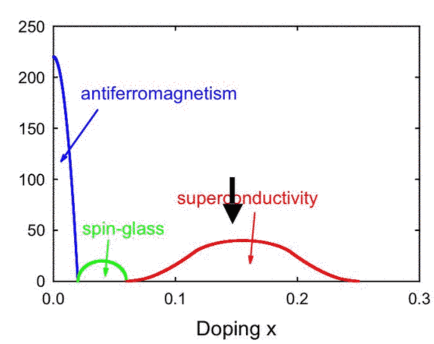
Optimally doped La_2CuO_4



- x=0.16
- $T_c(H$=0T)=38.5K
- $H_{c2}(T$=0K)=62T

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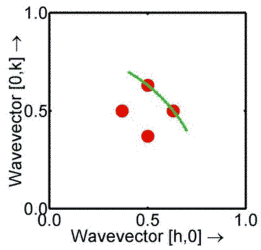
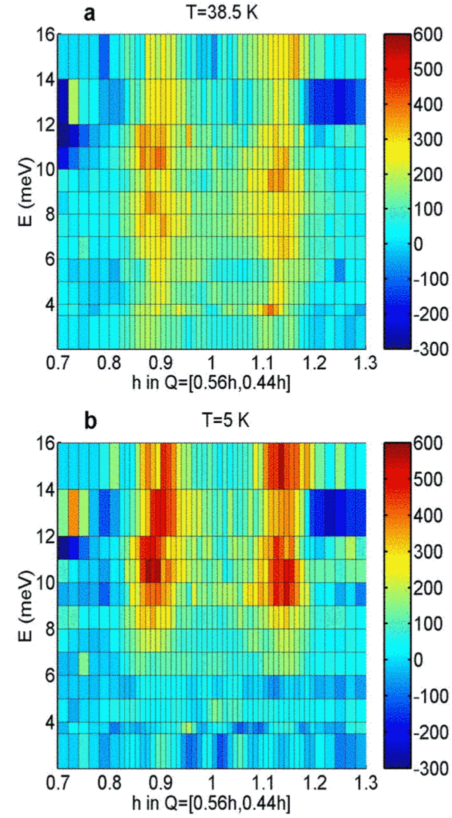
Zero-Field Data (x=0.163)



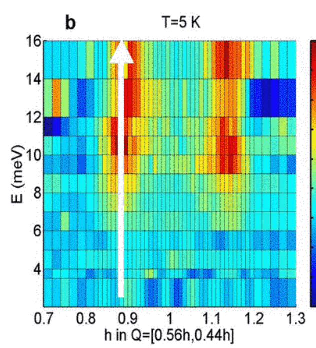
H=0T

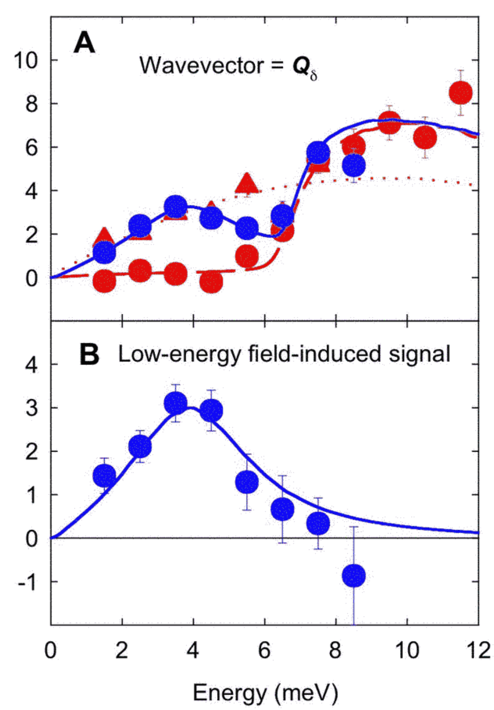


Energy-wavevector maps of the magnetic scattering

- Normal state signal is measured at T_c=38.5K.
- Superconducting state signal is measured at T=5K ($\ll T_c$).

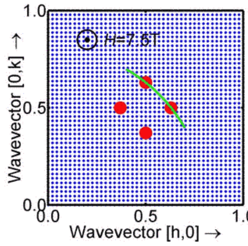
In-Field Data (H=7.5T, x=0.163)



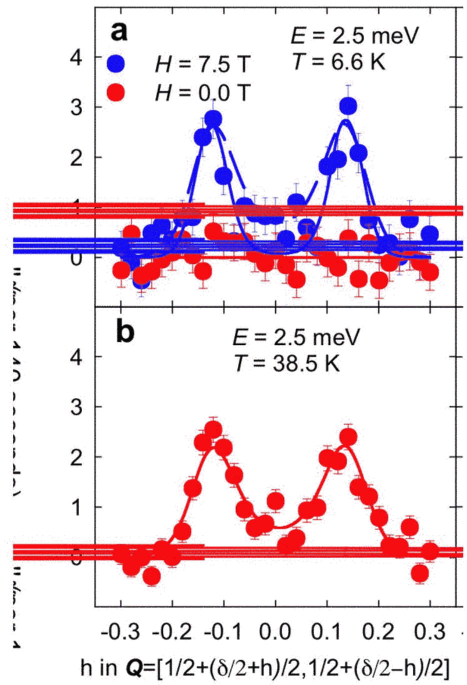


- An applied field induces signal below the spin gap
- Inverse lifetime is γ =4.3meV compared to normal state value γ_n=9.0meV).

Constant Energy Data (H=7.5T, x=0.163)



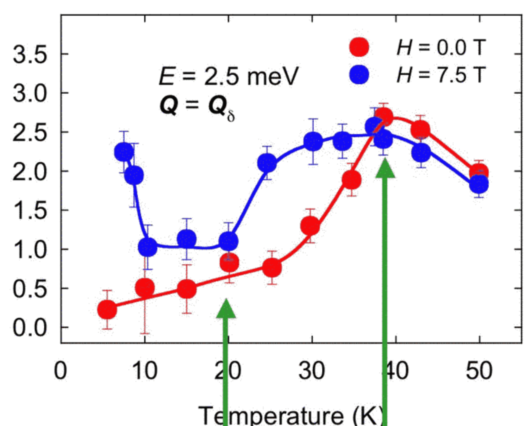
H=7.5T

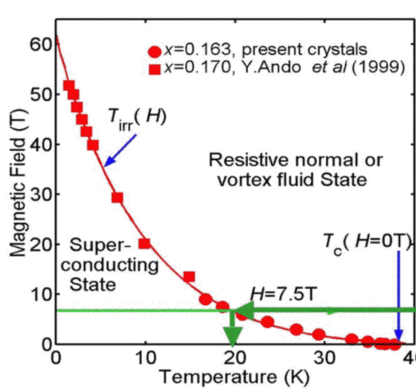


- Sharp field-induced peaks at low energies,
- Magnetic correlation length
  - $l_{H=7.5T} = 75Å$
  - $l_{H=7.5T} > l_{H=0T}(=24Å)$
  - $l_{H=7.5T} \leq a_v$ (=180Å)

Temperature dependence (x=0.163)

- $T>T_c$ small suppression
- $T_c>T>T_{irr}$ enhancement
- $T=T_{irr}$ drop in signal
- T=10K<T_{irr} rising signal





T_{irr}(H=7.5T)=19K

T_c(H=0T)=38.5K

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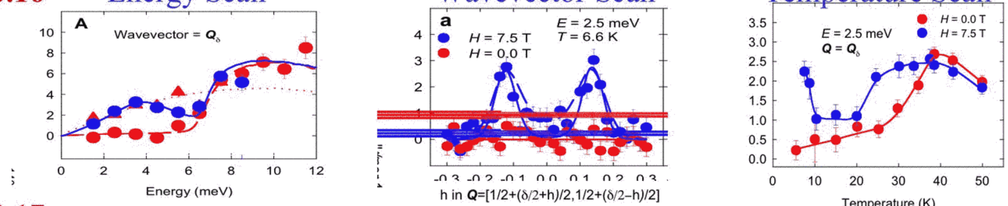
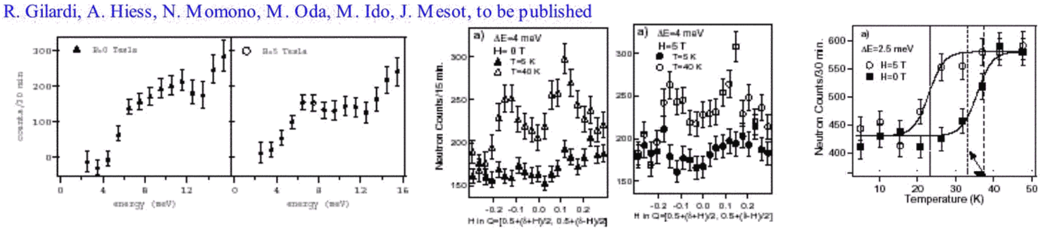
Other Optimally doped Samples

x=0.16 Energy Scan | Wavevector Scan | Temperature Scan



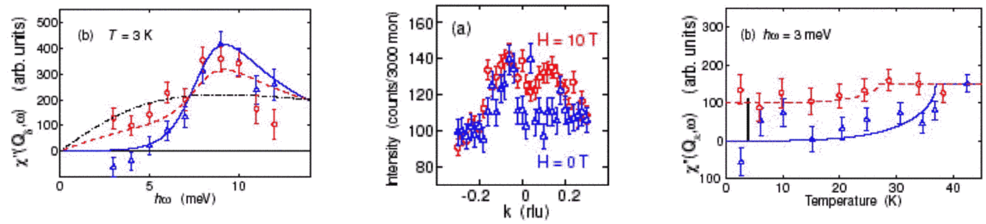
x=0.17

R. Gilardi, A. Hiess, N. Momono, M. Oda, M. Ido, J. Mesot, to be published

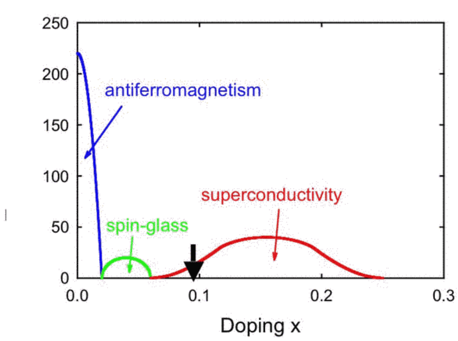


x=0.18

J.M. Tranquada, C.H. Lee, K. Yamada, Y.S. Lee, L.P. Regnault, H.M. Rønnow, Phys. Rev. B 66 014528 (2002)



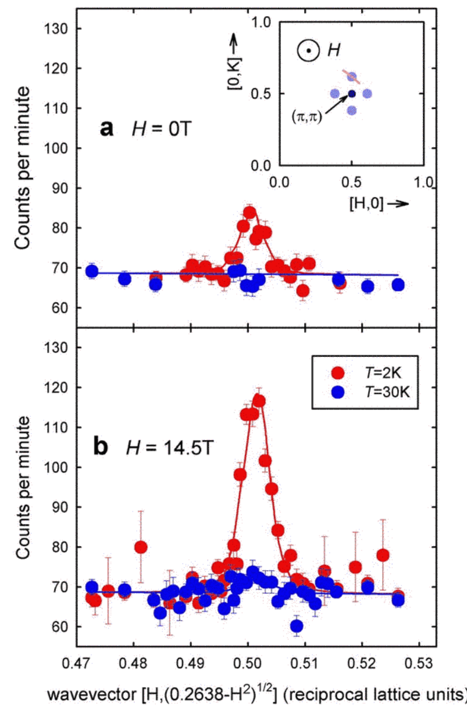
Under Doped La_2CuO_4



- x=0.10
- $T_c(H$=0T)=29K
- $H_{c2}(T$=0K)=45T

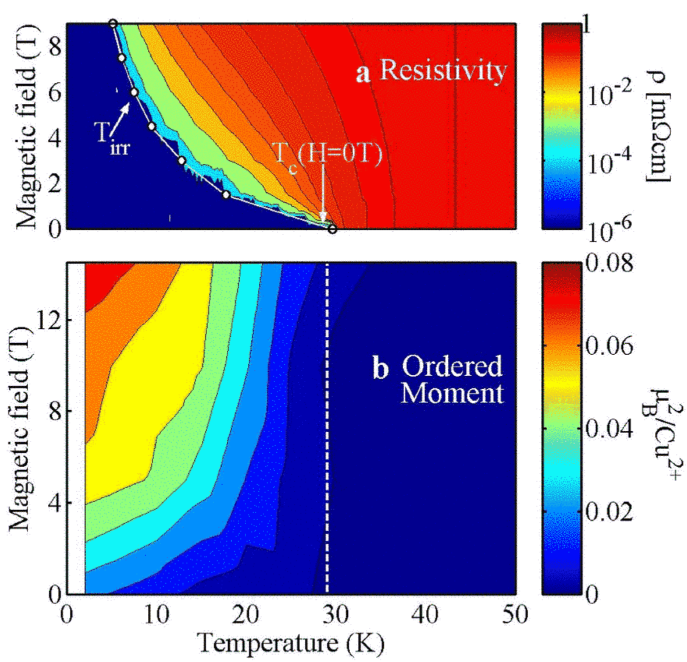
Elastic Scattering in Superconducting Plane (x=0.10)

- Zero-field signal increases in a applied magnetic field.
- The peaks give an in-plane correlation length of l_v>400Å.
- No elastic signal is observed above T_c=29K.



Phase diagram (x=0.10)

- Magnetic ordering occurs at $T_c(H=0T)$.
- Ordering increases with decreasing T and increasing H.
- Zero-resistivity is established within the magnetically ordered phase.



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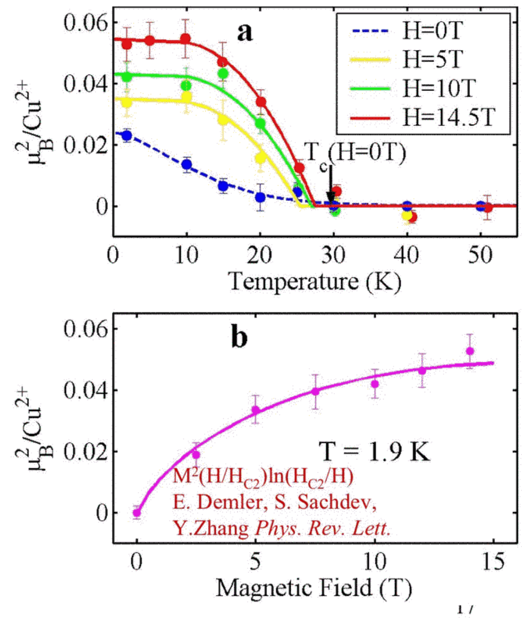
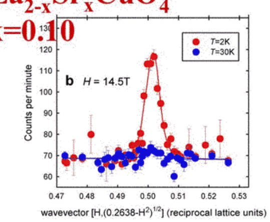
Field and Temperature Dependence of Field-Induced Order in the Superconducting Plane (x=0.10)

- The field-induced signal occurs at $T_c(H\text{=0T})$, not T_{irr}
- The T-dependence of the field-induced signal is different from the zero-field signal.
- The field-induced signal increases with field rapidly at first, then at a slower rate.

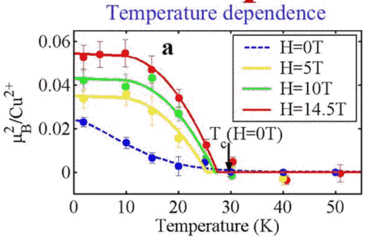


Other underdoped samples

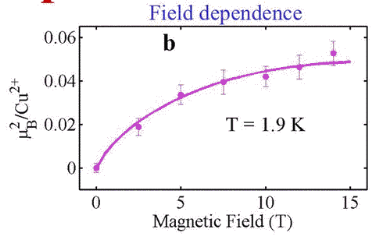
$La_{2-x}Sr_xCuO_4$
x=0.10



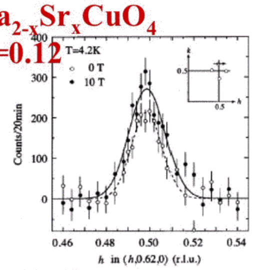
Temperature dependence



Field dependence



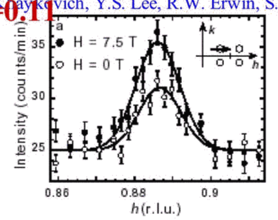
$La_{2-x}Sr_xCuO_4$
x=0.12

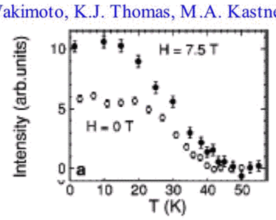


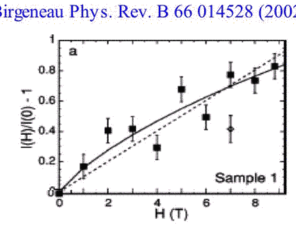
S. Katano, M. Sato, K. Yamada, T. Suzuki, T. Fukase Phys. Rev. B 62 R14 677 (2000)

La_2CuO_{4+y}
y=0.11

B. Khaykovich, Y.S. Lee, R.W. Erwin, S.-H. Lee, S. Wakimoto, K.J. Thomas, M.A. Kastner and R.J. Birgeneau Phys. Rev. B 66 014528 (2002)







In-plane Magnetism in underdoped $La_{2-x}Sr_xCuO_4$, (x=0.10)

- A magnetic field induces long-range antiferromagnetic order
- The order has a correlation length l_v>400Å which is much greater than both the vortex cores and the separation of the vortices.
- The field-induced ordering is large ($0.27\mu_B/Cu^{2+}$ at H=14.5T compared to $0.16\mu_B/Cu^{2+}$ at H=0T))
- The T-dependence of the field-induced signal is different from that of the zero-field signal
- The field-induced signal onsets at $T_c(H=0T)$ rather than T_{irr}.
- The results suggest that for $H>H_{c2}$ the system becomes antiferromagnetic rather than reverting to its normal state.

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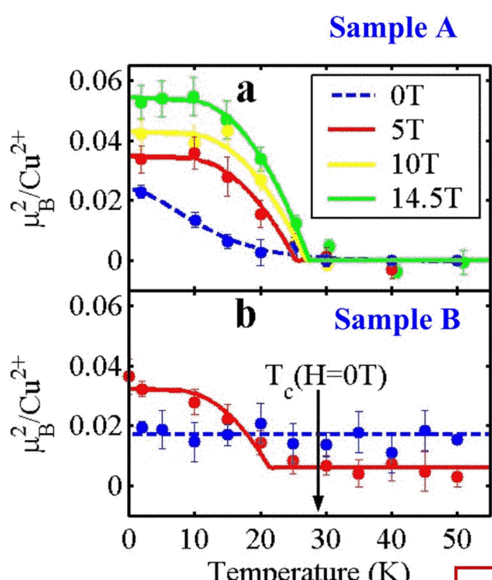
The Nature of the Zero-Field and Field-Induced Magnetism



- The zero-field signal is sample-dependent, and possible defect-induced.
- The field-induced signal is sample-independent.

The zero-field signal is intrinsic
The field-induced signal is extrinsic

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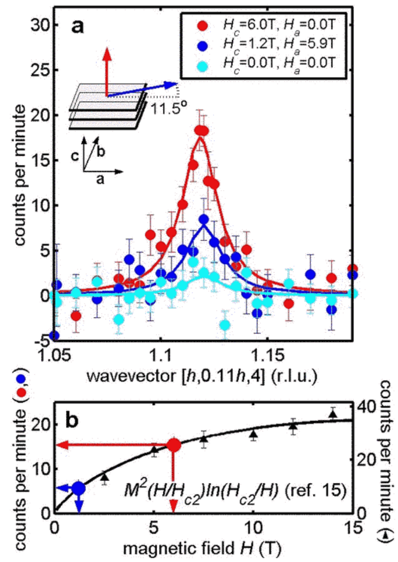
Dependence of field-induced signal on field direction (x=0.10)

- Red symbols show the signal with H=6T perpendicular to the CuO planes
- Dark blue symbols show the signal for field pointing 11.5 degrees from CuO planes
- Light blue symbols give the zero field signal.



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Dependence of field-induced signal on field direction (x=0.10) (cont.)

- Anisotropy in the field-effect reflects the anisotropies in other properties of LSCO.
  - Magnetoresistance gives the ratio of out-of-plane to in-plane normal state resistivity as ρ_c/ρ_{ab}~2000.
  - The superconducting coherence length within the CuO_2 plane is ξ_{ab}~30Å compared to ξ_c~1-2Å along **c**.
  - The ratio of the London penetration depths is λ_c/λ_{ab}~20.
- Anisotropy in the field-effect contrasts with the isotropic spin susceptibility as determined e.g. by NMR.

The field-induced signal is due to coupling of the field to the motion of the electrons rather than their spin. suggesting that the field-induced order comes from currents circulating within the planes – i.e. vortices – rather than a Zeeman effect.

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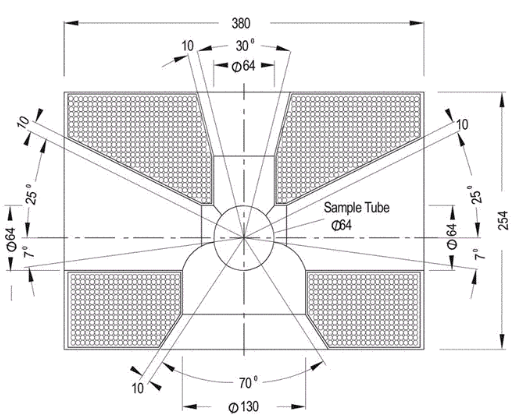
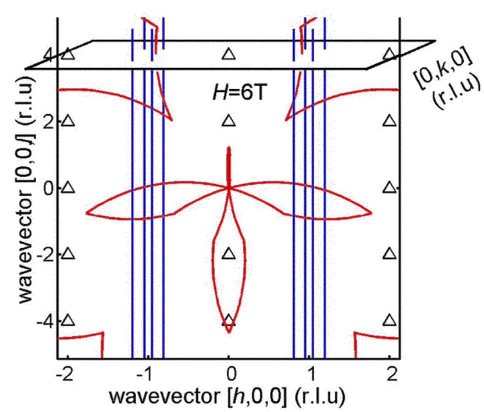
Probing Magnetism perpendicular to the superconducting plane

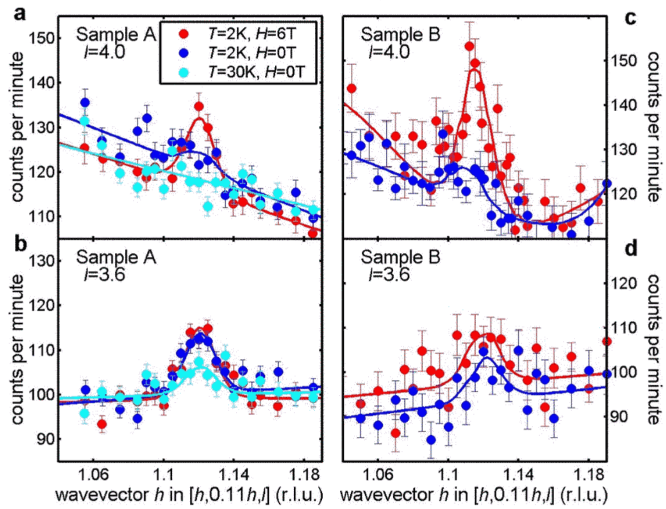
Probing the Magnetism perpendicular to the superconducting plane (x=0.10)





- The magnet windows severely restricts the reciprocal space regions that can be reached.
- Measurements took place around l=4.

Field-Induced Signal Perpendicular to superconducting plane (x=0.10)



- When L is a reciprocal lattice unit the zero-field signal is small and the field-induced signal is large.
- For other L the zero-field signal is large and the field-induced signal is small.

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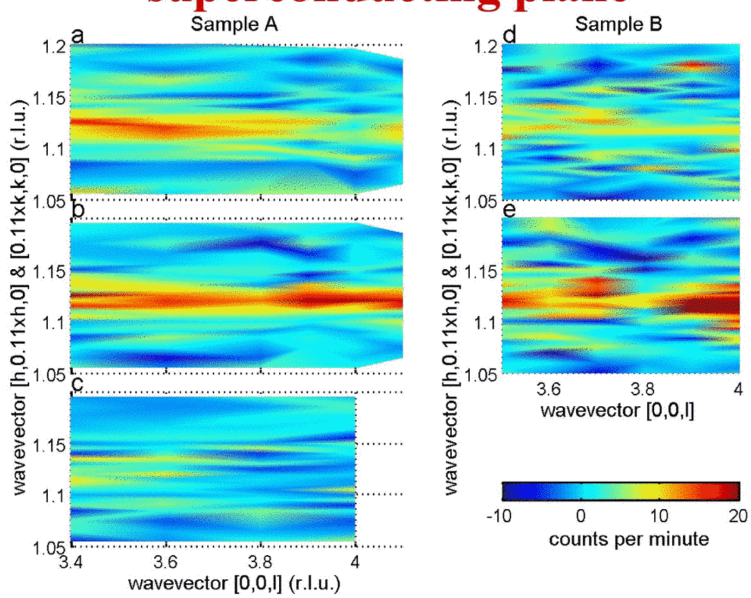
Field-Induced Signal Perpendicular to superconducting plane



The zero-field magnetism is quasi-2D
The field-induced magnetism is quasi-3D

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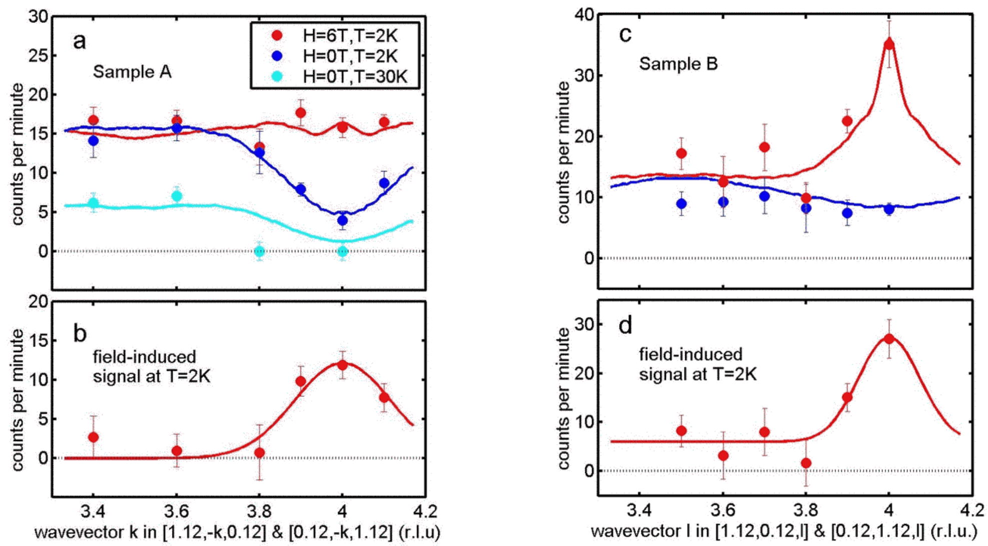
Field-Induced Signal Perpendicular to superconducting plane



- The correlations in a magnetic field extend over ~6 CuO_2 planes.

Interplay of Antiferromagnetism and Superconductivity Perpendicular to superconducting plane

Coherence length along the **c** axis is ξc~1-2Å, while inter-planar distance *d*=6.6Å

Phase coherent superconductivity established by Josephson coupling between the layers

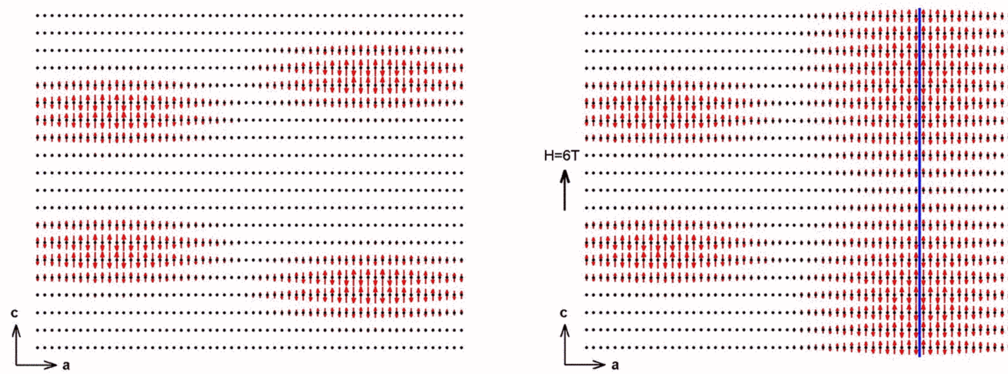
Magnetism is enhanced by a magnetic field suggesting stacking of vorticies

Stacked magnetic regions implies stacked superconducting regions

Interlayer Josephson couplings ~1μeV (optical conductivity)

Interlayer Antiferromagnetic coupling ~1μeV (parent compound)

Possible model for field-induced magnetism



- In zero field the magnetic order is short range perpendicular to the superconducting plane and centred around antiphase boundaries.
- Vortices can link these antiferromagnetic regions enhancing the signal at the reciprocal lattice points

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Out-of-Plane Magnetism in underdoped $La_{2-x}Sr_xCuO_4$, (x=0.10)

- The magnetic correlations are two dimensional with little dependence on the out-of-plane direction.
- A minimum at the reciprocal lattice point in the superconducting state suggests that the magnetic ordering is an odd function in real space
- A magnetic field enhances the intensity at all out-of-plane wavevectors in the superconducting state.
- This enhancement is greatest at the reciprocal lattice point suggested correlations over ~6 planes.
- Results imply stacked magnetism and hence straight vortex lines.
- Which in turn implies stacked superconducting regions

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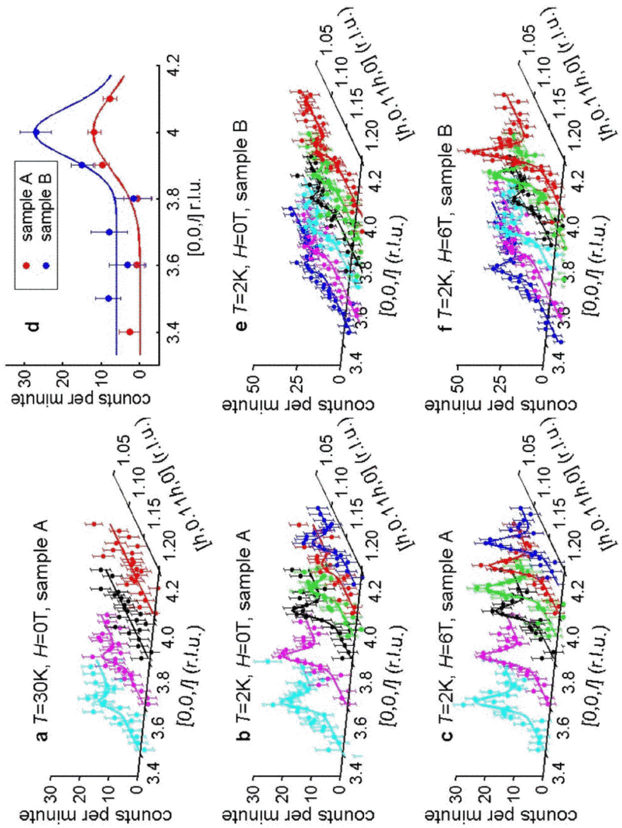
a T=30K, H=0T, sample A
b T=2K, H=0T, sample A
c T=2K, H=6T, sample A
d
sample A
sample B
[0,0,l] r.l.u.
e T=2K, H=0T, sample B
f T=2K, H=6T, sample B
counts per minute
[0,0,l] (r.l.u.)
[h,0,1] (r.l.u.)