The Coherence Length Dependence on Doping of Cuprates

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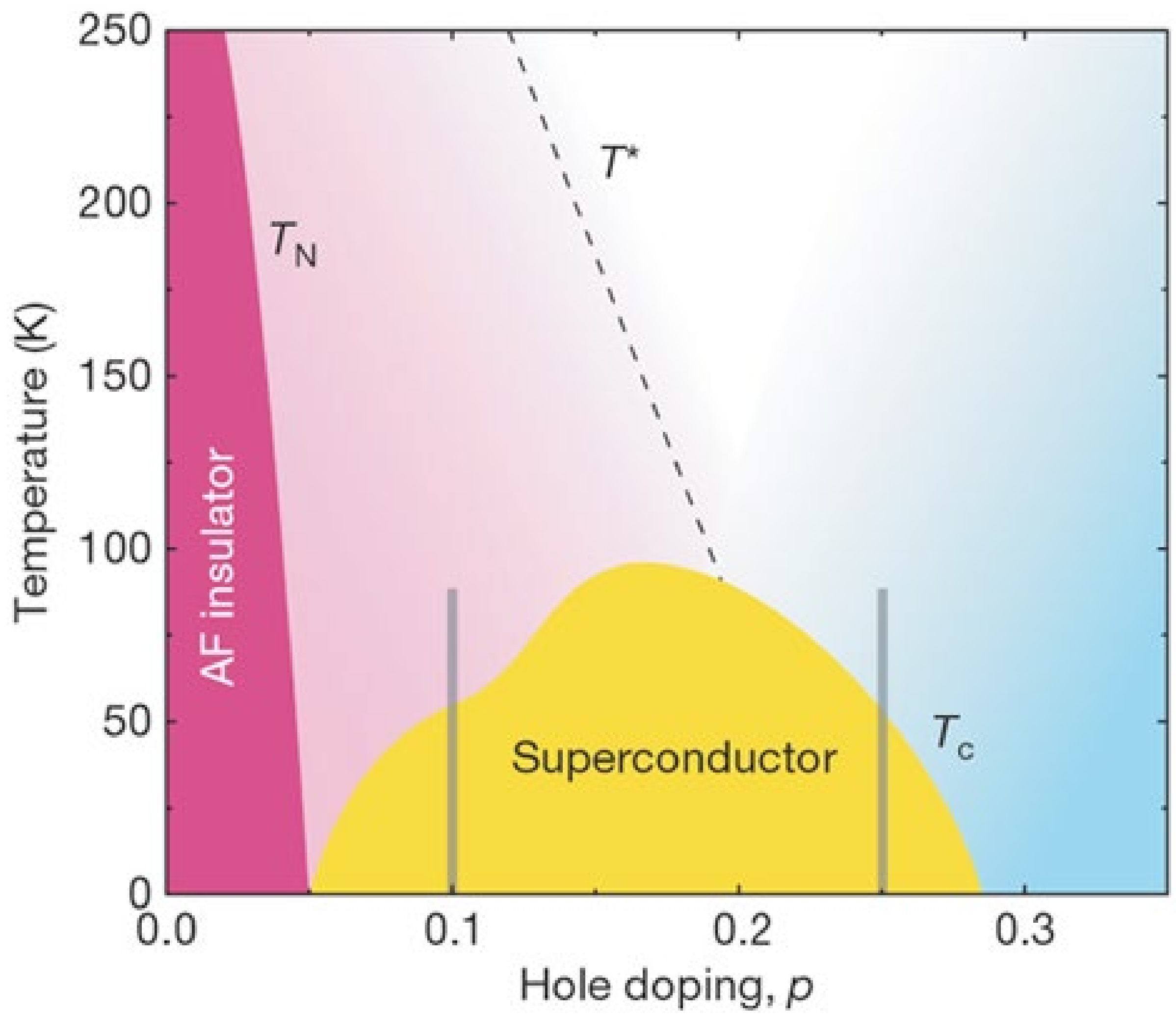
The Cuprates Family

- High Temperature SC – HTSC
- Nearly tetragonal unit cell with layers of CuO_2 planes
- Hole doping affects T_c
- Highest T_c is achieved at the optimal doping

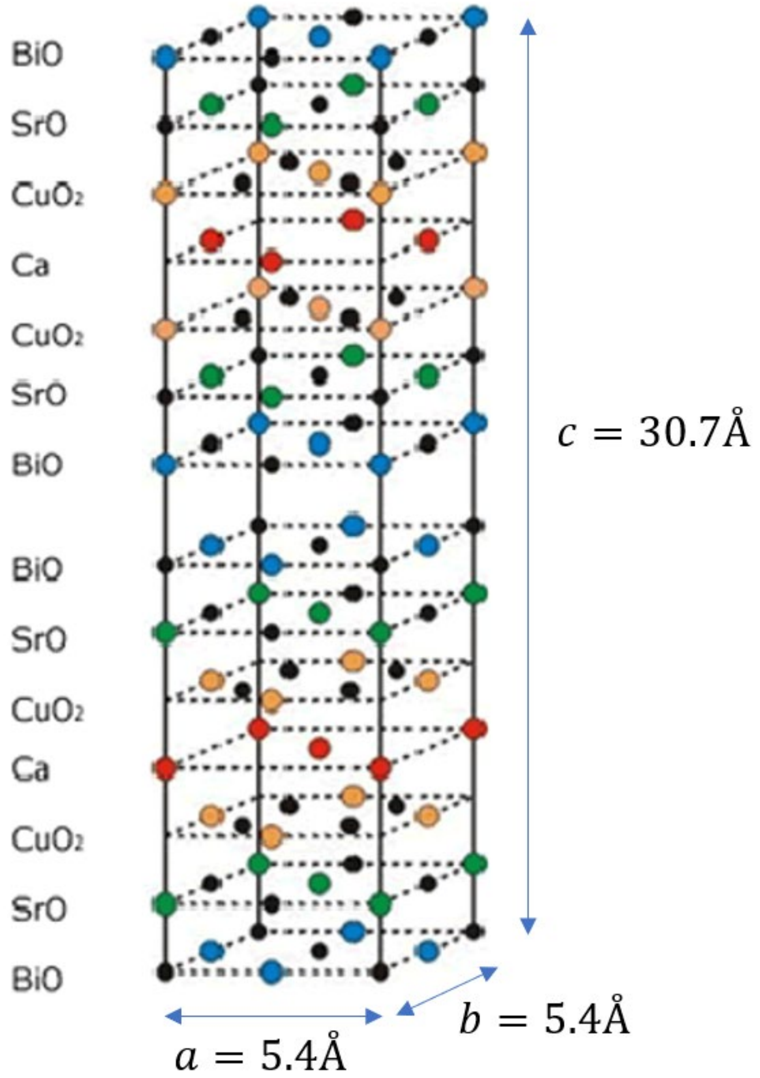


Norman, M. R. (2010). Fermi-surface reconstruction and the origin of high-temperature superconductivity. *Physics*, *3*, 86.

Bi-2212

$$Bi_2Sr_2CaCu_2O_{8+x}$$

- Hole doping by adding oxygen atoms to the material: electrons are drawn to the oxygen atoms and thus lowering the electron density in each unit cell



Vastola, J. (2016). The Effect of Impurities on the Superconductivity of BSCCO-2212.

Sample Preparation

- The Bi-2212 crystal was grown using a DC sputtering system
- The same sample was oxidized in an oxygen atmosphere following each measurement
- Over-doped regime

The sputtering system at Prof. Gad Koren's laboratory

The London Equation

- The superconducting stiffness definition: $\boldsymbol{J}_s = \rho_s \left(\frac{\hbar c}{e^*} \boldsymbol{\nabla} \varphi - \boldsymbol{A} \right)$

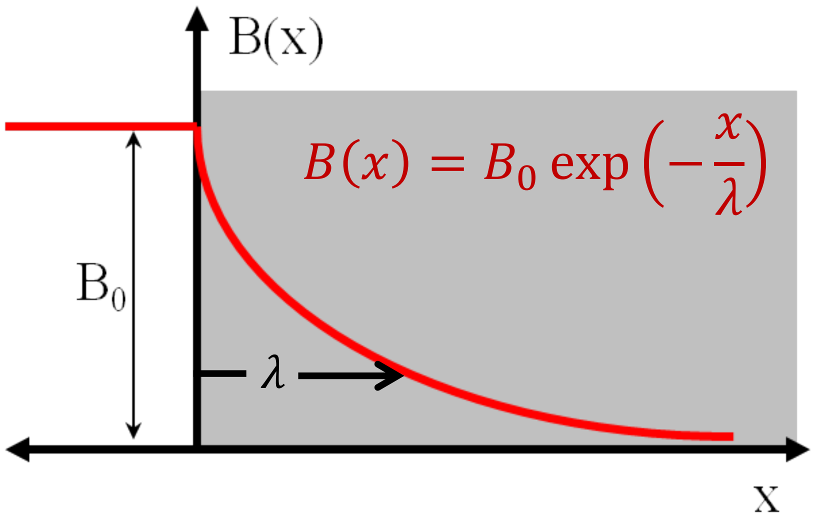
where φ is the phase of the complex order parameter: $\psi = |\psi| e^{i\varphi(x)}$

- When $\nabla\varphi = 0$ we get the London Equation:

$$\boldsymbol{J}_S = -\rho_S \boldsymbol{A}$$

The Meissner Effect

- The rotor of Maxwell's equation: $\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{B} = \mu_0 \boldsymbol{\nabla} \times \boldsymbol{J}$
- Apply the London equation to get the PDE for the magnetic field $\boldsymbol{B}$: $\boldsymbol{\nabla}^2 \boldsymbol{B} = \mu_0 \rho_s \boldsymbol{B}$
- The solution:



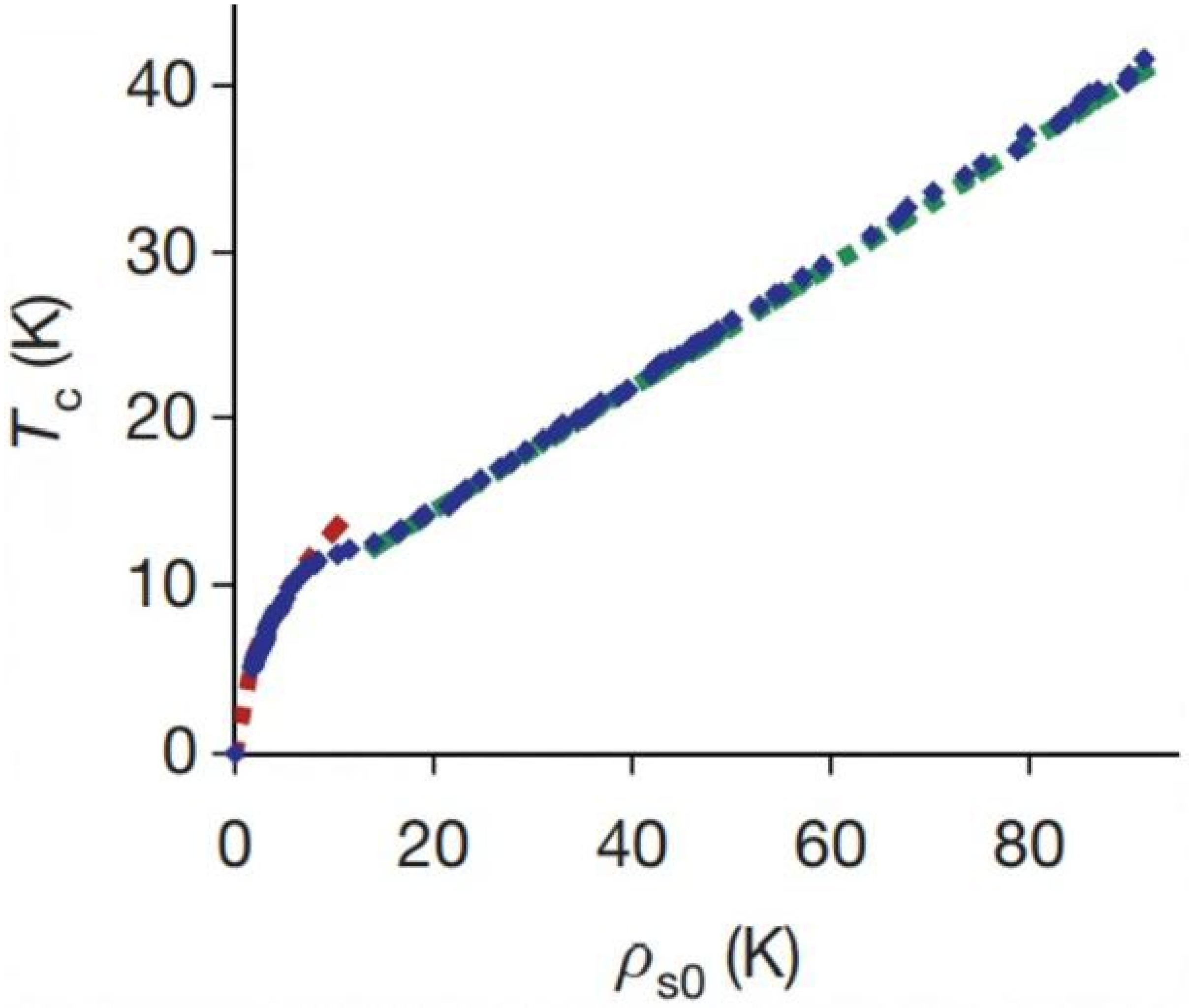
$$\rho_s = \frac{1}{\mu_0 \lambda^2}$$

The SC Stiffness

The Penetration Depth

The Uemura Relation

- Tc is linearly proportional to the superconducting stiffness



Božović, I., He, X., Wu, J., & Bollinger, A. T. (2016). Dependence of the critical temperature in overdoped copper oxides on superfluid density. Nature, 536(7616), 309-311.

The Coherence Length ξ

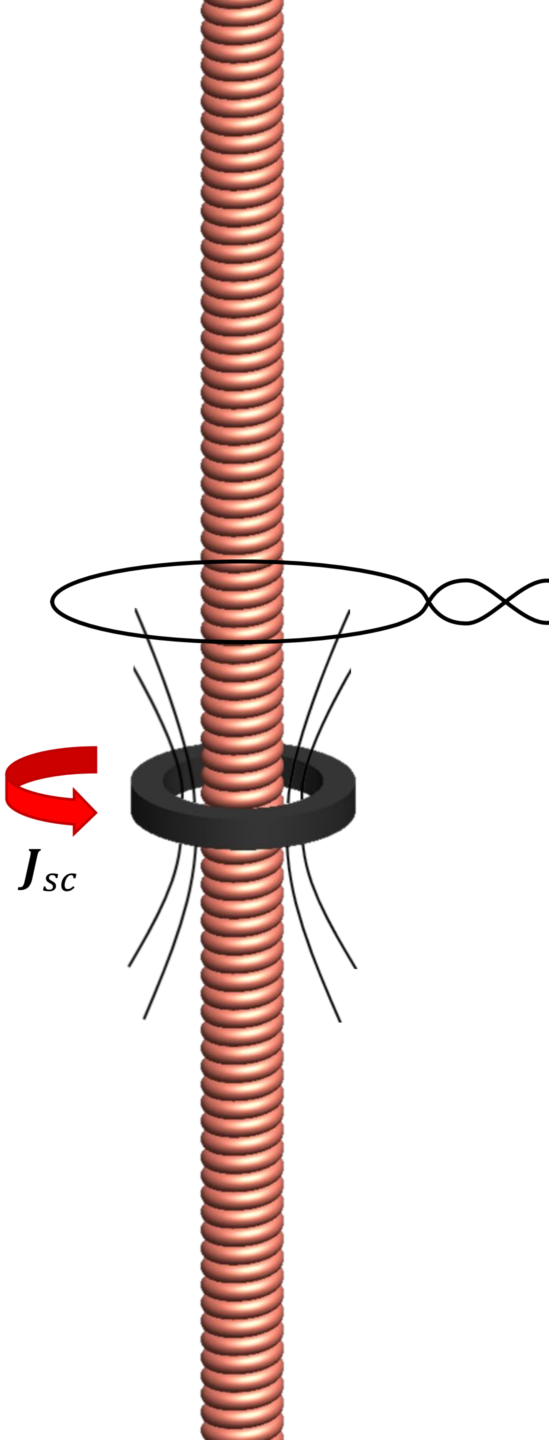
- The GL complex order parameter: $\psi = |\psi| e^{i\varphi(x)}$

- The coherence length ξ is the shortest distance in which the phase φ can smoothly complete 2π turn

- Also, ξ is the size of a vortex

Stiffnessometer: Principle of Operation

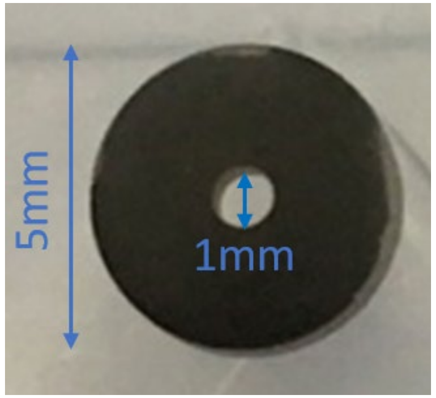
- A SC ring is centered around an infinitely long excitation coil
- A current I is applied to the coil, generating $\boldsymbol{A}_{ec}$ with $\boldsymbol{B} = 0$
- $\boldsymbol{A}_{ec}$ creates $\boldsymbol{j}_{sc}$ by London: $\boldsymbol{J}_s = -\rho_s \boldsymbol{A}$
- The magnetic moment of the ring, M_{sc}, is measured



- The proportionality between M_{sc} and I_{ec} yields ρ_s
- The break of this linear connection defines j_c and ξ

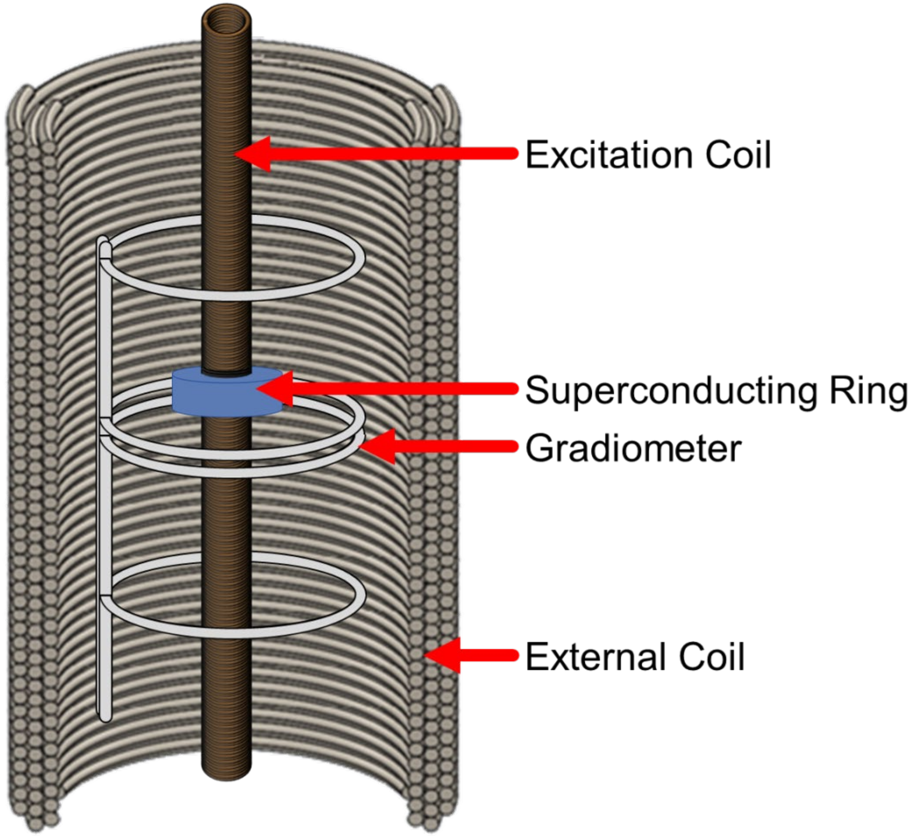
The Experimental Setup

Bi-2212 crystal on a STO ($SrTiO_3$) substrate ring:
$\emptyset_{in} = 1mm$; $\emptyset_{out} = 5mm$
$Thickness = 200nm$

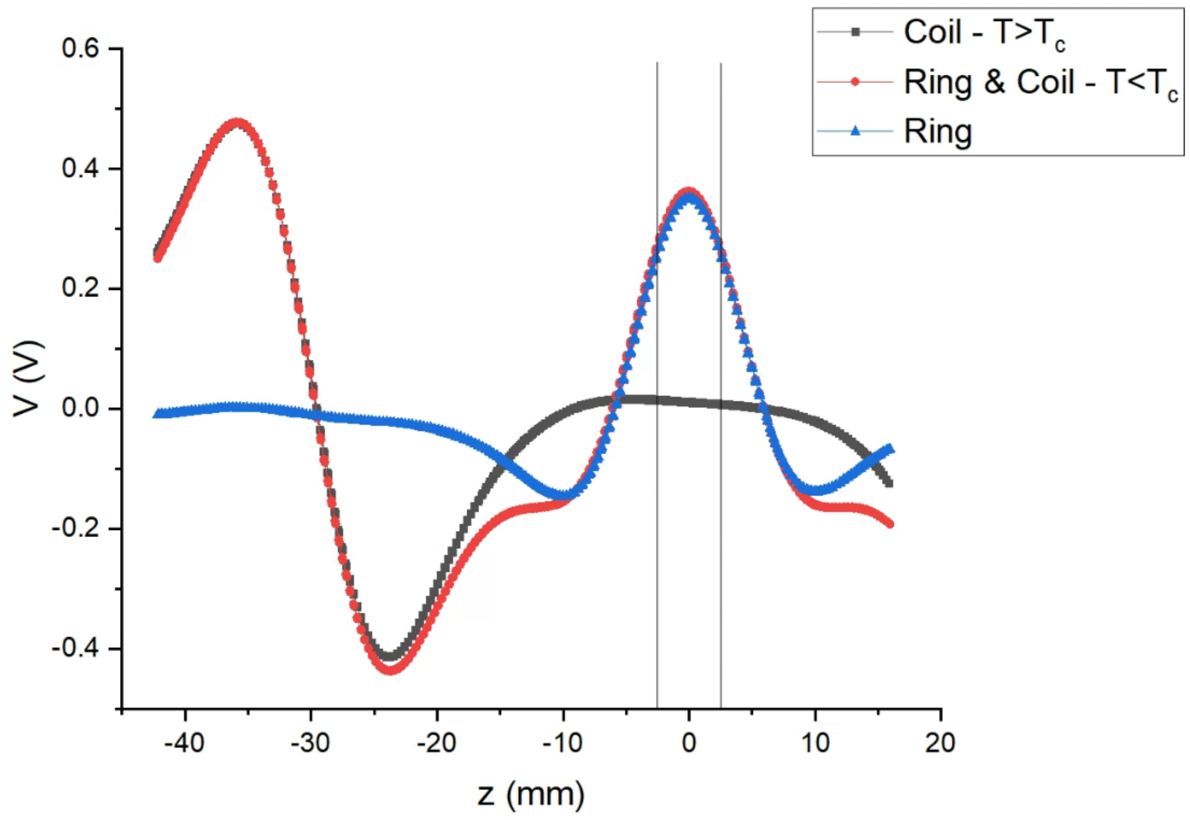


Copper coil:
$2\ Layers$; $N = 1940$
$\emptyset_{in} = 0.54mm$; $\emptyset_{out} = 0.8mm$
$Length = 60mm$

The *Quantum Design* MPMS3 magnetometer



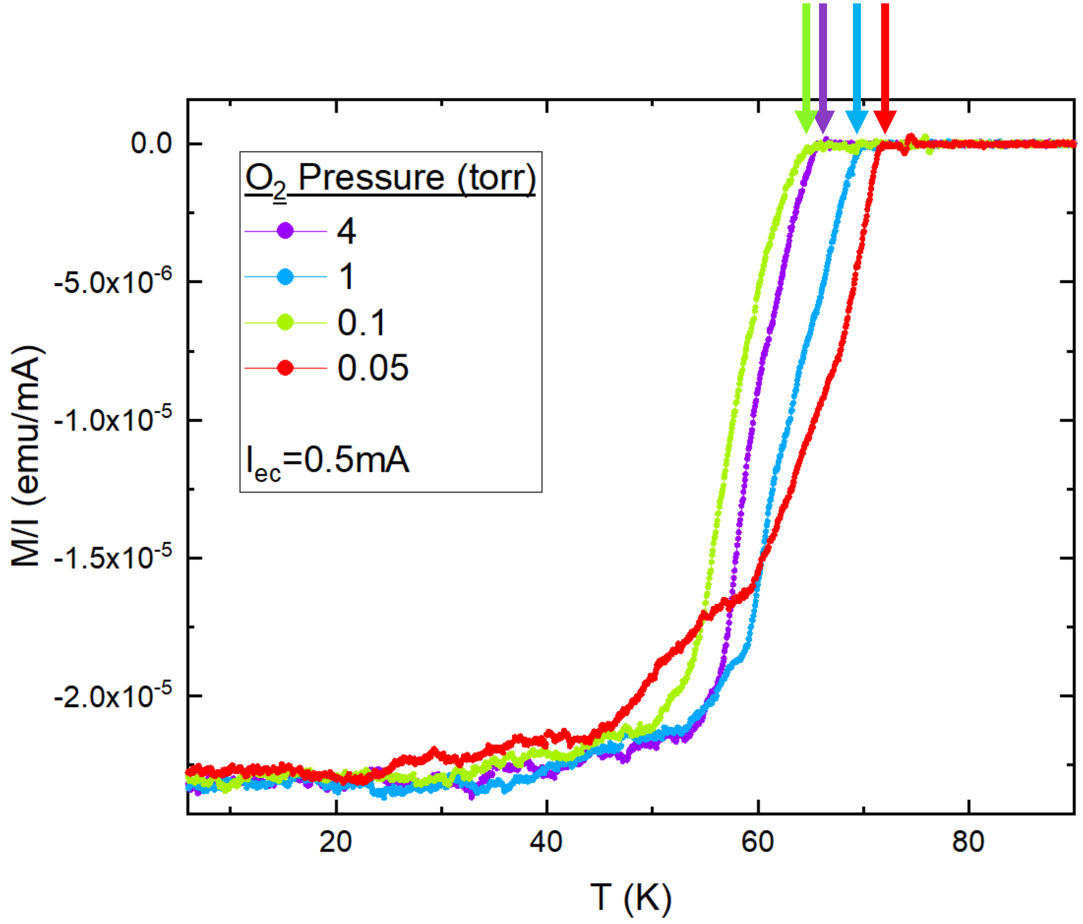
Stiffnessometer Measurements: Ring and Coil Signals



Magnetization as Function of Temperature

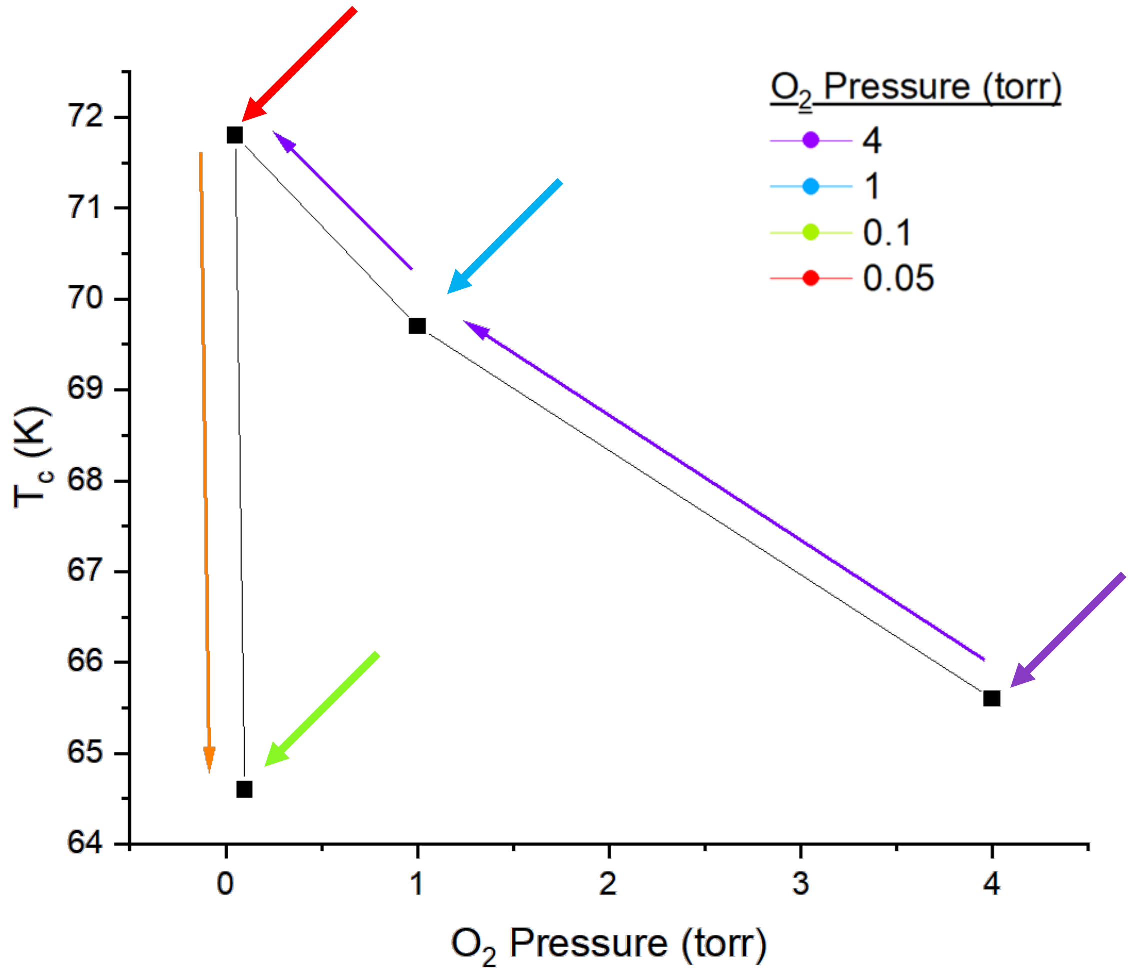
- A fixed current is applied on the excitation coil
- Temperature is gradually increased

- The critical temperature T_c is defined as the end of the phase transition
- In other words: T_c is the first temperature where the magnetization is zero



T_c as Function of O_2 Pressure

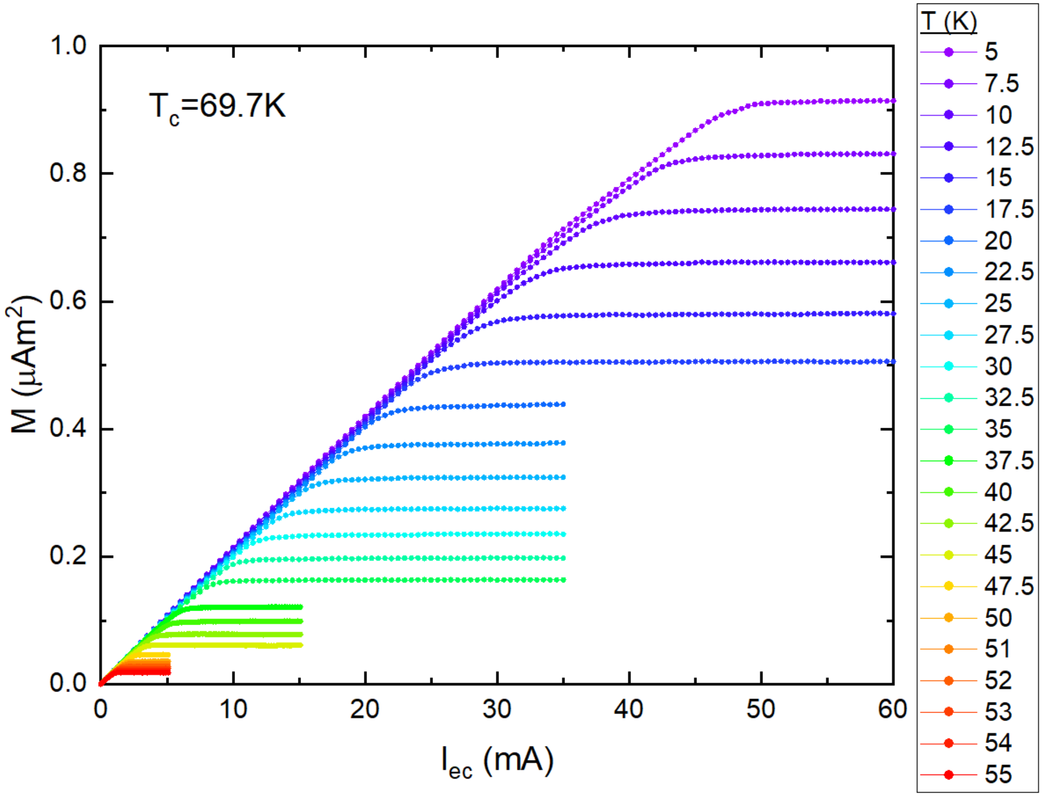
- T_c is inconsistently dependent on the pressure applied during doping
- Oxidations in exceeding pressures yield different T_c values from those achieved with receding pressures



Magnetization as Function of Applied Current

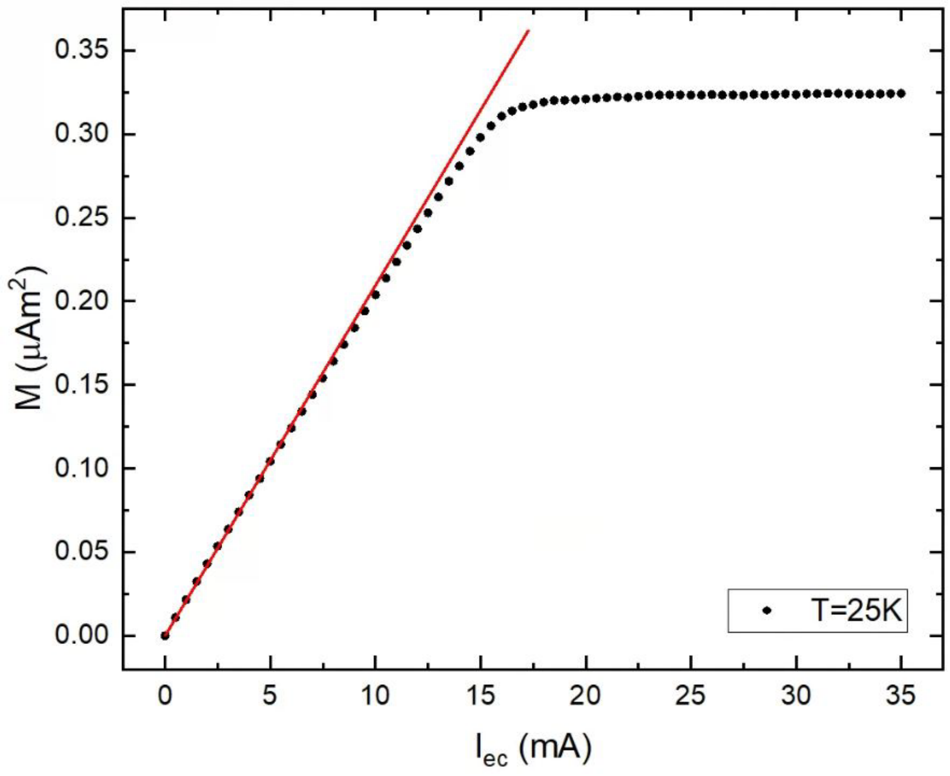
- The system is cooled below T_c with zero current in the excitation coil
- Current in the coil is gradually increased

- At low currents, the linear relation of the magnetic moment of the ring and the current in the coil is visible (by London)
- The linear trend changes at the critical current I_c

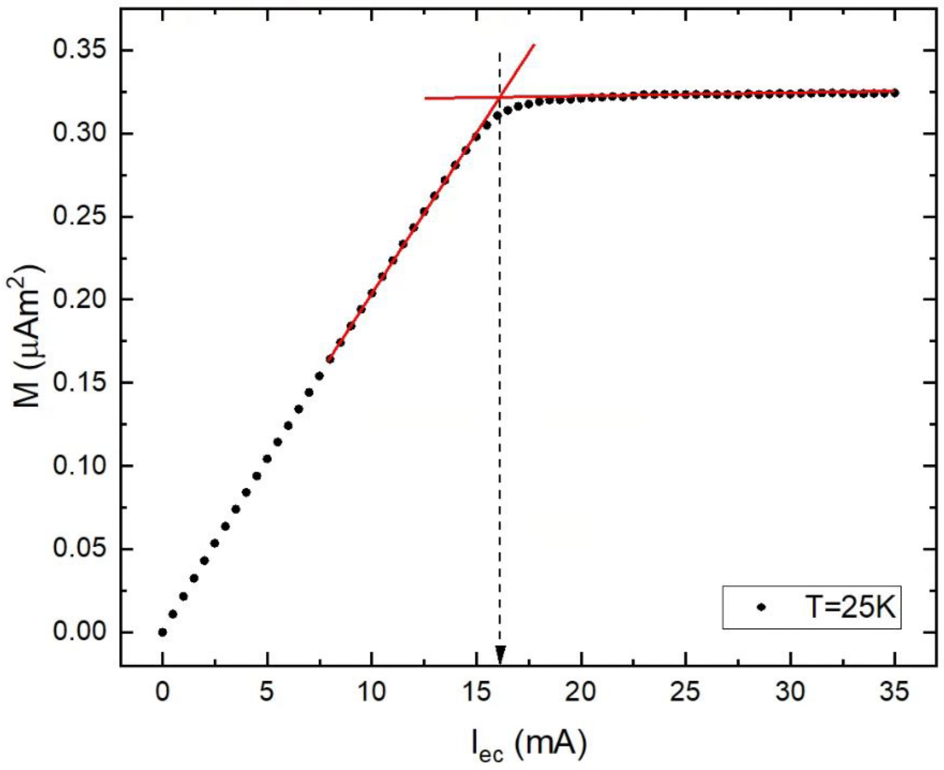


Extracting dM/dI and I_c

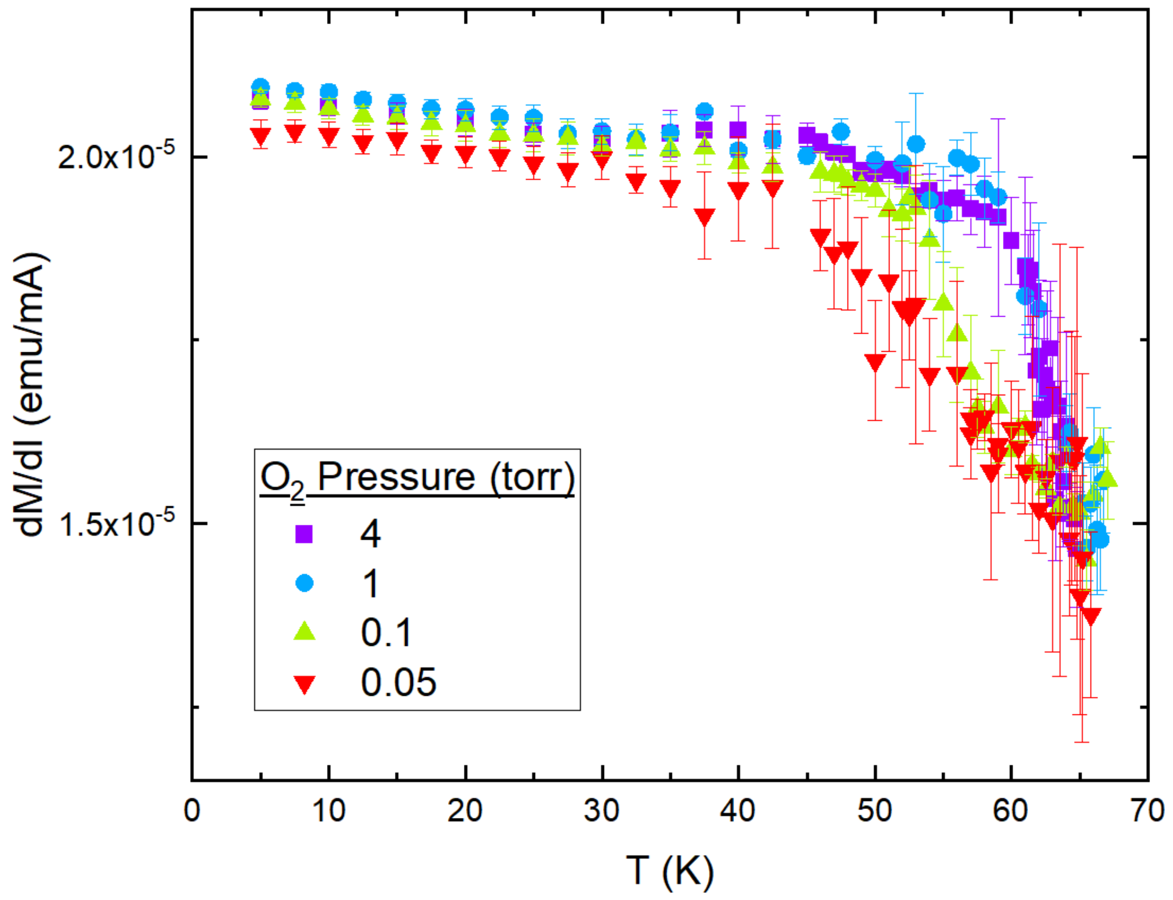
The linear slope at $I_{ec} \to 0$ sets dM/dI, hence the stiffness

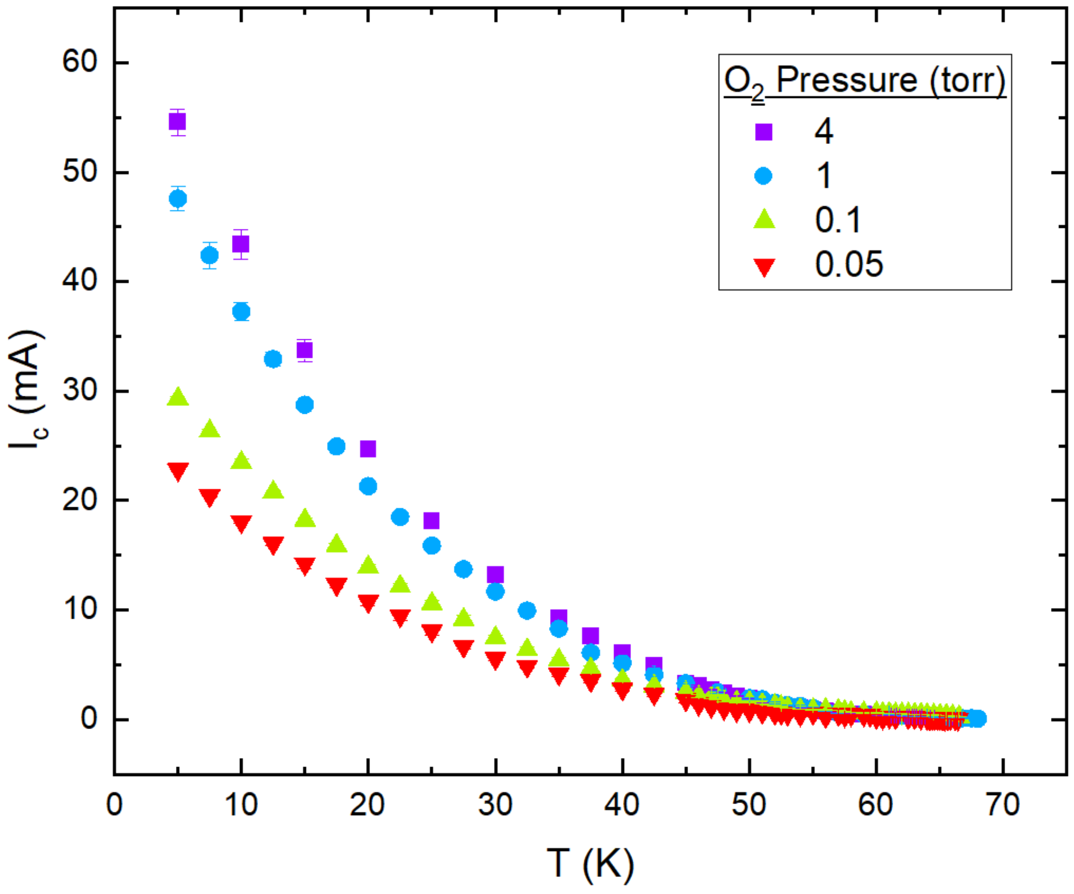


The breakpoint sets I_c, hence the coherence length



dM/dI and I_c Results





Extracting the Stiffness

Ampere: $\nabla \times \nabla \times A_{sc} = \mu_0 J_{sc}$ 2D London: $J_{sc} = -\frac{\psi^2}{\mu_0 \Lambda \psi_0^2}(A_{ec} + A_{sc})$

- Combine the two and switch to unitless variables:

$$A(r,z) \rightarrow \frac{A_{sc}(r,z)}{A_{ec}(r_{PL})}\hat{\theta} \quad ; \quad r, z, \Lambda \rightarrow \frac{r}{r_{PL}}, \frac{z}{r_{PL}}, \frac{\Lambda}{r_{PL}}$$

- Hence, the PDE:

$$\frac{\partial^2 A}{\partial z^2} + \frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} - \frac{A}{r^2} = \frac{1}{\Lambda}\left(A + \frac{1}{r}\right)\delta(z)$$

- With boundary conditions:

$$A(r = 0, z) = A(r \rightarrow \infty, z) = 0$$

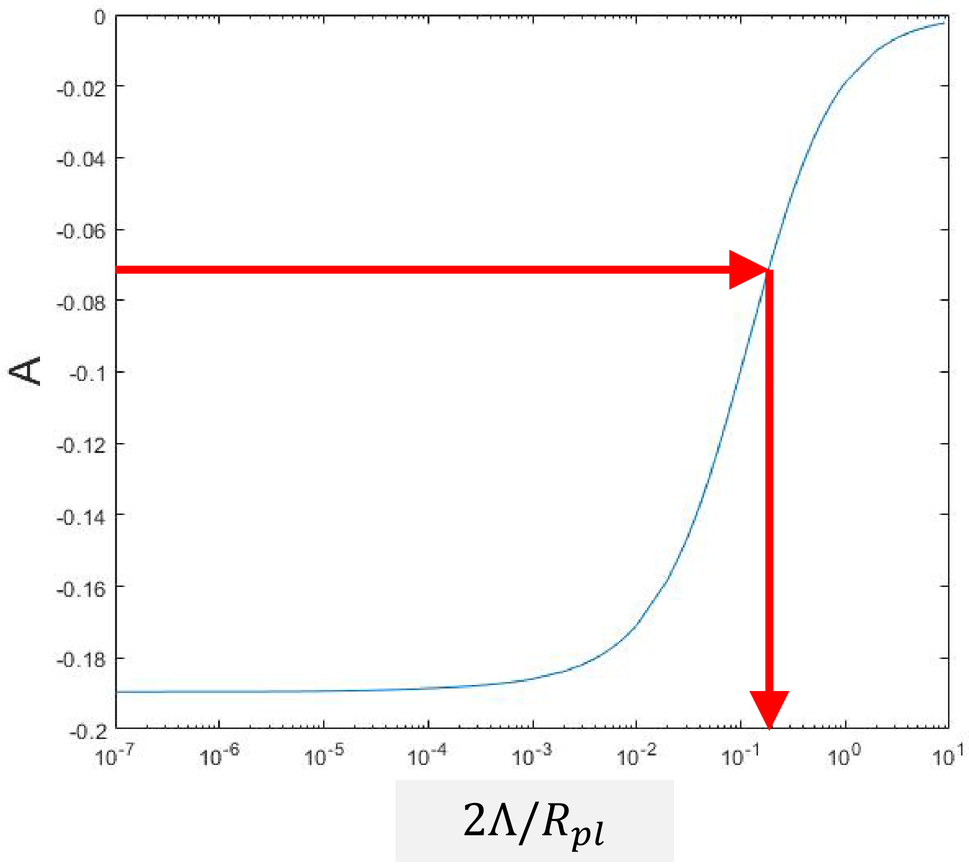
Extracting the Stiffness

- The normalized A is related to the M_{sc} of the ring:

$$A = G\,\frac{M_{sc}}{I_{ec}}$$

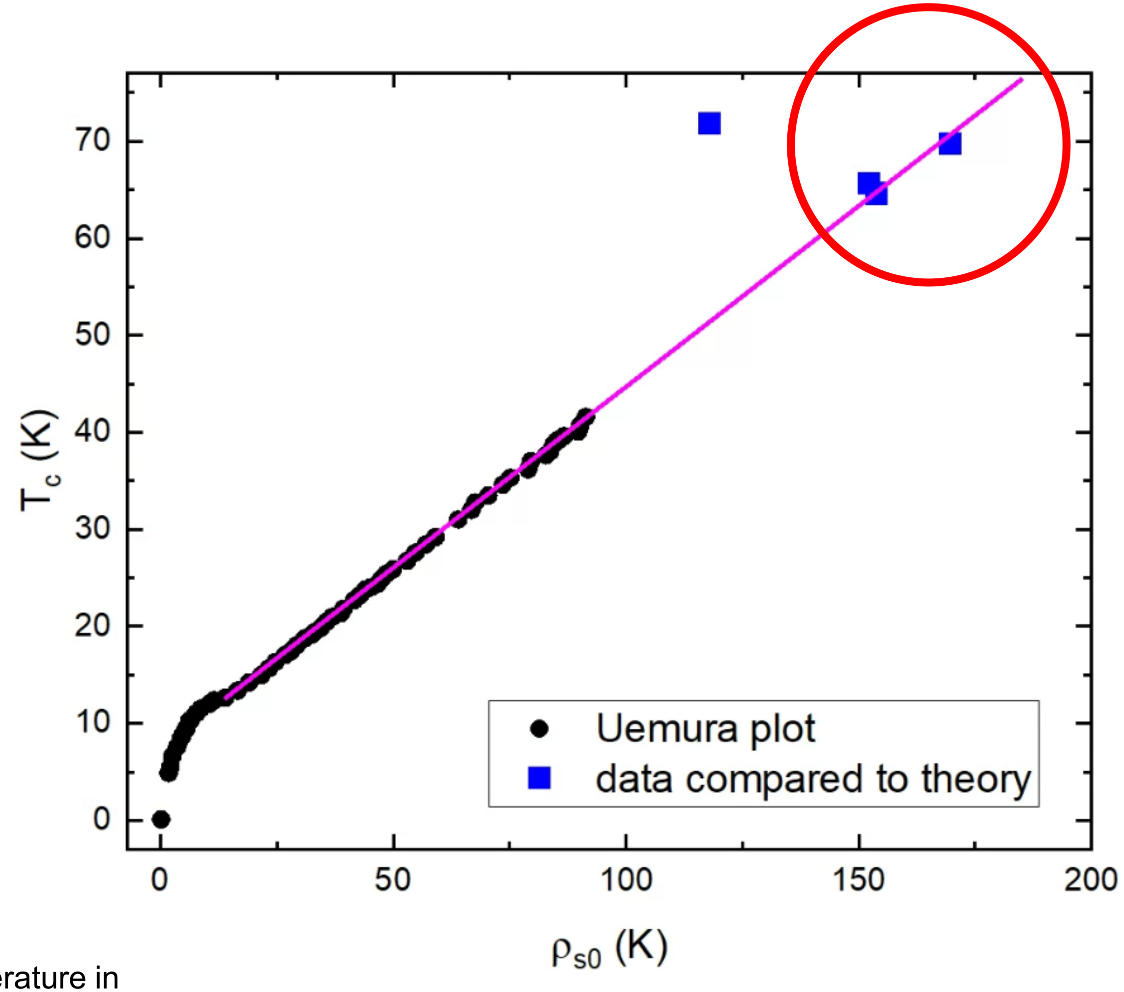
Where $G = \frac{g}{2\pi n R_{pl} r_{ec}}$ and $g \sim 1$ is a calibration factor.

A numerical solution to the PDE



Compliance to the Uemura Plot

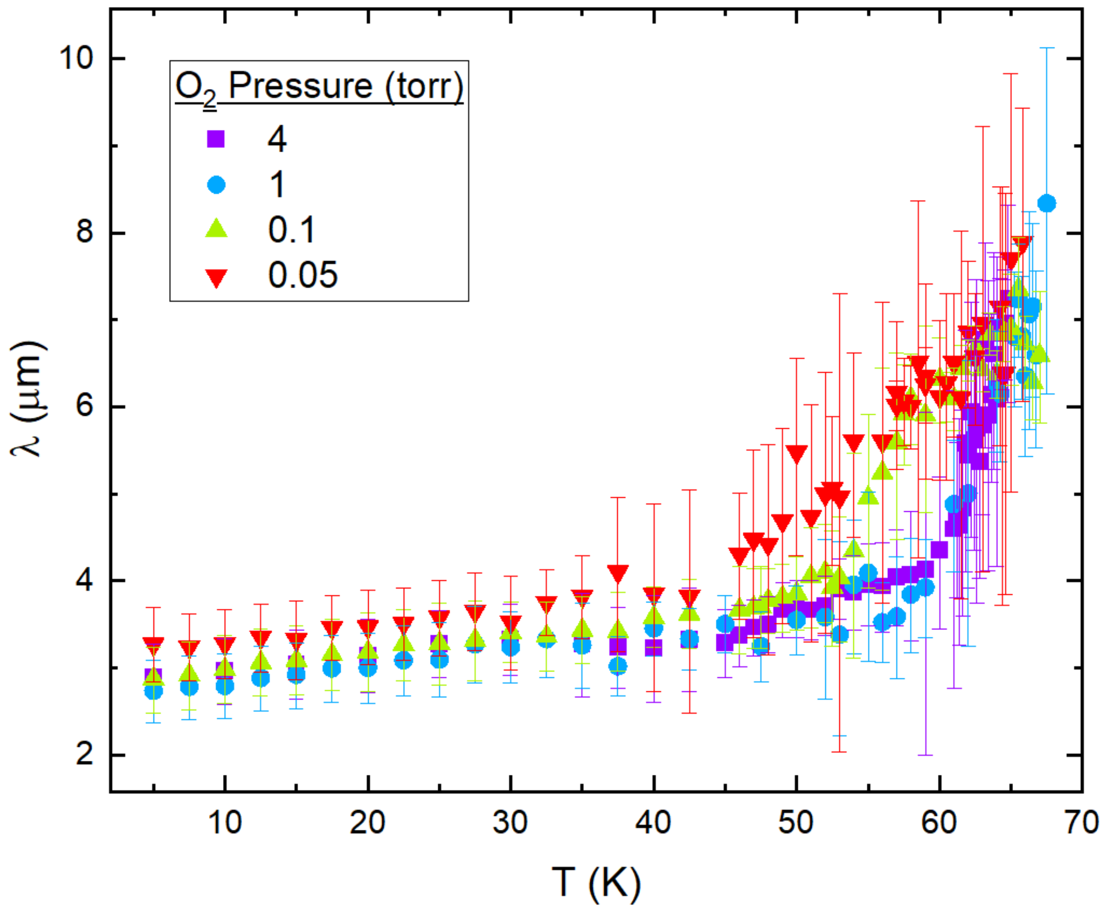
- g is found comparing the calculated stiffness to the Uemura plot at low T
- Three of the measurements comply with the linearity of the Uemura plot, as expected for the cuprates family
- The sample with oxidation level of 0.05torr does not comply



Božović, I., He, X., Wu, J., & Bollinger, A. T. (2016). Dependence of the critical temperature in overdoped copper oxides on superfluid density. Nature, 536(7616), 309-311.

The Penetration Depth

- At $T \rightarrow 0$, λ is about $3\mu m$



Calculation of ξ

GL equation for ψ: $-\psi_{rr} - \frac{\psi_r}{r} + A_{tot}^2\psi = \frac{1}{\xi^2}(\psi - \psi^3)$

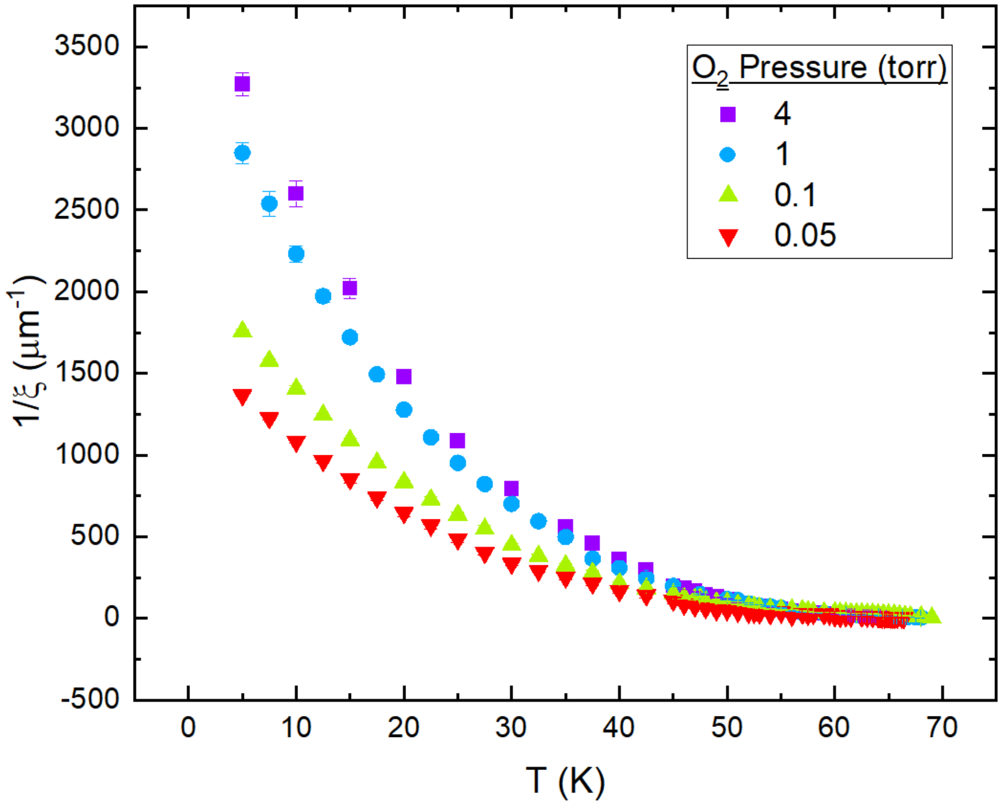
- Boundary conditions: $\psi_r(r_{in}, 0) = \psi_r(r_{out}, 0) = 0$
- In the limit $I \to I_c$: $\psi \ \to \ 0$ in the entire SC $\Rightarrow \psi^3$ is negligible
- Small ring $\Rightarrow A_{tot} \approx A_{coil}$
- Assuming cylindrical symmetry is respected and no vortices enter the sample
- Expecting ψ to grow from r_{in} to r_{out}, ψ_r goes from positive to zero $\Rightarrow \psi_{rr} < 0$

Hence, the GL equation for the outer radius of the ring:

$$-\psi_{rr} = \psi\left(\frac{1}{\xi^2} - A_{ec}^2\right)$$

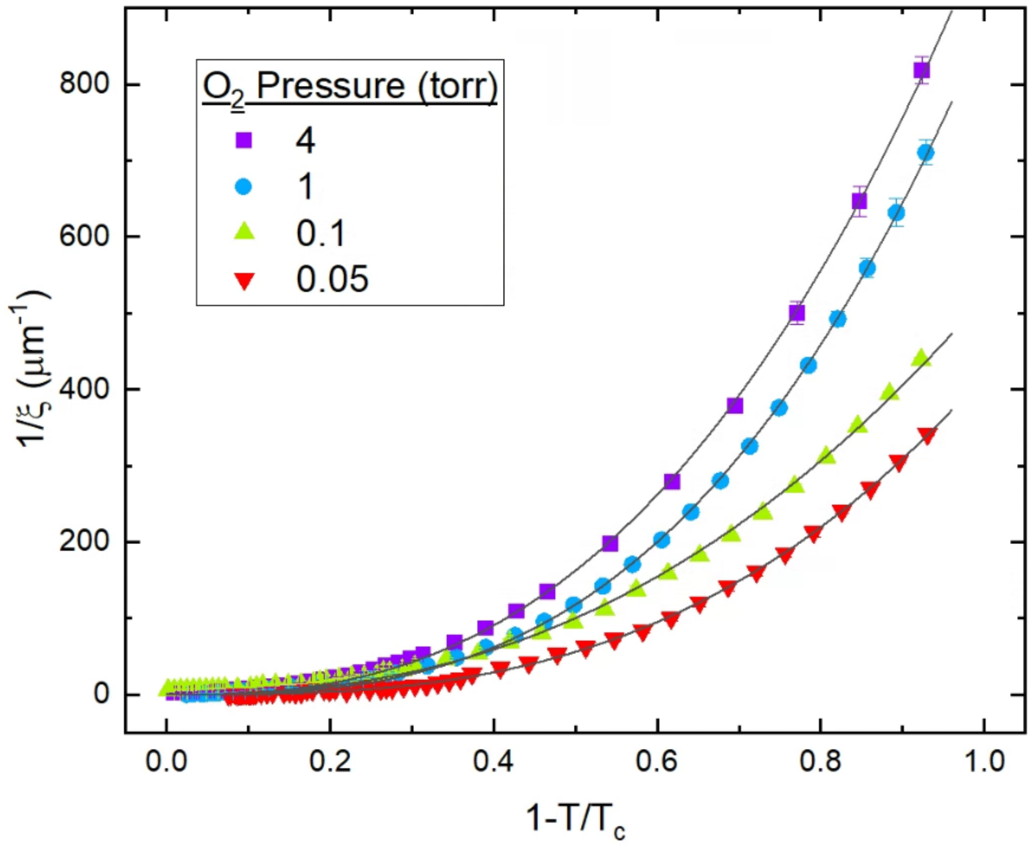
$$\psi_{rr} < 0 \Longrightarrow \left(\frac{1}{\xi^2} - A_{ec}^2\right) \geq 0 \Longrightarrow \frac{1}{\xi} \geq A_{ec}$$

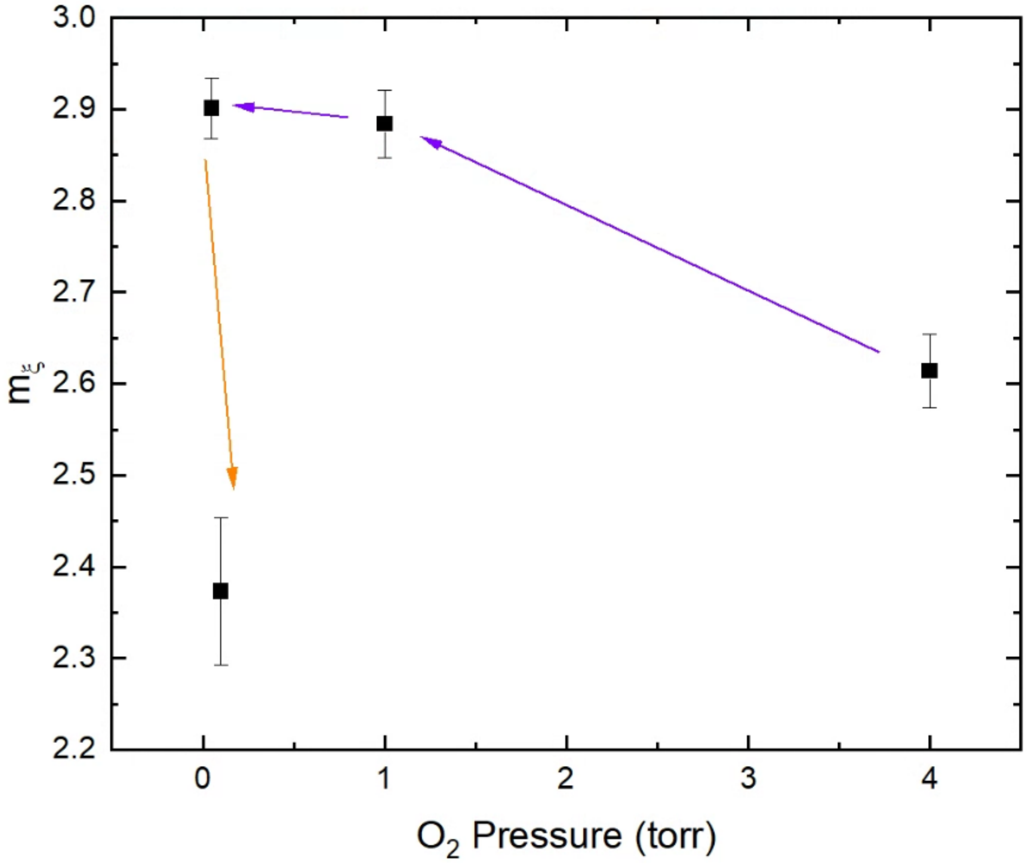
From here: $$J_c = \frac{\Phi_c}{\Phi_0} \simeq \frac{r_{out}}{\xi}$$



Comparison to the GL Theory

$$\xi^{-1} \propto \left(1 - \frac{T}{T_c}\right)^{m_\xi}$$

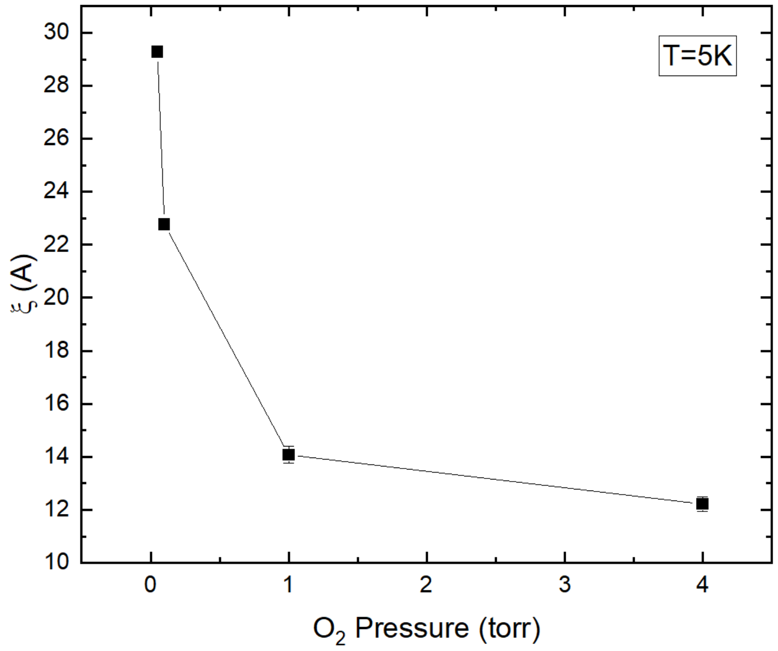




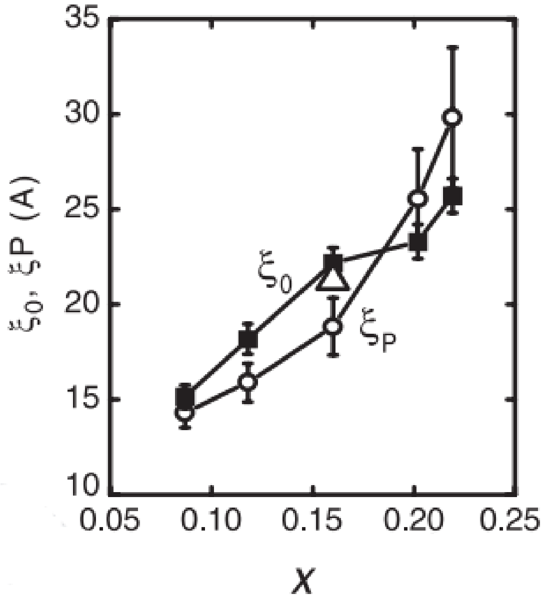
Comparison with Previous Works

The Stiffnessometer Technique:

Calculation Through I_c



- ■ Vortex-Nernst Method: Calculation Through H_{c2}
- ○ ARPES Method: Calculation Through the gap amplitude Δ_0

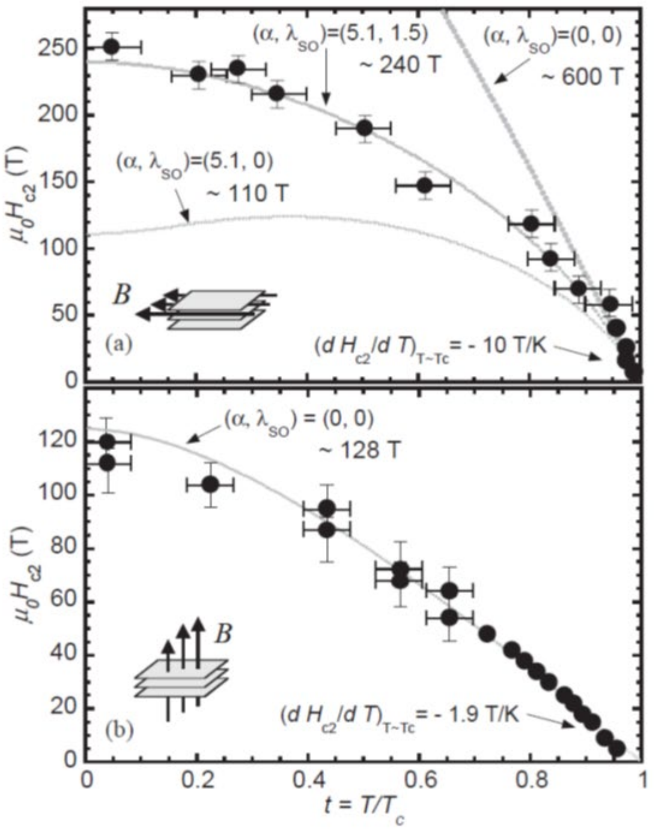


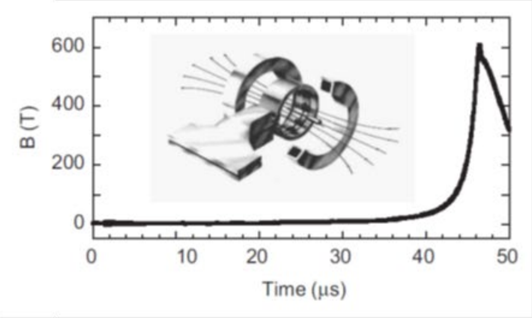
Wang, Y., Ono, S., Onose, Y., Gu, G., Ando, Y., Tokura, Y., ... & Ong, N. P. (2003). Dependence of upper critical field and pairing strength on doping in cuprates. Science, 299(5603), 86-89.

Ding, H., Engelbrecht, J. R., Wang, Z., Campuzano, J. C., Wang, S. C., Yang, H. B., ... & Hinks, D. G. (2001). Coherent quasiparticle weight and its connection to high-T c superconductivity from angle-resolved photoemission. Physical review letters, 87(22), 227001.

Comparison to Other Methods

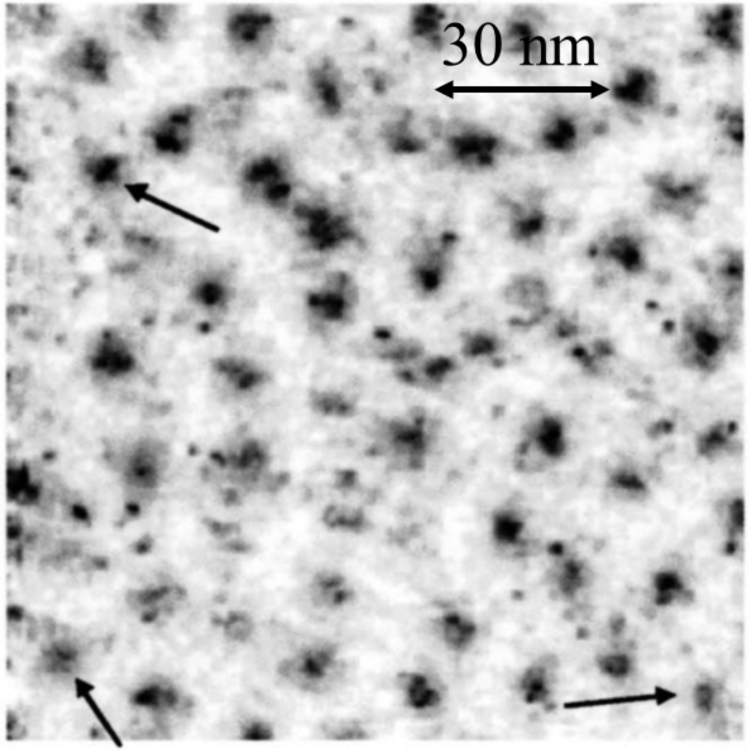
H_{c2} measurement





$\xi_{ab} = 1.7nm$

STM Studies of Vortex Cores in Bi2212



$\xi_{ab} = 2.2(3)\ nm$

T. Sekitani et al. Physica B 346–347 (2004) 319–324
S. H. Pan…J. C. Davis, PRL 85, 1536 (2000)

Conclusions

- We managed to measure the coherence length directly in low temperatures
- The T_c dependence on doping level was found to be inconsistent for different directions of oxidations
- The coherence length is consistently dependent on the oxidation level, regardless of the order of oxidations
- It was observed, that the higher the doping level gets, the smaller the coherence length becomes at low temperatures when at the over-doped regime

Future directions

- It is preferable to oxidize in only one of the directions: lower oxidation level first and then higher, or from higher to lower only
- Preparation of thinner samples (under 200nm) is desirable, for better agreement with the coherence length calculation assumptions such that we will get $h \ll \lambda$
- In order to collect more comprehensive results, it is recommended to oxidize under smaller pressures of oxygen to achieve an under-doped regime

Group Members

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