Supercurrents in the pseudogap regime of LSCO in YBCO/LSCO/YBCO junctions

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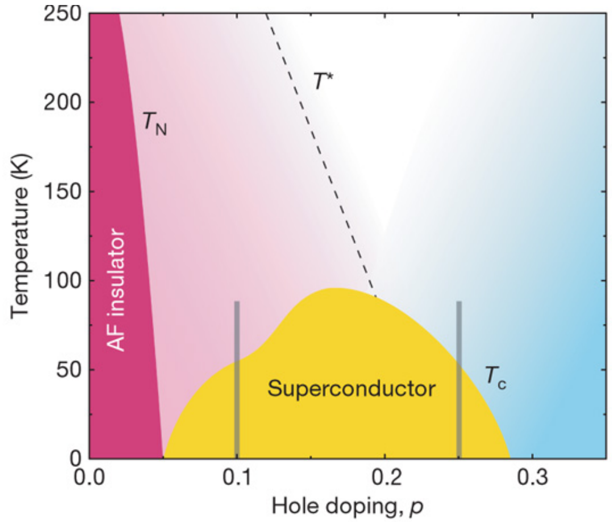
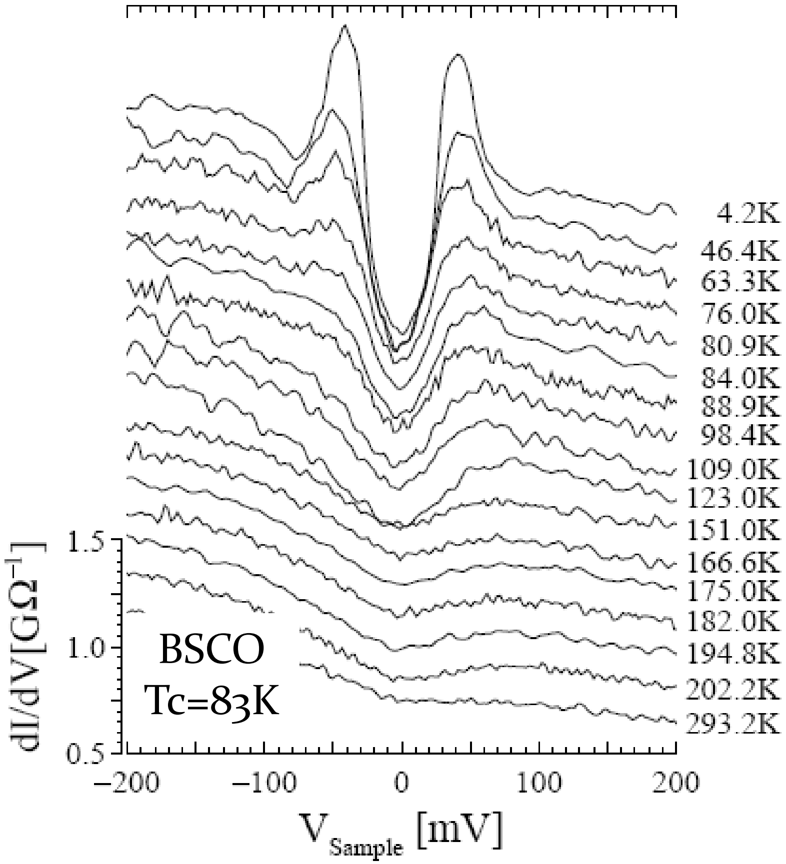
DIP meeting, Technion, March 19, 2013

The Pseudogap

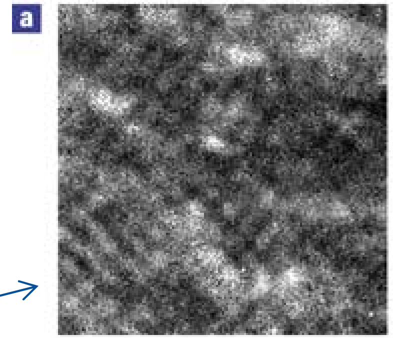
- Depletion of low-energy density of states of electrons below T*



- Experimental evidence:
  - Energy gaps in ARPES and STM.
  - Change of scattering rate in transport processes.
  - Drop in spin-lattice relaxation rate $1/TT^1$ in NMR.
  - Drop in heat capacity



Origin of the Pseudogap



- Competing order:
  - SDW, spin stripes
  - CDW, charge stripes, checkerboard
  - Nematic order (breaking of rotational symmetry without breaking translation symmetry)
- Fluctuating superconductivity
  - Gaussian fluctuations (Amplitude and phase)
    - Finite life time of Cooper pairs
    - Only one transition temperature
  - Phase fluctuations
    - Emergy & Kivelson 1995
    - Two transition temperatures (T* & Tc)
    - High-T_c Cuprates

Proximity Effect

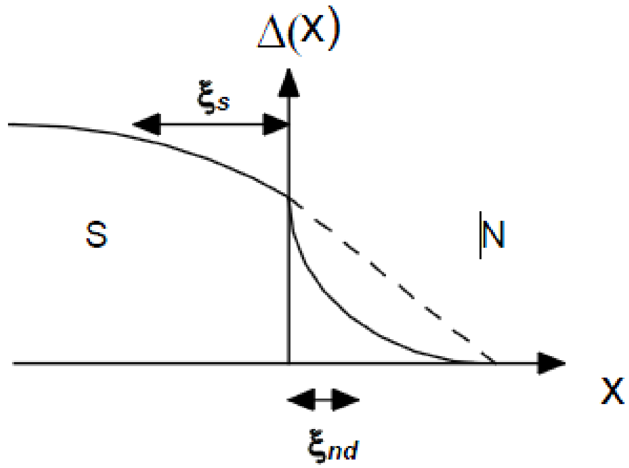
- Cooper pairs penetrate the metal via the Andreev reflection process.
- In the metal electrons lose coherence on a length scale of ξ_n

In the clean limit : $(\xi_n \ll l_n)$

- $\xi_{nc} = \dfrac{\hbar v_n}{2\pi k_b T}$

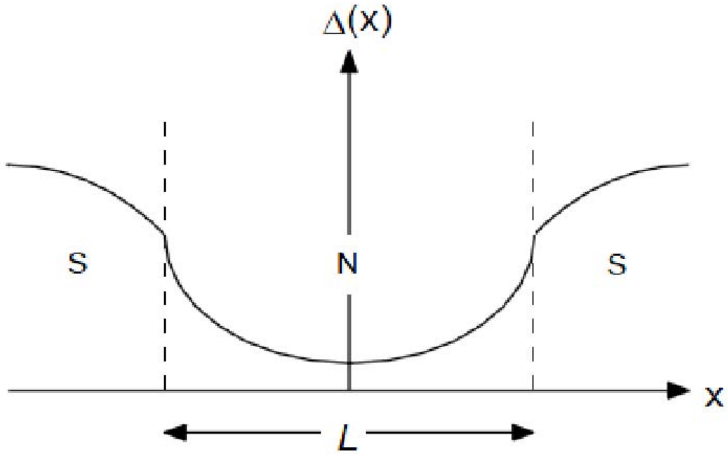
In the dirty limit : $(\xi_n \gg l_n)$

- $\xi_{nd} = \sqrt{\dfrac{\hbar D_n}{2\pi k_b T}}$



SNS Junction

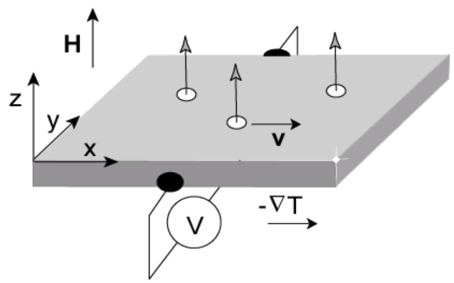
- Proximity effect from both superconductor sides leads to a supercurrent.
- Critical current in SNS junctions (DeGennes):
  - $J_c = \frac{\pi}{2e\rho_n\xi_n}\frac{|\Delta_0|^2}{k_b T_c}(1-\frac{T}{T_c})^2 e^{-L/\xi_n}\quad (L \gg \xi_n)$
  - $I_c \propto e^{-L/\xi_n}$



Previous experiments 1

- The vortex Nernst effect

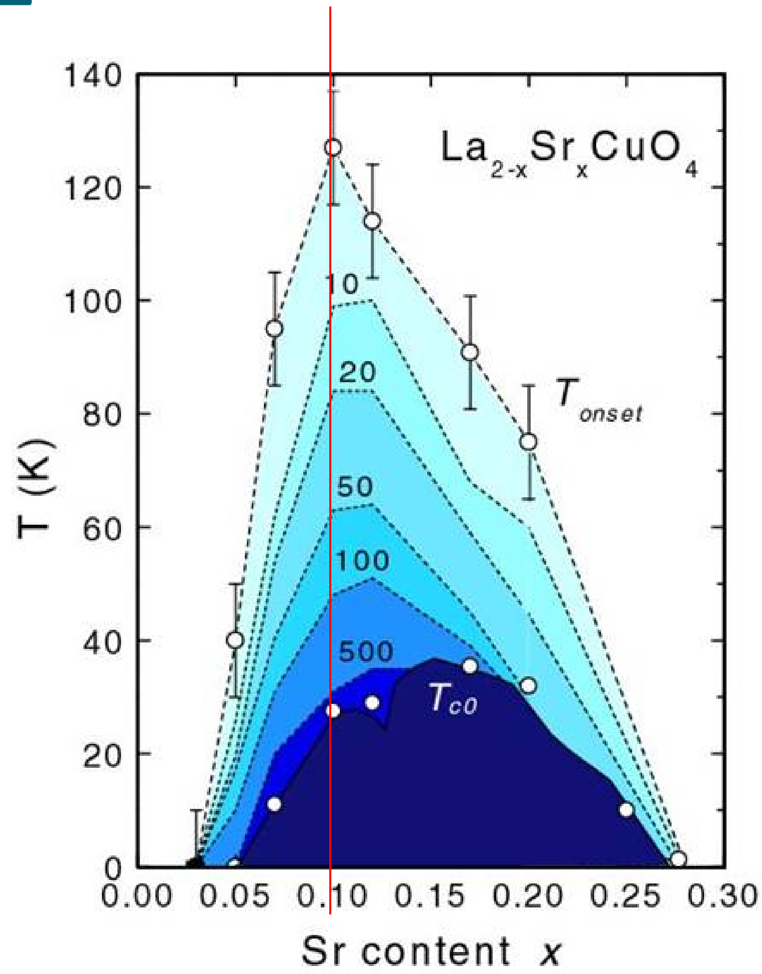
$$2eV_J = \hbar\dot{\phi} = 2\pi\hbar\dot{n}_v$$



$$\mathbf{E}_J = \mathbf{B} \times \mathbf{v}$$

$$e_y = E_y / |\nabla T|$$

- The Nernst signal is very small in normal metals
- Overdoped regime
  - Gaussian fluctuations
- Underdoped regime
  - Strong phase fluctuations



Wang & Ong, PRB **73**, 24510 (2006)

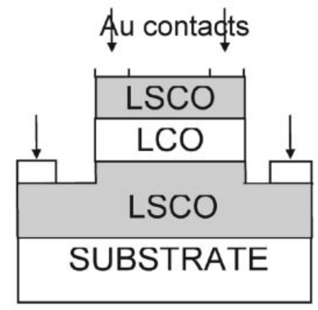
Previous experiments 2

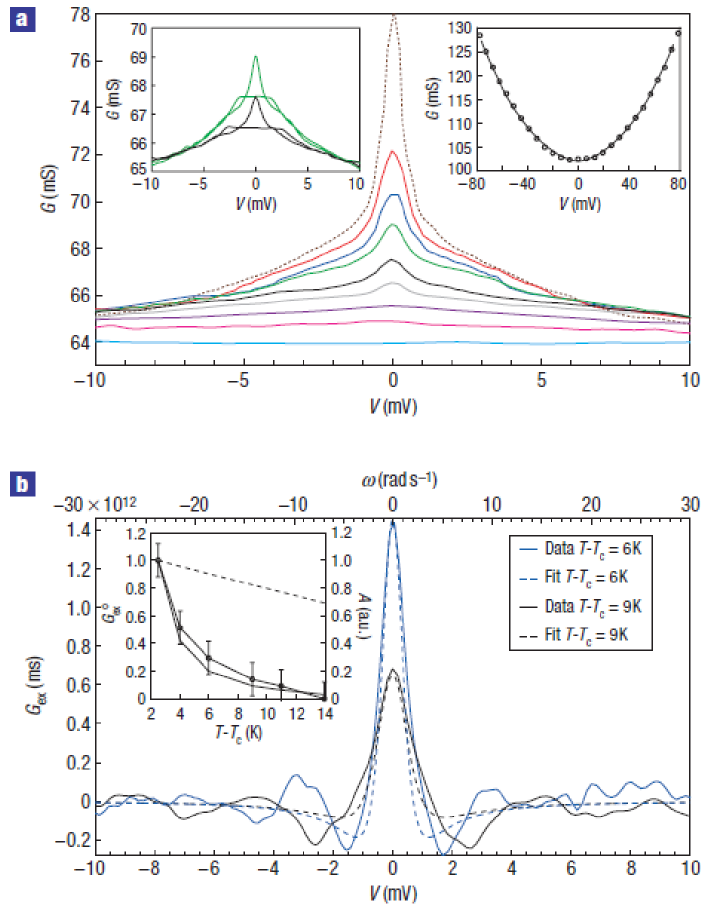
- Josephson Effect & ZBCP
  - Giant Proximity Effect in LCO
    - Bozovic et al. 2004

    Sizable supercurrent in 20nm barriers
    L=20nm >> $\xi_c = 0.5 - 1\text{nm}$

  - Excess Current (ZBCP) in OP-N-UD junctions
    - N. Bergeal et al. 2008

    up to 15K above Tc of the UD layer
    Gaussian Fluctuations





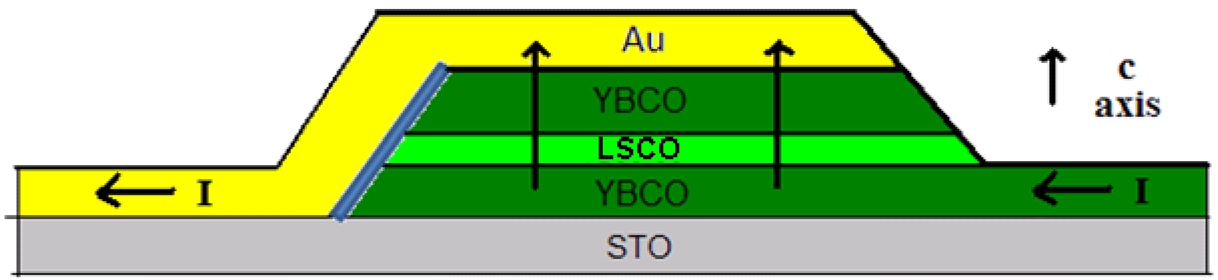
Motivation for the present study

- Detect superconducting fluctuations above T_c using the Josephson effect.
  - Superconductor fluctuations should preserve the coherence of the Cooper pairs (in the PG state)
    - High critical currents
    - High normal metal coherence length above Tc
  - Josephson junction cross section:

- Up to this day – no systematic measurements of the normal coherence lengths and critical currents as a function of the barrier thickness & doping

The present experiment

- A tri-layer of c-axis Josephson junction
  - In situ deposition of the layers
    - High quality interfaces
- (100nm **YBCO cover**) / (10-20nm **LSCO**) / (200nm **YBCO base**) junction
  - LSCO with various doping
  - 5 μm x 5 μm Area
- We measured the I-V curves as function of temperature below T_c(YBCO) ~ 90K
  - Then extract the critical current



Results 1

- IV curves
  - Not RSJ - like
  - Flux flow behavior
    - Trapping of vortices in the junction
- Microwave irradiation
  - AC Josephson Effect
    - Shapiro steps
    - $\nu = 2eV/\hbar$
    - 10.7Ghz ⟶ 22μV

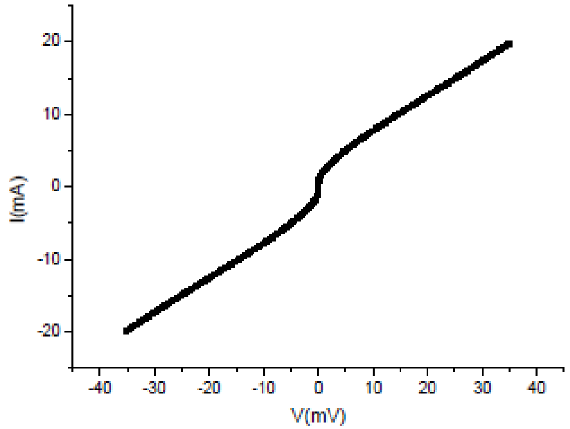
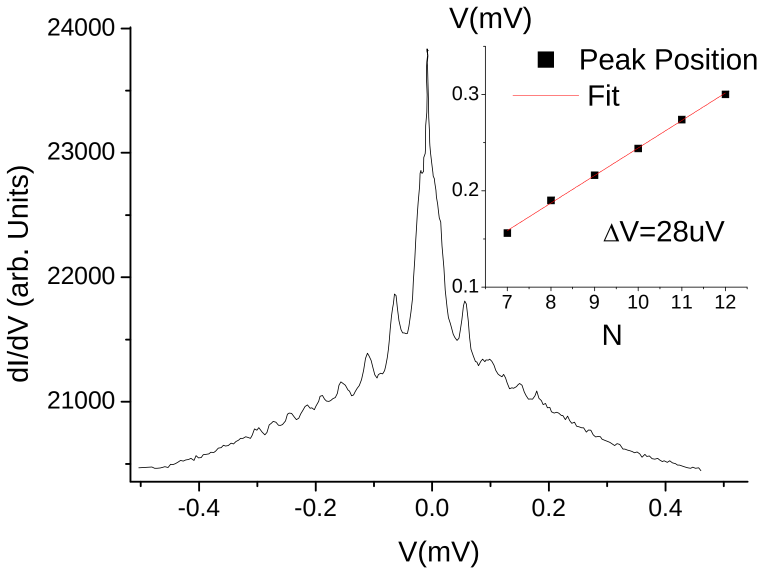
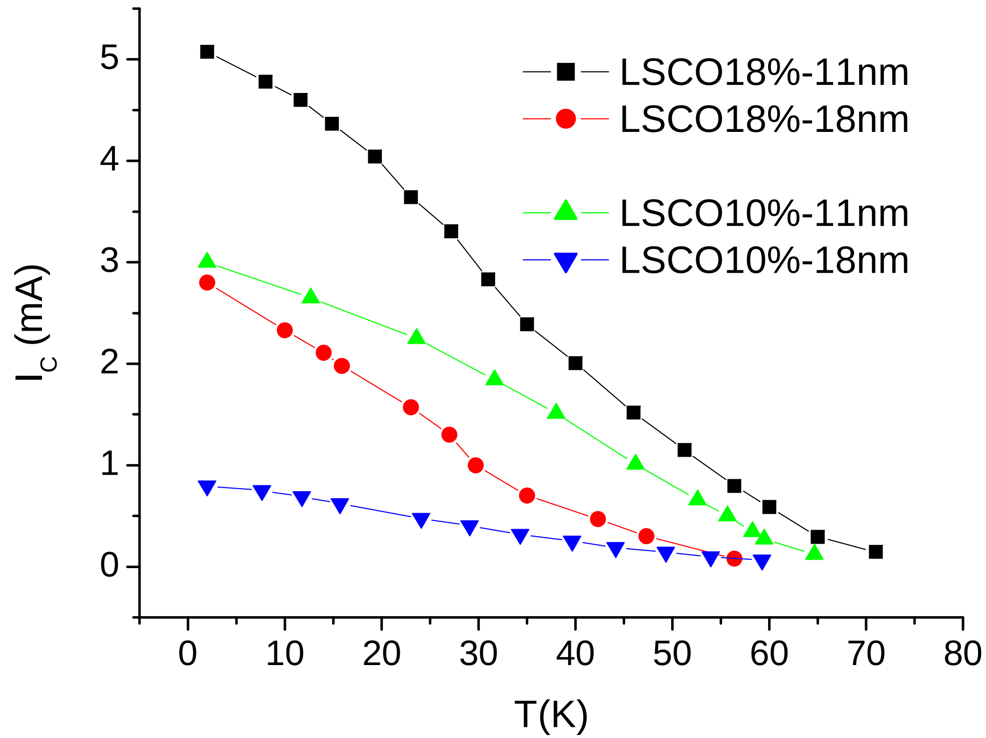


FIGURE 4.3: IV measurement of an SNS junction of Fig. 4.2 with a barrier of 15nm at a temperature of 68K.



Results 2

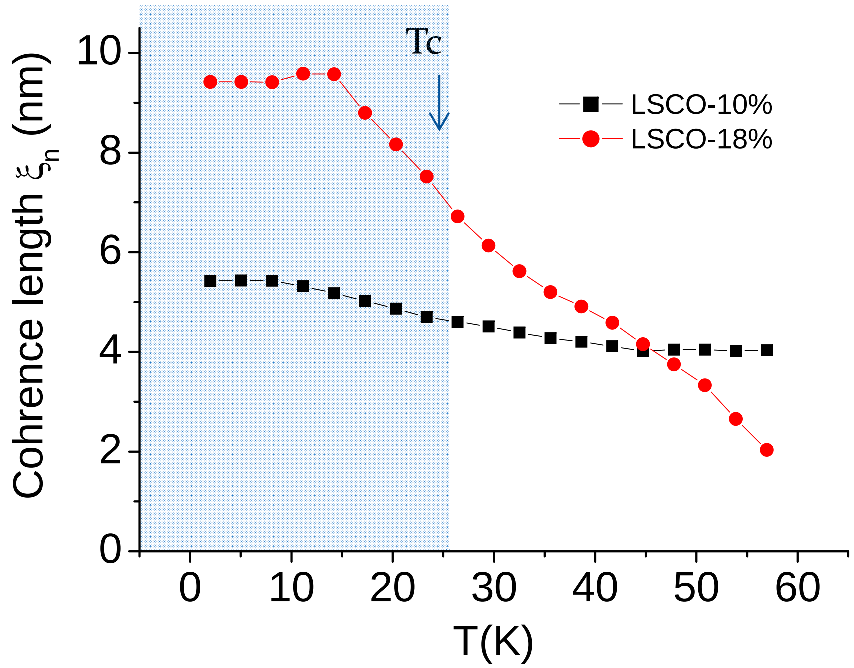
- Barriers of JJ's
  - LSCO10%
    - $T_c \cong 25K, T^* \sim 150\ K$
    - UD
  - LSCO18%
    - $T_c \cong 25K$
    - OD
  - Barrier thickness of
    - 18nm
    - 11nm



Critical current as function of temperature for LSCO 10% & 18% and barrier thicknesses of 11 nm & 18 nm

Results 3

- Extract ξ_n from the critical current dependence on the barrier length.
  - $I_c \propto e^{-L/\xi_n}$
- LSCO is a dirty superconductor (esp. in the c-axis direction)
  - From theory:
    - $\xi_n \propto \sqrt{D_n} \propto \sqrt{1/\rho}$
    - $\frac{\xi_{n(LSCO18\%)}}{\xi_{n(LSCO10\%)}} = \sqrt{\frac{\rho_{(LSCO10\%)}}{\rho_{(LSCO18\%)}}} \sim 2$
- Experimental results show that:
  - At 60 K $\xi_{n(LSCO10\%)} > \xi_{n(LSCO18\%)}$ which is not as predicted
  - But this can be explained by phase fluctuations in the PG state of the LSCO10%.



Coherence length as function of temperature of LSCO10% and LSCO18%

Conclusions

- We have measured the normal coherence length of an underdoped and overdoped LSCO above T_c using the Josephson effect.
- At high temperatures (>50K) the normal coherence length of underdoped LSCO is higher than that of overdoped LSCO.
  - It is in contrast to the theory of the proximity effect where the coherence length is proportional to the square root of the diffusion constant.
  - The results can be explained by the phase fluctuations scenario (pre-formed pairs in the pseudogap regime)