Direct probe of pairing fluctuations in the pseudogap regime of underdoped cuprates

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Cuprates superconductors: a consensus?

Cooper Pairs

\[ \Phi_0 = \frac{h}{2e} \]

LSCO break junction

Esteve et al, EPL '87

D wave order parameter

\[ d_{x^2-y^2} \]

Tsuei et al, PRL '94

Josephson effect

T=77K
f=93.37GHz
\( \Omega = 1.2 \)

Vertical step with resolution 2 nV
Cuprates phase diagram

- High Tc superconductors
- Hole-doped in the CuO$_2$ plane

\[ \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \]

\[ T_c = 90 \text{K} \]
Outline

1. The pseudogap in underdoped cuprates
   Single particle probes (spin and charge channels)
   Different scenarios; pairing fluctuations?

2. Probing pairs above Tc: a Josephson like experiment
   Standard Josephson experiments
   Pair susceptibility above Tc in BCS superconductor
   Designing an experiment to directly probe pairs in UnderDoped Cuprates
   How do we make junctions?

3. Only gaussian pair fluctuations between Tc and T*
   Josephson behavior at low temperature
   Electronic transport through localized states
   Gaussian fluctuations ... that’s all folks!

4. Fluctuations in cuprates
   Amplitude fluctuations
   Phase fluctuations

5. Conclusion
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Pseudogap in the spin channel (NMR)

➤ Knight-shift (Alloul '89)

UnderDoped YBCO

➤ $1/T_1 T$ (Takigawa '91)
Pseudogap in the charge channel (ARPES)

UnderDoped BSCCO

ARPES (Norman ‘98)
Pseudogap in the excitations spectrum

- Lost of spectral weight
- Both in charge and spin channels (Entropy)

Specific heat (Loram ‘97)
Scenarios for the Pseudogap ...

- RVB like
- QCP like
- Preformed pairs

- What is the « generic » phase diagram ?
- What is T* ?
- Relation between the Pseudogap and Superconductivity ?
Are there preformed pairs???

➢ Relation between the Pseudogap and Superconductivity?

➢ Mostly single particle excitations probes?

Incoherent Pair Tunneling as a Probe of the Cuprate Pseudogap

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(Received 19 August 1998)

➢ Janko et al PRL ‘99

➢ Pseudo-Josephson experiment

➢ Probing directly pairs

➢ Scenario independent
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Josephson effect

\[ I = I_c \sin(\varphi) \]
\[ \varphi = \varphi_1 - \varphi_2 \]

Phase sensitive probe

\[ \psi_2 = |\psi_2| e^{i\varphi_2} \]
\[ \psi_1 = |\psi_1| e^{i\varphi_1} \]

\[ \tau(T) \]
\[ T > T_c \]

\[ \xi(T) \]

Probing superconducting fluctuations?

\[ \frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} \]

Time dependence

\[ \xi(T) \]

Josephson equations
Pair susceptibility in the gaussian regime of fluctuations in a BCS superconductor

Fluctuating pairs

Rigid pair field

\[ T_c \text{ A } < T < T_c \text{ B } \]

\[ \tau = \frac{\pi \hbar}{8 k_B T_c \varepsilon} \]

\[ \varepsilon = \frac{(T - T_c)}{T_c} \]

\[ \chi^{-1}(q,\omega) = N_0 \varepsilon \left[ i \omega \tau + (1 + \xi^2 q^2) \right] \]

Frequency \[ \omega = \frac{2eV}{h} \]

Wave vector \[ q = \frac{2e}{\hbar c} H \left[ \lambda' + d / 2 \right] \]
Pair susceptibility in the gaussian regime of fluctuations in a BCS superconductor

\[ I_1(V, H) \propto \text{Im} \chi(\omega, q) \]

\[ I_{ex} = \frac{\hbar C^2 \omega L}{4 e d N_0} \frac{\omega \tau}{\varepsilon \left[ (\omega \tau)^2 + (1 + q^2 \xi^2)^2 \right]} \]

\( T_c A < T < T_c B \)

\( \varepsilon \) Excess current
Pair susceptibility in the gaussian regime of fluctuations in a BCS superconductor

Junctions Sn-SnO-Pb with $T_{c_{Sn}} < T < T_{c_{Pb}}$

$\Gamma_0 = \frac{16k_B}{h}(T - T_c)$

$\varepsilon = 1.48 \times 10^{-3}, \ 1.97 \times 10^{-3}, \ 2.45 \times 10^{-3}, \ 2.94 \times 10^{-3}, \ 3.91 \times 10^{-3}$
Pair susceptibility in the pseudogap regime of UD cuprates


Underdoped: fluctuating pairs

Optimally doped: rigid pair field

Tc UD < T < Tc OpD

➤ Up to T* (Tc OpD)
➤ Independent of a specific scenario !!!
➤ Difficult !!!
Design of the experiment

Requirements:

- Three different materials
- The barrier has to be compatible (epitaxy)
- Epitaxy at T~700°C --> impossible to underdope with oxygen

\[
\begin{array}{c|c|c}
\text{Layer} & \text{Material} & \text{Thickness} \\
\hline
\text{UD} & \text{YBa}_2\text{Cu}_{2.8}\text{(Co}_{0.2}\text{)}\text{O}_7 & 100 \text{ nm} \\
\text{UD} & \text{PrBa}_2\text{Cu}_{2.8}\text{(Ga}_{0.2}\text{)}\text{O}_7 & 30 \text{ or } 50 \text{ nm} \\
\text{OpD} & \text{NdBa}_2\text{Cu}_3\text{O}_7 & 200 \text{ nm} \\
\end{array}
\]

\[T^* \text{ (UD)} = 250 \text{ K}\]
\[T_c \text{ (UD)} = 61 \text{ K}\]
\[T_c \text{ (OpD)} = 90 \text{ K}\]

*J.P Contour (Thales/CNRS)*
The UnderDoped material ...

➢ Co-doped YBCO:
  - $T_c$ can be adjusted by doping (60 K)
  - Small disorder (Co in the chains)

Resistivity

$T_c = 60$ K  $\tau^* = 250$ K

$T_c = 60$ K

Hall Cste
Ga-doped PBCO:
- PBCO: weak insulator
- Standard compound in Josephson devices
- Ga doping: higher resistivity

Conduction in PBCO:
- Variable Range Hopping (bulk)
- Conduction through localized states (layer)
- Ga doping: reduction of their number

\[ G(T) = G_{\text{dir}} + G_{\text{res}} + \sum G_n(T) \]

\[ G(V) = G_0 + \alpha V^{4/3} + \beta V^{5/2} + ... \]
Mesas used in this study

Mesa structures
Junctions $40\mu m \times 40\mu m$ to $5\mu m \times 5\mu m$

- Good equipotentials
- Gold resistance in series (150 mΩ)
- Barrier resistance $\gg$ other resistances
**Characteristic temperatures**

- **Resistivity**
  - $T_c^{OpD}$
  - $90\,\text{K}$

- **Susceptibility**
  - $T_c^{UD}$
  - $61\,\text{K}$

**Josephson coupling at** $T_c^{UD}$

- **Josephson** $T < T_c^{UD} < T_c^{OpD}$
- **"Normal"** $T_c^{UD} < T_c^{OpD} < T$
- **Pseudogap** $T_c^{UD} < T < T_c^{OpD}$
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Josephson effect at low temperature ($T < T_c^{UD} < T_c^{OpD}$)

- RSJ Josephson I-V characteristics
  - Coupling $I_c R_n = 2 mV$
- Shapiro steps
  - $V_n = n \frac{h}{2e} f_0$

$4.2K$
$25K$
$30K$
$40K$

$f_0 = 8 GHz$

$\frac{1}{2}$
Transport through $\text{PrBa}_2\text{Cu}_{3-x}(\text{Ga}_x)\text{O}_7$ ($T_c^{UD} < T_c^{OpD} < T$)

- Quasiparticles: hopping through **Localized States**
- 50 nm: 3 LS
  30 nm: 1 or 2 LS
- Corresponding $T$ dependence

![Graph showing conductance vs. voltage](image)

$T = 85\, \text{K}$

$$G(V) = G_0 + \alpha V^{\frac{4}{3}} + \beta V^{\frac{5}{2}} + \gamma V^{\frac{18}{5}} + \ldots$$

- Weak dependence at low energy ($< 10\, \text{mV}$)
- Josephson effect: resonant tunneling through Localized States
Finaly, the test ... \((T_c^{UD} < T < T_c^{OpD})\)

Conductance measurements to be more sensitive

\[ I_{ex}(V) = A \frac{\omega / \Gamma_0}{\varepsilon [1 + (\omega / \Gamma_0)^2]} \]

\[ \Gamma_0 = \frac{16k_B}{h} (T - T_c) \]

\[ \varepsilon = \frac{T - T_c}{T_c} \]

\[ G_{ex}(V) = A \frac{2e}{\hbar \Gamma_0 \varepsilon [1 + (\omega / \Gamma_0)^2]^2} \left[ 1 - (\omega / \Gamma_0)^2 \right] \]

\( \gg \) How high in temperature will the peak survive?
Testing the fluctuating pairs ($T_c^{UD} < T < T_c^{OpD}$)

- An excess conductance peak
- Seen only 14K above $T_c$
- Far below $T_c$ (OpD)
- Far below $T^*$ (250 K)

Gaussian fluctuations?
Gaussian regime of fluctuations \((T_c^{UD} < T < T_c^{OpD})\)

- Width in energy \(\sim 1\) mV compatible with gaussian fluctuations
- Quantitative comparison with Scalapino-Ferrel’s model
- Thermal noise has to be taken into account \(\Gamma = \Gamma_0 + \Gamma_1\)

\[
\Gamma_1 = 4e^2 R k_B T / \hbar^2
\]
Only Gaussian fluctuations? \((T_c^{UD} < T < T_c^{OpD})\)

▶ The temperature dependence is controlled by the barrier.

▶ The temperature dependence of \(A\) calculated by Ferrel.

\[
I_{ex}(V) = A \frac{\omega/\Gamma_0}{\varepsilon[1 + (\omega/\Gamma_0)^2]}
\]

▶ What about the shape of the peak?
Shape of the peak ($T_c^{UD} < T < T_c^{OpD}$)

Background subtraction using microwaves

Excess conductance consistent with gaussian fluctuations
Shape of the peak \( T_{c UD} < T < T_{c OpD} \)

Background subtraction using microwaves

Two different temperatures
Conclusion of the experiment

Our conclusion

Gaussian fluctuations seen 15 K above $T_c \ll T^*$

- Fluctuation of the Order Parameter Amplitude
- Only one temperature scale in the problem

$T_c \text{ UD} < T < T_c \text{ OpD}$

$T - T_c = 6K$

Graph showing data and Gaussian distribution.
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   - Phase fluctuations

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Amplitude vs phase fluctuations ...

Our conclusion

Gaussian fluctuations seen 15 K above $T_c << T^*$

- Fluctuation of the Order Parameter Amplitude
- Only one temperature scale in the problem

$\Psi = \Psi_0 e^{i\theta}$

Amplitude Fluctuations

Phase Fluctuations

Ginzburg-Landau

Aslamasov-Larkin

Kosterlitz-Thouless

Nelson Halperin

Lifetime of the Cooper pairs

Stiffness of the condensate
Fluctuation of the amplitude of the OP

\[ \tau = \frac{\pi \hbar}{8k_B(T - T_c)} \]

Cooper pairs lifetime

vx Specific form of the fluctuating pair contribution
vx Infinite extension of the fluctuations (detection limit)

Conductivity

\[ \Delta \sigma_{D=2}^{\text{AL}} = \frac{e^2}{16\hbar d\varepsilon} \]
\[ \Delta \sigma_{D=3}^{\text{AL}} = \frac{e^2}{32\hbar \xi_{c0} \sqrt{\varepsilon}} \]
\[ \varepsilon = (T - T_c)/T_c \]
\[ \Delta \rho = -\rho^2 \Delta \sigma \]

Underdoped
- YBCO
- BSCCO
- LSCO

Leridon et al PRB, 2007
Caprara et al PRB 2009

Robust AL fluctuations
Fluctuation of the amplitude of the OP

**Nerst effect**

Dirty superconductor \( \text{Nb}_x\text{Si}_{1-x} \): \( \nu_{\text{fluct}} = 2000 \nu_{\text{norm}} \)

Pourret et al
Nature Phys. '06
PRB '07

\[
\xi_d = \frac{1}{\sqrt{\varepsilon}} 0.36 \sqrt{\frac{3 \hbar v_F \ell}{2 k_B T_c}}
\]

\[
l_B(B) = (\hbar/2eB)^{1/2}
\]
Fluctuation of the amplitude of the OP

What is the situation in cuprates?

- Nerst effect
- Ong's group
- Vortex-like objects above Tc

- Rullier-Albenque et al PRL '06
- Limited fluctuations in clean compounds

- Alloul et al EPL 2010
- In clean samples T* < Tc'
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Phase transition in 2D systems: 2D XY model

\[ H = -J \sum_{\langle ij \rangle} \cos(\varphi_i - \varphi_j) \]

Spin system

\[ J = \frac{\hbar^2 \rho_s}{4m} \]

Superfluid

\[ \Psi = \Psi_0 e^{i\varphi} \]

Superfluid density

\[ \xi(T) \sim e^{-b|T-T_{KT}|^{-1/2}} \]

Coherence length
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Phase transition in 2D systems: 2D XY model

\[ H = -J \sum_{\langle ij \rangle} \cos(\varphi_i - \varphi_j) \]

\[ J = \frac{\hbar^2 \rho_s}{4m} \]

\[ \Psi = \Psi_0 e^{i\varphi} \]

Spin system

Superfluid

Superfluid density

Bound vortices

Free vortices

\[ \rho_s \neq 0 \]

\[ \rho_s = \frac{2}{\pi} T_{KT} \]

\[ \rho_s = 0 \]

Universal stiffness jump
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Universal jump

\[ \frac{2T}{\pi} \]

\[ \rho_S = \lambda^{-2} \]

2 unit cells

--

\[ \Delta \rho(T) \text{ (nsec)} \]

Temperature (mK)

McQueeney et al
PRL '84

He\textsubscript{3}-He\textsubscript{4} mixture

Underdoped Ca-YBCO

Hetel et al Nature Phys. '07

- The actual thickness (2 u.c.) controls \( T_{KT} \)
- Thicker films do not show KT physics
- Scaling points towards a QCP at low doping
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Universal jump

\[ \frac{2T}{\pi} \]

\[ \rho_s = \lambda^{-2} \]

Thick films

Underdoped Ca-YBCO
Hetel et al Nature Phys. '07

FIG. 1. Superfluid density \( \rho_s \propto \lambda^{-2} \) (solid curves) and \( \sigma_1 \) (dashed curves) vs \( T \) for four films used in the present study.
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

**Coherence length**

Coherence length

Two characteristic temperatures: $T_c$ & $T_{KT}$

Bound vortices

Free vortices

Halperin-Nelson, JLTP '79

\[ \tau = \frac{T - T_{KT}}{T_{KT}} \]

\[ \tau_c = \frac{T_c - T_{KT}}{T_{KT}} \]

\[ \Delta \sigma = 0.37 b^{-1} \sigma_N^{squ} \sinh^2 [(b \tau_c / \tau)^{1/2}] \]

\[ \chi = \frac{M}{H} = - \left( \frac{k_B T}{d \Phi_0^2} \right) \xi_{KT}^2 \]
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Coherence length

Two characteristic temperatures: $T_c$ & $T_{KT}$

\[
\chi = \frac{M}{H} = -\left(\frac{k_BT}{d\Phi_0^2}\right)\xi_{KT}^2
\]

$T_{KT}$ $T_c$ Ong's group
Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Non-universal

Finite size effects & vortex-core energy

Cut-off in the long-range vortex interactions

No evidence of bulk KT physics

Benfatto et al, PRL '07, PRB '09
Conclusion

➤ Direct probe of pairing fluctuations above TC

➤ New type of junctions including UD and OpD layers

➤ Clear observation of a gaussian regime of fluctuations

➤ No signature of fluctuating pairs well above Tc (UD)

➤ Pseudogap : order in competition ???