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Spatially Resolved Tunneling Spectroscopy & Spin-Polarized Quasiparticle Transport in Cuprate Superconductors

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1. **Introduction**

   -- Doped Mott insulators & competing orders
   -- Unconventional pairing symmetry & mechanism

2. **Quasiparticle Tunneling Spectroscopy**

   -- Quasiparticle transport at N/S interface
   -- Generalized BTK theory
   -- Comparison of planar & STM junctions
   -- Directional & spatially resolved tunneling spectroscopy of cuprate superconductors
   -- Effects of impurities

3. **Spin-Polarized Quasiparticle Transport**

   -- Magnetic pair-breaking effects
   -- Conventional nonequilibrium superconductivity
   -- Suppression of high-temperature superconductivity by spin injection
   -- Implication of the microscopic mechanism

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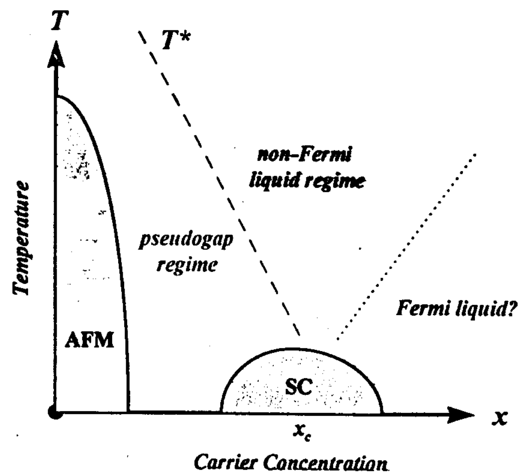
1. Introduction

A. Doped Mott Insulators & Competing Orders

- *Mott insulators: conduction blocked by e-e repulsion.* *(conventional band insulators: conduction blocked by Pauli exclusion principle)*
- *High-temperature superconductors are doped Mott insulators.*
- *Quasi-2D & proximity to a Mott insulating phase* → *unconventional normal-state properties.*
- *Relevance of a quantum critical point (x_c)?*



- ***Global Symmetries in Doped Antiferromagnetic Square Lattice:***

  * **S** -- *the electromagnetic U(1) symmetry;* *(broken by the appearance of superconducting order)*

  * **M** -- *the SU(2) spin rotation invariance symmetry;* *(broken by the appearance of magnetic order)*

  * **C** -- *the space group of the square lattice (including parity P);* *(broken by charge/spin density inhomogeneity)*

  * **T** -- *time reversal symmetry;*

- ***Competing Orders that Break "S", "C" and/or "T" Symmetries:***

  * $d_{x^2-y^2}$ -- *U(1) broken symmetry;*

  * $(d_{x^2-y^2} + id_{xy})$ -- *U(1), P, T broken symmetries & PT conserved;*

  * $(d_{x^2-y^2} + is)$ -- *U(1) and T broken symmetries;*

  * ***Wigner crystals*** -- *U(1) and "C" broken symmetries;*

  * ***Wigner crystals of hole pairs*** -- *U(1) and "C" broken symmetries;*

  * ***Orbital antiferromagnets*** -- *U(1), T, "C" broken symmetries;*

  * ***Stripe phase*** -- *U(1) & "C" broken symmetries;*

  * ***Circulating current phase*** -- *U(1) & "T" broken symmetries.*

  ↔ ***Relevance of doping level, disorder& thermal fluctuations.***

B. Unconventional Pairing Symmetry & Mechanism

- ***Predominantly $d_{x^2-y^2}$ pairing symmetry in all cuprate superconductors.***

  [Tsuei et al. (1994); van Harlingen (1995); Wei et al. (1998); Alff et al. (1998); Kirtley et al. (1999); Yeh et al. (2000)]

→ ***anisotropic superconducting gap & low-energy excitations.***

- ***Possibilities of secondary pairing components:***

* *Anyon superconductivity ⟷ $(d_{x^2-y^2}+id_{xy})$ pairing.*

* *Doppler effect on quasiparticle spectra at {110} surfaces*
⟶ $(d_{x^2-y^2}+is)$.

- **Existence of spin-charge separation:**

* Independent spectra of excitations for charge and for spin.

* Non-Fermi liquid behavior in the normal state.
⟷ Resonating valence bond (RVB) scenario? (spinons & holons)
⟷ Stripe-phase scenario, Luttinger liquid?

- Our experimental investigation:

* Scanning tunneling spectroscopy (STS),
→ pairing potential, pseudogap, pairing symmetry.

* Spin-injection & nonequilibrium effects,
→ spin & charge transport charateristics.

* ***Experimental signatures:***

Test	$d_{x^2-y^2}$	$(d_{x^2-y^2}+id_{xy})$	$(d_{x^2-y^2}+is)$
Splitting in ZBCP?	*no*	*yes*	*yes*
Quasiparticle bound states in vortex cores?	*no*	*yes*	*yes*
Local DOS at non-magnetic impurities?	*one peak at energy Ω*	*two peaks at energies ±Ω*	*two peaks at energies ±Ω*
Total flux at a π-junction?	*π-GBJ: $0.5\Phi_0$ (JJ: Φ_0)*	$< 0.5\Phi_0$	$< 0.5\Phi_0$

* ***Recent development:***

- ***Evidence of non-magnetic impurity-stabilized $(d_{x^2-y^2}+id_{xy})$ pairing from scanning SQUID microscopy:***

-- ***spontaneous magnetization with random signs and total flux $\Phi < 0.5\Phi_0$ on impurity sites (Y_2O_3, Y_2BaCuO_5, etc.)***
[Tafuri & Kirtley, cond-mat/0003106]

- ***Sp(2N) t-J model in the large-N limit for competing orders and quantum criticality in doped antiferromagnets:***

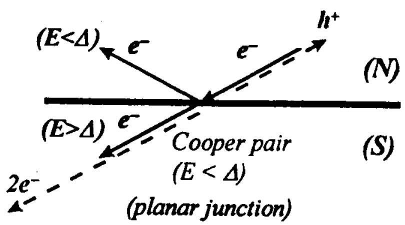
-- ***possibility of ground state $d_{x^2-y^2}$ with near by $(d_{x^2-y^2}+id_{xy})$ or $(d_{x^2-y^2}+is)$ states.*** *[Vojta, Zhang, and Sachdev, cond-mat/0003163]*

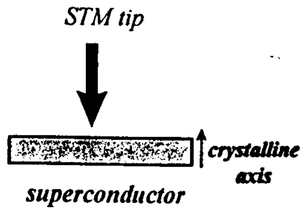
2. Quasiparticle Tunneling Spectroscopy

A. Quasiparticle transport at N/S interfaces

(N: normal metal; S: superconductor)

At $T << T_c$:





■ High-barrier tunnel junctions [large Z] ($Z \sim \frac{\text{barrier height}}{\text{Fermi energy}}$)

* $E > \Delta$: *transmission of electron-like quasiparticles over a charge diffusion length Λ_{Q^*}. (E: quasiparticle energy)*

* $E < \Delta$: *complete normal reflection.*

■ Low-barrier point-contact junctions [small Z]

* $E > \Delta$: *tranmission of electron-like quasiparticles over Λ_{Q^*}*

* $E < \Delta$: *reflection of holes and transmission of Cooper pairs.*

⟶ *Andreev reflection (with enhancement of conductance).*

■ General N/S interface [arbitrary Z]

* ***Normal and Andreev reflections.***

BTK theory: *Blonder, Tinkham and Klapwijk, Phys. Rev. B 25, 4515 (1982).*

Generalized BTK Theory

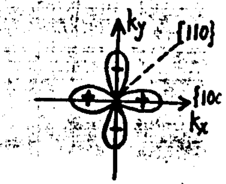
[Hu, Tanaka & Kashiwaya, (1994)]

SIN tunneling current: (for superconducting gap function Δ_k)

$$I_{NS} = G_{NN} \int e^{-(k_t/\beta)^2} d^2k_t \int dE_k \,[1 + A(E_k, \Delta_k, Z) - B(E_k, \Delta_k, Z)]\,[f(E_k - eV) - f(E_k)]$$

- A = Andreev reflection
- B = normal reflection
- k_t = transverse k-vector
- E_k = quasiparticle energy = $\sqrt{\xi_k^2 + \Delta_k^2}$
- ξ_k = normal state tight − binding energy relative to E_F $= -2t\,[\cos(k_x a) + \gamma \cos(k_y a)] + 4t'\,[\cos(k_x a)\cos(k_y a)]$

- $Z = \frac{2\pi m H}{\hbar^2 k_F^2}$ = barrier strength
- $f(E_k)$ = Fermi function = $\frac{1}{1 + \exp[E_k/(k_B T)]}$
- β = tunneling cone



$$(1 + A - B) = \left\{ \frac{16(1 + |\Gamma_+|^2)\cos^4\theta_k + 4Z^2(1 - |\Gamma_+\Gamma_-|^2)\cos^2\theta_k}{|4\cos^2\theta_k + Z^2[1 - \Gamma_+\Gamma_- \exp(i\varphi_k - i\varphi_+)|^2} \right\}$$

$$\Gamma_\pm = (E_k/|\Delta_{k,\pm}|) - \sqrt{(E_k/|\Delta_{k,\pm}|)^2 - 1} \qquad \exp(i\varphi_\pm) = \Delta_{k,\pm}/|\Delta_{k,\pm}|$$

$d_{x^2-y^2}$ gap function: $\Delta_k = \Delta_d[\cos(k_x a) - \cos(k_y a)] \approx \Delta_d \cos(2\theta_k)$

Mixed symmetries:

$$\begin{cases} (d_{x^2-y^2} + is) : \Delta_k = \Delta_d \cos(2\theta_k) + i\Delta_s \\ (d_{x^2-y^2} + id_{xy}) : \Delta_k = \Delta_d \cos(2\theta_k) + i\Delta'_d \sin(2\theta_k) \end{cases}$$

C. Comparison of Scanning Tunneling Spectroscopy (STS) & Planar Junctions

	STS	Planar Junctions
Junction Area	$10^{-8} \sim 10^{-5}$ μm²	$10^{2} \sim 10^{5}$ μm²
Tunnel Currents	$10^{-7} \sim 10^{-6}$ mA	$10^{0} \sim 10^{2}$ mA
Voltage Resolution	$10^{-2} \sim 10^{0}$ mV	$10^{-4} \sim 10^{-3}$ mV
Voltage Range	$>\sim 10^{2}$ mV	$\sim 10^{1}$ mV
Insulating Barrier	(vacuum gap)	(deposited layers of insulators)
Probing Depth	surface ($< 10^{2}$nm)	bulk

* Thermal smearing: At $T = 10.0$ K, $\delta V <\sim 10^{0}$ mV
  $T = 1.0$ K, $\delta V <\sim 10^{-1}$ mV
  $T = 0.1$ K, $\delta V <\sim 10^{-2}$ mV

↔ Voltage resolution must be smaller than the thermal smearing to be relevant.

D. Directional & Spatially Resolved Tunneling Spectroscopy Studies of Superconducting Cuprates

■ **Samples for STS studies:**

-- optimally doped & underdoped $YBa_2Cu_3O_{7-\delta}$ single crystals.

-- (Zn,Mg)-doped $YBa_2Cu_3O_{7-\delta}$ single crystals.

-- optimally doped & underdoped $La_{2-x}Sr_xCuO_{4-\delta}$ a-axis films.

■ **Quantitative analysis:**

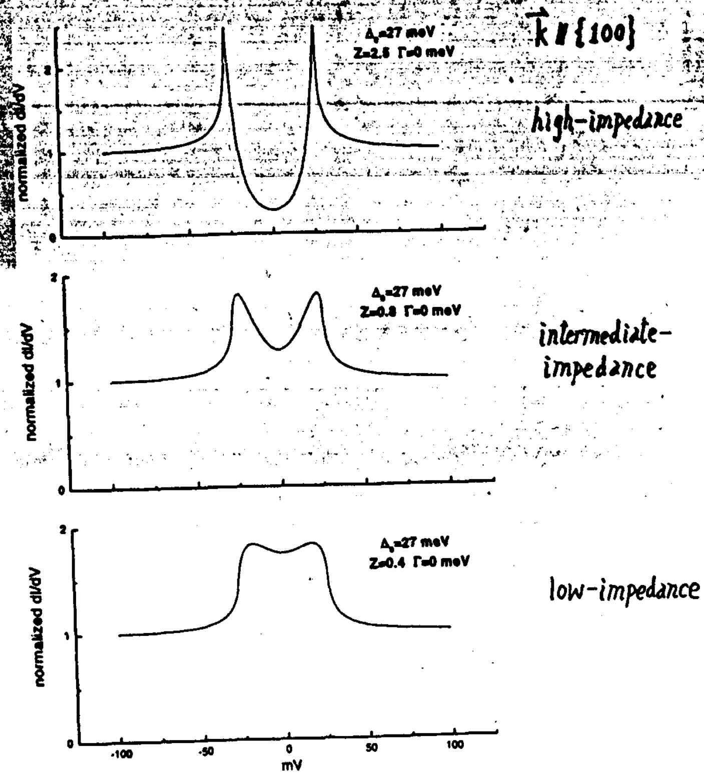
→ the purity of $d_{x^2-y^2}$-wave pairing symmetry.

→ doping dependence of the gap Δ_d & the $(2\Delta_d / k_B T_c)$ ratio.

→ comparison of STS in YBCO and in Bi-2212.

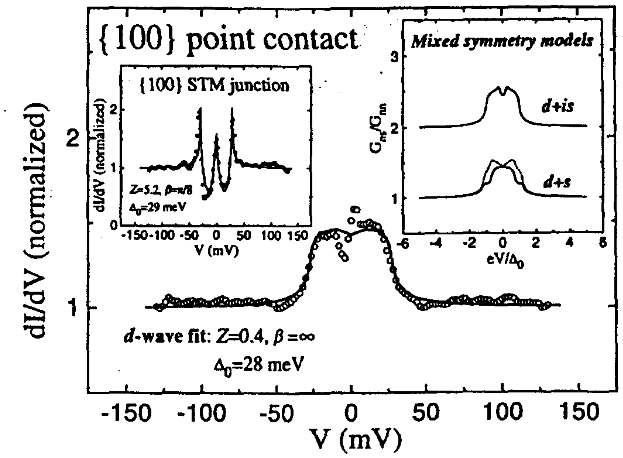
→ evidence of controlled impurity scattering in $d_{x^2-y^2}$ pairing state from local density of states (LDOS).

Effect of barrier strength (Z) on the in-plane {100} tunneling spectra of pure d-wave superconductors :



{100} Tunneling & Point-Contact Junctions in Optimally Doped $YBa_2Cu_3O_{7-\delta}$ Single Crystal

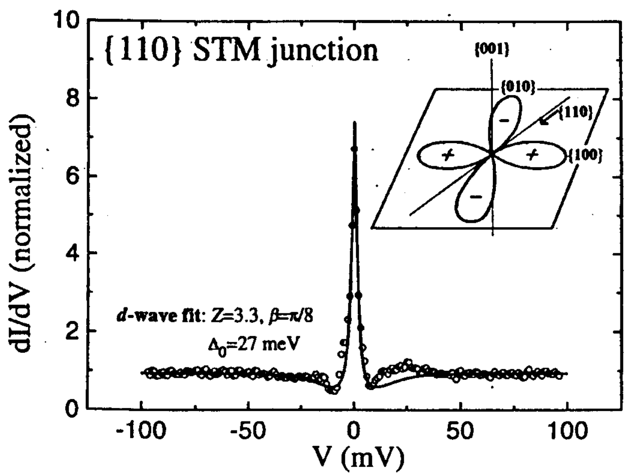
- ***Low-impedance point-contact junction: Andreev reflection.***
- ***High-impedance tunnel junction:***
  superconducting gap structure & ZBCP
  (any k-components different from perfect {100} contribute to ZBCP)



{110} Tunneling Junction in Optimally Doped $YBa_2Cu_3O_{7-\delta}$ Single Crystal

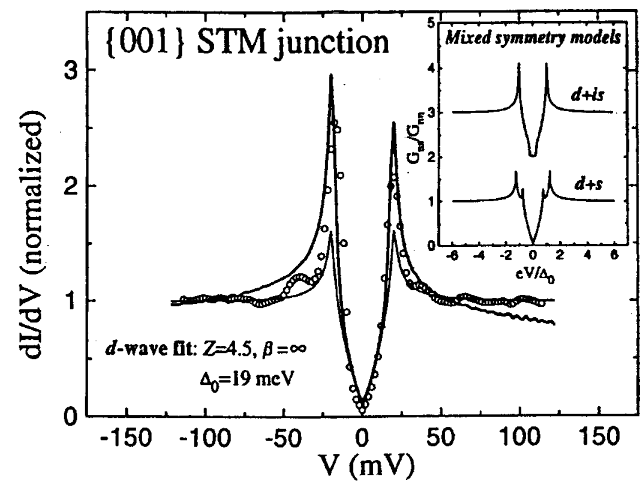
* *No splitting in the zero-bias conductance peak (ZBCP) at T = 4.2 K with voltage resolution = 1 meV.*

=> upper bound for a secondary pairing component < 5%.



{001} C-Axis Tunnel Junction in Optimally Doped $YBa_2Cu_3O_{7-\delta}$ Single Crystal

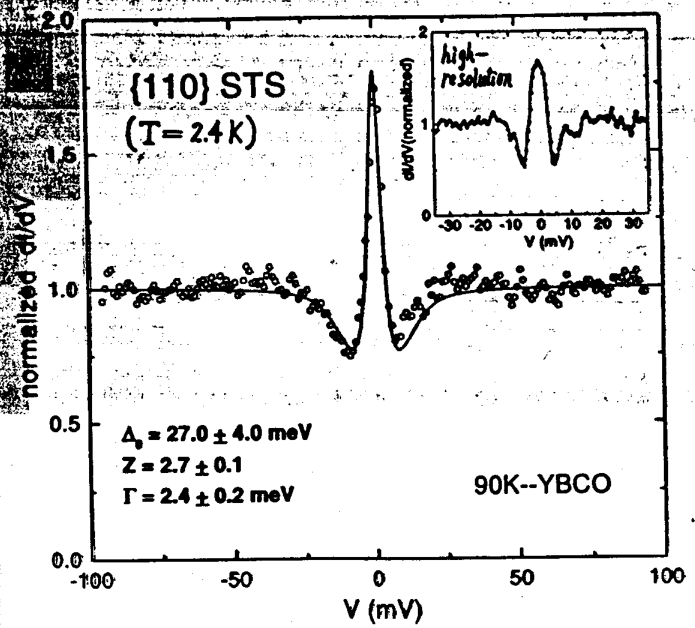
- *Theoretical fitting incorporates two-dimensional band structures & pure $d_{x^2-y^2}$ superconducting gap:*



Scanning Tunneling Spectra of Optimally Doped $YBa_2Cu_3O_{7-\delta}$ Single Crystal (T_c = 91 K)

Low-temperature & high-resolution STS studies

(Voltage resolution: 0.2 meV; Temperature: down to T = 2.4 K)



* *No splitting in the ZBCP within our experimental resolution.*

* *Temperature smearing ~ voltage resolution.*

Quality spectra allow quantitative BTK analysis :

Sample	T_c*(K)*	Δ_d*(meV)*	$(2\Delta_d/k_BT_c)$	*Z*
90K-YBCO{100}	91+-1	29+-3	7.5+-0.8	5.2+-0.5
90K-YBCO{110}	91+-1	27+-4	7.2+-0.8	2.7+-0.1
90K-YBCO{001}	91+-1	19+-4	4.9+-1.0	4.5+-0.5
YBCO(Zn,Mg){001}	86+-1	25+-3	6.7+-0.8	5.0+-0.5
60K-YBCO{110}	60+-4	22+-5	8.5+-1.9	3.6+-0.2
60K-YBCO{001}	60+-4	17+-1	6.6+-0.3	4.0+-0.5
LSCO (x=0.15) {110}	28+-5	15+-4	12.4+-3.3	1.1+-0.2
LSCO (x=0.125){110}	17+-5	15+-4	20.5+-5.5	1.2+-0.2
LSCO (x=0.10) {100}	10+-5	13+-2	30.1+-4.6	>1

* *Upper bound for possible ($d_{x^2-y^2}+id_{xy}$) and ($d_{x^2-y^2}+is$):*

90K-YBCO : < 5%

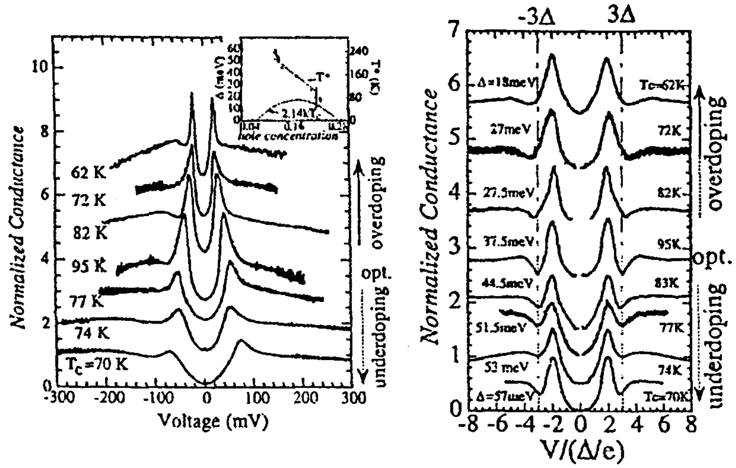
60K-YBCO : < 9%

underdoped LSCO : < 9%

* *Tunneling cone: 20° ~ 25°*

* Comparing the doping dependence of YBCO with BSCCO

(SIN & SIS c-axis point-contact data of Bi-2212)



* *From N. Miyakawa et al., Phys. Rev. Lett. 83, 1018 (1999):*

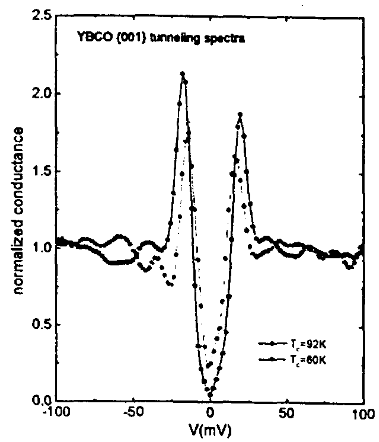
-- *The gap feature Δ^* increases with decreasing doping level, behaving like the pseudogap;*

-- *Additional features in the spectra:*

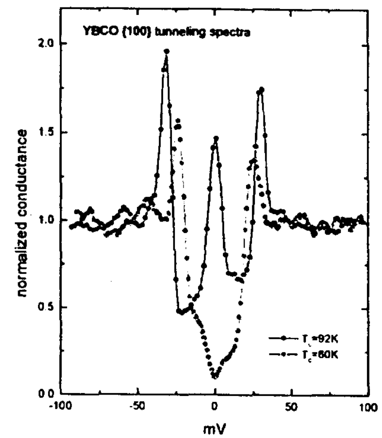
$\Omega_{dip} \sim 2\Delta^*$ $(3\Delta^*)$ and $\Omega_{hump} \sim 3\Delta^*$ $(4\Delta^*)$ for SIN (SIS).

* Comparison of optimally doped & underdoped YBCO:

(c-axis {001} tunneling)



(in-plane {100} tunneling)



- *With decreasing doping level:*

-- Δ_d *decreases,* ⟷ *decreasing superfluid density;*
-- $(2\Delta_d/k_BT_c)$ *increases,* ⟷ *increasing coupling.*
-- *satellite features* Ω_{dip} *and* Ω_{hump} *scale with* Δ_d:
($\Omega_{dip} \sim 2\Delta_d$ and $\Omega_{hump} \sim 3\Delta_d$).
-- *the relative intensity of satellite features increases.*

- *The satellite features are associated with the many-body effects of quasiparticle interaction with the background spin fluctuations.*

⟷ *increasing importance of spin fluctuations in underdoped samples.*

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Comparison of YBCO & Bi-2212 :

Sample	*Technique*	*p*	Δ_d *(meV)*	$(2\Delta_d/k_BT_c)^{**}$
YBCO(Zn,Mg){001}	STM	~ 0.18	25+-3	6.7+-0.8
90K-YBCO{100}	STM	~ 0.15	27+-4	7.2+-0.8
60K-YBCO{110}	STM	~ 0.10	22+-5	8.5+-1.9

Sample	*Technique*	*p*	Δ^* *(meV)*	$(2\Delta^*/k_BT^*)$
$Bi_2Sr_2CaCu_2O_{8+x}$	SIN & SIS	~ 0.22	~ 20	~ 6.6
	SIN & SIS	~ 0.16	~ 38	~ 6.6
	SIN & SIS	~ 0.10	~ 65	~ 6.6

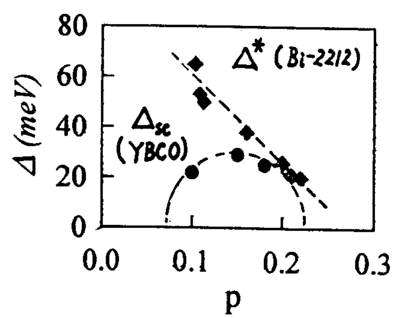
** *Mean-field for pure* $d_{x^2-y^2}$ *pairing:* $(2\Delta_d/k_BT_c)=4.28$

* *N. Miyakawa et al., Phys. Rev. Lett. 83, 1018 (1999).*

** *From ARPES & Knight shift data.*

--Bi-2212: $\Omega_{dip} \sim 2\Delta^*$ $(3\Delta^*)$ ***and*** $\Omega_{hump} \sim 3\Delta^*$ $(4\Delta^*)$ ***from SIN (SIS);***

--YBCO: $\Omega_{dip} \sim 2\Delta_d$ ***and*** $\Omega_{hump} \sim 3\Delta_d$ ***from STS.***



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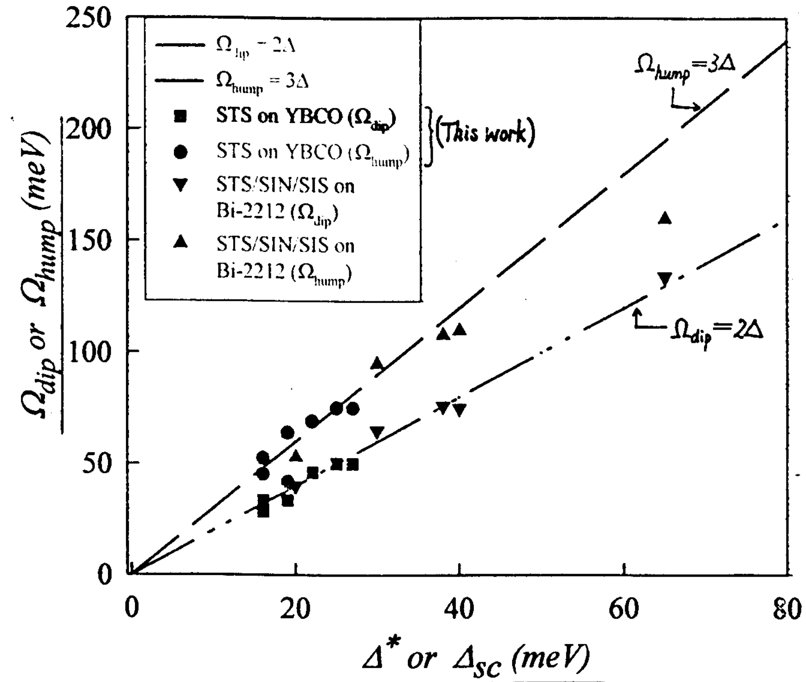
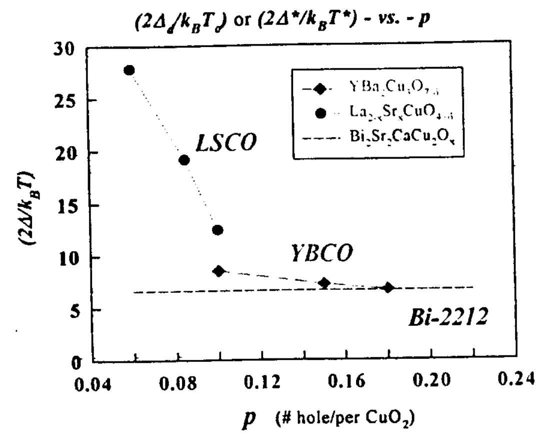
Ω_{dip} & Ω_{hump} *vs.* Δ_{SC} *in YBCO and* Δ^* *in Bi-2212*



Bi-2212 data: N. Miyakawa et al., PRL 83, (1999); and Ch. Renner and O Fisher, PRB 51, (1995).

Comparing ($2\Delta_d/k_BT_c$) ratio in $YBa_2Cu_3O_{7-\delta}$ & $La_{2-x}Sr_xCuO_4$ with ($2\Delta^*/k_BT^*$) ratio in $Bi_2Sr_2CaCu_2O_{8+x}$



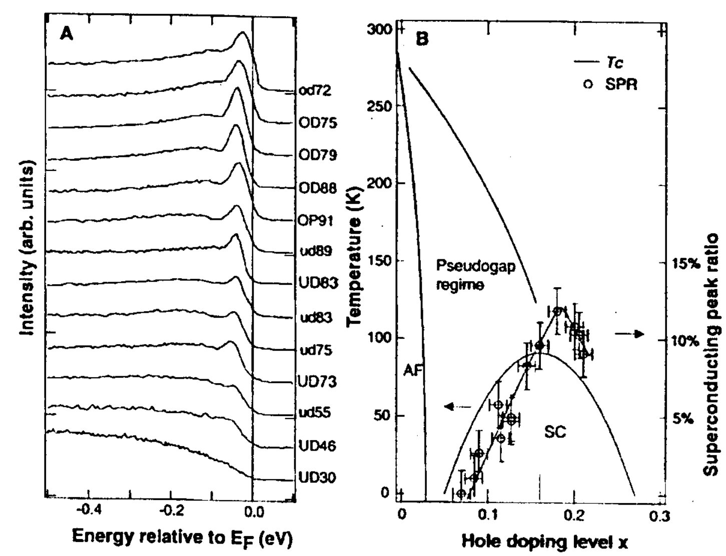
- Increasing ($2\Delta_d/k_BT_c$) ratio with decreasing doping.
  → stronger coupling in underdoped samples.
- Δ^* in $Bi_2Sr_2CaCu_2O_{8+x}$ does not vanish at T_c.
- T^*: the pseudogap temperature.
- On the other hand, the doping dependence of the normalized superconducting peak intensity from ARPES scales with T_c!

Signature of Superfluid Density in the Single Particle Excitation Spectrum of $Bi_2Sr_2CaCu_2O_{8+\delta}$

(D. L. Feng et al., submitted to Science)

A. Doping dependence of the superconducting state spectra of Bi-2212 at (π,0) for $T << T_c$

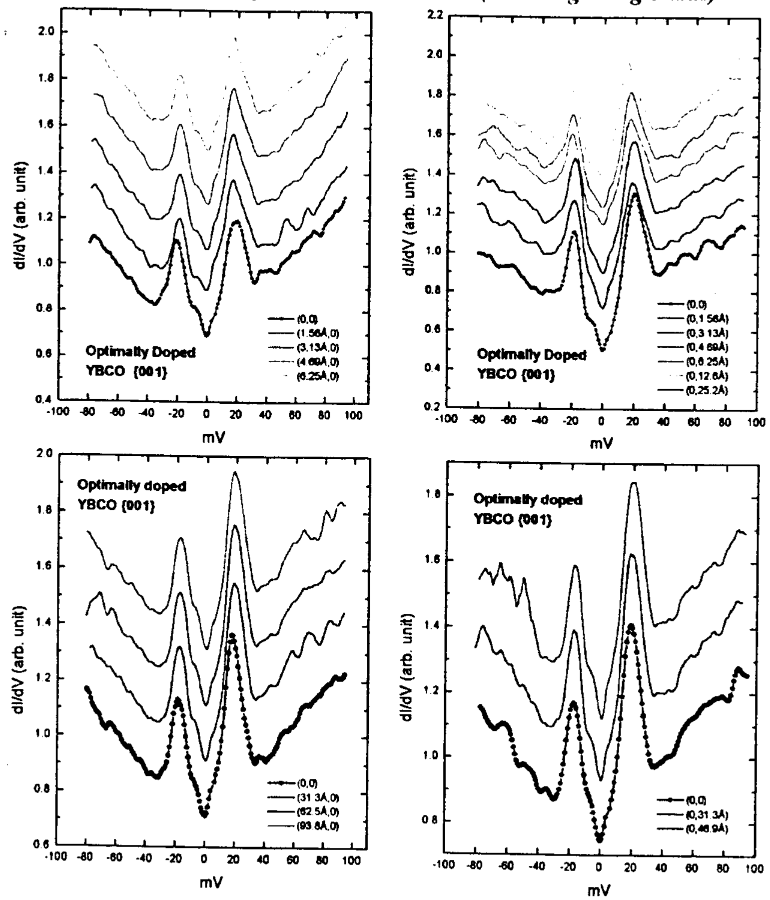
B. Doping dependence of the superconducting peak ratio, normalized relative to the intensity of the entirespectra



* Spatially resolved STS of pure YBCO:

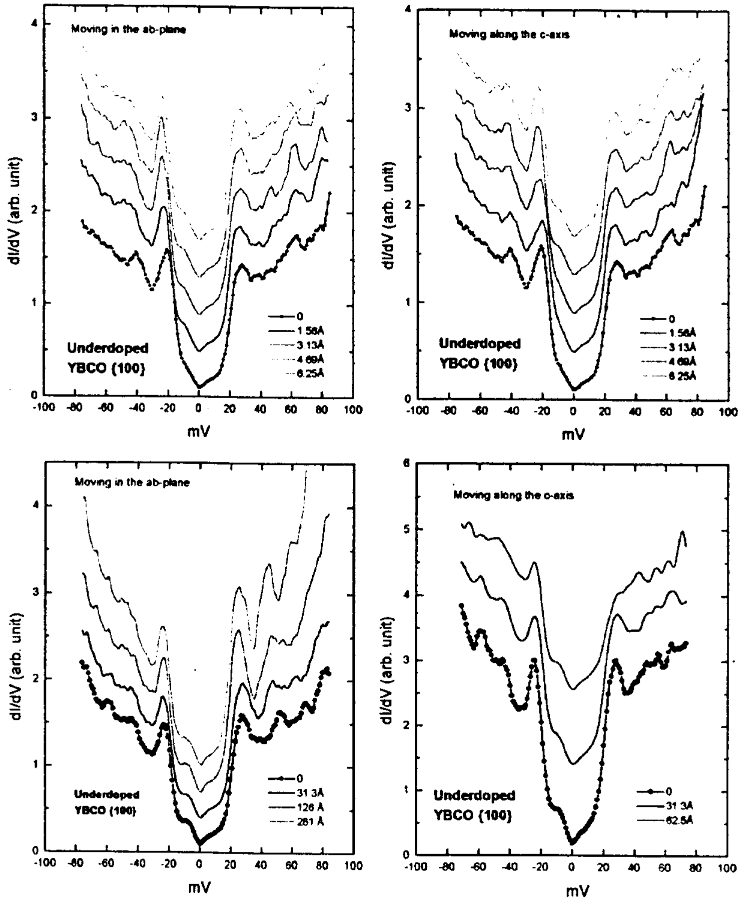
- *c-axis STS of optimally doped YBCO*

(scanning along a-axis) ***(scanning along b-axis)***



- *{100} STS of underdoped YBCO:*

(scanning along b-axis) ***(scanning along c-axis)***



* *Summary of spatially STS of pure YBCO:*

-- *For a narrow k-distribution of quasiparticles, Δ_d is spatially homogeneous over a macroscopic scale (~ 100 nm).*

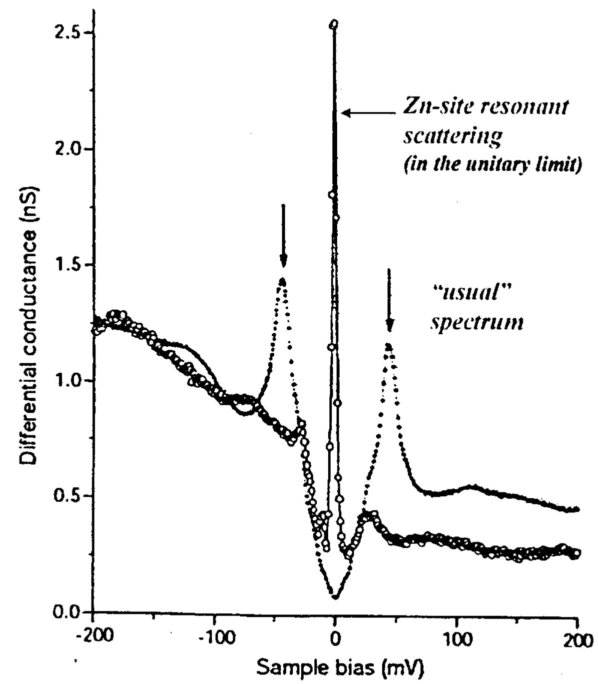
-- *The satellite features exhibit more sensitive c-axis spatial modulation.*

→ *STS of YBCO is insensitive to weak disorder & impurities.*

- *What about strong pair-breakers, such as Zn substitution?*

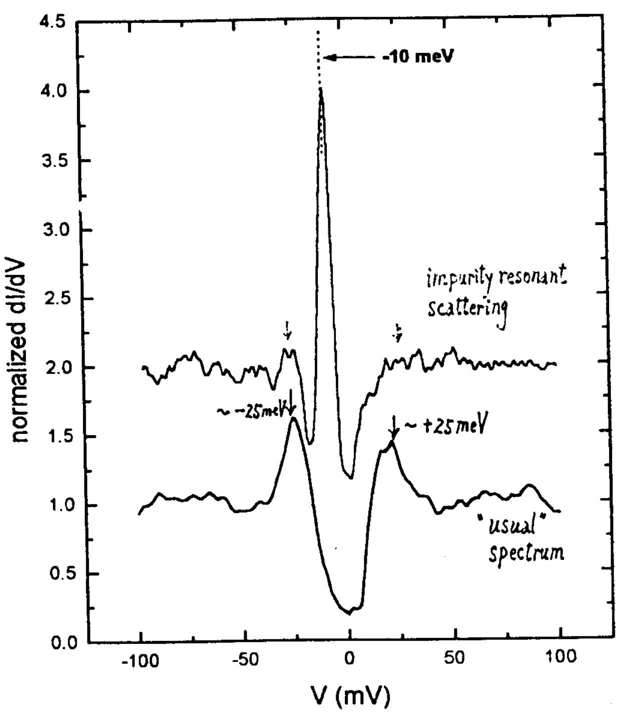
C-axis Tunneling Conductance Spectra on 0.6% Zn-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ [S. H. Pan et al., Nature 403 (2000)]

- *Comparison of the local differential conductance in the "usual" superconducting region (filled circles) and at the Zn impurity site (open circles). Resonant scattering peak Ω = -1.5 meV.*

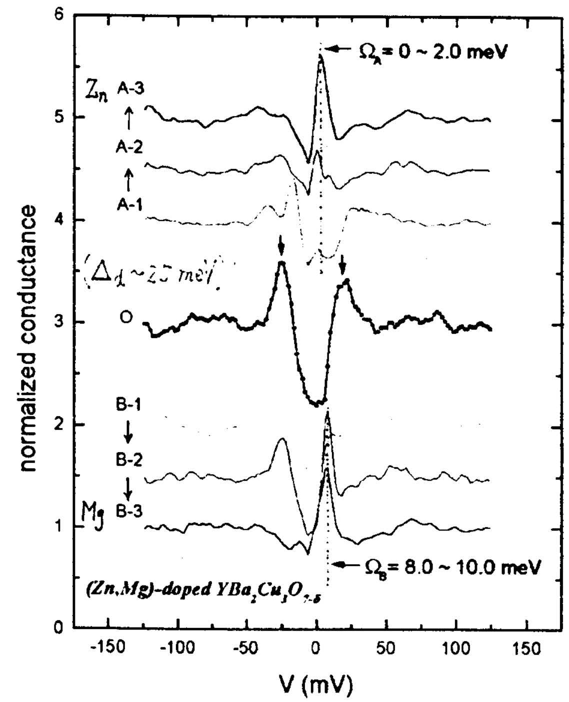


C-axis Tunneling Spectra of (Zn,Mg)-doped $YBa_2Cu_3O_{7-\delta}$
(Zn = 0.26%, Mg = 0.4%) [N.-C. Yeh et al., (2000)]

- ***Comparison of the local density of states in the "usual" superconducting region & that at an impurity site with a resonant scattering energy $\Omega_B \sim -10$ meV.***



Spatial evolution of c-axis tunneling spectra of (Zn,Mg)-doped $YBa_2Cu_3O_{7-\delta}$



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Scanning Tunneling Spectroscopy Studies of Non-Magnetic Impurity Scattering in (Zn,Mg)-doped $YBa_2Cu_3O_{7-\delta}$

- **Zn^{2+} replaces Cu^{2+} in the CuO_2 planes, and is known to incur strong pair-breaking effects in cuprates.**

  (0.26% Zn is equivalent to 0.4% substitution of Cu in CuO_2 planes).

  => Unitary-limit resonant scattering.

- **The Mg substitution site in $YBa_2Cu_3O_{7-\delta}$ is not established;**

  * If Mg^{2+} replaces Cu^{2+} in the CuO_2 planes,

  => weak scattering center with weak pair-breaking effects.

  * If Mg^{2+} replaces Y^{3+},

  => overdoping YBCO, positively charged impurity site.

- **Single resonant peak at an non-magnetic impurity site,**

  <=> essentially pure $d_{x^2-y^2}$ pairing symmetry in YBCO.

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Our STS results are consistent with the following studies:

* **Scanning-SQUID measurements on YBCO tri-crystals:**

-- Predominant $d_{x^2-y^2}$ symmetry (> 95%) from 0.5 K to 90 K.

[Kirtley et al., Science 285 (1999)]

* **Grain-boundary junctions:**

-- No splitting in ZBCP for H up to 12 Tesla and T down to 0.1 K.

[Alff et al., Phys. Rev. B 58 (1998); Phys. Rev. B 55 (1997)]

* **STS on oriented YBCO {110} films:**

-- ZBCP becomes sharper with decreasing T.

-- No splitting in ZBCP for H up to 7 Tesla and T down to 80 mK, implying < 0.1% secondary components.

[Kashiwaya et al., to appear in Physica C, (2000)]

* **C-axis STS on 0.6% Zn-substituted Bi-2212 single crystal:**

-- Single resonant scattering energy $\Omega_0 \sim -1.5$ meV at the Zn site.

[Pan et al., Nature 403, (2000)]

-- In contrast to the predictions for either $(d_{x^2-y^2}+id_{xy})$ or $(d_{x^2-y^2}+is)$ pairing. [Salkola & Schrieffer, Phys. Rev. B 58, (1998)]

* **Point-contact junctions of optimally & underdoped YBCO:**

[Deutscher et al., to appear in Physica C, (2000)]

3. Spin-Polarized Quasiparticle Transport

■ *Motivation* :

* **Injection of spin-polarized quasiparticles into cuprates allows studies of :**

-- *spin transport & spin-charge separation in the cuprates;*

-- *nonequilibrium superconductivity in d-wave superconductors.*

■ *Important Issues* :

* **Microscopic origin for the suppression of superconductivity by spin-polarized quasiparticles?**

-- *Relevance of paramagnetic effect due to excess spins?*

-- *Effects of excess quasiparticles?*

-- *Phase decoherence due to excess spins?*

* **Characteristic length & time scales of spin transport in cuprate superconductors.**

■ *Experimental Techniques* :

-- *Critical current density (J_c) measurements.*

-- *Scanning tunneling spectroscopy (STS).*

A. Magnetic Pair Breaking Effects in Superconductors:

* *Magnetic impurities are known to degrade superconductivity due to time-reversal symmetry breaking.*
(Abrikosov & Gor'kov, 1961; Maki, 1963)

* *What about spin-polarized quasiparticle currents?*

-- *Excess magnetic moments:*

⟶ *paramagnetic effect;*

⟶ *magnetic exchange interaction.*

-- *Nonequilibrium effects:*

⟶ *redistribution of quasiparticles;*

⟶ *modification of effective temperature & chemical potential.*

B. Conventional Nonequilibrium Superconductivity

■ ***Injection of charged quasiparticles with energy E_k***

-- $E_k > \Delta$: quasipaticle lifetime over time τ_{Q*} & length l_{Q*}

-- $E_k < \Delta$: normal & Andreev reflection

(Δ: energy gap of an s-wave superconductor)

↔ *nonequilibrium energy (T^*) : the even (energy) mode*

branch imbalance (Q^*) : the odd (charge) mode

(Charge neutrality provided by the BCS condensate.)

$$(\delta T^*/T) = (T^* - T)/T \sim \Sigma_k (\delta f_k/E_k)/\mathcal{N}_0$$

$$Q^* = \Sigma_k f_k q_k = \Sigma_k f_k (\xi_k/E_k)$$

$\delta f_k = f_k - f_k^0(E_k/k_BT)$, $E_k = (\Delta_k^2+\xi_k^2)^{1/2}$: qp energy,

$f_k^0(E_k/k_BT) = 1/[1+\exp(E_k/k_BT)]$,

: equilibrium quasiparticle distribution function,

ξ_k : normal-state energy relative to E_F.

-- Relaxation of non-equilibrium energy or charge:

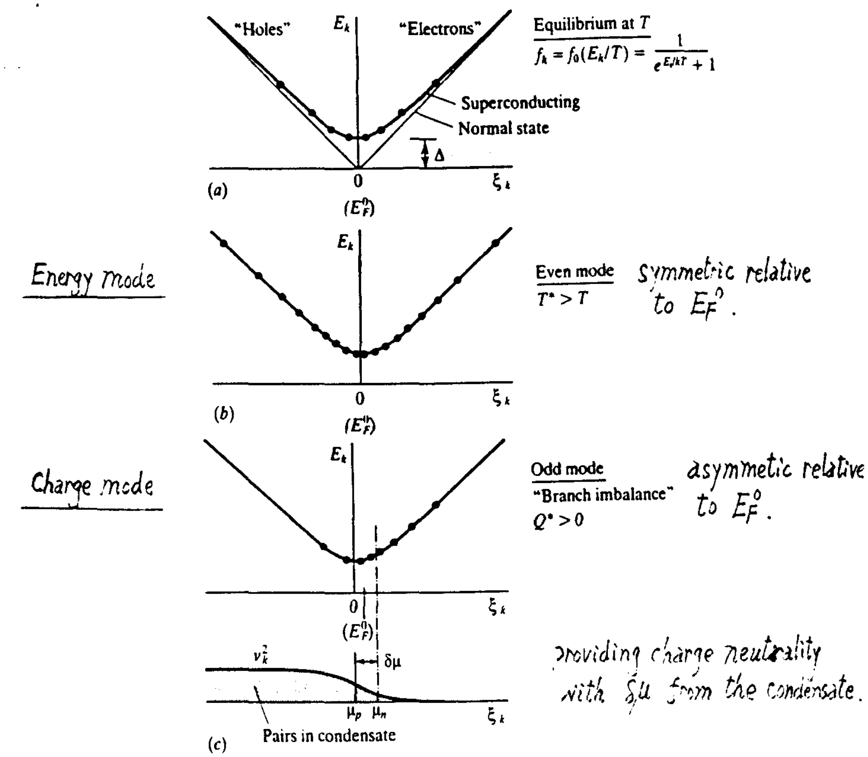
via inelastic phonon scattering & emission near T_c;

or elastic impurity scattering if $T \sim 0$ & anisotropic gap.

$\tau_{T*} \sim 3.7\tau_E k_B T_c/\Delta(T)$. ($\tau_E \sim$ e-ph inelastic scattering time)

$\tau_{Q*} \sim (4/\pi)\tau_E k_B T_c/\Delta(T)$, ↔ τ_{T*} & τ_{Q*} both diverges at T_c.

- Quasiparticle energy : $E_k = \sqrt{\Delta_k^2+\xi_k^2}$. (ξ_k : single-particle energy in the normal state.)
- Probability of quasiparticle occupied state : f_k , ($= f_0(E_k/T)$ if thermal equilibrium)
- BCS gap equation : $\Delta_k = \Sigma_{k'} V_{kk'}\Delta_{k'}(1-2f_k)/(2E_k)$.



■ *Injection of spin-polarized quasiparticles*

-- $E_k > \Delta$: ***quasiparticle lifetime over time*** τ_s ***& length*** l_s

-- $E_k < \Delta$: ***no effect due to complete <u>normal</u> reflection***
(Andreev reflection is forbidden.)

-- *Relaxation of spin polarized quasiparticles:*
via <u>spin-orbit scattering</u> or <u>magnetic exchange interaction</u>;

→ $(\tau_s >> \tau_{Q^*})$ & $(l_s >> l_{Q^*})$

→ *More significant pair-breaking effect of spin-polarized quasiparticles.*

* <u>Question</u>: *How is* τ_s *determined microscopically?*
<u>Pair-breaking</u> or <u>phase decoherence</u> due to spin injection?

↔ *Fermions (spin-polarized quasiparticles) interacting with Bosons (Cooper pairs).*

■ *Microwave-induced quasiparticles:*

-- *Redistribution of quasiparticle (qp) DOS provided that the inelastic electron-phonon scattering time is longer than the microwave cycle.*

↔ *<u>Enhancement</u> or <u>degradation</u> of superconductivity.*

-- *Departure of qp distribution (f_k) from thermal equilibrium:*

$$\delta f_k = f_k - f_k^0(E_k/k_BT), \quad E_k = (\Delta_k^2+\xi_k^2)^{1/2},$$
$$f_k^0(E_k/k_BT) = 1/[1+\exp(E_k/k_BT)],$$

f_k^0: ***equilibrium qp distribution function***

E_k: ***qp energy*** ξ_k: ***normal-state energy relative to*** E_F.

-- *Effective temperature shift (δT^*) due to* δf_k :

$$(\delta T^*/T) = (T^*-T)/T \sim \Sigma_k (\delta f_k/E_k)/\mathcal{N}_0$$

$\mathcal{N}_0$: ***normal-state density of states at the Fermi level***

↔ *The sign of* δT^* *depends on that of* δf_k .

Representative References:

1. *"Non-equilibrium Superconductivity, Phonons, and Kapitza Boundaries"*, NATO ASI Series, Plenum, New York (1981), K. E. Grey (ed.), and references therein.

2. J. Clarke, *Phys. Rev. Lett.* **28**, 1363 (1972).

3. M. Tinkham and J. Clarke, *Phys. Rev. Lett.* **28**, 1366 (1972).

4. M. Tinkham, *Phys. Rev. B* **6**, 1747 (1972).

5. A. Schmid and G. Schon, *J. Low Temp. Phys.* **20**, 207 (1975).

6. G. M. Eliashberg, *JETP Lett.* **11**, 114 (1970); *Sov. Phys. JETP* **34**, 668 (1972).

7. B. I. Ivlev et al., *JETP Lett.* **13**, 333 (1971); B. I. Ivlev et al., *J. Low Temp. Phys.* **10**, 449 (1973).

8. T. M. Klapwijk and J. E. Mooij, *Physica B* **81**, 132 (1976).

9. T. M. Klapwijk, J. N. van den Berg, and J. E. Mooij, *J. Low Temp. Phys.* **26**, 385 (1977).

10. A. Schmid, *Phys. Kond. Mat.* **8**, 129 (1968).

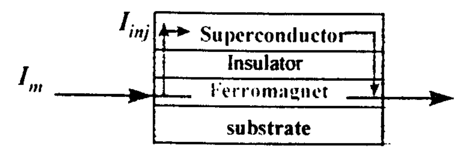
C. Suppression of High-Temperature Superconductivity by Spin Injection

■ *Technical Approach:*

-- *Fabrication of perovskite ferromagnet-insulator-superconductor (F-I-S) heterostructures:*

-- *Generate spin-polarized qp's by passing electrical currents through ferromagnetic manganites, which are half-metals with nearly 100% spin polarization.*

(F: CMR manganites; S: superconducting cuprates.)



* *Nearly perfect lattice match of the heterostructures:*

⟶ *Epitaxial growth of the F-I-S heterostructures, preventing interface magnetic scattering.*

* *Predominantly d-wave pairing symmetry in HTSC*

⟶ *Directional spin-injection & low-energy qp excitations.*

Current Research Status of Spin-Injection in High-Temperature Superconductors

- ***Experimental***

* ***V. A. Vas'ko et al.**, PRL 78, (1997); APL 73, (1998).*

-- *Report suppression of critical currents (J_c) & suppression of Andreev reflection in cuprate superconductors via spin injection.*

* ***Z. W. Dong et al.**, APL 71, (1997).*

-- *Report suppression of J_c in perovskite F-I-S.*

* ***N.-C. Yeh et al.**, PRB 60, (1999) & Physica B (2000);*
***J. Y. T. Wei et al.**, JAP 85 (1999).*

-- *Report initial slight increase & then sharp drop in J_c upon spin-injection, using pulsed current technique to minimize Joule heating.*

-- *Provide microscopic evidence of dynamic pair breaking based on STS.*

- ***Theoretical***

* *Spin-polarized quasiparticle transport & spectroscopy at various interfaces of ferromagnet & d-wave superconductor:*

-- *Zhu, Friedman and Ting, PRB 59, (1999).*

-- *Kashiwaya et al., PRB 60, (1999).*

-- *Zutic and Valls, PRB 60, (1999).*

* *Probing spin-charge separation, characteristic times, lengths:*

-- *Si, PRL 78, (1997); PRL 81 (1998).*

-- *Merrill and Si, PRL 83, (1999).*

Experimental

- ***Perovskite F-I-S heterostructures:***

-- *Ferromagnet (F): $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) & $La_{0.7}Sr_{0.3}MnO_3$ (LSMO)*

-- *Insulating barrier (I): YSZ or $SrTiO_3$ (STO)*

-- *Superconductor (S): $YBa_2Cu_3O_7$ (YBCO)*

-- *Substrate: $LaAlO_3$ (LAO)*

- ***Perovskite N-I-S heterostructures (control samples):***

-- *Non-magnetic metal: $LaNiO_3$ (LNO)*

-- *Insulating barrier: YSZ or $SrTiO_3$ (STO)*

-- *Superconductor: $YBa_2Cu_3O_7$ (YBCO)*

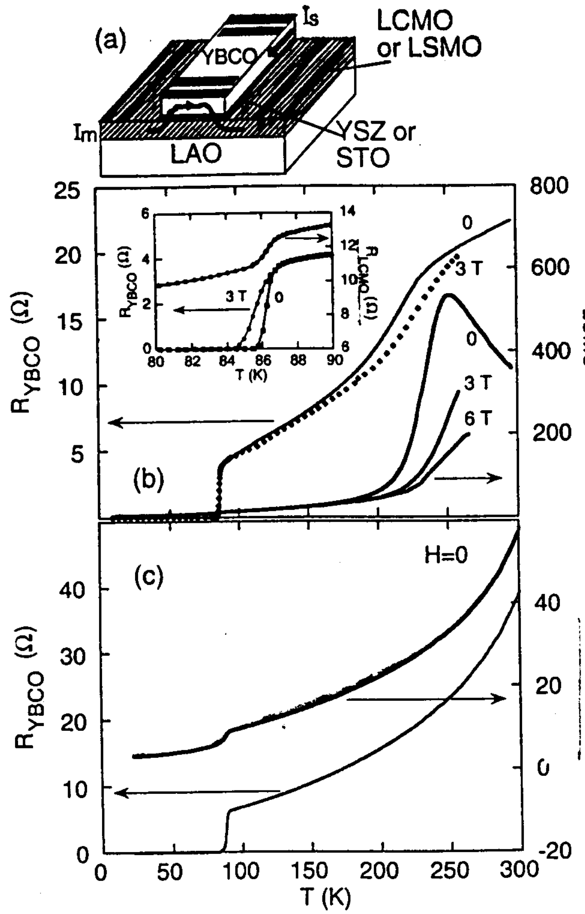
-- *Substrate: $LaAlO_3$ (LAO)*

*(*Pulsed laser deposition for epitaxial-film fabrication.)*

- ***Measurement Techniques:***

-- *Electrical transport: pulsed-current measurements of J_c*

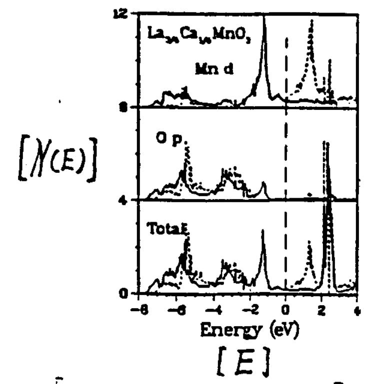
-- *Scanning tunneling spectroscopy: quasiparticle DOS.*



- **YBa$_2$Cu$_3$O$_7$:** $\rho_n(T_c) = 60\ \mu\Omega$ cm; $T_c = 89$ K.
- **La$_{0.7}$Ca$_{0.3}$MnO$_3$:** $\rho_n(300\ K) = 15\ m\Omega$ cm; $T_{Curie} = 260$ K.
- **La$_{0.7}$Sr$_{0.3}$MnO$_3$:** $\rho_n(300\ K) = 2\ m\Omega$ cm; $T_{Curie} = 320$ K.
- **Interface Resistance:** 0.1 Ω.

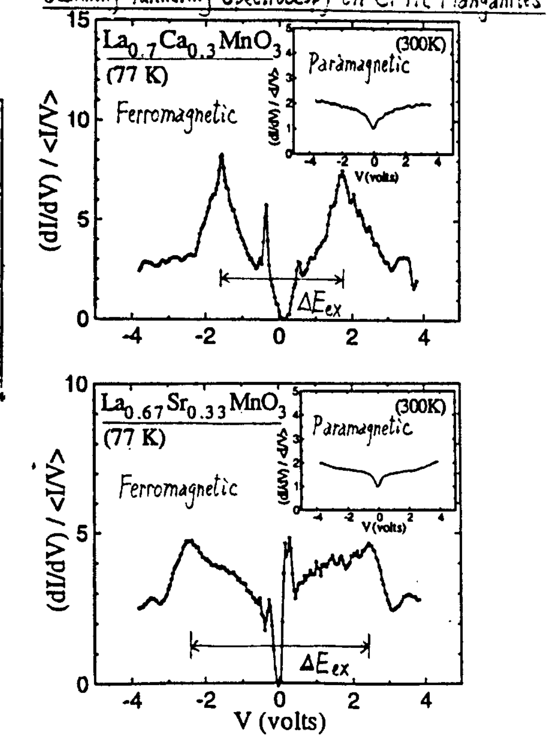
- **Direct evidence of half-metallic ferromagnetism in CMR manganites:** [Wei, Yeh and Vasquez, Phys. Rev. Lett. 79, 5150 (1997).] [J. Appl. Phys. 85 (1999)]

Band Structure Calculations



[Pickett and Singh, Phys. Rev. B 53, 1146 (1996).]

Scanning Tunneling Spectroscopy on CMR Manganites



Material	T_{Curie} (K)	ΔE_{ex}
La$_{0.7}$Ca$_{0.3}$MnO$_3$	260	3.3 ± 0.2
La$_{0.7}$Sr$_{0.3}$MnO$_3$	320	4.0 ± 0.2
La$_{2/3}$Sr$_{1/3}$MnO$_3$	360	5.0 ± 0.2

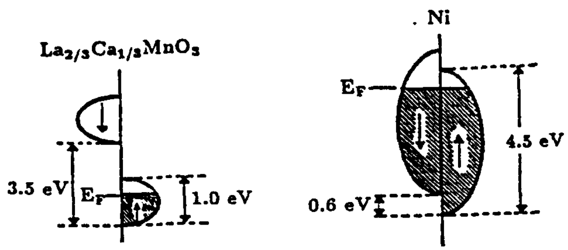
⇒ Knowledge of material properties and techniques to produce quality ferromagnetic films.

Tunneling Evidence of Half-Metallicity in Manganites

Double-exchange interaction ⊕ lattice distortion

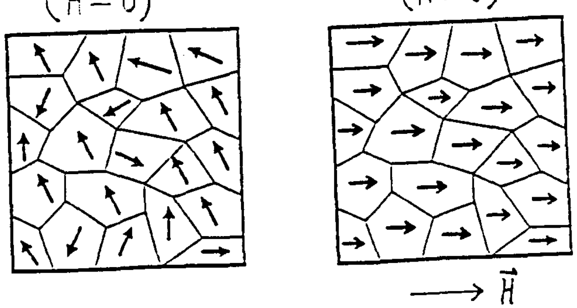
⟹ Half-metallicity & complete spin polarization;

⟹ Colossal negative magnetoresistance. (CMR).

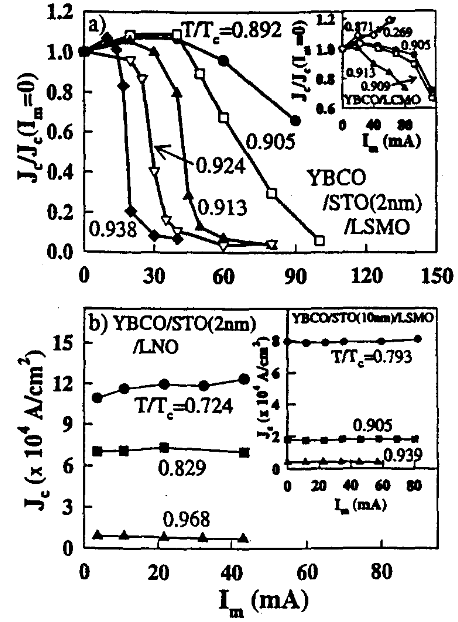


(100% spin polarization) (11% spin polarization)

(H = 0) (H > 0)



Effects of simple and spin-polarized quasiparticle injection current (I_m) on the J_c in N-I-S and F-I-S



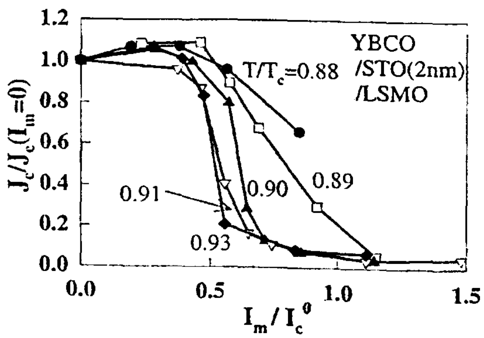
* *Strong dependence of J_c on I_m in F-I-S with thin insulating barrier.*

* *No suppression of J_c with increasing I_m in N-I-S and in F-I-S with thick barrier.*

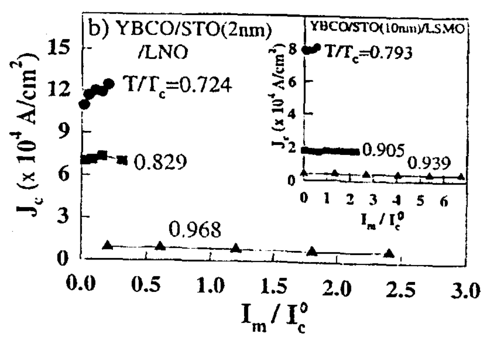
Comparison of Normalized Spin-Injection Effect on F-I-S & N-I-S Heterostructures

- *Normalized critical current $J_c/J_c^0(T)$ vs. normalized injection current I_m/I_c^0 (T):*

F-I-S



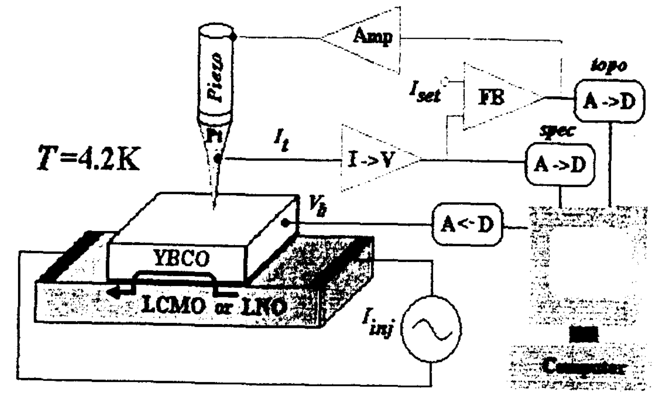
N-I-S



→ *(lifetime of spin-polarized qp's)* *(lifetime of simple qp's)*

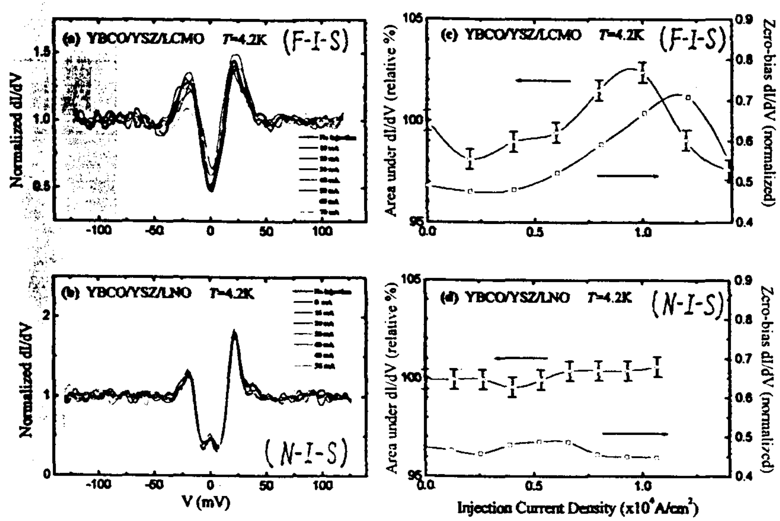
Microscopic Evidence of Pair-Breaking induced by Spin-Polarized Quasiparticles

Experimental Setup :



* *Differential conductance (dI/dV) ~ quasiparticle density of states (dN/dE).*
* *Bias voltage (V) ~ quasiparticle energy (E).*

Scanning Tunneling Spectroscopy of F-I-S and N-I-S Systems

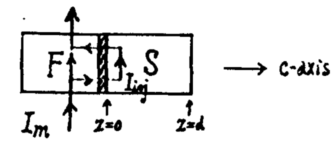


✱ Three major effects associated with spin-polarized currents:

- ⟨1⟩ Increasing quasiparticle density of states;
- ⟨2⟩ Broadening coherence peaks;
- ⟨3⟩ Shifts in the chemical potential.

Physical Concepts

- ***System of Investigation*:**



* *Steady-state excess spin moments **m(z)** in superconductor satisfies the diffusion equation & boundary conditions:*

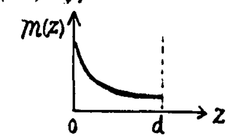
$D_s \partial^2 m/\partial z^2 = m/T_1$ — T_1: longitudinal spin relaxation time ($T_1^{-1} = \lambda_{so}^2 \tau_{tr,spin}$, $\lambda_{so} \sim 0.1$: spin-orbit coupling)

$D_s(\partial m/\partial z)_{z=0} = I_{spin}$ — D_s: diffusion coefficient

$D_s(\partial m/\partial z)_{z=d} = 0$ — $I_{spin} = (\mu_B/e) I_{inj}$ (d: thickness of YBCO) (I_{inj}: injected spin-polarized current) $(\delta_s)^2 = D_s T_1$ (δ_s: spin-diffusion length)

=> solution: $m(z) = \{ T_1 I_{inj}(\mu_B/e)/[\delta_s \sinh(d/\delta_s)] \} \cosh[(d-z)/\delta_s]$

average spin moments: $\overline{m} = (T_1/d)\, I_{inj}(\mu_B/e)$



- ***Experimental implications*:**

If pair-breaking efficiency (η) is proportional to $\overline{m}$,

=> pairing breaking effect may be enhanced by

-- *increasing spin-polarized injection current I_{inj};*

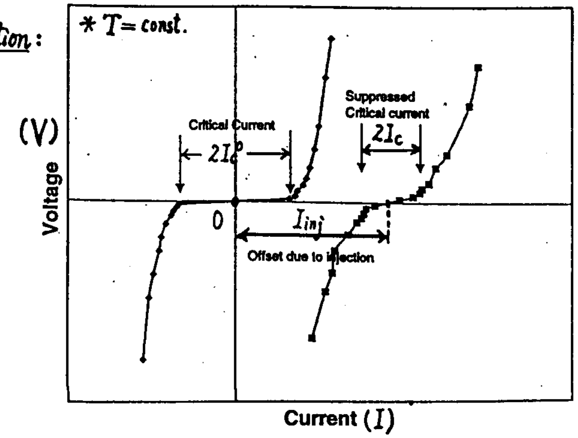
-- *decreasing superconductor thickness d.*

- ***Determining the efficiency (η) of pair-breaking:***

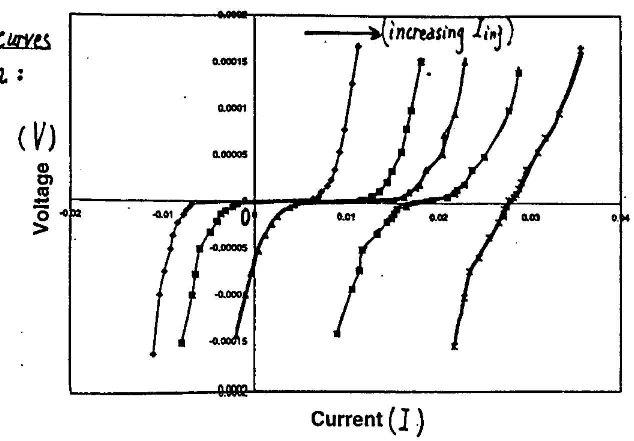
  $\eta = \Delta I_c / I_{inj}$ *(I_c: critical current, I_{inj}: spin-polarized current in S.)*

($\Delta I_c \equiv I_c^0 - I_c$)

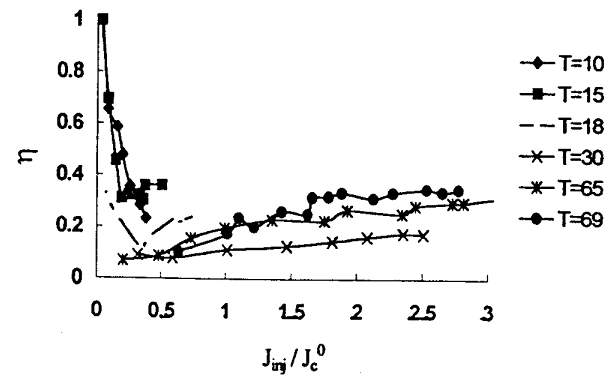
Effect of injection:



Shift of I-V curves under injection:



Temperature-dependent efficiency (η) vs. normalized injection current density (J_{inj}/J_c^0)



$\eta \sim \langle m \rangle \Sigma_k (1 - 2f_k)$;

$\langle m \rangle \sim T_1 I_{inj}/d$;

→ *relevance of quasiparticle re-distribution (nonequilibrium effect)*

Improvements to Theory

- ***Diffusion equation insufficient*** - *Must consider non-equilibrium effects*

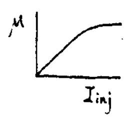
— *Equilibrium fermi function* f_k^0: $\dfrac{1}{1+exp\left[\dfrac{E_k}{k_bT}\right]}$

— *Define new pair-breaking efficiency* η: $\eta \propto \bar{m}\sum_k (1-2f_k)$
(Empirically, $\eta = \Delta I_c^0 / I_{inj}$.)

— *Under quasiparticle injection, there is a net change in chemical potential* μ:
(non-equilibrium quasiparticle distribution function $f_k(I_{inj}, T)$.)

$$f_k \rightarrow \frac{1}{1+exp\left[\dfrac{E_k-\mu}{k_bT}\right]}$$

- *Intially* μ *rises rapidly with increasing number of injected quasiparticles, and thus* η *drops rapidly at low T.* $\mu(I_{inj})$:

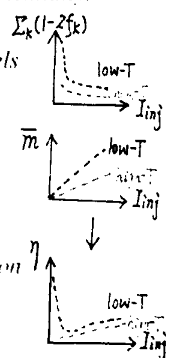


-*At small T* $f_k \propto exp\left[-\dfrac{E_k-\mu}{k_bT}\right] \Rightarrow (1-2f_k)$ *drops exponentially.*

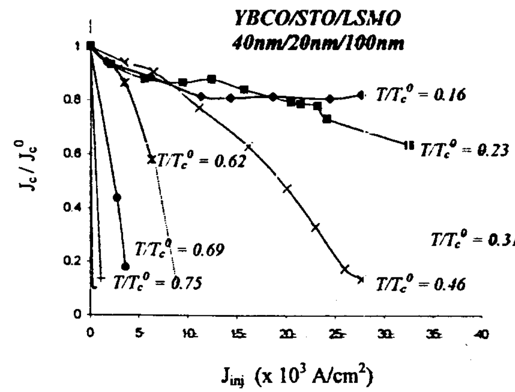
But eventually at high injections the chemical potential μ *levels off and the efficiency* η *is then determined by* $\bar{m}$. *(Remember that m is proportional to the* I_{inj}.*)*

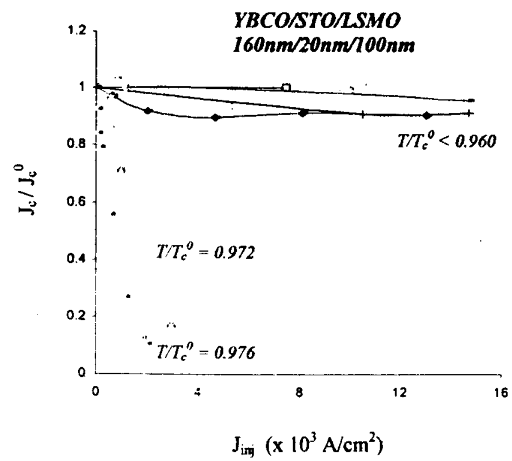
-*At high T, the effect of increasing* μ *is diminshed and* η *is dominated by* $\bar{m}$.

The cross-over temperature where η *becomes mostly depend on* μ *gives an estimate of* μ: $\mu \sim 35k_B$



Spin-injection dependence on the superconductor thickness





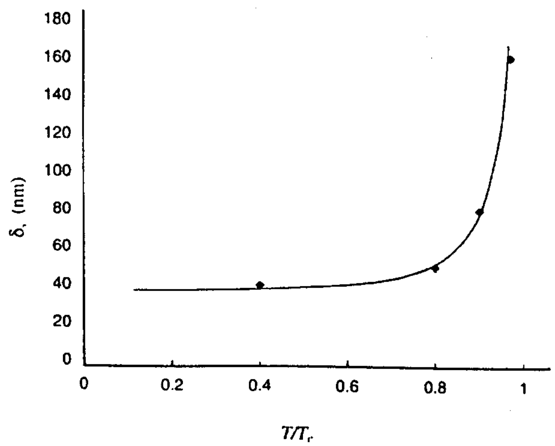
E. Implications of the Microscopic Mechanism for the Suppression of Superconductivity by Spin Injection

- ***Empirical estimate for the effective magnetic field:***

  $B_{eff} = \mu_0 m/\Omega <\sim 10^{-2}$ Tesla $<< H_{c1}$ (Ω: superconductor volume)

  ⟷ *irrelevance of paramagnetic effect.*

- ***Empirical estimate for the spin diffusion length $\delta_s(T)$:***



⟶ *Strong divergence of δ_s near T_c implies the relevance of spin-polarized quasiparticles to the loss of superconducting phase coherence.*

Summary

- ***Directional & spatial resolved tunneling spectroscopy on cuprate superconductors ⟶ predominant $d_{x^2-y^2}$ pairing in:***
  - -- optimally doped & underdoped $YBa_2Cu_3O_{7-\delta}$ (> 95%)
  - -- underdoped $La_{2-x}Sr_xCuO_{4-\delta}$ (> 90 %)
  - -- Zn-doped YBCO (> 95%).

- ***Comparison of YBCO & Bi-2212 tunneling spectroscopy:***

  * *STS on YBCO:* (maximum superconducting gap Δ_d)
  - -- Δ_d scales with T_c;
  - -- satellite features scale with Δ_d;
  - -- $(2\Delta_d/k_BT_c)$ increases with decreasing x;

  * *STS, SIN & SIS on Bi-2212:* (c-axis gap Δ^*)
  - -- Δ^* scales with the pseudogap T^*;
  - -- $(2\Delta^*/k_BT^*) \sim 6.6$ for all x;

  * *ARPES on Bi-2212:* $(\pi,0)$ superconducting peak
  - -- the relative intensity scales with T_c

  ⟷ *Relevance of the doping level & spin fluctuations to the pairing state and symmetry of high-temperature superconductivity.*

◆ ***Spin-injection studies in $YBa_2Cu_3O_{7-\delta}$:***

*** Evidence of nonequilibrium quasiparticle redistribution**

-- increasing suppression of superconductivity with

1) increasing spin injection (I_{inj});

2) decreasing superconductor thickness (d).

*** The c-axis spin diffusion length (δ_s):**

1) increases rapidly near T_c;

2) $\delta_s \sim 50$ nm for $T << T_c$ & 100 nm $< \delta_s < 200$ nm for $T \sim 0.9\, T_c$

*** Negligible paramagnetic effect due to injected spins.**

⟷ *"dephasing" (rather than pair breaking) effect of spin-polarized quasiparticles on Cooper pairs.*