Laura H. Greene
Lecture 2

Tunneling in High-Temperature Superconductors: Spectroscopy of Broken Symmetries

Laura H. Greene
Department of Physics
University of Illinois at Urbana-Champaign

Experiment:
M. Aprili, M. Covington, E. Badica, D. E. Pugel, H. Aubin, P. Hentges, Y. -M. Xia and M. B. Salamon
Dept. of Physics, University of Illinois at Urbana-Champaign

Sha Jain and D. G. Hinks,
Materials Science Division, Argonne Nat'l Lab

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Northwestern University

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Lecture II: NSF Boulder Summer School for Condensed Mattery Physics, July, 2000

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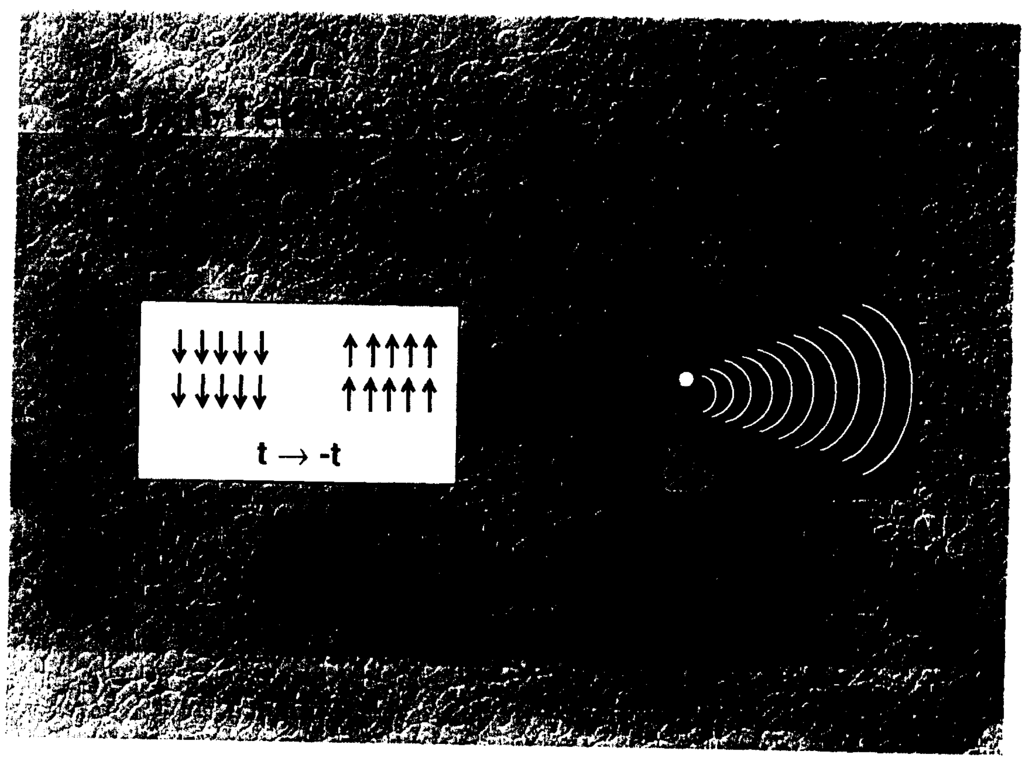

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Symmetry / Broken Symmetry

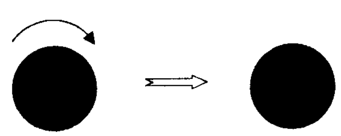
Symmetry State

Homogeneous wrt coordinates (distance, angle, phase, time, ..)

"The symmetry of the state is the **same** as that of the Hamiltonian"

Changing the coordinate does not produce a measurable change

Circle (Rotation Symmetry)



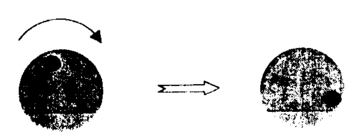
Broken Symmetry State:

Typically inhomogeneous wrt coordinates

"The symmetry of the state in lower than that of the Hamiltonian"

Changing a coordinate produces a measurable change

Dot breaks symmetry:



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Outline (Lecture II)

Symmetry, broken symmetry and d-wave SC

Experimental foundation

1. Materials Growth
2. Junction Fabrication and Diagnosticcs
3. Origin of the Andreev Bound State (ABS)
4. Andreev Bound State Diagnostcs

Origin of the Surface-Induced Andreev Bound State (ABS)

ABS Tunneling Spectroscopy

1. Crystallographic Orientation
2. Damage and Doping
3. Applied Magnetic field
   Magnitude, Hysteresis and Orientation of Field

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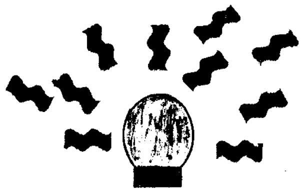
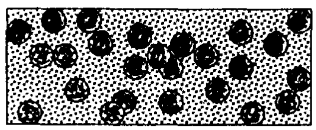
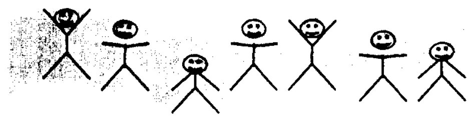
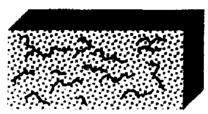
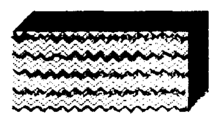
Phase Coherence

Incoherent	*Coherent*
 Lightbulb	 Laser
 Fans at football game	 Wave during half-time
 Electron waves in a metal	 Cooper pairs in a superconductor

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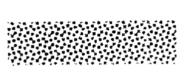
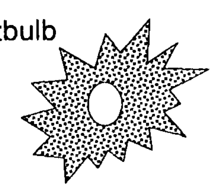
Spontaneous vs. Driven Broken Symmetry

I. Spontaneous: Phase Transition & Change in Macroscopic Properties
Charactarized by "Rigidity" of coordinate

Symmetry:	**Symmetric State**	**Broken Symmetry**	
Translational:	Liquid (water) or vapor	Solid (ice) 	
Time Reversal:	Paramagnet ($T>T_c$) ↑↓↑↑↓↑↓↓	Ferromagnet ($T<T_c$) ↑↑↑↑↑↑↑↑	
Gauge:	Normal Metal ($T>T_c$) 	Superconductor ($T<T_c$) 	

II <u>Driven</u> Gauge: Lightbulb  Laser 

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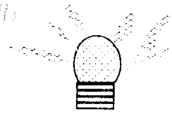
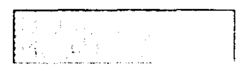
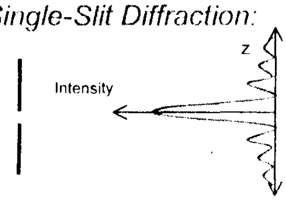
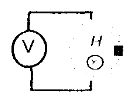
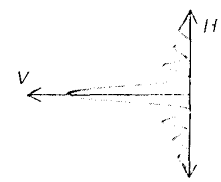
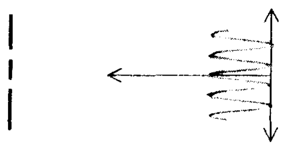
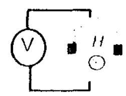
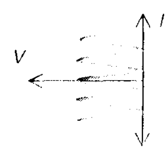
Some Ramifications of Broken Gauge Symmetry

	Photons (driven)	Electrons (spontaneous)
Gauge Symmetric		
Broken Gauge Symmetry	Laser 	Superconductor 
Results of Broken Gauge	Single-Slit Diffraction: 	rf Squid:  
	Double Slit Diffraction 	dc Squid:  

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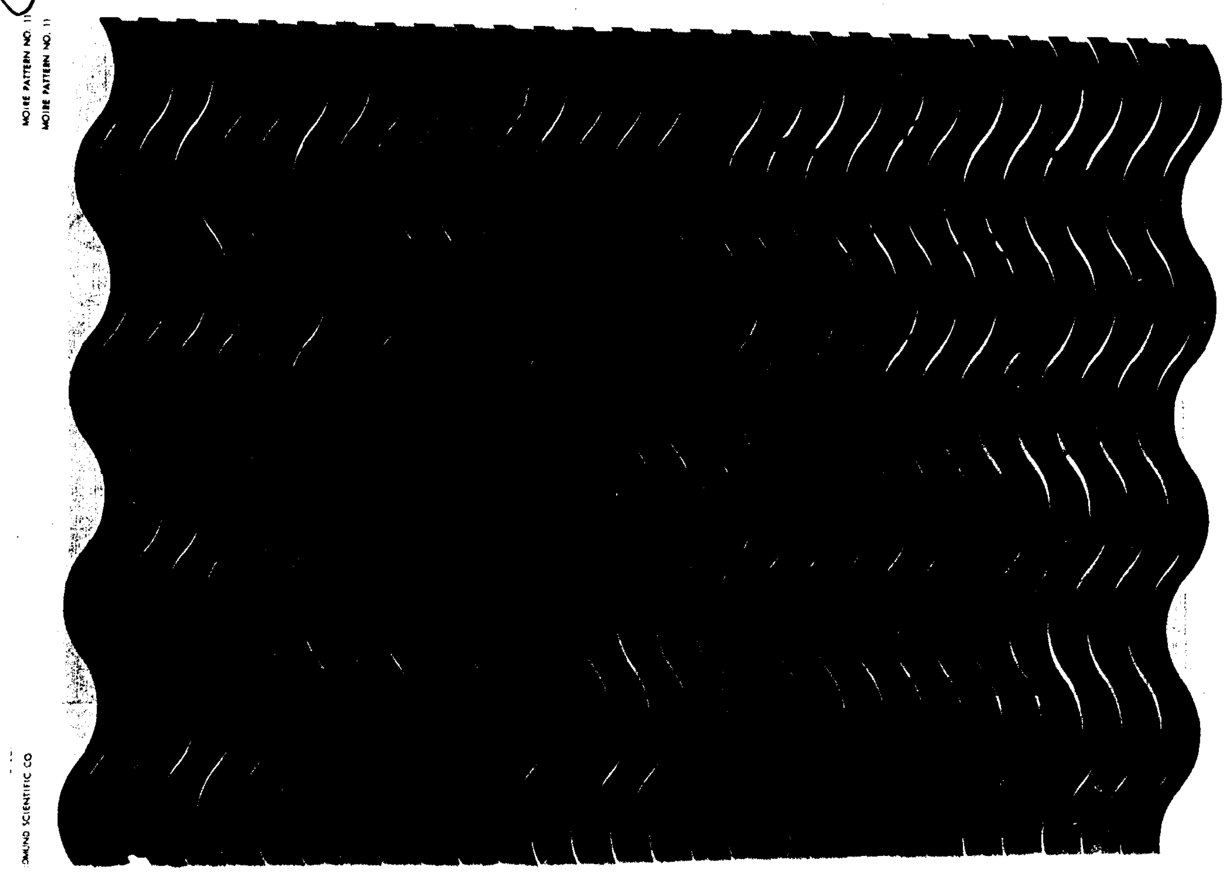

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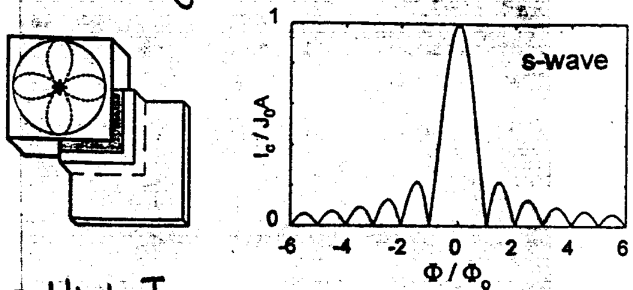
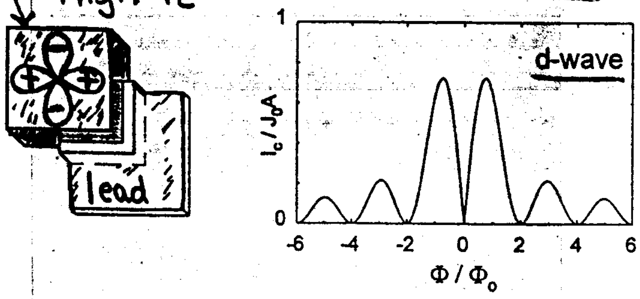
Josephson junction (Wollman, et al)

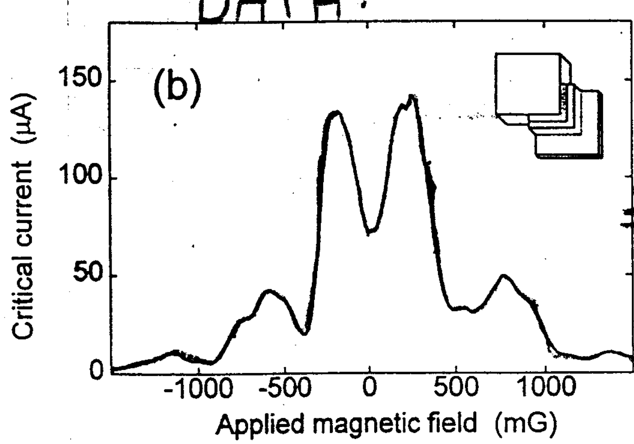


High Tc



$\pi/2$ Phase shift

DATA:



d-wave

1997 Buckley Prize: Van Harlingen, Ginsberg, Kirtley & Tsui

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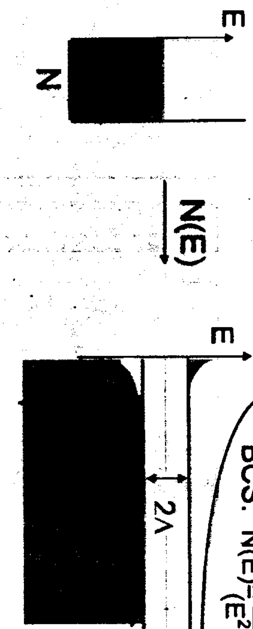
Superconductor: Energy Gap



BCS: $N(E) = \frac{N(0)\,E}{(E^2 - \Delta^2)^{1/2}}$

E_F

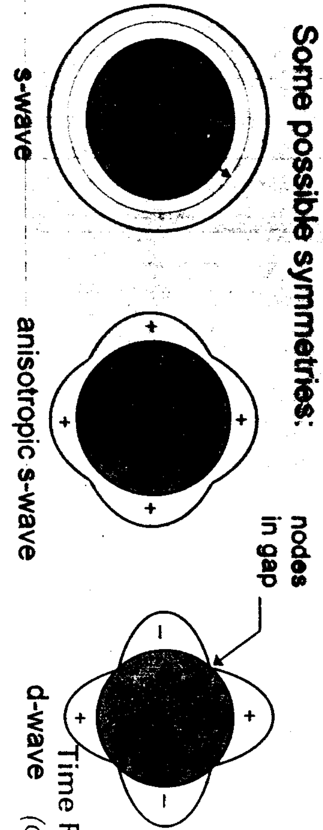
SPONTANEOUSLY BROKEN SYMMETRIES:

Gauge *(superconductor)*

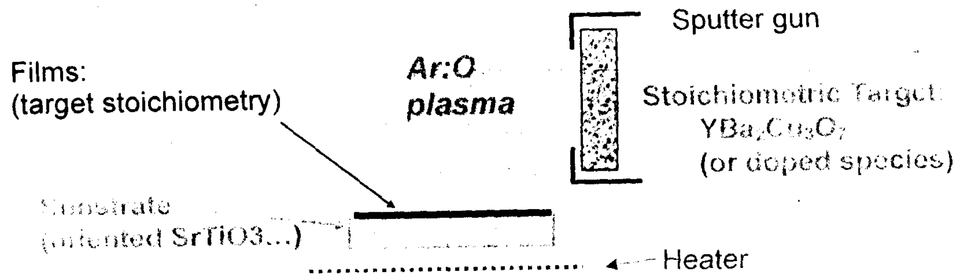
Reflection *(d-wave)*

Time Reversal *(d-wave + interface ...later...)*

Some possible symmetries:



Film Growth: Off-Axis Planar Magnetron Sputter Deposition:



Reproducible films of (001), (100) and (103) and (110)-oriented

$YBa_2Cu_3O_7$, $(Y_xPr_{1-x})Ba_2Cu_3O_7$, $YBa_2(Cu_xNi_{1-x})_3O_7$, $YBa_2(Cu_xZn_{1-x})_3O_7$

Materials Analysis includes:

- Electronic transport (resistivity vs. temperature, tunneling)
- Magnetization (susceptibility vs. temperature)
- Structural analysis (XRD, RBS, SEM, AFM, etc.,...)
- * Electron Paramagnetic Resonance (EPR) *

BSCCO single crystals: Jain & Hinks, ANL
Traveling solvent float zone furnace

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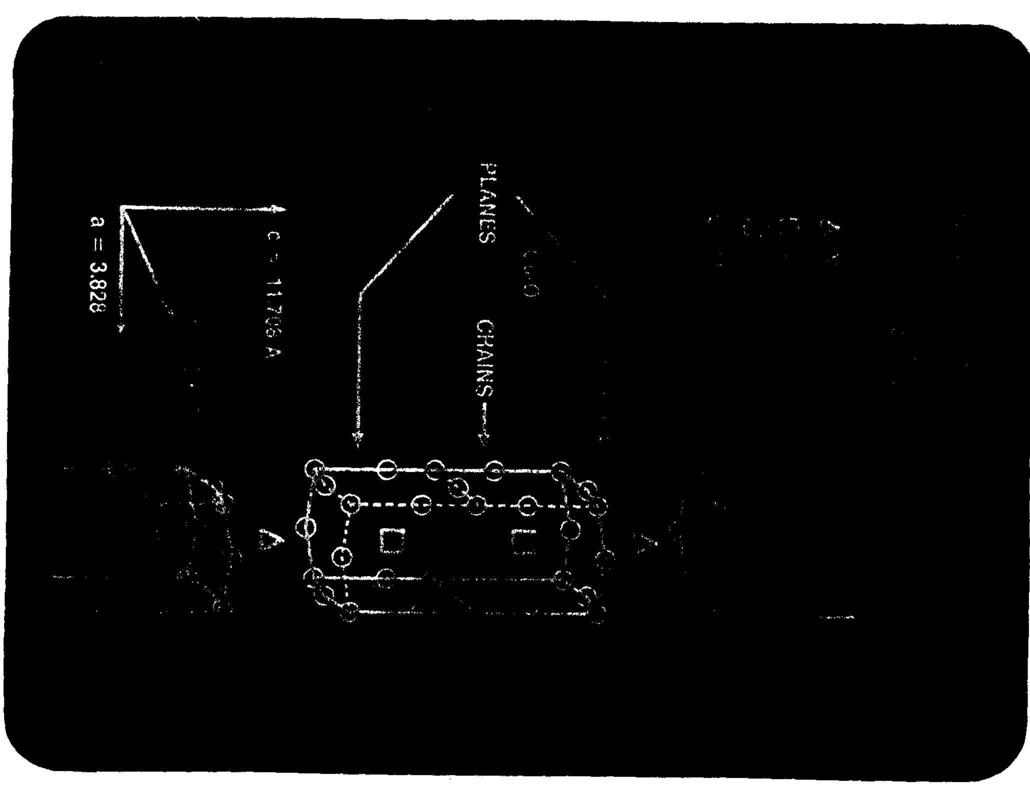
c/4 13

(6¾" x 9" APERTURE)

Bell Communications Research

SC0405

TITLE HIGHLY ANISOTROPIC 123
SEQUENCE NO. COHERENCE LENGTH



RE's
2Cu sites

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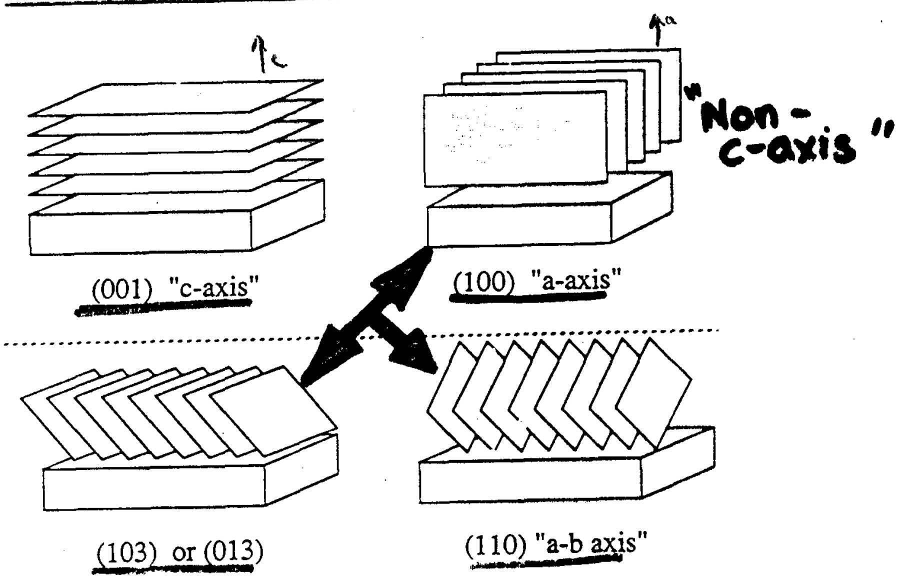
c/3

Possible Orientation of CuO2 Planes



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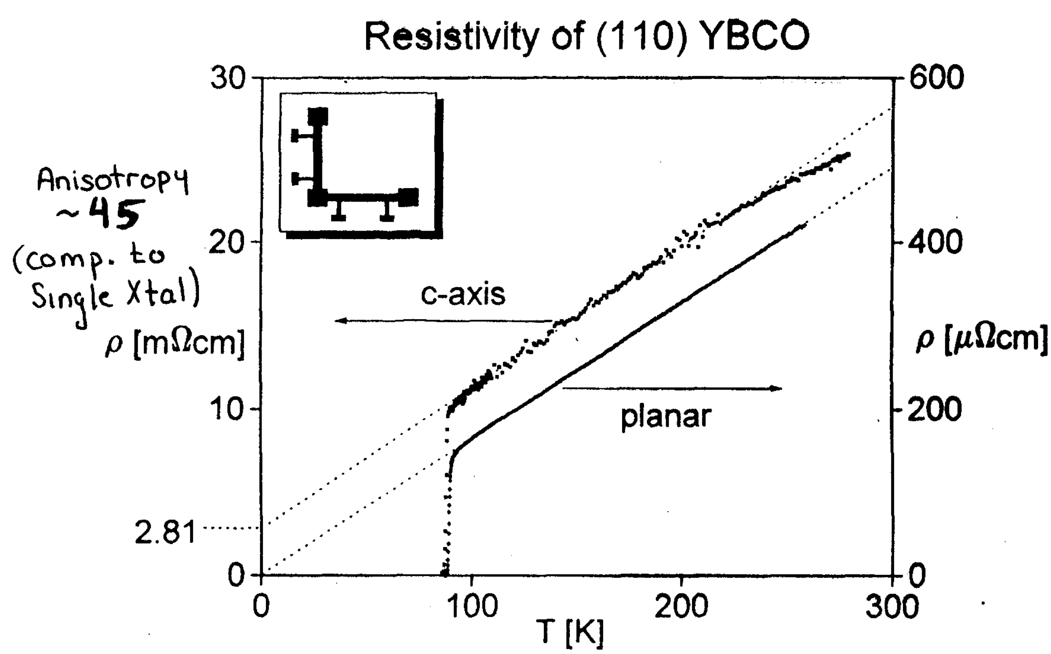
Film Quality -- snapshot:



M. Covington, R. Schurerer, K. Bloom, LHG, Appl. Phys. Lett. **68**, 1717 (1996).

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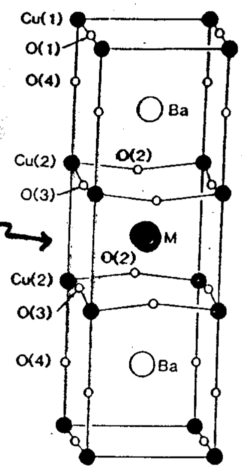
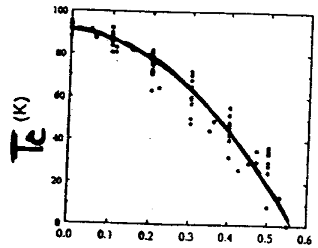
Pr-doped YBCO:

Pr →





x in

$(Y_{1-x}Pr_x)Ba_2Cu_3O_8$

eg: Neumeier & Maple Physica C 191 158 (92)

Pr substitutes for Y *

causes a "buckeling" of the CuO_2 planes

⇒ potential scattering

⇒ lowers T_c (in d-wave case, eg.)

X	T_c (K)
0	90
0.2	70
0.4	45
0.5	20

} Our experiments on c-axis (001) and a-b-plane (100),(110),(103) -oriented thin films

* Controversial interpretation since ~2 mos. ago: Pr → Ba, reduces T_c : (Pr → Y ; no T_c reduction)

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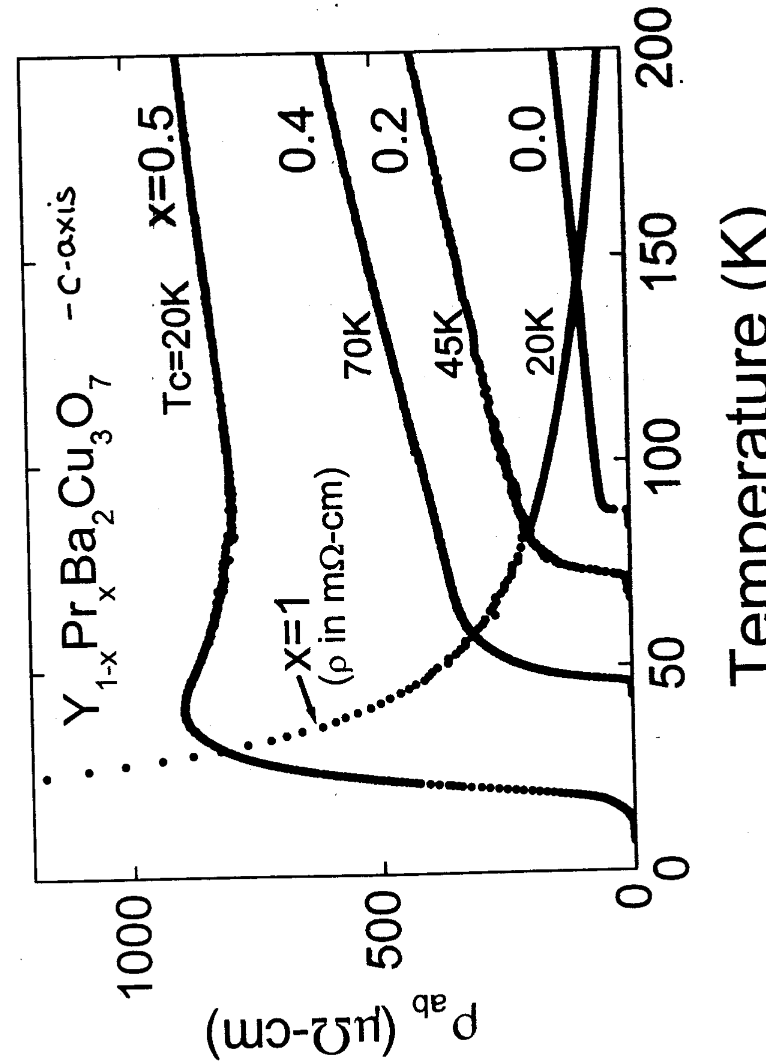
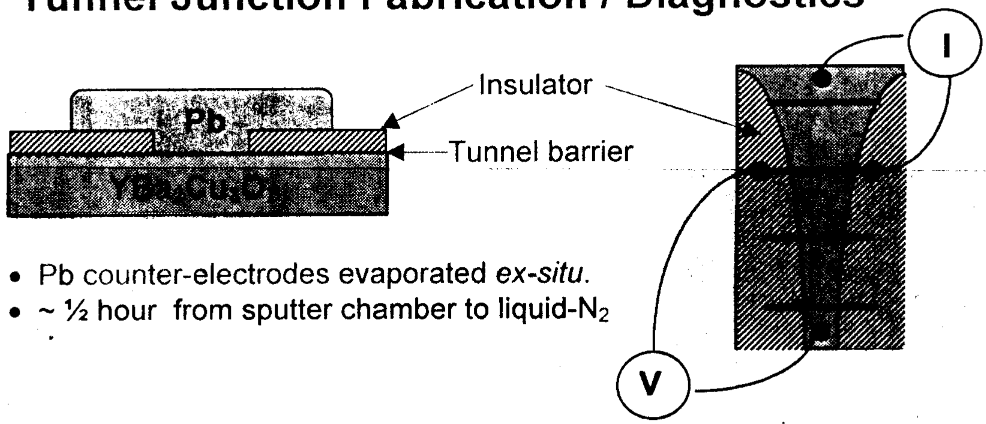


T_c & ρ(T) comp. to single crystal {Neumeier & Maple 1992

Tunnel Junction Fabrication / Diagnostics



- Pb counter-electrodes evaporated *ex-situ*.
- ~ ½ hour from sputter chamber to liquid-N_2

TUNNELING verified by:

* Pb counter electrode: *low-leakage <u>Pb gap</u> (~1% @ 4.2K) & phonons*

*** Junction <u>resistance</u>: scales with $1/A_{junction}$**

*** Little to no <u>temperature dependence</u>**

*** <u>REPRODUCIBLITY</u>: including film-to-film**

Also: <u>Normal-metal</u> counter-electrode (insulator formed by chemical techniques)

1. Covington .... Mirkin (NWU, Chemistry) PRL 79 281 (1997) / Chemical modification using SAM's / Cu
2. Hentges, .. Pafford, Westwood (UIUC, Chemistry) APS March '00 / Chemical modification : ZrO_2 / Ag
3. Badica, Aubin APS MARCH '00 / Bi
4. Aubin M^2S-HTSC-VI '00 / CaF_2 / Ag on BSCCO single crystals

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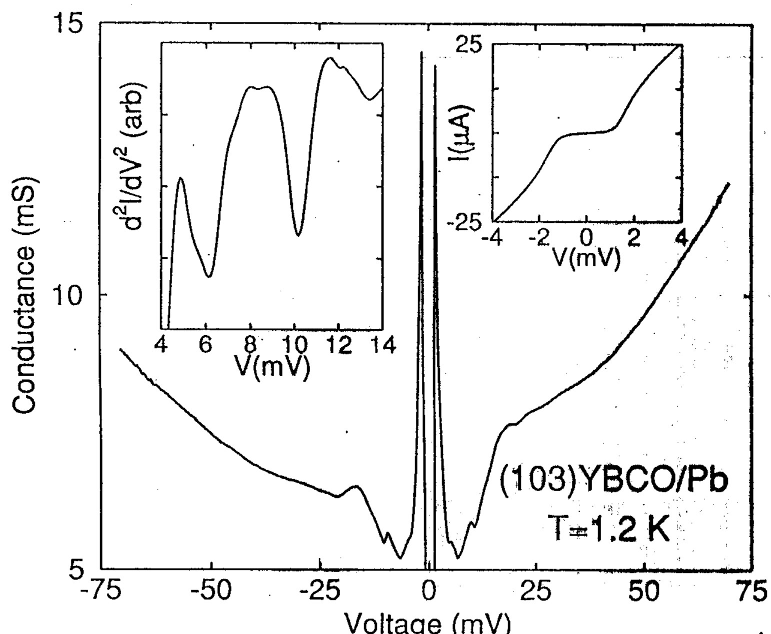
Overview of Tunnel Junctions

Pb / (001), (100), (103) and (110) oriented $YBa_2Cu_3O_7$



Zero-Bias Conductance Peak (ZBCP)

Background Shape

Oscillations

Gap-Like Feature → Pb^+ (filling YBCO states)

J. Lesueur, LHG, W. L. Feldmann and A. Inam, Physica C **191**, 325 (1992).

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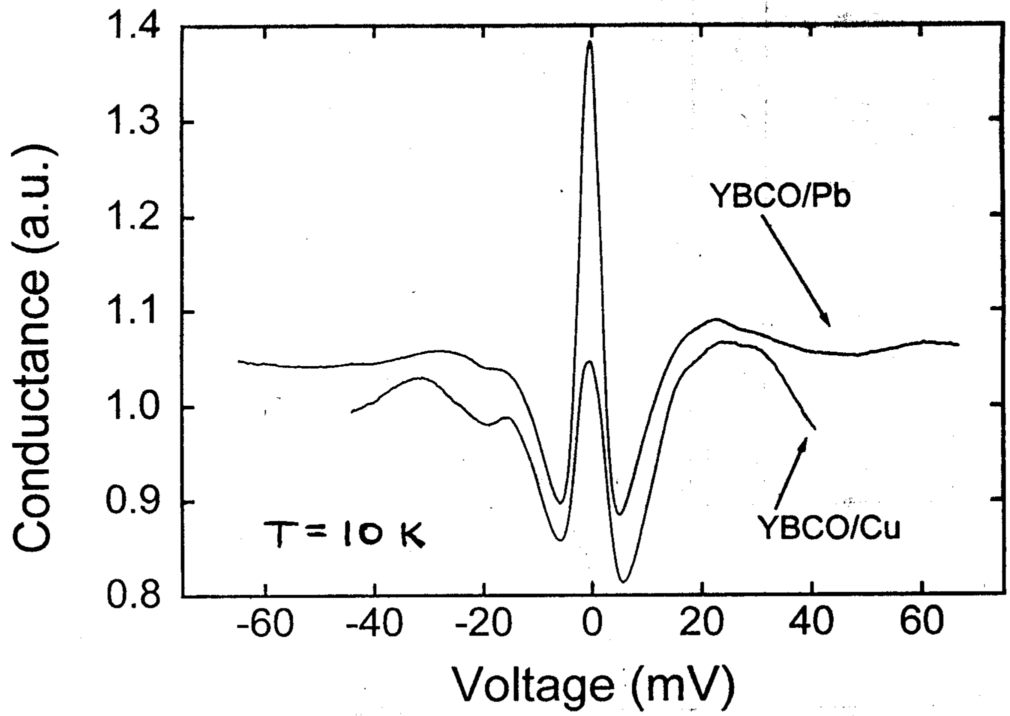
Reminder:

Zero-Bias Conductance Peak (ZBCP) **ONLY** observed in **ab**-plane tunneling

Rest of talk: **ab**-plane tunneling into **undoped** $YBa_2Cu_3O_7$



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Many phenomena may produce a ZBCP (zero-bias conductance peak) in the tunneling conductance

eg: magnetic /spin-flip scattering
Proximity / Josephson effects
shorts / pinholes through barrier
Cooper-pair tunneling
Reflectionless tunneling
Multiple Andreev reflections (MAR)
Inelastic processes
etc. . . . . .

Diagnostics required to test if ZBCP is an ABS

(Andreev bound state); intrinsic to d-wave sc.

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Zero Bias Conductance Peak (ZBCP) is an Andreev Bound State (ABS)

As shown by the data dependences upon: * DIAGNOSTICS *

1. **Crystallographic orientation**
   - ✓ Only seen in ab-plane tunneling (not in c-axis)
   - ✓ Not seen in specular (100) a-axis tunneline (**Alff, et al.**)
   - ✓ Magnitude depends on a-b orientation (Aubin, BSCCO Xtals)
2. **Temperature**
   - ✓ Split in ZBCP below T_s
   - ✓ Zero-bias conductance ~1/T below 40K, above T_s
3. **Magnetic Field**
   - ✓ Field Evolution
   - ✓ Saturation effects
   - ✓ Field Scale
   - ✓ Angular dependence / Orientation dep
   - ✓ Hysteresis
4. **Doping and disorder**
   - ✓ ZBCP reduces in size and disappears with increased doping and ion-induced damage.
   - ✓ This is shown to be a DoS effect (follows gap disorder dependence)
5. **Penetration depth (Walter et al.)**

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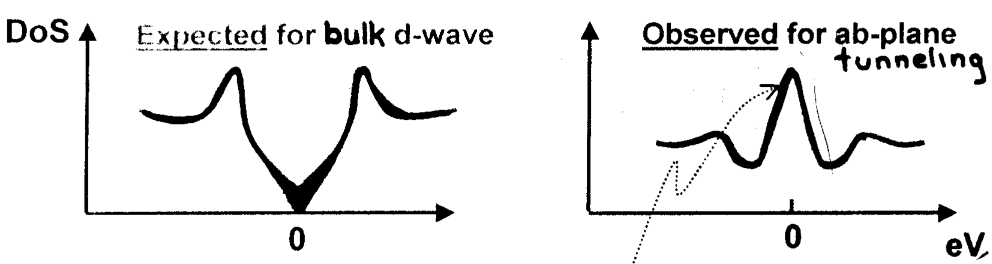
QUASI-PARTICLE (QP) TUNNELING SPECTROSCOPY

Conductance vs. Bias (Voltage) or *QP DoS vs. Energy*



The observed ***Zero-Bias Conductance Peak (ZBCP)*** *is a*

Surface-Induced Andreev Bound State (ABS),

Intrinsic to an unconventional (e.g., d-wave) superconductor at a symmetry-breaking surface (i.e., 110-direction of YBCO)

References:

Buchholtz, Zwicknagl (1982):	*For p-wave*
C. -R. Hu (1994):	*Applied to d-wave*
Buchholtz, Palumbo, Rainer, Sauls (1995)	*Thermodynamics*

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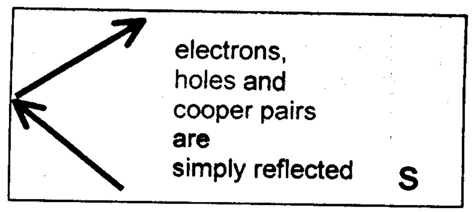
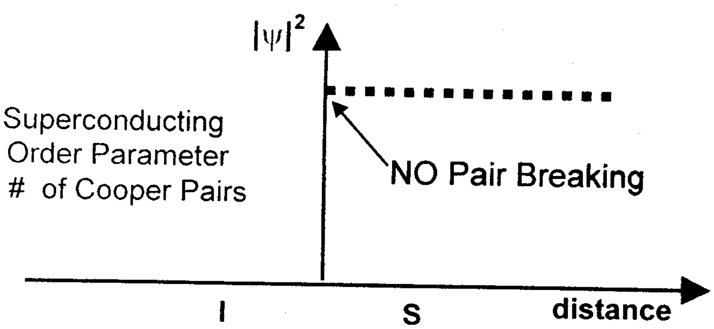
ANDREEV REFLECTION: For an S interface (No N) Conventional (s-wave) superconductor:

Insulator
or
Vacuum



ψ = Superconducting Order Parameter

$|\psi|^2 \sim \#$ of Cooper Pairs



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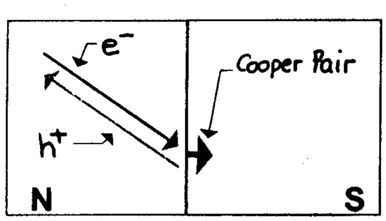
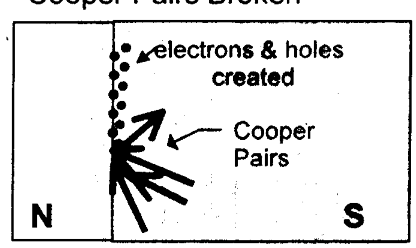
ANDREEV REFLECTION: For an NS interface Conventional (s-wave) superconductor:

From Normal metal:
Electron Retroreflected as a hole

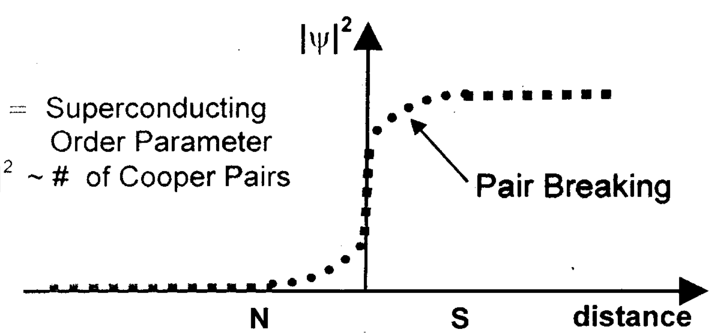


From Superconductor
Cooper Pairs Broken



ψ = Superconducting Order Parameter

$|\psi|^2 \sim \#$ of Cooper Pairs



PROXIMITY EFFECT

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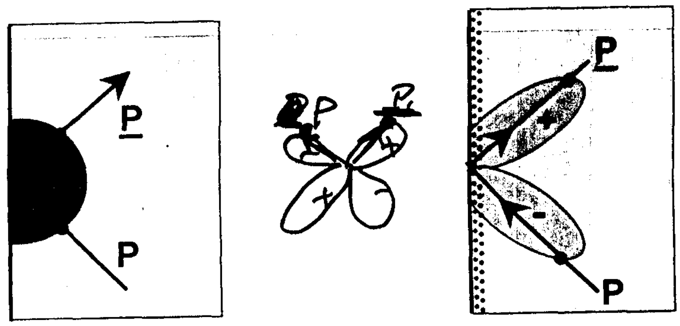
Surface-Induced Andreev Bound States:



s-wave:

No Andreev Reflection
(+ → + in order parameter)

Cooper Pairs not Broken

d-wave:

Strong Andreev Reflection
(+ → – in order parameter)

Cooper Pairs Broken

Electrons and Holes Created at Interface are BOUND between interface and Order Parameter Creating the Andreev Bound States

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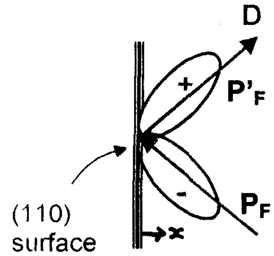
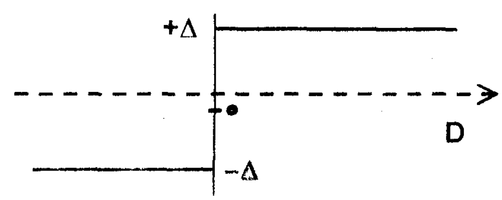
ORIGIN OF ANDREEV BOUND STATE

Quasi-Classical Trajectory along **D**:

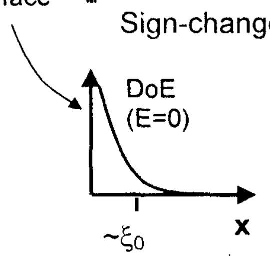


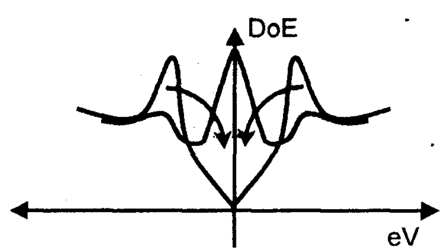


Sign-change of Order Parameter is only Boundary Condition

Solution to Andreev Equations:

Quasiparticle Bound State at surface (decay ~ξ_0)





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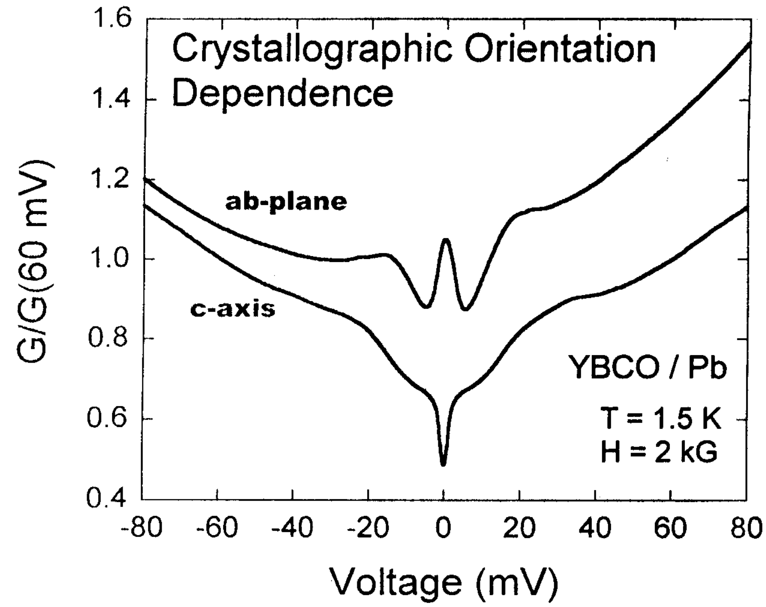

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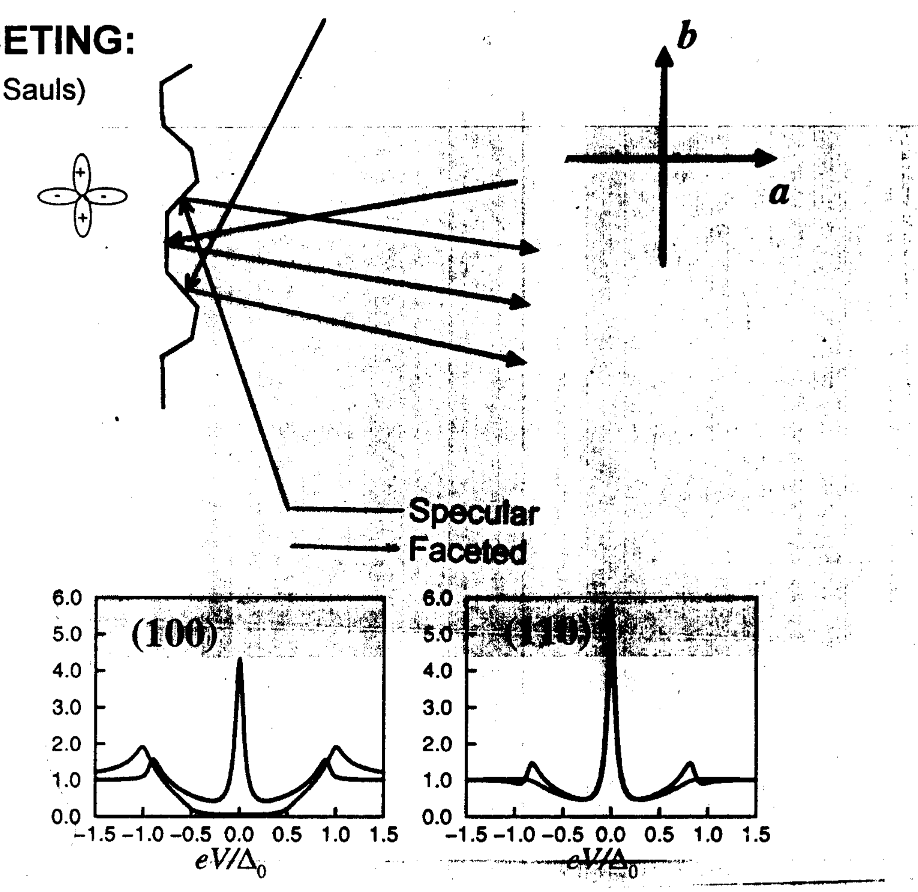
SURFACE FACETING:

(Fogelström, Rainer, Sauls)

Surface / facet orientation

NOT Global film orientation

Determines tunneling orientation



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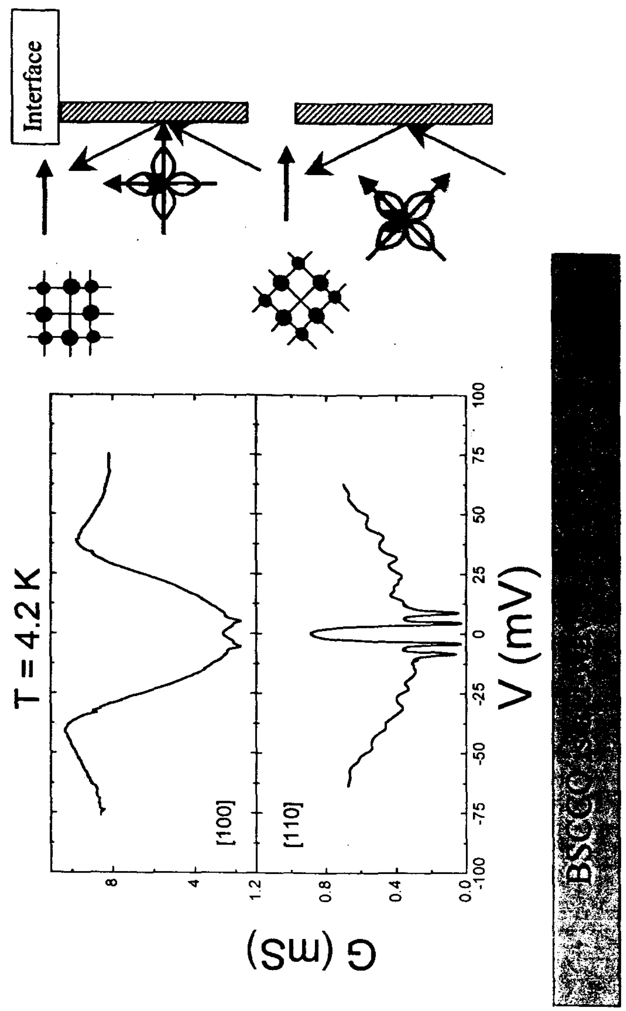
Tunneling into BSCCO single crystals
Orientational dependence in ab-plane



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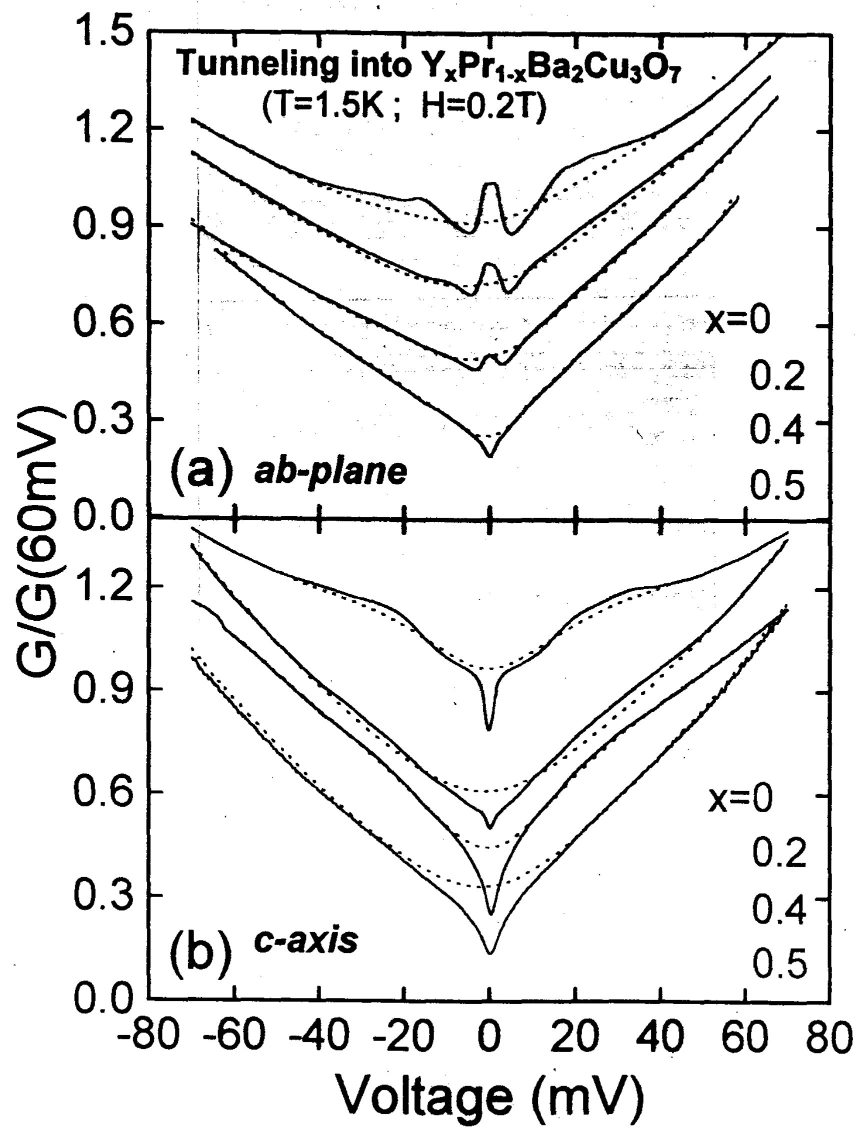

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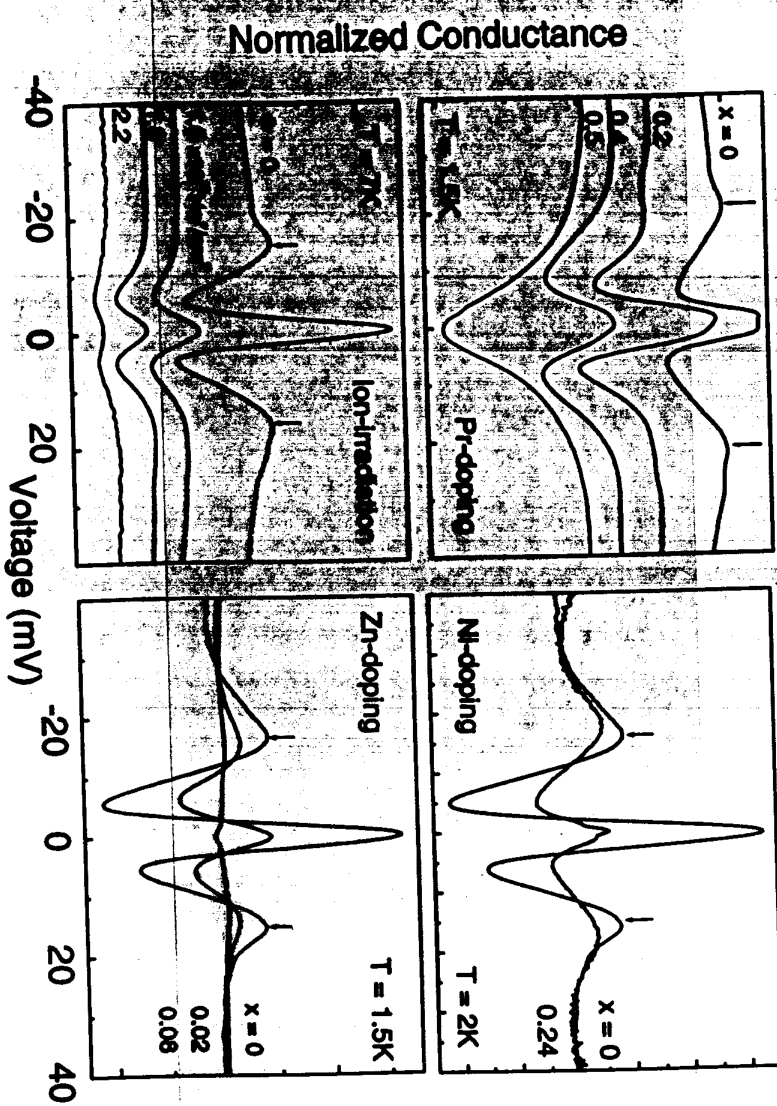
Tunneling Conductance of YBCO vs Doping/Disorder:
Pr, Ni, Zn-doping and Ion Irradaion



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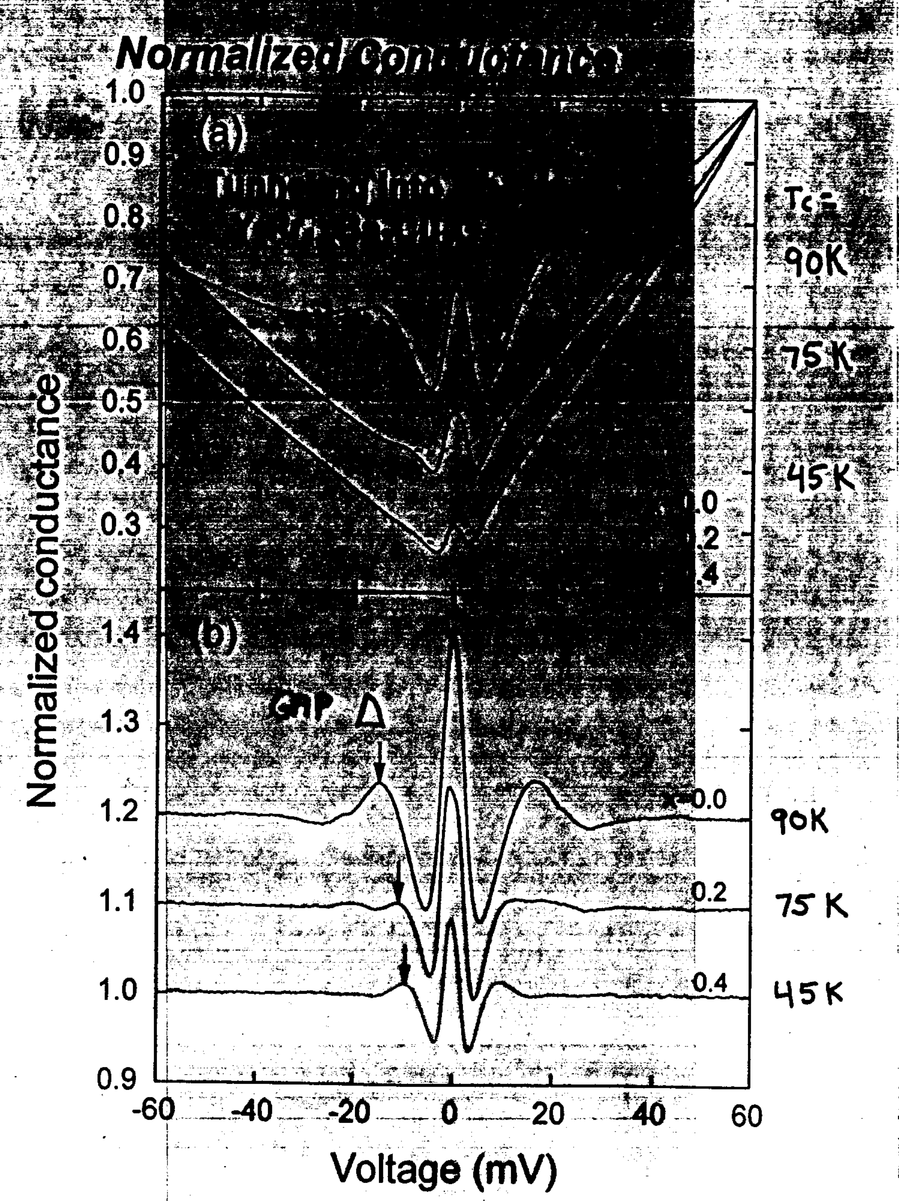
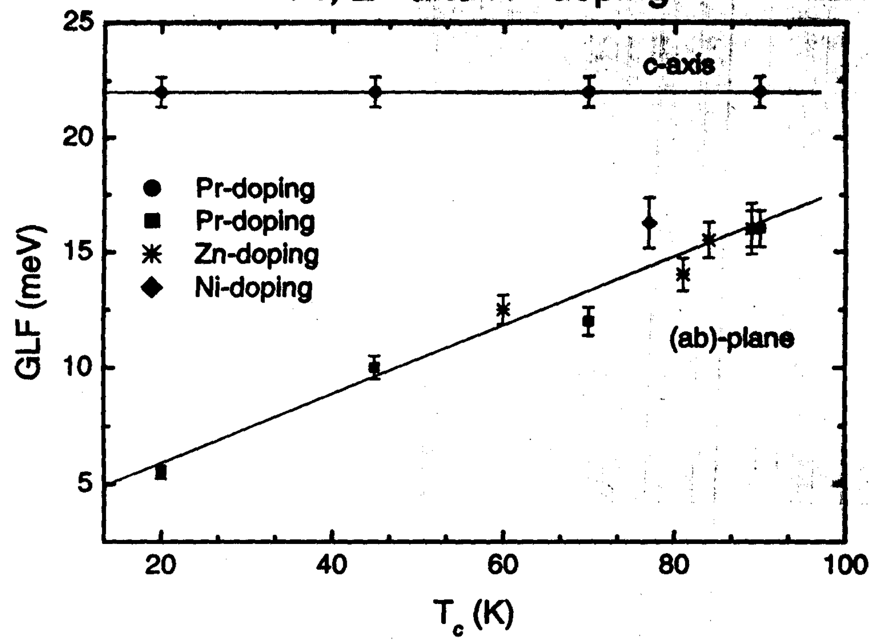


Scaling of the GLF with T_c in ab-Oriented YBCO Thin Films: Pr, Zn and Ni -doping



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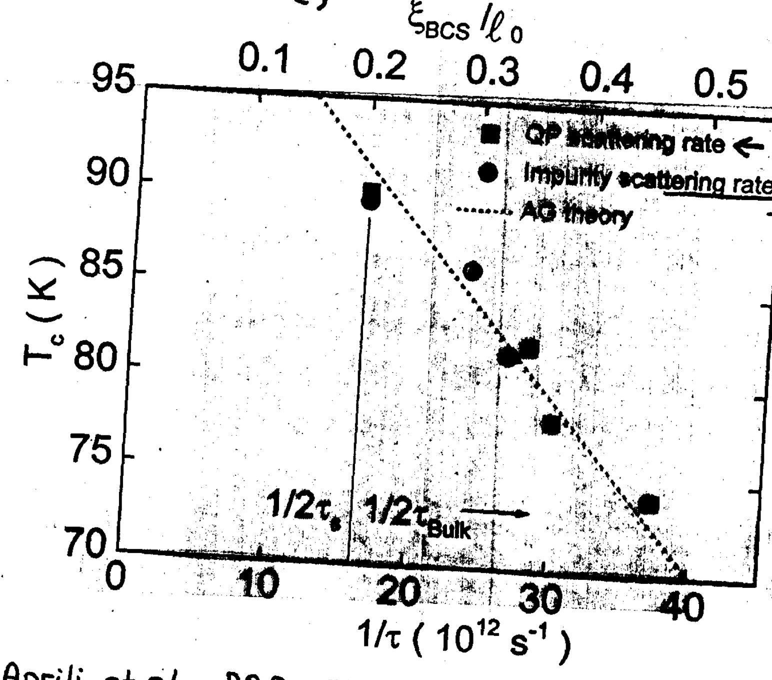
QP scattering rates measured by ABS height ($T < T_c$) Resistivity vs temperature ($T > T_c$)

SCALE WITH Damage



M. Aprili et al PRB 57 R8139 (1998).

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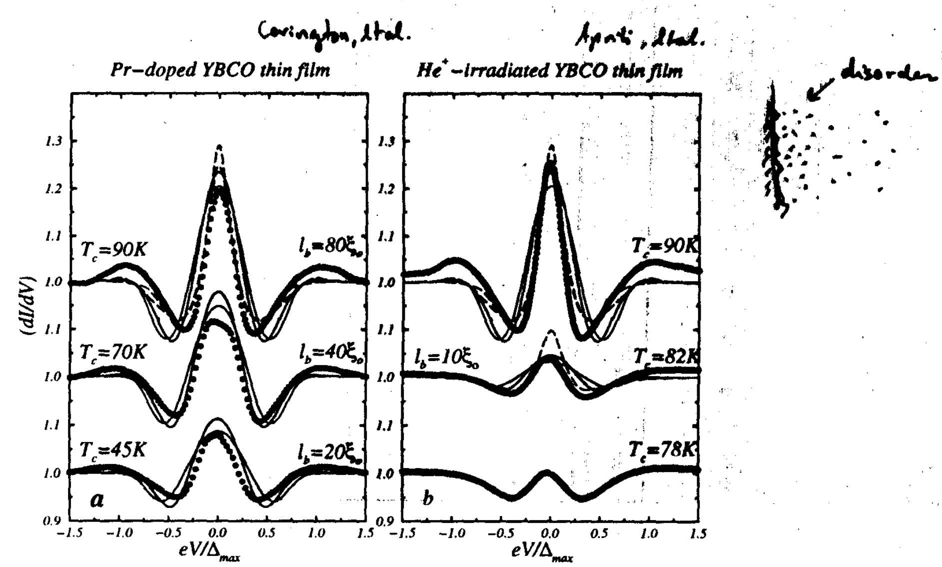
Comparison between Theory and Experiment

M. Fogelström



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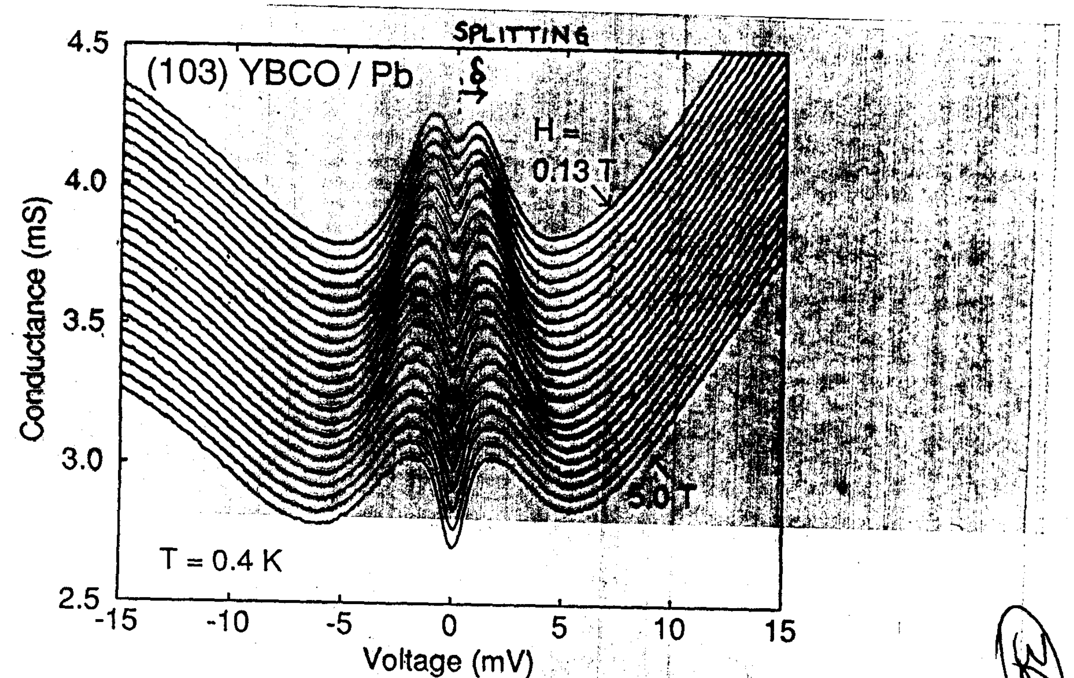
Magnetic field dependence:

J. Lesueur, LHG, A. Inam, W. L. Feldmann, Physica C 191, 325 (1992)
M. Covington, LHG, PRB (preprint), etc.,...



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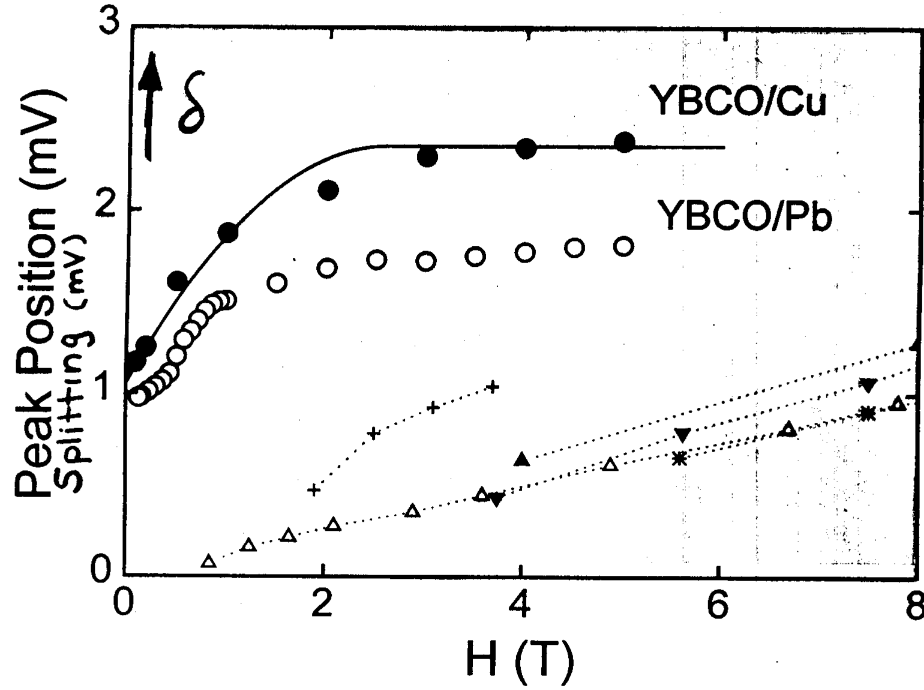
Magnetic Field Evolution of ZBCP



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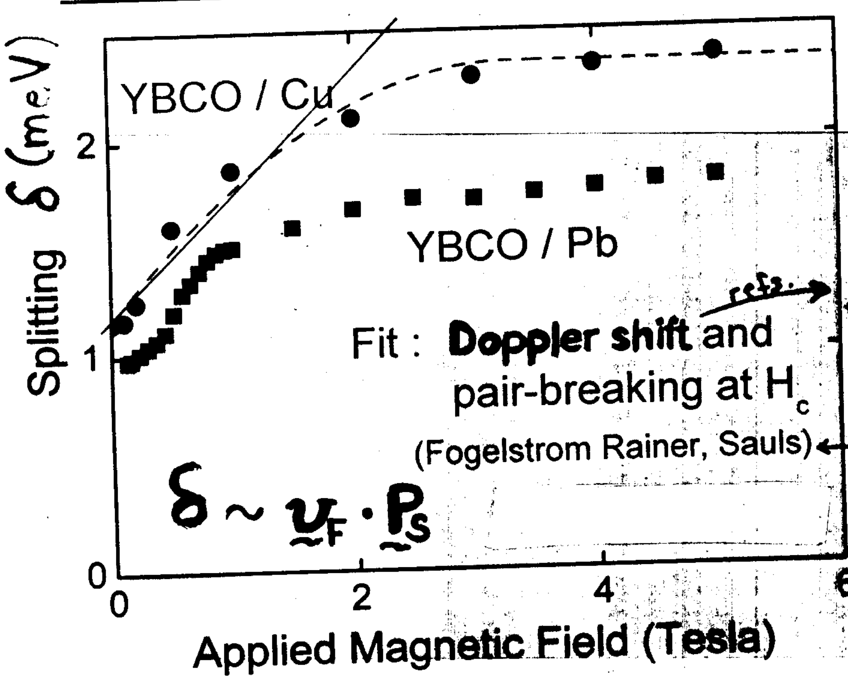
Magnetic field dependence: Magnitude



refs. S.K. Yip & J.A. Sauls PRL 2264 (1992); D. Xu, S.K. Yip & J.A. Sauls PRB 51 16233 (1995).

for ABS

J. Lesueur, LHG, A. Inam, W. L. Feldmann, Physica C 191, 325 (1992);
M. Covington, LHG, PRB (preprint), etc.,..
Fogelström, Rainer & Sauls PRL 79 281 (1997)
Covington et al, PRL 79 277 (1997) etc...

Field Scales : for LOW applied H

Experiment:

$\delta = \frac{1.5\,meV}{Tesla} \cdot H \quad = \Delta_0 \frac{H}{H^o_{exp}}$ for $\Delta_0 = 16\,meV$ $\quad H^o_{exp} \sim 10T$

compare

① Magnetic (Spin-flip/Zeeman) scattering [Anderson; Appelbaum (67)]

$\delta = g\mu_B H \quad = \Delta_0 \frac{H}{H^o_{mag}}$ for $g=2$ $\quad H^o_{mag} \sim 125\,T$

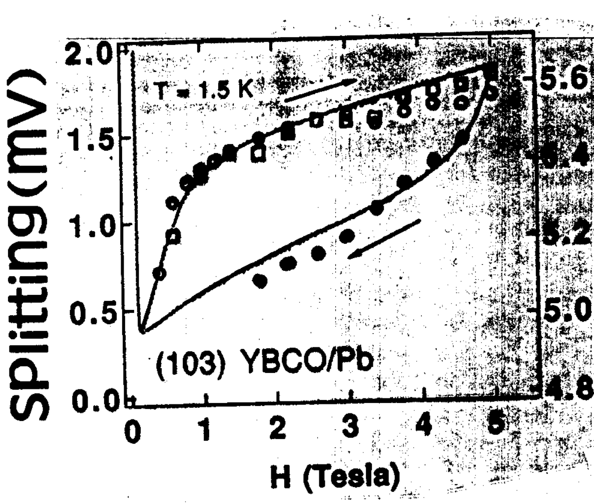
② Doppler shift : [shown by: Fogelström et al (97)]

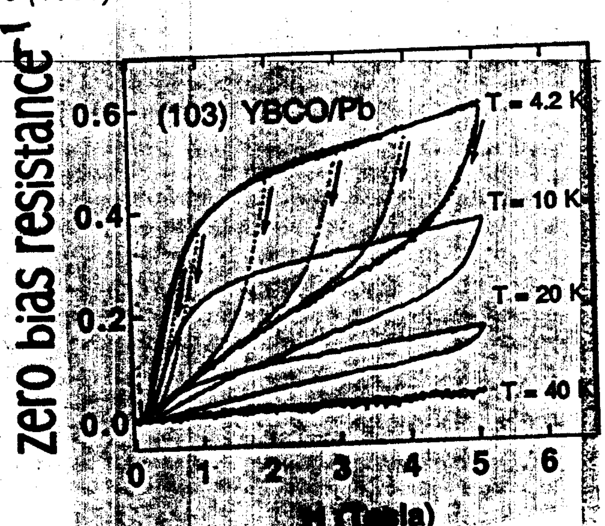
$\delta = \frac{e}{c} v_F H \lambda \sin\phi_c \quad = \Delta_0 \frac{H}{H^o_{Dop}}$ for $\phi = 10^o$ $\quad H^o_{Dop} \sim 1\text{-}10\,T$

Field scale of Experiment is consistent with Doppler shift

Magnetic field dependence: Hysteresis

*M. Aprili, E. Badica, LHG, PRL **83**, 4630 (1999)*

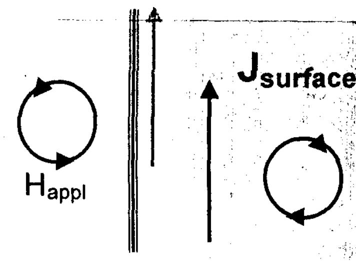




Consitent with Vortex Pinnning near Surface

verified by: Krupke & Deutscher PRL 83, 4634 (1999)

Model for Hysteresis
J. Sauls



$J_{surface} = J_{screening} - J_{vortices}$

Vortex distance: $d \sim (\phi_0 / H)^{1/2}$

- With increasing H_{appl} at low field, $J_{surf} \sim J_{screening}$
- With decreasing H_{appl} from higher field
  - Vortices separate due to magnetic pressure, and are driven towards interface
  - Surface pinning, enhanced by disorder, causes vortices to accumulate at interface

J_{suface} **becomes significantly reduced by $J_{vortices}$**

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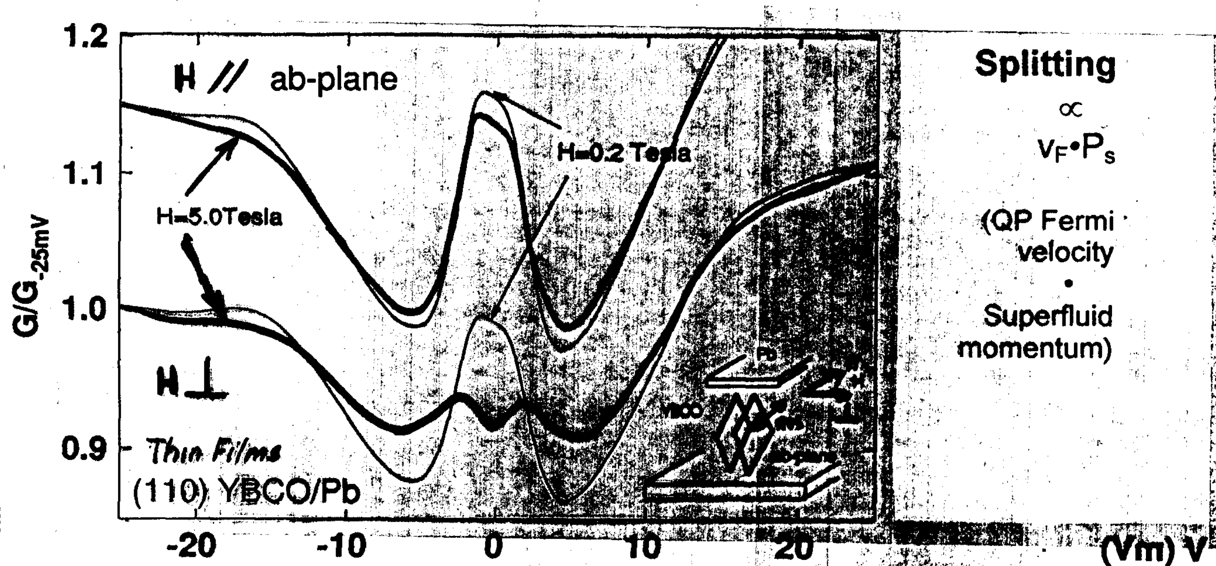
Magnetic field dependence: Orientation
*M. Aprili, E. Badica, LHG, PRL **83**, 4630 (1999)*



Splitting
$\propto$
$v_F \bullet P_s$
(QP Fermi velocity • Superfluid momentum)

⇒ Highly - anisotropic QP transport

ABS carry current parallel ab-planes (not in c-axis direction)

Verified by: Krupke & Deutscher PRL 83, 4634 (1999)

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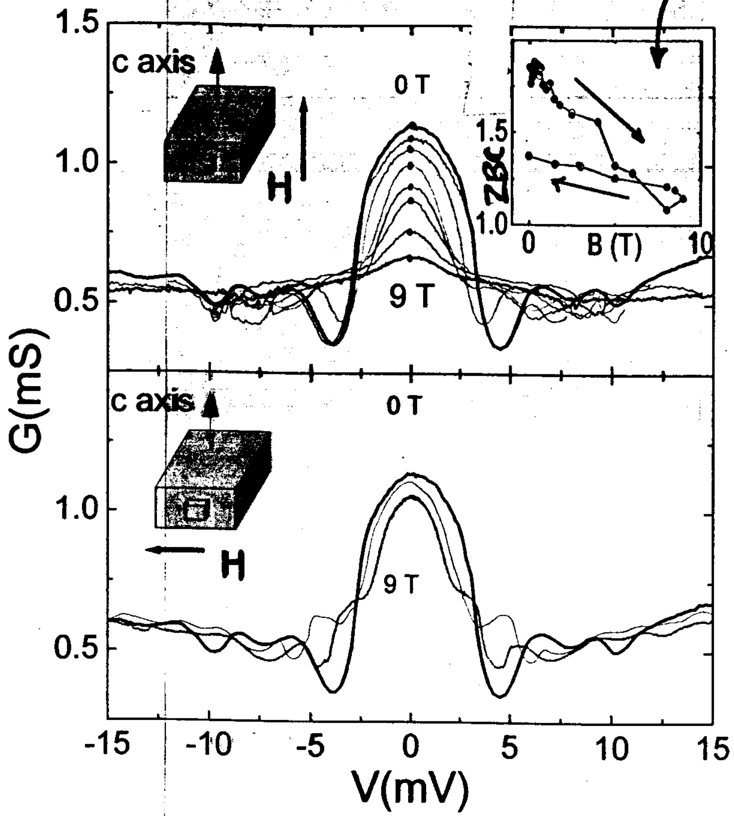
Magnetic Field Dependence : Orientation

Tunneling into BSCCO single crystals
Anisotropic QP transport & **hysteresis**

H. Aubin



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CONCLUSIONS II

1. Control of materials and junction fabrication is crucial to physics.
   ⇒ **Materials / Junction Diagnostics Crucial !!!**

2. In-plane tunneling into Pr, Ni and Zn-doped, and ion-irradiated $YBa_2Cu_3O_7$ shows $\Delta \sim T_c$
   ⇒ ***Superconducting state is probed (so can do spectroscopy)***

3. ZBCP diagnostics, (i.e., dependencies, as listed below) prove:
   ⇒ **The *ZBCP is an Andreev Bound State, which must exist at the surface of an unconventional superconductor.***

4. *ABS Tunneling Spectroscopy:*
   - ***Crystal orient:*** ***d-wave***
   - ***Doping & damage:*** ***QP scattering rates below T_c***
   - ***H_{appl} magnitude:*** ***Doppler shift / pair breaking***
   - ***H_{appl} hysteresis:*** ***Vortex pinning by surface and defects***
   - ***H_{appl} angle:*** ***Anisotropy of QP transport***

Tunneling is a Powerful Phase-Sensitive Probe of Unconventional Superconductivity