Origin of High-Temperature Superconductivity

Nature's great puzzle

C. C. Tsuei

IBM T.J. Watson Research Center

Yorktown Heights, NY 10598

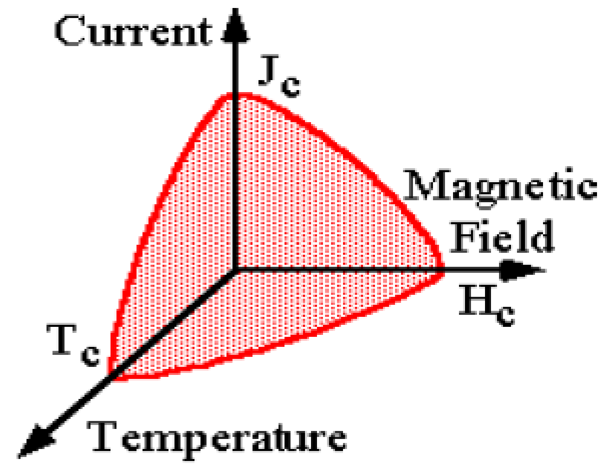
Basic characteristics of superconductors:

- Perfect electrical conduction

Kamerlingh Onnes (1911)

capacity of carrying an electrical current without energy loss

$R = 0$, if $T < T_C$ and $J < J_C$.



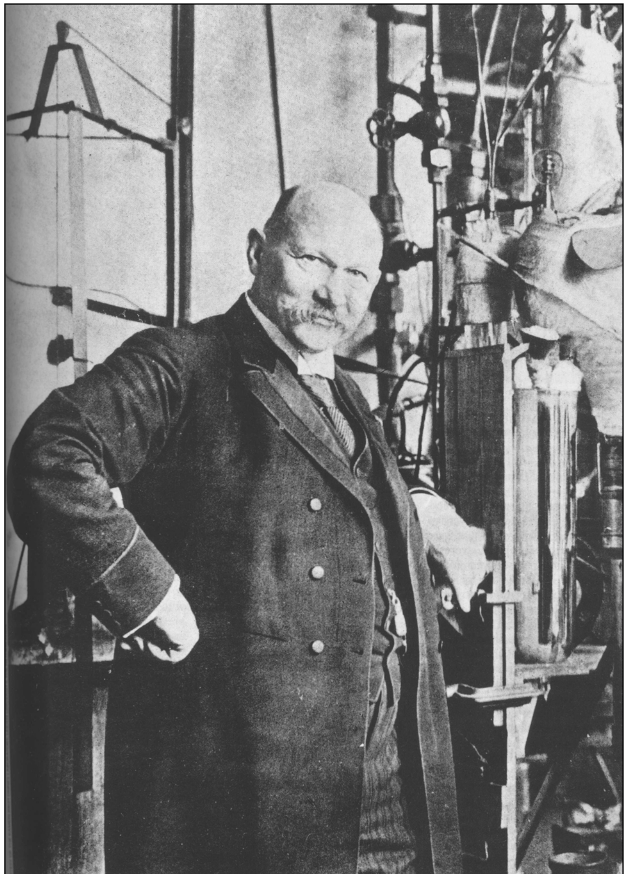
- Perfect diamagnetism

W. Meissner and R. Ochsenfeld (1933)

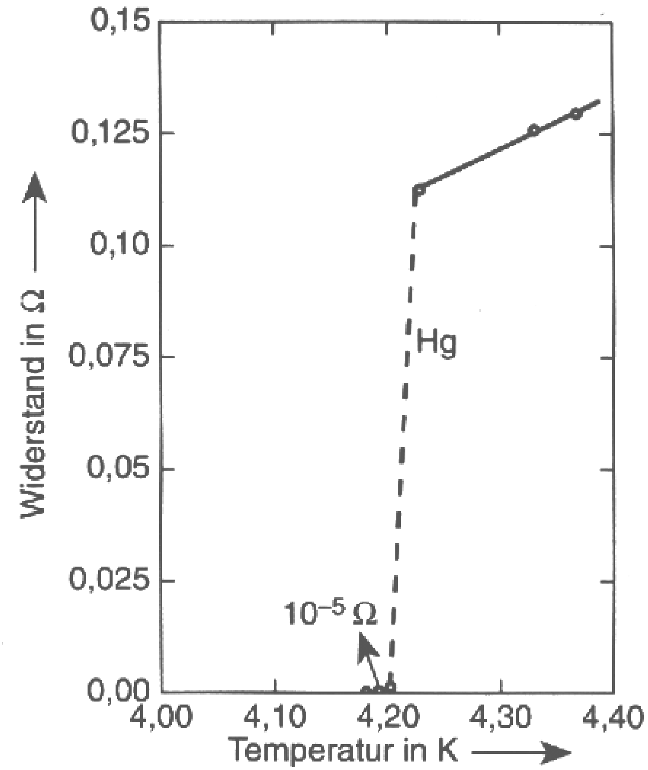
ability to expel a magnetic field

if $H < H_C$

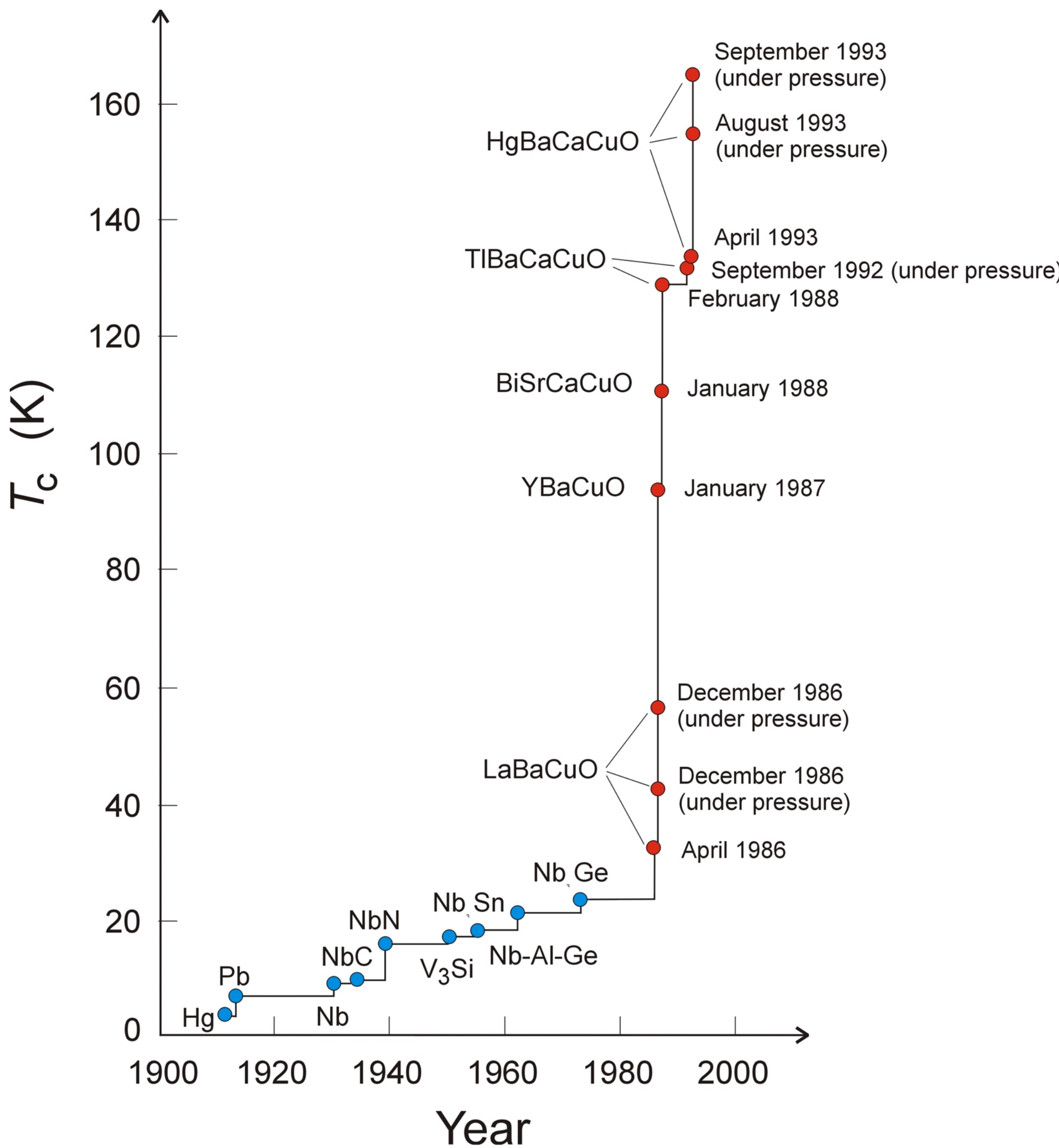
The discovery of low-temperature superconductors

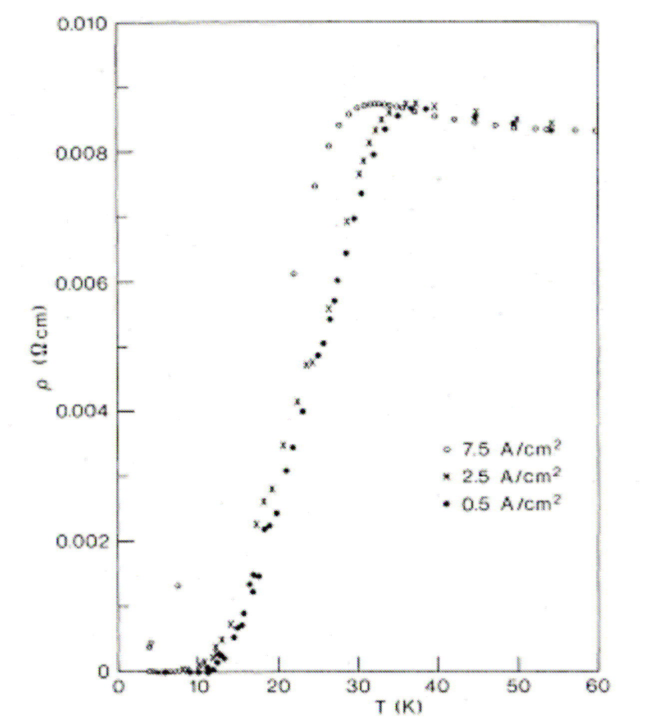


Heike Kamerlingh Onnes (1911)



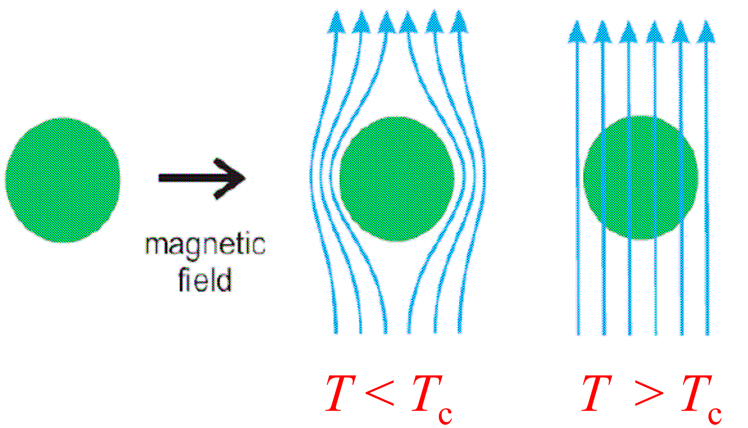
The discovery of high-temperature superconductors (HTS)



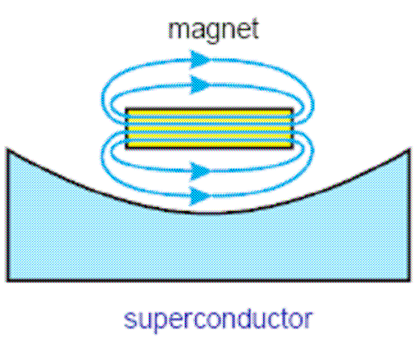


Bednorz and Mueller (1986)

The Meissner effect:



Levitation of a magnet:

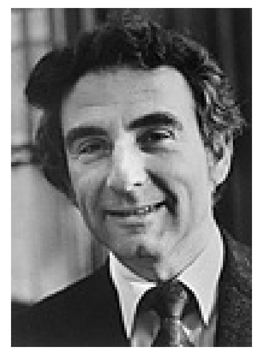


BCS Theory of Superconductivity

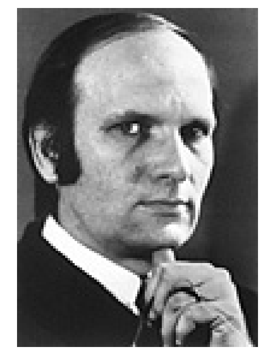
Phys. Rev. **108**, 1175 (1957).

The Nobel Prize in Physics 1972

John Bardeen



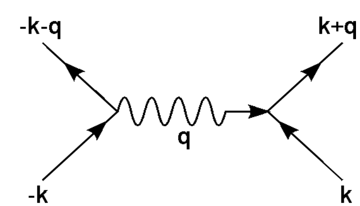
Leon Neil Cooper



John Robert Schrieffer

The BCS pairing glue in conventional superconductors:

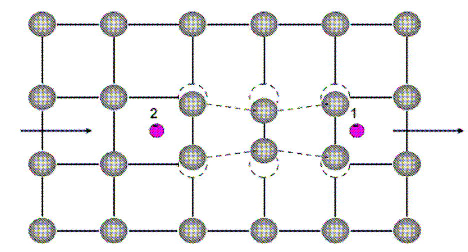
Phonon-mediated attractive interaction between electrons



BCS Theory: ***How to glue the electrons into pairs against their Coulomb repulsion***?

Cooper pairs are formed by two electrons, which overcome their Coulomb repulsion and experience an attraction through phonon exchanges

Classical analogy: hard balls rolling on a spring mattress.



QM description:

Below Tc, electrons are bound into Cooper pairs(bosons) of anti-parallel spins.
Energy gap: a finite amount of energy is required to break the pair.

$$\Delta(T) > 0, \quad T < T_c$$

Any number of these pairs could have the same energy state (bosonic condensation).
This macroscopic quantum coherent state can be described by:

BCS pair wave function,

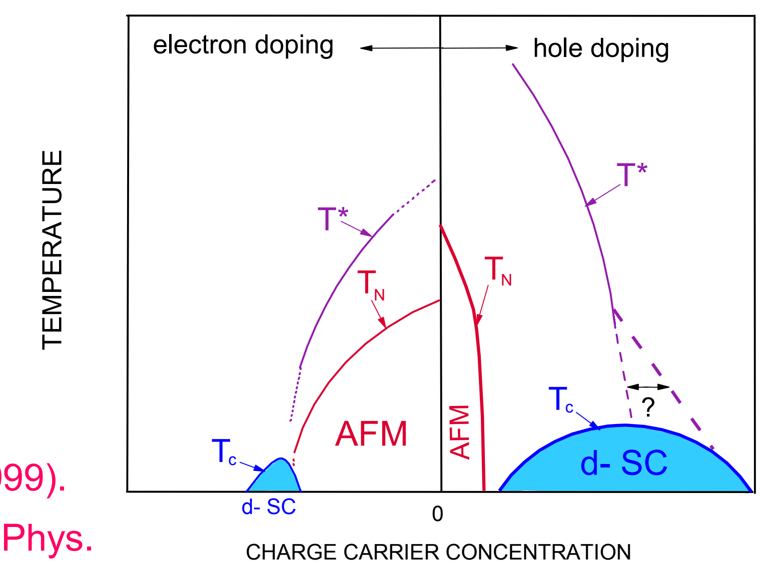
$$\Psi(\mathbf{k}) = |\Psi|\, e^{i\phi} \propto \Delta(\mathbf{k})$$

The ***normal state*** in cuprate superconductors is definitely not normal !!

Outstanding issues to be settled:

- origin of pseudogap
- preformed Cooper pairs
- nanometer scale charge inhomogeneity
- anomalous transport properties
- doping effect (doping-induced evolution from a non-FL to FL behavior)
- - - - - -

Phase diagram of cuprate superconductors

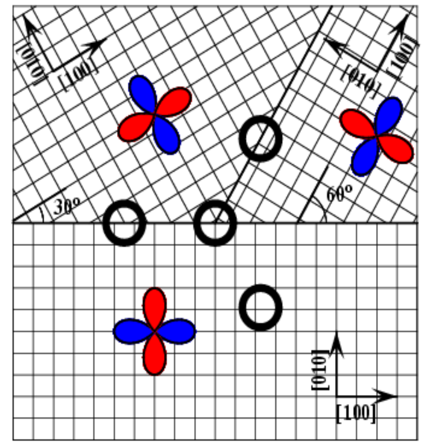


T. Timusk and B. Statt, Rep. Prog. Phys. **62,** 61 (1999).
A. Damascelli, Z. Hussain and Z-X Shen Rev. Mod. Phys. **75**, 473 (2003).

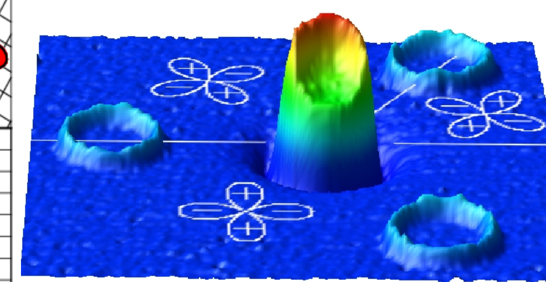
The superconducting state:

- d-wave pairing symmetry has been observed in both electron- and hole-doped cuprate superconductors.
- The d-wave pair state is robust against TRSB, and a large variation in temperature and doping.
- Experiments probing the nature of nodal excitations in 2D d-wave superconductors support BCS in the context of the FL formalism.
- No consensus on the microscopic pairing mechanism. Contenders include:

Tricrystal geometry



Scanning SQUID microscope image



*C.C. Tsuei et al., PRL **73**, 593 (1994)*

*C.C. Tsuei and J.R. Kirtley, Rev. Mod. Phys. **72**, 969 (2000)*

- ***superexchange interaction***
- ***AF magnetic fluctuations***
- ***phonons***

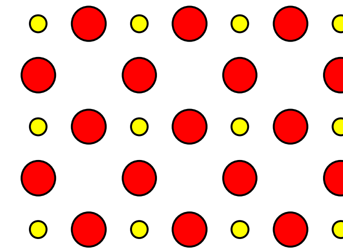
Origin of High-Temperature Superconductivity

Nature's great puzzle

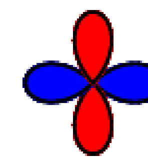
How to piece together the puzzle?

pick the right pieces!!

Key findings about HTS:



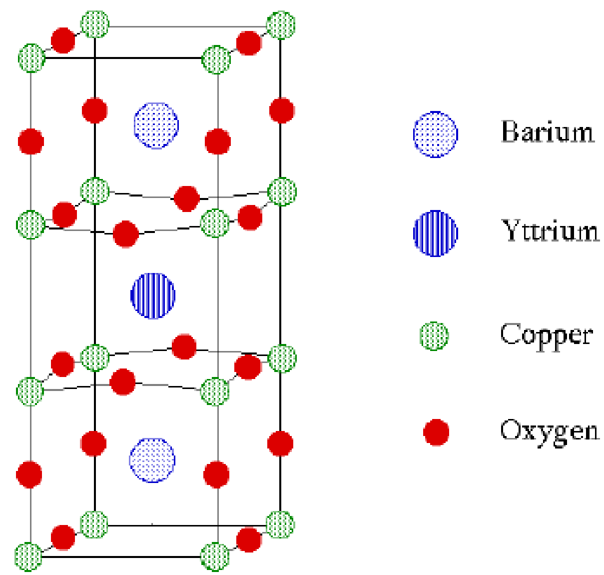
- *2D layered structure, strongly correlated electron systems*
- *doping effects (on T_c , n_s , - - - -)*
- *d-wave pairing symmetry*



- *anomalous normal state (T^*, ρ , R_H , - - -),*

  *d-wave like pseudogap in the single particle excitation spectrum below T**
- *doping-dependent isotope effects*
- *nano-scale C_{4v} symmetry-breaking in electronic structure*
- *- - - -*

An example of the high-temperature superconductors:



$YBa_2Cu_3O_{6+x}$ | (YBCO)

$T_c \sim 100K$

Note: Cu-O square lattice with Cu-O-Cu buckling bonds

Symmetry Breaking and Order Parameter

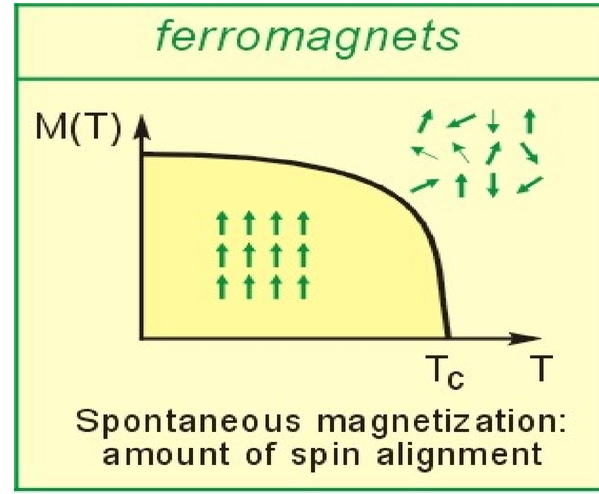
- Big Bang, Parity Nonconservation

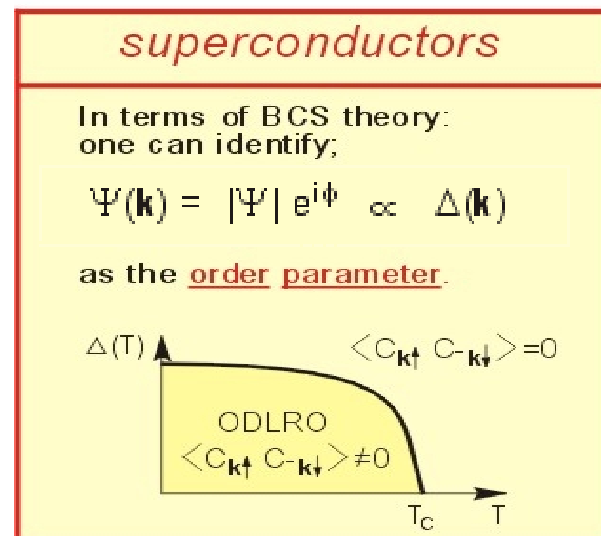
  Ferromagnetic
  Superconducting   Phase transitions

- Full Symmetry Group: G

  Symmetry Breaking → H, H ⊂ G

- Order Parameter: a measure of the amount of symmetry breaking



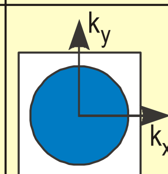
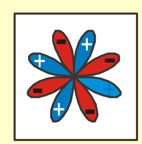
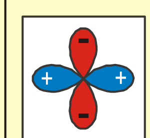
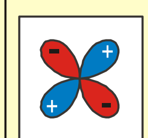


SUPERCONDUCTIVITY

A state of spontaneously broken symmetry

$$T > T_c: \quad G = \underbrace{G_{xtl}}_{\text{crystal}} \times \underbrace{R_{spin}}_{\text{spin rotation}} \times \underbrace{U(1)}_{\text{gauge}} \times \underbrace{T}_{\text{time reversal}}$$

$T < T_c$: The global gauge symmetry U(1) is always broken.

Group-theoretic notation	A_{1g}	A_{2g}	B_{1g}	B_{2g}
Order parameter basis function	constant	$xy(x^2-y^2)$	x^2-y^2	xy
Wave function name	s-wave	g	$d_{x^2-y^2}$	d_{xy}
Schematic representation of $\Delta(k)$ in B.Z.				

- Conventional superconductors: s-wave, only U(1) broken at T_c
- **Unconventional superconductors**: such as d-wave

OP has nodes ($\Delta = 0$ on FS)
$\Delta(\mathbf{k})$ changes its sign as a function of $\mathbf{k}$

Phase-sensitive test for a definitive determination of pairing symmetry

Phase-sensitive experiment:

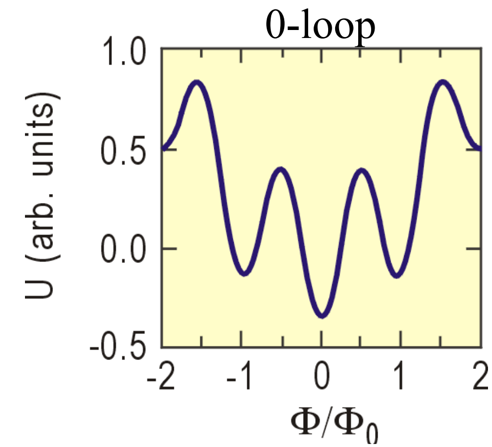
Bulaevskii, Kuzii & Sobyain (1977).
Geshrenbein, Larkin & Barone (1987).
Sigrist & Rice (1992)

Pair tunneling + Flux quantization

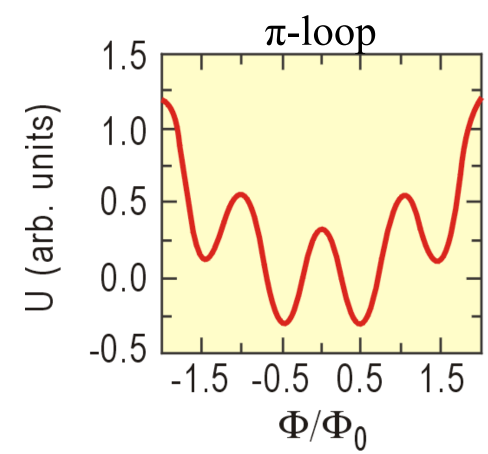
$$I_s = -|I_c| \sin \Delta\varphi_{ij} = |I_c| \sin\left(\Delta\varphi_{ij} + \pi\right) \qquad I_c \propto \Psi_i \Psi_j^* \propto e^{i(\varphi_i - \varphi_j)}$$

$$\Phi_a + I_s L + \frac{\Phi_0}{2\pi} \sum_{ij} \Delta\varphi_{ij} = n\Phi_0$$

$$U(\Phi, \Phi_a) = \frac{\Phi_0^2}{2\pi} \left\{ \left(\frac{\Phi + \Phi_a}{\Phi_0} \right)^2 - \frac{L|I_c|}{\pi\Phi_0} \cos\left[\left(\frac{2\pi\Phi}{\Phi_0} \right) + \theta \right] \right\}; \quad \theta = 0, \pi$$



SC loop containing Josephson jns.	**even**	number of sign changes in I_s	**0**	integer flux quantization
	odd		π	½ integer



As a function of the loop geometry, the presence and absence of the ½ Φ_o effect can be used for probing the phase of the order parameter, Δ(k).

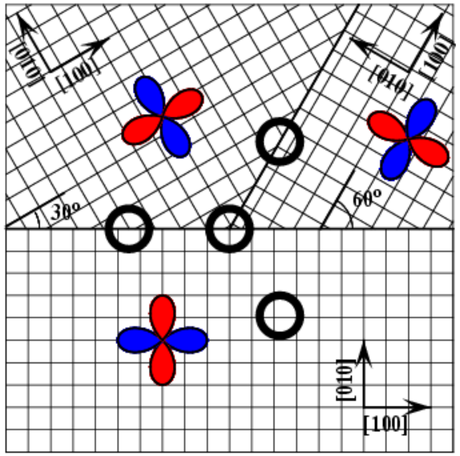
Techniques for observing the ½ Φ_o effect:

SQUID interferometry: Wollman, van Harlingen et al. (1993).
Brawner & Ott (1994), Mathai, …Welstead (1995).

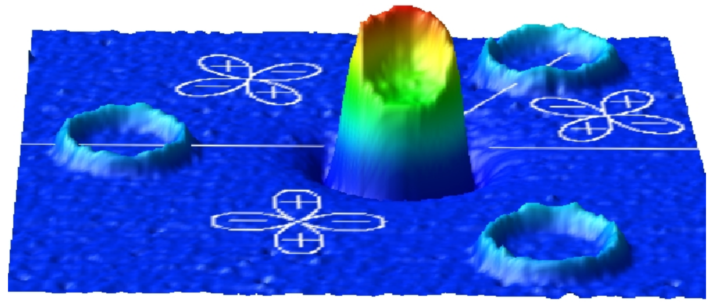
Josephson jn modulation: Wollman, van Harlingen et al. (1995).
Miller et al. (1995), Iguchi and Wen (1994)

Tricrystal magnetometry: Tsuei, Kirtley et al. (1994)

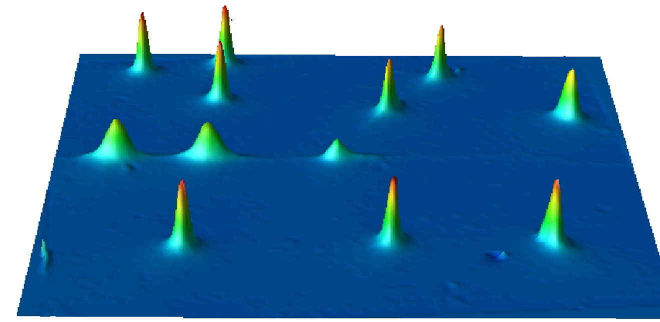
Tricrystal geometry



Scanning SQUID Microscope Images



C. C. Tsuei et al., PRL **73**, 593 (1994)



J.R. Kirtley et al., PRL **76**, 1336 (1996)

YBCO epitaxial film 4.2 K

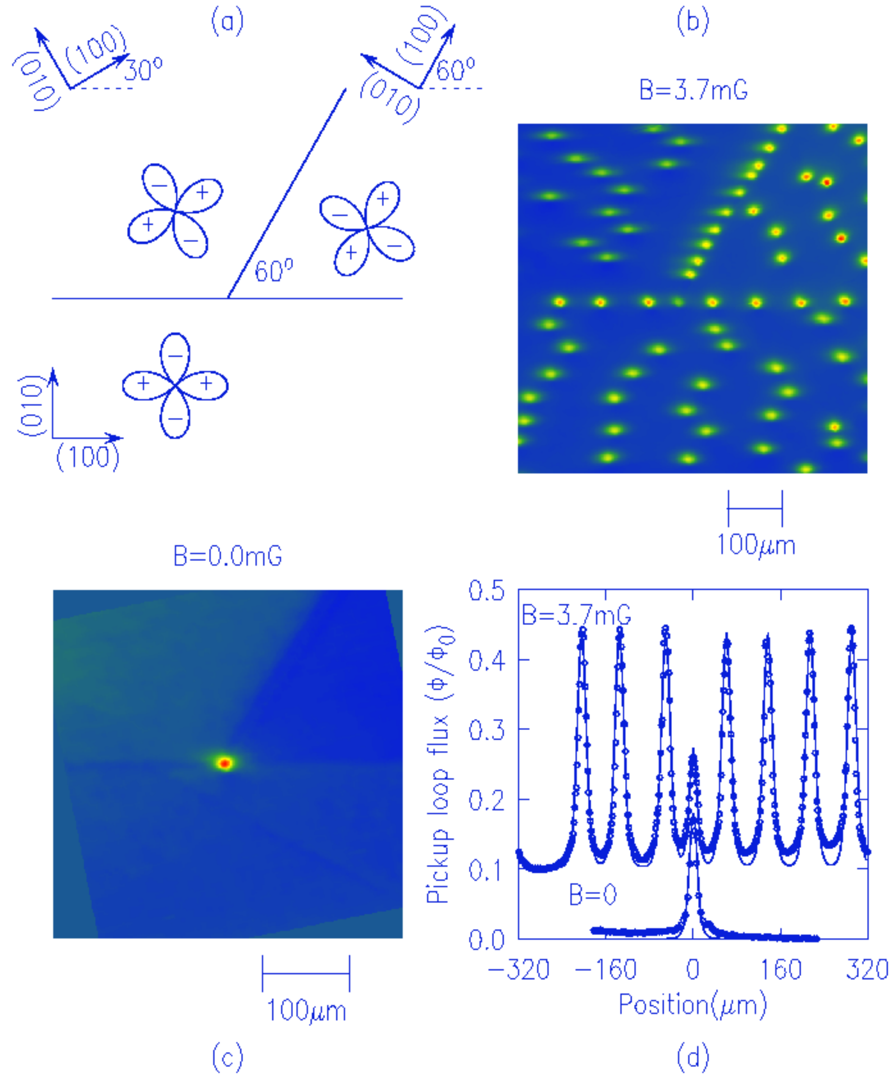
- effect of disorder at the gb junction interface was taken into consideration
- a yes or no pairing symmetry test.
- well – adapted for testing the gap symmetry of various cuprate superconductors, and especially the doping dependence of a particular cuprate system.

C.C. Tsuei and J.R. Kirtley, Rev. Mod. Phys. 72, 969 (2000)

The original tricrystal experiment was repeated and confirmed by A. Sugimoto et al.

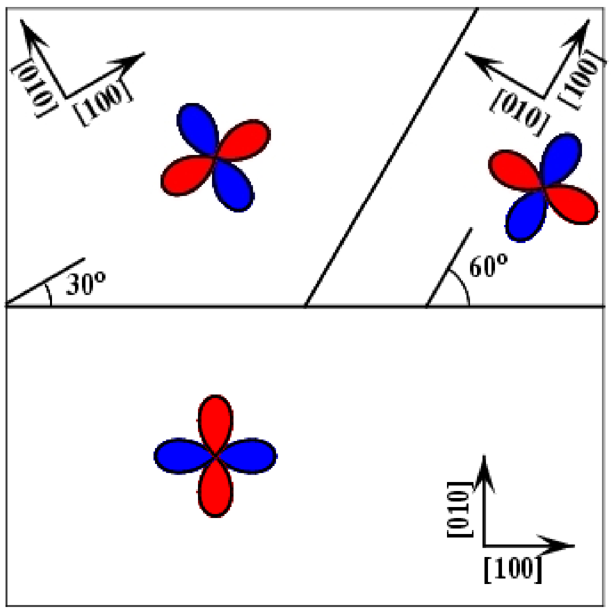
Physica C **367,** 28 (2002).

$Bi_2Sr_2CaCu_2O_8$

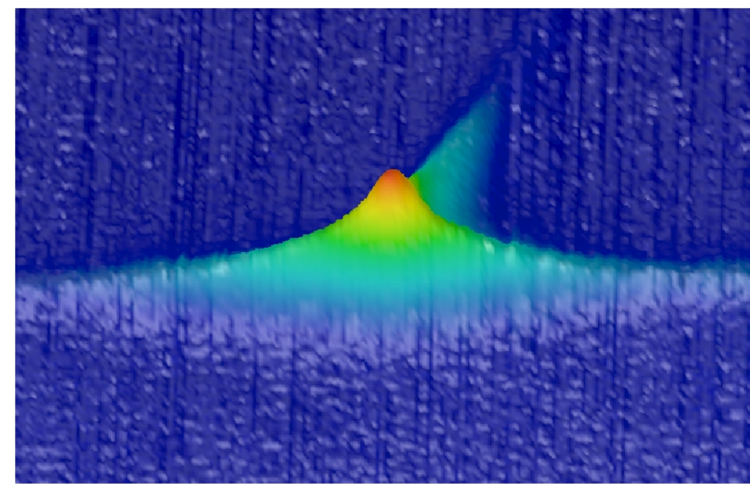


J.R. Kirtley, C.C. Tsuei, H. Raffy, Z.Z. Li, A. Gupta, J. Z. Sun, S. Megert, Europhys. Lett. **36,** 707 (1996).

Tricrystal pairing symmetry tests of electron doped cuprates

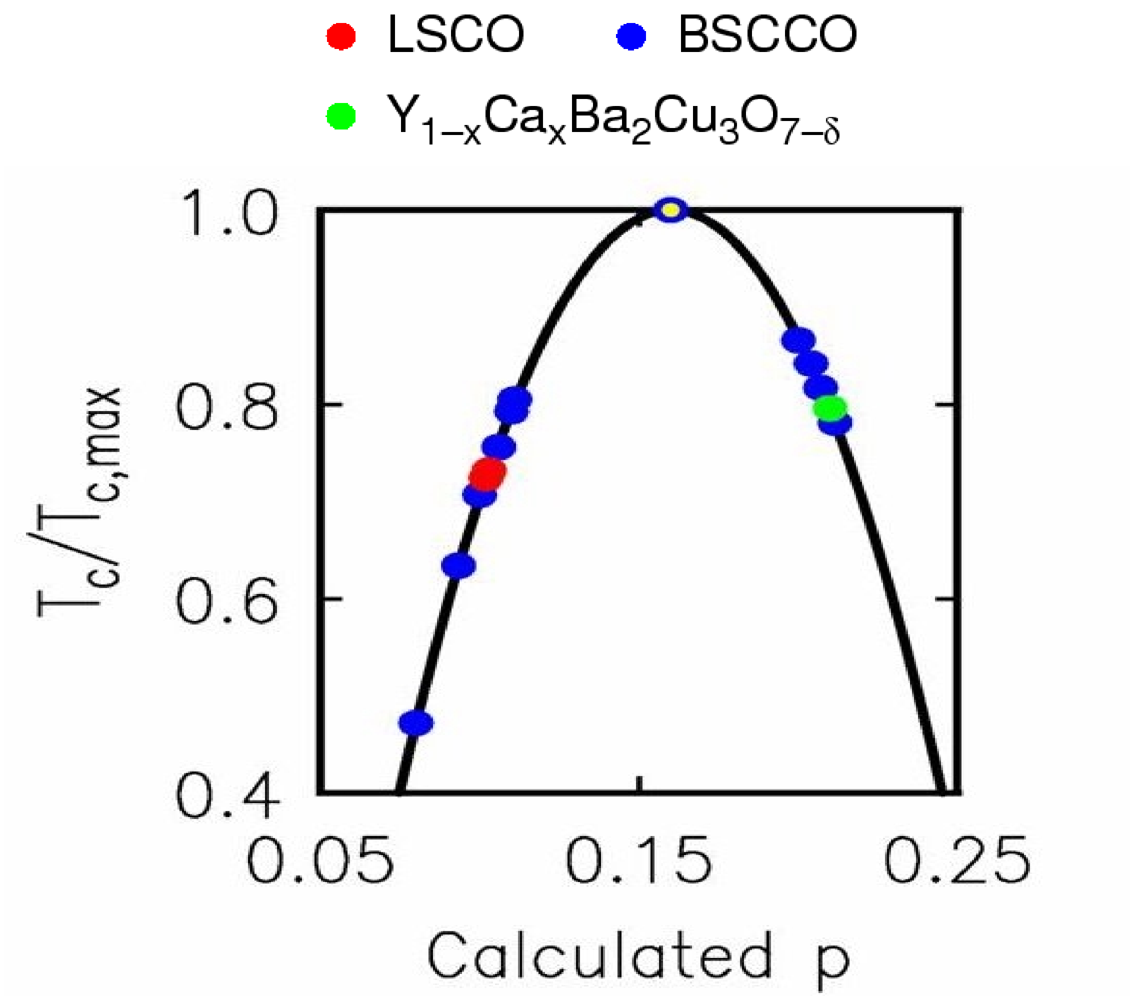


$Nd_{1.85}Ce_{0.15}CuO_{4-y}$



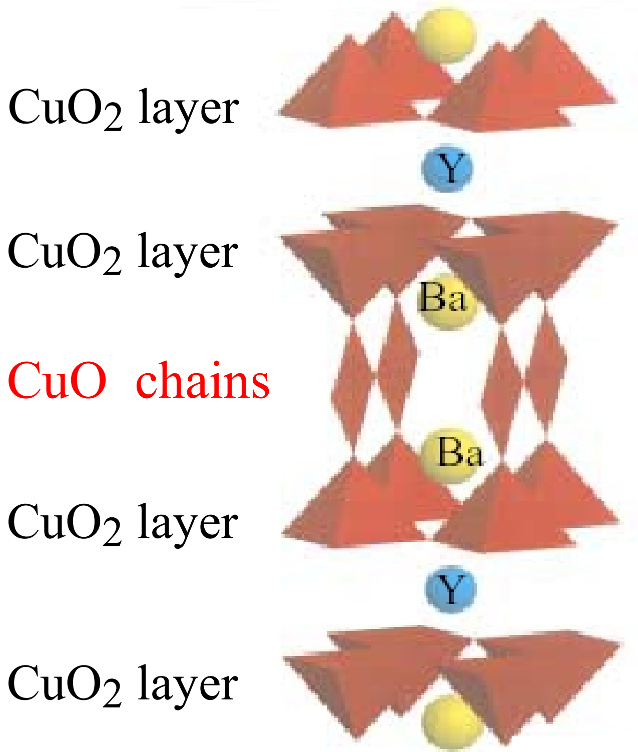
C.C. Tsuei and J.R. Kirtley, PRL **85**, 182 (2000)

Doping Dependence of Pairing Symmetry



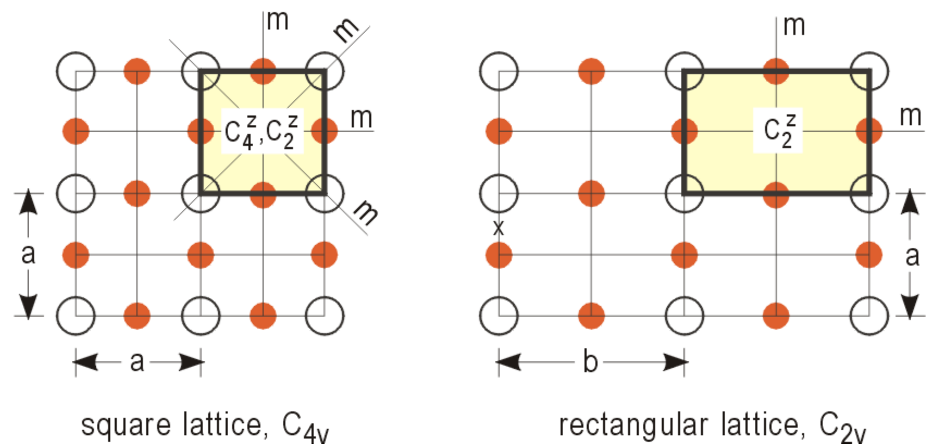
$T_c = T_{c,max}[1 - 82.6(p - 0.16)^2]$, M.R. Presland et al. Physica C **176C**, 95 (1991).

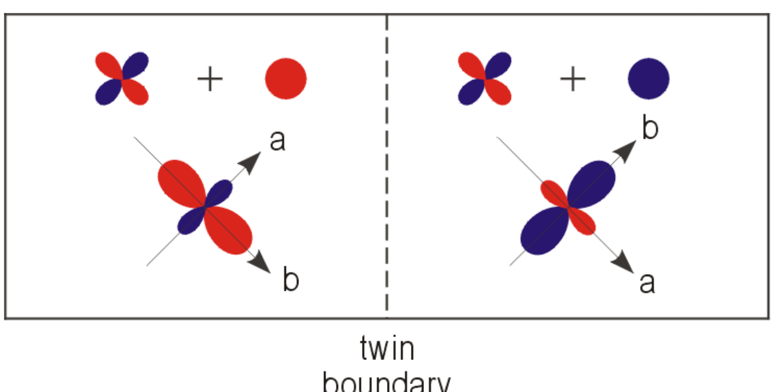
Crystal Structure and Allowed Pair States In YBCO



double CuO_2 planes plus Cu-O chains

Structure and point-group symmetry of the CuO_2 layer
● = oxygen , ○ = copper

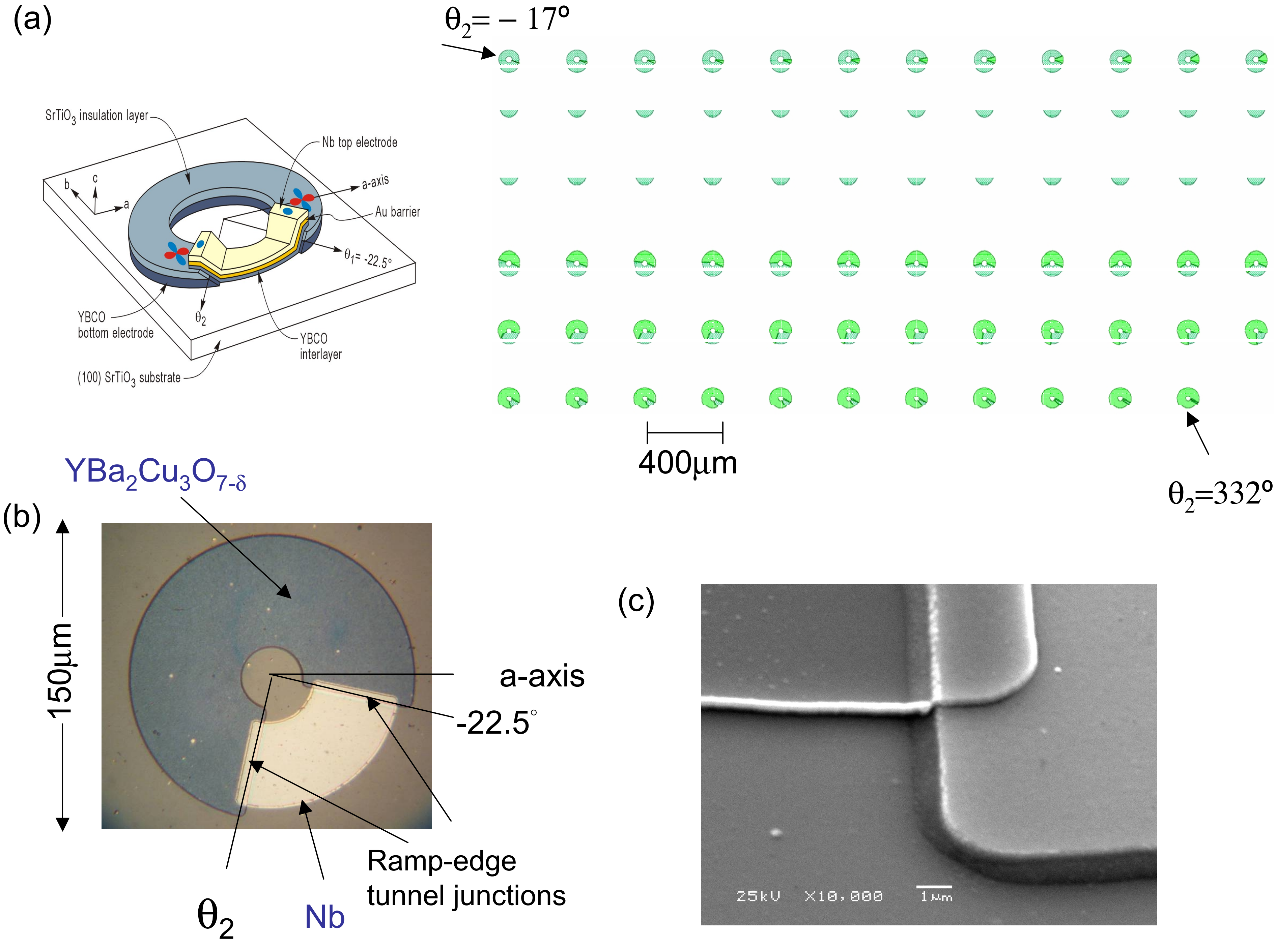




top view

M. Walker, J.L-Strathmann PRB **54**, 588 (1996)

K. Kouznetsov et al. PRL **79** 3050 (1997)


(a)
SrTiO3 insulation layer
Nb top electrode
a-axis
Au barrier
θ1= -22.5°
θ2
YBCO bottom electrode
YBCO interlayer
(100) SrTiO3 substrate
θ2= – 17°
400μm
θ2=332°
YBa2Cu3O7-δ
(b)
150μm
a-axis
-22.5°
Ramp-edge tunnel junctions
θ2
Nb
(c)
25kV X10,000 1μm