Compensated electron and hole pockets in an underdoped high-T_C superconductor

2010/07/23 Summer seminer

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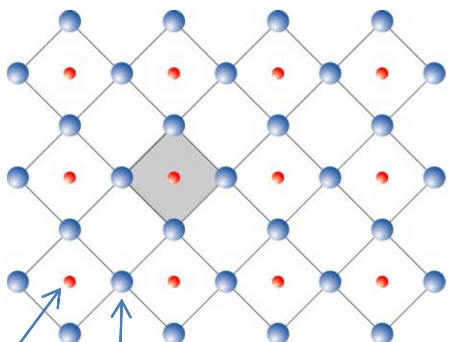
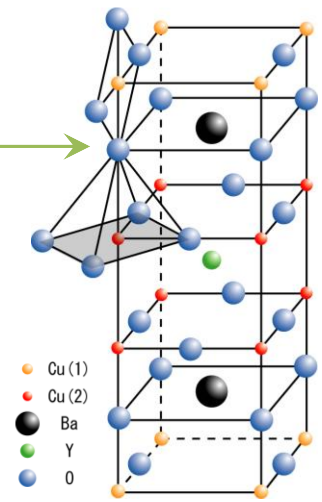
S.E. Sebastian, et al., PRB 81, 214524 (2010)

Introduction

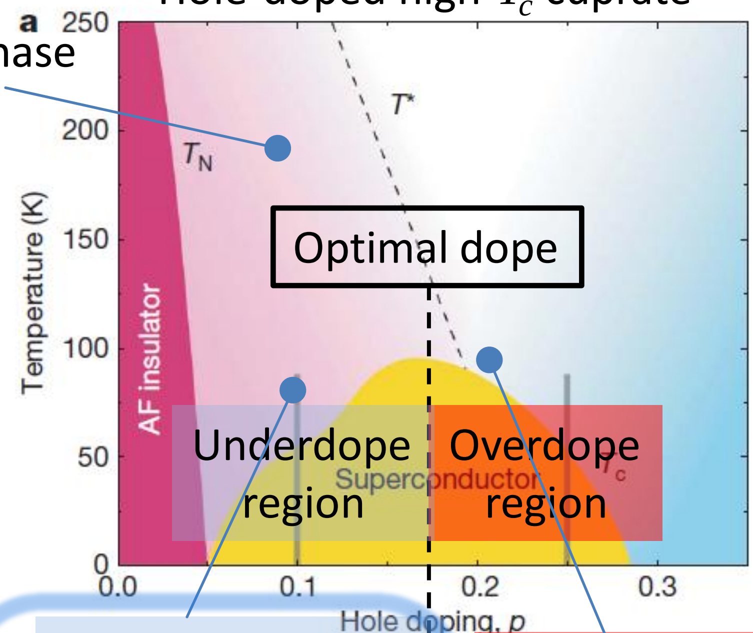
High-T_c superconductor $YBa_2Cu_3O_{6+x}$

"Stage of the S.C."
CuO_2 layer



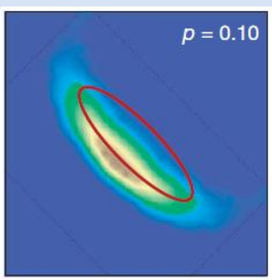


Phase diagram of
Hole-doped high-T_c cuprate



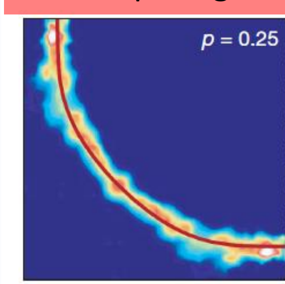
Low – lying excitations in **underdoped high-T_c cuprate** is not clarified.

Underdope region



Fermi arcs (≠ surface)
(Pseudogap phase)

Overdope region



Fermi surface(F.S.)
(normal state)

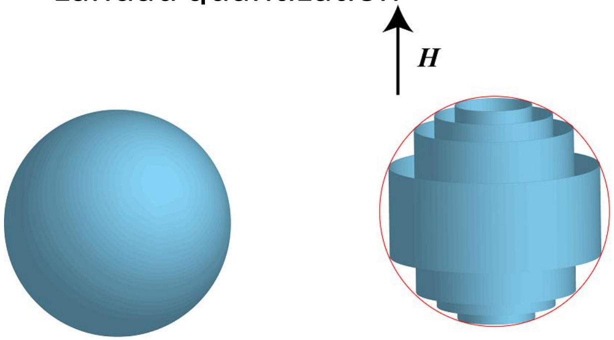
N. Doiron-Leyraud, et al., *Nature* 447, 565 (2007)

Tl-2201

Experiment

Quantum oscillation (Q.O.) : powerful probe to study topology of F.S.

Magnetic field // c axis
⇒Landau quantization

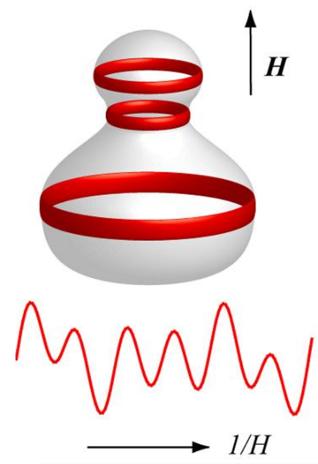


H going up, Landau level goes across Fermi level.

Conductor electrons cannnot have more energy than E_f

➡ Fermi level : changing periodically to $1/H$ (T^{-1})

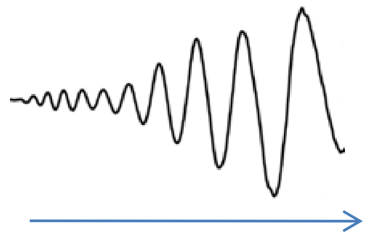
Exfremal cross-sectional -area of F. S. can be obtained !



Onsager expression

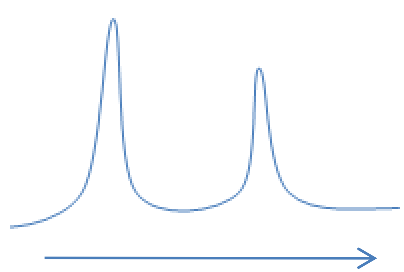
$$F = \Delta\left(\frac{1}{B}\right) = \frac{2\pi e}{\hbar c S}$$

$$A_k = \frac{2\pi e}{\hbar} F$$



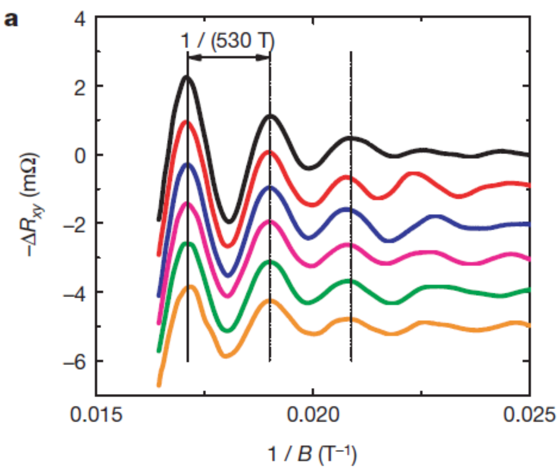
H (T)

1. x-axis translation
($\mu_0 H$) T→ ($1/\mu_0 H$) T^{-1}
to make the graph periodic
2. Fourier translation
wavelength (T^{-1})
→ frequency (T)



spectra F (T)

Experiment



Hall resistance of $YBa_2Cu_3O_{6.5}$

The first observation of Q.O. in underdoped high-T_c cuprate

N. Doiron-Leyraud, et al., *Nature* 447, 565 (2007)

Recent study about Q.O. in

underdoped $YBa_2Cu_3O_{6+x}$

by Suchitra E. Sebastian et al. ($x = 0.56$)

Experimental remarks

- Measurement of Contactless conductivity
- Wide range in field $28 \leqq \mu_0 H \leqq 85$ T
- High resolution enough to identify more distinct Q.O. frequencies
- Angular dependence of out-of-plane & in-plane rotation (θ and ϕ)

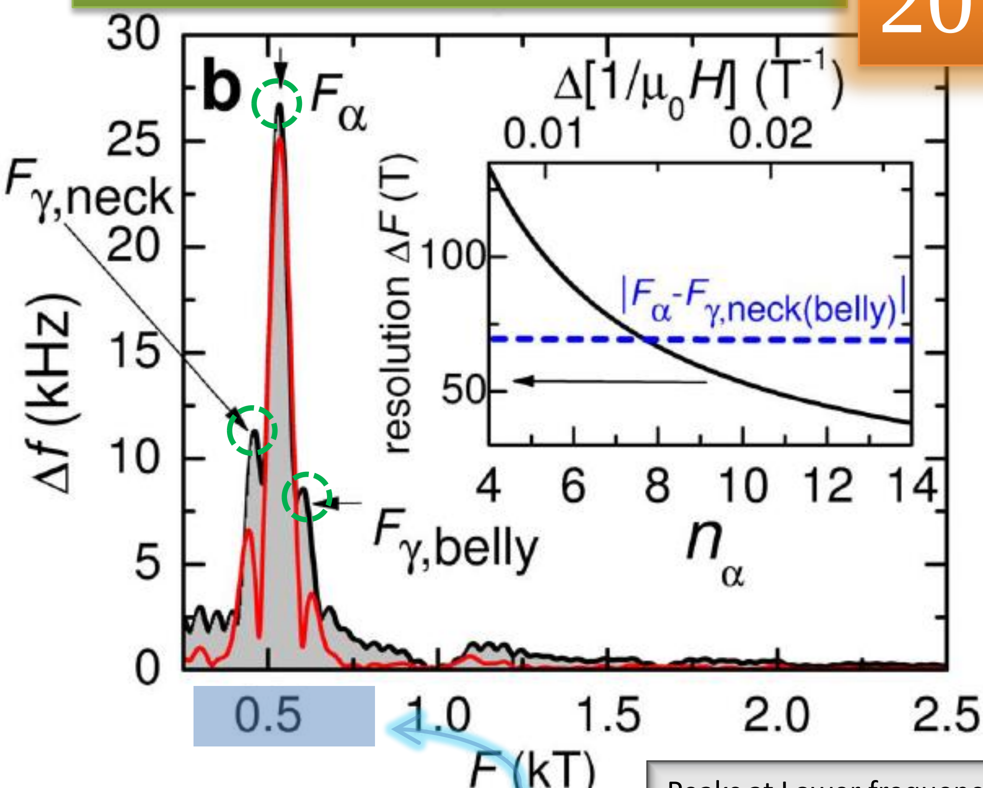
Remarkable results and new interpretations I introduce from now were offered !!

S.E. Sebastian, et al., *Nature* 454, 200 (2008)
S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Results and analysis

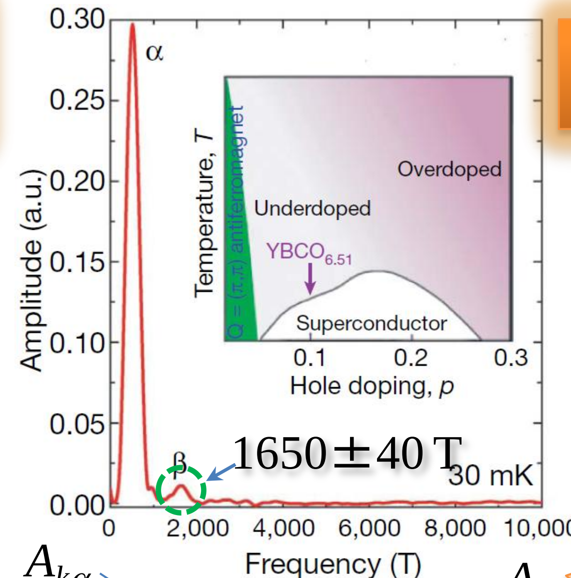
What is derived from these spectra ?

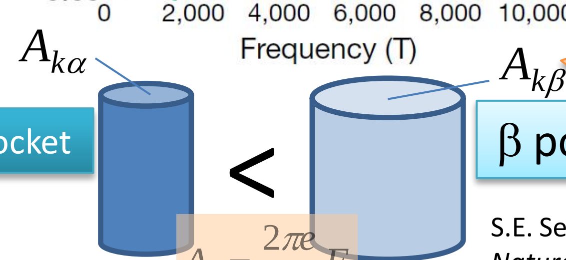
2010



Peaks at Lower frequencies meaning small F.S. (pocket)

2008





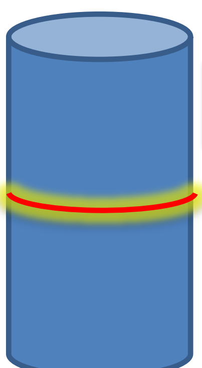
α pocket

β pocket

New!!

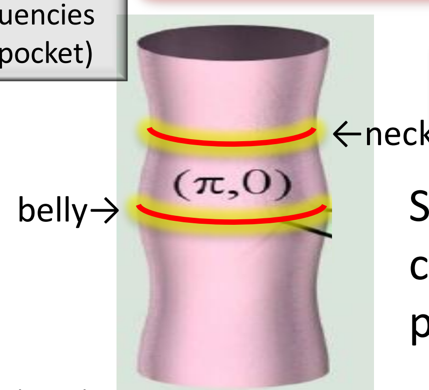
$$A_k = \frac{2\pi e}{\hbar} F$$

S.E. Sebastian, et al., *Nature* 454, 200 (2008)



α pocket

Supposed F. S. Cylinder α for the peak of dominant frequency F_α .



γ pocket

「波打ってる」

Supposed the ***corrugated*** cylinder γ for two satellite peaks. $F_{\gamma,neck}$, $F_{\gamma,belly}$

S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Results and analysis

Analysis by Fourier translation

Fitting !

$$\Delta f = \sum_{i=\alpha,\gamma} \Delta f_{i,0} R_T R_D J_0\left(\frac{2\pi \Delta F_{i,\theta}}{\mu_0 H \cos\theta}\right)\cos\left(\frac{2\pi F_i}{\mu_0 H}\right)$$

↑ amplitude

$$F_{i,(\text{neck,belly})}\cos\theta = F_i \pm \Delta F_{i,\theta}$$

↑ Effect of deapth of corrugation of sheet i ,angle θ

Temperature Damping factor

$$R_T = (2\pi^2 k_B m_i^* T / e\hbar\mu_0 H) / \sinh(2\pi^2 k_B m_i^* T / e\hbar\mu_0 H)$$

Dingle Damping factor

$$R_D = \exp\left(\frac{-\Gamma_i}{\mu_0 H}\right)$$

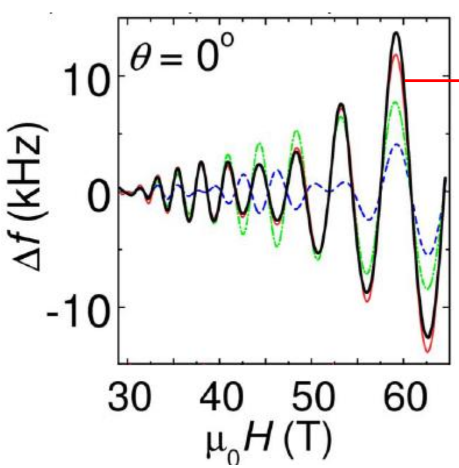
Γ_i : damping constant

J_0 : Bessel function (phase smearing)

Results

$x = 0.56$

Red one



S.E. Sebastian, et al.,PRB 81, 214524 (2010)

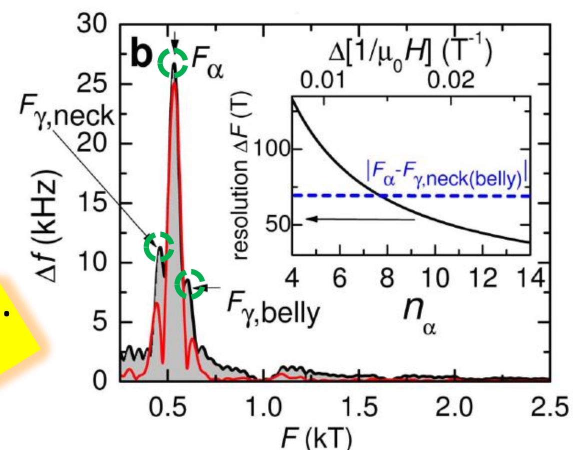
α pocket

$F_{\alpha,0} = 531 \pm 2$ T, $\Delta F_{\alpha,0} \leqq 11$ T

γ pocket

$F_{\gamma,0} = 532 \pm 2$ T, $\Delta F_{\gamma,0} = \mathbf{72} \pm 11$ T

Corresponding to…



$F_\alpha = 531 \pm 2$ T

$F_{\gamma,\text{neck}} = 460 \pm 4$ T, $F_{\gamma,\text{belly}} = 604 \pm 4$ T

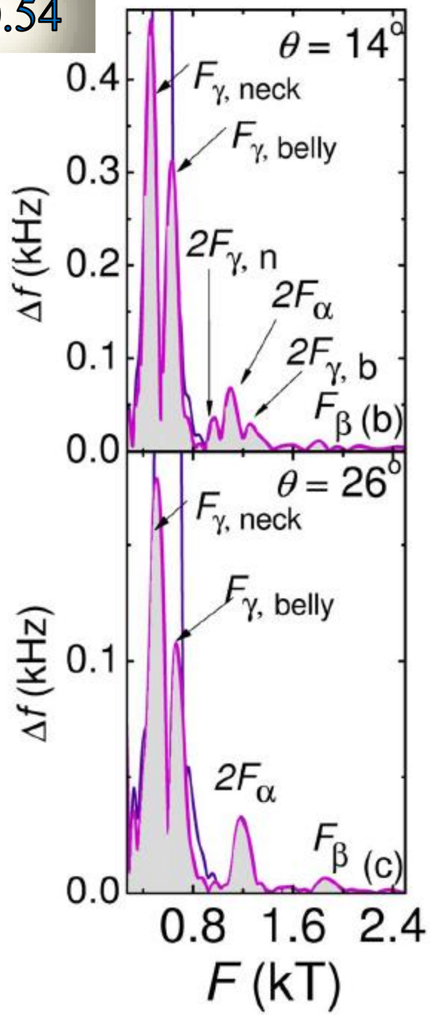
Reasonable results !

and we can subtract the dominant α component.

Results and analysis

Analysis by Yamaji's expression

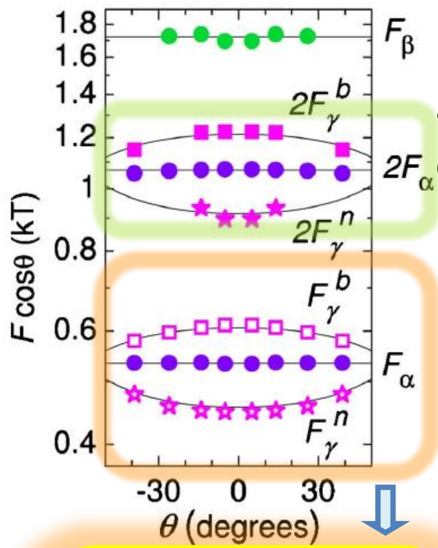
$x = 0.54$



γ (neck+belly) and β components after subtracting α

S.E. Sebastian, et al.,PRB 81, 214524 (2010)

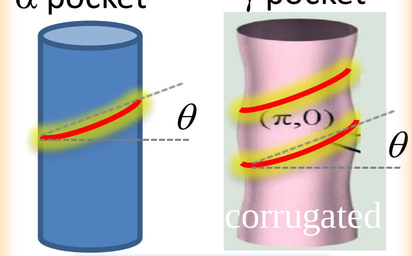
Angular dependence (about θ)



Harmonics are also observed!!

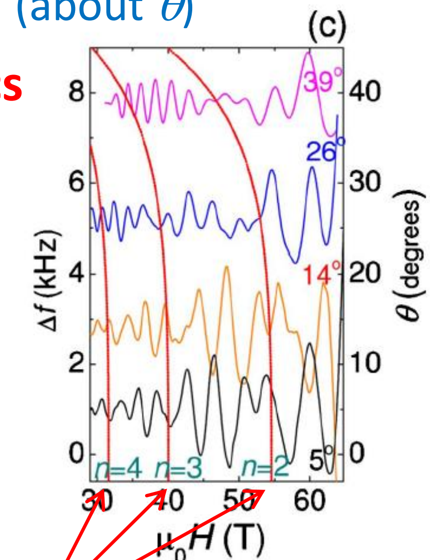
Similarly sized

α pocket γ pocket



Onsager expression

$$F = \Delta\left(\frac{1}{B}\right) = \frac{2\pi e}{\hbar c S}$$



Fitting

Detecting locations of **nodes** in oscillation component of γ (neck+belly)

$$\mu_0 H_n \cos\theta = \frac{8\Delta F_{\gamma,\theta}}{4n+3}$$

n : number of node

$H_{n,i}$: the field at nth node

Yamaji's expression

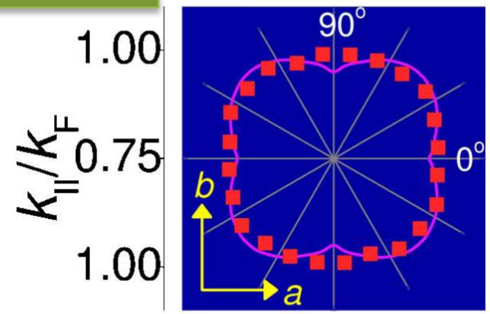
$$\Delta F_{i,\theta} = \Delta F_{i,0} J_0(k_{\parallel} c \tan\theta)$$

Results and analysis

Angular dependence of In-layer rotation (ϕ)

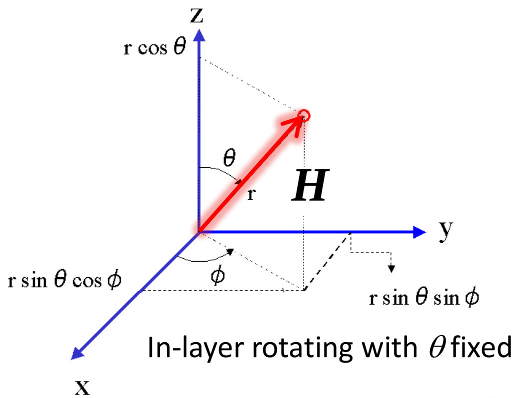
α pocket : independent on ϕ
because of less corrugation
periodic in $1 / \mu_0 H\cos\theta$

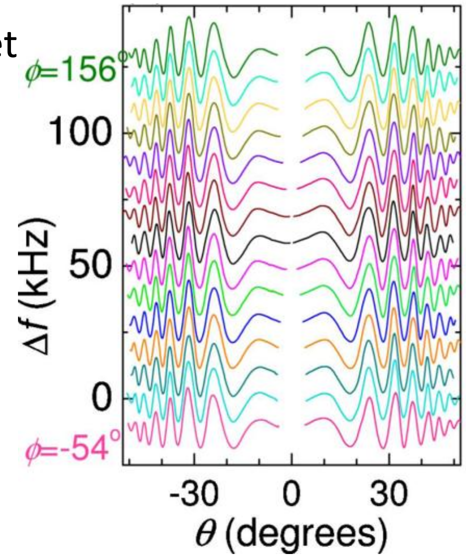
The topology of γ pocket



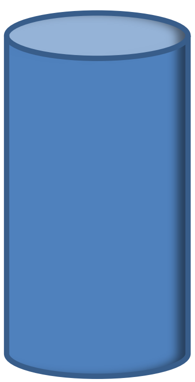
In-layer dispersion in γ pocket

Consistent with numerous
F.S. reconstruction models



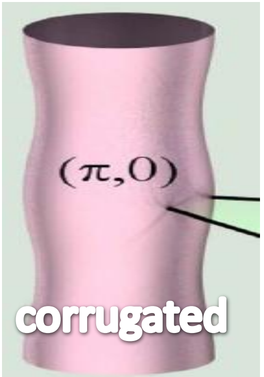


α pocket

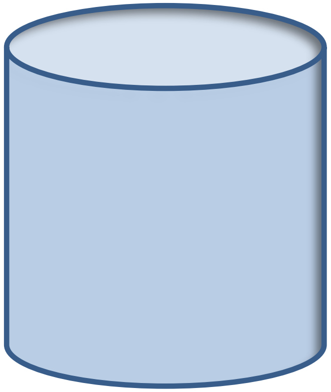


γ pocket

New!!



β pocket

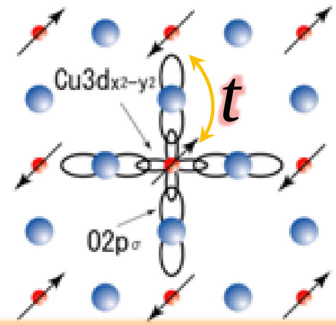


Similar size

S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Discussion

In-layer dispersion ($\boldsymbol{k} = (k_x, k_y)$)   Cu $d_{x^2-y^2}$ like band



$$\varepsilon(\mathbf{k}) = -4t\left[u(\mathbf{k}) + 2r\frac{v(\mathbf{k})^2}{1-2ru(\mathbf{k})}\right]$$

$$u(\mathbf{k}) \equiv \tfrac{1}{2}(\cos k_x + \cos k_y)$$
$$v(\mathbf{k}) \equiv \tfrac{1}{2}(\cos k_x - \cos k_y)$$

t : the nearest neighbor (in-laye hopping integrals

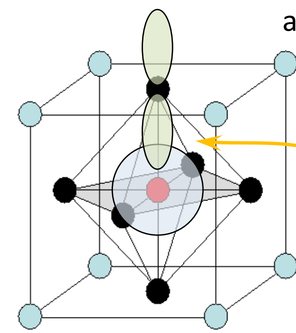
STEP1

Tight binding model

If r is small…

r : the range parameter of in-layer hopping via **axial orbital**

axial orbital: Hybrid of mostly Cu 4s and apical O $2p_z$



● : Cu ● : O

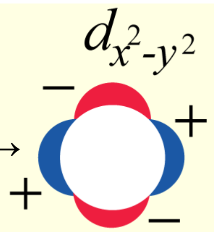
$$\varepsilon(\mathbf{k}) = \text{const.} - 2t(\cos k_x + \cos k_y) + 4t' \cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y),$$

Hopping to next neighbor $t' = rt$
third neighbor $t'' = rt/2$

STEP2

Considering interlayer hopping… ← axial orbital

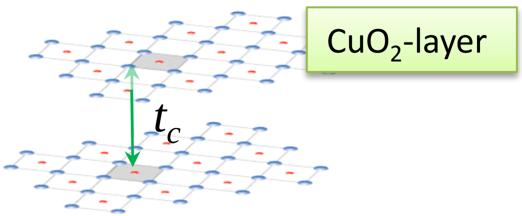
t_c : 4-fold rotation symmetry ←gap function $\Delta(\mathrm{k})$→



$$r \longrightarrow r + (t_c^0/t)\cos k_z$$

k_z : interlayer dispersion

t_c: interlayer hopping integrals



For $YBa_2Cu_3O_{6+x}$ (x~0.5) , t ~400meV

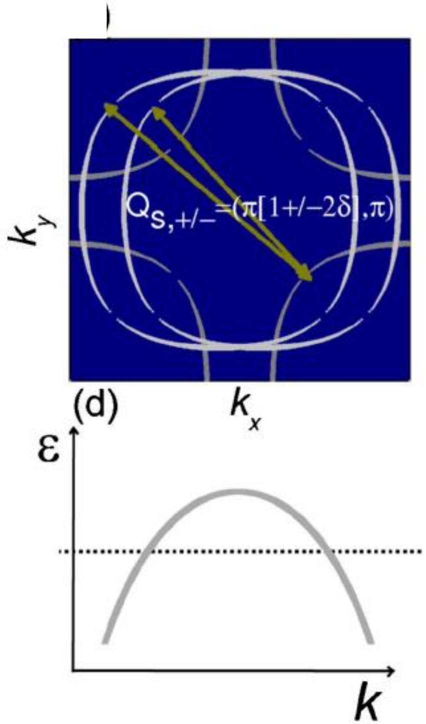
t_c^0 causes to r vary 0.28 ~ 0.32 → **Perturbation in $r(k)$**

Discussion

r perturbation → k_z dispersion → Corrugation of pockets

Same symmetry in k_z (thickness of lines) *and gap* Δ …

Nodal point $(\pi/2, \pi/2)$: $\Delta = 0$, k_z ~ min
Antinodal point $(0, \pi)$: Δ ~ max, k_z ~ max



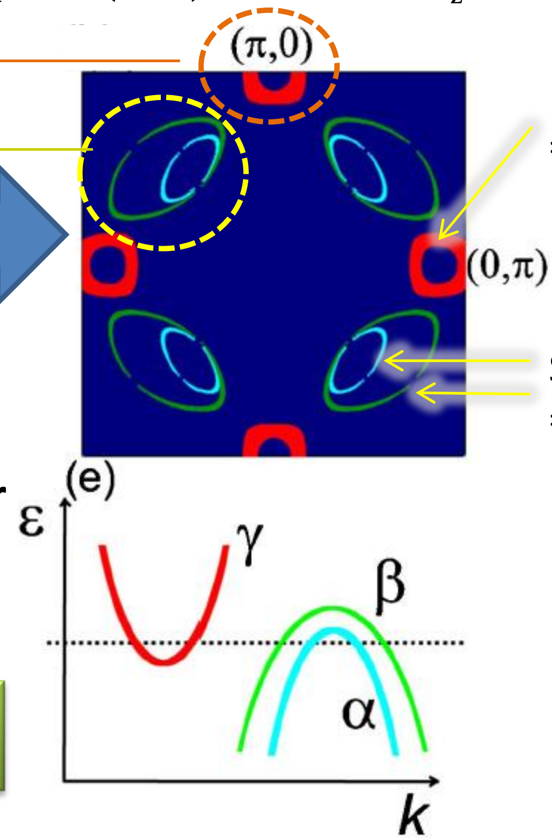
Unreconstructed F. S.
& band structure

Reconstruction

Translational symmetry-breaking order

by incommensurate vector
$$Q_{s,\pm} = (\pi[1 \pm 2\delta], \pi)$$
Order parameter : Δ_s

First instability



Large k_z
= corrugated
γ pocket ?

Small k_z
= less corrugeted
α,β pocket ?

Reconstructed F. S.
& band structure

S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Discussion

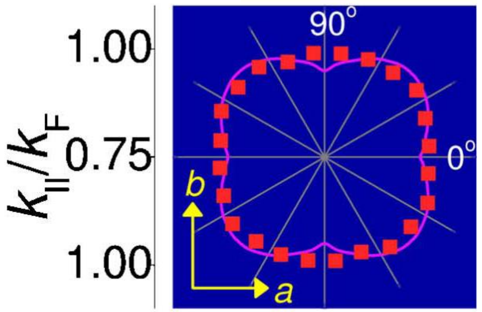
What kind of order reconstructs F.S. ?

Translational symmetry-breaking order

Incommensurate vector

$Q_{s,\pm} = (\pi[1 \pm 2\delta], \pi)$

Order parameter : Δ_s



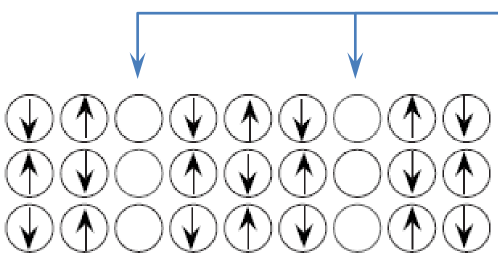
S.E. Sebastian, et al.,PRB 81, 214524 (2010)

(1) Stripe structure

Typically $\delta = 1/8$

「しま模様」

stripe SDW



Charge stripe
(antiphase domain wall)

A. J. Mills, et al.,PRB 76, 220503 (2007)

(2) Helical structure ←considered now

Typically $\delta = 1/16$

「らせん状」

helical SDW

or DDW $\Delta_{\mathbf{k}} = i2\Delta_{\mathrm{DDW}}(\cos k_x - \cos k_y)$

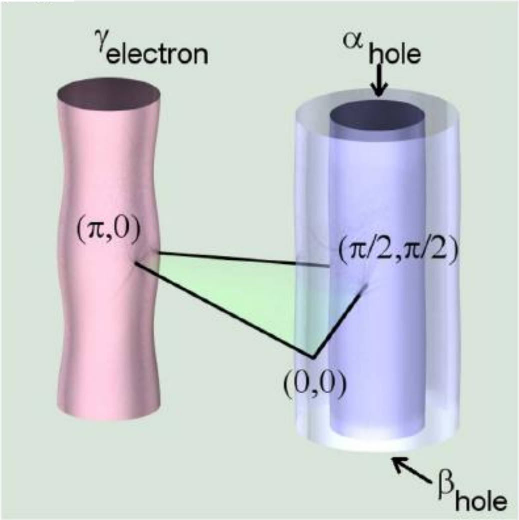
Adjusting $\Delta_s = 0.625t$ yields ($p \sim 0.117$)

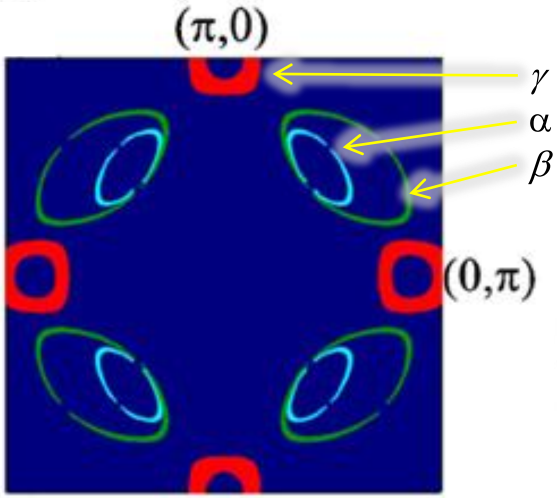
- three pockets of size (within2%)
- carrier type
- corrugation depth
- shape

(observed $t \sim 100\mathrm{meV}$)

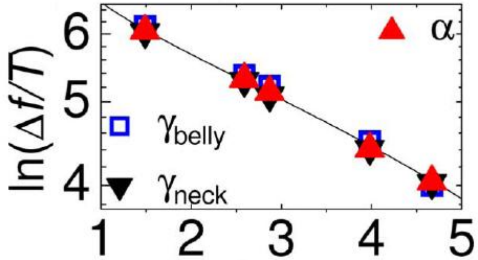
consistent with results !

Discussion





γ electorn-pocket (at antinodal point)
α hole-pocket (at nodal point)
β hole-pocket (at nodal point)



$$R_T = (2\pi^2 k_B m_i^* T / e\hbar\mu_0 H) / \sinh(2\pi^2 k_B m_i^* T / e\hbar\mu_0 H)$$

Compensated two pockets

α **hole**-pocket
γ **electron**-pocket

occupying 1.91±0.01 % of B.Z.

(for example, x=0.56)

$$m_\alpha^* \approx m_\gamma^* \approx 1.6 m_e$$

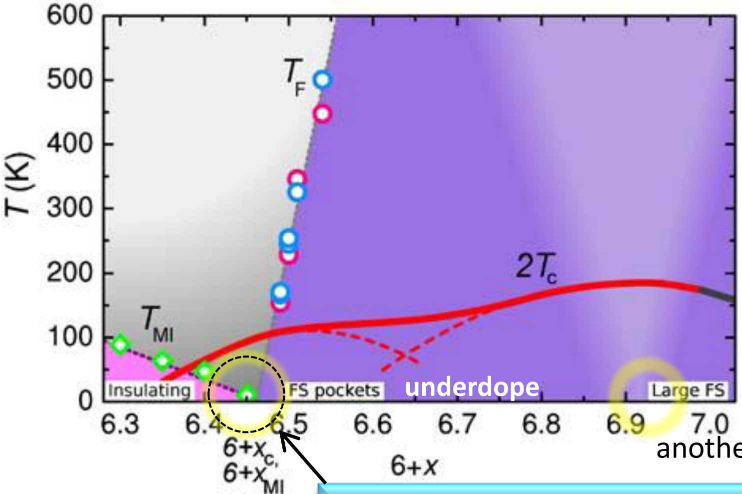
β pocket acts as a reservoir of charge carriers, satisfying Luttinger count in the SDW state.

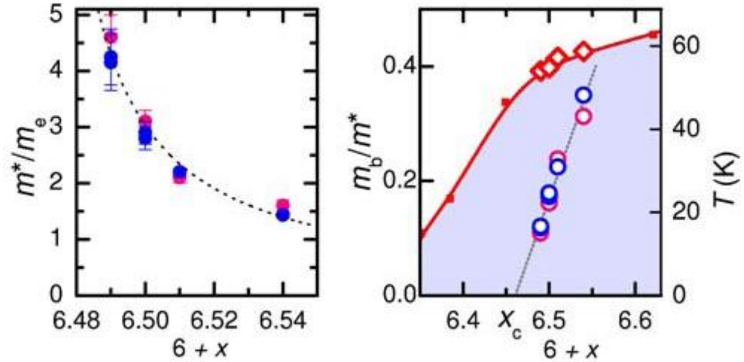
S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Discussion

Excitonic insulator instability

Metal-insulator Phase diagram under field





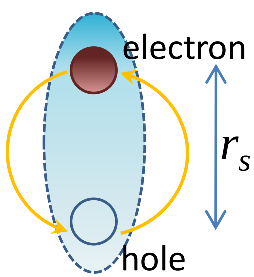
Observed divergence of effective mass

$x_c = 0.46$

metal-insulator QCP ?

S.E. Sebastian, et al., Proc. Natl.Acad. Sci. U.S.A. **107, 6175 2010**

Exiton : electron-hole pair (boson)



Analogy to hydrogen atom

$x = 0.56$

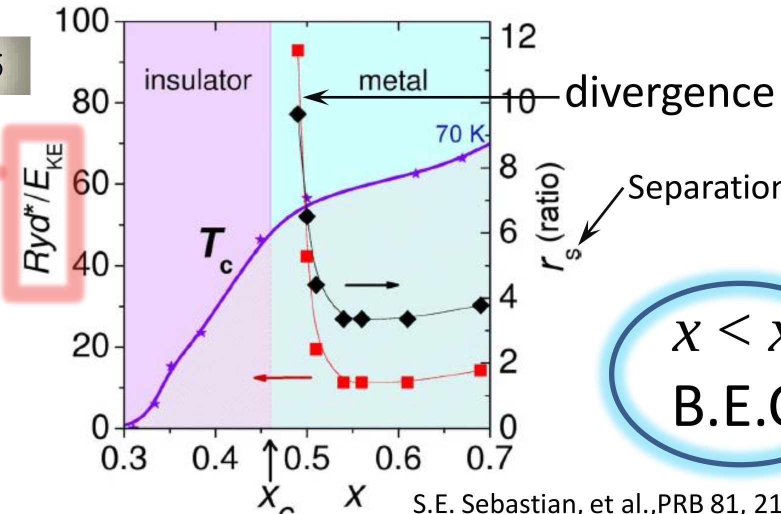
Binding energy
$Ry^* \sim 430meV$

effective "Rydberg"

$\vee\!\!\!\vee$

Individual kinetic energy
$E_{KE} \sim 37meV$

$$Ry^* = \frac{\mu}{m_e}\frac{1}{\epsilon^2}Ry \quad E_{ke} = \frac{e\hbar F}{m^*} \quad a^* = \epsilon\frac{m_e}{\mu}a_0 \quad r_s \approx \frac{1}{a^*}\sqrt{\frac{1}{\pi n}}$$



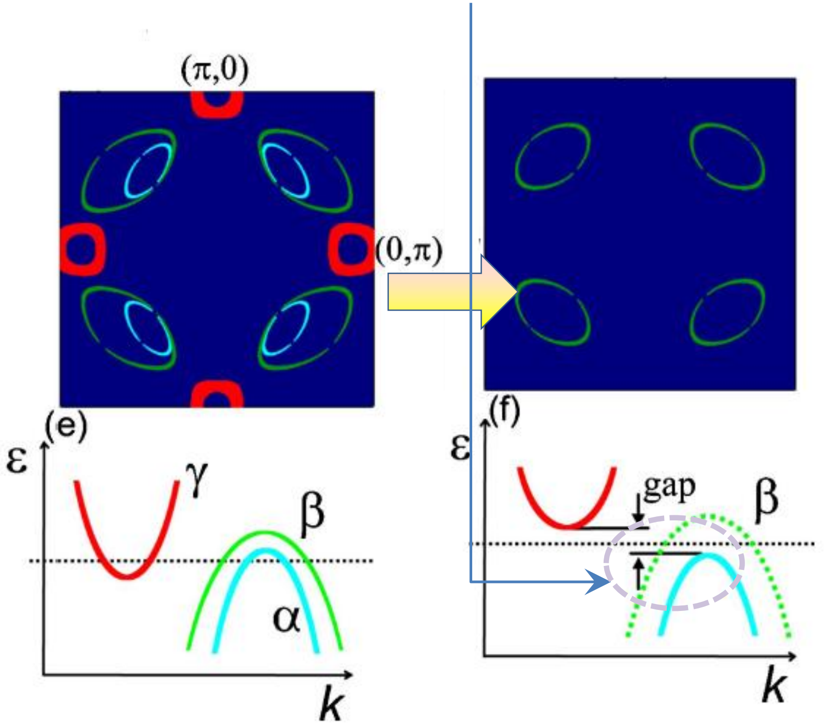
$x < x_c$
B.E.C.

S.E. Sebastian, et al.,PRB 81, 214524 (2010)

Discussion

Secondary instability ~Destruction of compensated pockets ~

Gap due to excitonic insulator instability $(x < x_c)$



Observed F.S. (and band)

F.S. after secondary reconstruction

Acoompanying **charge order** "stripelike"

by $Q_c = 2Q_s = (\pm 4\delta\pi, 0)$

- Phonon broading
- superlatice

- spin order
- magnetic excitation

(This order can accompany SDW.)

Additional new couplings

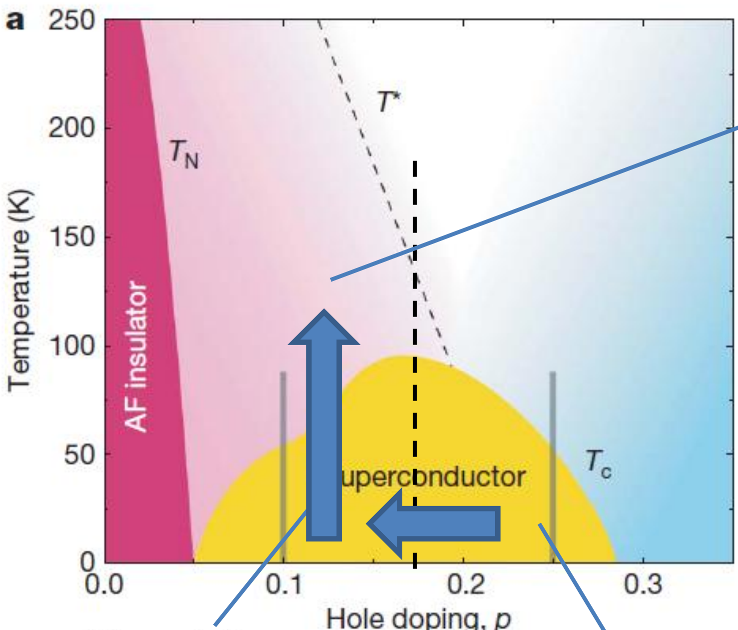
$\varepsilon_{k+n\mathbf{Q}s}$ & $\varepsilon_{k+(n\pm 2)\mathbf{Q}s}$

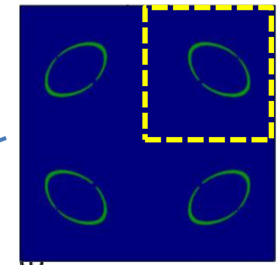
Destruction of pockets or Creation open F.S. sheets

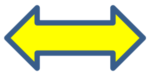
S.E. Sebastian, et al.,PRB 81, 214524 (2010)

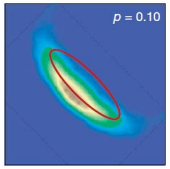
Discussion

Reconcilation with ARPES experiments

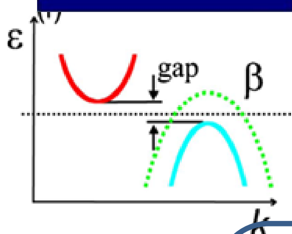


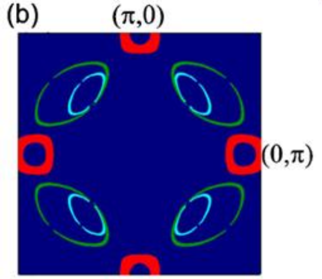


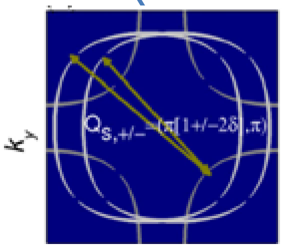




F.S. in underdoped YBCO
after 2nd reconstruction







Q.O.(Tl- dope)

Through ARPES ,we can see…

Normal state ($T > T_c$, B=0)

Incoherent S.C. pairs destroying the spectral weight

Through Q.O…

Quantum vortex liquid state

N. Doiron-Leyraud, et al., *Nature* 447, 565 (2007)
S.E. Sebastian, et al.,PRB 81, 214524 (2010)

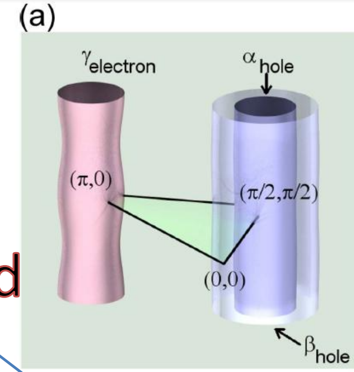
Summary

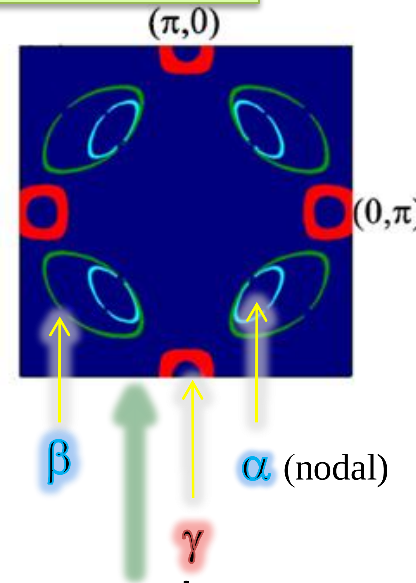
High-resolution Quantum Oscillation measurements

Small hole-pocket : α ←cylindrical

Large hole-pocket : β ←cylindrical

Small electron-pocket : γ ←corrugated





k_z dispersion

($d_{x^2-y^2}$ symmetry)

α , γ :<u>Compensated</u> by each other

・Equal volume & mass ・Opposite charge

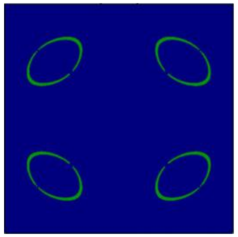
・Helical density wave model is consistent with <u>these results</u>.

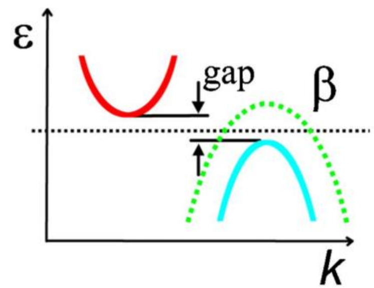
Translational symmetry-breaking order !

・Secondary F.S. instability by ...

・excitonic insulator ? : QCP

・stripelike charge order





S.E. Sebastian, et al.,PRB 81, 214524 (2010)