20aAD-10

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円筒容器中の超流動ヘリウム３-B相における準粒子状態

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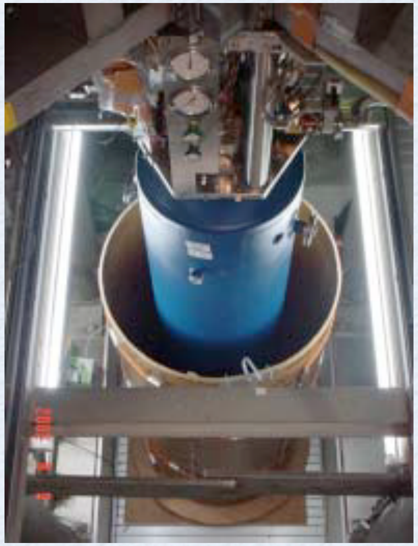
B-phase in cylinder

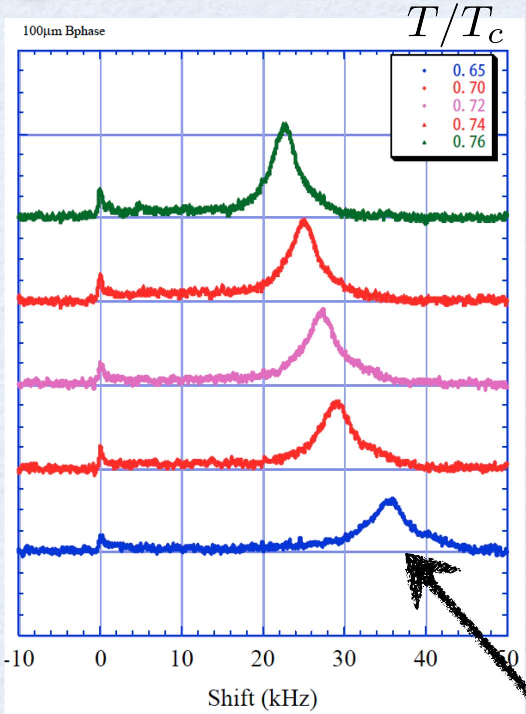
Rotating cryostat in ISSP



最高回転速度~12rad/s
試料半径 50μm, 100μm

数本の渦を侵入させることが可能
マヨラナゼロモード

NMR spectra

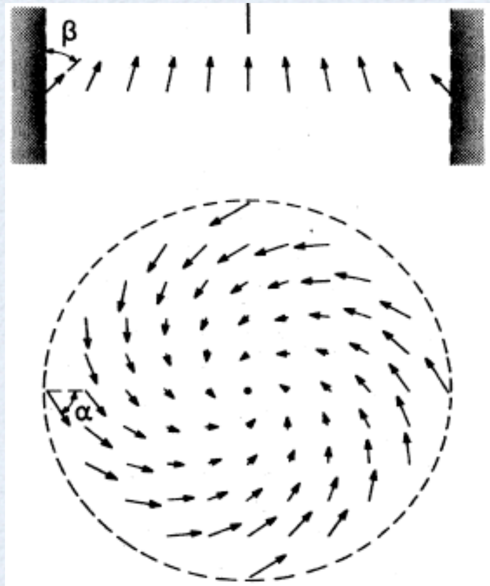


R. Ishiguro, Dr. Thesis (2003).

$$\Delta f_B^2 = \Omega_B^2 \sin^2\beta \propto \frac{|\Delta_B|^2}{\chi_B} \sin^2\beta$$

マヨラナエッジ状態
異方的スピン帯磁率

flare-out texture



M.M. Salomaa and G.E. Volovik, Rev. Mod. Phys. **59**, 533 (1987).

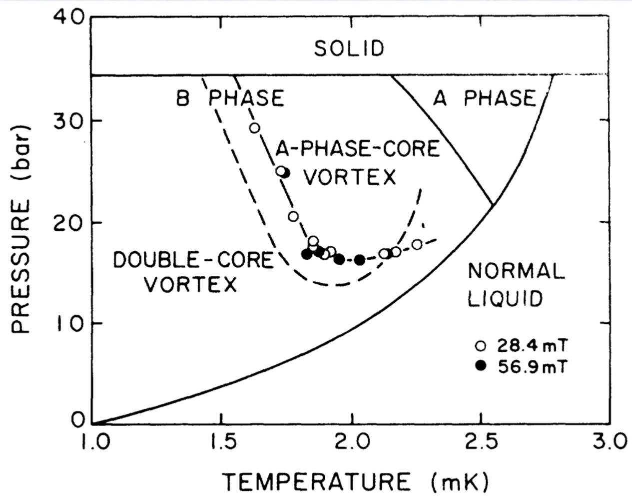
$\beta = 63.4°$
edge

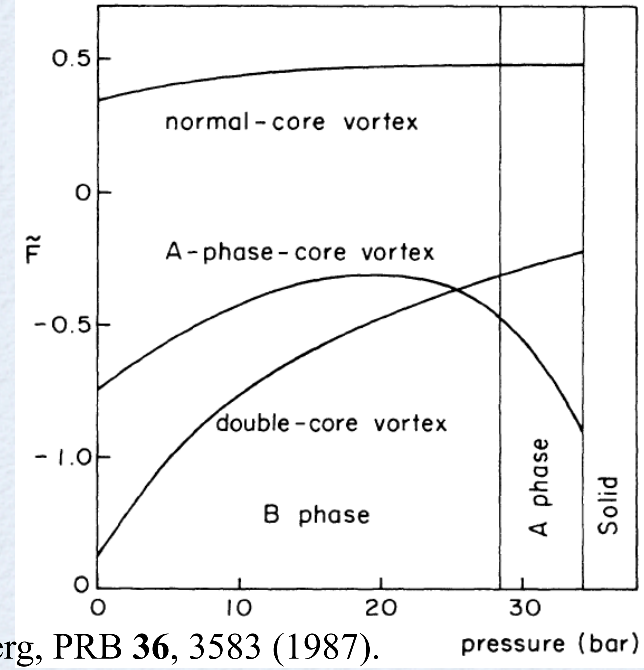
Outline of research

- n-texture
- Quasiparticle states (vortex, edge)
- Spin susceptibility
- NMR spectrum

Vortex in B-phase

Phase diagram of vortex



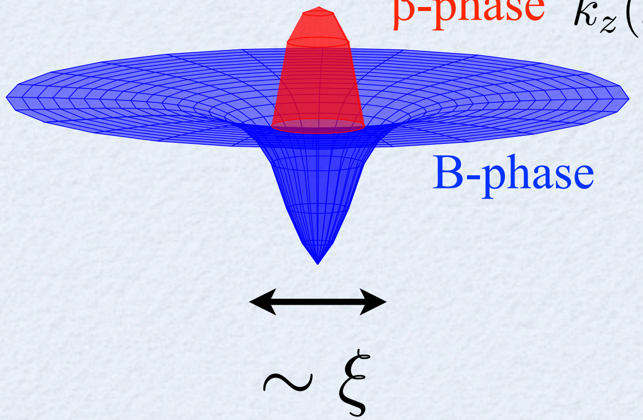


Thuneberg, PRB **36**, 3583 (1987).

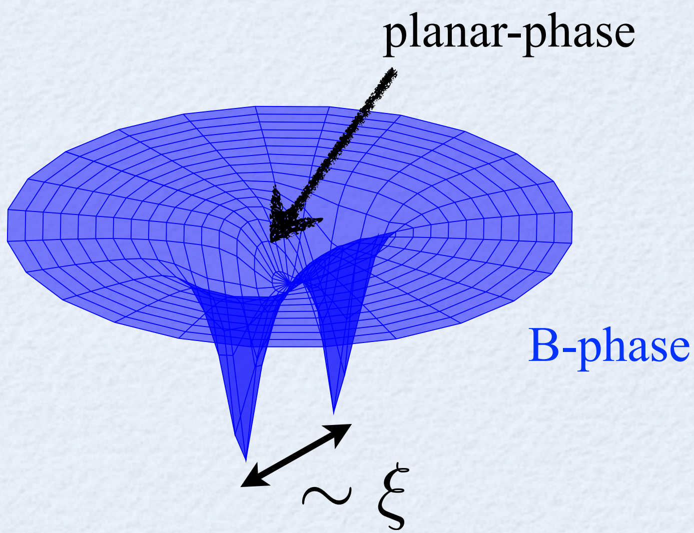
A-phase-core vortex

A-phase $(k_x + ik_y)\hat{z}$ $L_z = 1, S_z = 0$

β-phase $k_z(\hat{x} + i\hat{y})$ $L_z = 0, S_z = 1$



double-core vortex



Quasi-classical Eilenberger theory

$$\Delta/E_F \ll 1 \qquad \int d\xi_k \widehat{\sigma}_z \widehat{G}(\boldsymbol{k},\boldsymbol{r},\omega_n) \equiv \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) \equiv -i\pi \begin{pmatrix} \hat{g} & i\hat{f} \\ -i\underline{\hat{f}} & -\underline{\hat{g}} \end{pmatrix}$$

Eilenberger equation

$$-i\hbar \boldsymbol{v}_F \cdot \boldsymbol{\nabla} \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) = \left[\begin{pmatrix} i\omega_n \hat{1} & -\hat{\Delta}(\boldsymbol{k}_F,\boldsymbol{r}) \\ \hat{\Delta}^\dagger(\boldsymbol{k}_F,\boldsymbol{r}) & -i\omega_n \hat{1} \end{pmatrix}, \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) \right]$$

$\widehat{g}$ ↓ ↑ $\hat{\Delta}$

Gap equation

$$\hat{\Delta}(\boldsymbol{k}_F,\boldsymbol{r}) = N_0 \pi k_B T \sum_{-\omega_c \le \omega_n \le \omega_c} \left\langle V(\boldsymbol{k}_F,\boldsymbol{k}'_F) \hat{f}(\boldsymbol{k}'_F,\boldsymbol{r},\omega_n) \right\rangle_{\boldsymbol{k}'_F}$$

pair potential : $V(\boldsymbol{k}_F,\boldsymbol{k}'_F) = 3g_1 \boldsymbol{k}_F \cdot \boldsymbol{k}'_F$

Local density of states (LDOS)

$$\hat{g} = \begin{pmatrix} g_0 + g_z & g_x - ig_y \\ g_x + ig_y & g_0 - g_z \end{pmatrix}$$

$$N(\boldsymbol{r},E) = \langle N(\boldsymbol{k}_F,\boldsymbol{r},E) \rangle_{\boldsymbol{k}_F} = N_0 \langle \mathrm{Re}[g_0(\boldsymbol{k}_F,\boldsymbol{r},\omega_n)|_{i\omega_n \to E + i\eta}] \rangle_{\boldsymbol{k}_F}$$

Dispersion

Riccati equations

$$-i\hbar \boldsymbol{v}_F \cdot \boldsymbol{\nabla} \widehat{g}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) = \left[\begin{pmatrix} i\omega_n \hat{1} & -\hat{\Delta}(\boldsymbol{k}_F, \boldsymbol{r}) \\ \hat{\Delta}^\dagger(\boldsymbol{k}_F, \boldsymbol{r}) & -i\omega_n \hat{1} \end{pmatrix}, \widehat{g}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) \right]$$

$$\widehat{g} \equiv -i\pi \begin{pmatrix} \hat{g} & i\hat{f} \\ -i\underline{\hat{f}} & -\underline{\hat{g}} \end{pmatrix}$$

$$\begin{pmatrix} \hat{g} & i\hat{f} \\ -i\underline{\hat{f}} & -\underline{\hat{g}} \end{pmatrix} = \begin{pmatrix} (\hat{1} + \hat{a}\hat{b})^{-1} & 0 \\ 0 & (\hat{1} + \hat{b}\hat{a})^{-1} \end{pmatrix} \begin{pmatrix} \hat{1} - \hat{a}\hat{b} & 2i\hat{a} \\ -2i\hat{b} & -(\hat{1} - \hat{b}\hat{a}) \end{pmatrix}$$

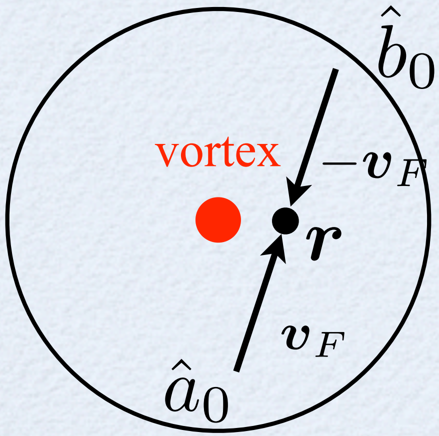
Riccati equations

toward $\boldsymbol{v}_F$

$$\hbar \boldsymbol{v}_F \cdot \boldsymbol{\nabla} \hat{a}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) = \hat{\Delta} - \hat{a}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) \hat{\Delta}^\dagger \hat{a}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) - 2\omega_n \hat{a}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n)$$

toward $-\boldsymbol{v}_F$

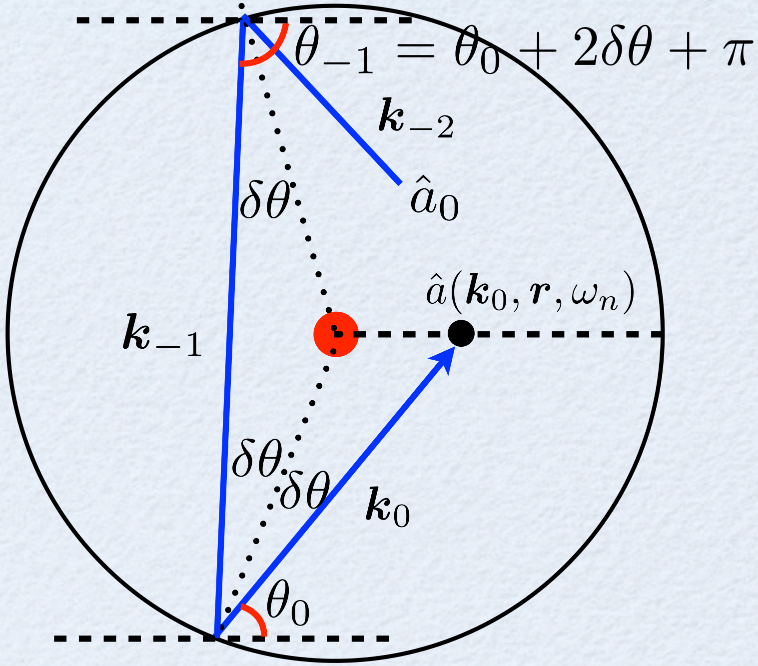
$$-\hbar \boldsymbol{v}_F \cdot \boldsymbol{\nabla} \hat{b}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) = \hat{\Delta}^\dagger - \hat{b}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) \hat{\Delta} \hat{b}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n) - 2\omega_n \hat{b}(\boldsymbol{k}_F, \boldsymbol{r}, \omega_n)$$



Numerical method

オーダーパラメーターが空間変化しているため、
a, bの初期値を決定することができない。
ただし、コヒーレンス長よりも十分長い積分経路をとれば初期値によらない解を得られる。

Y. Nagai *et al.*, arXiv:1202.2661.



$$k_{-1,x} = -k_{0,x} \cos[2(\theta_0 + \delta\theta)] - k_{0,y} \sin[2(\theta_0 + \delta\theta)]$$

$$k_{-1,y} = -k_{0,x} \sin[2(\theta_0 + \delta\theta)] + k_{0,y} \cos[2(\theta_0 + \delta\theta)]$$

$$\hbar \boldsymbol{v}_F(\boldsymbol{k}_{-1}) \cdot \boldsymbol{\nabla} \hat{a}(\boldsymbol{k}_0, \boldsymbol{r}, \omega_n) = \hat{\Delta}(\boldsymbol{k}_0, \boldsymbol{r}) - \hat{a}(\boldsymbol{k}_0, \boldsymbol{r}, \omega_n) \hat{\Delta}^\dagger(\boldsymbol{k}_0, \boldsymbol{r}) \hat{a}(\boldsymbol{k}_0, \boldsymbol{r}, \omega_n) - 2\omega_n \hat{a}(\boldsymbol{k}_0, \boldsymbol{r}, \omega_n)$$

$$\hbar \boldsymbol{v}_F(\boldsymbol{k}_0) \cdot \boldsymbol{\nabla} \hat{a}(\boldsymbol{k}_{-1}, \boldsymbol{r}, \omega_n) = \hat{\Delta}(\boldsymbol{k}_{-1}, \boldsymbol{r}) - \hat{a}(\boldsymbol{k}_{-1}, \boldsymbol{r}, \omega_n) \hat{\Delta}^\dagger(\boldsymbol{k}_{-1}, \boldsymbol{r}) \hat{a}(\boldsymbol{k}_{-1}, \boldsymbol{r}, \omega_n) - 2\omega_n \hat{a}(\boldsymbol{k}_{-1}, \boldsymbol{r}, \omega_n)$$

$$\hat{\Delta}(\boldsymbol{k}, \boldsymbol{r}) = i C_{\mu i}(\boldsymbol{r}) \hat{\sigma}_\mu \hat{\sigma}_y k_i$$

$$C_{\mu x}(\boldsymbol{r}) \to -C_{\mu x}(\boldsymbol{r}) \cos[2(\theta_0 + \delta\theta)] - C_{\mu y}(\boldsymbol{r}) \sin[2(\theta_0 + \delta\theta)]$$

$$C_{\mu y}(\boldsymbol{r}) \to -C_{\mu x}(\boldsymbol{r}) \sin[2(\theta_0 + \delta\theta)] + C_{\mu y}(\boldsymbol{r}) \cos[2(\theta_0 + \delta\theta)]$$

A-phase-core vortex

$T = 0.2T_c, R = 40\xi_0$

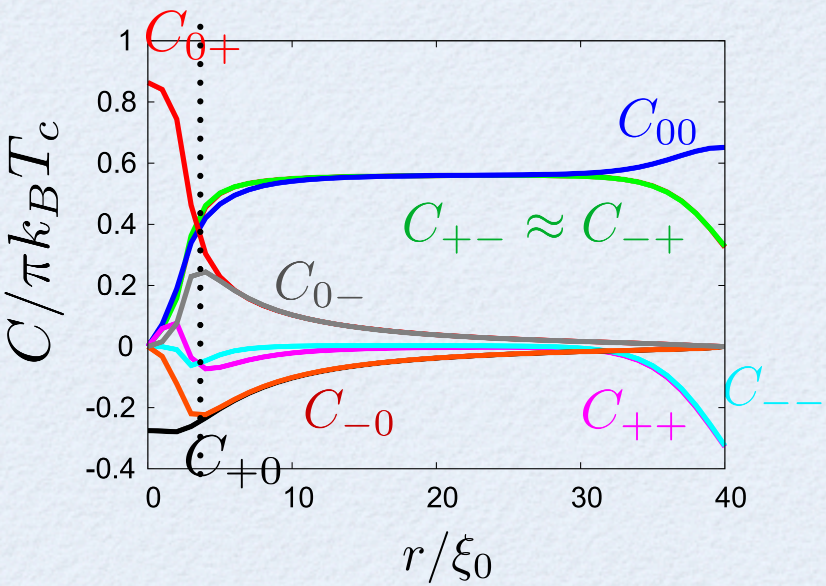
Order parameter

$$\hat{\Delta}(\boldsymbol{k},\boldsymbol{r}) = iC_{\mu i}(\boldsymbol{r})\hat{\sigma}_\mu\hat{\sigma}_y k_i$$

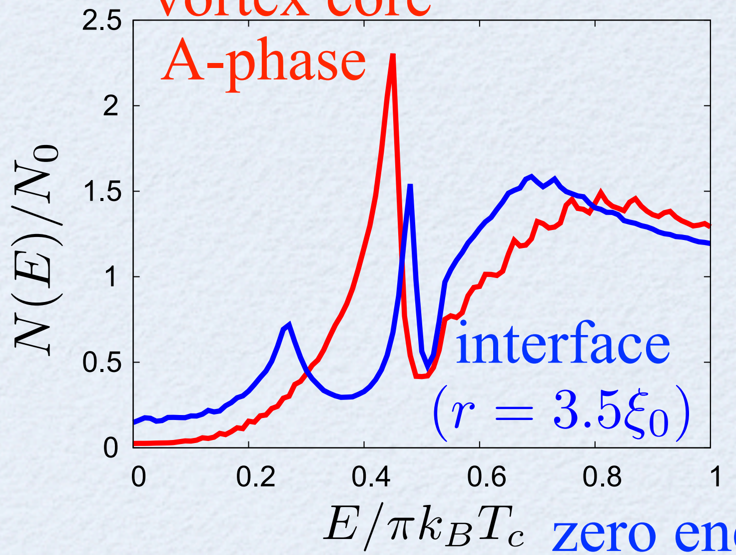
β-phase

$$C = \begin{pmatrix} C_{++}e^{-i\phi} & C_{+0} & C_{+-}e^{i\phi} \\ C_{0+} & C_{00}e^{i\phi} & C_{0-}e^{2i\phi} \\ C_{-+}e^{i\phi} & C_{-0}e^{2i\phi} & C_{--}e^{3i\phi} \end{pmatrix}$$

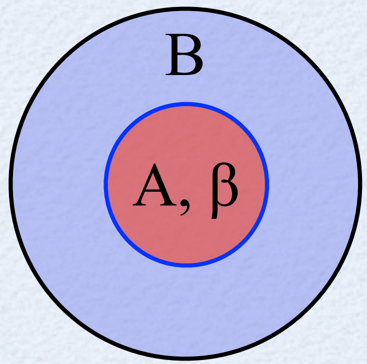
A-phase B-phase



LDOS

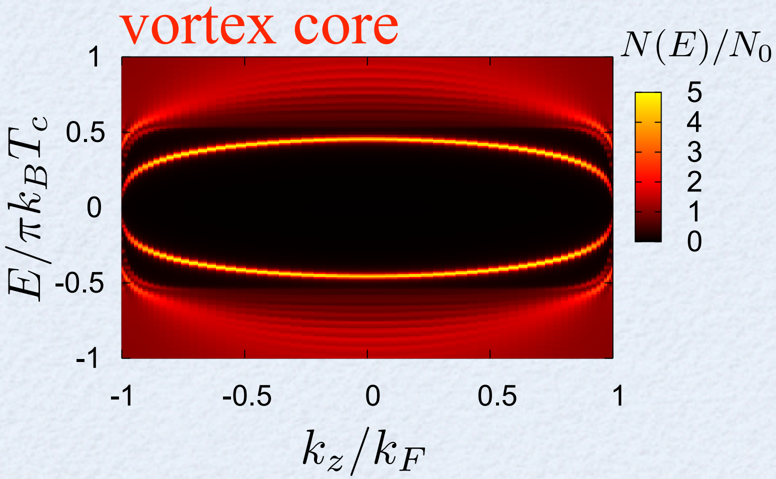


zero energy state double peaks

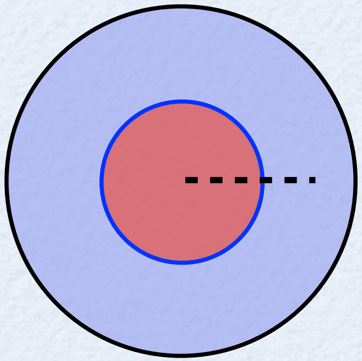


A-phase-core vortex

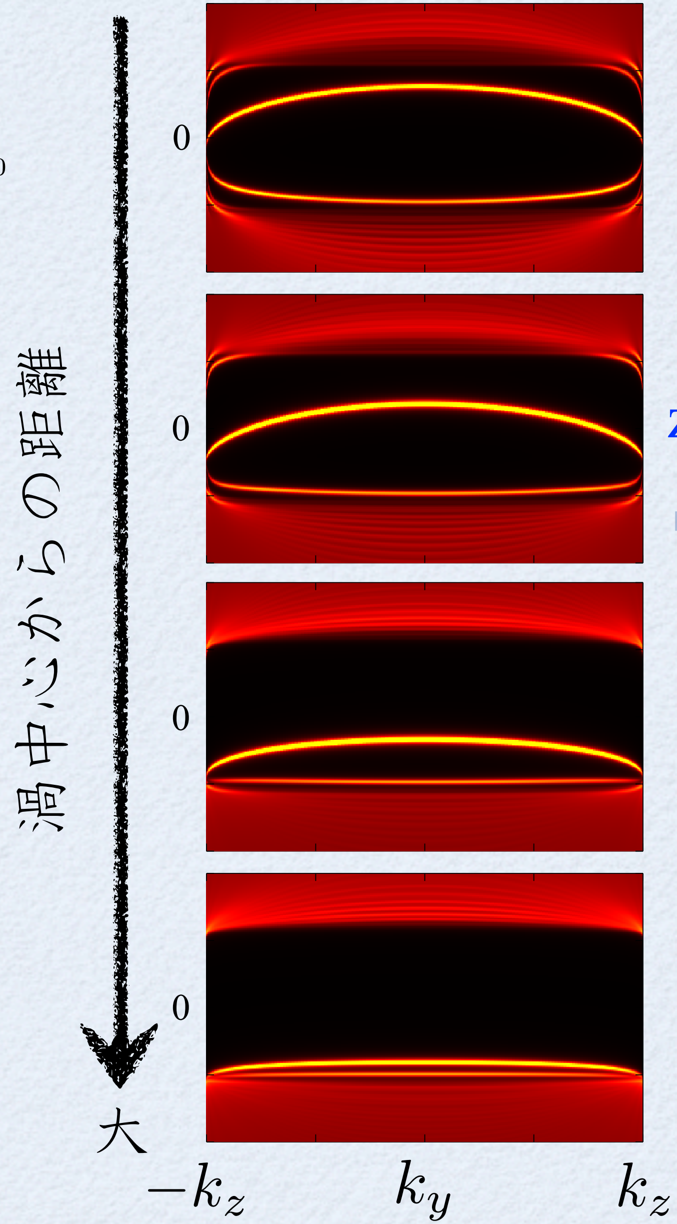
Dispersion



A相のギャップエッジ



トポロジカル超流動体間の
トポロジカル相転移



ブランチが
zero energyを横切る

➡ zero energy state

２つのブランチ

➡ double peaks

Double-core vortex

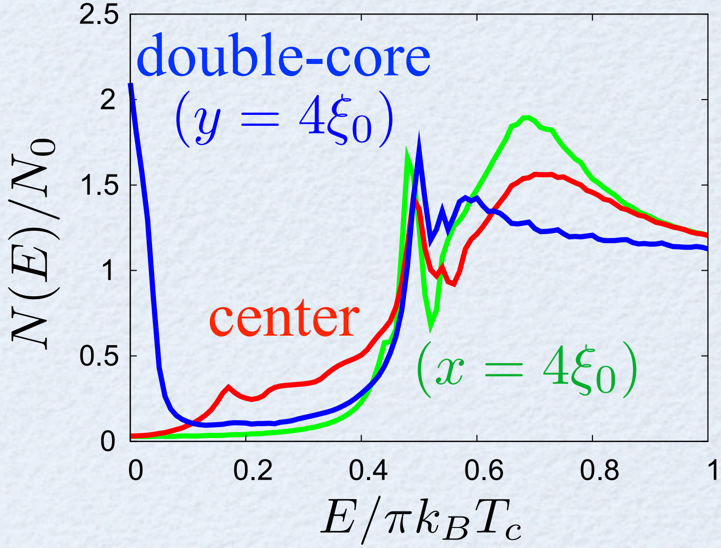
Order parameter

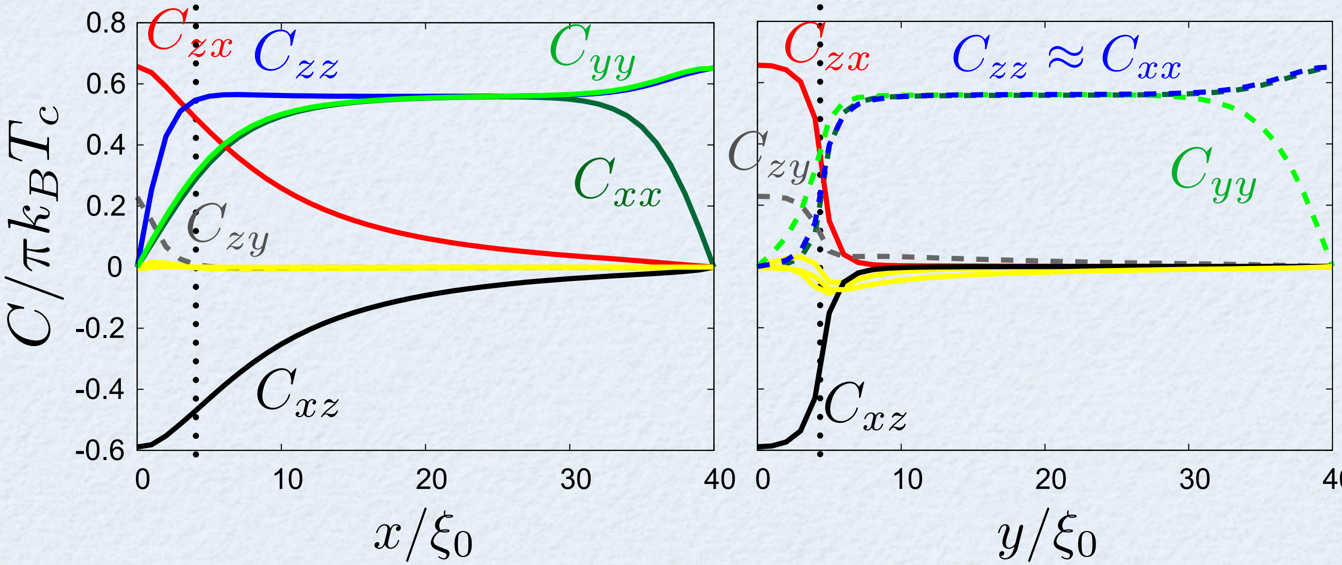
$$\hat{\Delta}(\boldsymbol{k}, \boldsymbol{r}) = iC_{\mu i}(\boldsymbol{r})\hat{\sigma}_\mu \hat{\sigma}_y k_i$$

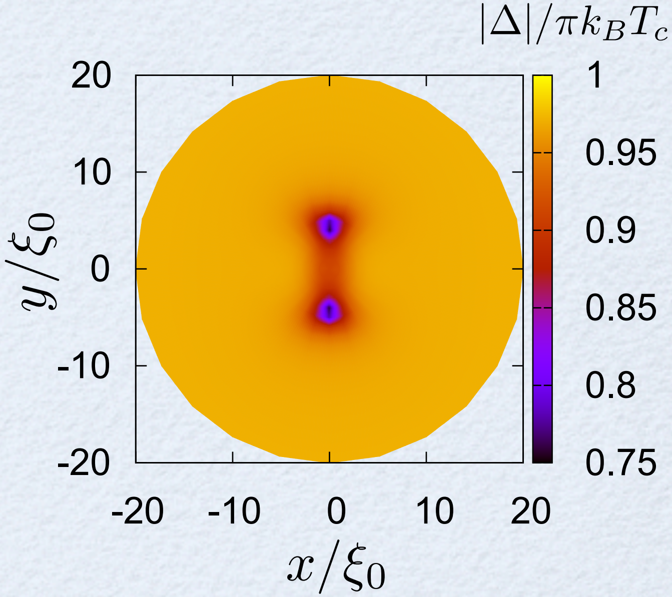
$$C(r = R) = \begin{pmatrix} C_{++}e^{-i\phi} & \underline{C_{+0}} & C_{+-}e^{i\phi} \\ \underline{C_{0+}} & C_{00}e^{i\phi} & \underline{C_{0-}e^{2i\phi}} \\ C_{-+}e^{i\phi} & \underline{C_{-0}e^{2i\phi}} & C_{--}e^{3i\phi} \end{pmatrix}$$

center: planar-like

LDOS zero energy peak



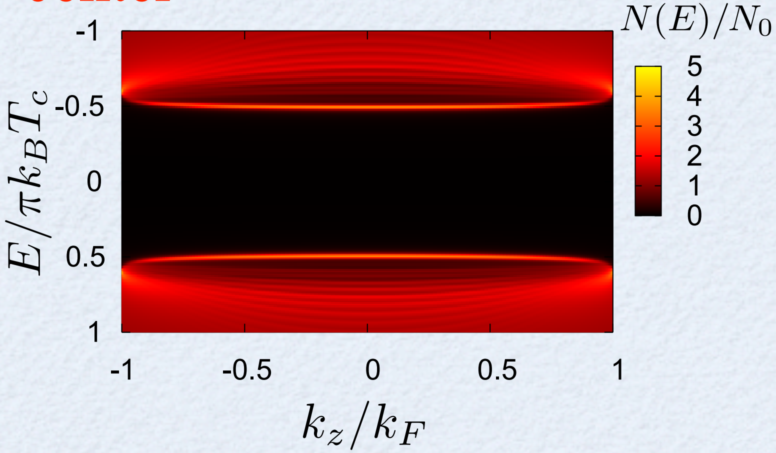


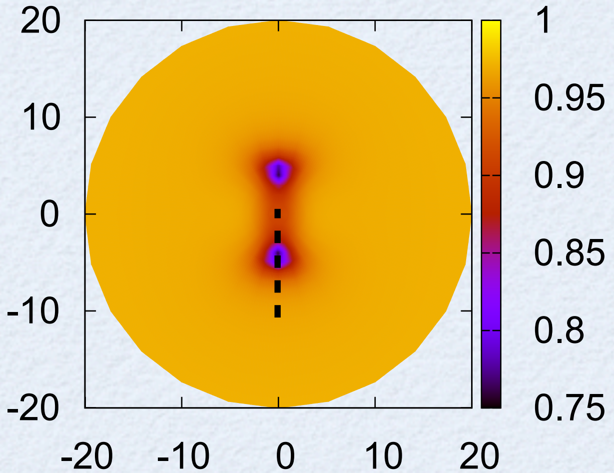


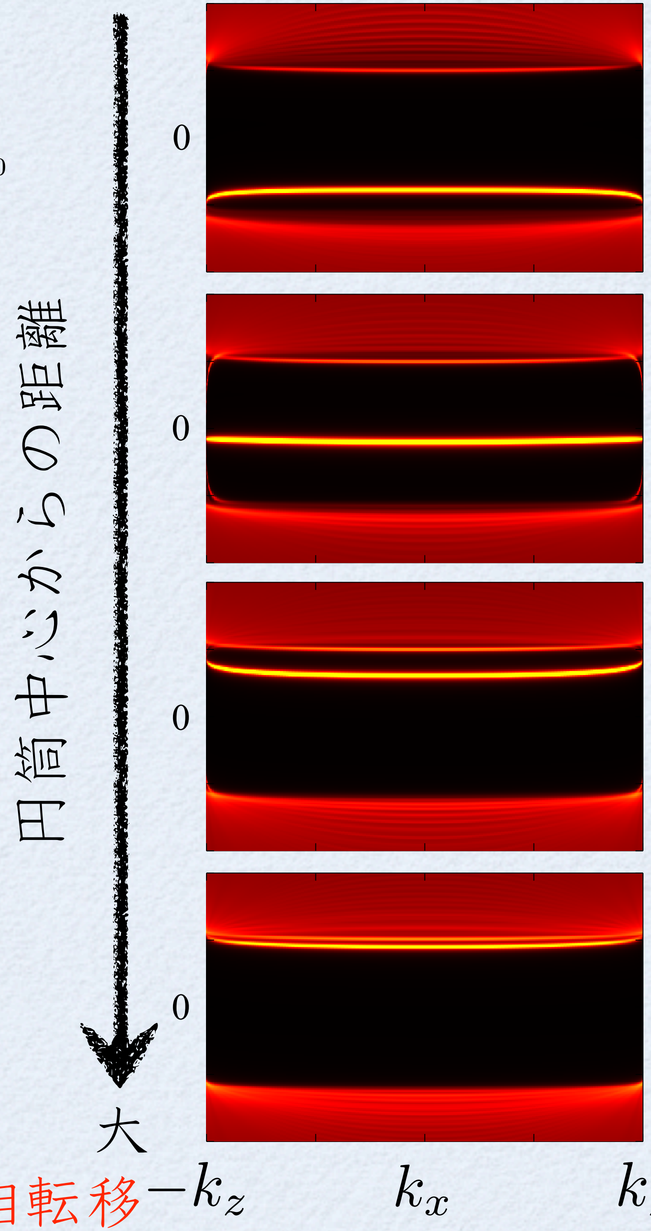
Double-core vortex

Dispersion

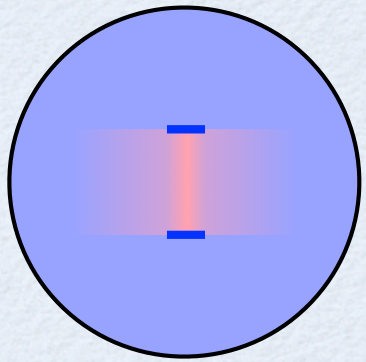
center







flat bandが
zero energyを横切る
→ zero energy peak



x方向: 連続変化
→ edge stateなし

y方向: 相変化
→ edge state

2D B-phase (planar-phase),
3D B-phase 間のトポロジカル相転移

Summary

B相の渦周りに異なるトポロジカル超流動体間のトポロジカル相転移によるエッジ状態が存在

- **A-phase-core vortex**

  A相⇔B相

- **Double-core vortex**

  2D B相⇔3D B相

→ ゼロエネルギー状態

Future prospects

- **n-texture**
- **Spin susceptibility**
- **NMR spectrum**