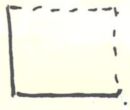
Dx'

Graphene 的对称性

π-flux 的为什么会有 Dirac cone?



· Unconventional superconductivity

$$\Psi_{\alpha_1\alpha_2}(r_1, r_2) = \Phi(\vec{R})\, \phi(\vec{r_1} - \vec{r_2})\, \chi_{\alpha_1\alpha_2}$$

$$\Phi(\vec{R}) = e^{i\vec{q}\cdot\vec{R}} \quad \text{— PDW}$$

isotropic system: $\phi(\vec{r_1} - \vec{r_2}) = Y_{lm}(\Omega)\, R(r)$

就是在动量有限大的地方配对

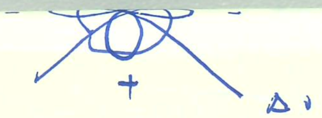
· $R_n(r)$ has nodes — extended s wave

1. conventional superconductivity: $R_{n=0}(r)$

positive-definite: ~~Gap~~ wavefunction 不变号的

d-wave superconductivity

$$\phi(\vec{r}) = \sum_{k} e^{i\vec{k}\cdot\vec{r}}\, \Delta(k)$$



$$\Delta(\phi) = \Delta_d \cos(2\phi)$$

- Fractional superconductivity:

$$\Delta(\phi) \propto \cos(\alpha\phi)$$

- p-wave ^3He A-B phases:

$l = 1$, p_x, p_y, p_z

$s = 1$,   3个

$$\Delta_{\mu\alpha}(k) = \sum_{k'} g(k-k')\, C^{\dagger}_{k'\alpha} \underline{(i\sigma_2 \sigma^{\mu})}_{\alpha\beta}$$

$$k'^{\alpha}\, k'\, C_{k'\beta}$$

Singlet pairing: $\boxed{C^{\dagger}_{\alpha}\,(i\sigma_2)\,C^{\dagger}_{\beta}}$

anti-symmetric $(i\sigma_2\sigma_\alpha)$

$\Downarrow$

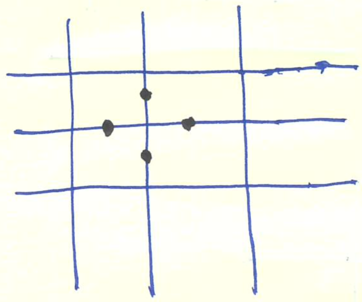
<u>charge conjugation matrix</u>

$$(i\sigma_2 c^+) = \begin{pmatrix} c_\downarrow^+ \\ -c_\uparrow^+ \end{pmatrix} = \begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix}$$

- $\psi \; (i\sigma_y \otimes i\sigma_y)$

- Cuprate:

CuO$_2$



$$H_0 = -t\sum_{\langle i,j\rangle} c_i^+ c_j + h.c - \mu \sum c_{i\sigma}^+ c_{j\sigma}$$

$$H_{int} = -\frac{V}{2}\sum_{\delta=\pm\hat{x}} \left(c^+_{i+\delta\downarrow} c_{i\uparrow} - c^+_{i+\delta\uparrow} c^+_{i\downarrow}\right)$$

$$\underline{\left(c_{i\uparrow} c_{i+\delta\downarrow} - c_{i\downarrow} c_{i+\delta\uparrow}\right)}$$

$\downarrow$

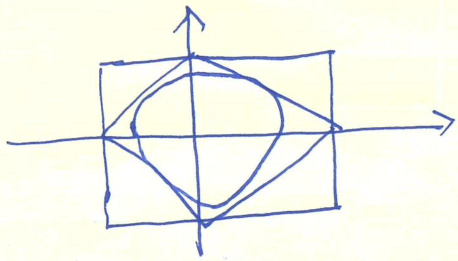
不同 site 之间的 pairing;

<u>phenomenological interaction</u>

Hydride

if: $u = 0$, $\varepsilon_k = 0$, $\langle n_i \rangle = c_{i\sigma}^\dagger c_{i\sigma} = 1$

H — —H : $\underline{c_i - (-1)^i c_i}$



$$\boxed{\cos k_x + \cos k_y - u = 0}$$

$$H_{pair} = -\frac{V}{2N} \sum \left(c^\dagger_{-k'\downarrow} c_{k'\uparrow} - c^\dagger_{-k'\uparrow} c^\dagger_{k'\downarrow} \right)$$

$$\left(c_{k\uparrow} c_{-k\downarrow} - c_{-k\uparrow} c_{k\downarrow} \right) e^{i(k'\sigma - k\cdot\sigma)}$$

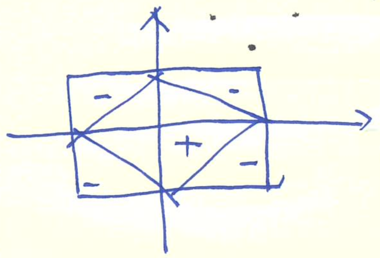
$$= -\frac{V}{2N} \sum_{k,k'} \underline{4\left(\cos k_x \cos k'_x + \cos k_y \cdot \cos k'_y\right)}$$

$$\underline{c^\dagger_{-k'\downarrow} c^\dagger_{k'\uparrow} c_{k\uparrow} c_{-k\downarrow}}$$

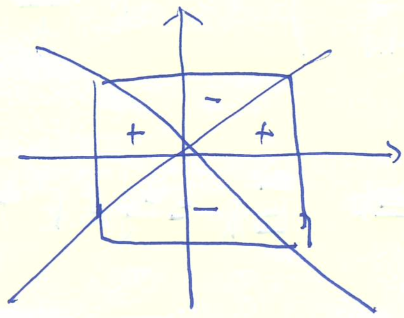
$$= -\frac{V}{N}\sum_{k,k'}\Big\{(\cos k_x - \cos k_y)(\cos k'_x - \cos k'_y) + \underbrace{(\cos k_x + \cos k_y)(\cos k'_x + \cos k'_y)}_{s\,\text{wave}}\Big\}\, C^+_{-k'\downarrow} C^+_{k'\uparrow} C_{k\uparrow} C_{-k\downarrow}$$

分解成 s波 和 d波

$\cos k_x - \cos k_y$



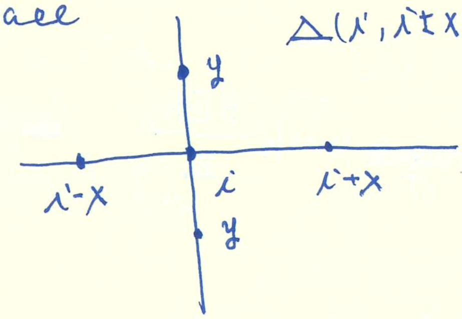
$\cos k_x + \cos k_y$



• $$\frac{1}{N} H_{MF} = -\frac{V}{N}\sum_k \Big\{ \Delta_s^*(\cos k_x + \cos k_y)\, C_{k\uparrow} C_{-k\downarrow} + h.c + \Delta_d^*(\cos k_x - \cos k_y)\, C_{k\uparrow} C_{-k\downarrow} + h.c) + \frac{1}{V}(\Delta_s^*\Delta_s + \Delta_d^*\Delta_d)\Big\}$$

Real space

$\Delta(i, i\pm x) = \Delta(i, i\pm y)$



⑥

$$\Delta(i, i\pm x) = -\Delta(i, i\pm y)$$

singlet pairing 出现 s波和d波

$$\frac{H}{N} = \frac{1}{N}\sum_k \left(C_{k\uparrow}^{+} \; C_{-k\downarrow} \right) \begin{pmatrix} \varepsilon_k - \mu & \Delta_d(\cos k_x - \cos k_y) \\ \Delta_d(\cos k_x - \cos k_y) & -(\varepsilon_k - \mu) \end{pmatrix} \begin{pmatrix} C_{k\uparrow} \\ C_{-k\downarrow}^{+} \end{pmatrix} + \frac{1}{N}\sum_k (\varepsilon_k - \mu) + \frac{1}{V}\Delta_d^{*}\Delta_d$$

$$\Rightarrow \quad E_k = \pm\sqrt{\xi_k^2 + \Delta_k^2}$$

$$\Rightarrow \quad \frac{1}{N}\sum_k E_k\left(\alpha_{k\uparrow}^{+}\alpha_{k\uparrow} - 1/2\right) + \left(\beta_{-k\downarrow}^{+}\beta_{-k\downarrow} - 1/2\right)$$

occupy $\downarrow$ unoccupy $\downarrow$

- Self - consistency:

$$\frac{F}{N} = -\frac{1}{V}\sum_k \frac{-2}{\beta}\log\left(e^{\frac{\beta}{2}E_k} + e^{-\frac{\beta}{2}E_k}\right) + \frac{|\Delta_d|^2}{V}$$

$$\Rightarrow \quad \frac{F}{N} = -\frac{2}{\beta}\int\frac{d^2k}{(2\pi)^2}\log 2\cosh\frac{\beta E_k}{2} + \frac{|\Delta_d|^2}{V}$$

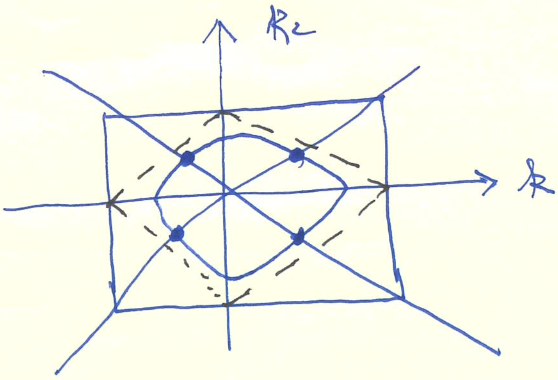
$$\frac{\partial F}{\partial \Delta} = -\frac{2}{\beta}\int \frac{d\vec{k}}{(2\pi)^2}\,\frac{\sinh\frac{\beta E_k}{2}}{\cosh\frac{\beta E_k}{2}}\,\frac{\Delta_d}{2\sqrt{\xi_k^2+\Delta^2}}\,(\cos k_x-\cos k_y)^2 + \frac{2\Delta_d}{V} = 0$$

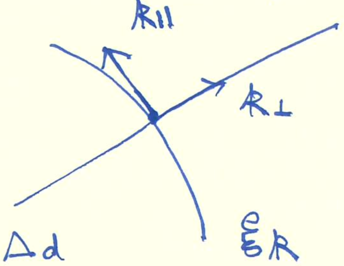
$$\Delta_d = V\int\frac{d\vec{k}}{(2\pi)^2}\tanh\frac{\beta E_k}{2}\,\frac{\Delta_d}{E_k}\,(\cos k_x-\cos k_y)^2$$

$\downarrow$ iteration

- Excitation : $E_k = \sqrt{\xi_k^2+\Delta^2(\vec{k})}$

nodal particle: $E_k = 0;\quad \xi_k = \Delta(k) = 0$





$$H(k) = \begin{pmatrix} \xi(k) & \Delta(k) \\ \Delta(k) & -\xi(k) \end{pmatrix}$$

$$= \hbar v_F\,\delta k_\perp\,\tau_z + \Delta_d\,\delta k_\parallel\,\tau_x$$

d 波的 nodal ~~line~~ pin 就是 Dirac cone