Two-dimensional p-wave superconducting states with magnetic moments on a conventional s-wave superconductor

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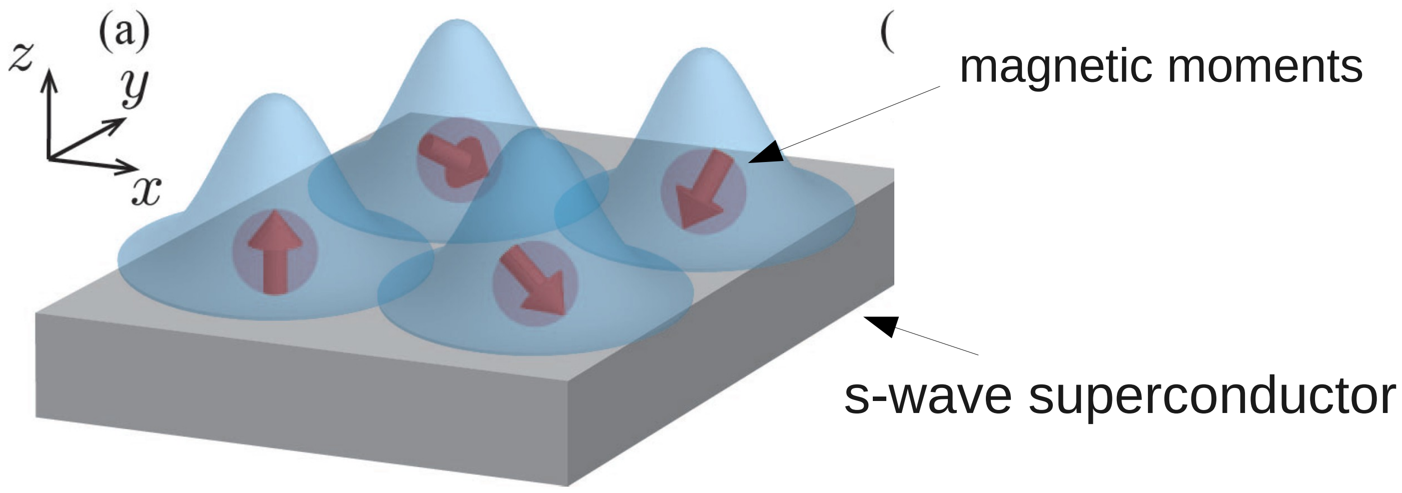
arXiv:1306.3686

Journal club – Jelena Klinovaja
Basel – 25.06.13

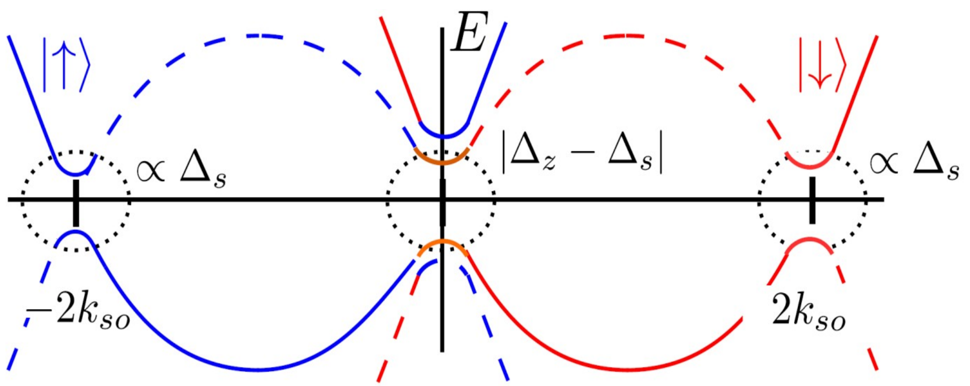
Outline

How to induce p-wave superconductivity?

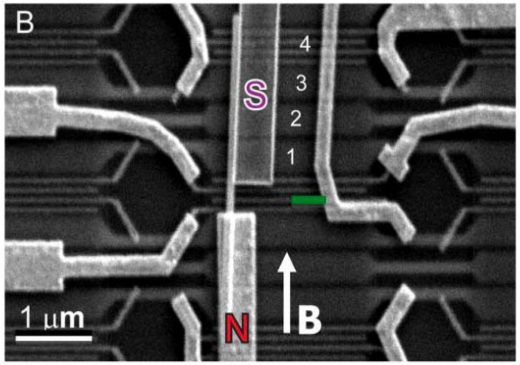


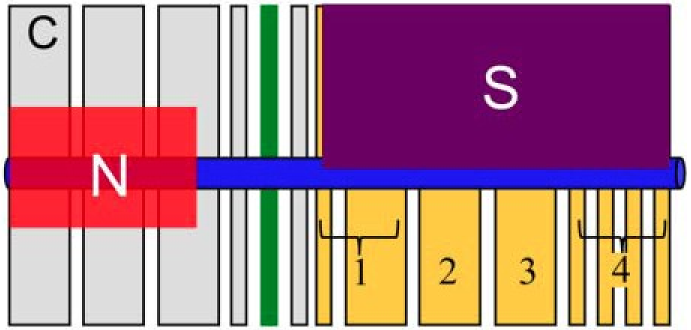
Possible motivation – 1D wires

spin-orbit interaction + s-wave => p-wave => Majorana



Klinovaja and Loss, PRB 86, 085408 (2012)





Mourik et al., Science 336, 1003 (2012)

Sato and Fujimoto, PRB 79, 094504 (2009)
Lutchyn et al., PRL 105, 077001 (2010)
Oreg et al., PRL 105, 177002 (2010)
Alicea, PRB 81, 125318 (2010)

Possible motivation – 1D wires

The SOI interaction can be gauged `away'!

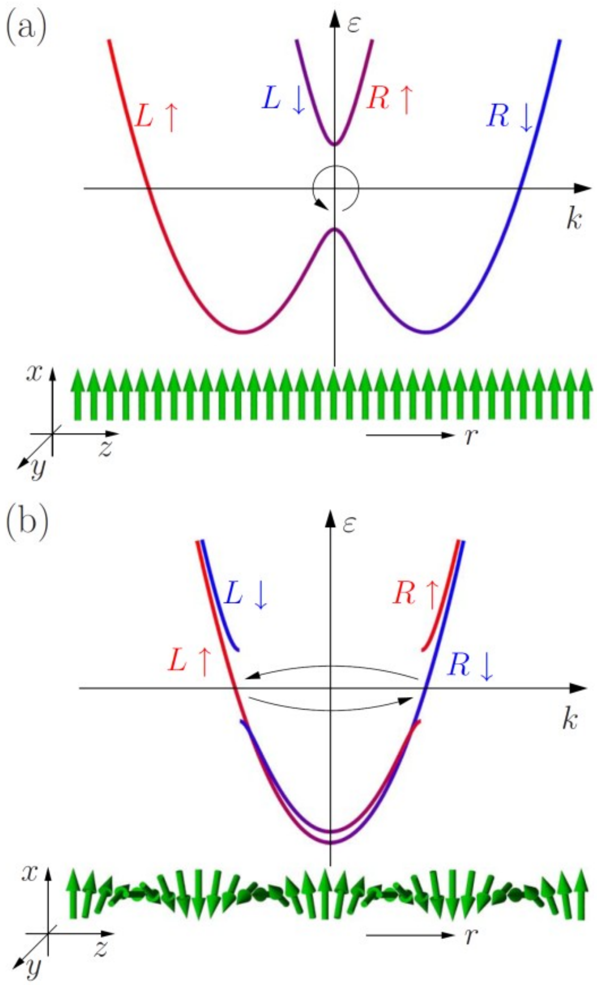
Braunecker, Japaridze, Klinovaja, and DL, PRB 82, 045127 (2010)

Gauge trafo

$$\Psi_\sigma = e^{-i\sigma k_{so}x}\widetilde{\Psi}_\sigma$$

$\Updownarrow$

$B \neq 0$

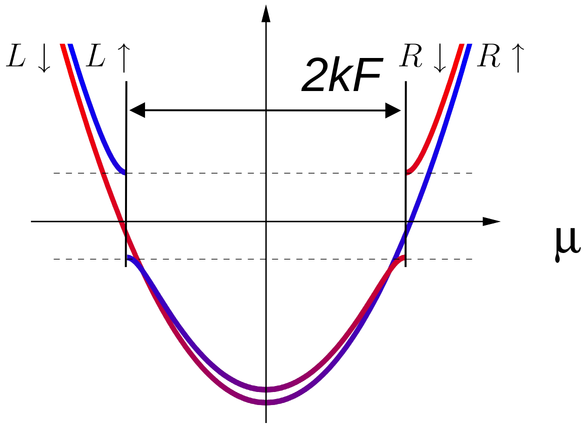


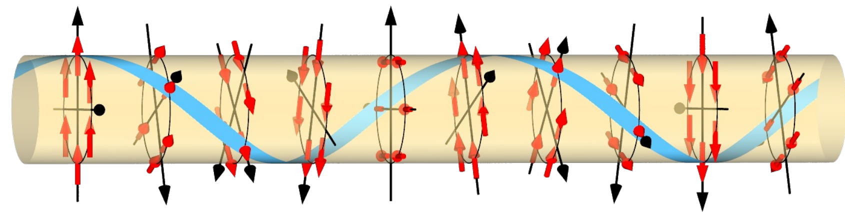
Only rotating field
and **no** SOI anymore!

$$\widetilde{\mathbf{B}} = B(\cos(2k_{so}x)\mathbf{e}_x - \sin(2k_{so}x)\mathbf{e}_y)$$

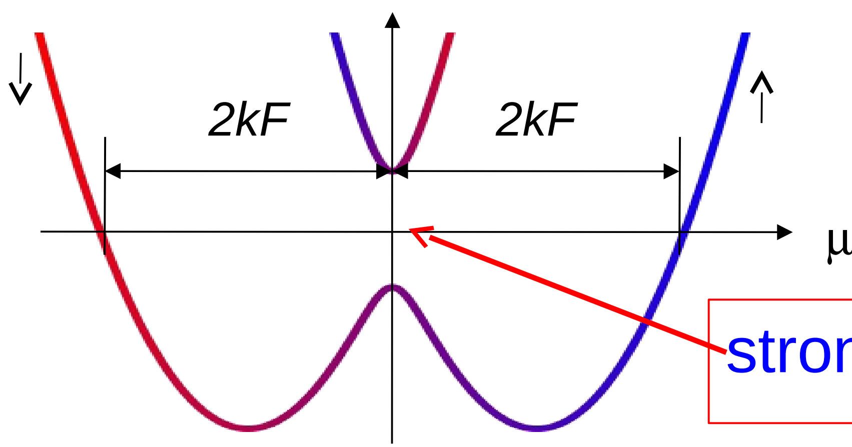
Rotating Field - Nuclear Helimagnet in 1D

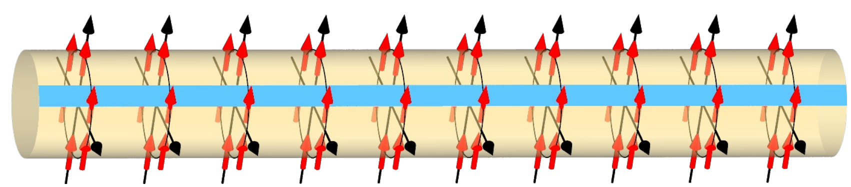
Braunecker, Simon, and Loss, PRL 102, 116403 (2009) & PRB 80, 165119 (2009)





local spin basis transformation:
spin-dependent shift in k-space

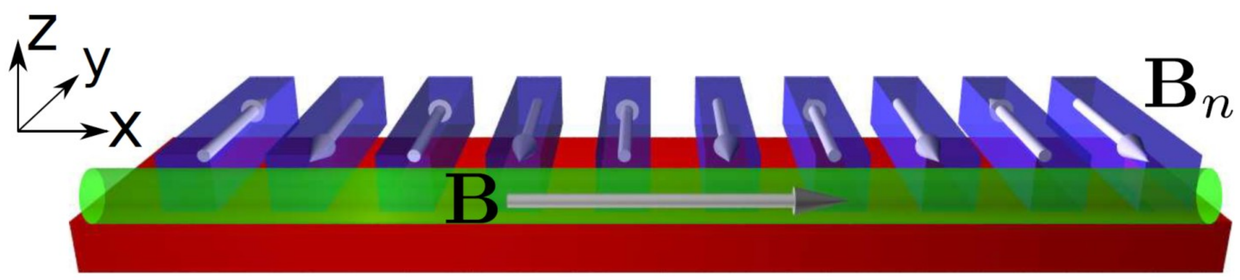




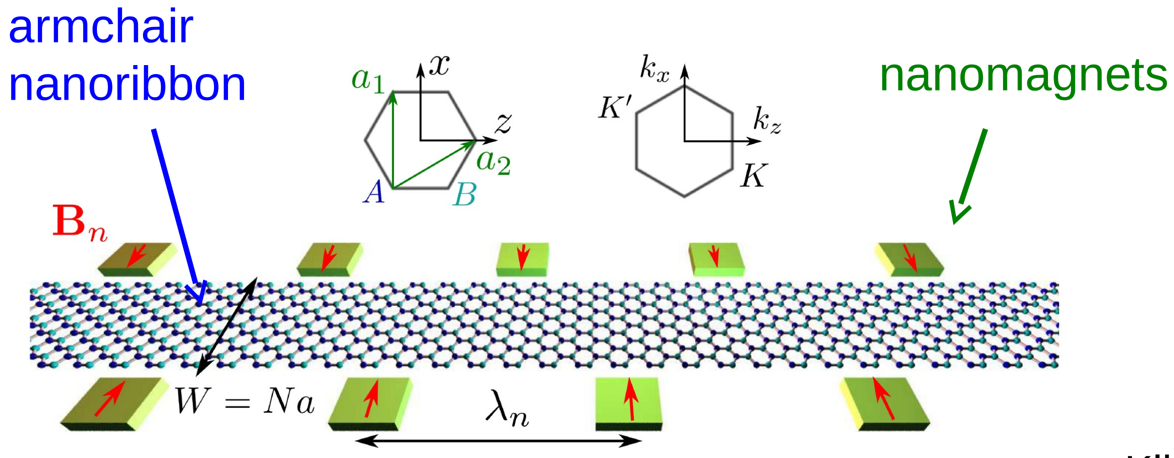
strong renormalization of Zeeman gap!

Confirmed by DMRG, see Stoudenmire, Alicea, Starykh, Fisher, PRB 84, 014503 (2011)

Rotating Field - Nanomagnets



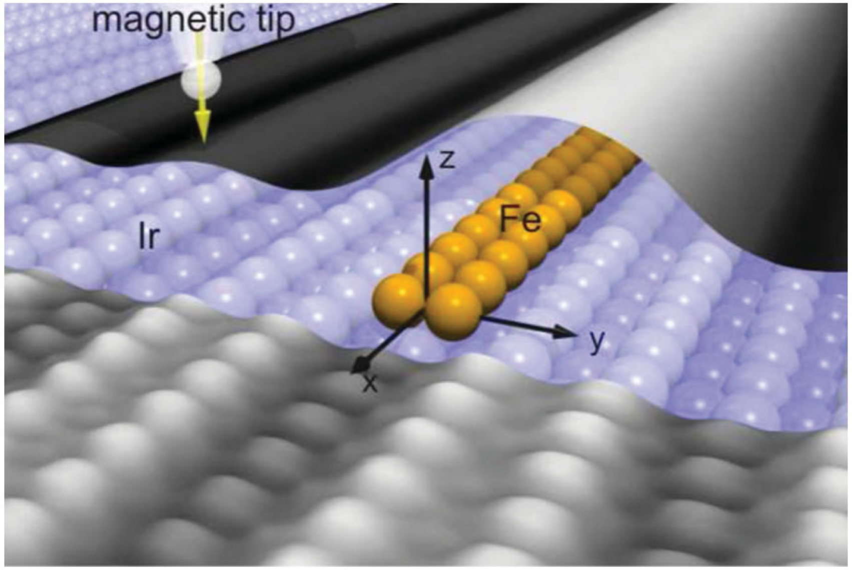
Klinovaja, Stano, and Loss, PRL 109, 236801 (2012)

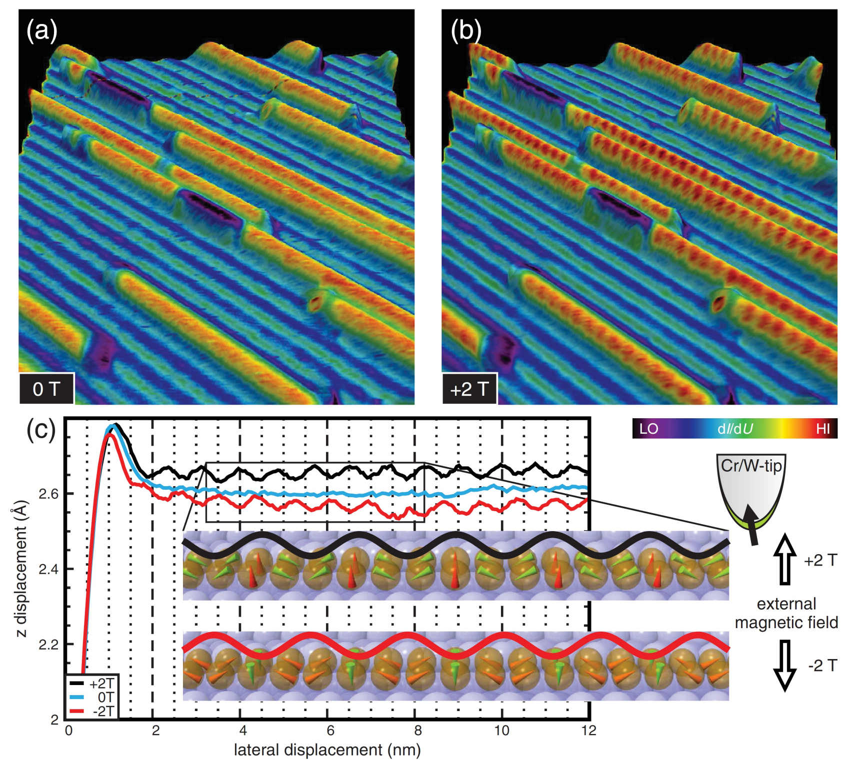


Klinovaja and Loss, PRX 3, 011008 (2013)

Δso = 10 meV for λ = 200 nm

Rotating Field – 2D - magnetic atoms





Roland Wiesendanger group; PRL **108**, 197204 (2012)

2D Lattice – Bound states (Shiba states) around magnetic atoms

$$H = \frac{1}{2}\sum_{\alpha\beta}\int \mathrm{d}\boldsymbol{r}\left[\psi^\dagger_\alpha(\boldsymbol{r})h_{\alpha\beta}(\boldsymbol{r})\psi_\beta(\boldsymbol{r}) - \psi_\alpha(\boldsymbol{r})h^T_{\alpha\beta}(\boldsymbol{r})\psi^\dagger_\beta(\boldsymbol{r})\right.$$
$$\left. + \psi^\dagger_\alpha(\boldsymbol{r})\Delta_{\alpha\beta}(\boldsymbol{r})\psi^\dagger_\beta(\boldsymbol{r}) + \psi_\alpha(\boldsymbol{r})\Delta^\dagger_{\alpha\beta}(\boldsymbol{r})\psi_\beta(\boldsymbol{r})\right],$$

$$h_{\alpha\beta}(\boldsymbol{r}) = \xi(\boldsymbol{r})\delta_{\alpha\beta} - J\boldsymbol{S}(\boldsymbol{r})\cdot\boldsymbol{\sigma}_{\alpha\beta}$$

Kinetic energy: $\xi(\boldsymbol{r}) = \left[-\frac{1}{2m}\frac{\partial^2}{\partial \boldsymbol{r}^2} - \mu\right]$

Coupling to magnetic moments: $\boldsymbol{S}(\boldsymbol{r}) = \sum_i \boldsymbol{S}_i\delta(\boldsymbol{r} - \boldsymbol{r}_i)$

s-wave superconductivity: $\Delta_{\alpha\beta}(\boldsymbol{r}) = \Delta_0 i\sigma^y_{\alpha\beta}$

H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A. I. Rusinov, Sov. Phys. JETP 29, 1101 (1969)
L. Yu, Acta Phys. Sin. 21, 75 (1985)

Shiba state

Single moment: $+s_z$-direction

Bogoliubov-de Gennes (BdG) equation

$$(\xi_k - E)u_{k\uparrow} - \frac{JS}{V}\sum_l u_{l\uparrow} + \Delta_0 v_{k\downarrow} = 0$$

$$(\xi_k + E)v_{k\downarrow} + \frac{JS}{V}\sum_l v_{l\downarrow} - \Delta_0 u_{k\uparrow} = 0$$

Solution:

$$E_0 \;=\; \Delta_0 \left[1 - (\pi JSN_0/2)^2\right] / \left[1 + (\pi JSN_0/2)^2\right]$$

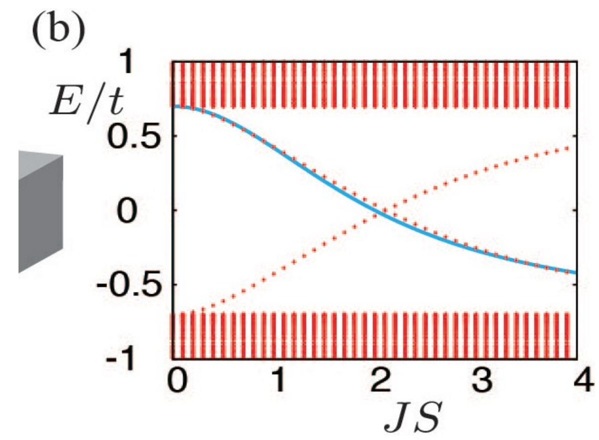
N_0 - the density of states in the normal phase

$$u_\uparrow(\boldsymbol{r}) \sim \frac{\sin(p_\mathrm{F} r - \delta_+)}{p_\mathrm{F} r}\exp\left[-\frac{r}{\xi_0}|\sin(\delta_+ - \delta_-)|\right]$$

$$v_\downarrow(\boldsymbol{r}) \sim \frac{\sin(p_\mathrm{F} r - \delta_-)}{p_\mathrm{F} r}\exp\left[-\frac{r}{\xi_0}|\sin(\delta_+ - \delta_-)|\right]$$

$$\tan\delta_\pm \;=\; \pm\pi JSN_0/2$$

$$\xi \;=\; v_\mathrm{F}/(\pi\Delta)$$



H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A. I. Rusinov, Sov. Phys. JETP 29, 1101 (1969)
L. Yu, Acta Phys. Sin. 21, 75 (1985)

2D Lattice of Shiba states

Magnetic momentum: $S(\sin\theta\cos\phi,\ \sin\theta\sin\phi,\ \cos\theta)$

electron operators:

$$\psi_\uparrow = \sum_i \left[\cos\frac{\theta_i}{2} u_\uparrow(\boldsymbol{r}-\boldsymbol{r}_i)\alpha_i - e^{-i\phi_i}\sin\frac{\theta_i}{2} v_\downarrow^*(\boldsymbol{r}-\boldsymbol{r}_i)\alpha_i^\dagger\right]$$

$$\psi_\downarrow = \sum_i \left[e^{i\phi_i}\sin\frac{\theta_i}{2} u_\uparrow(\boldsymbol{r}-\boldsymbol{r}_i)\alpha_i + \cos\frac{\theta_i}{2} v_\downarrow^*(\boldsymbol{r}-\boldsymbol{r}_i)\alpha_i^\dagger\right],$$

$$H_{\text{eff}} = \sum_i E_0 \alpha_i^\dagger \alpha_i + \sum_{\langle ij\rangle}\left[\bar{t}_{ij}\alpha_i^\dagger\alpha_j + \left(\bar{\Delta}_{ij}\alpha_i^\dagger\alpha_j^\dagger + \text{H.c.}\right)\right]$$

$$\bar{t}_{ij} = \hat{z}_i^\dagger \hat{z}_j \bar{t}_0,$$

$$\bar{\Delta}_{ij} = \hat{z}_i^\dagger i\sigma_y \hat{z}_j^* \bar{\Delta}_0$$

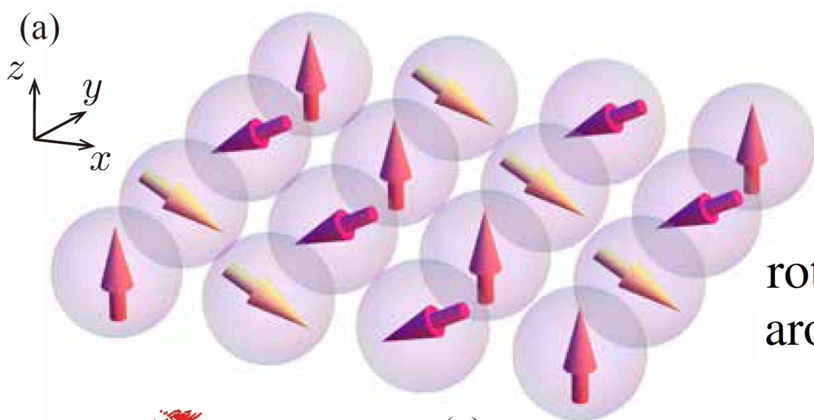
depend only on the relative direction of the two moments

$$\hat{z}_i = \begin{pmatrix} \cos\frac{\theta_i}{2} \\ e^{i\phi_i}\sin\frac{\theta_i}{2} \end{pmatrix}$$

$$\bar{t}_0 = \int \mathrm{d}\boldsymbol{r}\left[\,(u_i\xi(\boldsymbol{r})u_j - v_i\xi(\boldsymbol{r})v_j) + \Delta_0\,(u_iu_j + v_iv_j)\,\right]$$

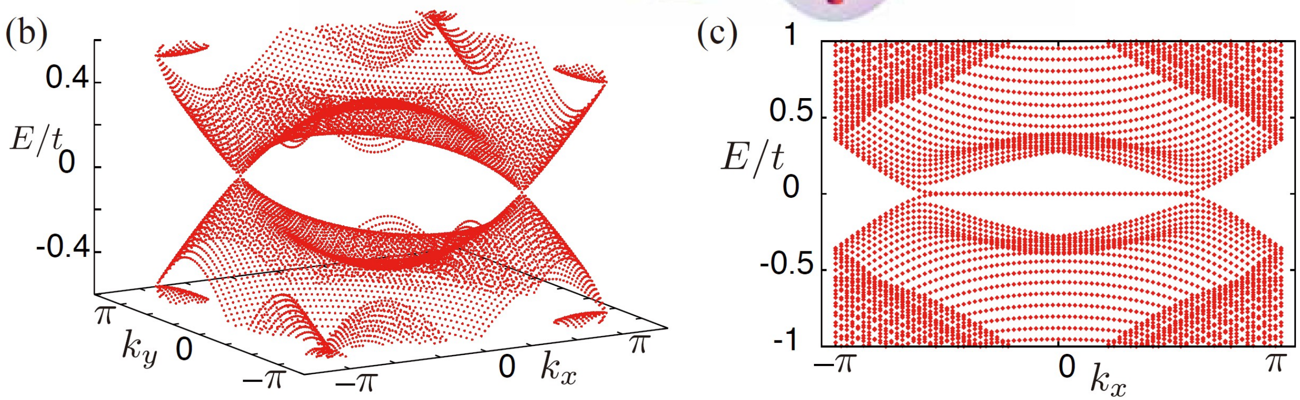
$$\bar{\Delta}_0 = \int \mathrm{d}\boldsymbol{r}\left[\,(u_i\xi(\boldsymbol{r})v_j + v_i\xi(\boldsymbol{r})u_j) + \Delta_0\,(u_iu_j - v_iv_j)\,\right]$$

Nodal superconductor: $p_x + p_y$-wave pairing state



all the moments lie in the $s_x s_z$- plane

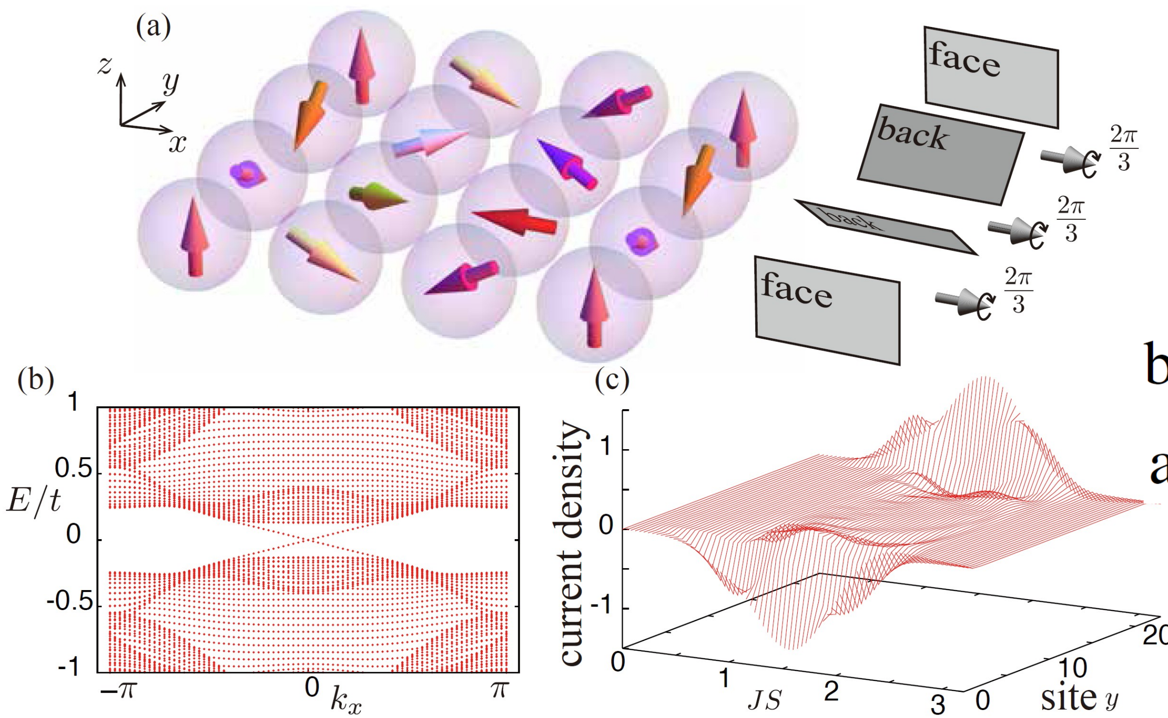
rotate by $2\pi/3$
around s_y-axis along both x- and y-directions



Nodes on the line $k_x = -k_y$

mostly flat Andreev bound states

Chiral p-wave superconductor: $p_x + ip_y$-wave pairing



by $2\pi/3$ within

$s_x s_z$-plane along x-direction

by $2\pi/3$

around s_x-axis along y-direction

two chiral Majorana edge channels localized at the open boundaries in the energy gap

current along x -direction:

$$j_i = \sum_{k_x \sigma} 2t \sin k_x \; \alpha^\dagger_{i\sigma}(k_x)\alpha_{i\sigma}(k_x)$$

topological criterion:

trivial phase: $JS > (JS)_c$

$JS = (JS)_c \sim 2.7t$

Results:

"We have proposed a new way of creating effective two-dimensional unconventional superconductivity by local moments on the conventional spin-singlet s -wave superconductor."