PS-10

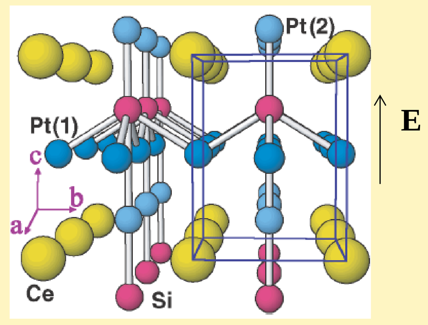
Inhomogeneous noncentrosymmetric superconductors in magnetic fields

K. Aoyama[a,b], L. Savary[c] and M. Sigrist[d]

[a] Young Researcher Development Center, Kyoto University, Japan
[b] Department of Physics, Kyoto University, Japan
[c] Department of Physics, University of California, Santa Barbara, USA
[d] Institute for Theoretical Physics, ETH Zurich, Switzerland

Non-centrosymmetric superconductor (NCS)

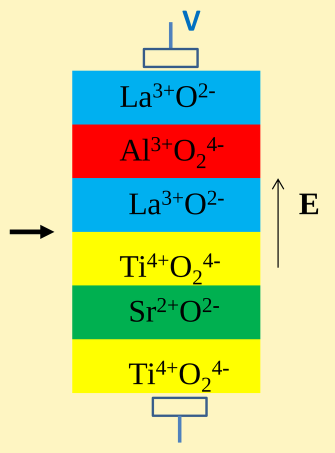
Heavy-fermion superconductor $CePt_3Si$

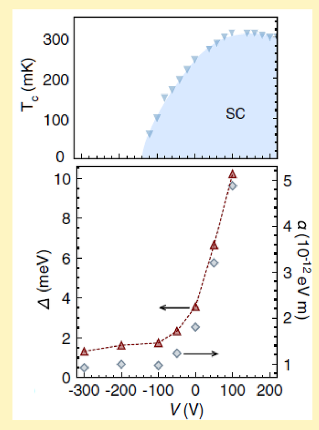


E. Bauer, Phys. Rev. Lett. **92**, 027003 ('04)

3D system

$LaAlO_3$ - $SrTiO_3$ Interface superconductor





2D system

N. Reyren *et al.*, Science **317**, 1196 ('07)
A. D. Caviglia *et al.*, PRL **104**, 126803(10).

Lack of an inversion center

Anisotropic potential gradient: $\mathbf{E}=\nabla V$ ･･･Rashba spin-orbit coupling (RSOC): $\boldsymbol{\sigma}\cdot(\mathbf{k}\times\mathbf{E})$
$=\alpha_R\,\boldsymbol{\sigma}\cdot(\mathbf{k}\times z)$

Coupling constant $\alpha_R \propto \nabla_z V$

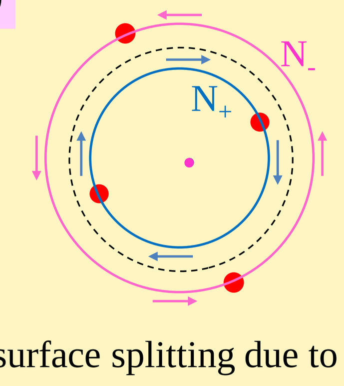
Sign and strength of Rashba spin-orbit coupling depend on the direction of the mirror symmetry breaking.

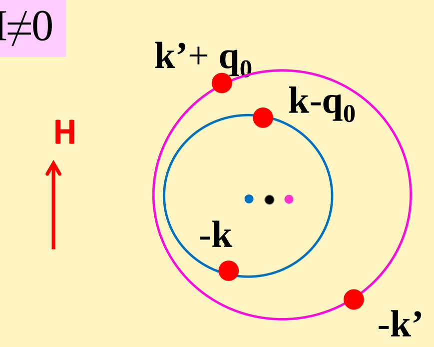
NCS in a magnetic field

Field-induced Helical SC state

R. P. Kaur et al., PRL **94**, 137002 ('05)

H=0 H≠0





Fermi surface splitting due to the Rashba spin-orbit coupling $\alpha_R\boldsymbol{\sigma}\cdot(\mathbf{k}\times z)$

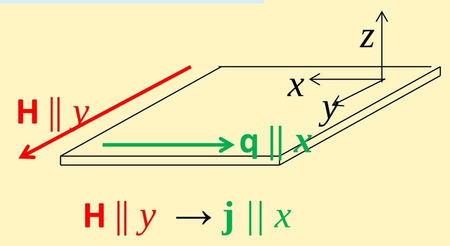
Zeeman effect
--> Fermi surface shift ⊥H
--> SC state with a modulation ⊥H

$\Delta = \exp[-\,i\,q\,x]$

$q \propto (N_- - N_+)\,\mu_B H \sim \alpha_R \mu_B H$

･･･**Helical SC state**

Magneto-electric effect



Magnetic field -->phase modulation (Helical state)
--- supercurrent

･･･magneto-electric effect

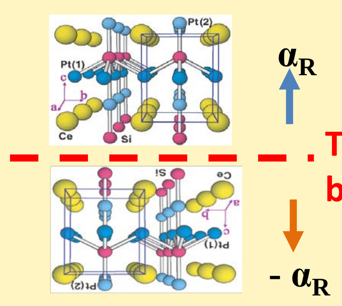
Spatially inhomogeneous NCS in a magnetic field

Spatially inhomogeneous RSOC

･Electric field applied to 2D SC film

･Crystalline defect ･･･Twin boundary

Spatial variation of RSOC constant α_R

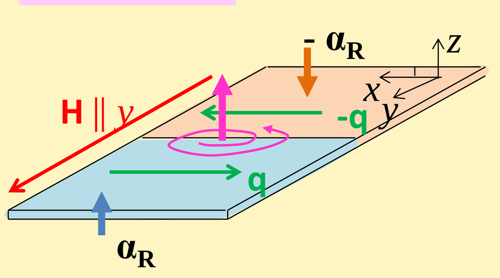


Sign change of α_R

Internal field at inhomogeneity of RSOC

Two domains with opposite noncentrosymmetricities α_R $-\alpha_R$

Side-by-side

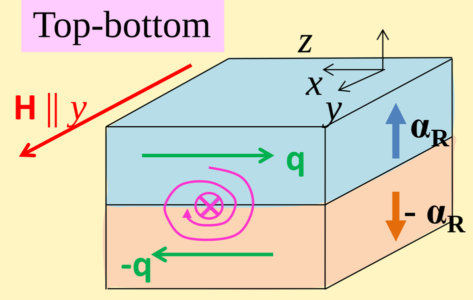


Internal field ⊥H

Vortex perpendicular to the field

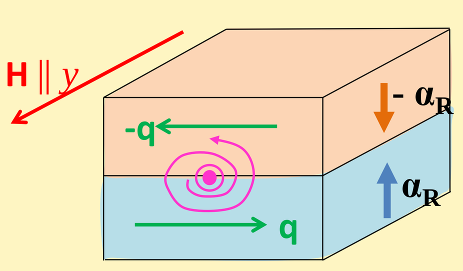
KA & M. Sigrist, PRL **109**, 237007 ('12)

Top-bottom



Internal field **antiparallel** to H

Enhancement of $H_{c1,c2}$?

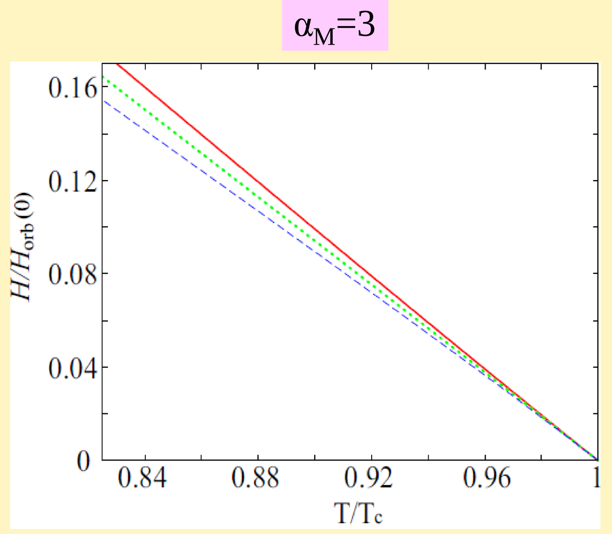


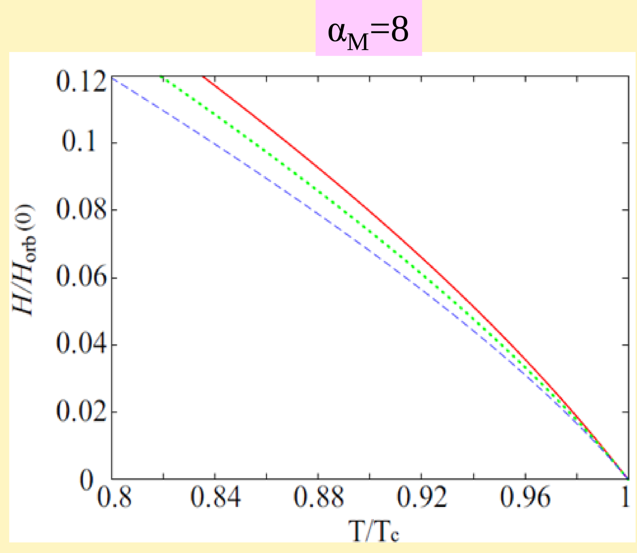
Internal field **parallel** to H

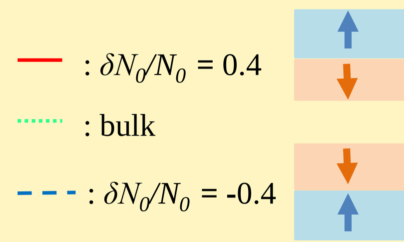
Suppression of $H_{c1,c2}$?

Result and Conclusion

Upper critical field $H_{c2}(T)$



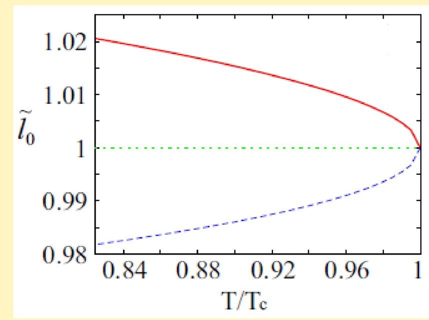


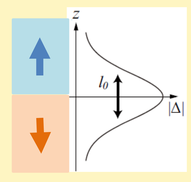


$H_{c2}(T)$ is enhanced (suppressed) at the twin boundary with positive (negative) $\delta N_0/N_0$.

α_M :larger ･Shift of $H_{c2}(T)$ at the twin boundaries becomes remarkable.
･$H_{c2}(T)$ is suppressed by the paramagnetic pair-breaking effect.

Effective magnetic length l_n





l_0 is longer (shorter) for positive (negative) $\delta N_0/N_0$.

Bulk: $l_0 = r_H = 1/\sqrt{2eH}$

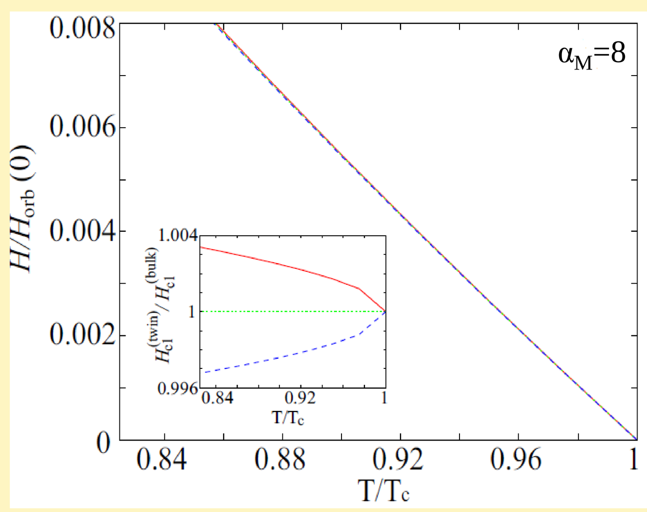
Twin boundary: $l_0 \sim 1/\sqrt{2e\,H_{eff}}$

Internal field introduced at the twin boundary with positive (negative) $\delta N_0/N_0$ weakens (strengthens) the external field.

Lower critical field $H_{c1}(T)$

Vortex-line energy: $e_v = 2\pi\int_0^\infty r dr\left[\frac{|\Delta_0|^2 K_\perp \hbar^2}{\xi^2} f_{GL} - \left(-\frac{|a^{(2)}|^2}{4a^{(4)}}\right)\right]$

$H_{c1}(T)$: $\frac{H_{c1}(T)}{H_{orb}(0)} = \frac{4\pi}{\Phi_0}e_v \Big/ \frac{\Phi_0}{2\pi\xi_0^2} = \left(\frac{\xi_0}{\xi}\right)^2\left(\frac{\xi}{\lambda_L}\right)^2\frac{1}{2}\int_0^\infty \tilde{r} d\tilde{r}\left(f_{GL}+\frac{1}{2}\right)$



$H_{c1}(T)$ is enhanced (suppressed) at the twin boundary with positive (negative) $\delta N_0/N_0$.

But, the shift of $H_{c1}(T)$ is very small.

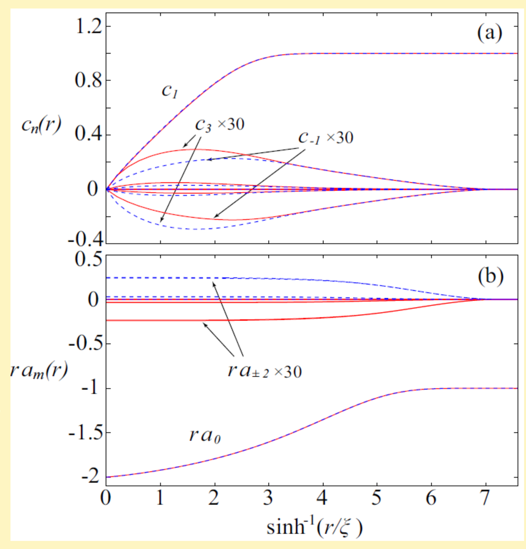
$$\frac{e_v}{e_{v0}} \simeq 1 + R_v\frac{\delta N_0}{N_0}\frac{\alpha_M\sqrt{1-T/T_c}}{(\lambda_L/\xi)\ln(\lambda_L/\xi)}$$ R_v=0.215

λ_L/ξ : large ---> δe_v: small

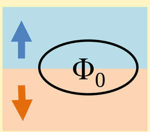
Spatial dependences of c_n and a_m

In the presence of twin boundaries, $c_{1\pm2}$ and $a_{\pm2}$ appear ($e^{\pm i2\theta}$ in Δ and $\mathbf{A}$).

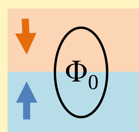
→ occurrence of 2 fold symmetry in Δ and **B**



Magnetic flux distribution B(x,z)



— : $\delta N_0/N_0$ = 0.4
counter internal field at TB
→ flux tends to sit on TB.



- - : $\delta N_0/N_0$ = -0.4
strengthening internal field at TB
→ flux tends to escape from TB.

--- Consistent with the previous physical picture for $H_{c2}(T)$

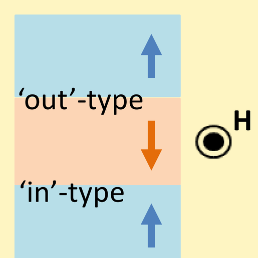
Conclusion

KA , L. Savary, and M. Sigrist, PRB **89**, 174518 ('14)

H_{c1} and H_{c2} at twin boundaries of a noncentrosymmetric superconductor with RSOC

Magneto-electric effect ---> Shift of H_{c1} and H_{c2} at the twin boundary

In a specimen containing crystal domains, *physical* H_{c2} and H_{c1} are determined at 'out'- and 'in'-type twin boundaries, respectively.



H_{c2} at the 'out'-type twin boundary is higher than its bulk value.

The upper critical field obtained from experimental probes quite sensitive to superconductivity can be higher than H_{c2} determined by bulk measurements.

Theoretical framework

Ginzburg Landau free energy

$$\mathcal{F}_{GL} = \int dz d\mathbf{r}_\perp\Big[a^{(2)}|\Delta|^2 + a^{(4)}|\Delta|^4 + K_\perp|\boldsymbol{\Pi}_\perp\Delta|^2 + K_z|\Pi_z\Delta|^2 + \underbrace{K_{me}(\hat{z}\times\mathbf{B})\cdot\{\Delta^*\boldsymbol{\Pi}_\perp\Delta + \Delta(\boldsymbol{\Pi}_\perp\Delta)^*\}}_{\text{Magneto-electric effect due to RSOC}} + \frac{(\nabla\times\mathbf{A})^2}{8\pi}\Big]$$

$$\boldsymbol{\Pi} = -i\hbar\nabla + (2e/c)\mathbf{A} \qquad \nabla\times\mathbf{A}=\mathbf{B}$$

$$a^{(2)} = N_0\left(\ln\frac{T}{T_c} + 2\gamma g^2\mu_B^2 B^2\right) \qquad K_{me} = \frac{\delta N_0}{N_0}g\mu_B\frac{K_\perp}{v_\perp} \qquad \frac{\delta N_0}{N_0} = \frac{N_+ - N_-}{(N_+ + N_-)/2} \propto \frac{\alpha_R}{E_F}$$

Paramagnetic pair-breaking effect due to Zeeman field

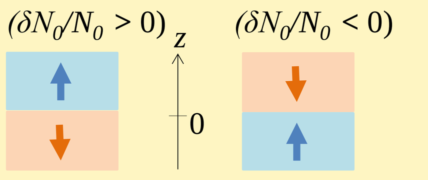
RSOC

($N_\pm$: DOS of 2 bands split by RSOC)

Model for twin boundary system

K_{me} --> $K_{me}(z) = \tilde{K}\,\mathrm{sgn}(z)$

･$\tilde{K} > 0$ ($\delta N_0/N_0 > 0$) ･$\tilde{K} < 0$ ($\delta N_0/N_0 < 0$)



Length scales

$\xi^{-2} = |a^{(2)}|/(\hbar^2 K_\perp)$ ･･･SC coherence length
$r_H^{-2} = 2eH/(c\hbar)$ ･･･magnetic length
$\lambda_L^{-2} = 32\pi K_\perp|\Delta_0|^2 e^2/c^2$ ･･･London penetration depth length

parameters

$|\delta N_0/N_0|$: **strength of RSOC**

Sign of $\delta N_0/N_0$: **stacking order of twinning domains**

$\alpha_M = \sqrt{2}H_{orb}(0)/H_p(0)$: **strength of paramagnetic effect**

Upper critical field $H_{c2}(T)$

H ∥y : $\mathbf{A} = zH\hat{x}$ $\Delta(\mathbf{r}) = \sum_n C_n(z)\,e^{i\frac{2\pi n}{L_x}x}$

Variational approximation

Twin boundary effect ･･･correction to harmonic potential introduced by **A** → $C_n(z) = C_n\frac{1}{\sqrt{l_n\sqrt{\pi}}}e^{-z^2/2l_n^2}$ l_n : variational parameter

(※ without twin boundary, $l_n = r_H = 1/\sqrt{2eH}$)

GL quadratic term

$$\mathcal{F}^{(2)}_{GL} = \sum_n |C_n|^2\left[a^{(2)} + K_\perp\hbar^2\Big(\underbrace{\frac{2\pi n}{L_x}}_{n=0}\Big)^2 + \frac{K_\perp}{2}\Big(\frac{2eH}{c}\Big)^2 l_n^2 + \frac{K_z\hbar^2}{2}\frac{1}{l_n^2} - \underbrace{\frac{2}{\sqrt{\pi}}\frac{2eH}{c}\tilde{K}\hbar l_n}_{\text{Twin boundary effect}}\right]$$

$$\frac{2\tilde{K}\hbar r_H}{\sqrt{\gamma_{FS}K_\perp K_z\hbar^2}} = \frac{1}{2e^{\gamma_E}}\frac{\delta N_0}{N_0}\alpha_M\sqrt{\frac{H}{H_{orb}(0)}}$$

1. Minimization of $\mathcal{F}^{(2)}_{GL}$ with respect to n and l_n

2. $\mathcal{F}^{(2)}_{GL}$ = 0 ---> $H_{c2}(T)$

Lower critical field $H_{c1}(T)$

Cylindrical coordinate system

$$\Delta(r,\theta) = |\Delta_0|\sum_n c_n(r)e^{in\theta}$$
$$A_\theta(r,\theta) = \frac{c\hbar}{2e\xi}\sum_m a_m(r)e^{im\theta} \qquad B(r,\theta) = \frac{1}{r}\partial_r[rA_\theta(r,\theta)] = \frac{c\hbar}{2e\xi}\frac{1}{r}\partial_r\Big[r\sum_m a_m(r)e^{im\theta}\Big]$$

Boundary condition

$$\Delta(r,\theta) = \begin{cases}|\Delta_0|e^{i\theta} & (r\to\infty),\\ 0 & (r\to 0),\end{cases} \quad \& \quad \Phi_0 = \int_0^{2\pi}d\theta\int_0^\infty r dr B(r,\theta) = 2\pi\frac{c\hbar}{2e\xi}\Big[\lim_{r\to\infty}ra_0(r) - \lim_{r\to 0}ra_0(r)\Big]$$

GL equations

$\delta\mathcal{F}_{GL}/\delta c_k = 0$ & $\delta\mathcal{F}_{GL}/\delta a_k = 0$ ---> Numerical solution