Nonreciprocal Phenomena in Chiral Materials

- Left and Right in Quantum Dynamics –

Naoto Nagaosa

RIKEN Center for Emergent Matter Science (CEMS)
and
Dept. Applied Phys. Univ. Tokyo

東京大学
THE UNIVERSITY OF TOKYO

RIKEN CEMS

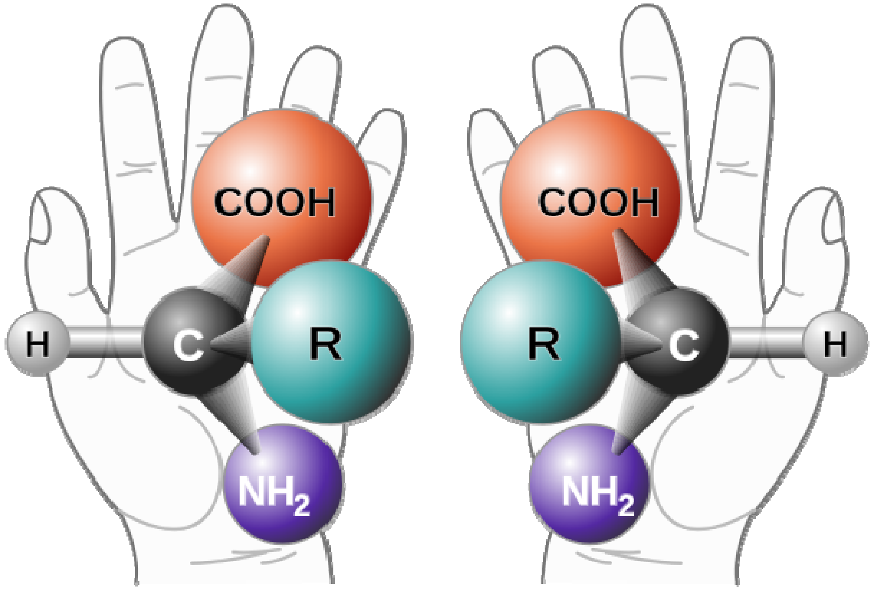
Collaborators

U.Tokyo: Ryohei Wakatsuki, Keita Hamamoto,
Hiro Ishizuka, Motohiko Ezawa

Saitama Univ.: Shintaro Hoshino

Exp: Y. Tokura, Y. Iwasa, K.S. Takahashi, K. Yasuda,
S. Koshikawa, S. Shimizu, Y. Kaneko, Y. Saito,
T. Ideue, H. Yasuda, R. Yoshimi

Left and Right (chirality) is a crucial issue in sciences



No Inversion I
No Mirror M

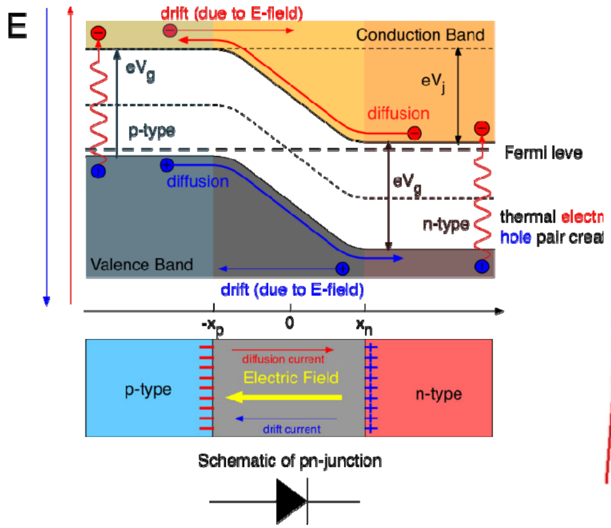
From Wikipedia

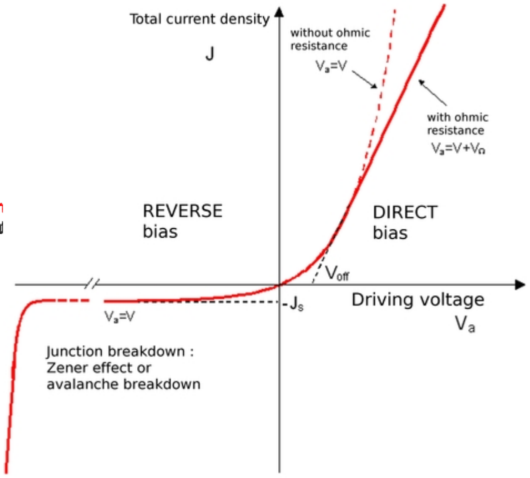
Physics parity violation of weak interaction
Chemistry chiral molecules
Biology chirality of DNA

M. Gardner, The Ambidextrous Universe. Left, Right and the Fall of Parity, *Basic Books Inc.* (1964)

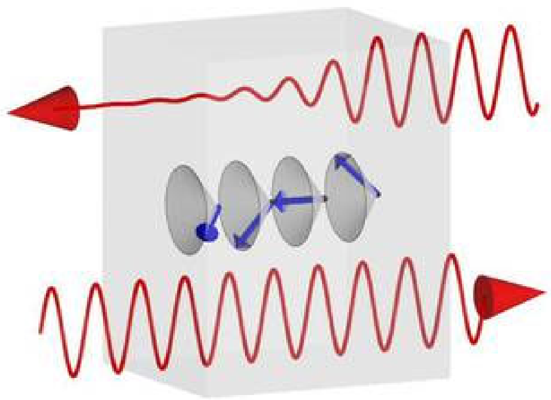
Directional response is useful

pn junction





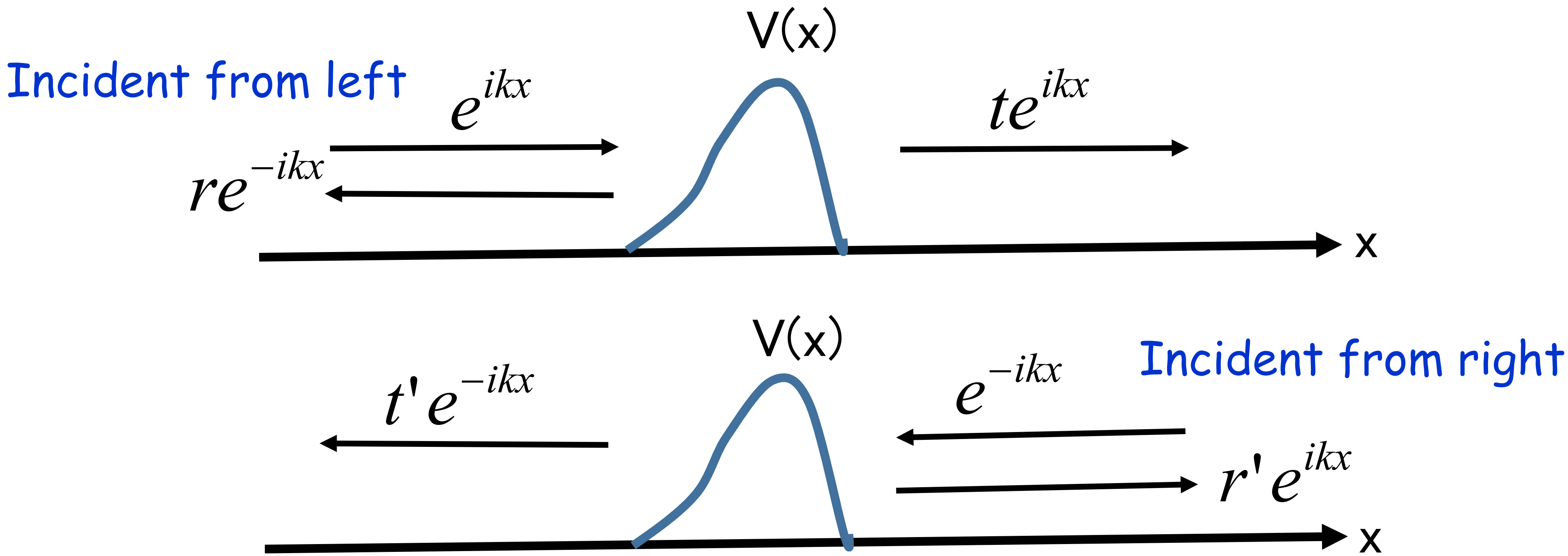
optical isolator



http://quantumwise.com/publications/tutorials/item/828-silicon-p-n-junction

http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_09.html

Fundamental viewpoint from physics   Right and Left directions of flow



$$|t'|^2 = |t|^2 \quad |r'|^2 = |r|^2$$

Unitary nature of S matrix: conservation of prob.

➡ Role of dissipation and classical nature

$$t' = t$$

Time-reversal symmetry T: S=S^Transpose

Asymmetry between *t* and -*t*

1. Microscopic time-reversal symmetry breaking

   external magnetic field   B
   magnetic ordering   M

2. Macroscopic irreversibility

   dissipation of energy
   diffusion

Non-reciprocal transport in non-centrosymmetric system

Time-reversal symmetry of microscopic dynamics vs irreversibility

$$\sigma_{\mu\nu}(k,\omega,B)=\sigma_{\nu\mu}(-k,\omega,-B)$$

Onsager's reciprocal relation
for linear response

Magnetochiral optical effect
directional dichroism

$$\varepsilon_{\mu\mu}(k,\omega,B)=\varepsilon_0+\alpha k\cdot B$$

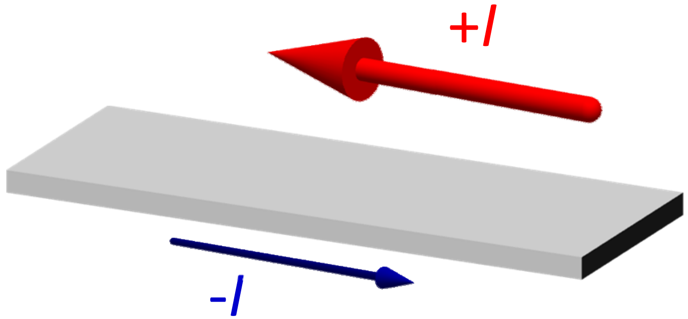
e.g. electromagnon in multiferroics
A. Loidl, Y.Tokura

$k \rightarrow I$ G. L. J. A. Rikken (2001)

"dichroism" of the electric current magnetochiral anisotropy

$R\,(+I) \neq R\,(-I)$

$R = R_0\,(1 + \beta B^2 + \boxed{\gamma BI})$

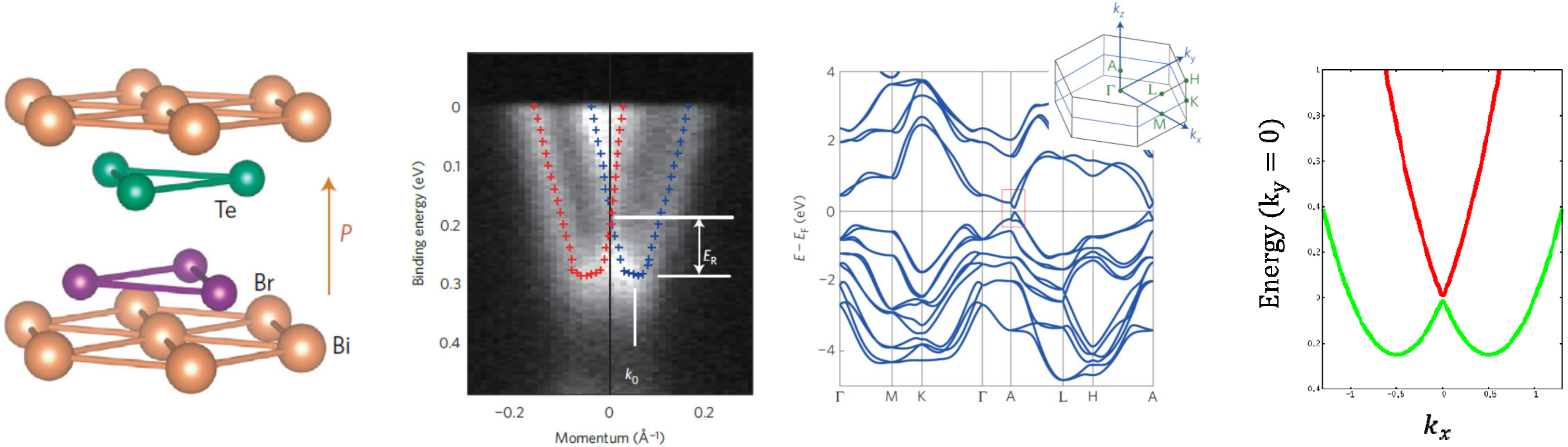


Broken inversion symmetry $\Leftrightarrow$ $\gamma \neq 0$

Nonlinear response $J=\sigma E+\alpha BE^2$

Band structure in noncentrosymmetric crystal

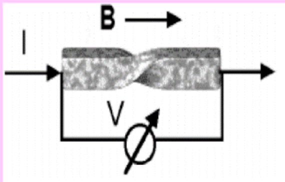
Time-reversal symmetry ➡ $\varepsilon_{\uparrow}(k) = \varepsilon_{\downarrow}(-k)$



K. Ishizaka *et al. Nat. Mater.* **10**, 521 (2011).

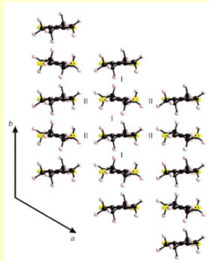
Magnetochiral anisotropy – tiny effect

Bi helices



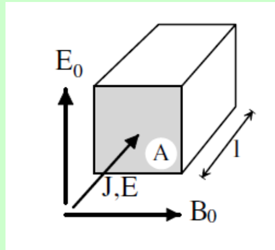
G. L. J. A. Rikken *et al.* *PRL* **87**, 236602 (2001).

Organics



F. Pop *et al.* *Nat. Commun.* **5**, 3757 (2014).

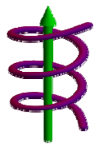
Si FET

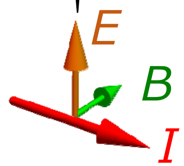


G. L. J. A. Rikken *et al.* *PRL* **94**, 016601 (2005).

	Bi helices	Organics	Si FET
$\gamma\,(\mathrm{T}^{-1}\mathrm{A}^{-1})$	10^{-3}	10^{-2}	10^{-1}

$$\gamma \sim 10^4 T^{-1} A^{-1}$$



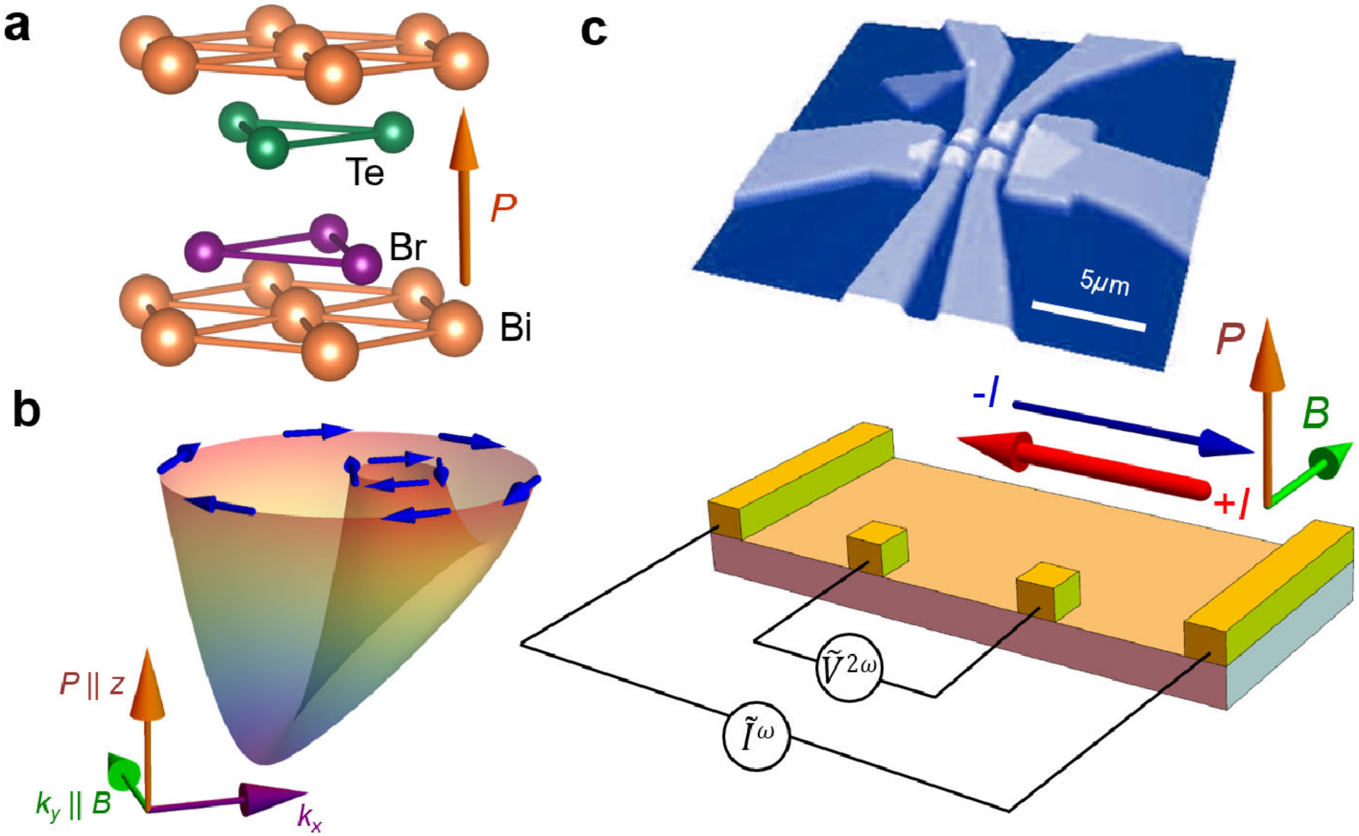


$$R = R_0\,(1 + \beta B^2 + \gamma B I)$$

$$\mu_B B,\ \varepsilon_{SOI} << \varepsilon_F$$

Enhanced magnetochiral anisotropy in BiTeBr

Y.Iwasa G, Y.Tokura G, NN G   Nature Phys. 2017



Magnetochiral anisotropy in Rashba model

K. Hamamoto

$$H = \frac{k_z^2}{2m_\parallel} + \frac{k_x^2 + k_y^2}{2m_\perp} + \lambda\left(k_x\sigma_y - k_y\sigma_x\right) - B_y\sigma_y$$

Boltzmann equation

$$-e\boldsymbol{E}\cdot\frac{\partial f}{\partial \boldsymbol{k}} = -\frac{1}{\tau}(f - f_0)$$

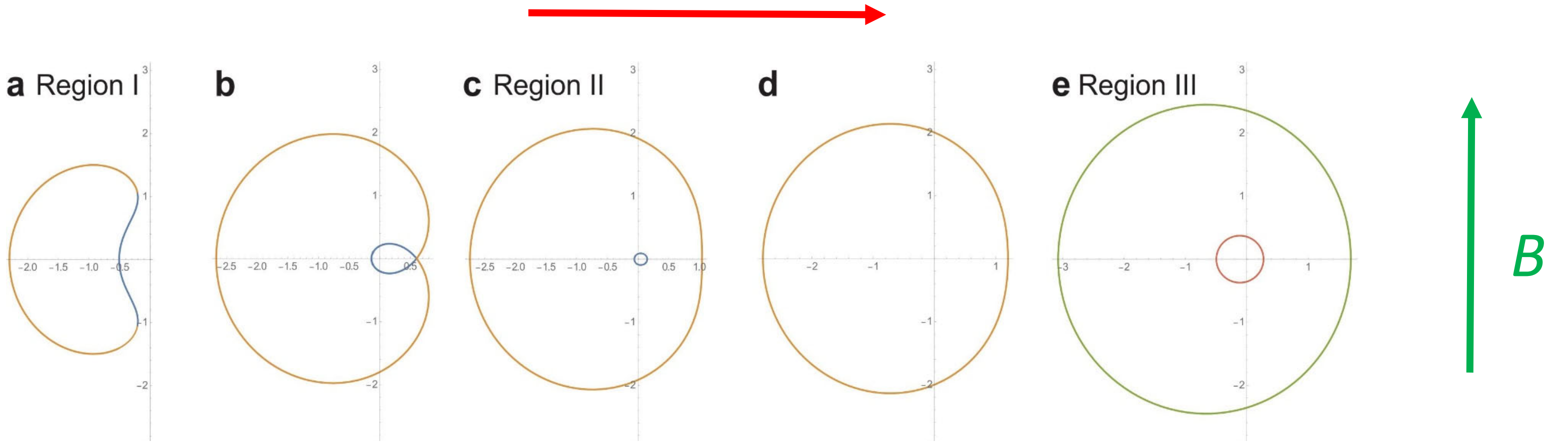
Expand in E

$$f = f_0 + f_1 + f_2 + \cdots,$$

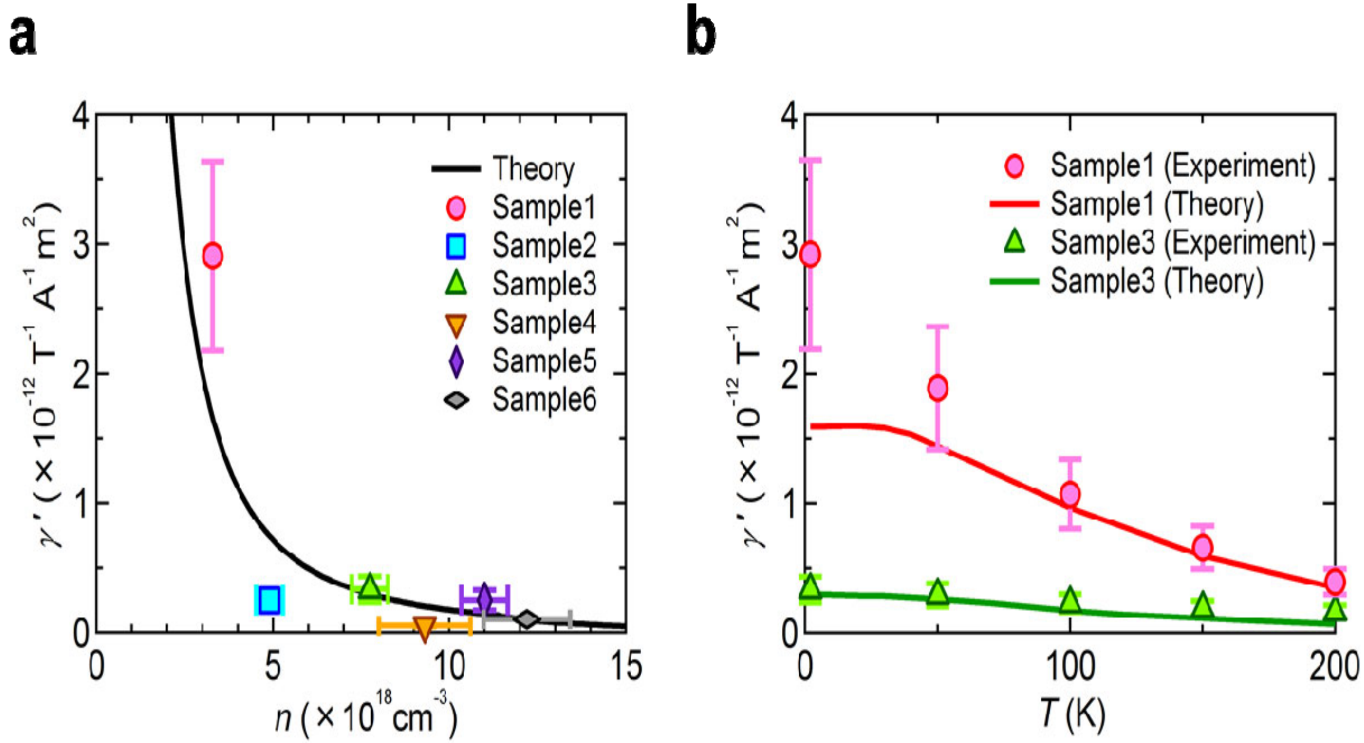
$$J_x = J_x^{(1)} + J_x^{(2)} = \sigma_1 E_x + \sigma_2 E_x^2$$

γ is independent of τ in the single relaxation time approx. like Hall coefficient

γ diverges as n → 0 　 increasing Fermi energy 　 γ is zero when two FSs coexist



No fitting parameters !



$$\gamma \sim 1 T^{-1} A^{-1}$$

$$\gamma' = \gamma A$$

A cross section of the sample

Chiral anomaly in Weyl semimetals

$$\frac{dQ^5}{dt} = \frac{2\nu}{(2\pi)^2}\frac{e^2}{\hbar^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

$$Q^5 = \frac{\nu e^2\tau}{4\pi^2\hbar^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

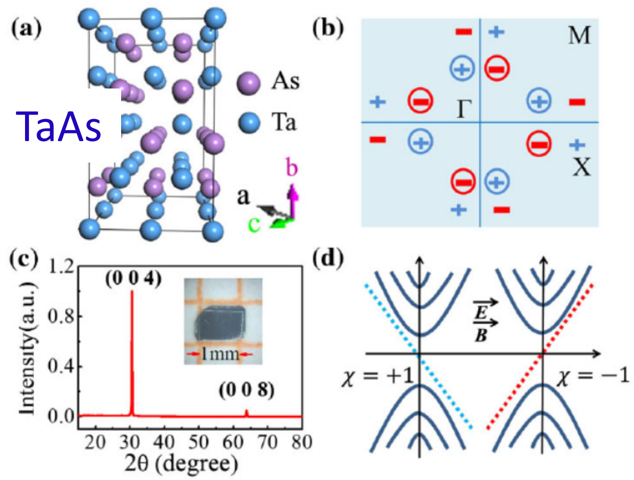
$$\boldsymbol{J} = -(e^2/h^2)\mu^5\boldsymbol{B}$$

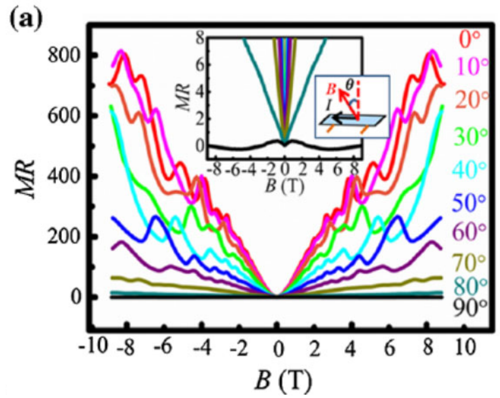
μ_5 chemical potential difference in non-equilibrium steady state

$$\Delta J \propto \tau(B\cdot E)B$$

K. Fukushima, D. Kharzeev

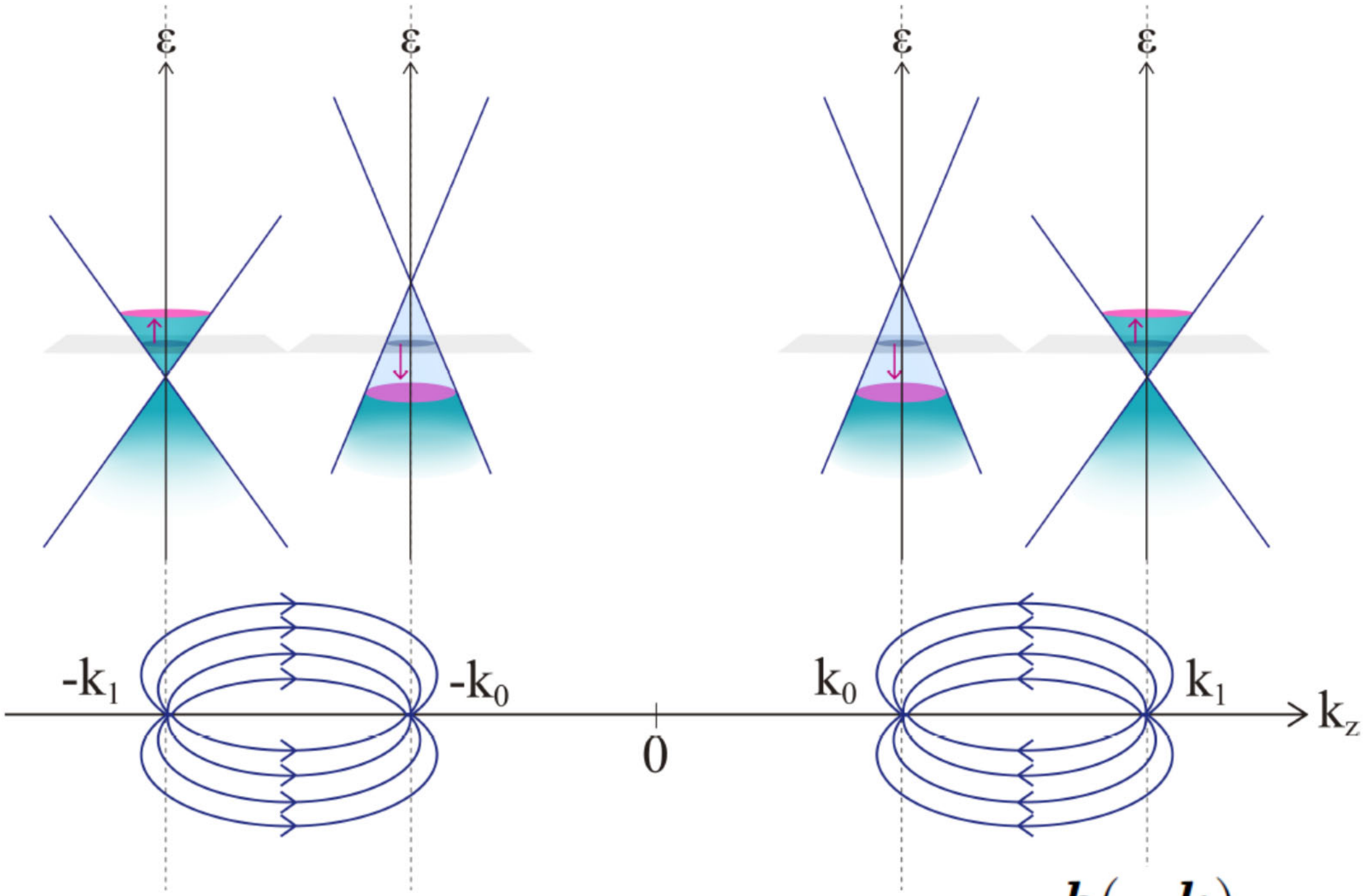
X. Huang et al., PRX 2015





negative magnetoresistance
due to chiral anomaly

Weyl fermions in noncentrosymemtric semimetals



$$\boldsymbol{b}(-\boldsymbol{k}) = -\boldsymbol{b}(\boldsymbol{k})$$

Magnetochial anisotropy in noncentrosymemtric Weyl semimetals

T. Morimoto, NN PRL2016

$$\Delta\sigma_\pm = \frac{1}{3} e^2 v_\pm^2 \tau \frac{dD_\pm(\epsilon)}{d\epsilon} \Delta\epsilon_\pm$$

$$\Delta\sigma_\pm = \pm\nu \frac{e^4}{6\pi^2\hbar^2} \frac{v_\pm^2 \tau^2}{\epsilon_\pm} \boldsymbol{E}\cdot\boldsymbol{B}.$$

$$\rho = \rho_0(1 + \gamma \boldsymbol{I}\cdot\boldsymbol{B})$$

$$\gamma' = \gamma A$$

$$\gamma' = -\frac{2\delta\sigma/(\boldsymbol{E}\cdot\boldsymbol{B})}{\sigma^2} = -\frac{12\pi^2\hbar^4}{\nu}\left(\frac{v_+^2}{\epsilon_+} - \frac{v_-^2}{\epsilon_-}\right)\left(\frac{\epsilon_+^2}{v_+} + \frac{\epsilon_-^2}{v_-}\right)^{-2}$$

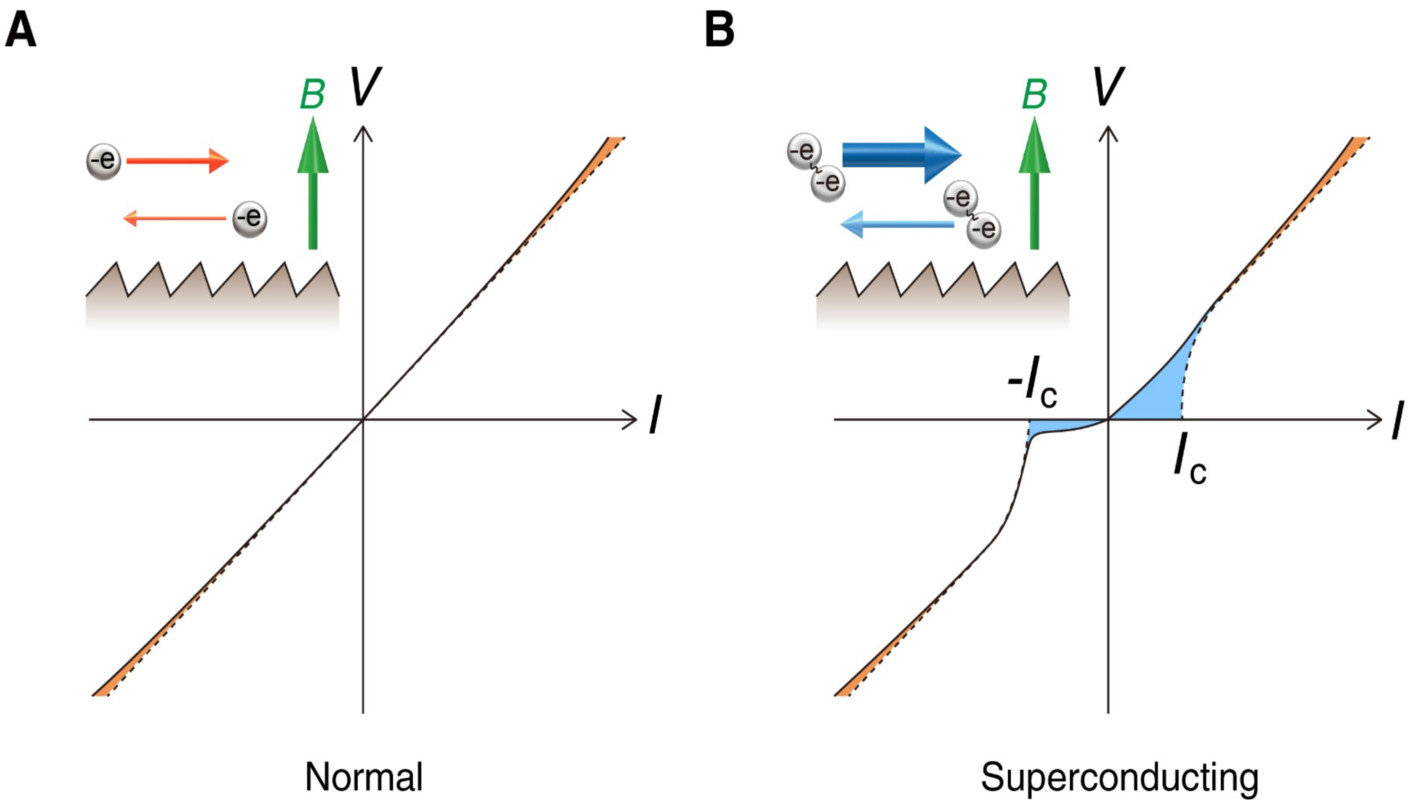
$v \sim 4\times10^5 m/\sec$ $|\varepsilon_\pm| \sim 10 meV$ ⇨ $\gamma' \simeq 3\times10^{-8}\times \mathrm{m}^2\mathrm{T}^{-1}\mathrm{A}^{-1}$

$\gamma \sim 10 T^{-1}A^{-1}$ TaAs

$$\gamma' \boldsymbol{J}\cdot\boldsymbol{B} \simeq 3\times10^{-4}\times(J/(1\mathrm{A/cm}^2))(B/1\,\mathrm{T})$$

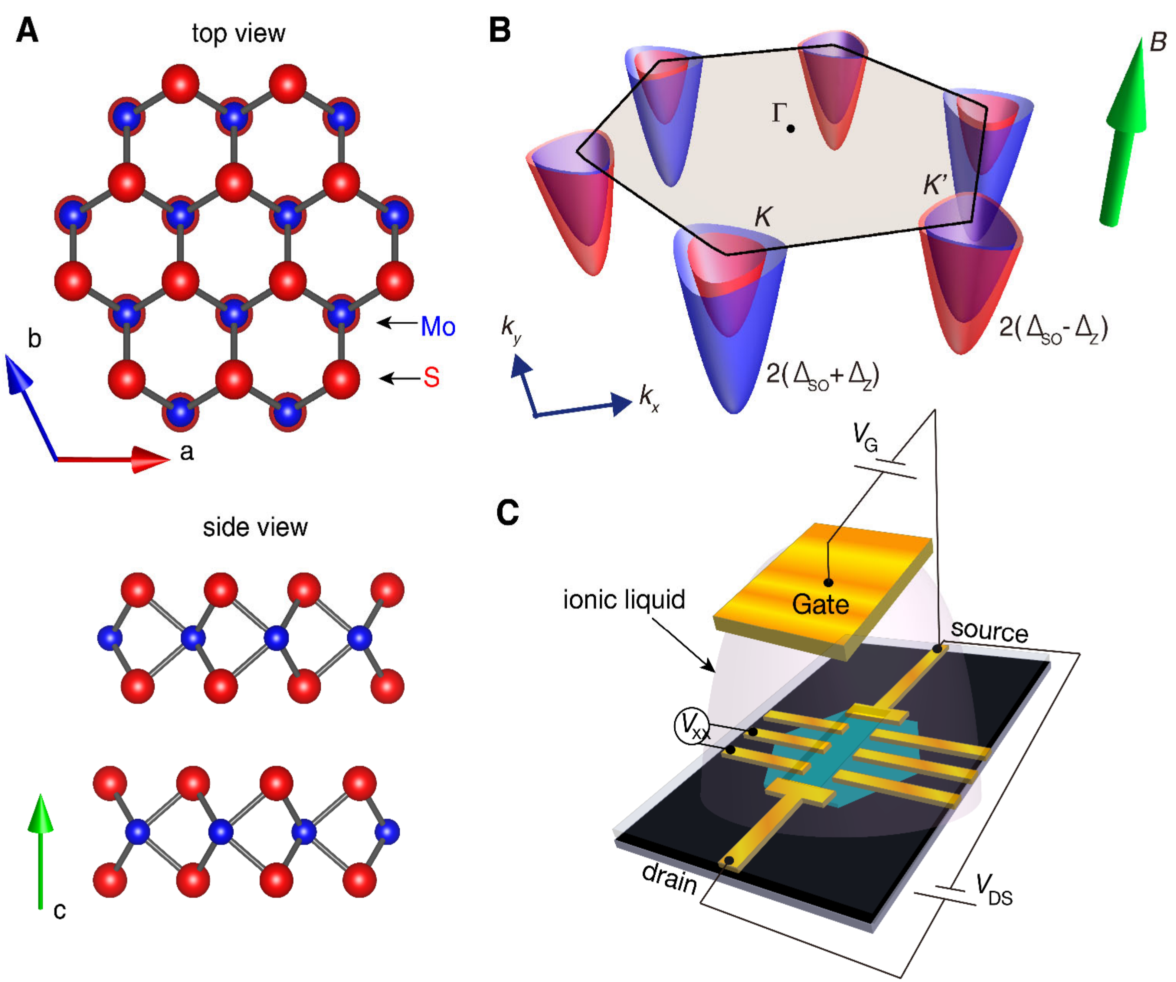
Giant enhancement of non-reciprocal response in superconductor

Wakatsuki, Saito et al. Science Adv. 2017



$$\Delta_{SC} \sim \mu_B B,\ \varepsilon_{SOI} << \varepsilon_F$$

Band structure and spin splitting in MoS2



Paraconductivity due to SC fluctuation in noncentrosymmetric MoS2

$$H_{k\sigma\tau} = \frac{\hbar^2 k^2}{2m} + \tau_z \lambda k_x \left(k_x^2 - 3k_y^2\right) - \Delta_Z \sigma_z - \Delta_{SO} \sigma_z \tau_z,$$

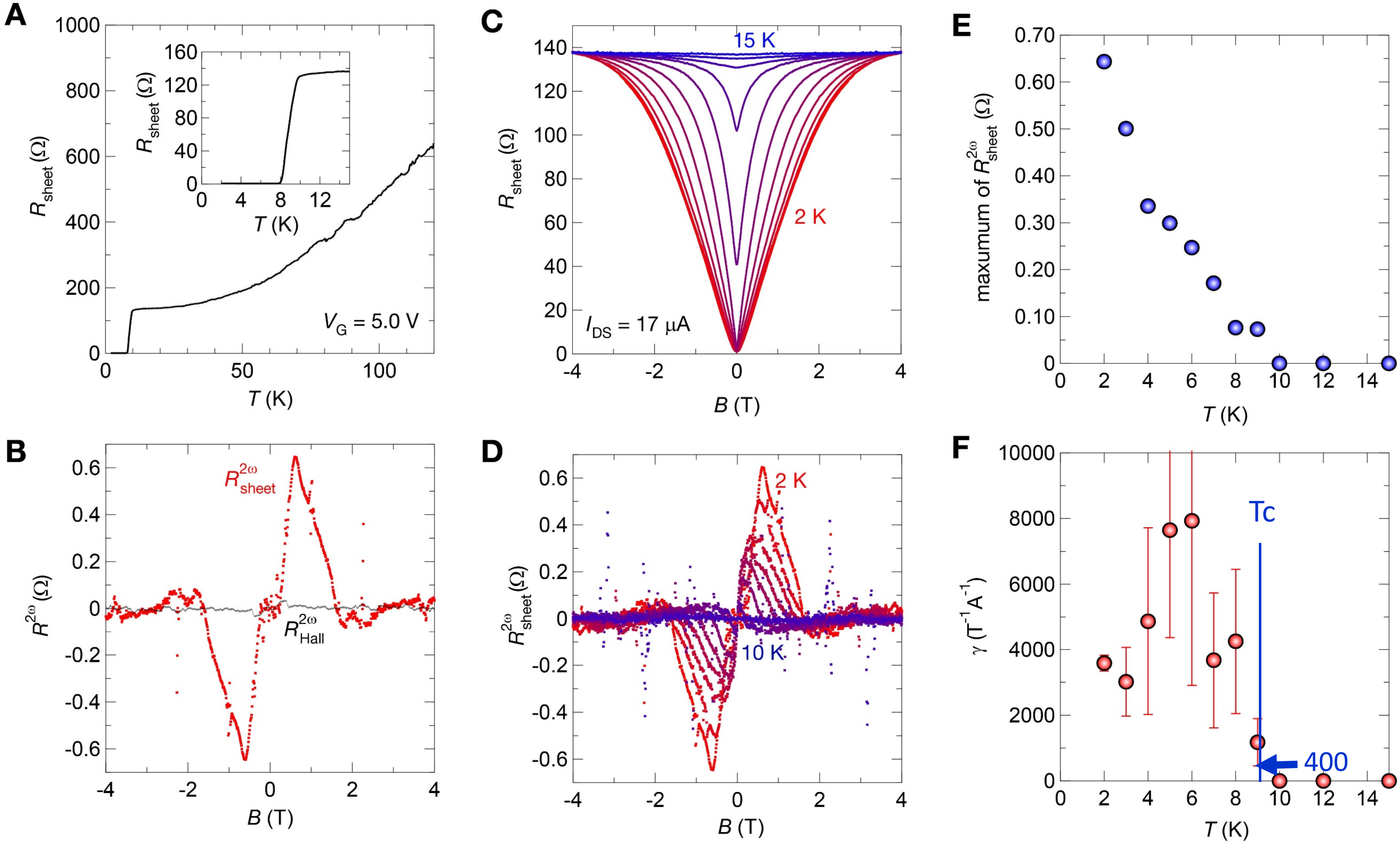
$$F = \int \mathrm{d}\,\boldsymbol{r} \Psi^* \left[a + \frac{\boldsymbol{p}^2}{4m} + \frac{\Lambda B}{\hbar^3}\left(p_x^3 - 3p_x p_y^2\right)\right]\Psi + \frac{b}{2}\int d\,\boldsymbol{r} |\Psi(\boldsymbol{r})|^4,$$

$$\Lambda = \frac{93\zeta(5)}{28\zeta(3)} \frac{g\mu_{\mathrm{B}} \Delta_{\mathrm{SO}} \lambda}{(\pi k_{\mathrm{B}} T_{\mathrm{c}})^2}$$

$$\boldsymbol{j} = \frac{e^2}{16\hbar} \epsilon^{-1} \boldsymbol{E} - \frac{\pi e^3 m \Lambda B}{64\hbar^3 k_{\mathrm{B}} T_{\mathrm{c}}} \epsilon^{-2} \boldsymbol{F}(\boldsymbol{E})$$

$$\frac{\gamma_S}{\gamma_N} \sim \left(\frac{\varepsilon_F}{k_B T_c}\right)^3$$

$$\epsilon = \frac{T - T_c}{T_c} \qquad \boldsymbol{F}(\boldsymbol{E}) = \left(E_x^2 - E_y^2, -2E_x E_y\right)$$



A
R_{sheet} (Ω)
T (K)
V_G = 5.0 V
B
$R^{2\omega}$ (Ω)
$R^{2\omega}_{sheet}$
$R^{2\omega}_{Hall}$
B (T)
C
R_{sheet} (Ω)
15 K
2 K
I_{DS} = 17 μA
B (T)
D
$R^{2\omega}_{sheet}$ (Ω)
2 K
10 K
B (T)
E
maxumum of $R^{2\omega}_{sheet}$ (Ω)
T (K)
F
γ ($T^{-1}A^{-1}$)
Tc
400
T (K)

<table>
<tr><td colspan="2"></td><td>Rashba SC ($B \perp \hat{z}$)</td><td colspan="2">TI surface + SC ($B \perp \hat{z}$)</td><td>TMD ($B \parallel \hat{z}$)</td></tr>
<tr><td colspan="2">Symmetry</td><td colspan="2">C_∞</td><td>Hexagonal</td><td>Trigonal</td></tr>
<tr><td rowspan="4">$T > T_0$</td><td rowspan="2">Normal</td><td colspan="4">$V = a_1 I(1 + \gamma_N B I)$</td></tr>
<tr><td>[Sec. II A]
$\gamma_N = 0$ (E_F>0)
$\gamma_N \sim \frac{\alpha}{e(m\alpha^2 E_{FR})^{3/2}}$ (E_F<0)</td><td>[Sec. II B 1]
$\gamma_N \sim \frac{\mathrm{sgn}\, E_F}{e m v_F E_F^2}$</td><td>[Sec. II B 2]
$\gamma_N \sim \frac{|E_F|\lambda}{e v_F^5}$</td><td>[Sec. II C]
$\gamma_N \sim \frac{m\Delta_{SO}\lambda}{e E_F^3}$</td></tr>
<tr><td rowspan="2">Paraconductivity</td><td colspan="4">$V = a_1 I(1 + \gamma_S B I)$</td></tr>
<tr><td>Parity mixing (E_F>0)
$\gamma_S \sim \frac{r_{t,s} E_F \alpha}{e T_0^3 E_{FR} \ln(E_c/T_0)}$
q-cubic term (E_F<0)
$\gamma_S \sim \frac{1}{e m \alpha E_{FR} T_0}$</td><td>$\gamma_S \sim \frac{1}{e m v_F E_F T_0}$</td><td>$\gamma_S \sim \frac{E_F^2 \lambda}{e v_F^5 T_0}$</td><td>$\gamma_S \sim \frac{m\Delta_{SO}\lambda}{e T_0^3}$</td></tr>
<tr><td rowspan="3">$T < T_0$</td><td colspan="4">KT transition</td><td>No KT transition</td></tr>
<tr><td>$T_{KT} < T < T_0$</td><td colspan="3">[Sec. III A]
$V = a_1 I(1 + \gamma_S B I)$
$\gamma_S \sim (T_0 - T)^{-1}$ ($T \to T_0$)
$\gamma_S \sim (T - T_{KT})^{-3/2}$ ($T \to T_{KT}$)</td><td rowspan="2">Viscous vortex flow
[Sec. III A,B]
$V = a_1' B I(1 + \gamma_S B I)$
$\gamma_S \sim \frac{m\Delta_{SO}\lambda}{e T_0 E_F (T_0 - T)}$
Ratchet mechanism
[Sec. III C]
$V = a_1' B I(1 + \gamma_S' I)$</td></tr>
<tr><td>$T < T_{KT}$</td><td colspan="3">$V = a_3 I^3 + a_4' B I^4$</td></tr>
</table>

S. Hoshino et al. 2018

$\frac{1}{emv_{\mathrm{F}}E_{\mathrm{F}}T_0}$	$\gamma_{\mathrm{S}} \sim \frac{E_{\mathrm{F}}^2\lambda}{ev_{\mathrm{F}}^5T_0}$	$\gamma_{\mathrm{S}} \sim \frac{m\Delta_{\mathrm{SO}}\lambda}{eT_0^3}$
on		No KT transition
[Sec. III A] $a_1 I(1+\gamma_{\mathrm{S}}BI)$ $)^{-1}$ $(T \to T_0)$ $_{\mathrm{KT}})^{-3/2}$ $(T \to T_{\mathrm{KT}})$		***Viscous vortex flow*** [Sec. III A,B] $V = a_1' BI(1+\gamma_{\mathrm{S}}BI)$ $\gamma_{\mathrm{S}} \sim \frac{m\Delta_{\mathrm{SO}}\lambda}{eT_0E_{\mathrm{F}}(T_0-T)}$
$a_3 I^3 + a_4' BI^4$		***Ratchet mechanism*** [Sec. III C] $V = a_1' BI(1+\gamma_{\mathrm{S}}' I)$

S. Hoshino et al. 2018

Number of vortices
Dissipative dynamcis
of vortices

Ratchet motion of vortex and nonreciprocal transport

PHYSICAL REVIEW B **71**, 024519 (2005)

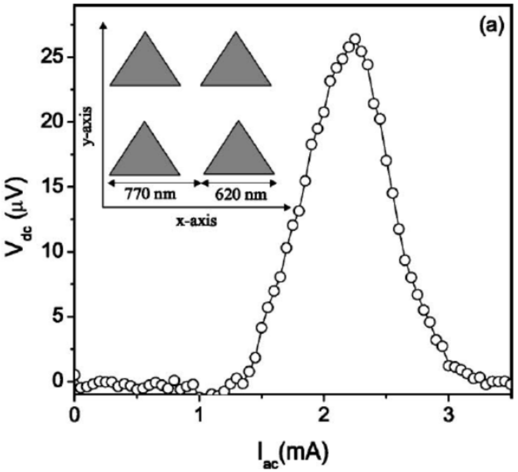
Experimental ratchet effect in superconducting films with periodic arrays of asymmetric potentials

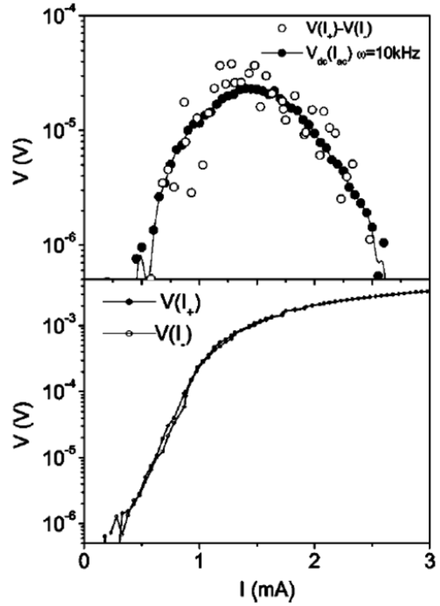
J. E. Villegas,[1] E. M. Gonzalez,[1] M. P. Gonzalez,[1] J. V. Anguita,[2] and J. L. Vicent[1]

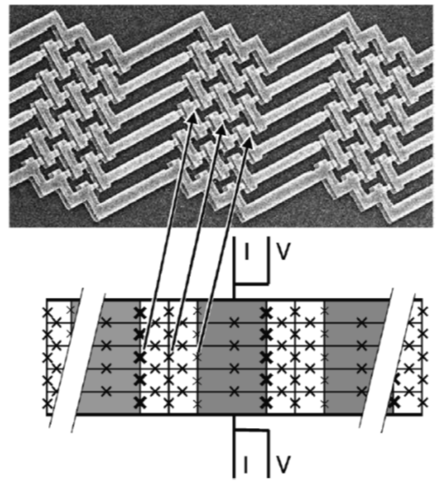
VOLUME 90, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 7 FEBRUARY 2003

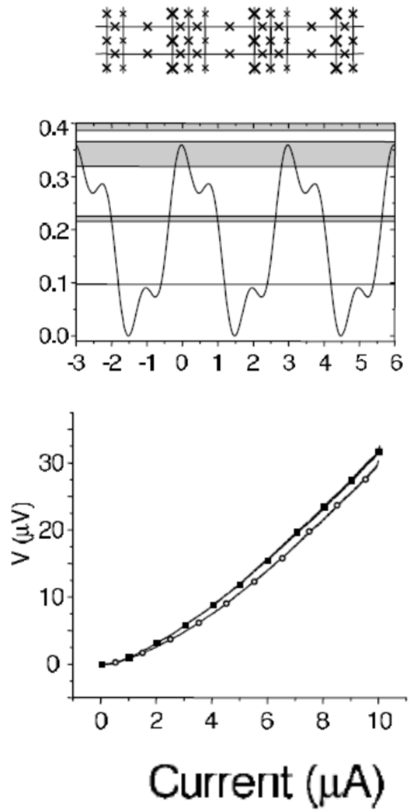
Quantum Ratchet Effect for Vortices

J. B. Majer, J. Peguiron, M. Grifoni, M. Tusveld, and J. E. Mooij

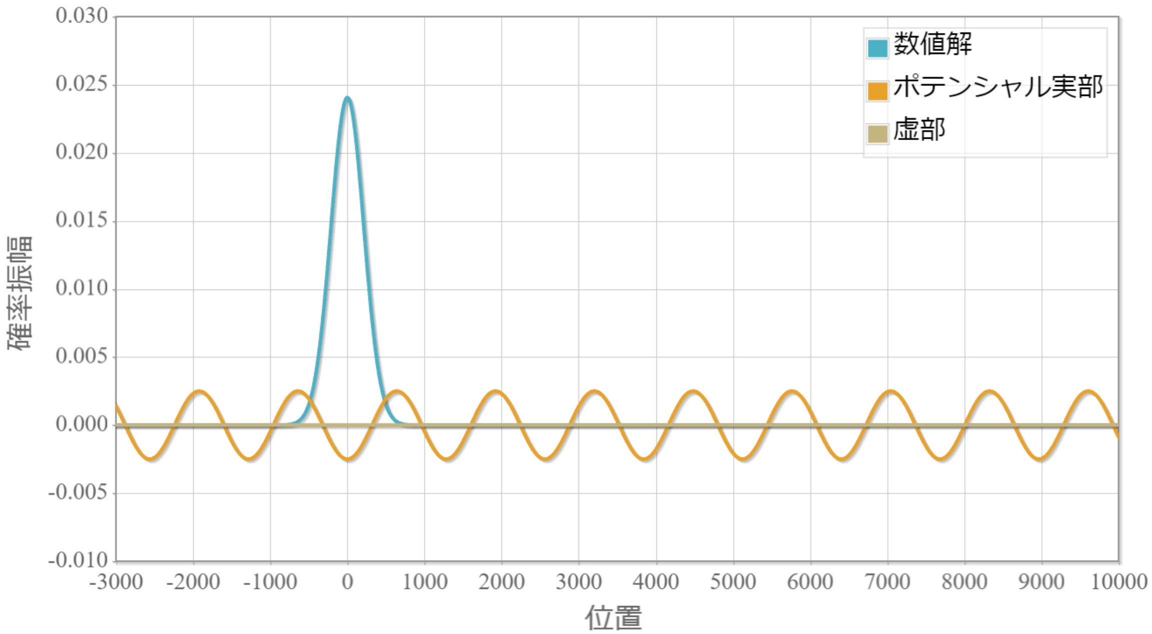








A quantum particle in periodic potential



http://www.natural-science.or.jp/article/20180529143612.php

Quantum dissipation
by coupling to heat bath

$$\hat{\mathscr{H}} = \frac{P^2}{2M} + V(q) + \sum_{\alpha} P_{\alpha}^2 / 2m_{\alpha} + \frac{1}{2} \sum_{\alpha} m_{\alpha} \omega_{\alpha}^2 (x_{\alpha} + q\lambda_{\alpha} / m_{\alpha} \omega_{\alpha}^2)^2$$

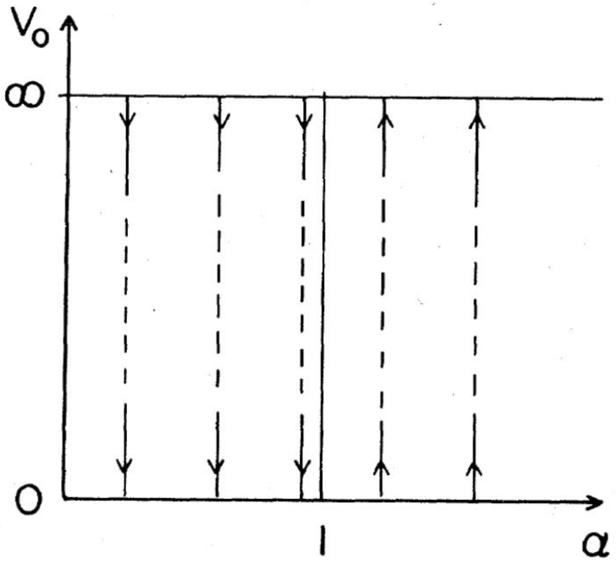
$$V(q) = -V \cos(2\pi q / q_0) - Fq$$

RG study

$$H=\frac{1}{2}\int\frac{d\omega}{2\pi}S_{\Lambda}(\omega)\,|\phi(\omega)|^{2}-V_{0}\Lambda\int d\tau\cos\phi(\tau)$$

$$S_{\Lambda}(\omega)=\frac{\alpha}{2\pi}|\omega|+\frac{\omega^{2}}{\Lambda}$$

α dimensionless dissipation strength



$$\frac{\partial V_0}{\partial l}=-\left[\frac{1}{\alpha}-1\right]V_0(l)+O(V_0^3)$$

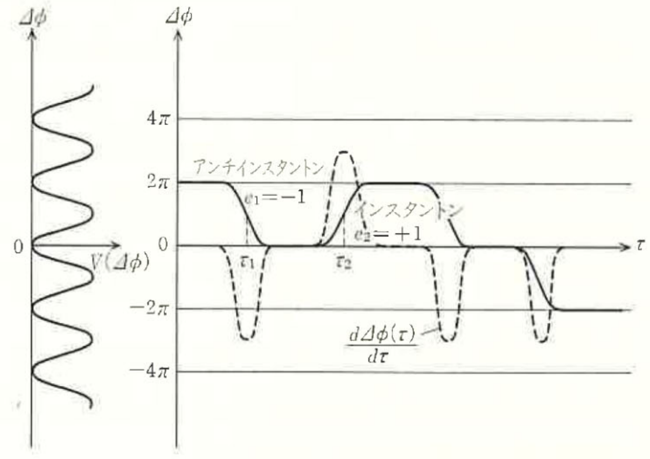
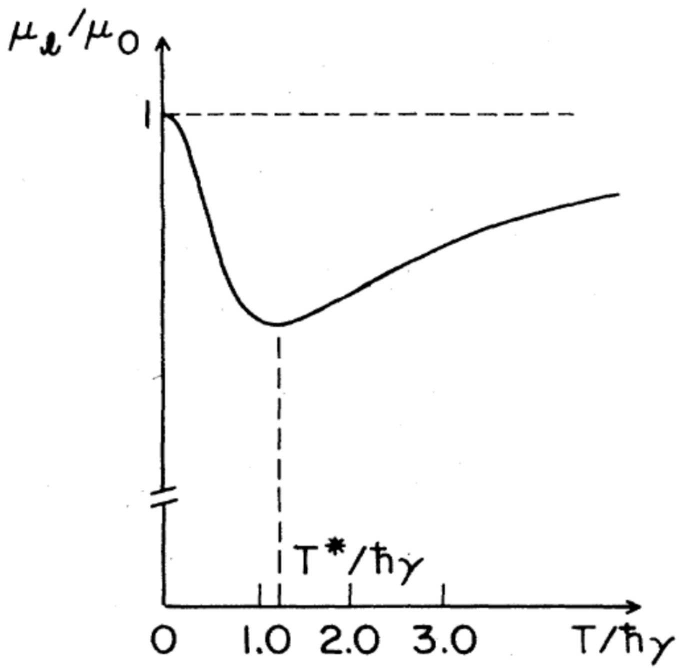


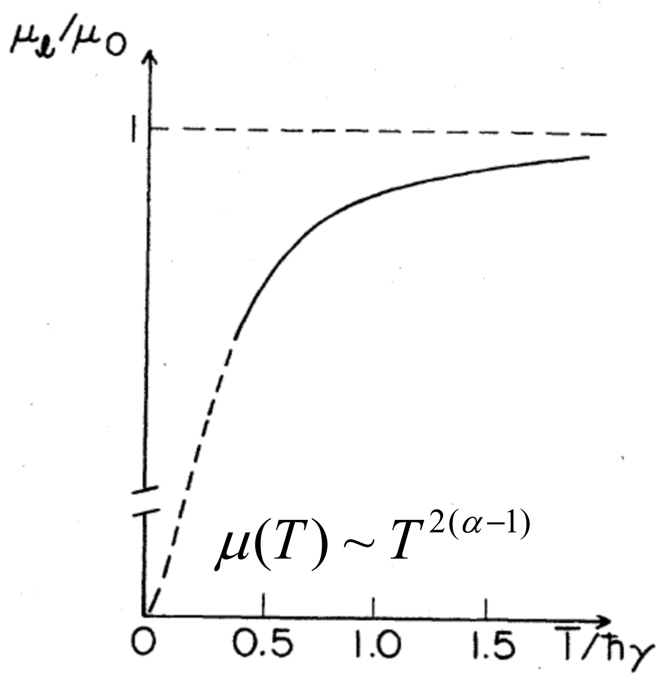
図 5-4　インスタントン，アンチインスタントンを含んだ配置

duality $\alpha\rightarrow 1/\alpha$

Linear Mobility



$\alpha < 1$



$\alpha > 1$

Fisher-Zwerger PRB1985
Furusaki-Nagaosa PRB1993
Kane-Fisher PRB1992

Summary

- Non-linear and non-reciprocal responses in nontrosymmetric systems contain rich physics

- Time-reversal symmetry breaking plays an important role

- Magnetochiral anisotropy
  - dissipation
  - quantum-classical crossover
  - duality between bosons and vortices

Symmetry   Quantum Geometry   Electron Correlation   Irreversibility

For a review see Y.Tokura, N.Nagaosa, Nature Communications 2018