Workshop on Dirac Electron Systems 2011, National Institute for Materials Science, Jan.19, 2011

Magnetoresistance in organic Dirac fermion system

Takao Morinari

Yukawa Institute for Theoretical Physics, Kyoto University

Collaborators

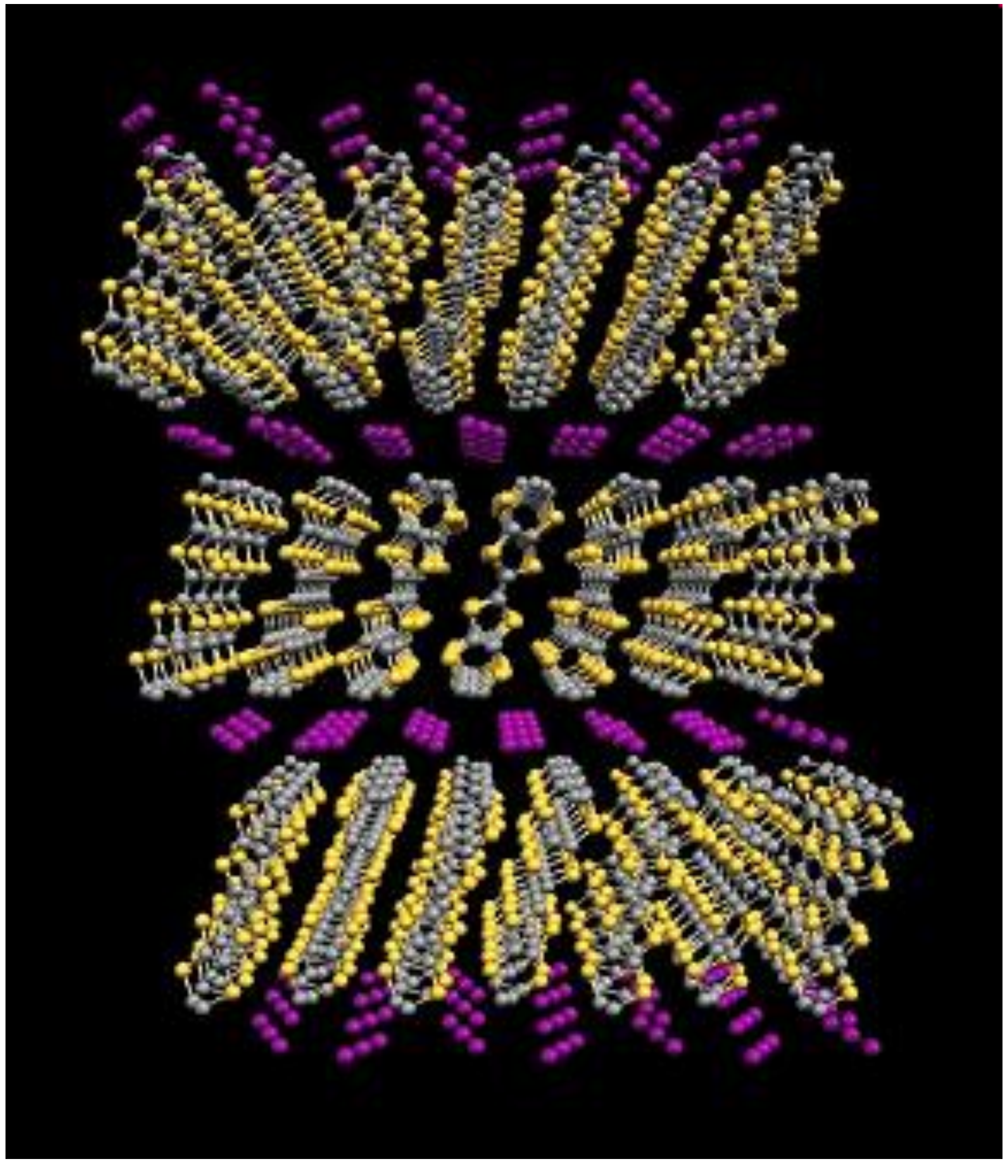
Takami Tohyama (YITP)

Takahiro Himura (YITP)

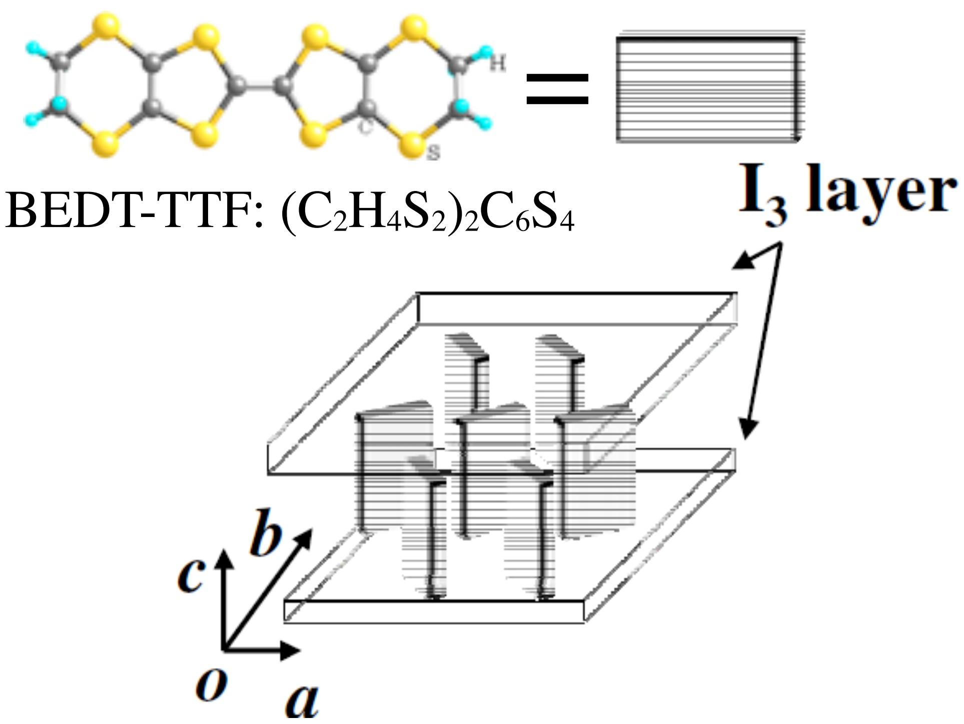
Outline

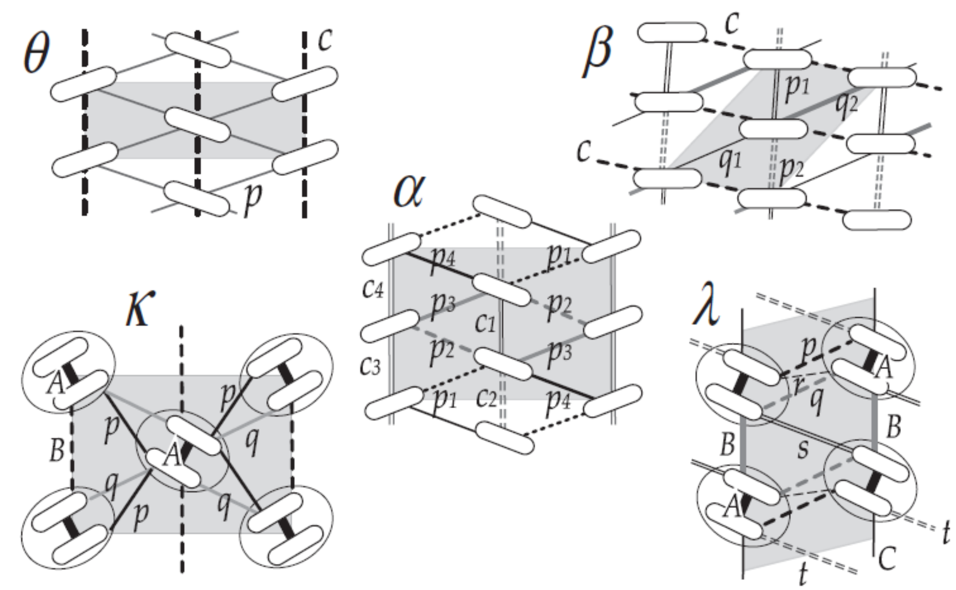
1. α-(BEDT-TTF)$_2$I$_3$ under pressure
2. Inter-layer magnetoresistance
   Zero energy Landau level effect
3. Inplane magnetoresistance
   Inter-Landau level transitions
   Electron-electron interaction effect
4. Summary

α-(BEDT-TTF)$_2$I$_3$: Crystal Structure



Courtesy of N. Tajima (RIKEN)

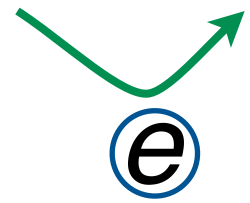




C. Hotta, JPSJ **72**, 840 (2003)

Carriers?

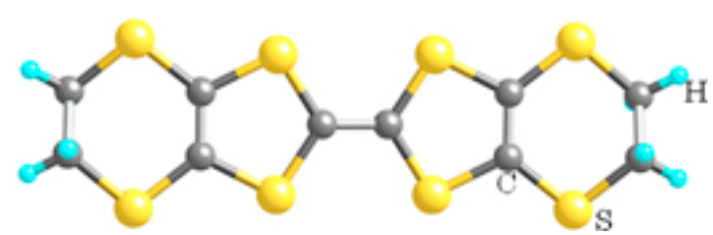
$$\left(\text{BEDT-TTF}\right)_2\,\text{I}_3$$

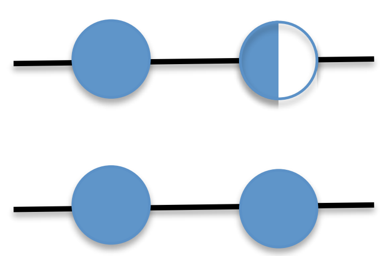


$$\left[\left(\text{BEDT-TTF}\right)_2\right]^{+}\left[\text{I}_3\right]^{-}$$

1/2 hole per (BEDT-TTF)-molecule

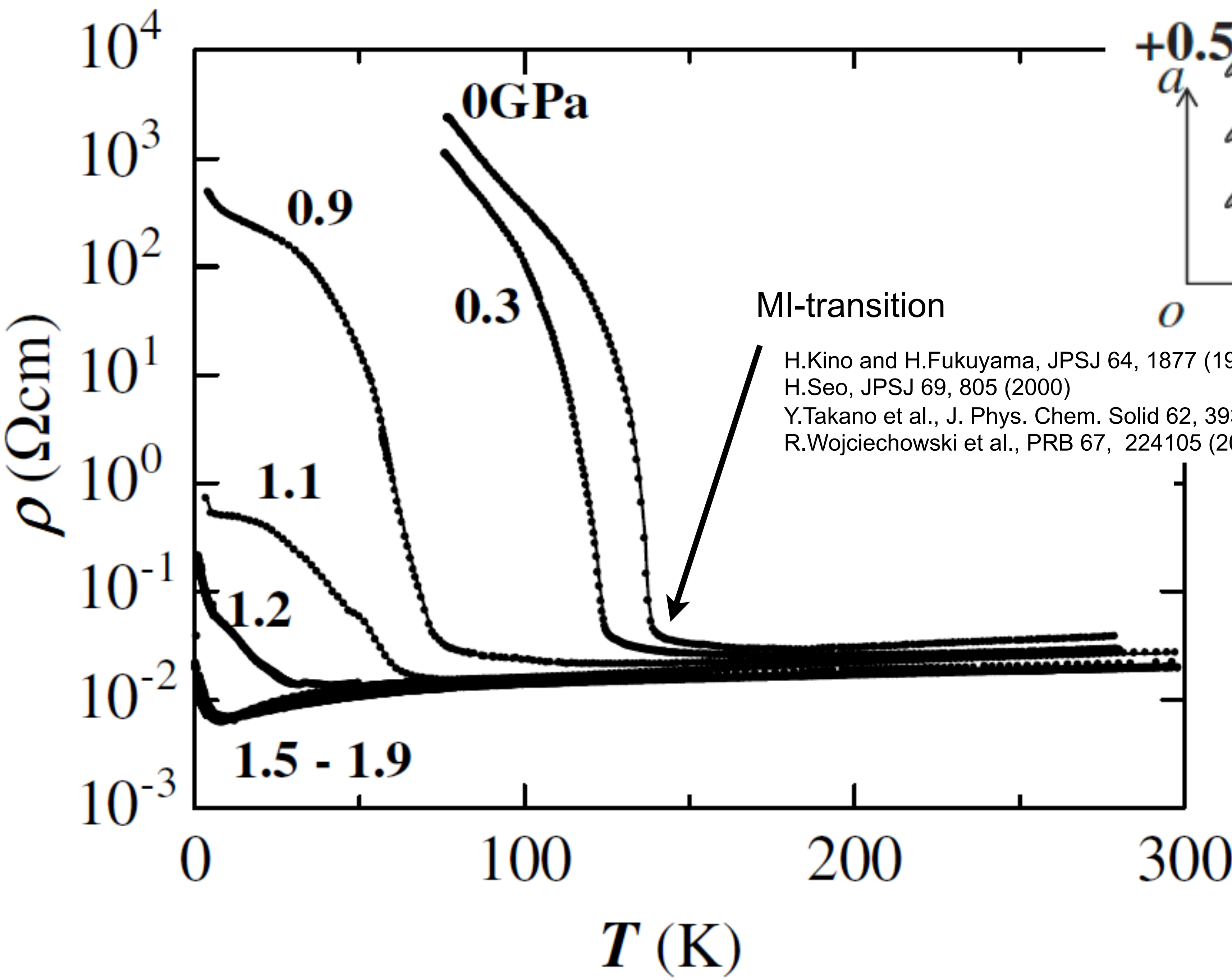
Molecular orbitals



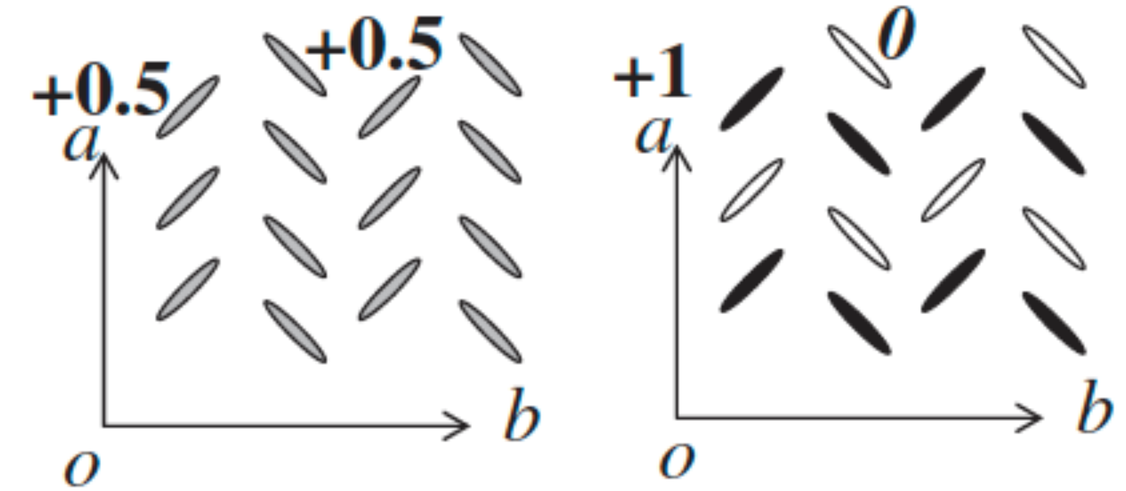


3/2 electrons per molecule

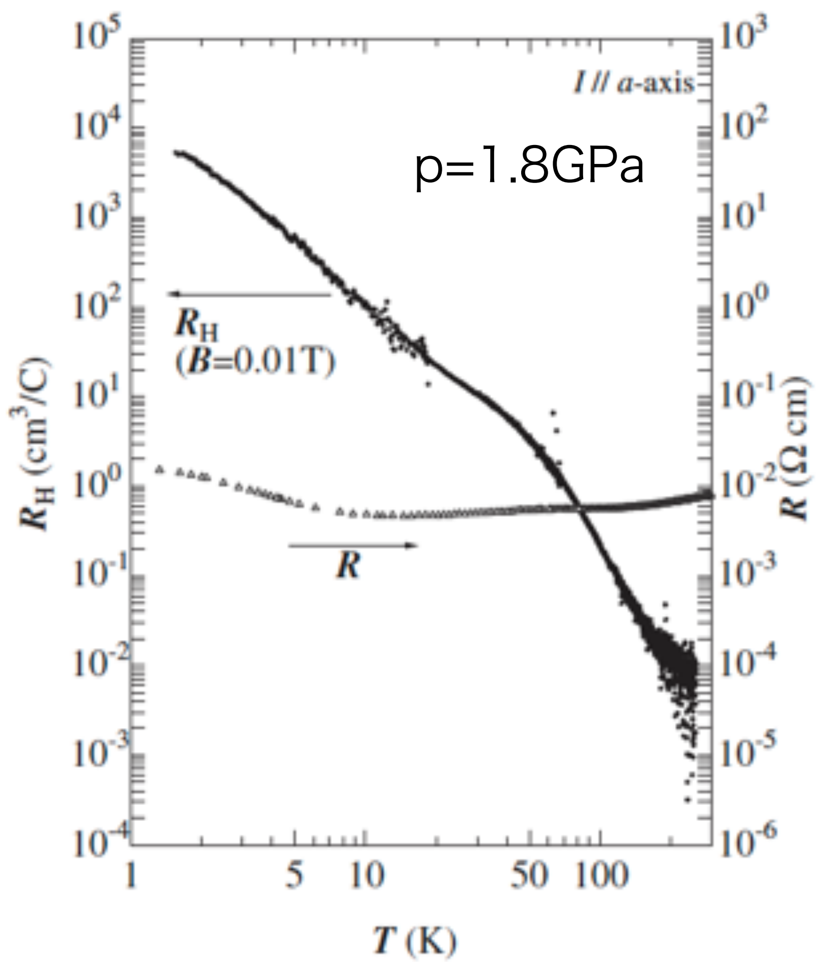
Resistivity under pressure



MI-transition



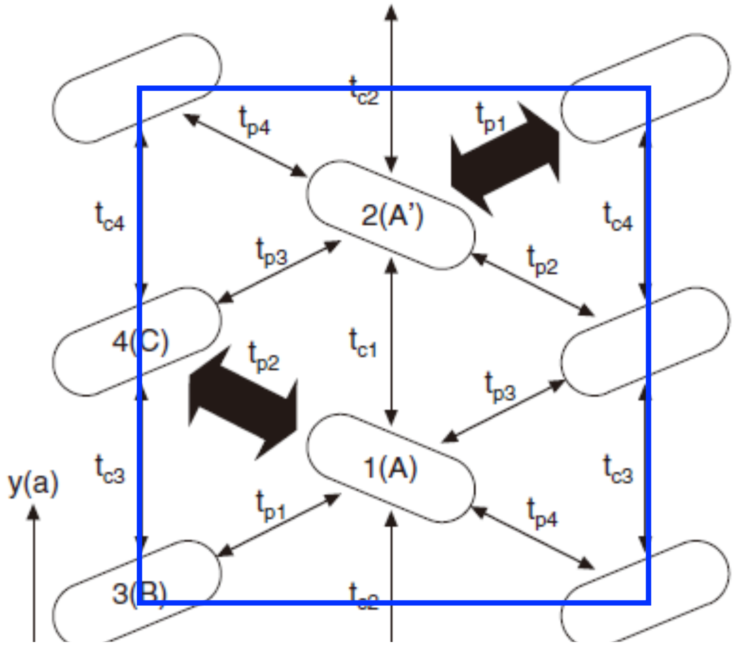
H.Kino and H.Fukuyama, JPSJ 64, 1877 (1995)
H.Seo, JPSJ 69, 805 (2000)
Y.Takano et al., J. Phys. Chem. Solid 62, 393 (2001)
R.Wojciechowski et al., PRB 67, 224105 (2003)



N. Tajima *et al.*, Europhys. Lett. **80**, 47002 (2007)

N.Tajima *et al.*, J. Phys. Soc. Jpn. **75**, 051010 (2006)

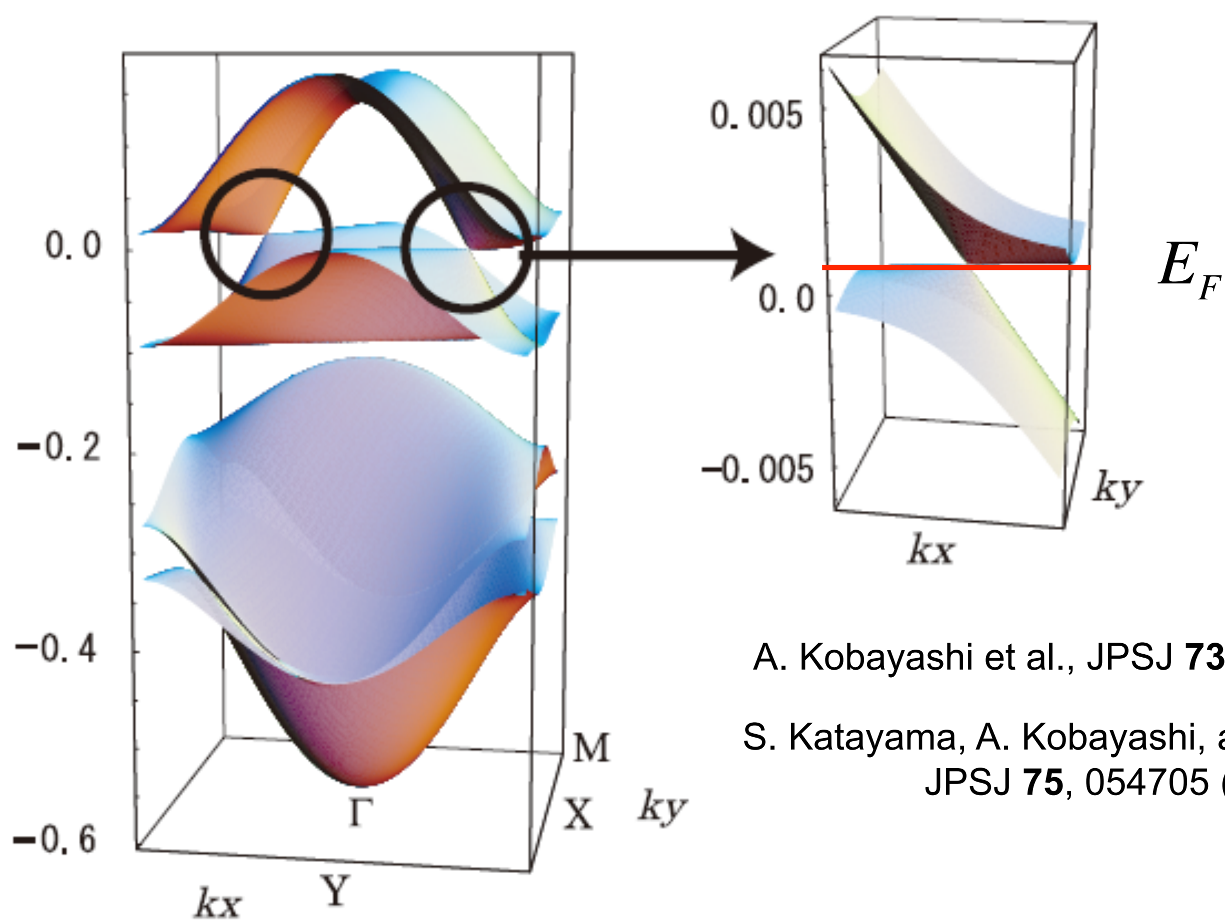
Tight-binding model analysis



Transfer integrals

$$t_A(P) = (1 + K_A P) t_A(0)$$

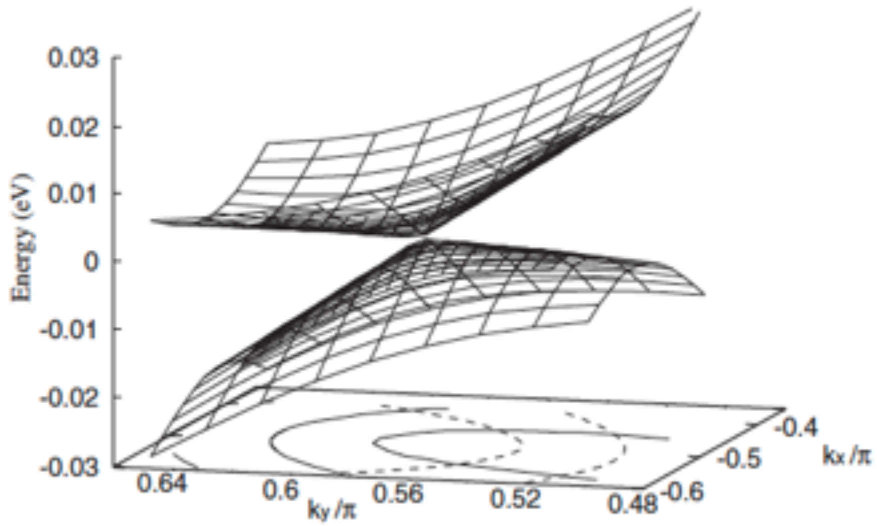
R. Kondo, S. Kagoshima, and J. Harada,
Rev. Sci. Instrum. 76, 093902 (2005)



A. Kobayashi et al., JPSJ **73**, 3135 (2004)

S. Katayama, A. Kobayashi, and Y. Suzumura,
JPSJ **75**, 054705 (2006)

First principles calculation

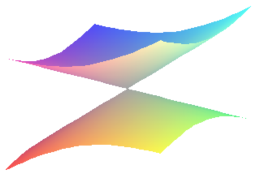


H. Kino and T. Miyazaki, J. Phys. Soc. Jpn. **75**, 034704 (2006)

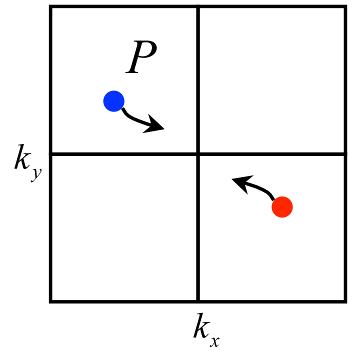
S. Ishibashi *et al*, J. Phys. Soc. Jpn. **75** ,015005 (2006)

Dirac fermions in α-(BEDT-TTF)$_2$I$_3$

- Bulk system
- The Fermi energy is at the Dirac point.
- The Dirac cone is *tilted*.



- The contact points move by changing pressure.

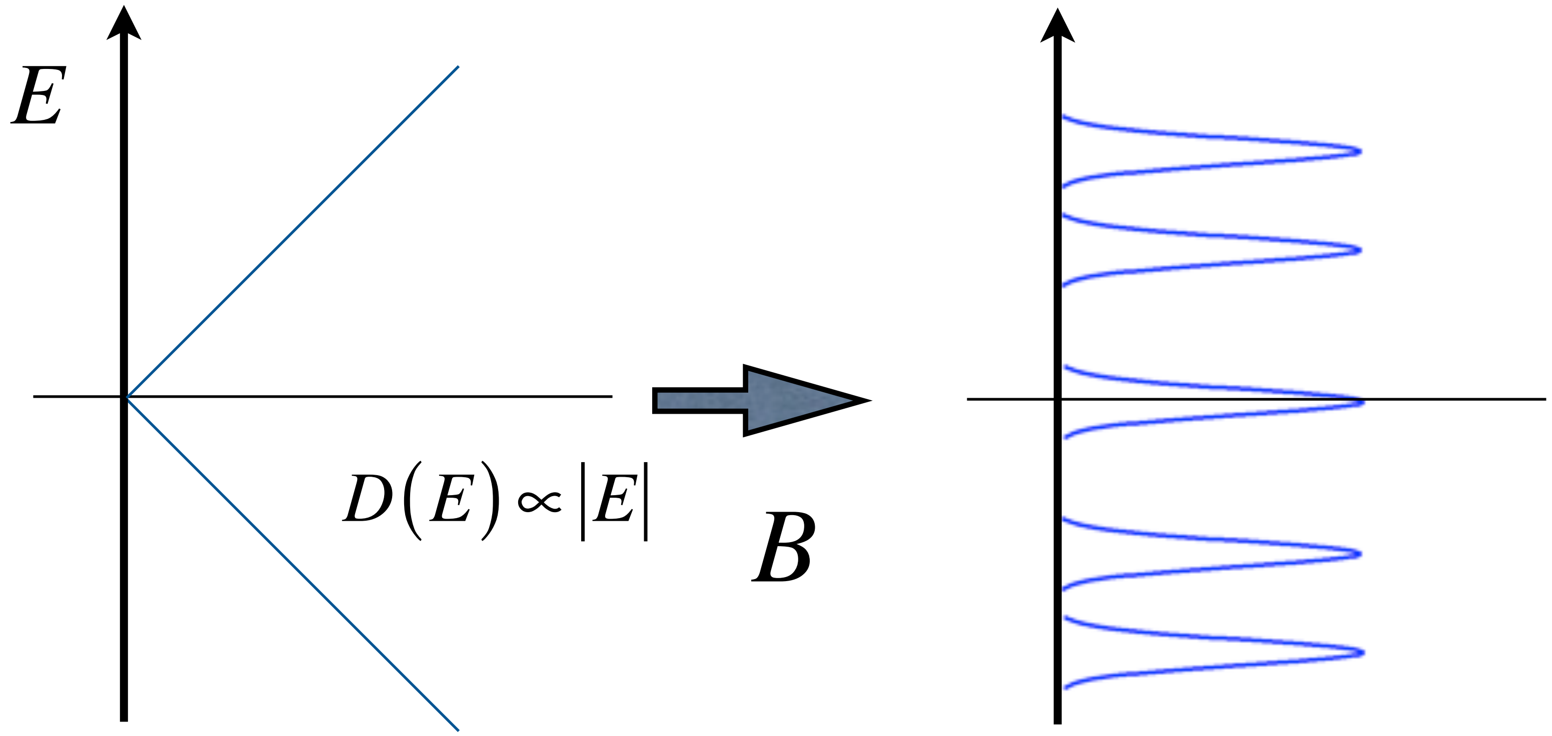


- Need to apply pressure.

Outline

1. α-(BEDT-TTF)$_2$I$_3$ under pressure
2. Inter-layer magnetoresistance
   Zero energy Landau level effect
3. Inplane magnetoresistance
   Inter-Landau level transitions
4. Conclusion

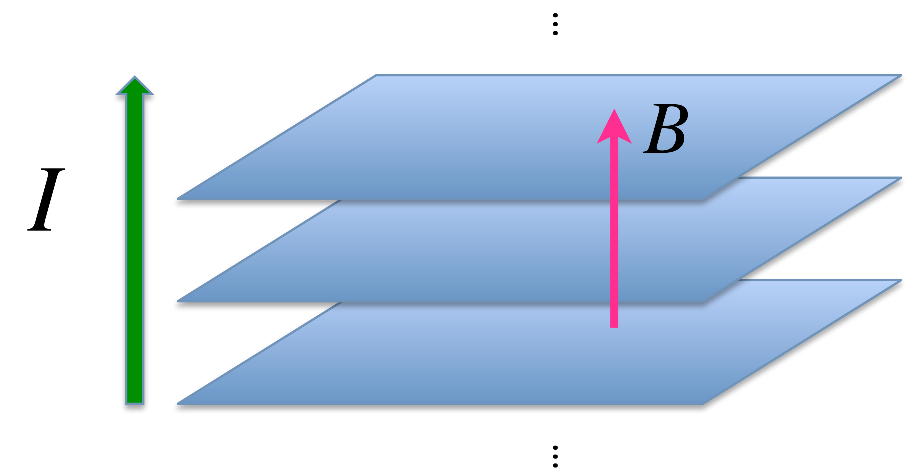
Landau levels of Dirac fermions



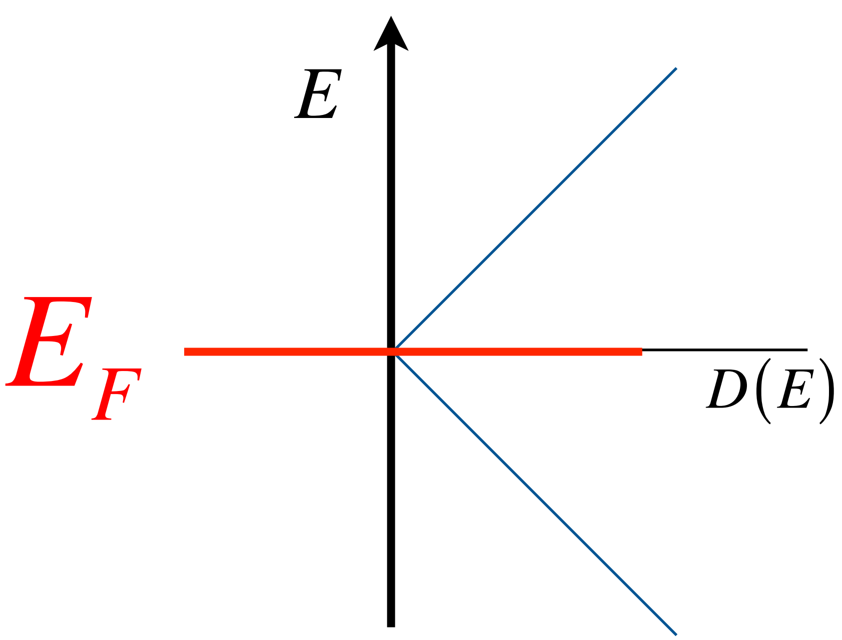
$$E_n = \mathrm{sgn}(n)\sqrt{2e\hbar v_F^2 |n| B} \quad \longleftrightarrow \quad \varepsilon_n = \left(n + \frac{1}{2}\right)\hbar\omega_c$$

- Zero energy Landau level
- Not even-spaced
- Large energy gap

Interlayer magnetoresistance

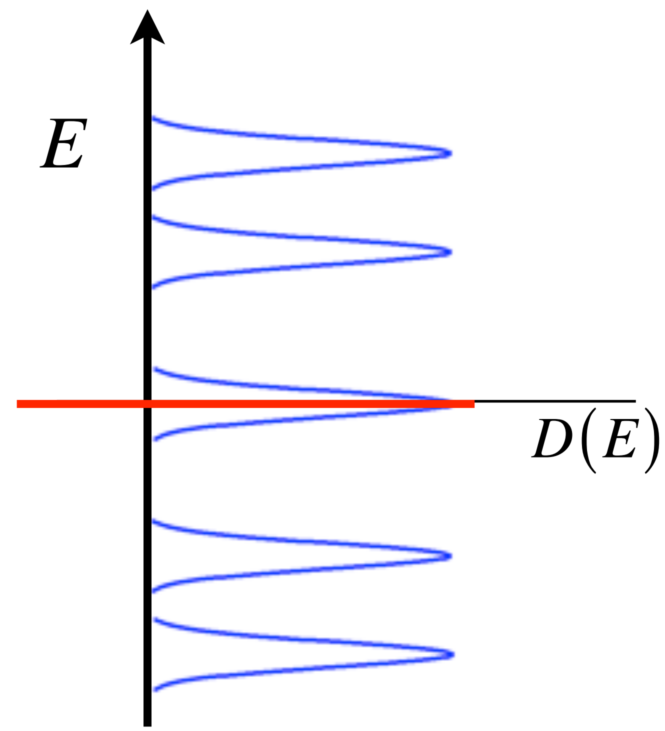


$B = 0$



High resistivity

$B \neq 0$



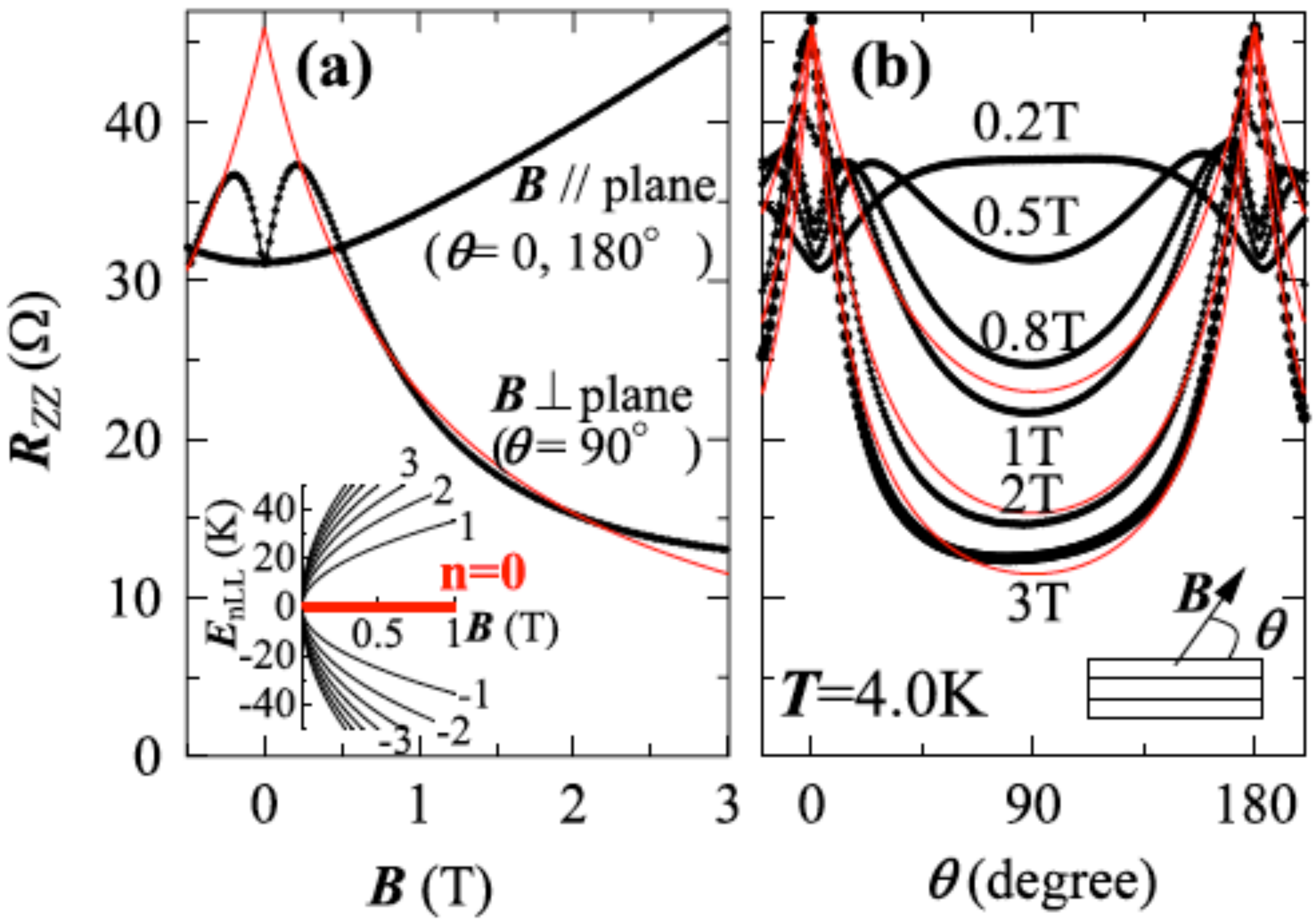
Low resistivity

$$D(E_F) \propto B$$

$$\rho_z \propto \frac{1}{B}$$

T. Osada, JPSJ **77**, 084711 (2008).

2. Interlayer magnetoresistance: Experiment



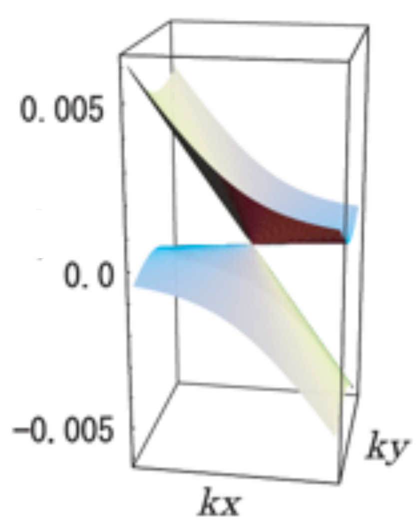
N.Tajima, S.Sugawara, R.Kato, Y.Nishio, and K.Kajita,
Phys. Rev. Lett. 102, 176403 (2009).

Zero energy Landau level effect!

2. Interlayer magnetoresistance

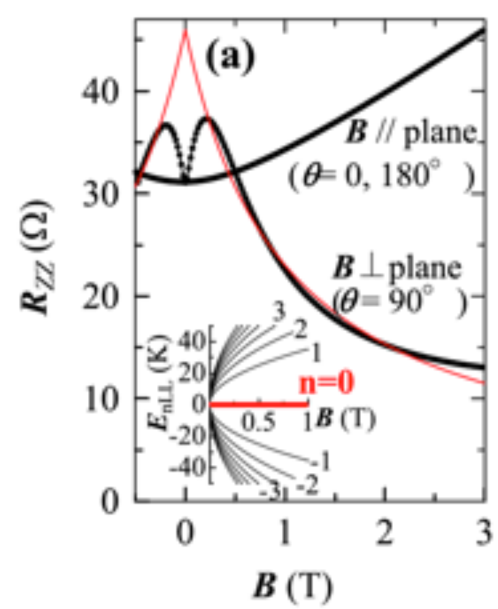
Zero energy Landau level effect

- Zeeman splitting?
- Tilted Dirac cone?
- Positive MR region?



A. Kobayashi et al., JPSJ **73**, 3135 (2004)

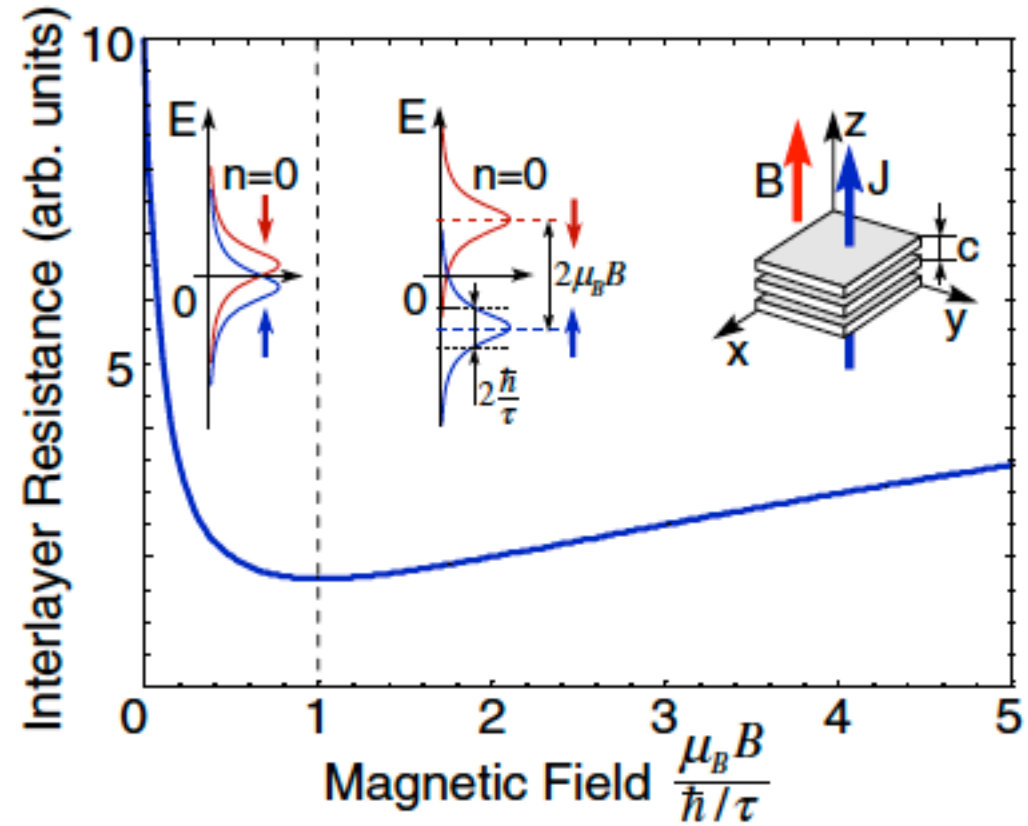
S. Katayama, A. Kobayashi, and Y. Suzumura, JPSJ **75**, 054705 (2006)



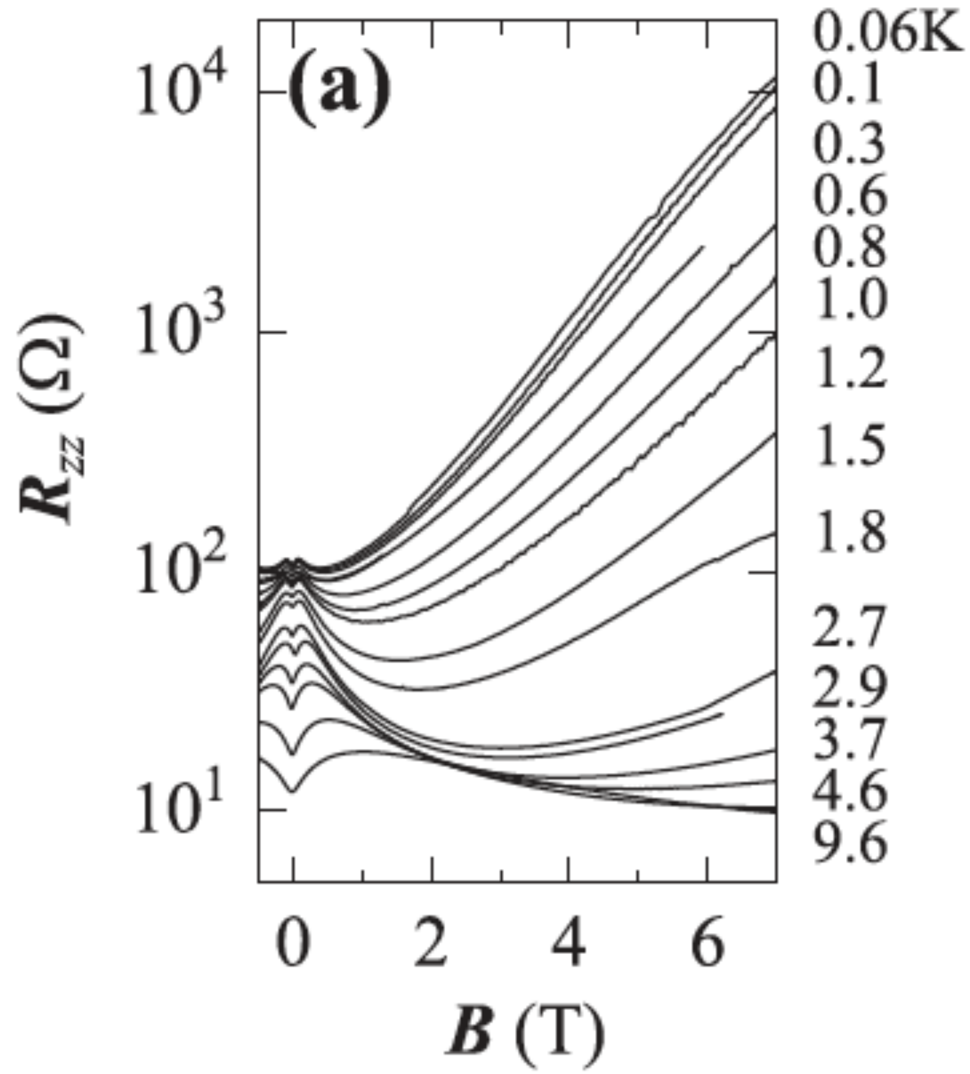
N.Tajima *et al.*, Phys. Rev. Lett. 102, 176403 (2009).

Zeeman splitting?

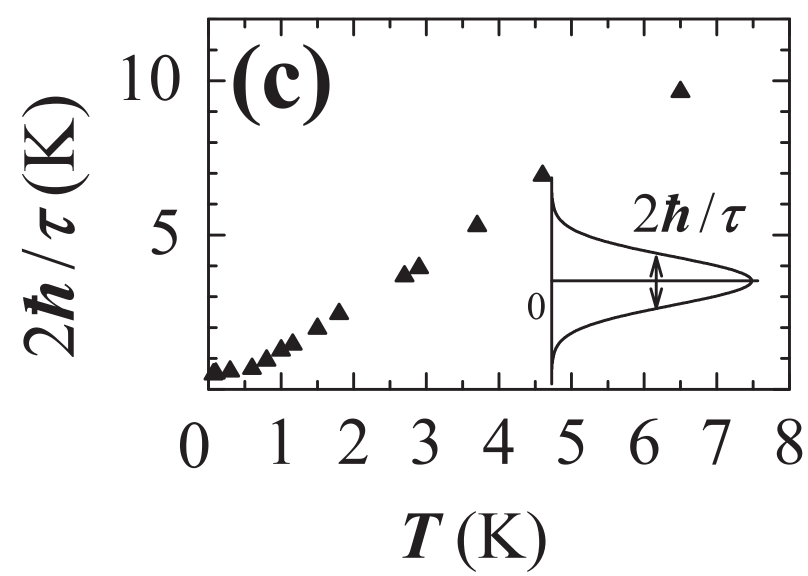
$$E_0 \pm \frac{1}{2} g \mu_B B \qquad g \simeq 2$$



T. Osada, JPSJ **77**, 084711 (2008).

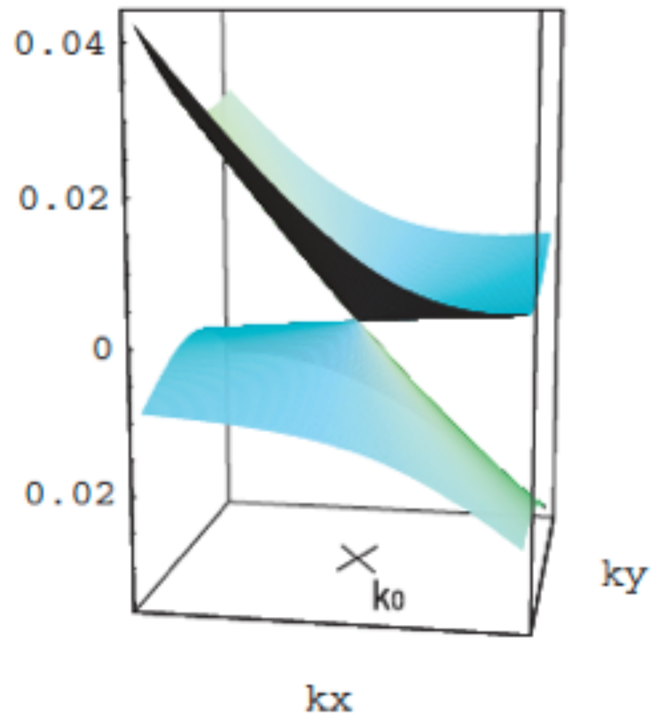


N.Tajima *et al.*, Phys. Rev. Lett. 102, 176403 (2009).



$$\Gamma \sim 1\mathrm{K}$$

Tilted Dirac cone?



$$\mathcal{H} = \begin{pmatrix} v_0^x k_x + v_0^y k_y + v_z^x k_x + v_z^y k_y & v_x^x k_x + v_x^y k_y - i\left(v_y^x k_x + v_y^y k_y\right) \\ v_x^x k_x + v_x^y k_y + i\left(v_y^x k_x + v_y^y k_y\right) & v_0^x k_x + v_0^y k_y - v_z^x k_x - v_z^y k_y \end{pmatrix}$$

A.Kobayashi *et al.*, J. Phys. Soc. Jpn. 76, 034711 (2007).

$$\mathcal{H} = \mathcal{H}_{\mathrm{Dirac}} + v_0 k_x$$

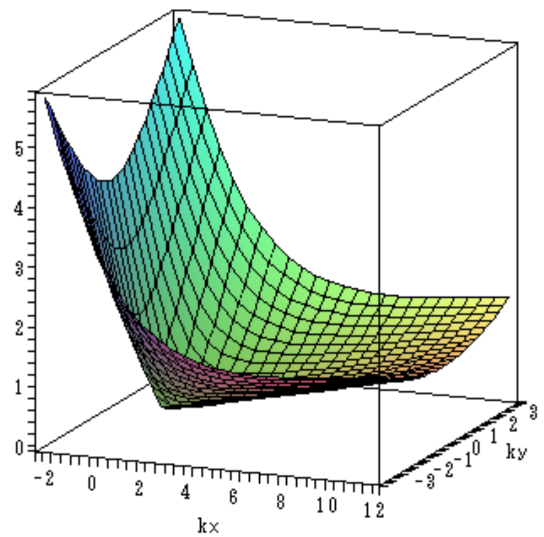
Landau levels

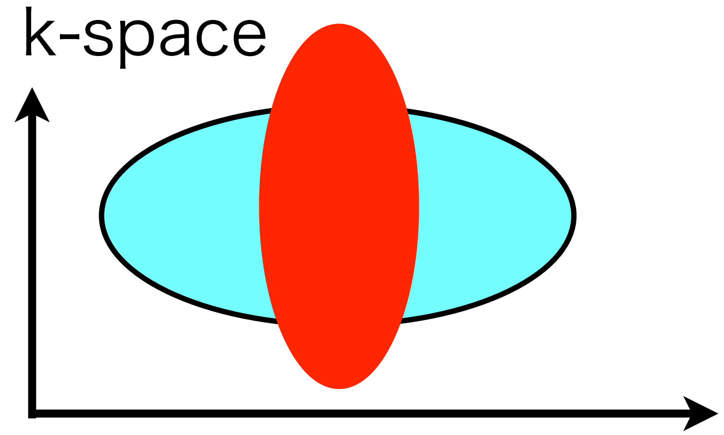
$$E_n = (\text{tilt param.}) \times \sqrt{nB}$$

TM, T.Himura, and T. Tohyama,
J. Phys. Soc. Jpn. 78, 023704 (2009).

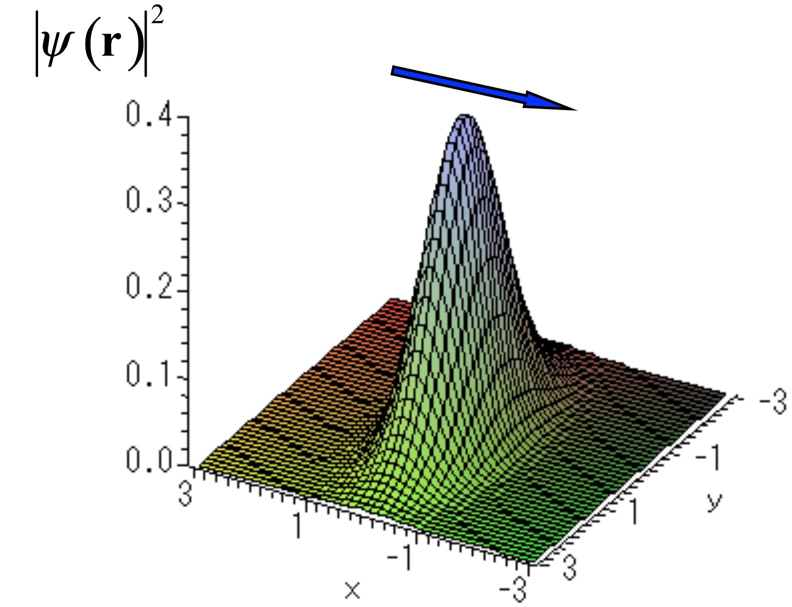
M. O. Goerbig, J.-N. Fuchs, G. Montambaux,
and F. Piechon, Phys. Rev. B 78, 045415 (2008).

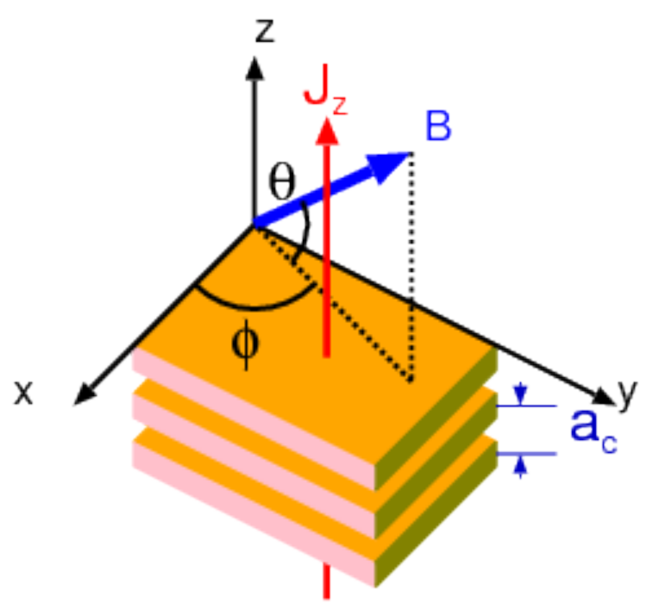
Effect of tilted Dirac cone

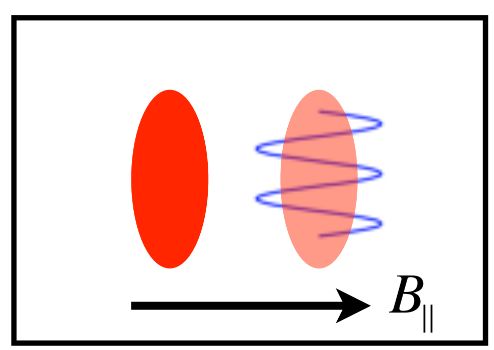




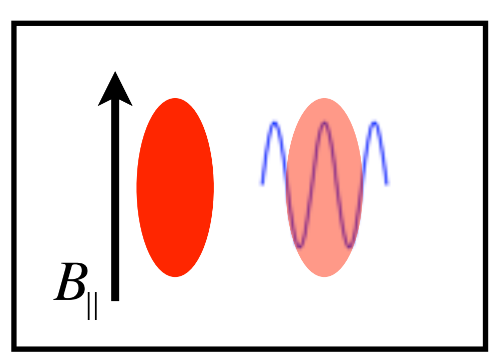
Tilt direction



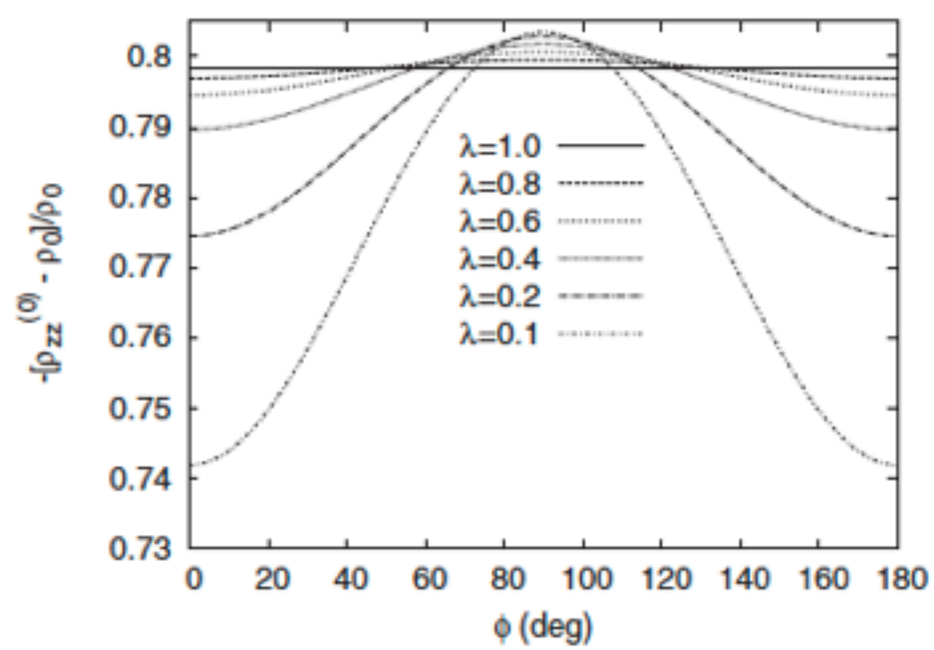




Large resistivity



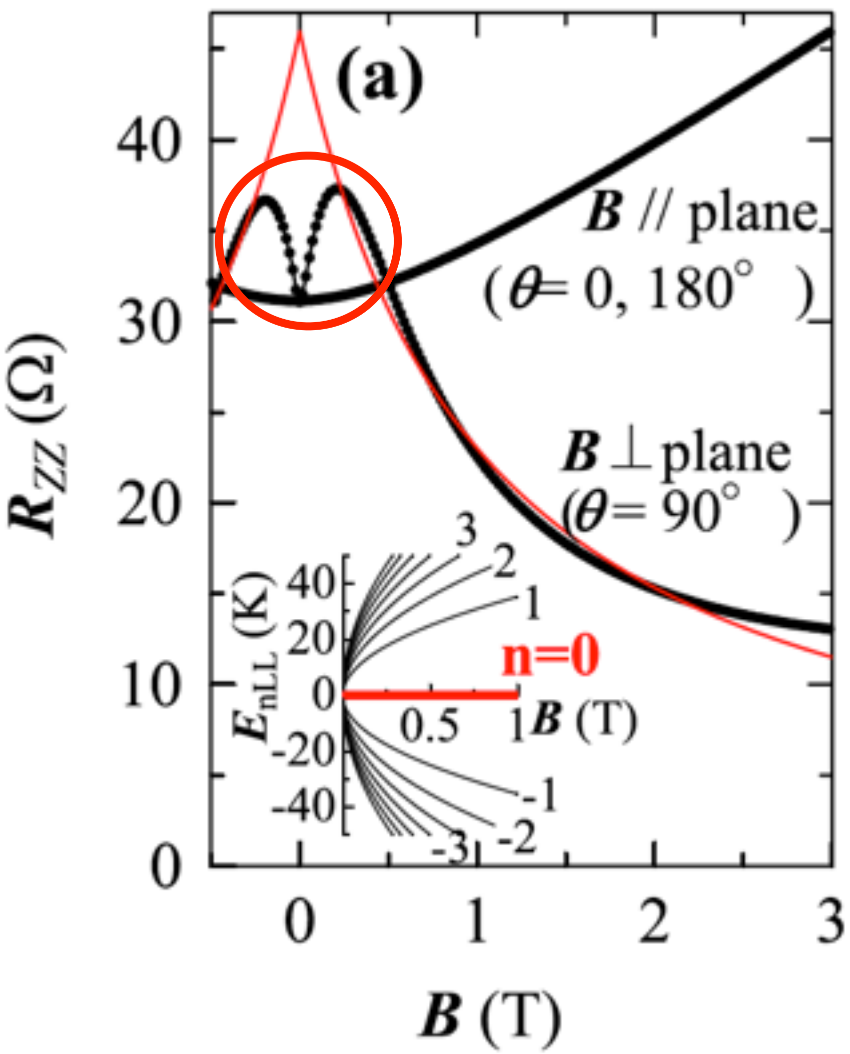
Low resistivity



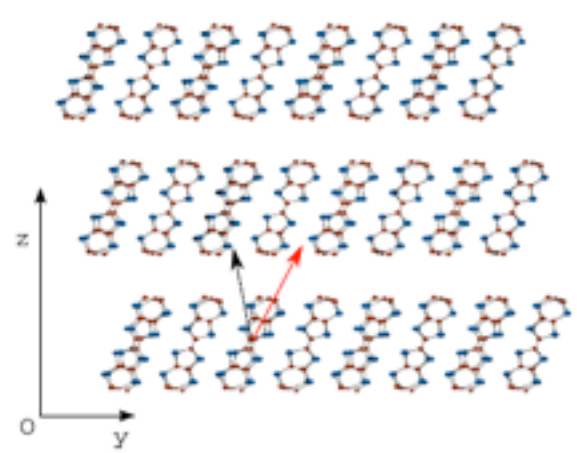
$$\lambda = \sqrt{1-\left(\frac{v_0}{v_D}\right)^2}$$

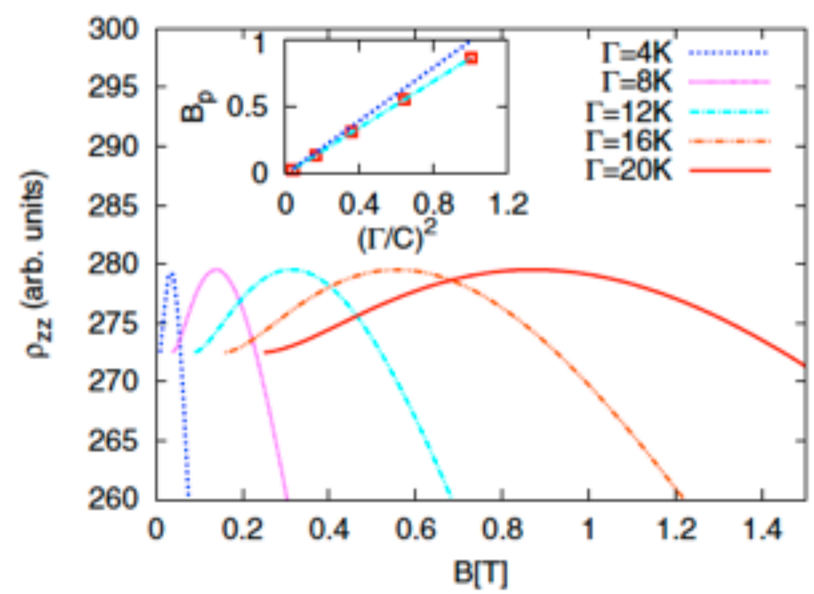
Positive MR?

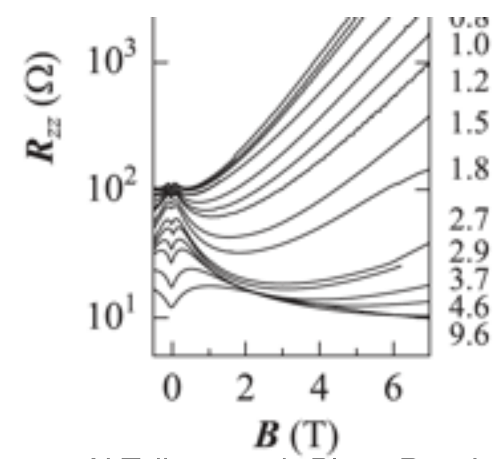
T.M. and T. Tohyama, J. Phys. Soc. Jpn. 79, 044708 (2010).



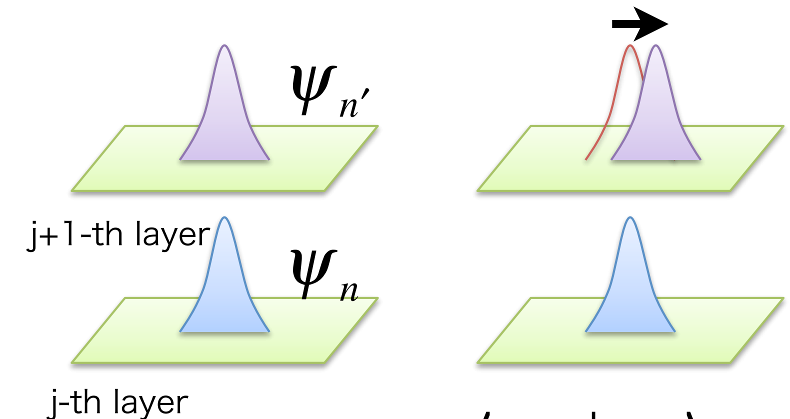
N.Tajima, S.Sugawara, R.Kato, Y.Nishio, and K.Kajita, Phys. Rev. Lett. 102, 176403 (2009).



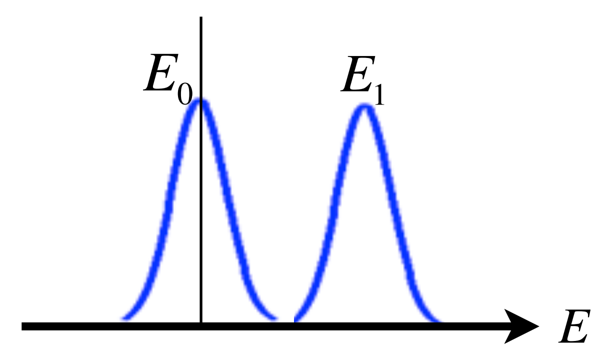




N.Tajima *et al.*, Phys. Rev. Lett. 102, 176403 (2009).



$$\langle \psi_{n'} | \psi_n \rangle \neq 0$$

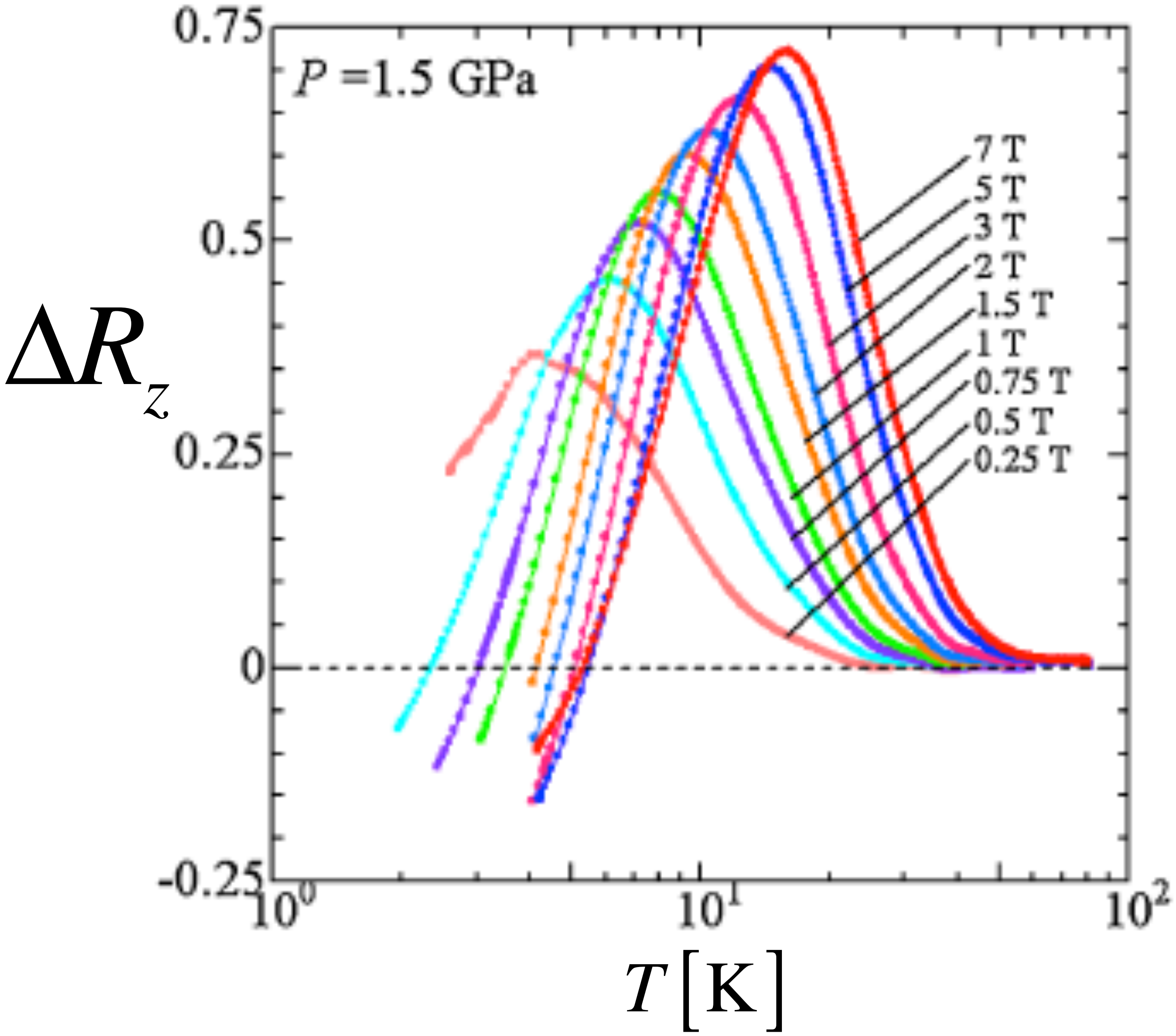


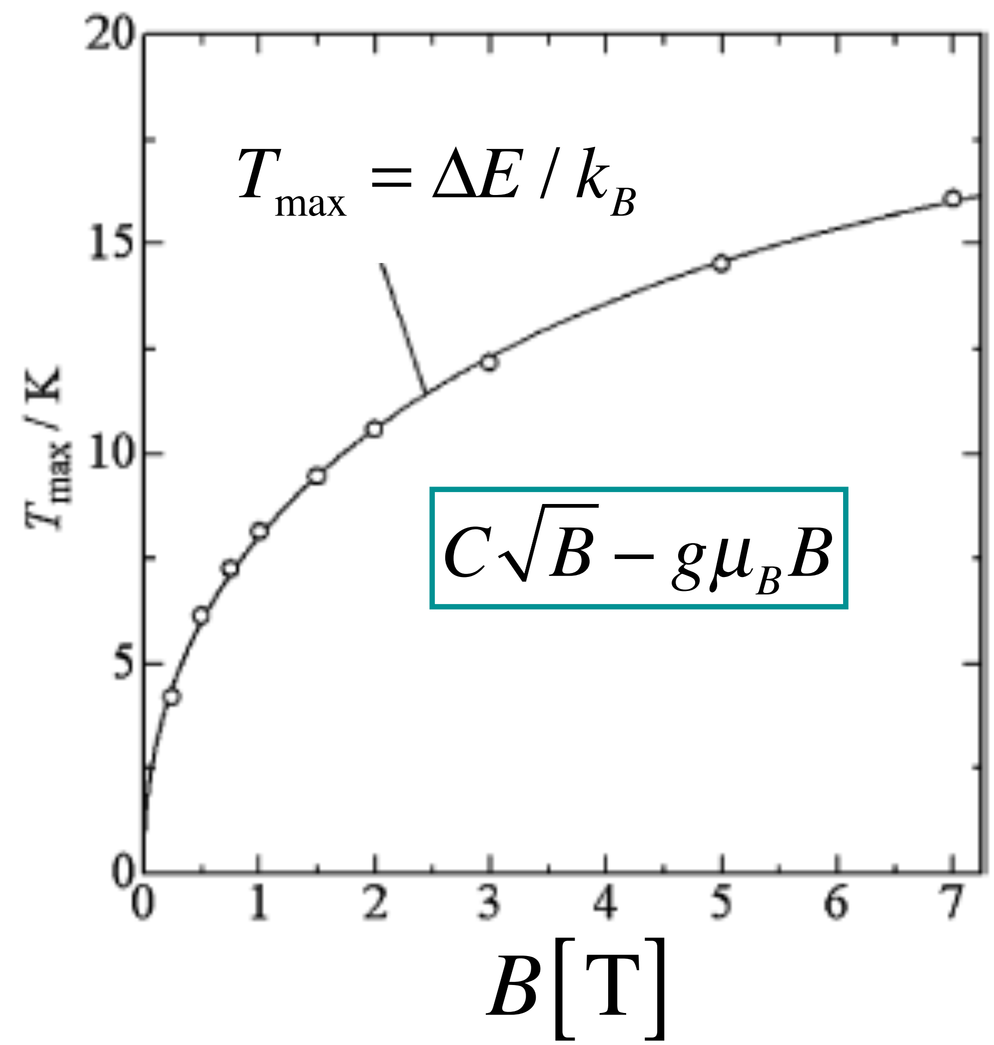
$$E_n = C\sqrt{nB}$$

$$C = 10\mathrm{K}/\mathrm{T}^{1/2}$$

T-dep. of positive MR

S.Sugawara, M.Tamura, N.Tajima, R.Kato, M.Sato, Y.Nishio, and K.Kajita,
J. Phys. Soc. Jpn. **79**, 113704 (2010)





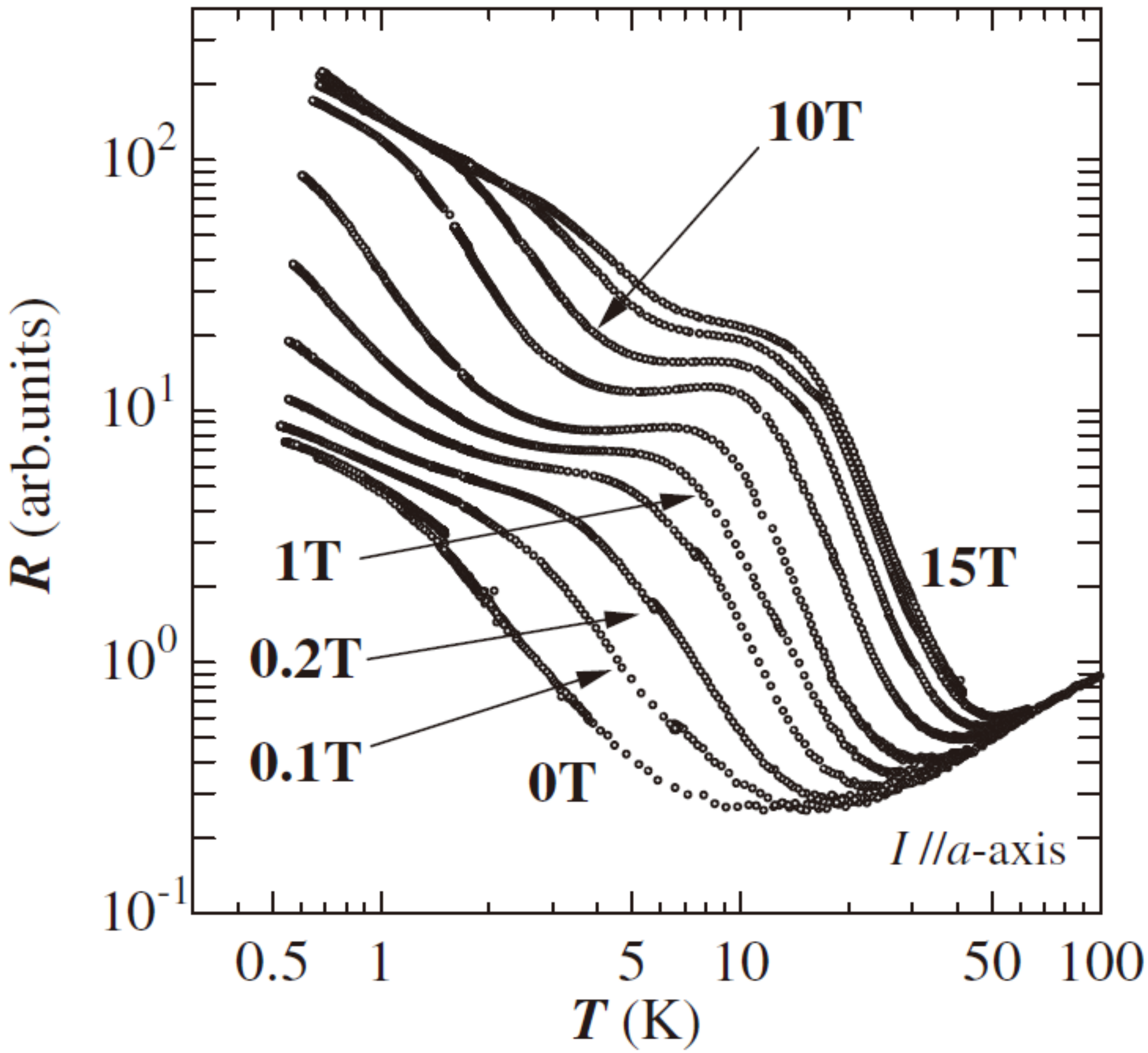
$$C = 9.3\,\mathrm{K/T}^{1/2}$$

$$v_F = 2.4 \times 10^4\,\mathrm{m/s}$$

Outline

1. α-(BEDT-TTF)$_2$I$_3$ under pressure
2. Theories suggesting Dirac fermion spectrum.
3. Inter-layer magnetoresistance
   Zero energy Landau level effect
4. Inplane magnetoresistance
   Inter-Landau level transitions
5. Conclusion

4. In-plane MR: Experiment



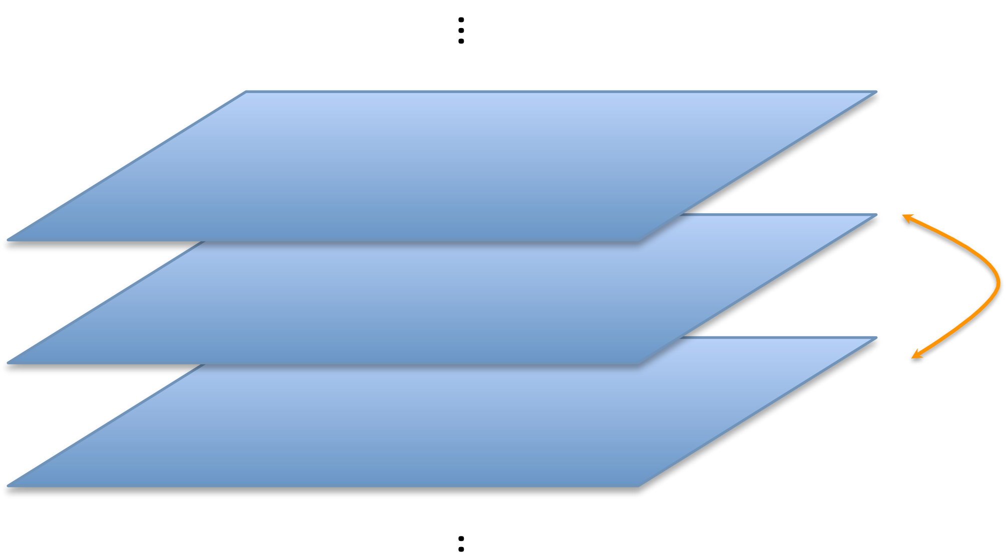
N.Tajima, S.Sugawara, M.Tamura, Y.Nishio, and K.Kajita,
J. Phys. Soc. Jpn. 75, 051010 ('06).

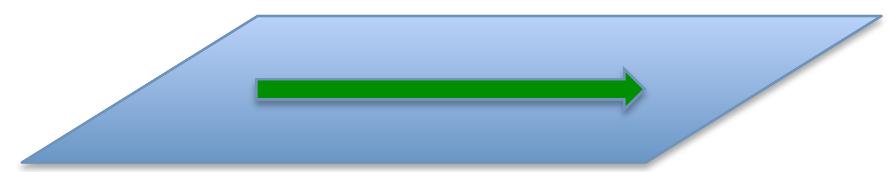
4. In-plane magnetoresistance

What makes difference from the interlayer MR?

Interlayer MR

Inplane MR





Same Landau levels

Different Landau levels

Reflect the Landau level structure

Calculation steps

T.M. and T.Tohyama, PRB 82, 165117 (2010).

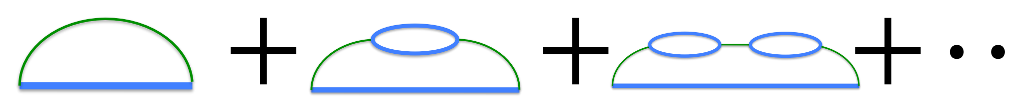
Matrix element

$$\langle n,k | \hat{v}_x | n',k' \rangle \qquad \hat{v}_x = v \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Electron-electron interaction

RPA

$$\Sigma_n =$$



Kubo formula

$$\sigma_{xx} = \frac{e^2}{\hbar} \left(\frac{\hbar v}{\ell} \right)^2 \sum_n \frac{1}{2-\delta_{n,0}} \int_{-\infty}^{\infty} dE \left(-\frac{\partial f}{\partial E} \right) \frac{\Gamma_n / \pi}{(E-E_n)^2 + \Gamma_n^2} \left[\frac{\Gamma_{|n|+1} / \pi}{(E-E_{|n|+1})^2 + \Gamma_{|n|+1}^2} + \frac{\Gamma_{-|n|-1} / \pi}{(E-E_{-|n|-1})^2 + \Gamma_{-|n|-1}^2} \right]$$

Self-energy formula

$$\Sigma_{n,k}^{RPA}(\omega+i\delta)=-\frac{1}{\pi}\sum_{\mathbf{q},n'}e^{-\frac{1}{2}q^2\ell_B^2}\frac{n_<!}{n_>!}\left(\frac{\ell_B^2q^2}{2}\right)^{|n-n'|}\left[L_{n_<}^{|n-n'|}\left(\frac{\ell_B^2q^2}{2}\right)\right]^2 V_q$$

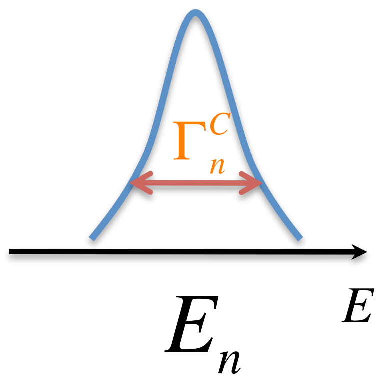
$$\times\int_{-\infty}^{\infty}d\varepsilon\,\mathrm{Im}\left[\frac{1}{\varepsilon_q(\varepsilon)}\right]\frac{f(E_{n'})+n(\varepsilon)}{\omega+i\delta-E_{n'}+\varepsilon}$$

$$\mathrm{Im}\left[\frac{1}{\varepsilon_q(\varepsilon+i\delta)}\right]=\frac{D_2V_q}{(1-D_1V_q)^2+(D_2V_q)^2}$$

$$D_1=-\frac{1}{2\pi\ell_B^2}e^{-\frac{1}{2}q^2\ell_B^2}\sum_{n_1,n_2,s}\frac{n_<!}{n_>!}\left(\frac{\ell_B^2q^2}{2}\right)^{|n_1-n_2|}\left[L_{n_<}^{|n_1-n_2|}\left(\frac{\ell_B^2q^2}{2}\right)\right]^2 P\frac{f(E_{n_2,s})-f(E_{n_1,s})}{\varepsilon-E_{n_2,s}+E_{n_1,s}}$$

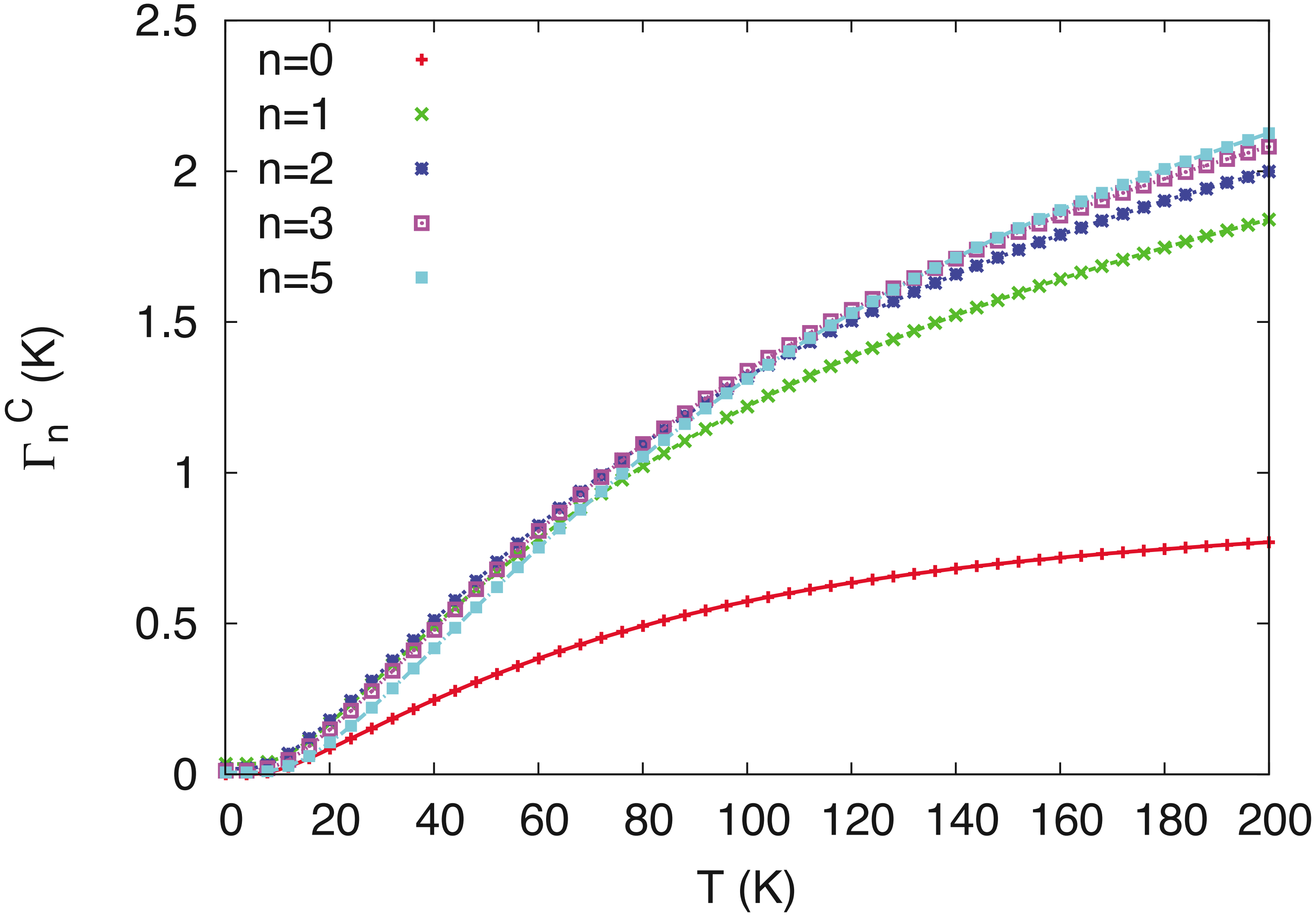
$$D_2=\frac{1}{2\ell_B^2}e^{-\frac{1}{2}q^2\ell_B^2}\sum_{n_1,n_2,s}\frac{n_<!}{n_>!}\left(\frac{\ell_B^2q^2}{2}\right)^{|n_1-n_2|}\left[L_{n_<}^{|n_1-n_2|}\left(\frac{\ell_B^2q^2}{2}\right)\right]^2$$
$$\times\left[f(E_{n_2,s})-f(E_{n_1,s})\right]\delta(\varepsilon-E_{n_2,s}+E_{n_1,s})$$

$$-\mathrm{Im}\,\Sigma_n^{RPA}(E_n+i\delta)=\Gamma_n^C$$



Landau level broadening

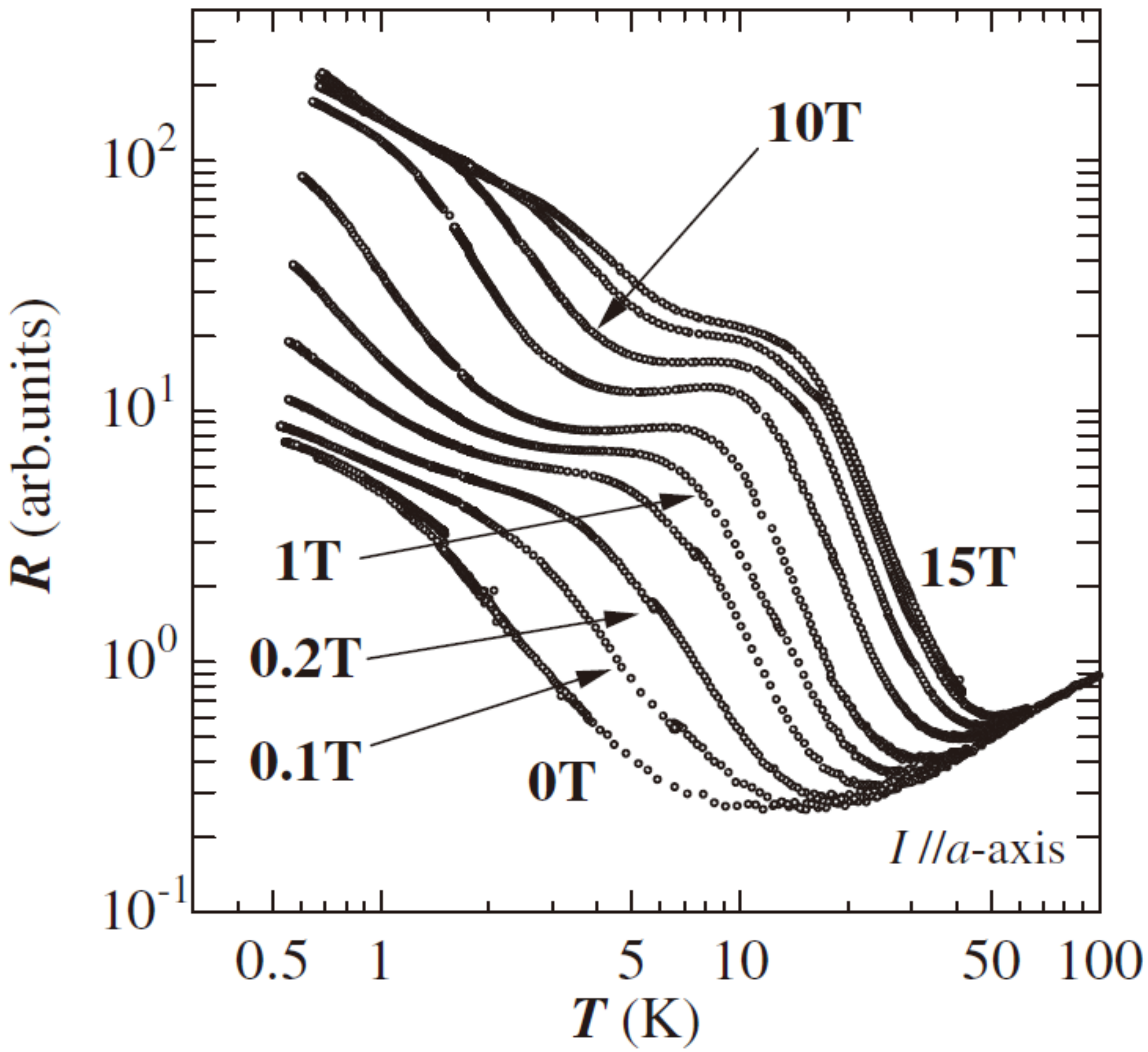
T.M. and T.Tohyama, PRB 82, 165117 (2010).



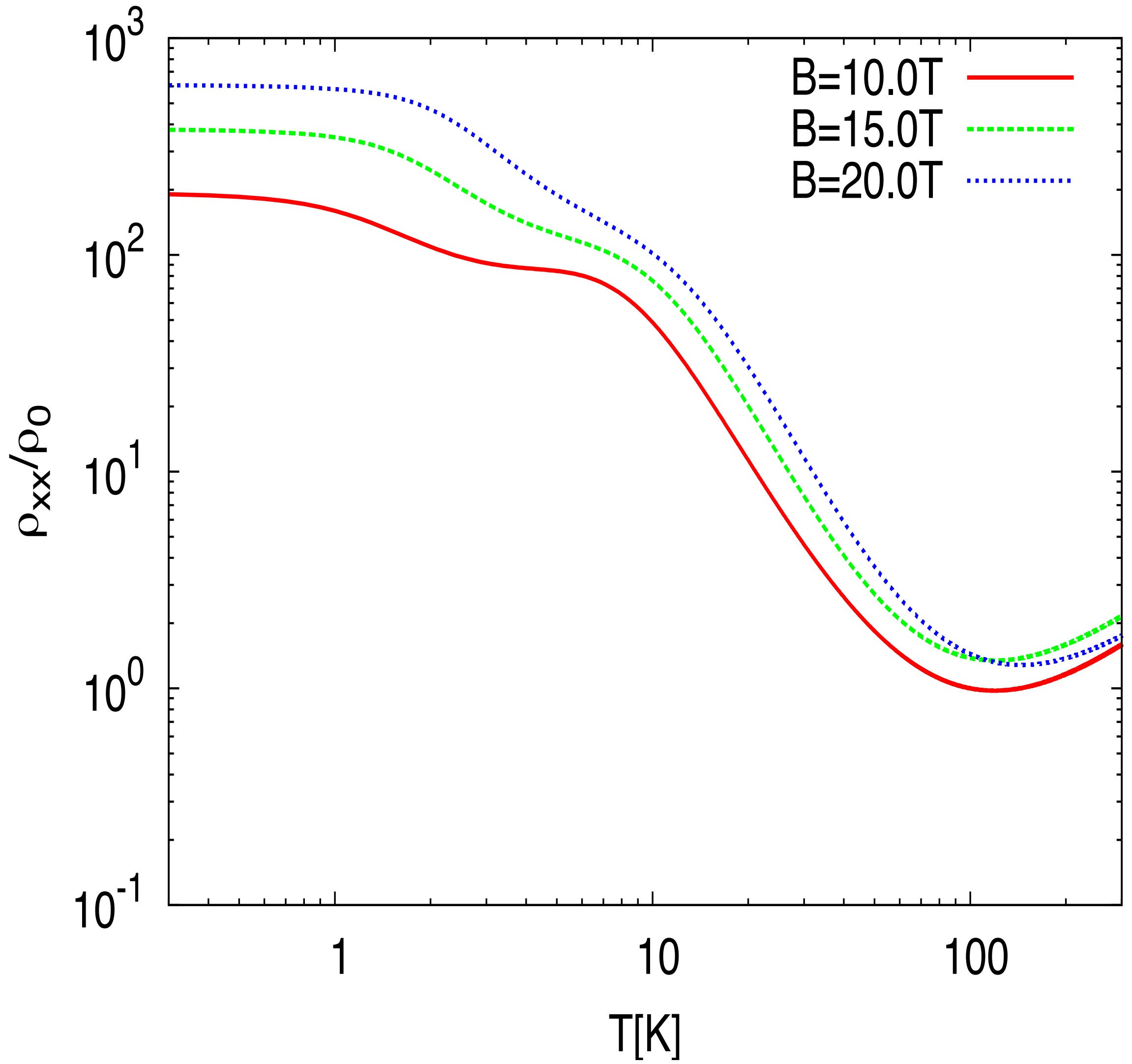
$$\sqrt{\frac{2}{B}}\frac{\hbar v_F}{\ell_B} = 10\mathrm{KT}^{-1/2}$$

$$\epsilon = 300$$

Experiment and theory

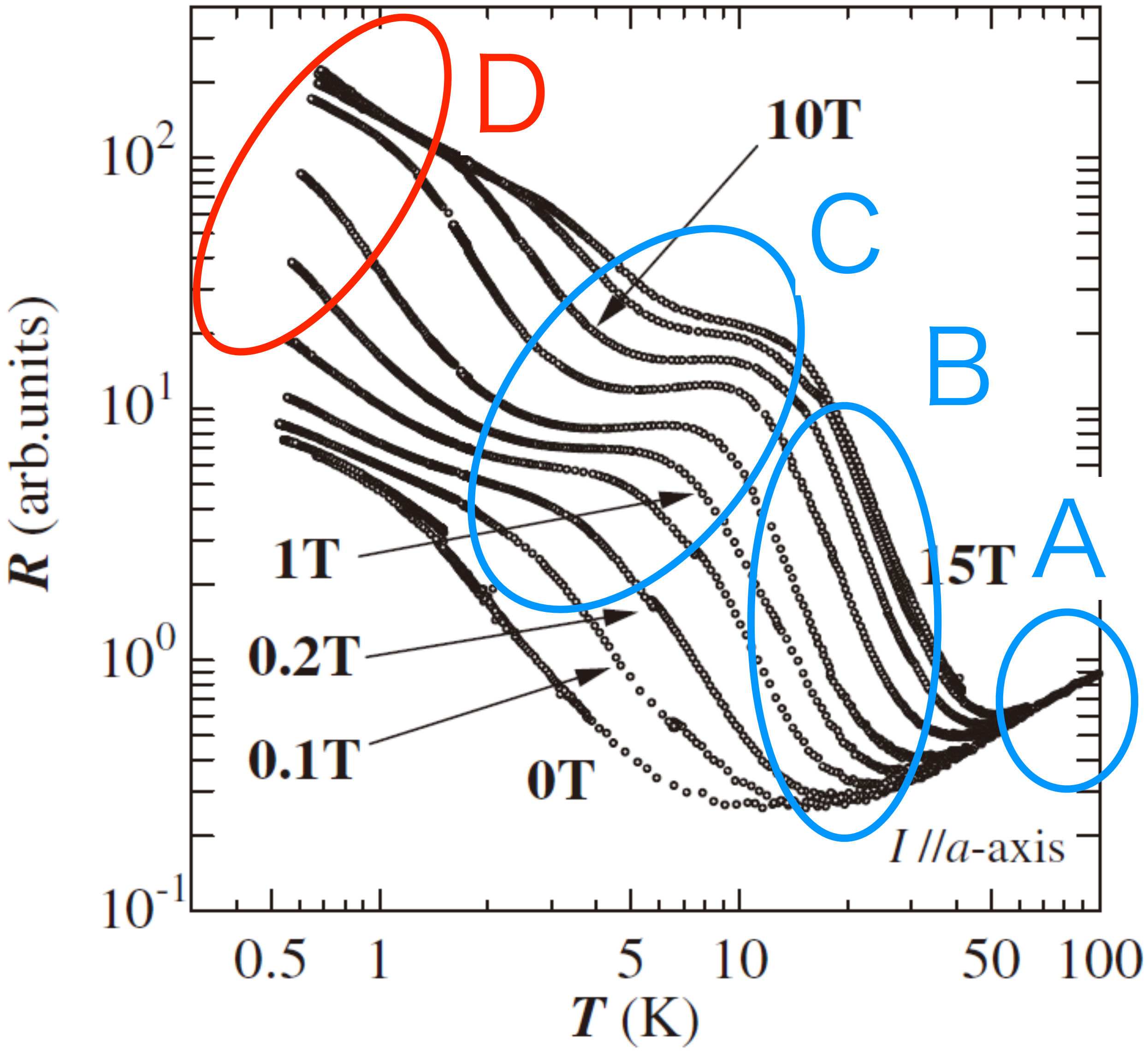


N.Tajima, S.Sugawara, M.Tamura, Y.Nishio, and K.Kajita,
J. Phys. Soc. Jpn. 75, 051010 ('06).

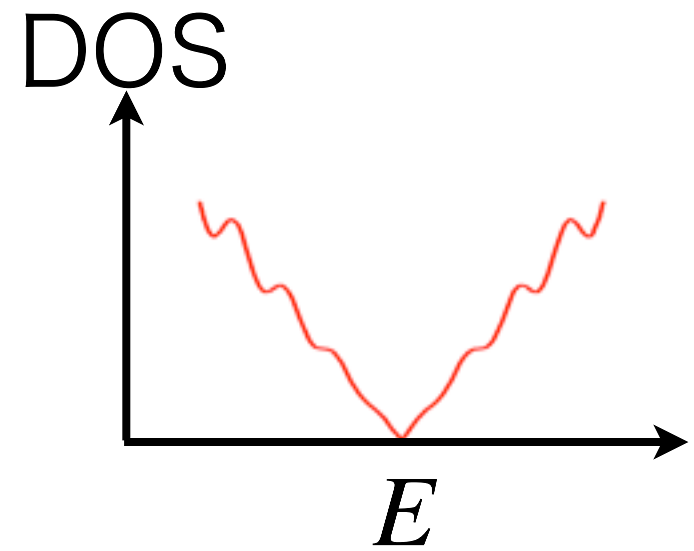


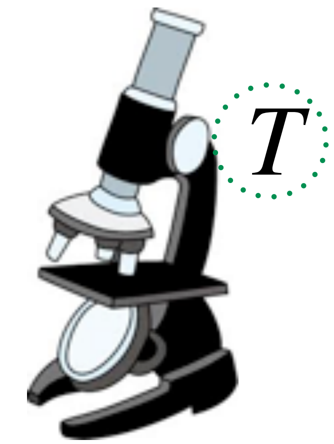
T.M. and T.Tohyama, PRB 82, 165117 (2010).

Interpretation



N.Tajima, S.Sugawara, M.Tamura, Y.Nishio, and K.Kajita, J. Phys. Soc. Jpn. 75, 051010 ('06).





A. *B* is negligible.
plasmon modes

B. Landau level splitting effect

C. $E_1 - E_0$

D. Valley splitting

Summary

α-(BEDT-TTF)$_2$I$_3$ under pressure

is a Dirac fermion system.

Magnetoresistance experiments are well described by the Dirac fermions.

Inter-layer MR

- Zero-energy Landau level
- Tilted cone can be detected.

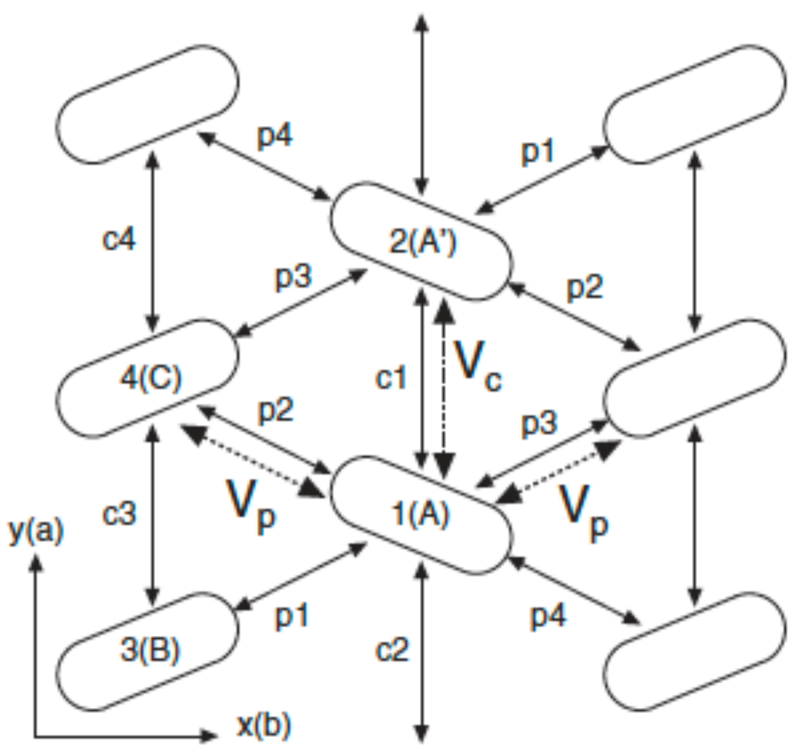
In-plane MR

- Reflect the Landau level structure

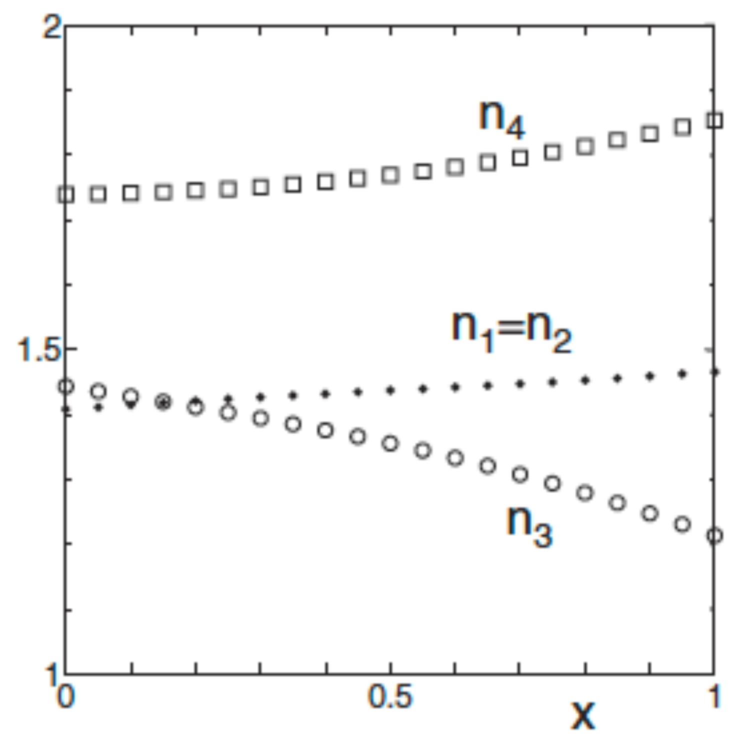
End

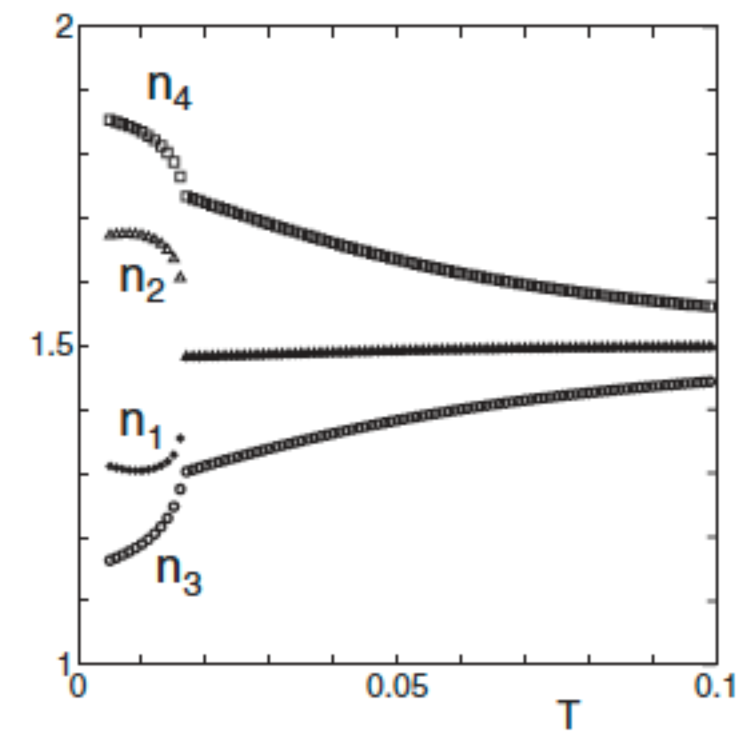
Appendix

Charge Disproportionation



Mean field calculation result





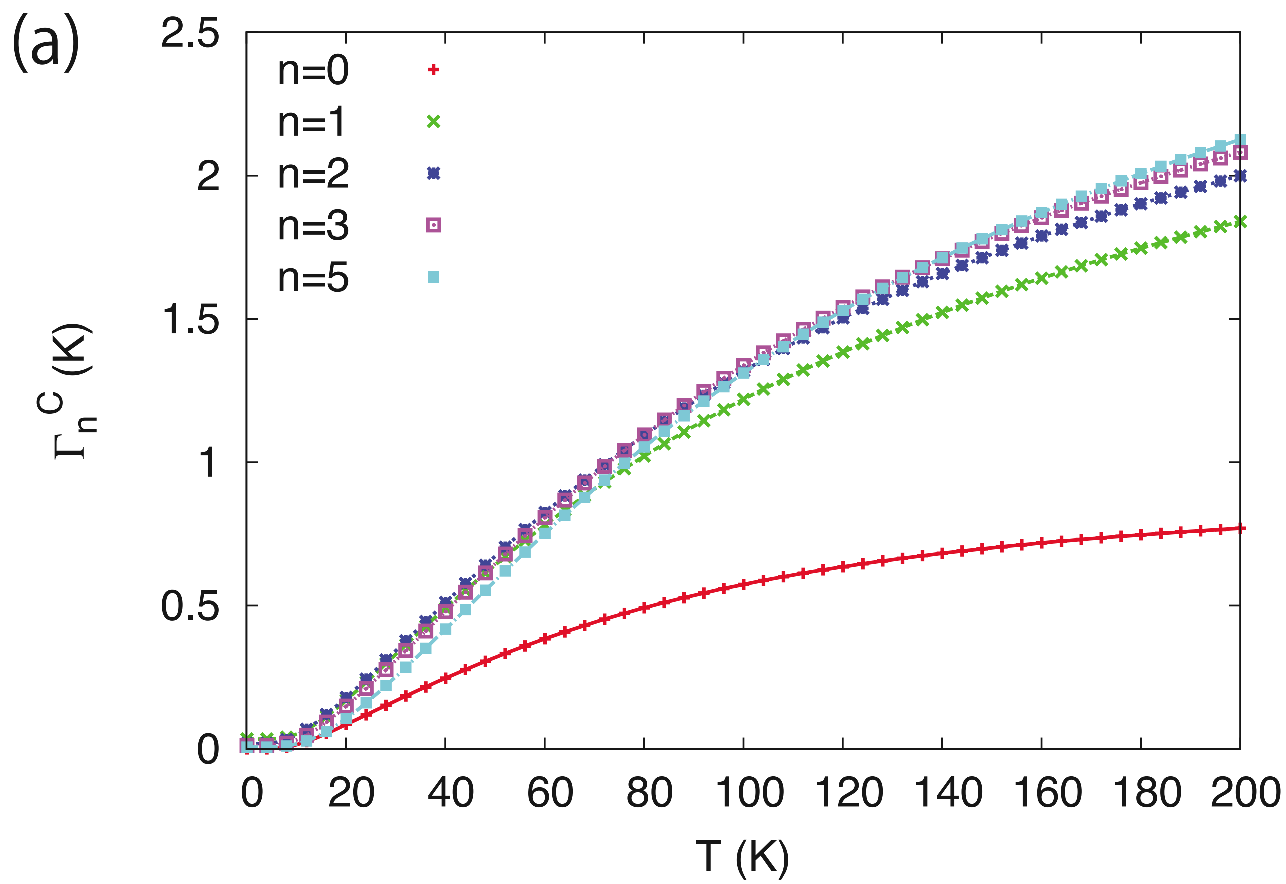
$$V_c = 0.17x,\ V_p = 0.05x, U = 0.4x$$

A. Kobayashi, S. Katayama, Y. Suzumura, and H. Fukuyama, J. Phys. Soc. Jpn. **76**, 034711 (2007).

Landau level broadening

T.M. and T.Tohyama, PRB 82, 165117 (2010).

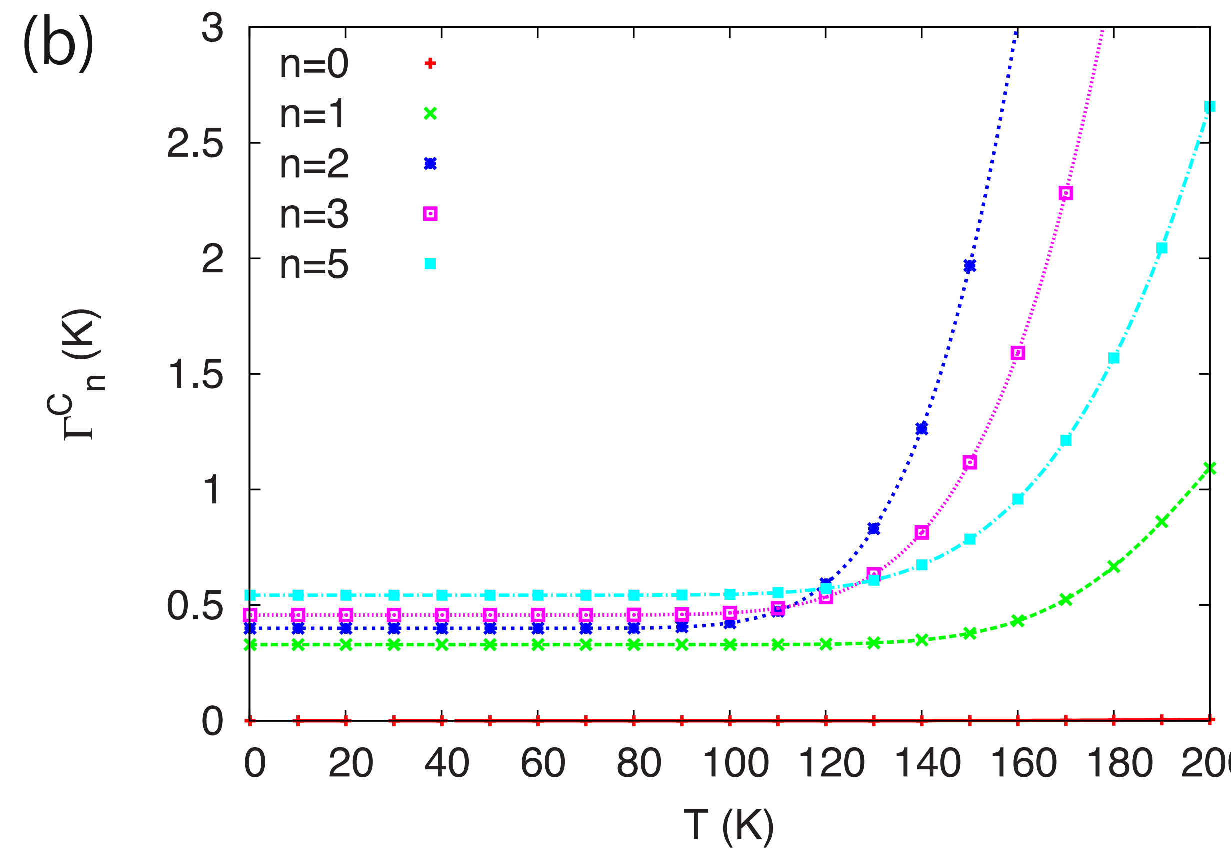
α-(BEDT-TTF)$_2$I$_3$



$$\sqrt{\frac{2}{B}}\frac{\hbar v_F}{\ell_B} = 10\mathrm{KT}^{-1/2}$$

$$\epsilon = 300$$

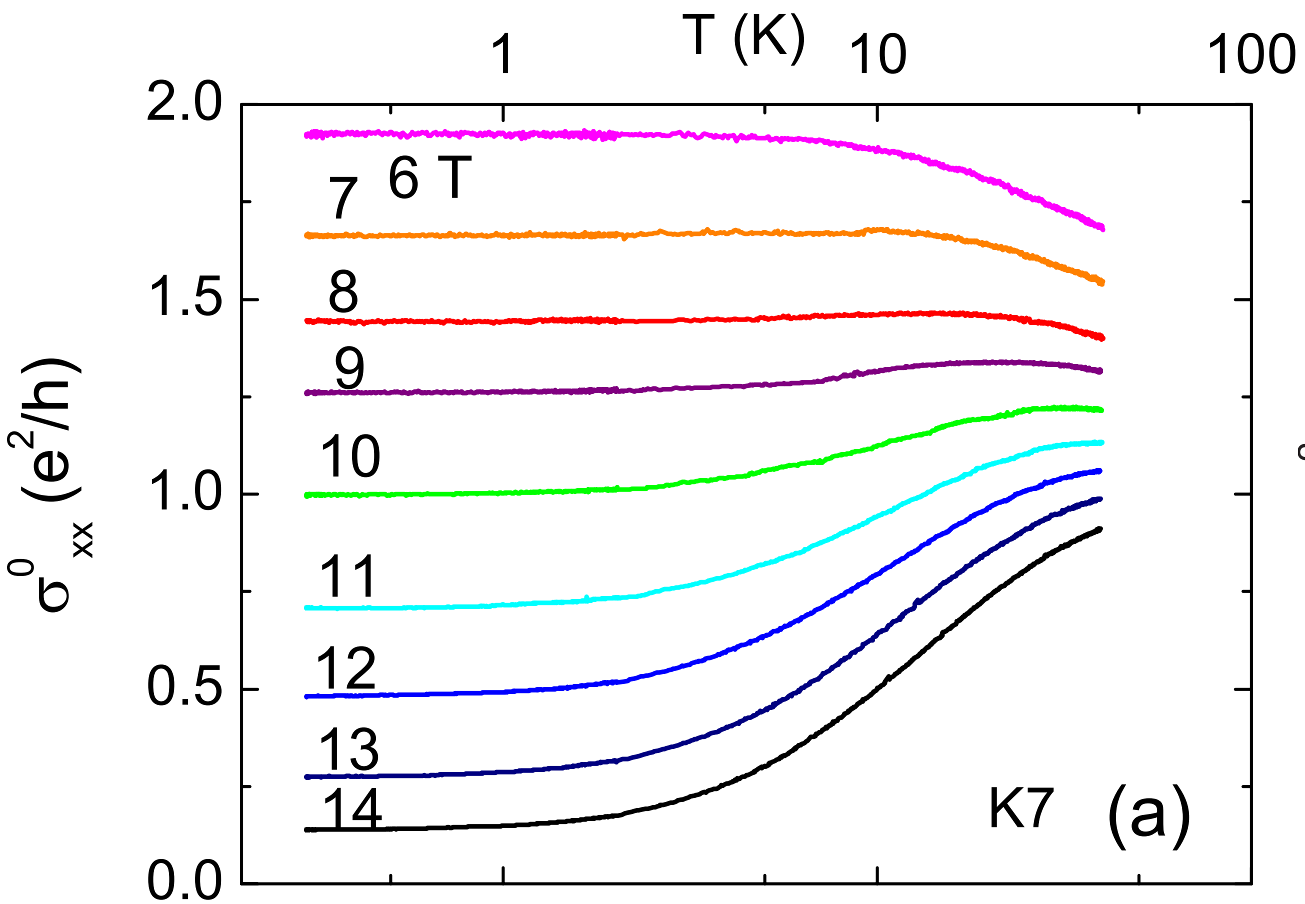
Graphene



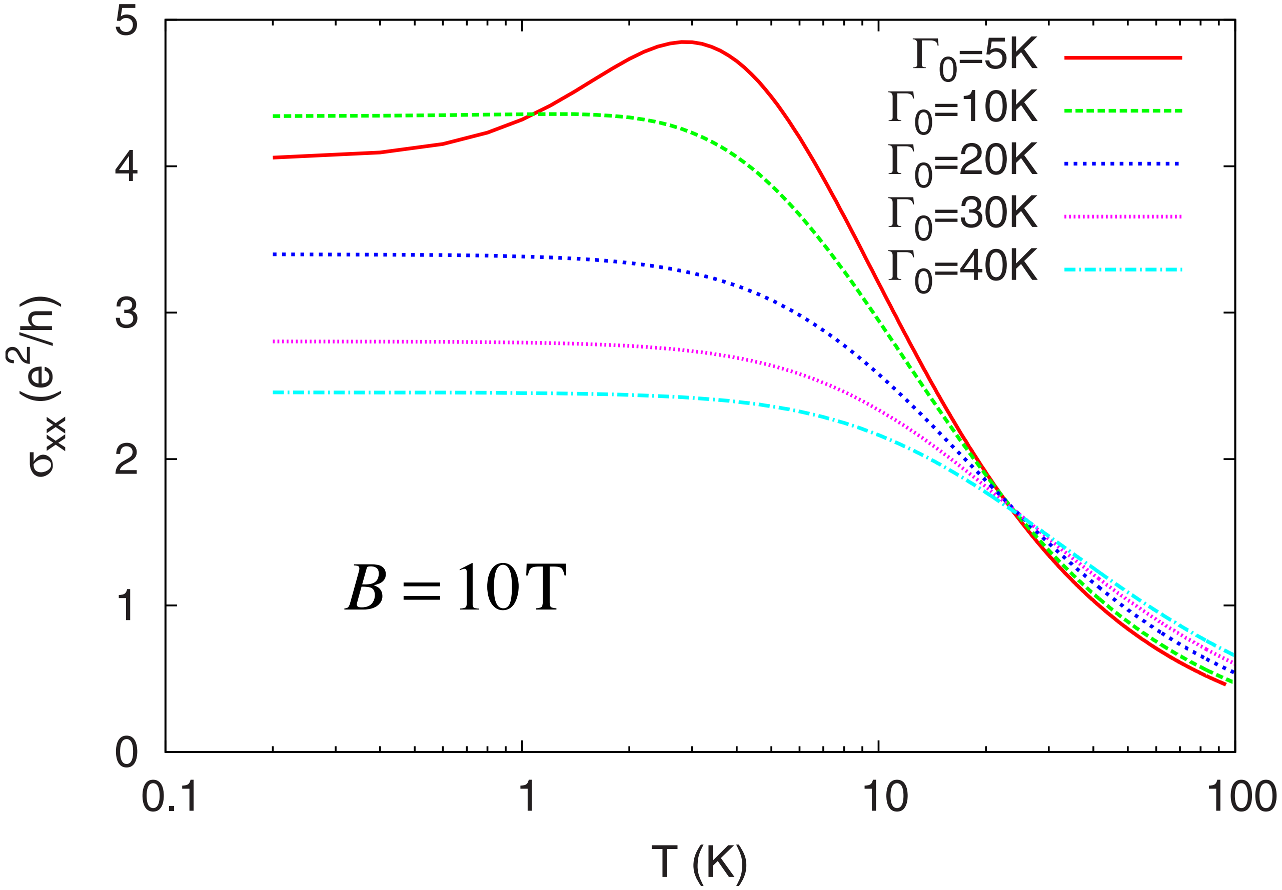
$$\sqrt{\frac{2}{B}}\frac{\hbar v_F}{\ell_B} = 400\mathrm{KT}^{-1/2}$$

$$\epsilon = 2.5$$

Graphene case



J. G. Checkelsky, L. Li, and N. P. Ong,
Phys. Rev. Lett. **100**, 206801 (2008).



T.M. and T.Tohyama, PRB 82, 165117 (2010).