Optical Conductivity of MoS_2

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IPM

10 Mehr 92

Outline

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- Inversion Symmetry
- Gapped Graphene & Valley contrasting effect
- Monolayer MoS2&optical measurement
- Optical Conductivity of Monolayer MoS2
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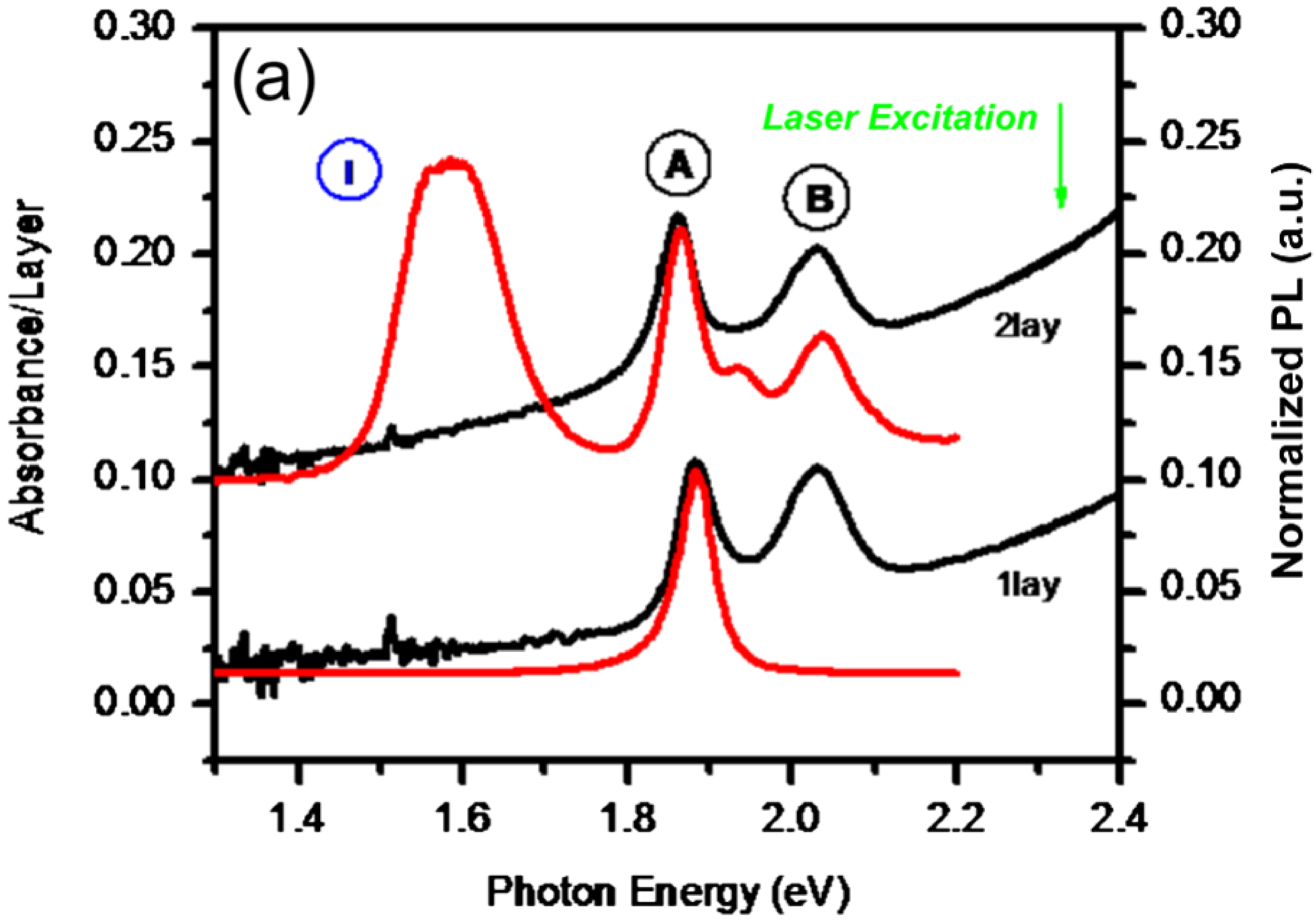
Motivation

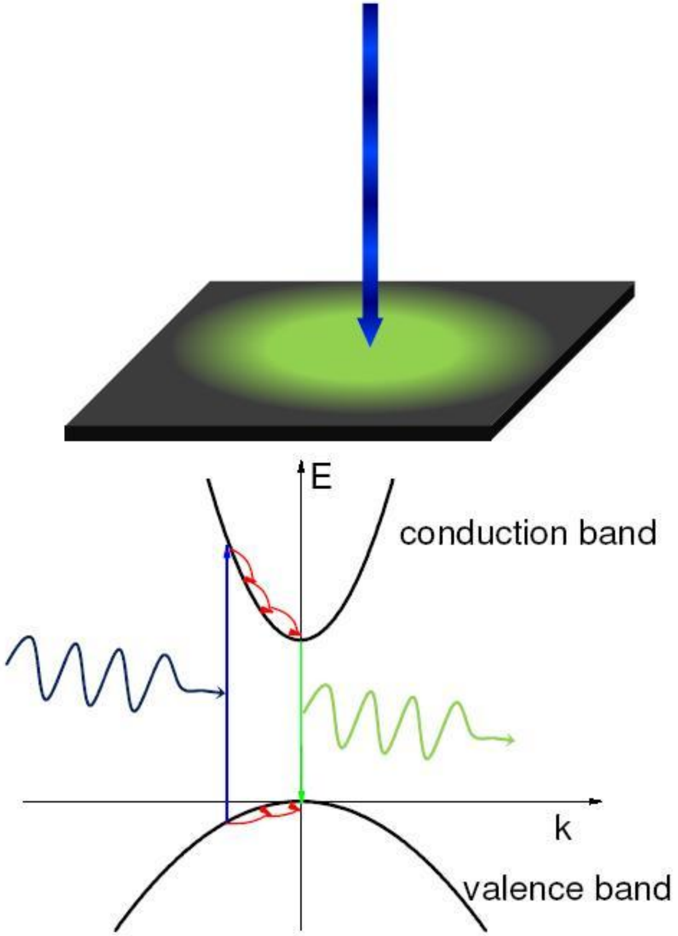


Kin Fai Mak, et al Phys.Rev.Lett. 105, 136805 (2010)

Optical phenomena

Photoluminescence:
Excitonic , Free electron,…

Absorbance:
Inter-band , intra-band

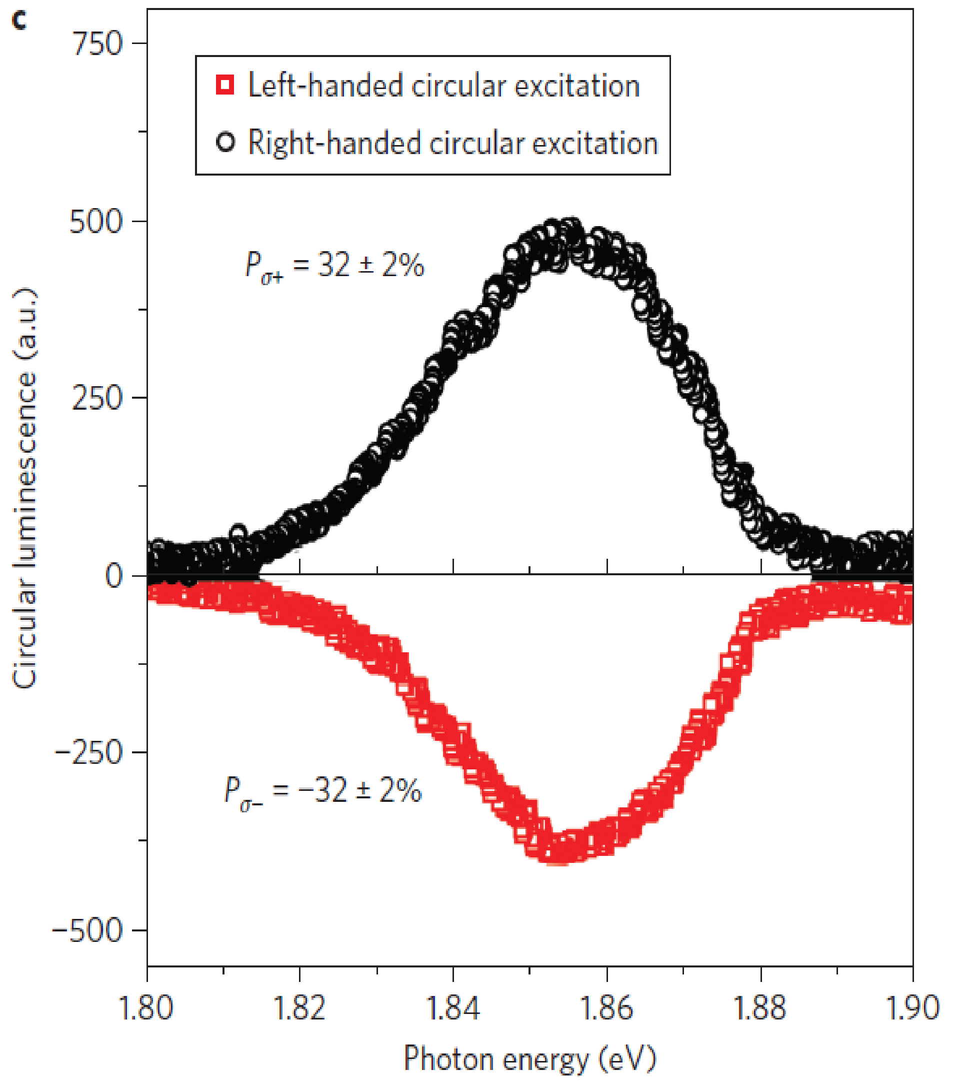


Circular dichroism

$$\text{Right-handed light}: \sigma_{xx} + i\sigma_{xy}$$

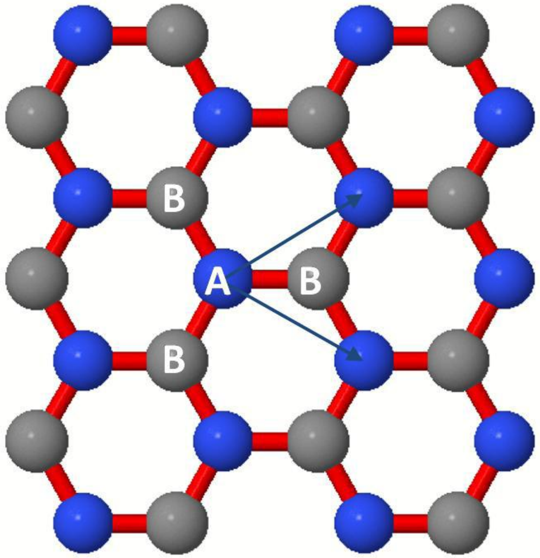
$$\text{Left-handed light}: \sigma_{xx} - i\sigma_{xy}$$

$$P = \frac{|\mathcal{P}_+|^2 - |\mathcal{P}_-|^2}{|\mathcal{P}_+|^2 + |\mathcal{P}_-|^2}$$



Inversion symmetry(real space)

$$P:(x,y)\rightarrow(-x,-y)\ \text{and}\ a\leftrightarrow b$$



$$H=\Delta\sum_{i}[a^{\dagger}(R_i^a)a(R_i^a)-b^{\dagger}(R_i^b)b(R_i^b)]+t_0\sum_{ij}a^{\dagger}(R_i^a)b(R_j^b)+H.c.$$

$$PHP^{-1}=\Delta\sum_{i}[b^{\dagger}(-R_i^a)b(-R_i^a)-a^{\dagger}(-R_i^b)a(-R_i^b)]+t_0\sum_{ij}b^{\dagger}(-R_i^a)b(-R_j^b)+H.c.$$

$$PHP^{-1}=-\Delta\sum_{i}[a^{\dagger}(R_i^a)a(R_i^a)-b^{\dagger}(R_i^b)b(R_i^b)]+t_0\sum_{ij}b^{\dagger}(R_i^b)a(R_j^a)+H.c.$$

In gapped Graphene inversion symmetry is broken.

Inversion symmetry(k space)

$$P : (q_x, q_y) \to (-q_x, -q_y), K \leftrightarrow K' \text{ and } a \leftrightarrow b$$

$$P = U\tau_x\sigma_x \text{ where } U : \vec{q} \to -\vec{q}$$

$$H = \Delta\sigma_z + v(\tau_z q_x \sigma_x + q_y \sigma_y)$$

$$\begin{aligned} PHP^{-1} &= \Delta(-\sigma_z) + v((-\tau_z)(-q_x)\sigma_x + (-q_y)(-\sigma_y)) \\ &= -\Delta\sigma_z + v(\tau_z q_x \sigma_x + q_y \sigma_y) \end{aligned}$$

In gapped Graphene inversion symmetry is broken.

Time revesal symmetry

$$\mathcal{T} = i\tau_x s_y \mathcal{K}$$

Symmetry of band structure

Time reversal symmetry

$$E(k, \tau, s) = E(-k, -\tau, -s)$$

Inversion symmetry

$$E(k, \tau, s) = E(-k, -\tau, s)$$

Time reversal and Inversion symmetry

$$E(k, \tau, s) = E(k, \tau, -s)$$

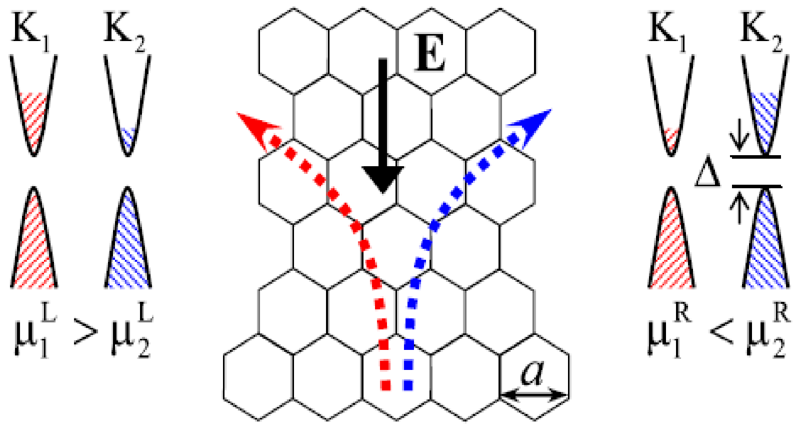
Inversion symmetry breaking& valley Hall effect

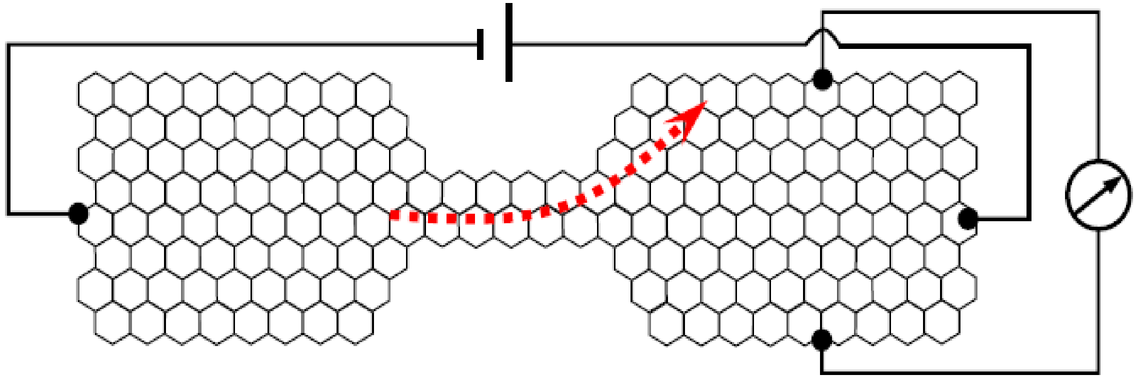
$$H = \frac{\sqrt{3}}{2} at(q_x \tau_z \sigma_x + q_y \sigma_y) + \frac{\Delta}{2}\sigma_z$$

$$\boldsymbol{\Omega}_n(\boldsymbol{q}) = \boldsymbol{\nabla}_{\boldsymbol{q}} \times \langle u_n(\boldsymbol{q})| i \boldsymbol{\nabla}_{\boldsymbol{q}} | u_n(\boldsymbol{q})\rangle$$

$$\Omega(\boldsymbol{q}) = \tau_z \frac{3a^2t^2\Delta}{2(\Delta^2 + 3q^2a^2t^2)^{3/2}}$$

$$\sigma_H = \frac{2e^2}{\hbar} \int_{BZ} \frac{d\boldsymbol{k}}{(2\pi)^2} g(\boldsymbol{k}) \boldsymbol{\Omega}(\boldsymbol{k}) \cdot \hat{\boldsymbol{z}}$$





Di Xiao, et al Phys.Rev.Lett. **99,** 236809 (2007).

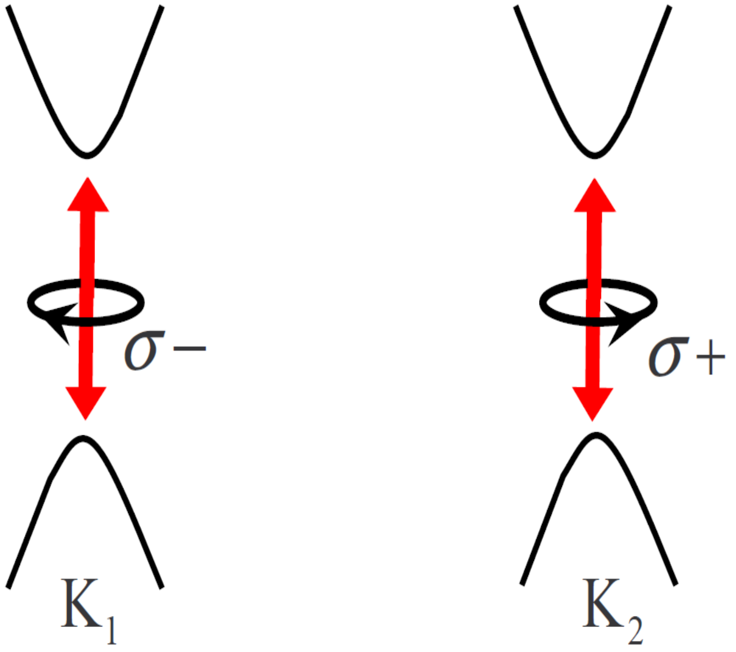
Inversion symmetry breaking& valley pumping

$$H = v(\tau_z k_x \sigma_x + k_y \sigma_y) + \Delta \sigma_z$$

$$\Omega = -\tau_z \frac{v^2 \Delta}{2(\Delta^2 + v^2 k^2)^{3/2}}$$

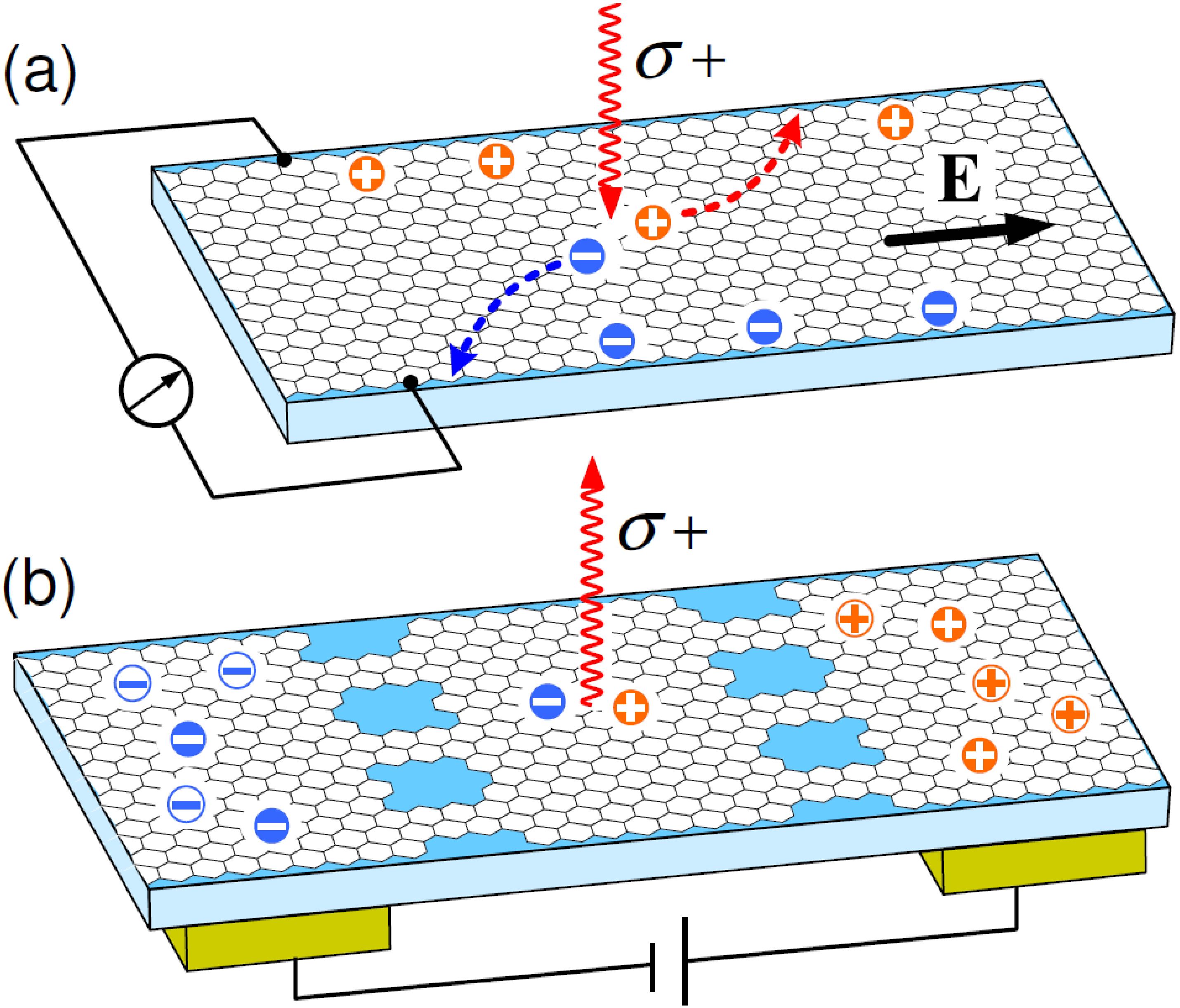
$$\mathcal{P}_\alpha^{ci}(\boldsymbol{k}) \equiv \langle u_{c,\boldsymbol{k}} | \hat{p}_\alpha | u_{i,\boldsymbol{k}} \rangle$$

$$\mathcal{P}_\pm \equiv \mathcal{P}_x^{cv} \pm i \mathcal{P}_y^{cv}$$



$$\eta(\boldsymbol{k}) \equiv \frac{|\mathcal{P}_+(\boldsymbol{k})|^2 - |\mathcal{P}_-(\boldsymbol{k})|^2}{|\mathcal{P}_+(\boldsymbol{k})|^2 + |\mathcal{P}_-(\boldsymbol{k})|^2}$$

W.Yao, D.Xiao, Q.Niu, Phys. Rev. B 77, 235406 (2008).



$$\sigma_H = \pm 4\delta n \Omega_0 e^2/\hbar$$

$$\Omega_0 = 2\hbar^2 v_0^2/\Delta^2$$

Light Emitting Diode(LED)

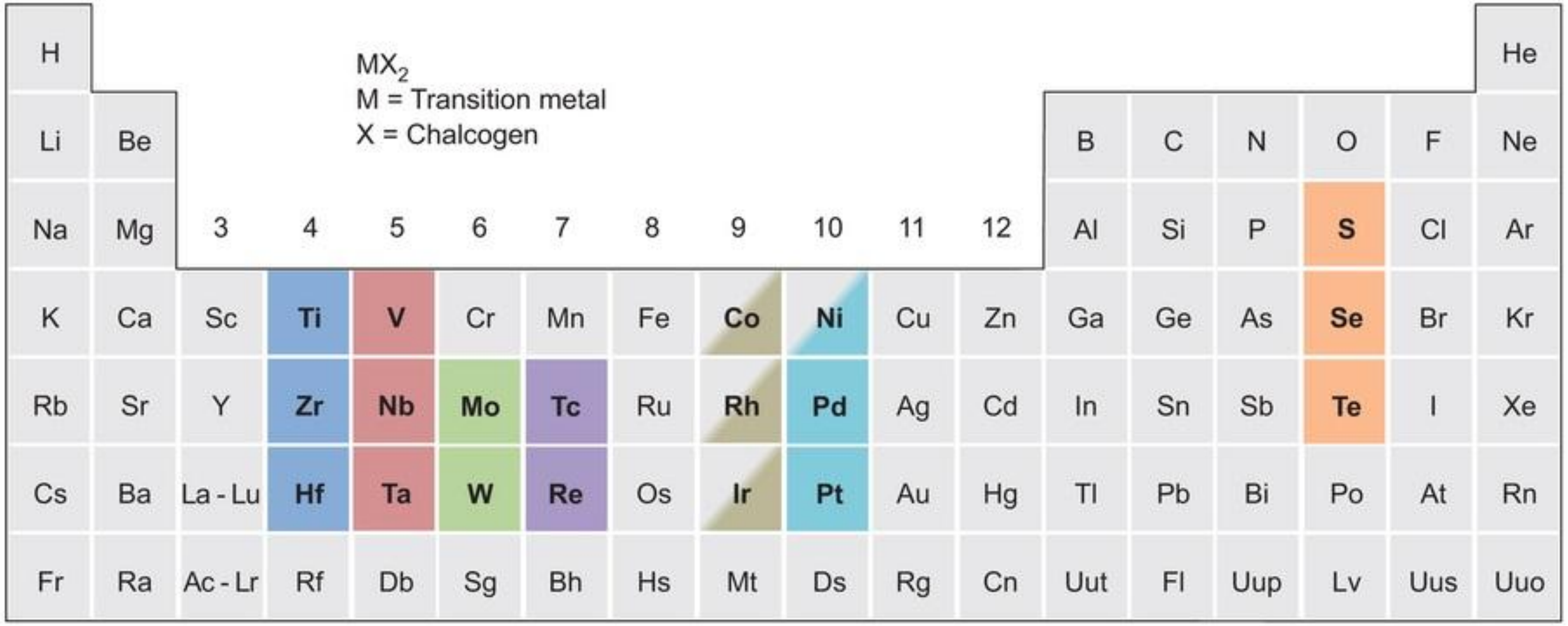
Electrically controlled emission polarization

W.Yao, D.Xiao, Q.Niu, Phys. Rev. B 77, 235406 (2008).

Monolayer Transition metal dichalcogenides semiconductor

- Direct Band Gap in visible range
- Broken inversion symmetry

Layered Compounds: Transition metal dichalcogenides (MX_2)

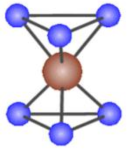


HfS_2: *Insulator*

$TiSe_2, WTe_2$: *Semimetal*

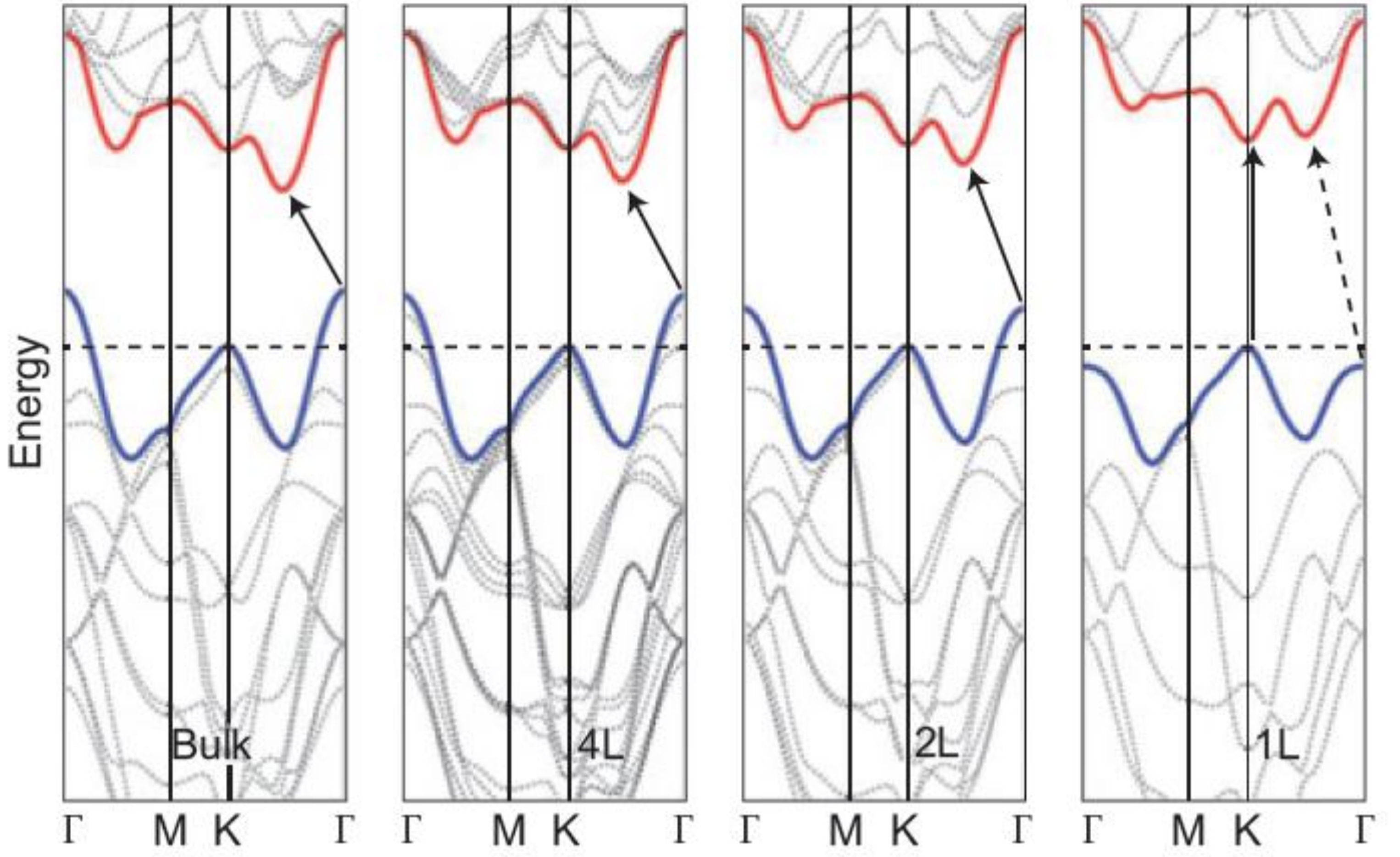
MoS_2, WS_2: *Semiconductor*

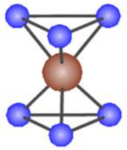
NbS_2, VSe_2: *Metal*



Chhowalla et al, Nature Chemistry 5, 263–275 (2013)

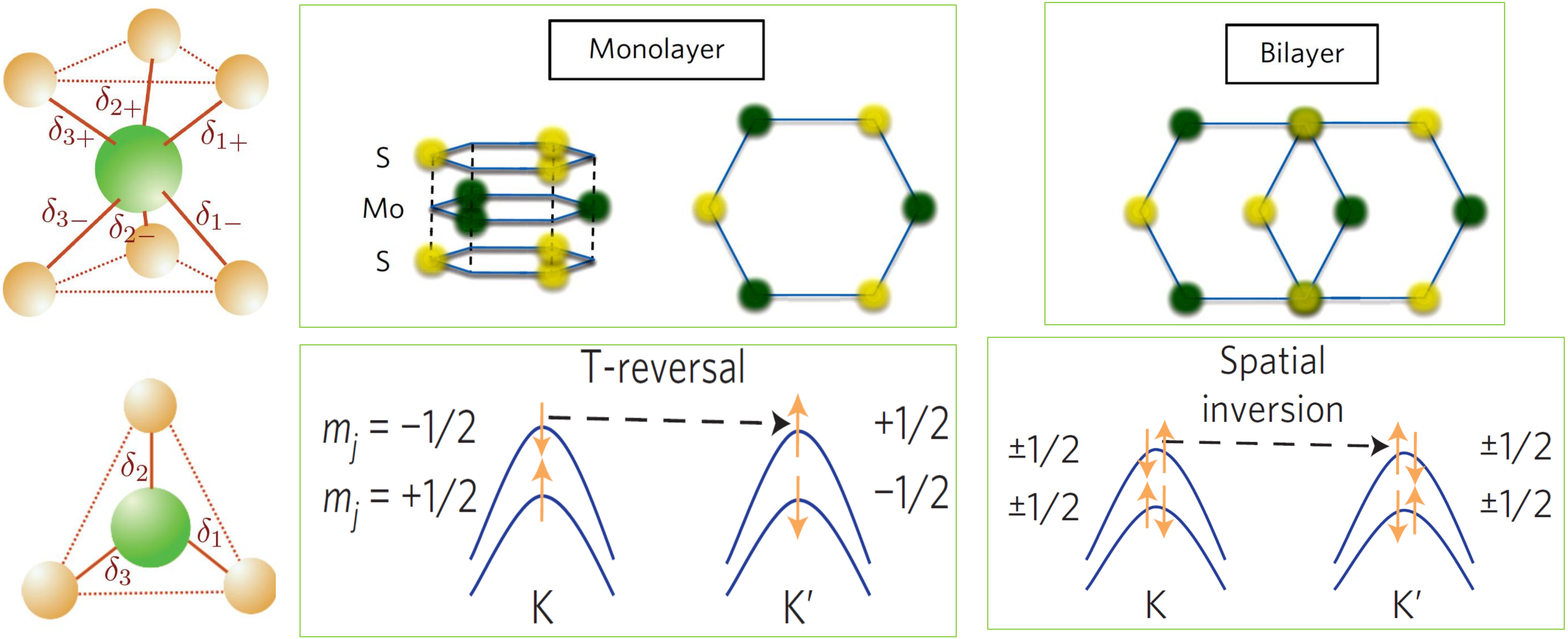
Band Structure: DFT





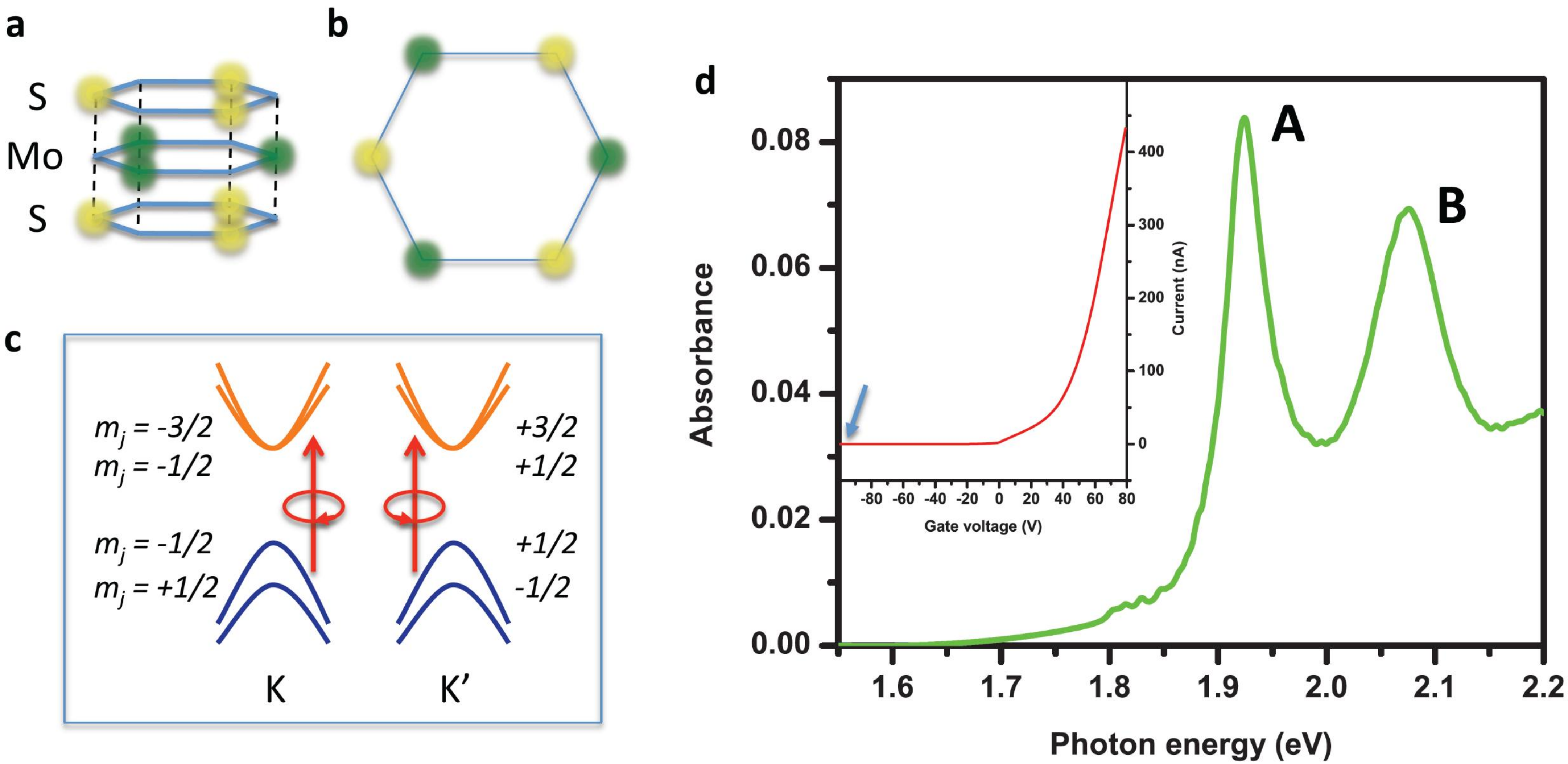
Nature Chemistry 5, 263–275 (2013)

Symmetry & band structure



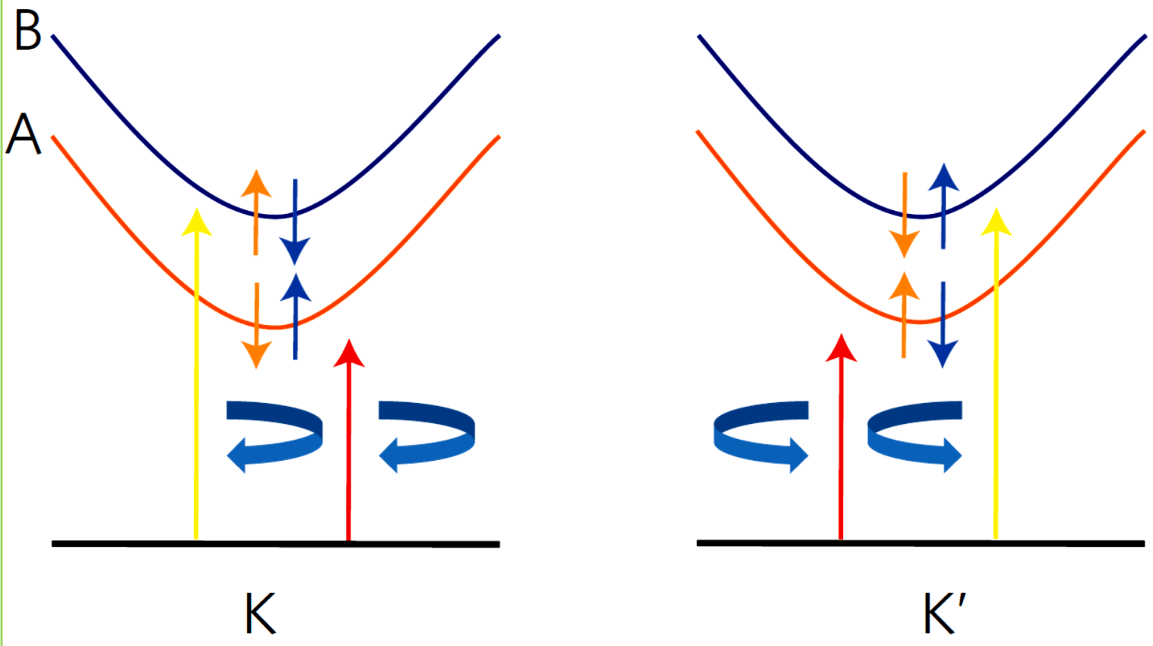
K. F. Mak et al., Nature Nanotech. 7, 494 (2012).

Optical Absorbance

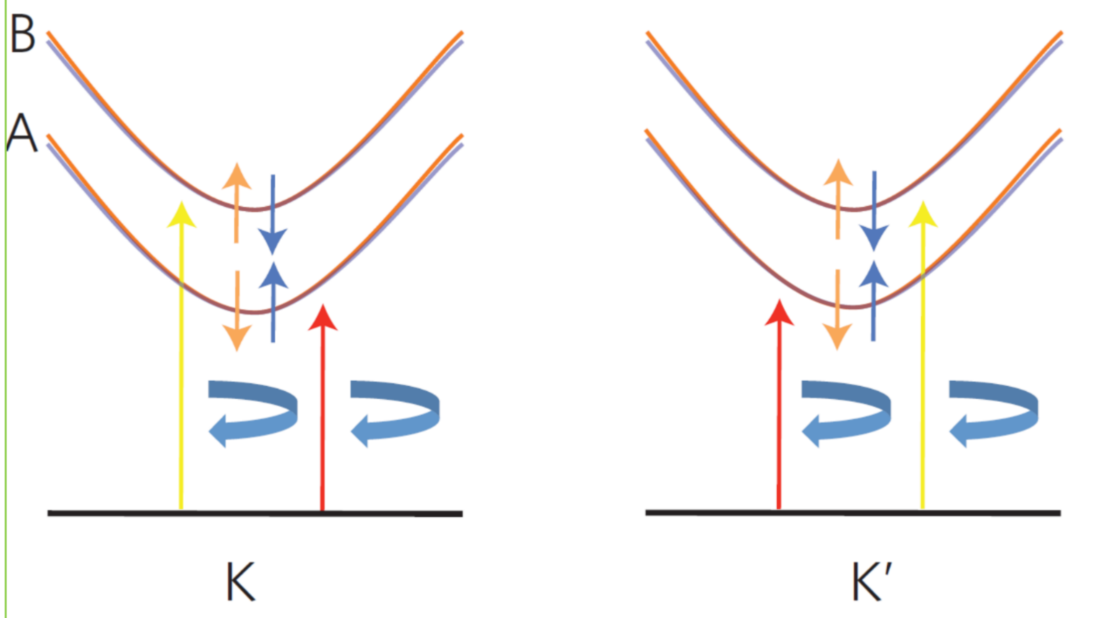


Excitonic Absorbance

Coupled valley-spin excitonic absorption

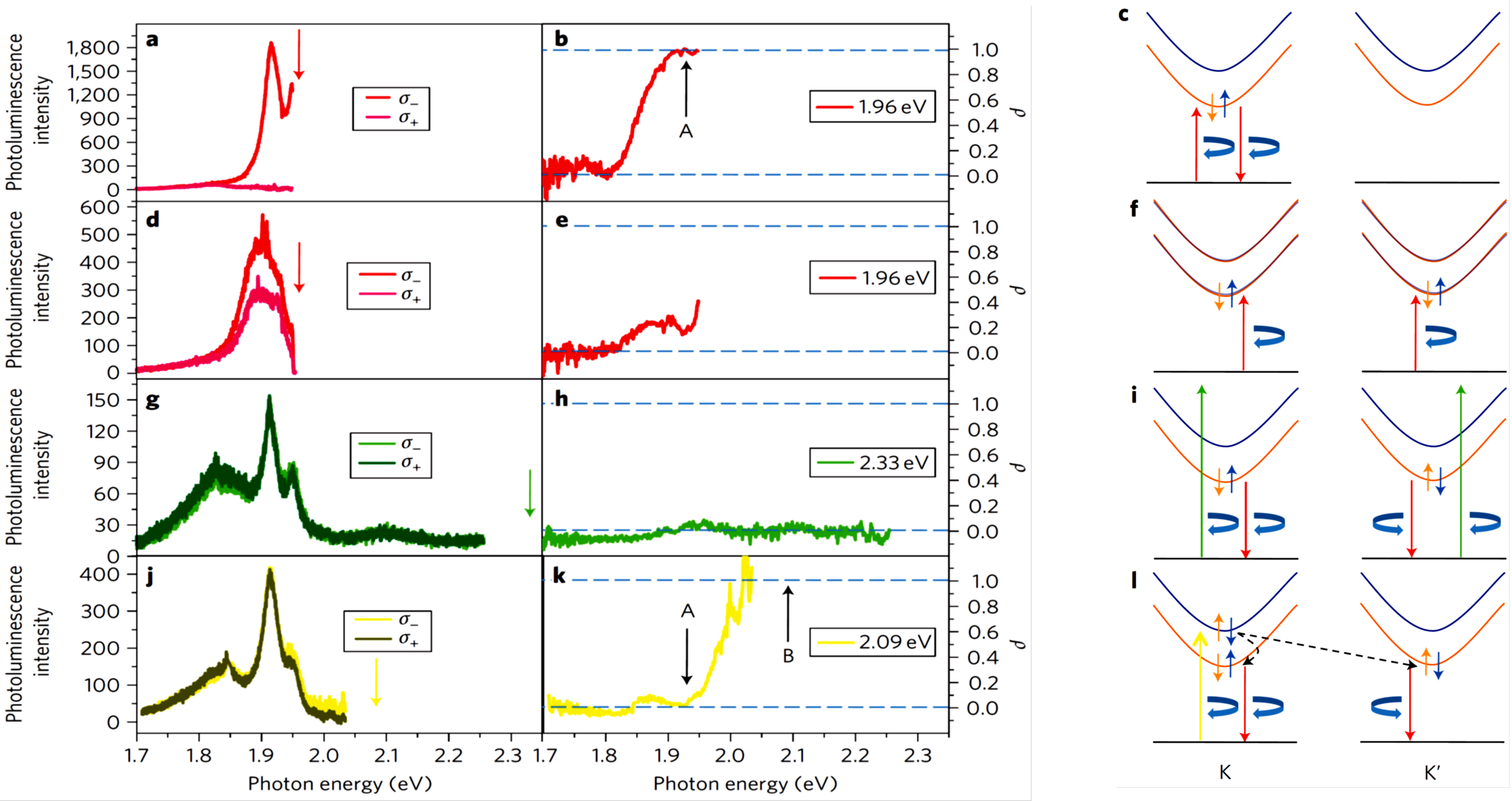


Decoupled valley and spin
Optical spin orientation



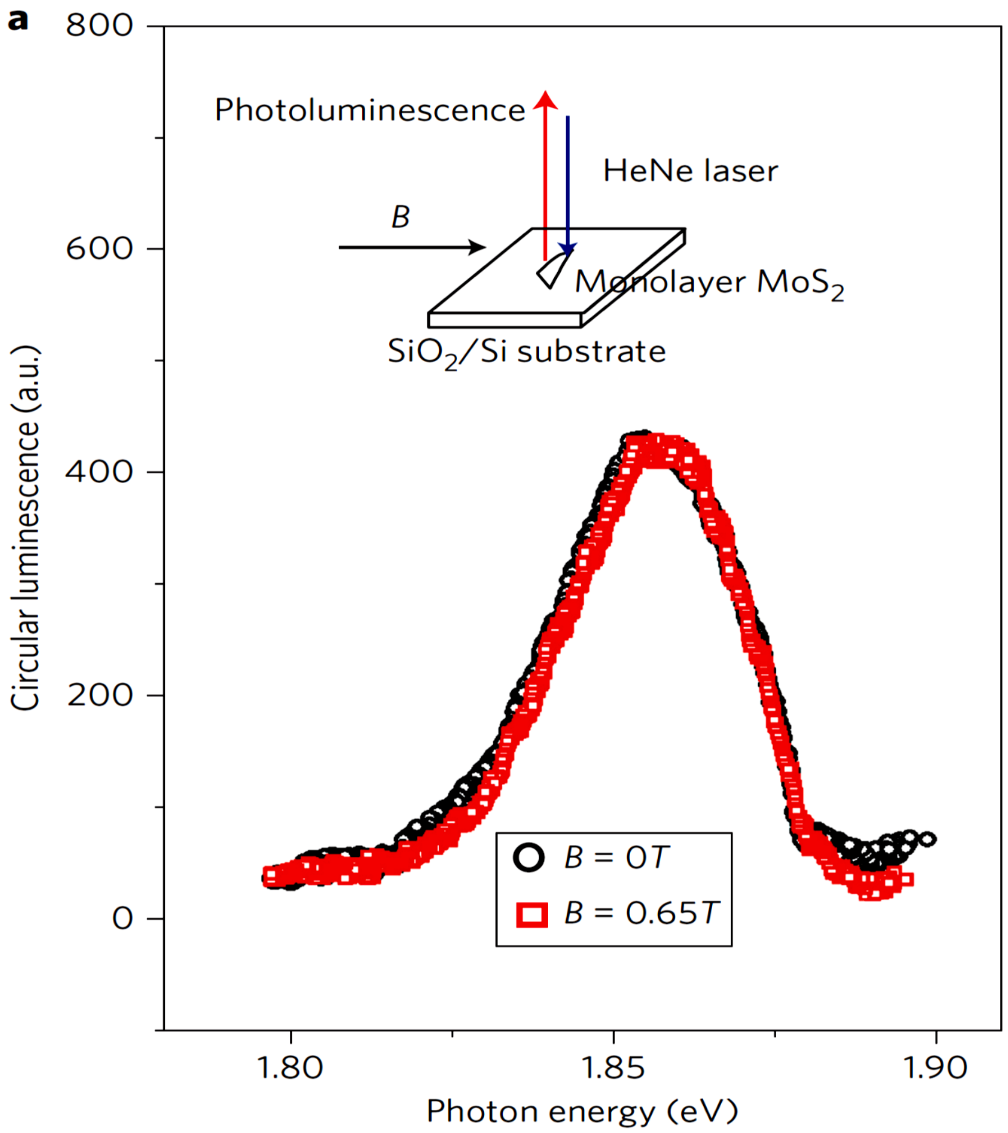
$$|\mathcal{P}_{\pm}(\boldsymbol{k})|^2 = \frac{m_0^2 a^2 t^2}{\hbar^2}\left(1 \pm \tau \frac{\Delta'}{\sqrt{\Delta'^2 + 4a^2t^2k^2}}\right)^2$$

Optically Induced Valley Polarization



K. F. Mak et al., Nature Nanotech. 7, 494 (2012).

No Hanle effect



Luminescence Polarization :

$$P(B) \approx \frac{P(B=0)}{1+(g\mu_B B\tau_S/\hbar)^2}$$

Zeng et al, Nature NanoTech. 7, 409 (2012).

Lattice and Orbital symmetry& Circular Dichroism

1)Lattice symmetry

Wave vector point group at the K(K') point is C_{3h}:

$$R(2\pi/3)|c,K\rangle = e^{-i2\pi/3}|c,K\rangle$$
$$R(2\pi/3)|v,K\rangle = e^{+i2\pi/3}|v,K\rangle$$
$$R(2\pi/3)|c,K'\rangle = e^{+i2\pi/3}|c,K'\rangle$$
$$R(2\pi/3)|v,K'\rangle = e^{-i2\pi/3}|v,K'\rangle$$

2)Atomic orbital symmetry

Conducion band: d_{z^2}

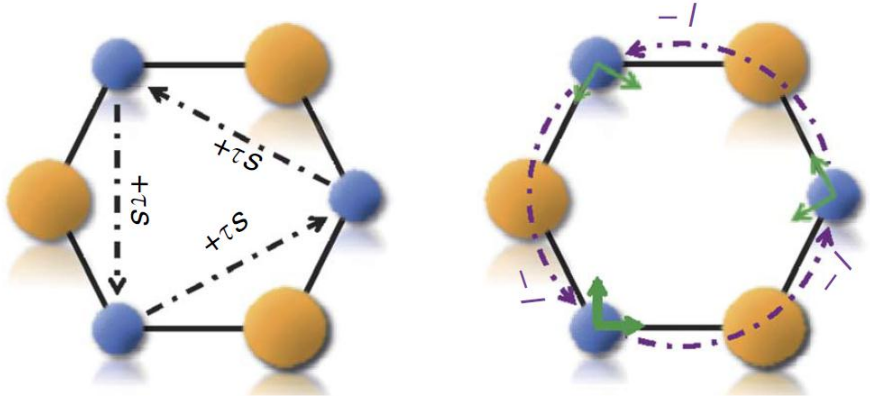
Vallence band: $d_{xy}, d_{x^2-y^2}$

$$R(2\pi/3)|c,K\rangle = |c,K\rangle$$
$$R(2\pi/3)|v,K\rangle = e^{+i4\pi/3}|v,K\rangle$$
$$R(2\pi/3)|c,K'\rangle = |c,K'\rangle$$
$$R(2\pi/3)|v,K'\rangle = e^{-i4\pi/3}|v,K'\rangle$$

Both symmetries lead to

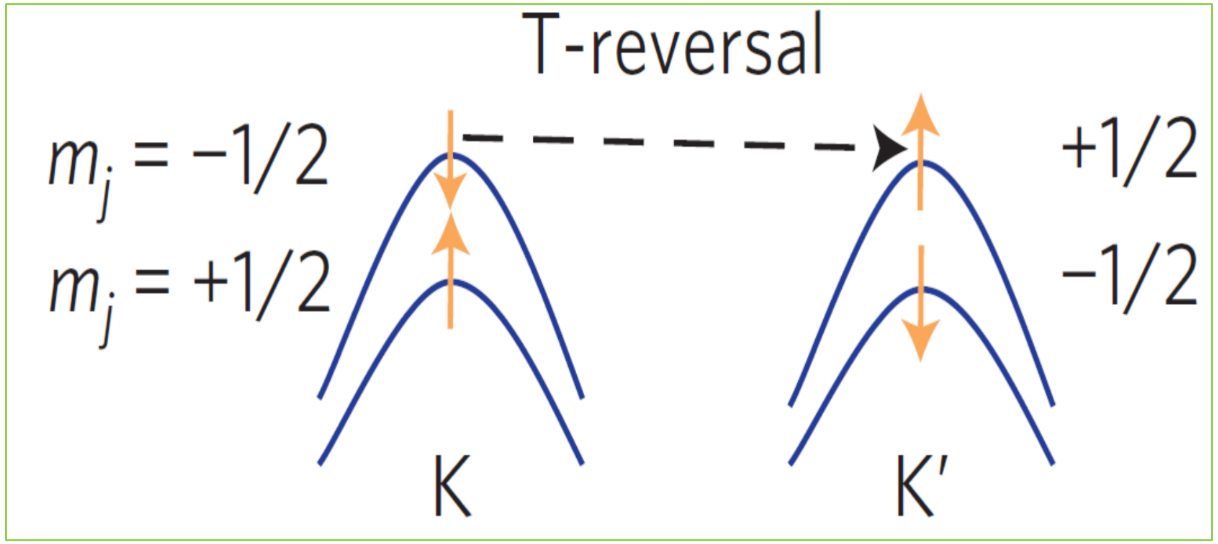
$$R(2\pi/3)|c,K\rangle = e^{-i2\pi/3}|c,K\rangle$$
$$R(2\pi/3)|v,K\rangle = |v,K\rangle$$

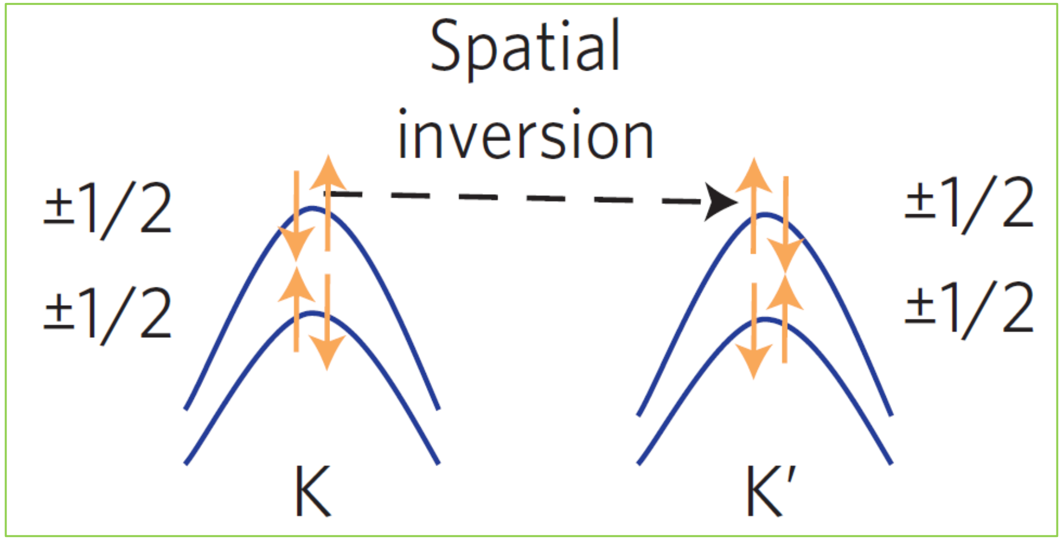
$$R(2\pi/3)|c,K'\rangle = e^{+i2\pi/3}|c,K'\rangle$$
$$R(2\pi/3)|v,K'\rangle = |v,K'\rangle$$



T. Cao, et al., Nature Commun. 3, 887 (2012).

Spin-Valley coupling

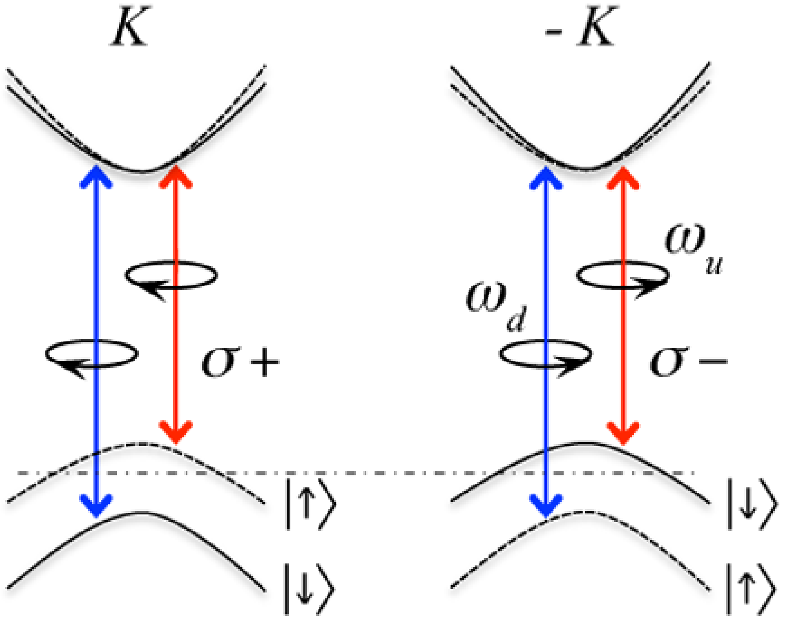


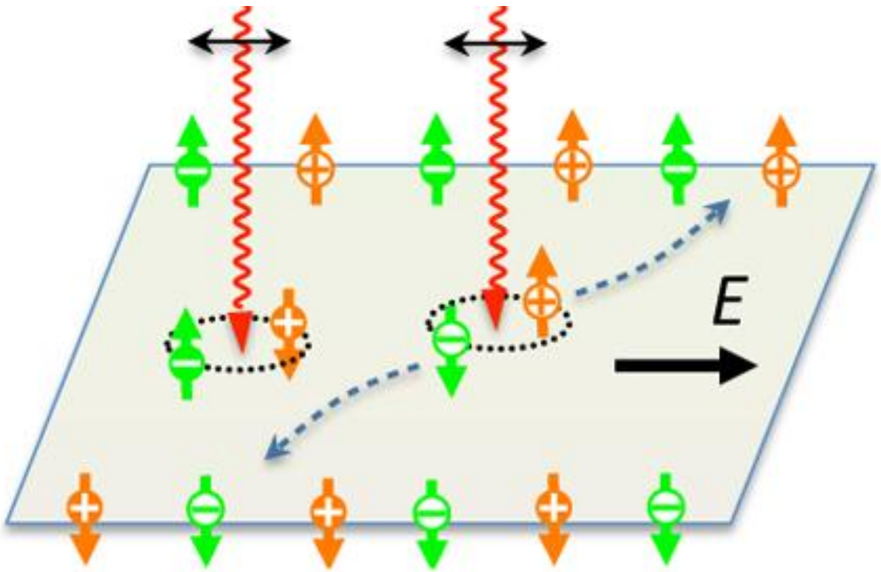


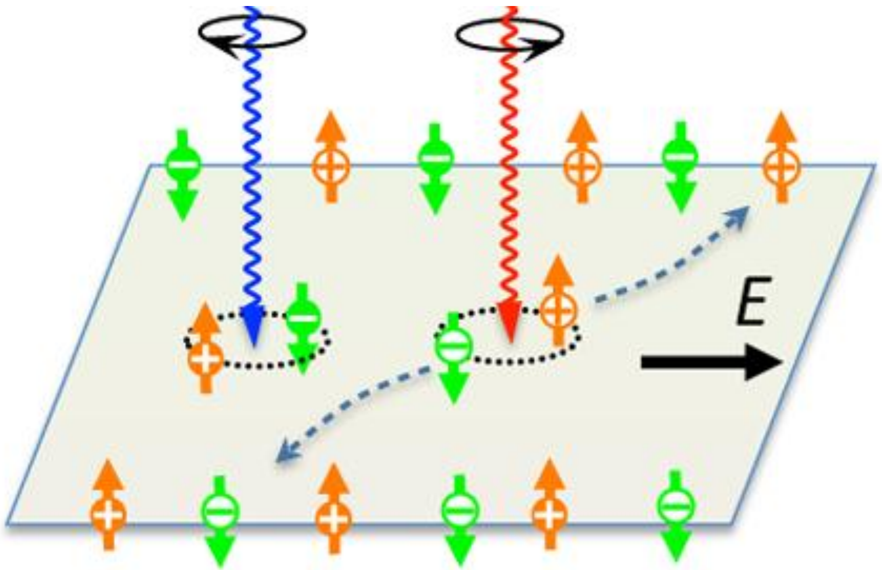
K. F. Mak et al., Nature Nanotech. 7, 494 (2012).

Spin-Valley coupling

Hole doped system







Di Xiao, *et al* , Phys. Rev. Lett. **108**,196802 (2012)

Optical Conductivity

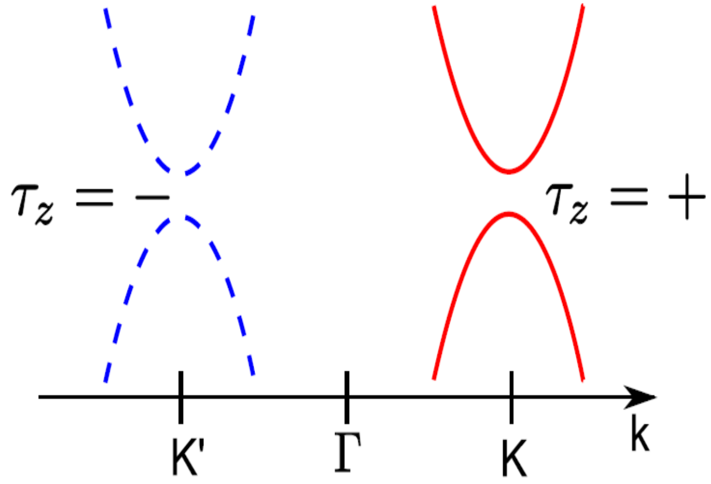
H.R, and Reza Asgari (to be submitted)

Hamiltonian

Monolayer MoS_2 Hamiltonian

$$\mathcal{H}_{\tau s} = \frac{\Delta}{2}\sigma_z + \lambda\tau s\frac{1-\sigma_z}{2} + t_0 a_0 q\cdot\sigma_\tau + \frac{\hbar^2|q|^2}{4m_0}(\alpha+\beta\sigma_z)$$

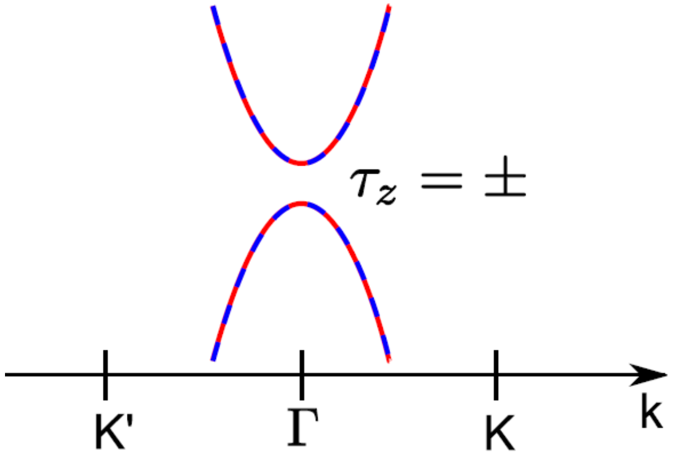
$$\sigma_\tau = (\tau\sigma_x, \sigma_y)$$



H. R, A. G. Moghaddam, R. Asgari, Phys. Rev. B 88, 085440 (2013).

Toplogical insulator thin film Hamiltonian

$$\mathcal{H}_\tau = \epsilon_0 + \tau\frac{\Delta}{2}\sigma_z + t_0 a_0 q\cdot\sigma + (\alpha+\tau\beta\sigma_z)|q|^2$$



Z_2 symmetry invariant:

$\beta\Delta > 0:$ Trivial phase

$\beta\Delta < 0:$ Non-Trivial phase

Shun-Qing Shen, Topological Insulator, Springer(2012).
H.-Z. Lu,et al Phys.Rev.B 81, 115407(2010).

Kubo's Formula

$$\sigma_{xy} = -i\frac{e^2}{2\pi h}\int d^2q\frac{f(\varepsilon_c)-f(\varepsilon_v)}{\varepsilon_c-\varepsilon_v}\{\frac{\langle\psi_c|\hbar v_x|\psi_v\rangle\langle\psi_v|\hbar v_y|\psi_c\rangle}{\hbar\omega+\varepsilon_c-\varepsilon_v+i0^+}+\frac{\langle\psi_v|\hbar v_x|\psi_c\rangle\langle\psi_c|\hbar v_y|\psi_v\rangle}{\hbar\omega+\varepsilon_v-\varepsilon_c+i0^+}\}$$

$$\sigma_{xx} = -i\frac{e^2}{2\pi h}\int d^2q\frac{f(\varepsilon_c)-f(\varepsilon_v)}{\varepsilon_c-\varepsilon_v}\{\frac{\langle\psi_c|\hbar v_x|\psi_v\rangle\langle\psi_v|\hbar v_x|\psi_c\rangle}{\hbar\omega+\varepsilon_c-\varepsilon_v+i0^+}+\frac{\langle\psi_v|\hbar v_x|\psi_c\rangle\langle\psi_c|\hbar v_x|\psi_v\rangle}{\hbar\omega+\varepsilon_v-\varepsilon_c+i0^+}\}$$

$$|\psi_{c,v}\rangle = \frac{1}{D_{c,v}}\begin{pmatrix}-cq^* \\ h_{c,v}\end{pmatrix} \quad , \quad \varepsilon_{c,v} = a_1 + b(\alpha+\beta)q^2 - h_{c,v}$$

$$h_{c,v} = d \mp \sqrt{d^2+c^2q^2} \quad , \quad d = \frac{a_1-a_2}{2} + b\beta q^2 \quad , \quad D_{c,v} = \sqrt{c^2q^2+h_{c,v}^2}$$

$$\hbar v_x = \frac{\partial H}{\partial q_x} = c\sigma_x + 2b\alpha q_x + 2b\beta q_x\sigma_z$$

$$\hbar v_y = \frac{\partial H}{\partial q_y} = c\sigma_y + 2b\alpha q_y + 2b\beta q_y\sigma_z$$

Wang-Kong Tse and A.H.MacDonald,Phys.Rev.B 84,205327(2011).
T. Stauber, N. M. R. Peres, and A. K. Geim,Phys.Rev.B 78,085432 (2008).
Zhou Li and J. P. Carbotte Phys. Rev. B 86, 205425(2012).

Optical spin/valley Conductivity

$$\sigma_{xy}^{s} = \frac{\hbar}{2e}\sum_{\tau}[\sigma_{xy}^{\tau,\uparrow} - \sigma_{xy}^{\tau,\downarrow}]$$

$$\sigma_{xy}^{v} = \frac{1}{e}\sum_{s}[\sigma_{xy}^{K,s} - \sigma_{xy}^{K',s}]$$

$$\sigma_{xx} = \sum_{\tau}[\sigma_{xx}^{\tau,\uparrow} + \sigma_{xx}^{\tau,\downarrow}]$$

$$\sigma_{xy}^{hyp} = \frac{1}{e}\sum_{s}[\sigma_{xy}^{\Gamma^{+}} - \sigma_{xy}^{\Gamma^{+}}]$$

Optical Hall Conductivity

$$
\begin{aligned}
\sigma_{xy}^{\Re,\tau s} &= \tau\frac{e^2}{h}[G_{\tau s}(\omega,q_{\rm F}) - G_{\tau s}(\omega,q_c)]\\
\sigma_{xy}^{\Im,\tau s} &= \tau\frac{\pi e^2}{2h}\frac{\Delta'_{\tau s}-\beta' q_{0,\tau s}^2}{\hbar\omega' n(\omega')}\\
&\times [\Theta(2\varepsilon'_{\rm F} - \lambda'\tau s - 2\alpha' q_{0,\tau s}^2 - \hbar\omega') - (\omega'\to-\omega')]\\
&\times \Theta(n(\omega') - (1+2\beta'\Delta'_{\tau s}))
\end{aligned}
$$

$$
\begin{aligned}
G_{\tau s}(\omega,q) = &\frac{\Delta'_{\tau s}}{\hbar\omega' n(\omega')}\ln\left|\frac{\hbar\omega'\frac{m(q)}{n(\omega')} - 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}{\hbar\omega'\frac{m(q)}{n(\omega')} + 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\right|\\
&+\frac{1}{4\beta'\hbar\omega' n(\omega')}\ln\left|\frac{\hbar\omega'\frac{m(q)}{n(\omega')} - 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}{\hbar\omega'\frac{m(q)}{n(\omega')} + 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\right|\\
&-\frac{1}{4\beta'\hbar\omega'}\ln\left|\frac{\hbar\omega' - 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}{\hbar\omega' + 2\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\right|
\end{aligned}
$$

$$
\begin{aligned}
m(q) &= 1 + 2\beta'\Delta'_{\tau s} + 2\beta'^2 q^2\\
n(\omega') &= \sqrt{1+4\beta'\Delta'_{\tau s} + \beta'^2(\hbar\omega')^2}\\
\hbar\omega' &= \hbar\omega/t_0\\
\varepsilon'_{\rm F} &= \varepsilon_{\rm F}/t_0\\
\lambda' &= \lambda/t_0\\
m(q_{0,\tau s}) &= n(\omega')
\end{aligned}
$$

$$
\begin{aligned}
\Delta'_{\tau s} &= (\Delta - \lambda\tau s)/2t_0\\
\alpha' &= \hbar^2\alpha/(4m_0a_0^2t_0)\\
\beta' &= \hbar^2\beta/(4m_0a_0^2t_0)
\end{aligned}
$$

Optical Longitudinal Conductivity

$$\begin{aligned}\sigma_{xx}^{\Re,\tau s} &= -\frac{\pi e^2}{4h}\frac{1}{n(\omega')}(1-\frac{1+4\beta'\Delta'_{\tau s}}{2}(\frac{2q_{0,\tau s}}{\hbar\omega'})^2)\\ &\times [\Theta(2\varepsilon'_{\mathrm{F}}-\lambda'\tau s-2\alpha' q_{0,\tau s}^2-\hbar\omega')-(\omega'\to-\omega')]\\ &\times \Theta(n(\omega')-(1+2\beta'\Delta'_{\tau s}))\\ \sigma_{xx}^{\Im,\tau s} &= -\frac{e^2}{h}[H_{\tau s}(\omega,q_{\mathrm{F}})-H_{\tau s}(\omega,q_c)]\end{aligned}$$

$$\begin{aligned}H_{\tau s}(\omega,q) &= \frac{(1+2\beta'\Delta'_{\tau s})m(q)-(1+4\beta'\Delta'_{\tau s})}{2\beta'^2\hbar\omega'\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\\ &+ \frac{1+4\beta'\Delta'_{\tau s}}{2\beta'^2(\hbar\omega')^2}\ln\left|\frac{\frac{\hbar\omega'}{2}-\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}{\frac{\hbar\omega'}{2}+\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\right|\\ &+ \frac{(1+2\beta'\Delta'_{\tau s})(1+4\beta'\Delta'_{\tau s})+\beta'^2(\hbar\omega')^2}{2\beta'^2(\hbar\omega')^2 n(\omega')}\\ &\times \ln\left|\frac{\frac{\hbar\omega'}{2}\frac{m(q)}{n(\omega')}-\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}{\frac{\hbar\omega'}{2}\frac{m(q)}{n(\omega')}+\sqrt{(\Delta'_{\tau s}+\beta' q^2)^2+q^2}}\right|\end{aligned}$$

Xiao's Model

$\alpha = 0 \quad , \quad \beta = 0$

$$\mathcal{H}_{\tau s} = \frac{\Delta}{2}\sigma_z + \lambda\tau s\frac{1-\sigma_z}{2} + t_0 a_0 q \cdot \sigma_\tau$$

Di Xiao, *et al* , Phys. Rev. Lett. **108**,196802 (2012)

$$\begin{aligned}
\sigma_{xy}^{\Re,\tau s} &= \tau\frac{e^2}{h}[g_{\tau s}(\omega, q_{\rm F}) - g_{\tau s}(\omega, q_c)] \\
\sigma_{xy}^{\Im,\tau s} &= \tau\frac{\pi e^2}{4h}\frac{\Delta-\lambda\tau s}{\hbar\omega}[\Theta(2\varepsilon_{\rm F} - \lambda\tau s - \hbar\omega) - (\omega\to-\omega)] \\
&\times \Theta(\hbar\omega - (\Delta - \lambda\tau s))
\end{aligned}$$

$$\begin{aligned}
\sigma_{xx}^{\Re,\tau s} &= -\frac{\pi e^2}{8h}(1+(\frac{\Delta-\lambda\tau s}{\hbar\omega})^2)\Theta(\hbar\omega - (\Delta-\lambda\tau s)) \\
&\times [\Theta(2\varepsilon_{\rm F} - \lambda\tau s - \hbar\omega) - (\omega\to-\omega)] \\
\sigma_{xx}^{\Im,\tau s} &= -\frac{e^2}{h}[h_{\tau s}(\omega, q_{\rm F}) - h_{\tau s}(\omega, q_c)]
\end{aligned}$$

$$\begin{aligned}
g_{\tau s}(\omega, q) &= \frac{\Delta-\lambda\tau s}{4\hbar\omega}\ln\left|\frac{\hbar\omega - \sqrt{(\Delta-\lambda\tau s)^2 + 4t_0^2q^2}}{\hbar\omega + \sqrt{(\Delta-\lambda\tau s)^2 + 4t_0^2q^2}}\right| \\
h_{\tau s}(\omega, q) &= \frac{\Delta-\lambda\tau s}{2\hbar\omega}\frac{\Delta-\lambda\tau s}{\sqrt{(\Delta-\lambda\tau s)^2 + 4t_0^2q^2}} \\
&+ \frac{1}{4}[1+(\frac{\Delta-\lambda\tau s}{\hbar\omega})^2]\ln\left|\frac{\hbar\omega - \sqrt{(\Delta-\lambda\tau s)^2 + 4t_0^2q^2}}{\hbar\omega + \sqrt{(\Delta-\lambda\tau s)^2 + 4t_0^2q^2}}\right|
\end{aligned}$$

Numerical Parameter

$$m_e = 0.37\, m_0 \quad m_h = -0.44\, m_0$$

$$\lambda = 0.08eV, \Delta = 1.9eV, t_0 = 1.68eV, \alpha = 0.43, \beta = 2.21$$

$$m_e = 0.5\, m_0 \quad m_h = -0.5\, m_0$$

$$t_0 = 1.51eV,\ \alpha = 0,\ \beta = 1.77$$

$$t_0 = 2.02eV,\ \alpha = 0,\ \beta = 0$$

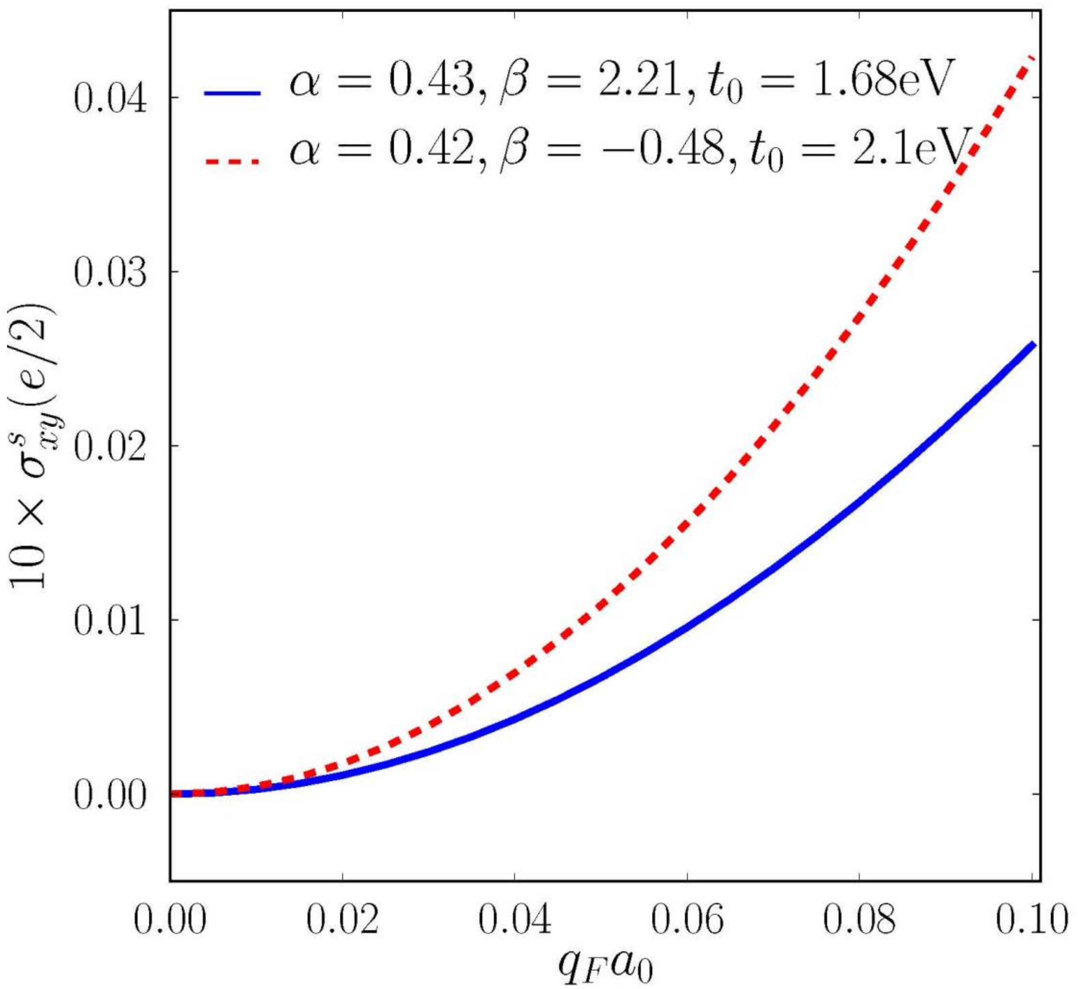
Static limit

Hole doped case

$$\sigma^s_{xy} = \frac{\hbar}{e}[\sigma^{K\uparrow}_{xy} - \sigma^{K\downarrow}_{xy}] = \frac{e}{2\pi}\frac{\mu + \frac{\hbar^2(\alpha-\beta)}{4m_0}q_{\mathrm{F}}^2}{\Delta - \lambda + 2\mu + \frac{\hbar^2\alpha}{2m_0}q_{\mathrm{F}}^2}$$

$$\sigma^v_{xy} = \frac{2}{e}[\sigma^{K\uparrow}_{xy} + \sigma^{K\downarrow}_{xy}] = -\frac{e}{h}\mathcal{C}^K + \frac{2}{\hbar}\sigma^s_{xy}$$

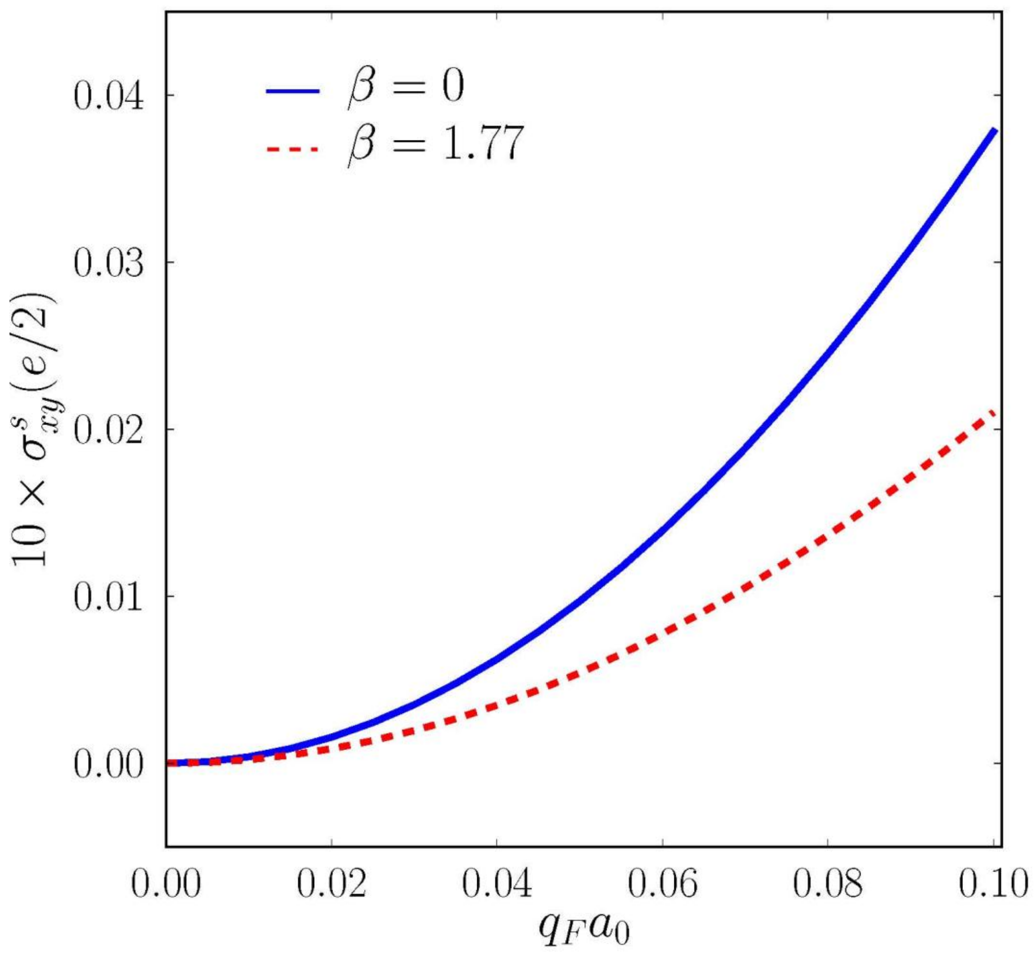
$$\mathcal{C}^K = \frac{\mathrm{sign}(\Delta - \lambda) + \mathrm{sign}(\Delta + \lambda)}{2} - \mathrm{sign}(\beta)$$



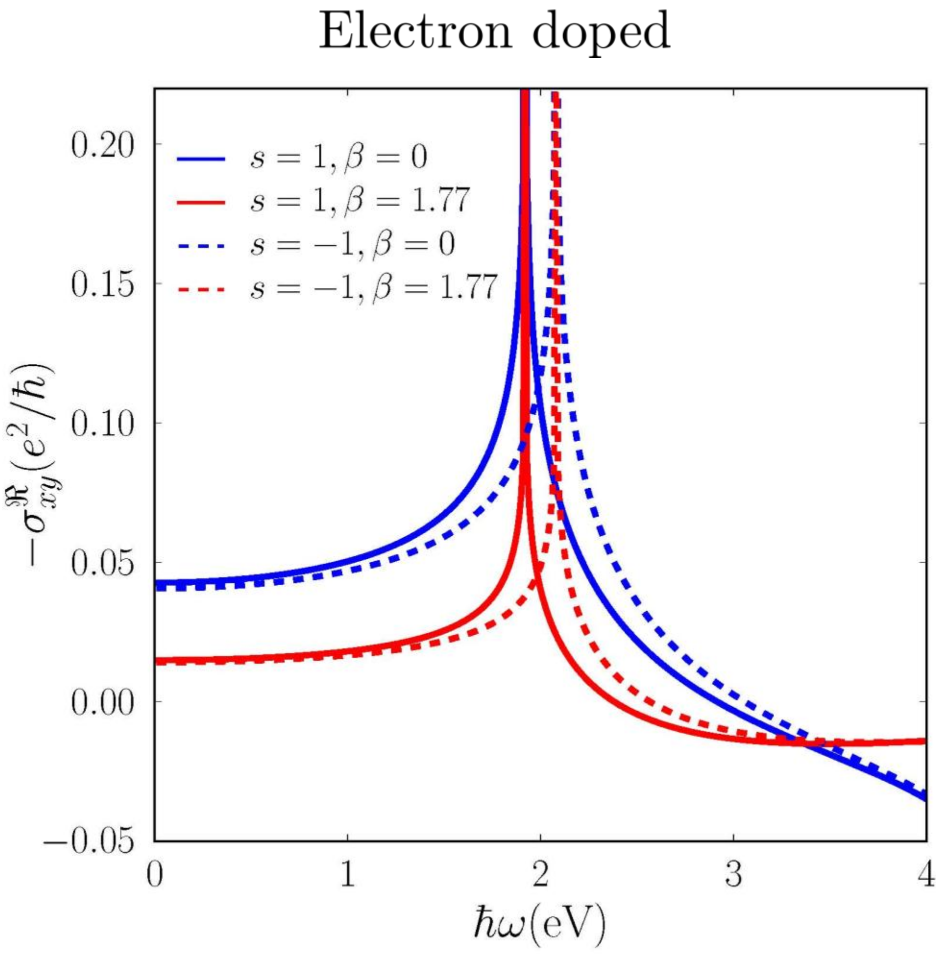
Static limit: the effect of Beta

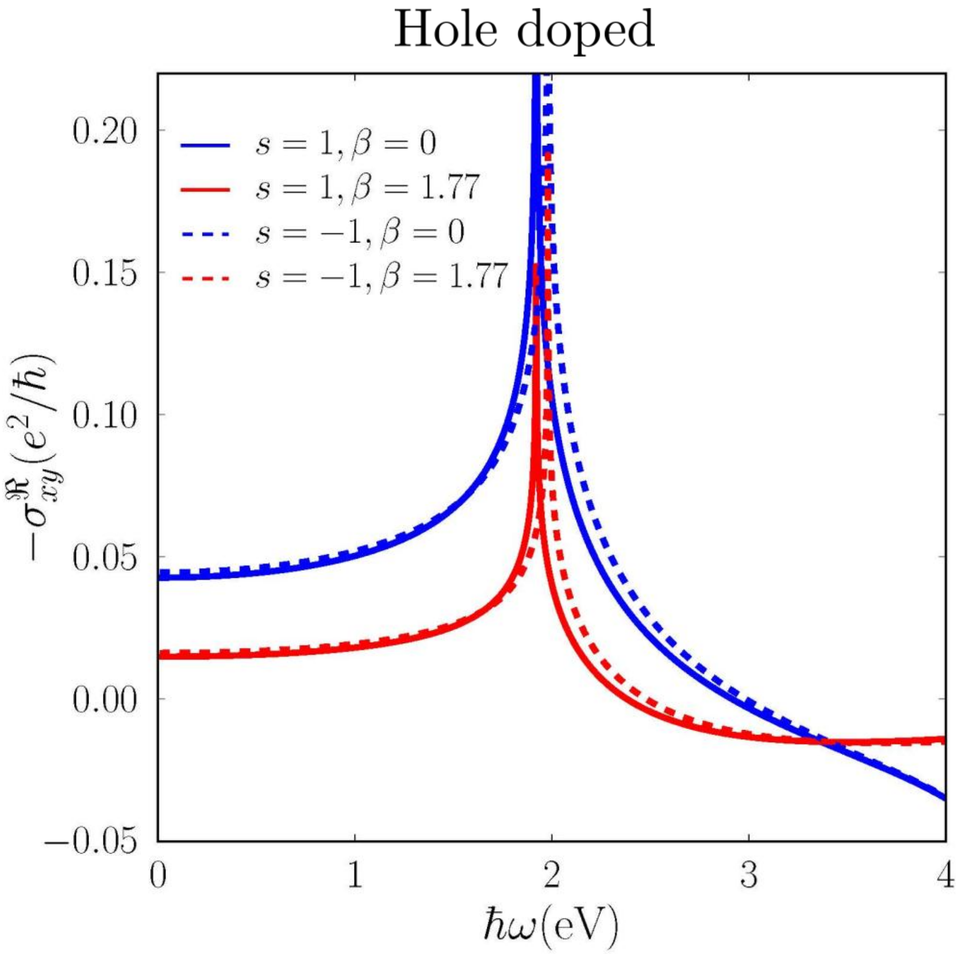
$$\lambda = 0.08eV,\ \Delta = 1.9eV,$$

$$set_1 : t_0 = 1.51eV,\ \alpha = 0,\ \beta = 1.77$$
$$set_2 : t_0 = 2.02eV,\ \alpha = 0,\ \beta = 0$$



Dynamical Hall Conductivity



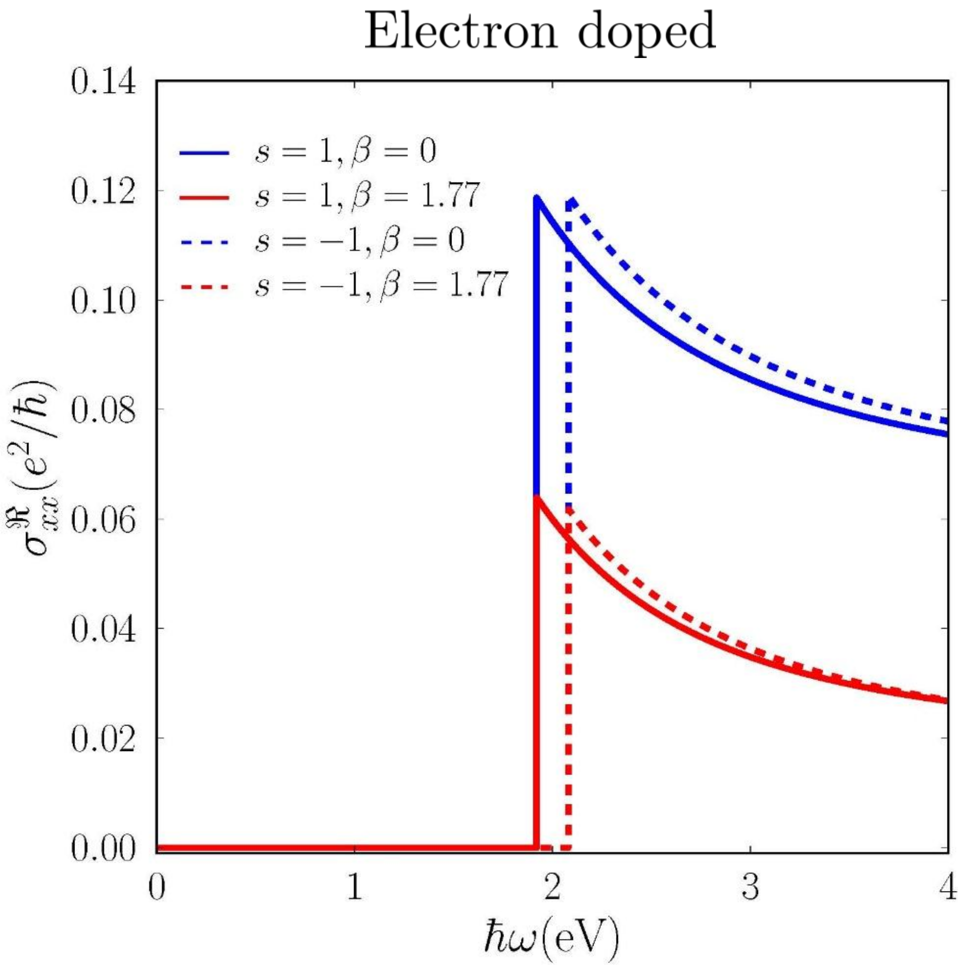


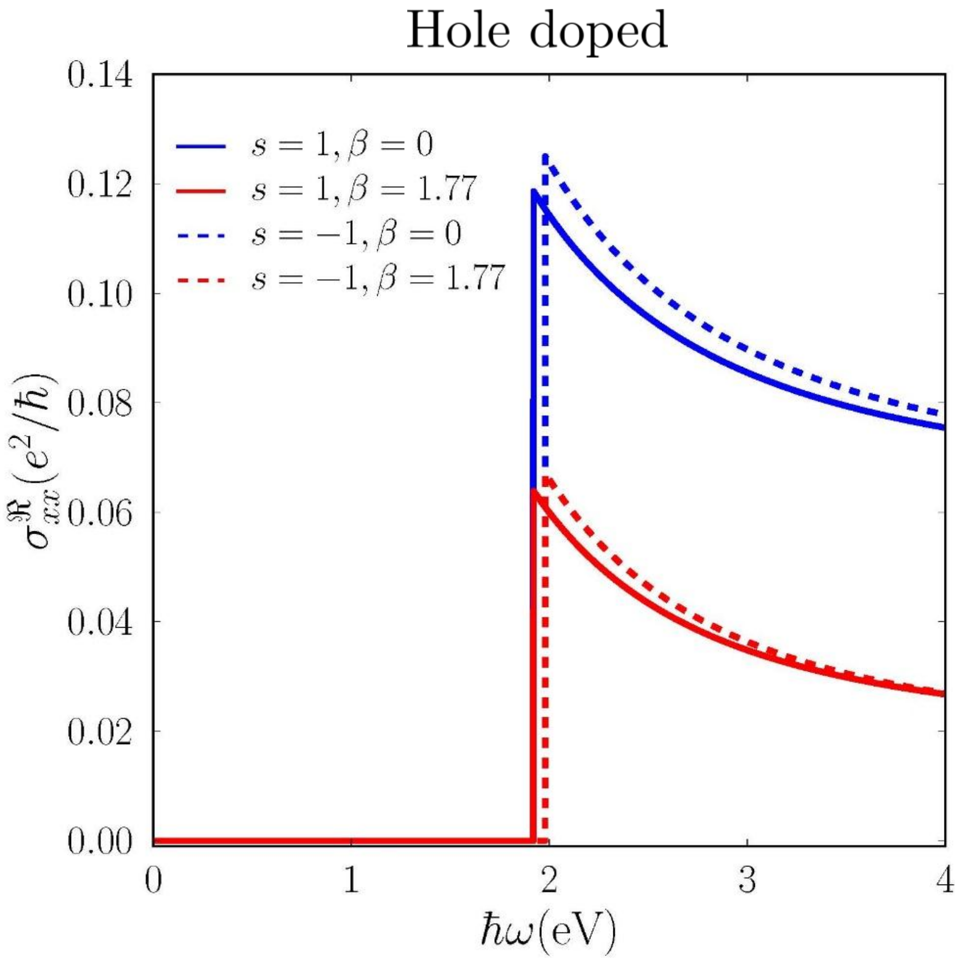
$$\hbar\omega = \sqrt{(\Delta - \lambda\tau s)^2 + 4t_0^2 {q_{\mathrm{Fs}}}^2}$$

$$\hbar\omega' m(q_{\mathrm{Fs}}) n(\omega')^{-1} - 2\sqrt{(\Delta'_{\tau s} + \beta' {q_{\mathrm{Fs}}}^2)^2 + {q_{\mathrm{Fs}}}^2} = 0$$

$$\hbar\omega' - 2\sqrt{(\Delta'_{\tau s} + \beta' {q_{\mathrm{Fs}}}^2)^2 + {q_{\mathrm{Fs}}}^2} = 0$$

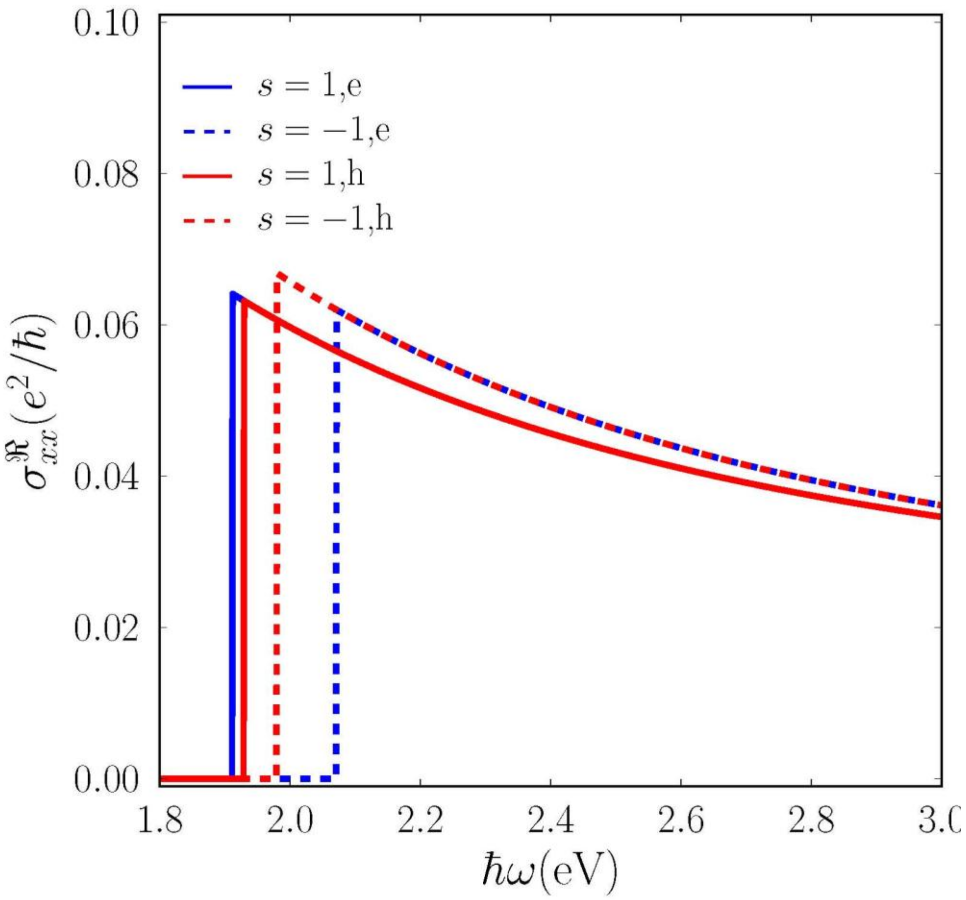
Dynamical Longitudinal Conductivity

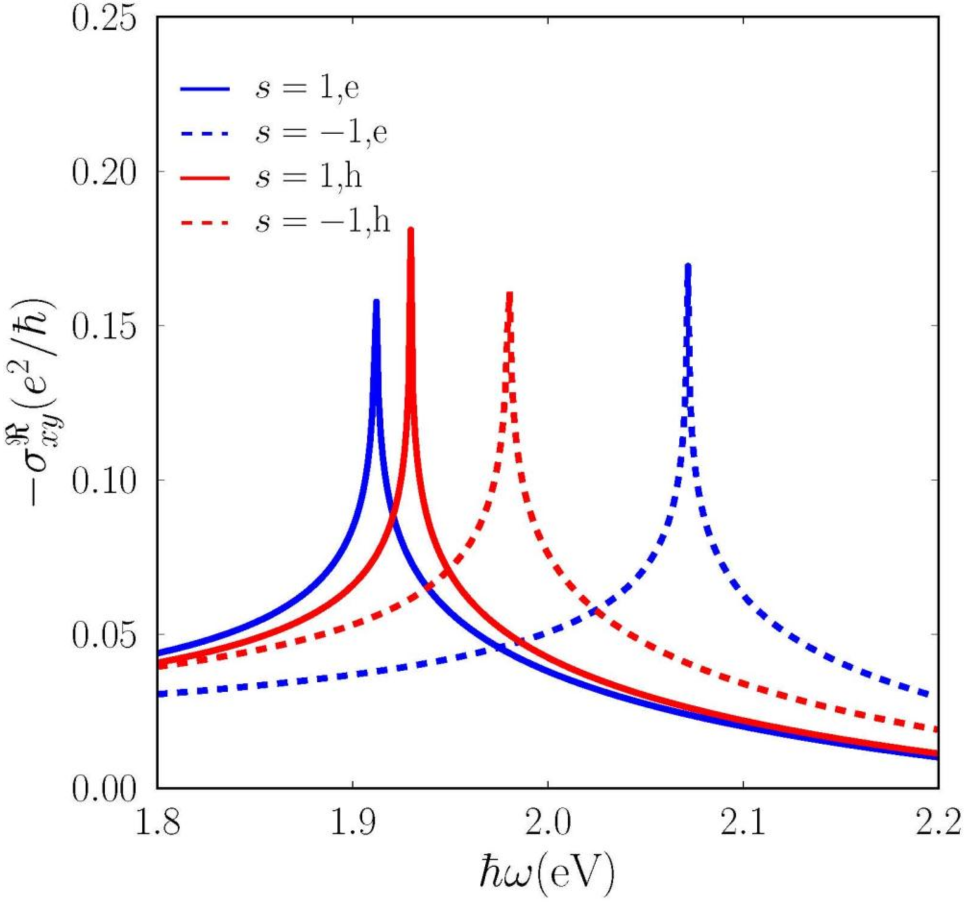




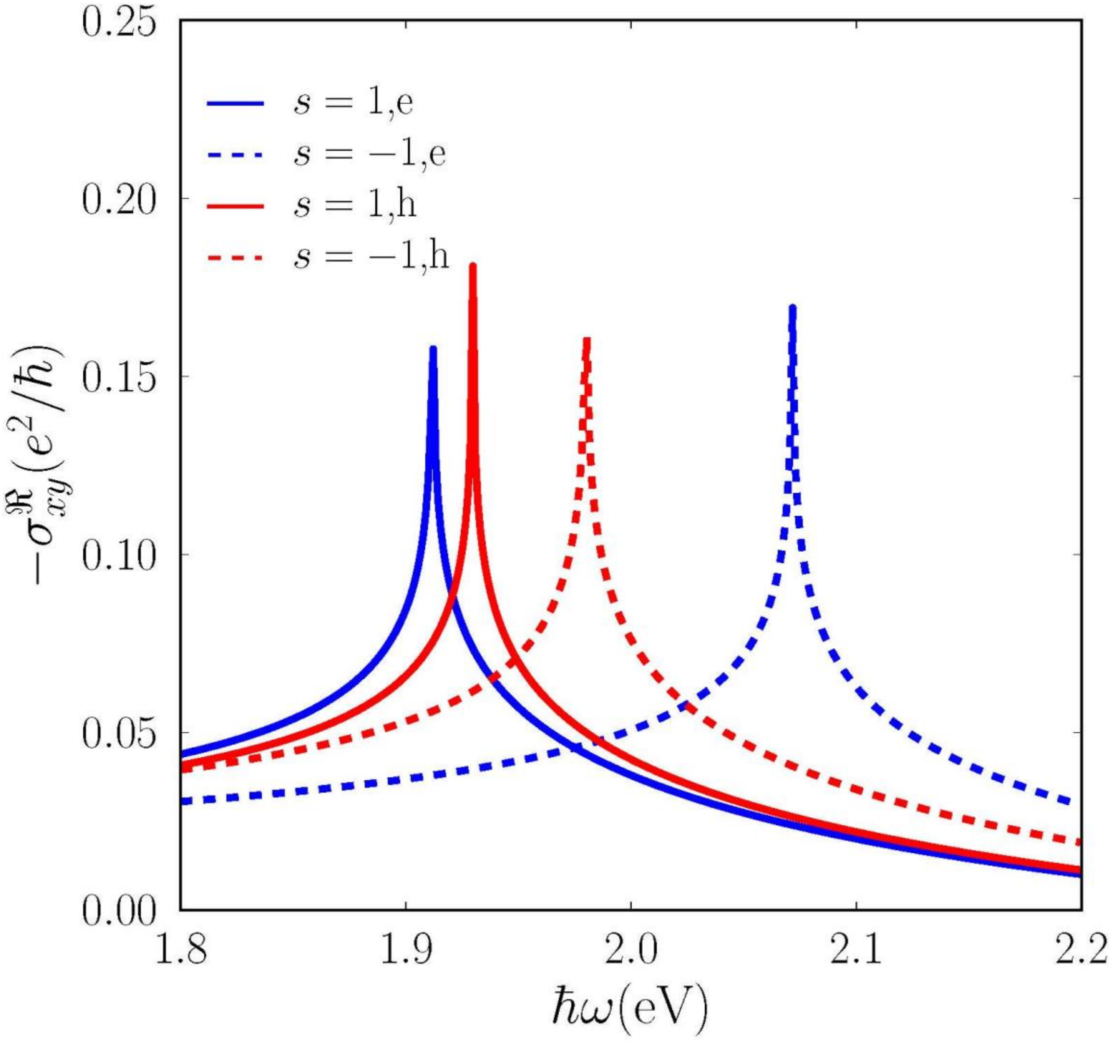
Optical Conductivity(mass asymmetry)

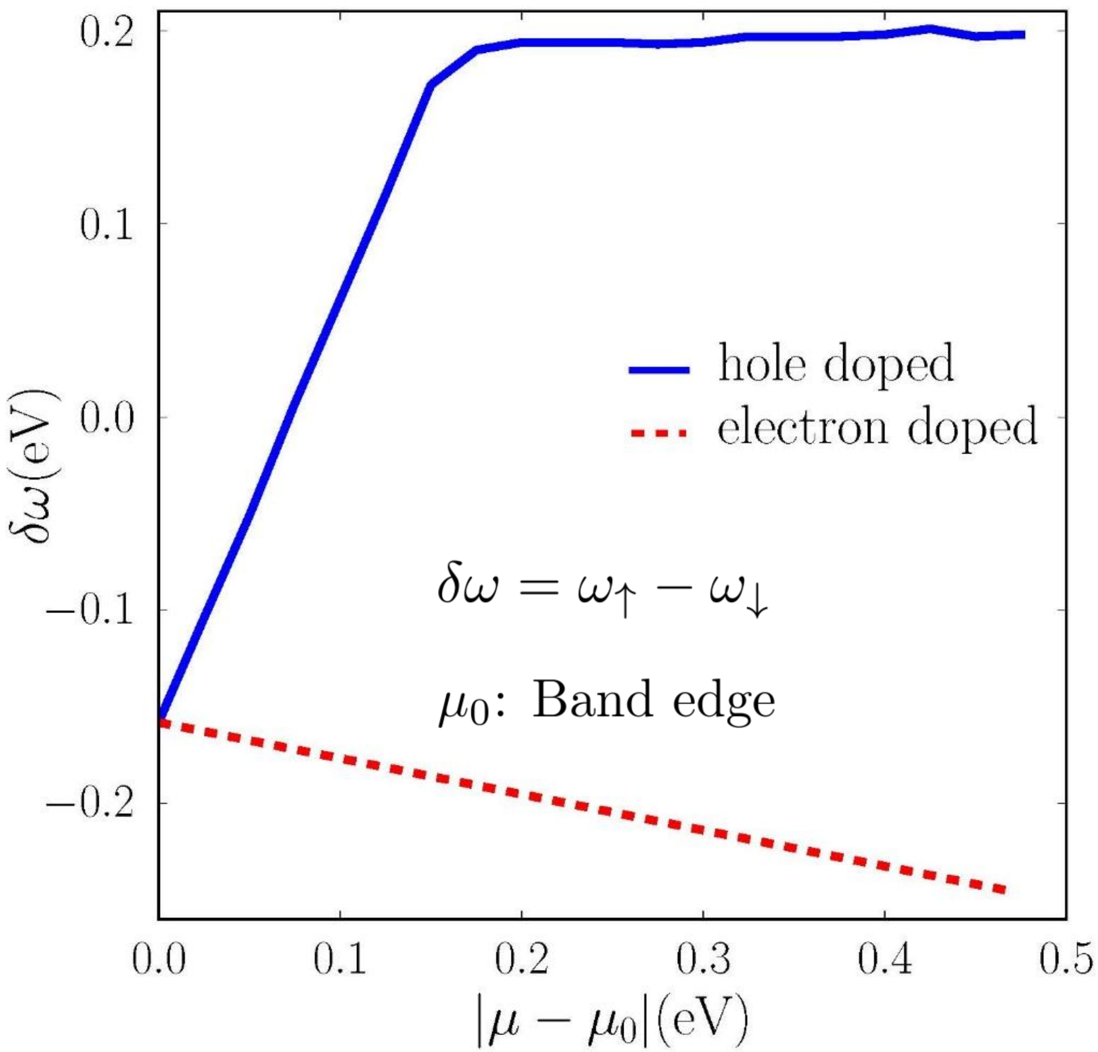
$$\lambda = 0.08eV, \Delta = 1.9eV, t_0 = 1.68eV, \alpha = 0.43, \beta = 2.21$$





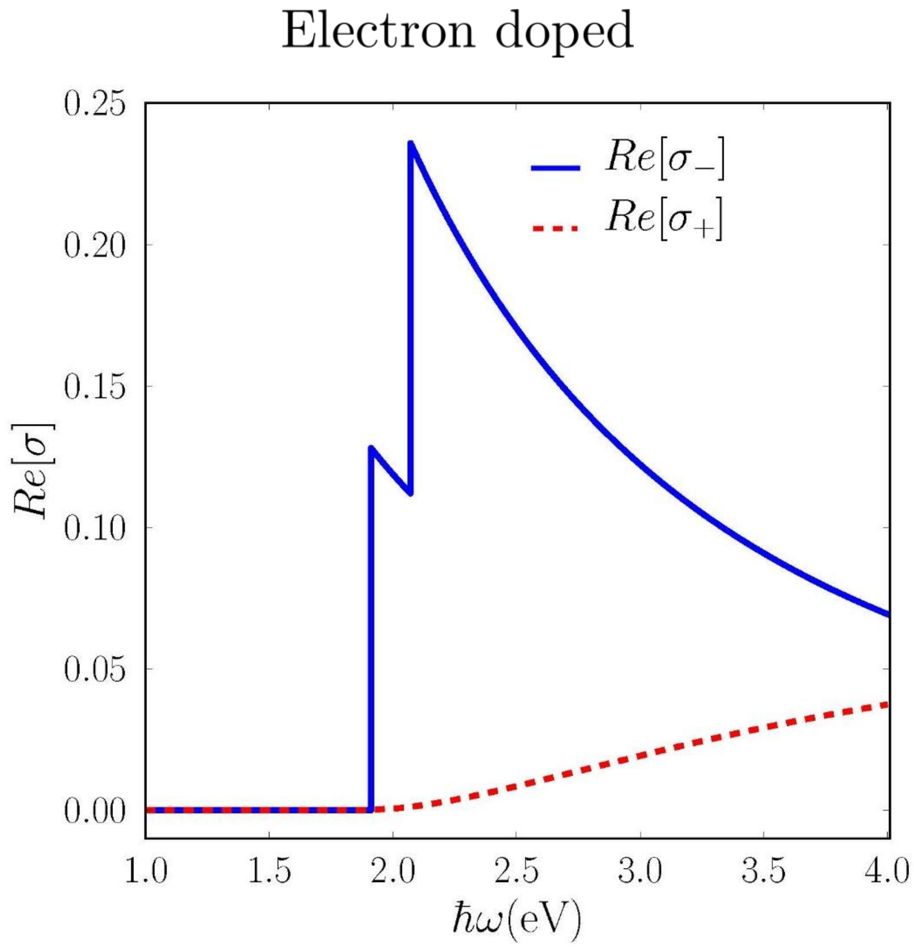
Tuning the spin splitting by Fermi energy

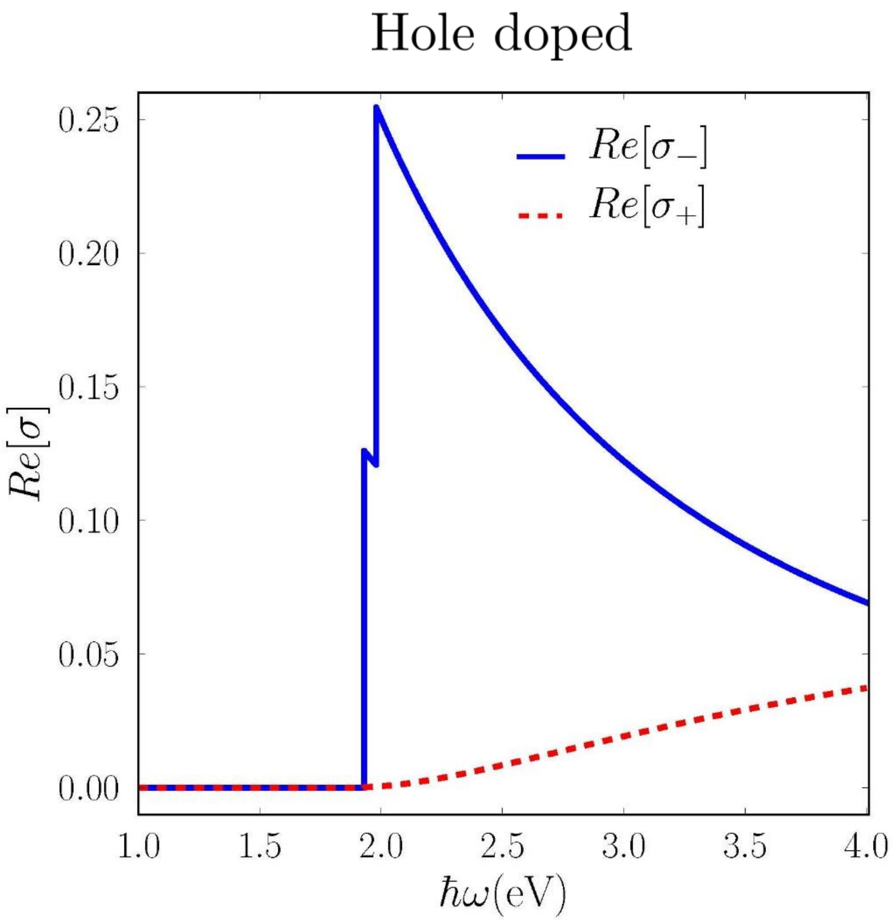




Circular Polarization

$$\sigma_{\pm}(\omega) = \sigma_{xx}(\omega) \pm i\sigma_{xy}(\omega)$$



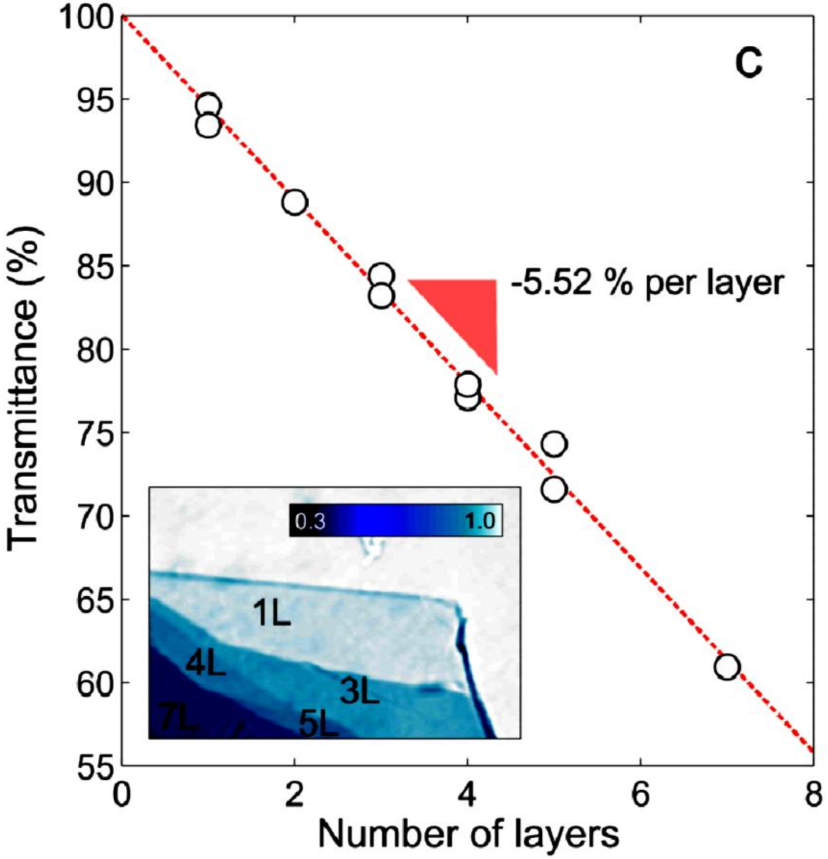


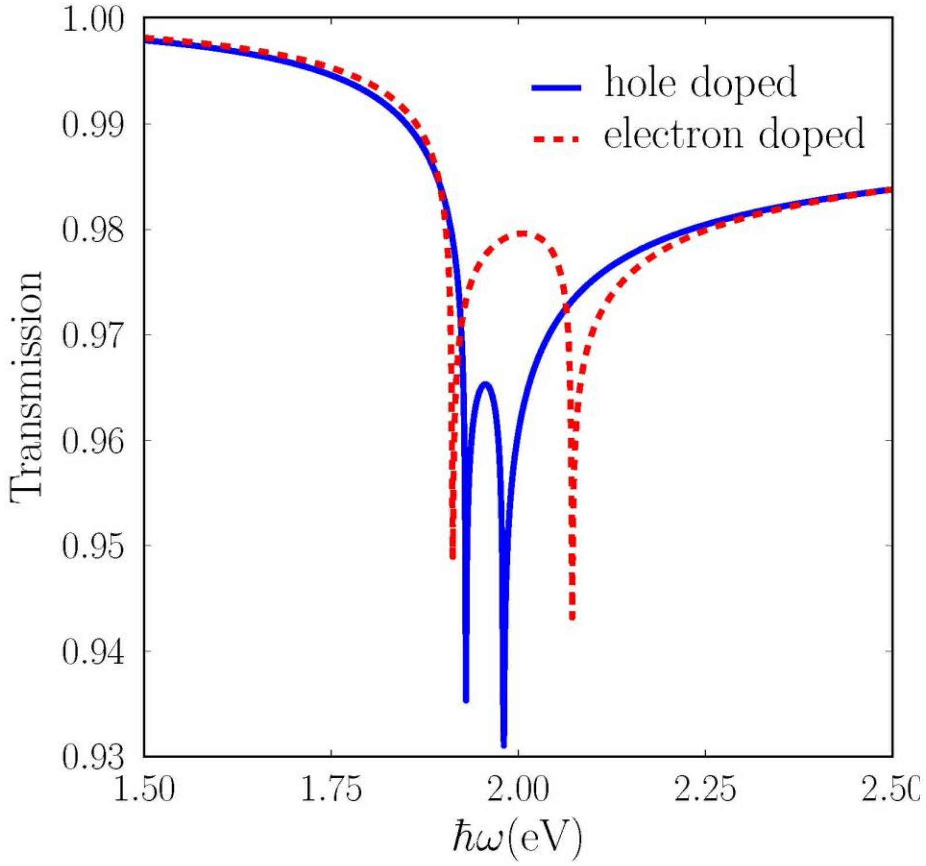
Optical Transmission

Ultra thin film approximation

A. C.-Gomez et al, Private communication

$$T(\omega) = \frac{1}{2}\{|\frac{2}{2+Z_0\sigma_+(\omega)}|^2 + |\frac{2}{2+Z_0\sigma_-(\omega)}|^2\}$$





Vacuum impedance: $Z_0 = 376.73\Omega$

Summary

- Inversion symmetry breaking leads to valley contrasting physics
- Circular dichroism in monolayer MoS2 can be describe by intrinsic optical conductivity
- Charge, spin, and valley Hall effect
- Optical valley pumping

Thank You!