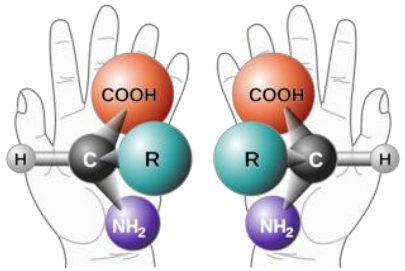
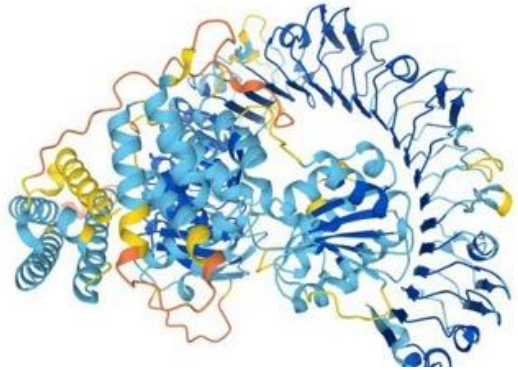
Topology, Spin and Orbital in DNA-like Chiral Materials

Binghai Yan

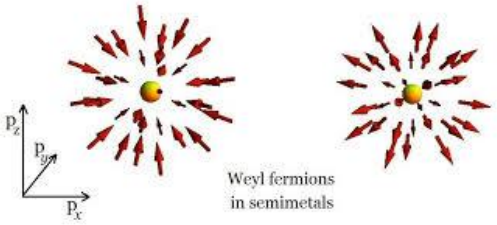
2026 Principles and Applications of Symmetry in Magnetism Summer School
Colorado State University, Jul 16,2026

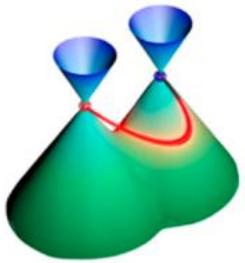
Chirality in chemistry, biology and physics



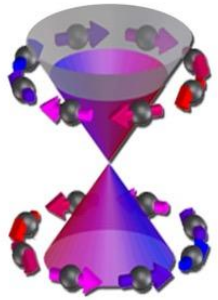


Mystery of homochirality in life

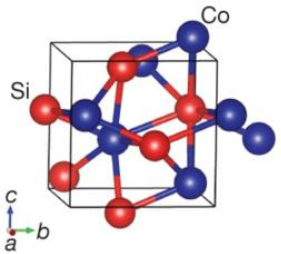




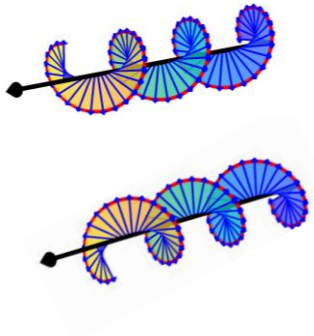
Weyl fermions



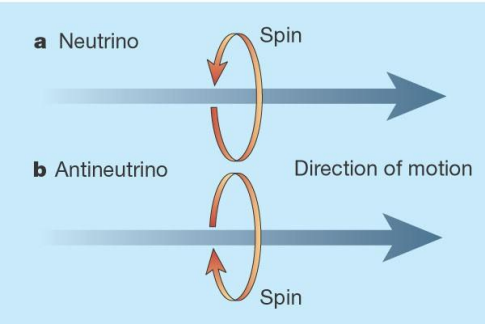
Topological Surf. States



Handedness of geometry



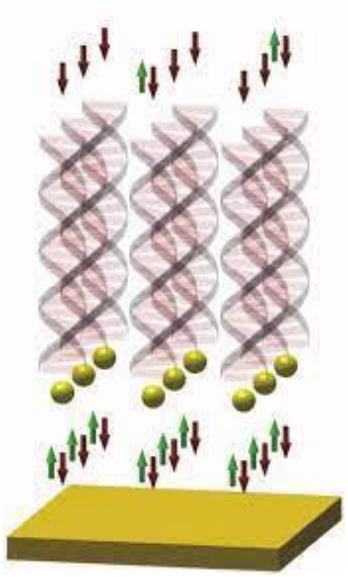
Photons

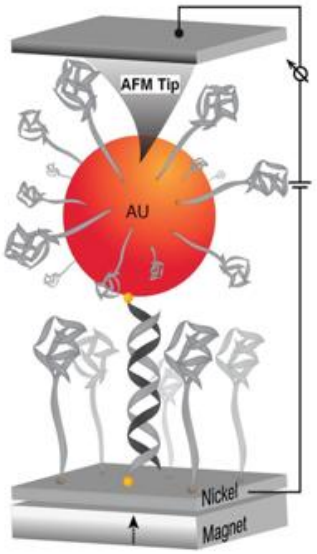


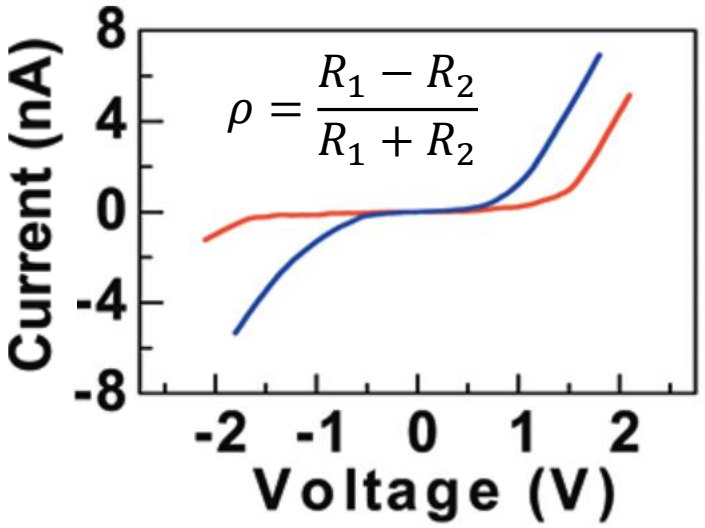
Neutrino

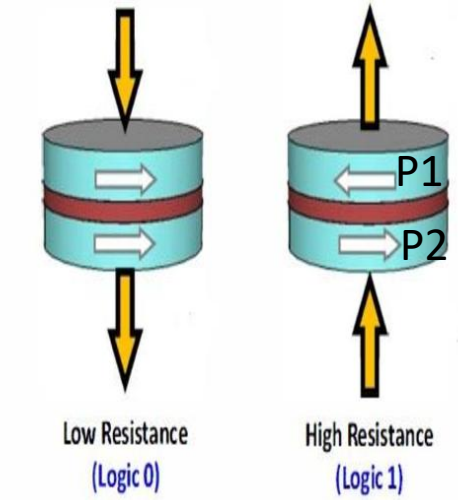
Spin-momentum locking

Chirality Induced Spin Selectivity (CISS)









Magnetic tunneling junction

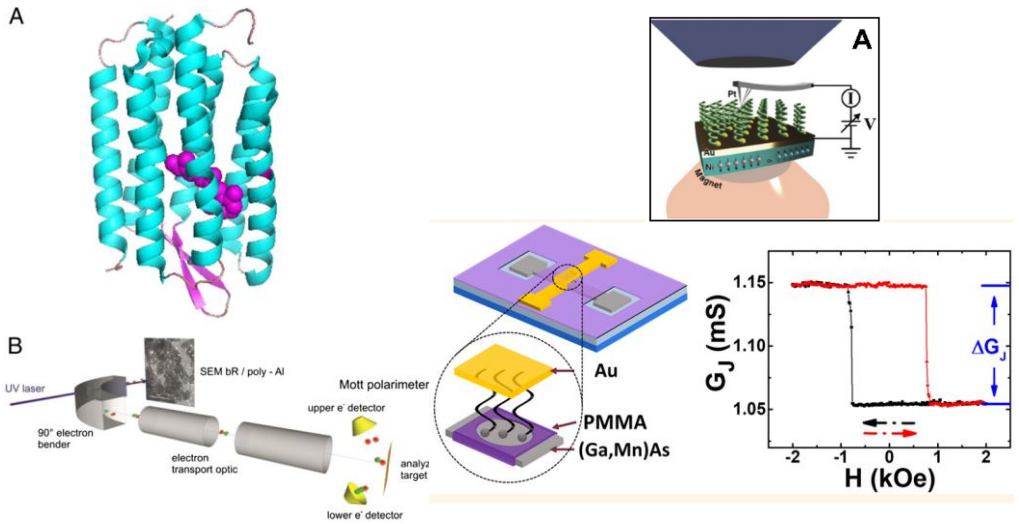
R. Naaman, D. Waldeck, et al.
Science 1999, 2011

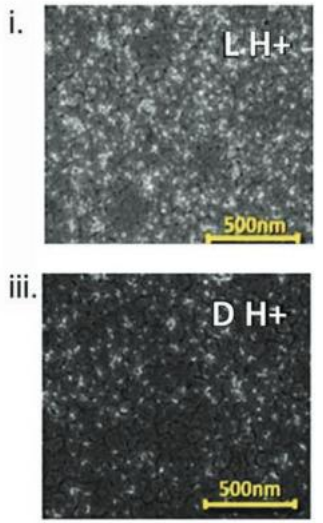
- Room temperature
- Organic molecules
- High polarization

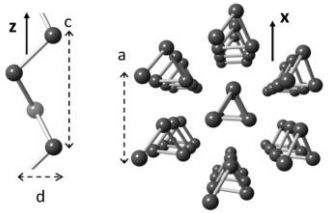
How does chirality interact with spin?

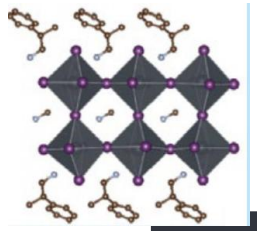
- Where is the strong SOC from?
- Why is the polarization so high?

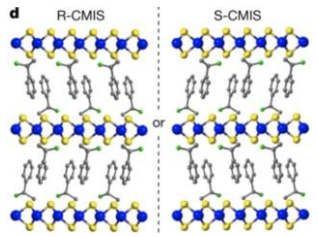
CISS in different aspects

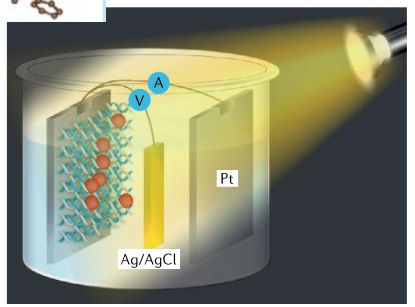










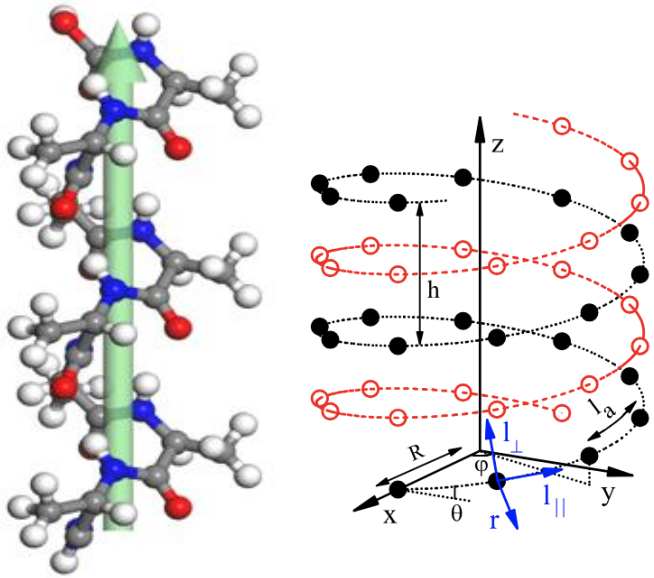


	Photoemission	Magnetoresistance	Enantiomer separation	Water splitting

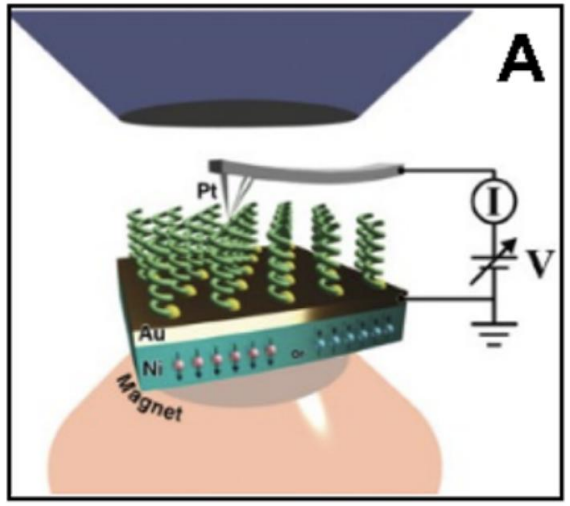
Detection	Magnetization	Resistance	Adsorption speed	O_2 generation efficiency
Metal Contacts	Au, Ag, Cu, Si, Al	Au, Pt Ni+Au, Co+Au	Ni+Au, Co+Au	Pt, F-TiO2

CISS works robustly at room temperature (RT).

CISS works for a zoo of chiral molecules (DNA, peptide, helicene etc) and even inorganic materials, where SOC < RT.



Where is the strong SOC from?



REVIEW 2022
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Theory of Chirality Induced Spin Selectivity: Progress and Challenges

Ferdinand Evers, Amnon Aharony, Nir Bar-Gill, Ora Entin-Wohlman, Per Hedegård, Oded Hod, Pavel Jelinek, Grzegorz Kamieniarz, Mikhail Lemeshko, Karen Michaeli, Vladimiro Mujica, Ron Naaman, Yossi Paltiel, Sivan Refaely-Abramson, Oren Tal, Jos Thijssen, Michael Thoss, Jan M. van Ruitenbeek, Latha Venkataraman, David H. Waldeck, Binghai Yan, and Leeor Kronik**

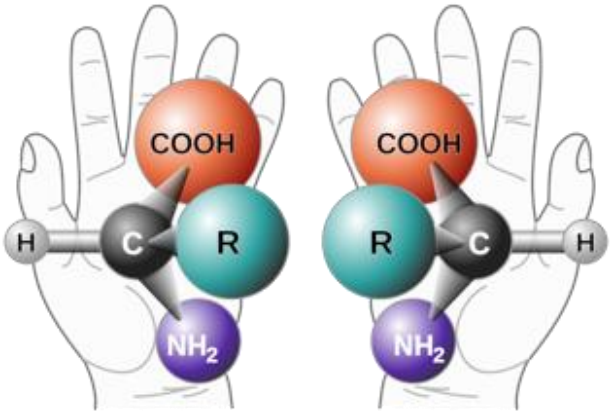
Enhance SOC in chiral molecules

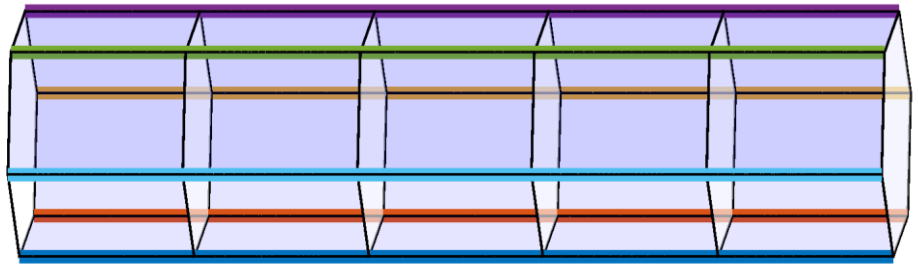
- Strong correlation
- Electron-phonon interaction
- Beyond Born-Oppenheimer
- Effect of the nuclei
- ……

Electrode serves SOC?

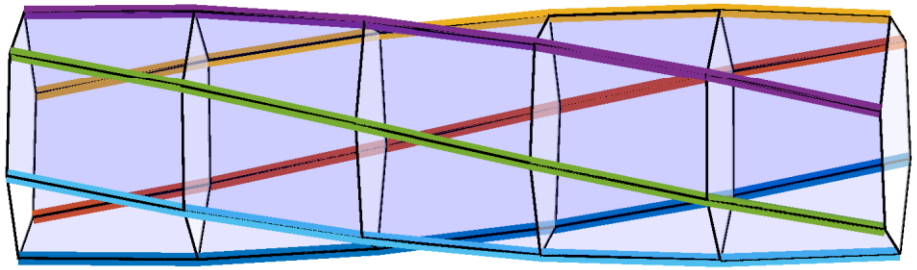
-- What does chirality do?

How do electrons feel chirality?





Particle in a box

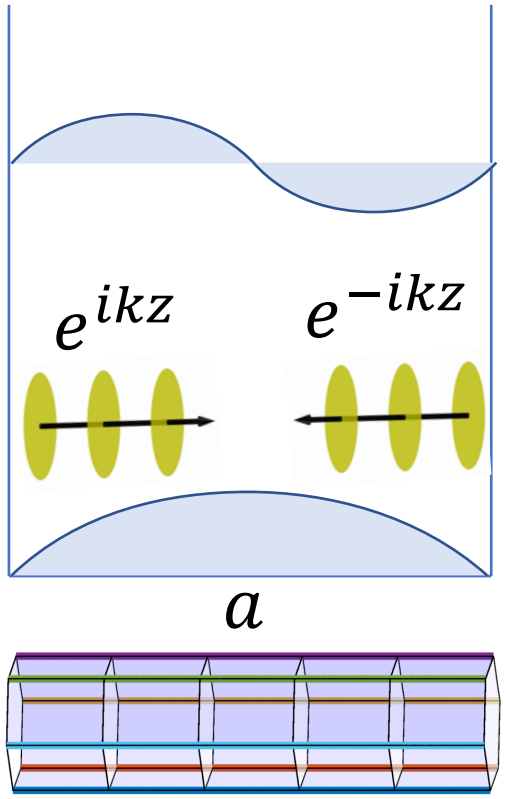


Particle in a chiral box

Particle in a box

$$\cos(kz) = \frac{1}{2}(e^{ikz} + e^{-ikz})$$

$$k = \pi/a$$



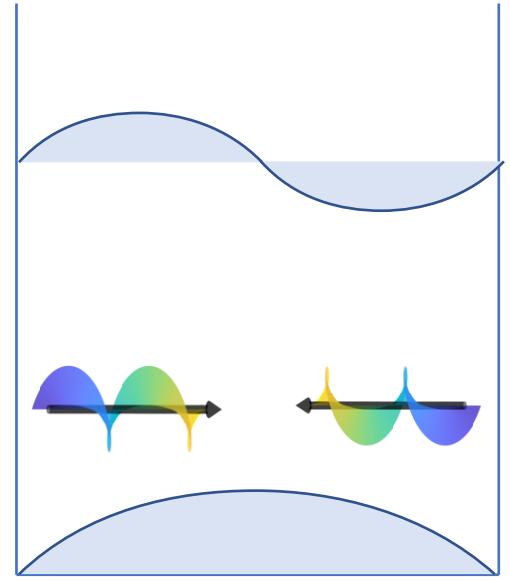
	Momentum
ψ^+	$+k$
ψ^-	$-k$
$\psi = \psi^+ + \psi^-$	0

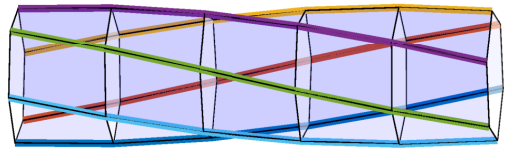
Particle in a chiral box

$$\cos(kz + \boldsymbol{l}\varphi) = ½$$

$$(e^{ikz}e^{il\varphi} + e^{-ikz}e^{-il\varphi})$$

$\boldsymbol{l}$ *is* Orbital angular momentum





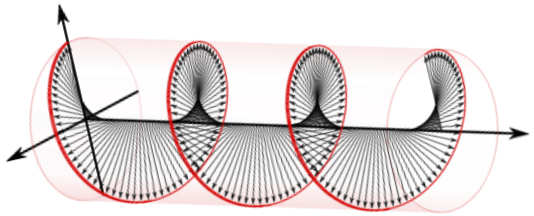
	Momentum	Orbital
ψ^+	$+k$	$+l$
ψ^-	$-k$	$-l$
$\psi = \psi^+ + \psi^-$	0	0

Orbital-momentum locking

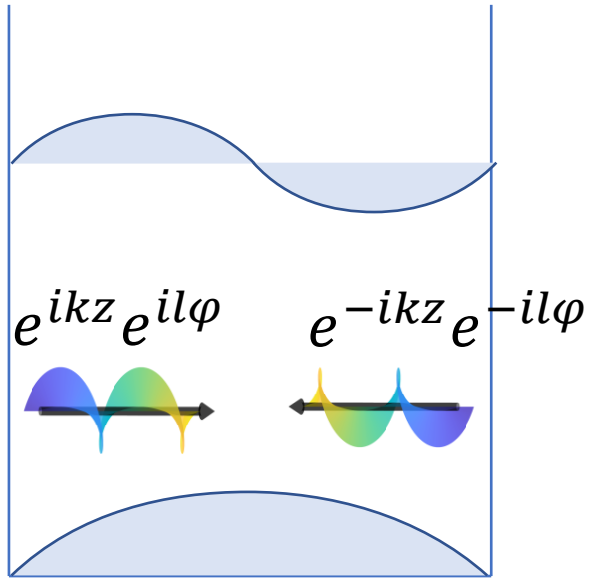
Chiral geometry leads to **electronic chirality**:

$k||l$ (right handed)

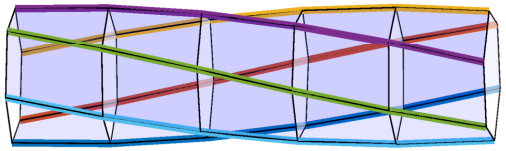
$-k||l$ (left handed)



Similar to CP light



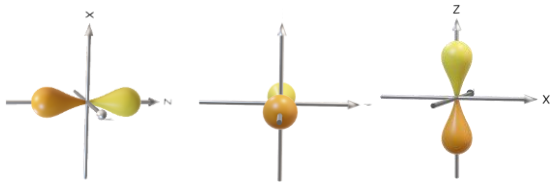
a



χ

Orbital Angular Momentum (OAM)

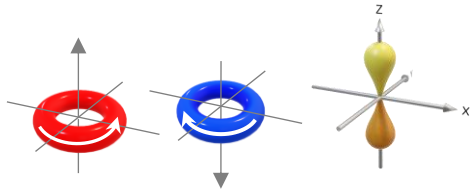
p_x, p_y, p_z



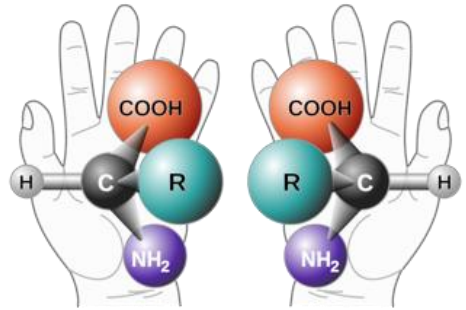
$p_x + ip_y$

$p_x - ip_y$

p_z



$l_z = +1$ $l_z = -1$ $l_z = 0$

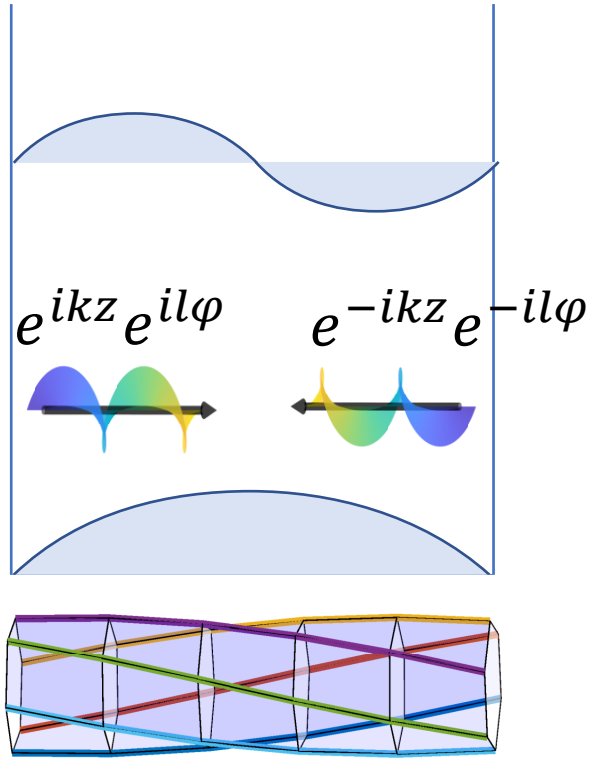


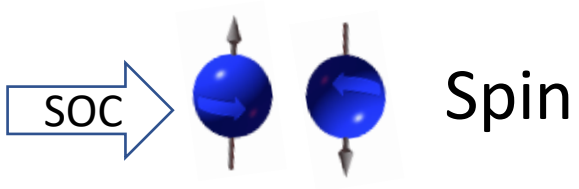
Not limited to a helical structure

Time-reversal $l(k) = -l(-k)$

Only require inversion-breaking

Detect the electronic chirality

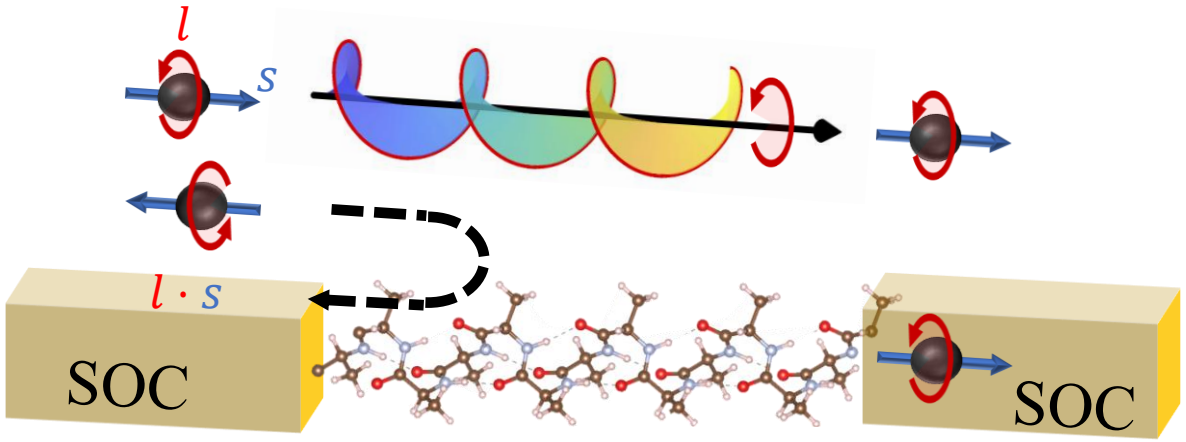




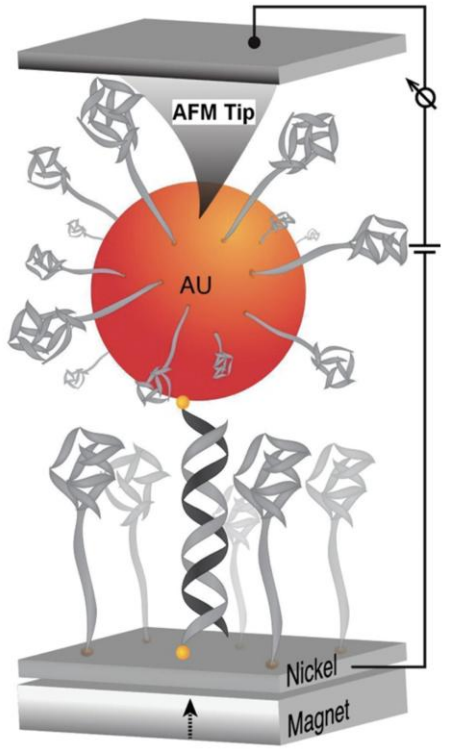
Chiral state 1 + (–1) = 0

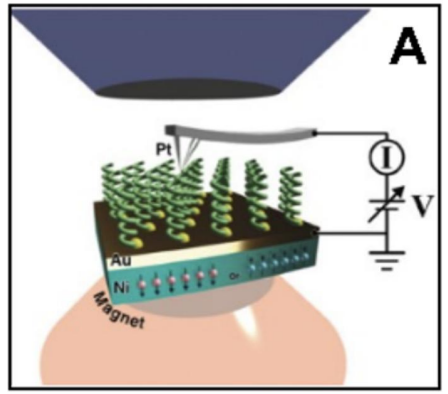
Achiral state 0 + 0 = 0

CISS magnetoresistance



Orbital/spin filter

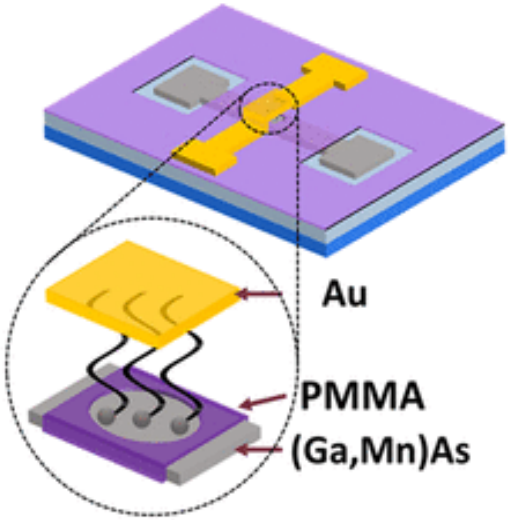


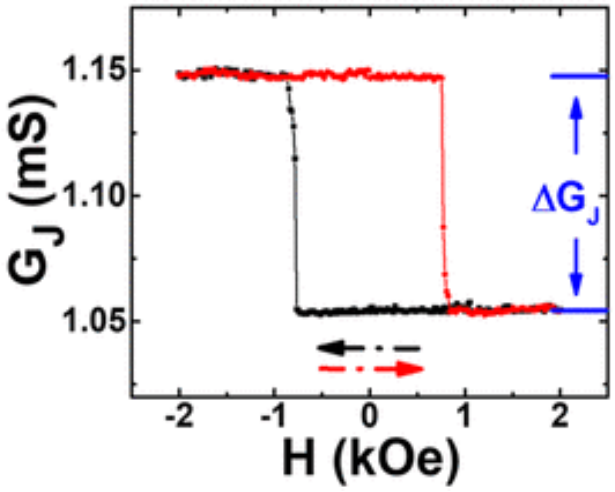


Y. Liu, J. Xiao, J. Koo and B. Yan, Nature Mater. **20**, 638 (2021)

Experiment verification?

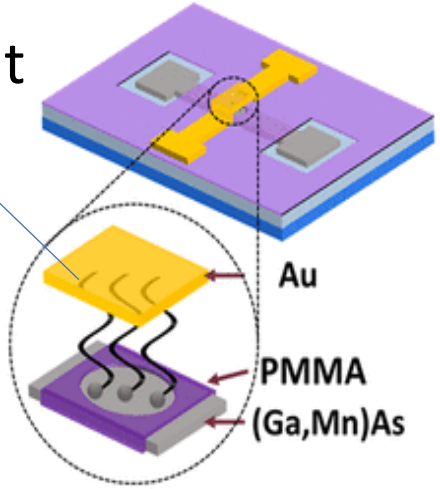
Peng Xiong (Florida)





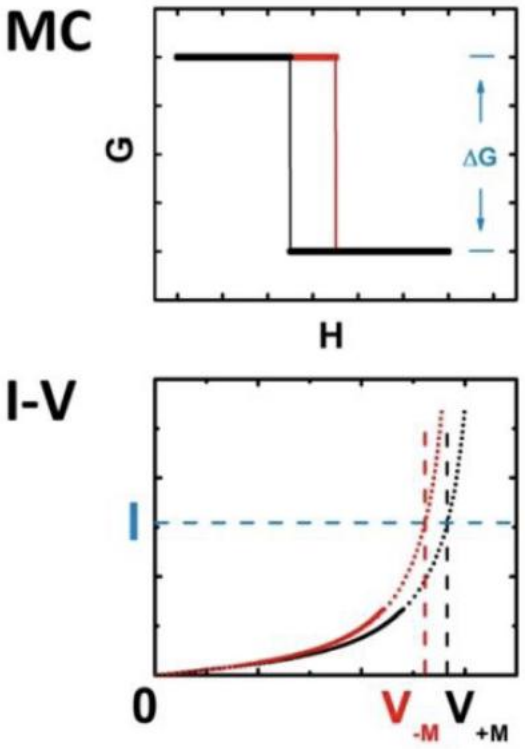
New experiment

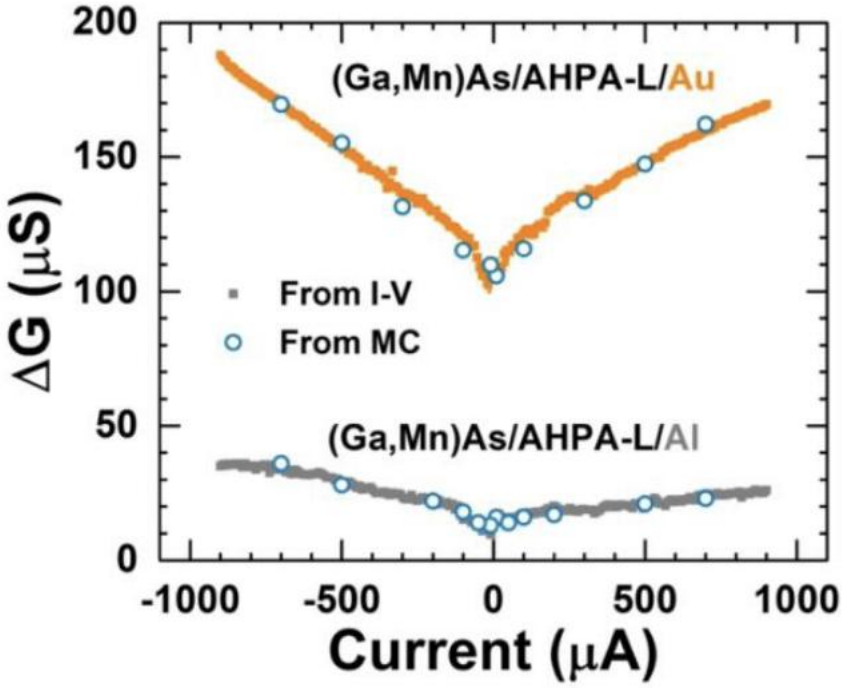
Au vs Al

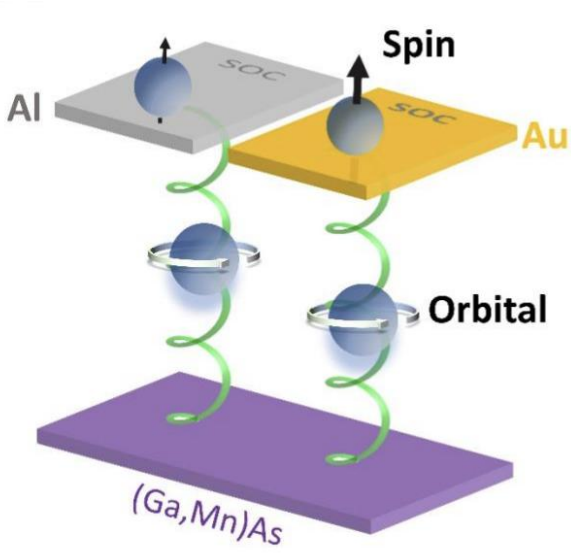


T. Liu, P. Xiong et al. ACS Nano 14, 15983 (2020)

Experiment verification



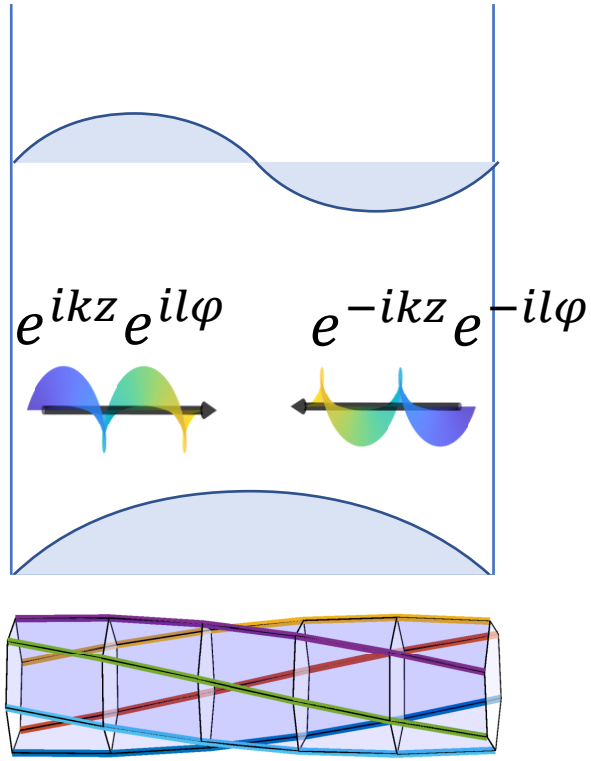


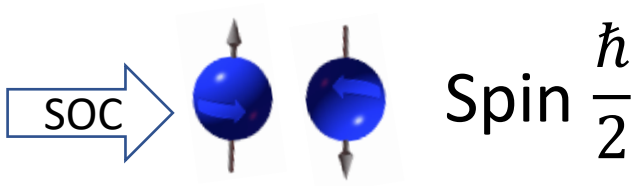


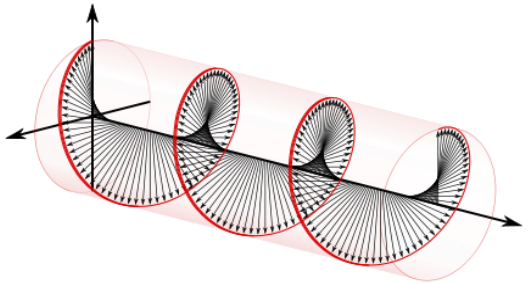
Electrode tunes the magnetocondutance by SOC.

Y. Adhikari, T. Liu, et al. Nat Commun 14, 5163 (2023).

Detect the electronic chirality







Circuarly Polarized Light

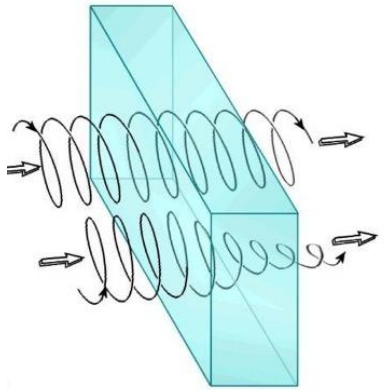
Chiral	**1 + (–1) = 0**
Achiral	**0 + 0 = 0**

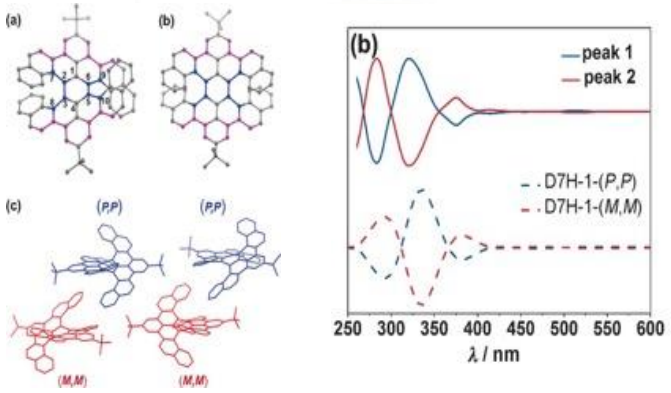
Chirality + CP light

Chiral materials selectively absorb or emit circularly polarized light (CPL)

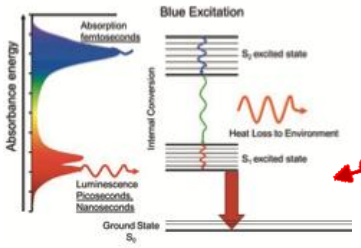
Adsorption

Circular Dichroism (CD)

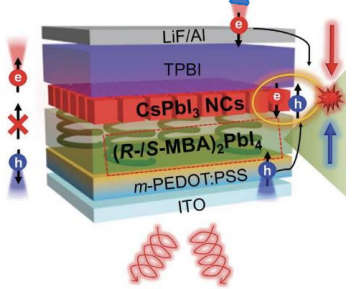




Luminescence of CPL



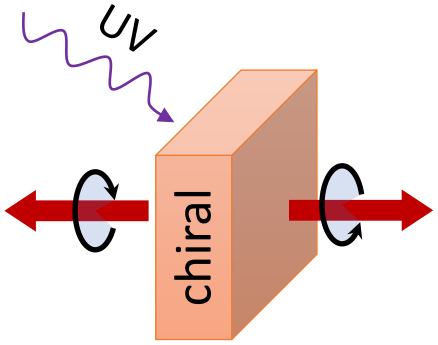
Photoluminescence (PL)

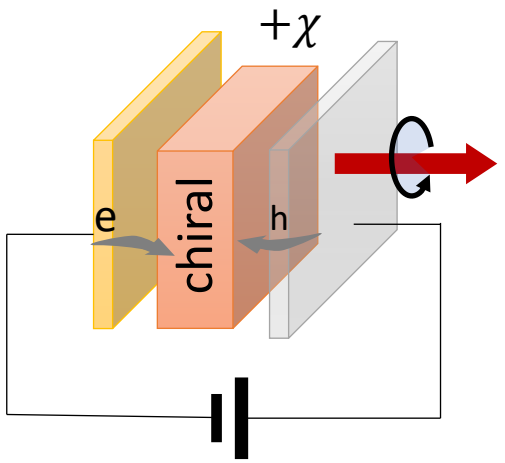


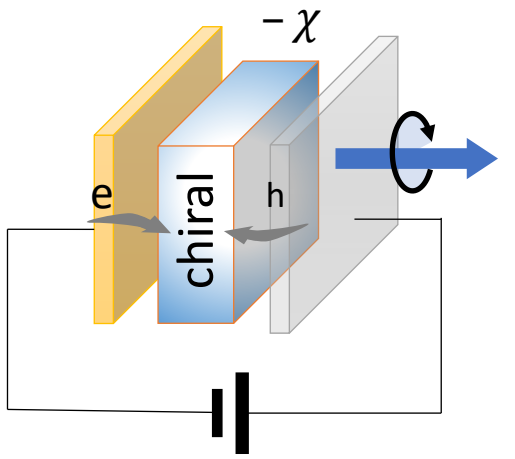
Electroluminescence (EL)

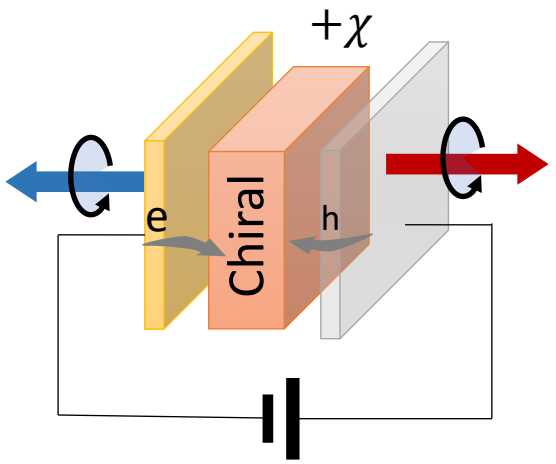
Kim et al Science 2021
2.6%

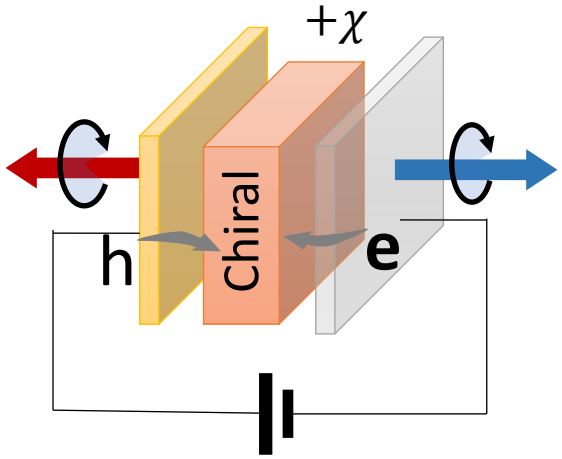
Known facts











Our work

Reserve current

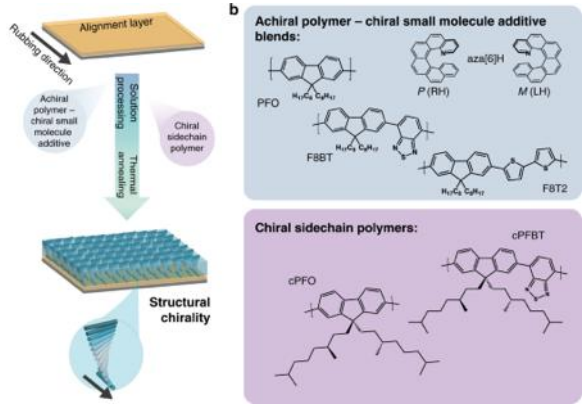
Circular polarized Electroluminescence (CP-EL)

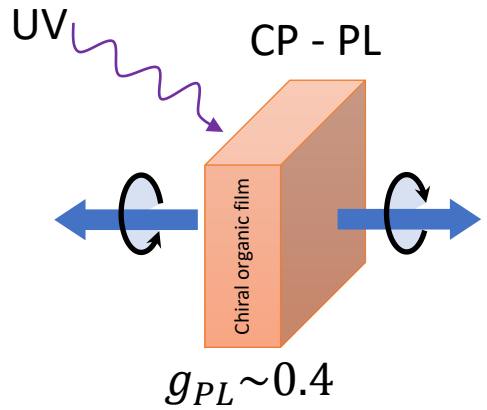
π-conjugated polymers

Li Wan

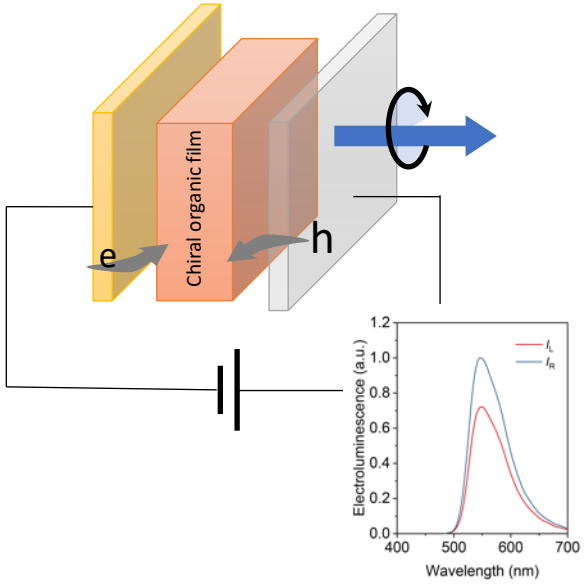
Matt Fuchter

Imperial College,
Linkoping Uni. / MPI-Halle

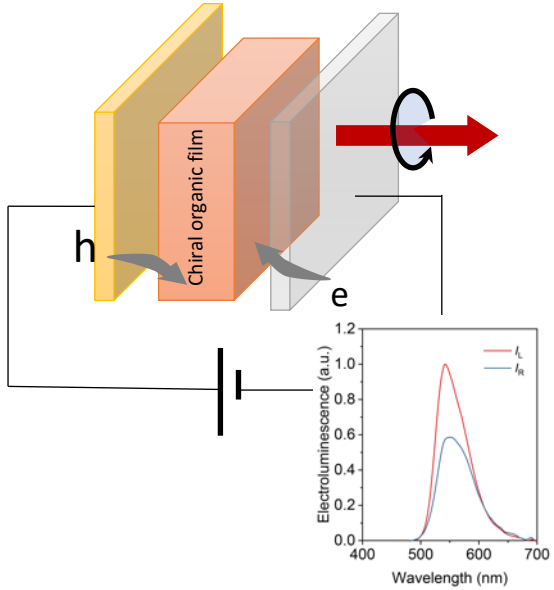


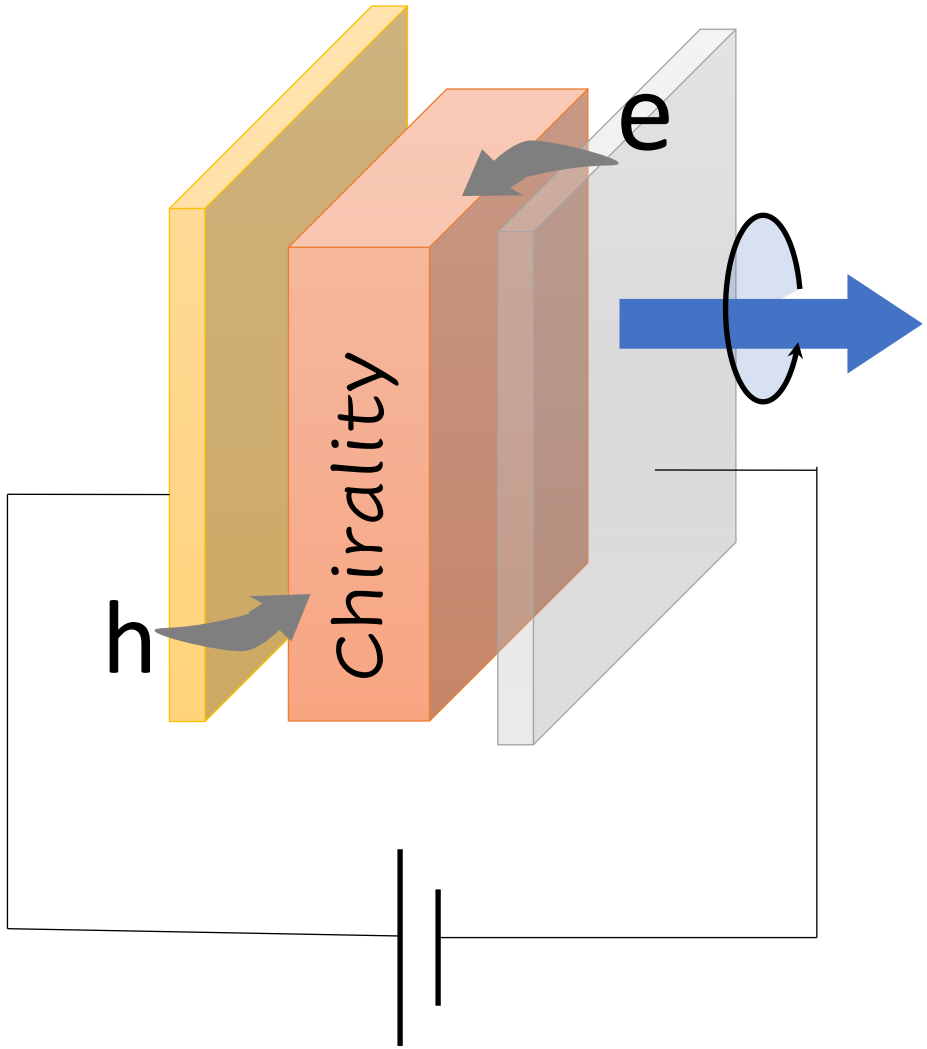


CP - EL

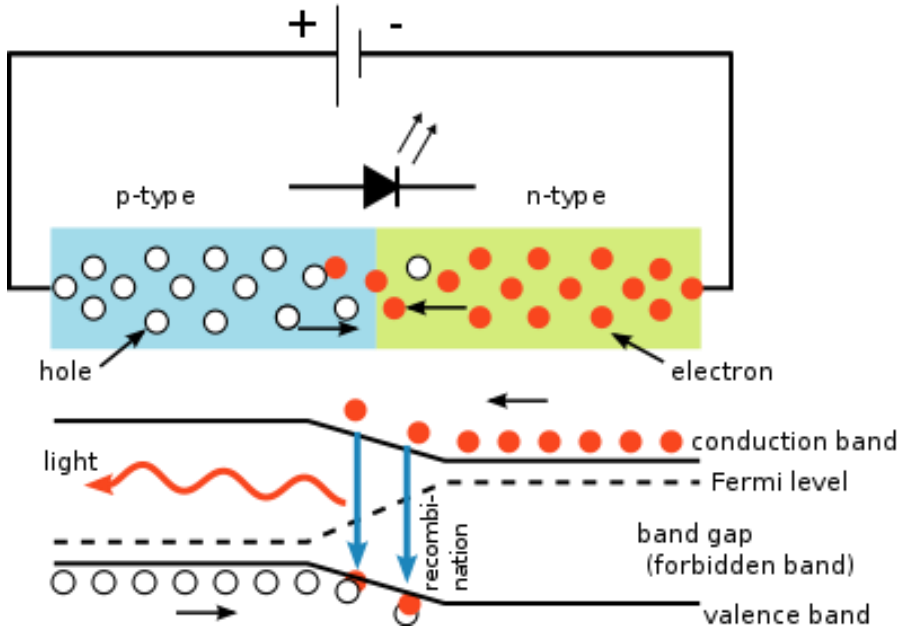


The same chiral film

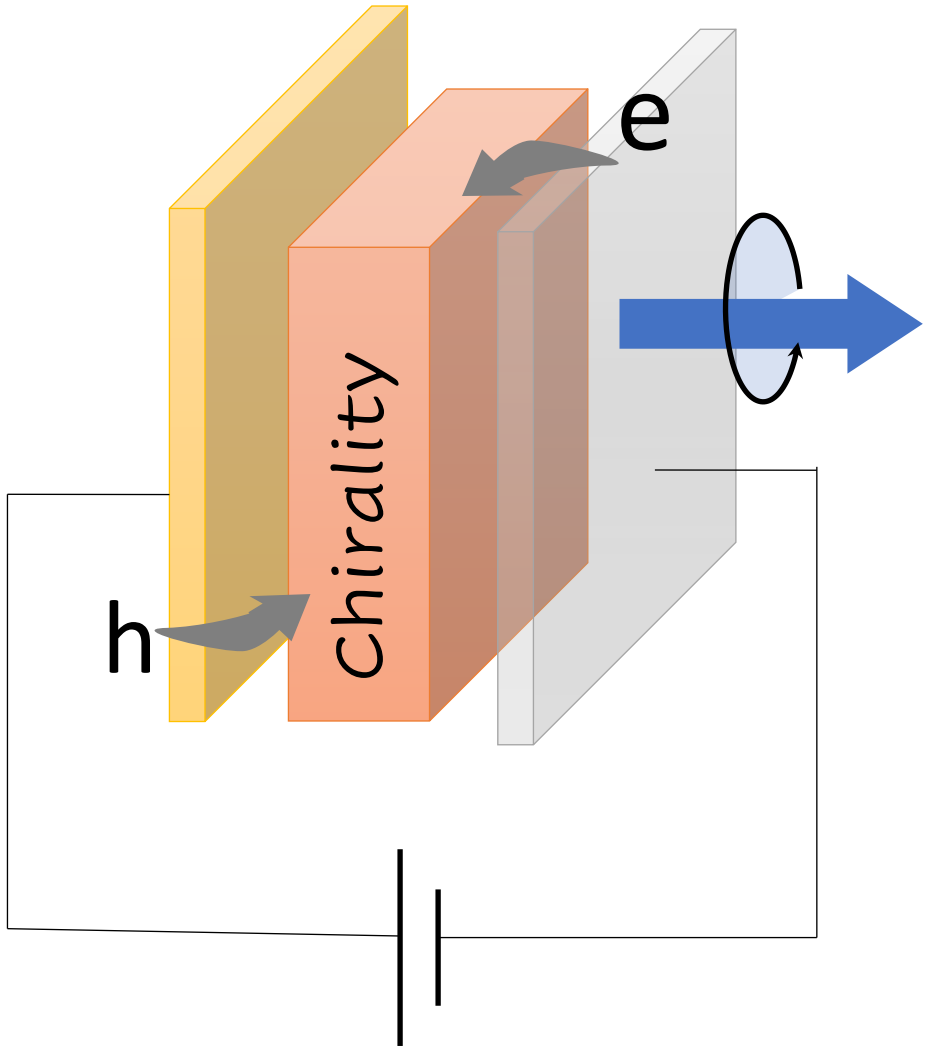


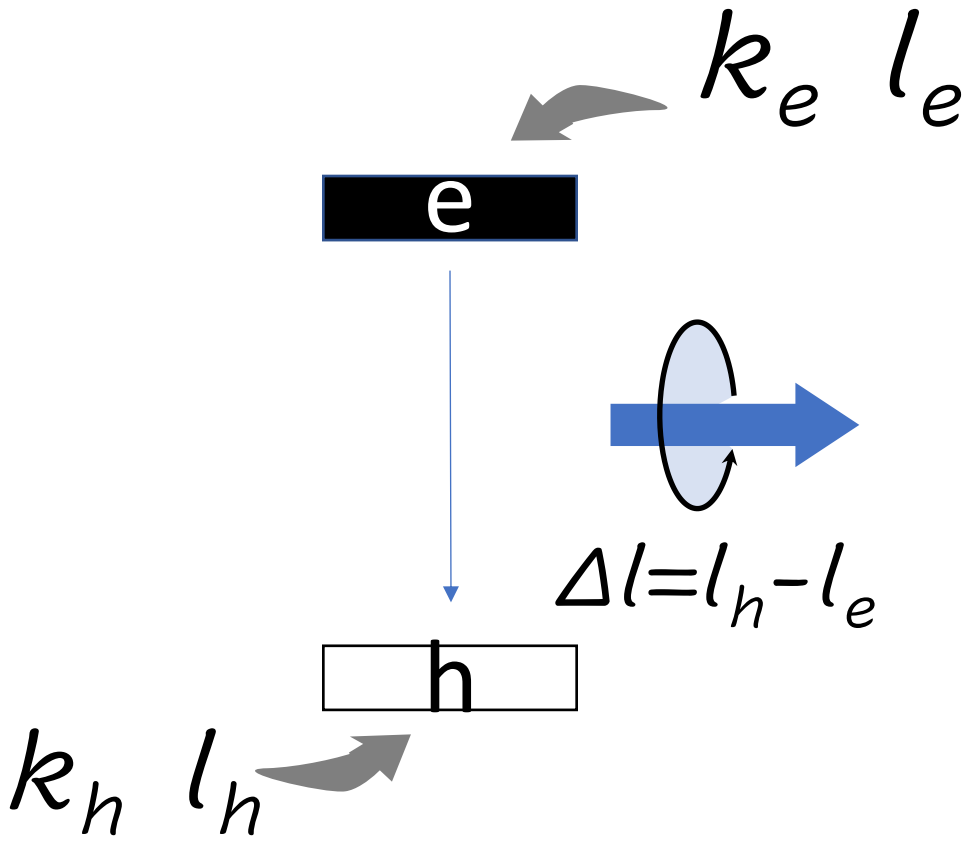


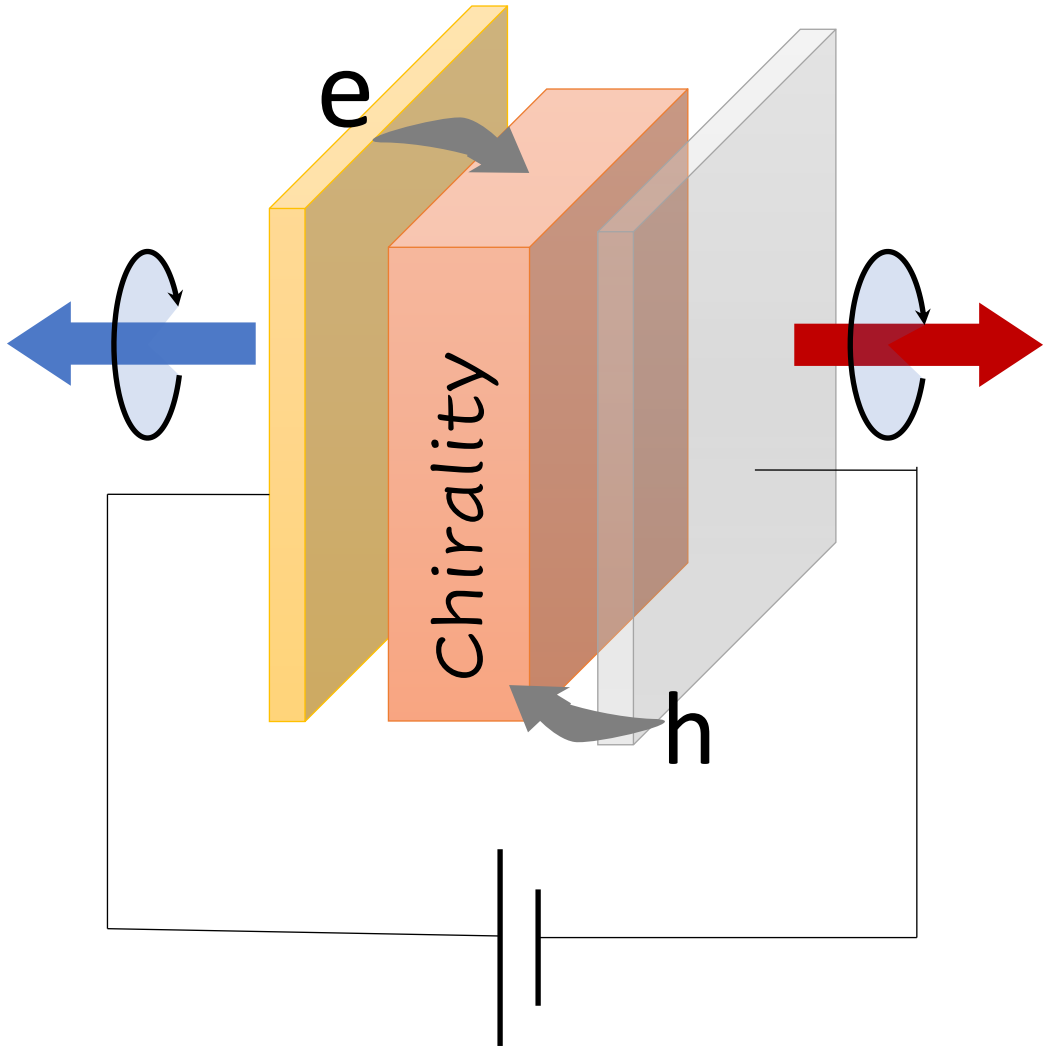
Solid state p-n junction LED



Orbital–momentum locking







Orbital–momentum locking

$-k_e\ -l_e$

e

$\Delta l=-(l_h-l_e)$

h

$-k_h\ -l_h$

Article | Published: 05 December 2022

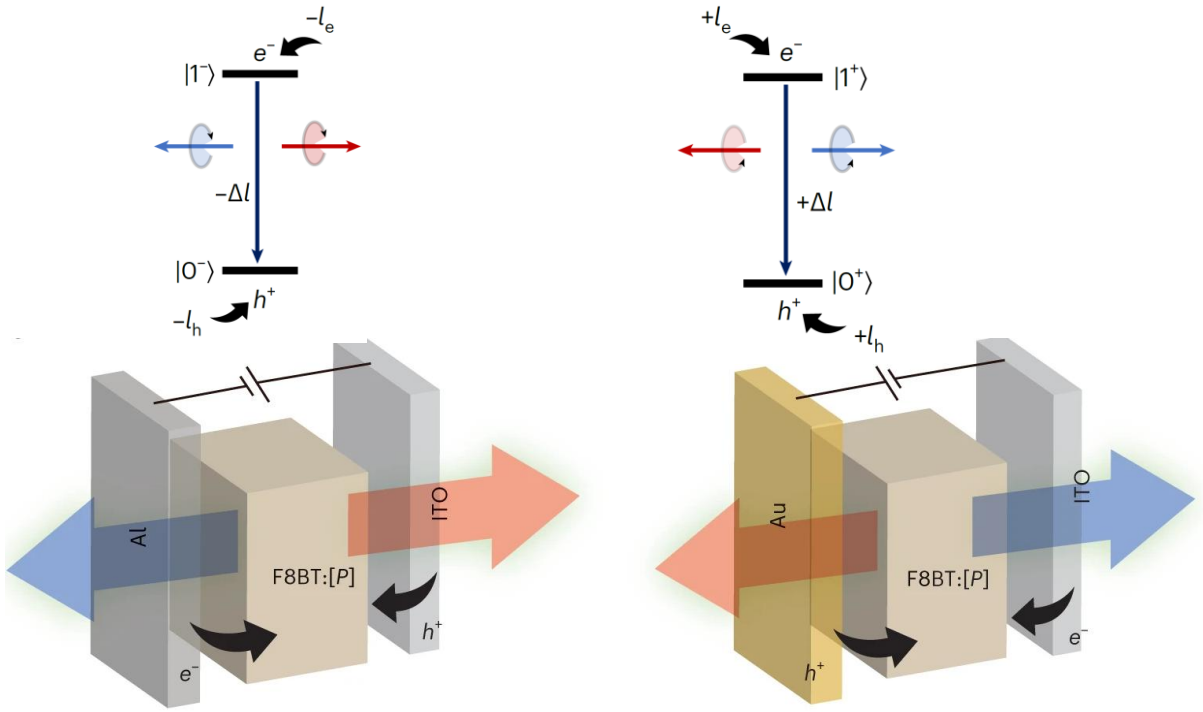
Anomalous circularly polarized light emission in organic light-emitting diodes caused by orbital–momentum locking

Li Wan, Yizhou Liu, Matthew J. Fuchter & Binghai Yan

Nature Photonics **17**, 193–199 (2023) | Cite this article

$$I_L - I_R = -\frac{2\pi e^2}{\hbar} I_0 \,\mathrm{Im}[x^{01}y^{10}]\delta - \frac{2\pi e}{\hbar c} I_0 \,\mathrm{Im}[m_x^{01}x^{10} + m_y^{01}y^{10}]\delta$$

Anomalous (Berry phase) ***Conventional***

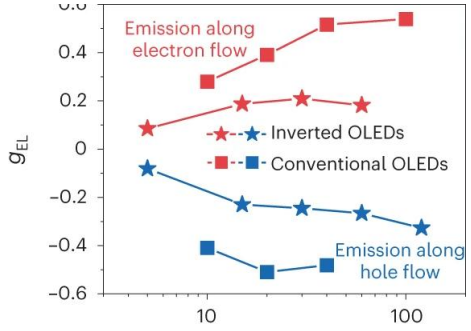


Generalization to inversion-breaking solids
(e.g., chiral crystals, TMD)

- Berry curvature dipole
- An inverse process of CPGE
- **Electric switch of CPL handedness (fast)**

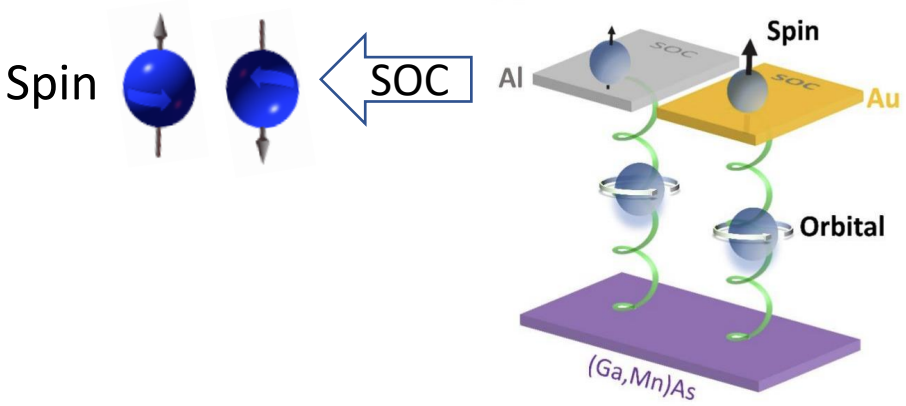
Y. Liu and B. Yan, PRB 2024

Experiment

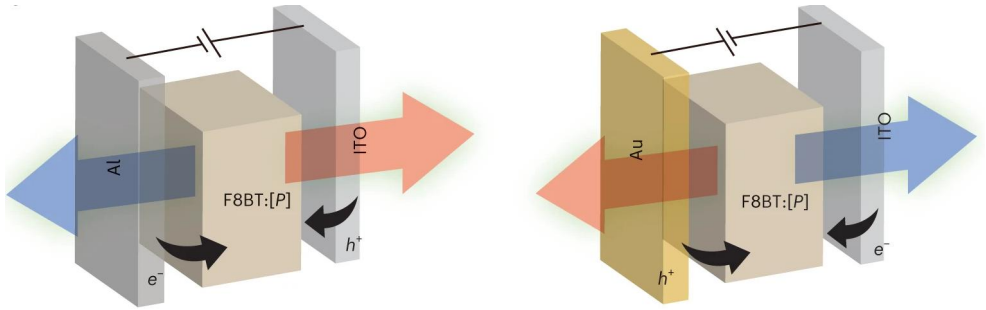


Summary

Chirality information transfers from geometry to electron orbital.
The orbital generates spin via SOC (e.g., in electrodes).
The orbital can be transfer to CP light.

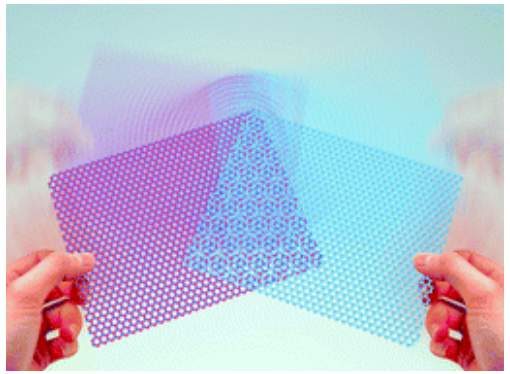


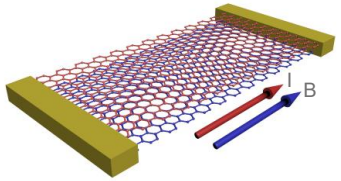
Spintronics

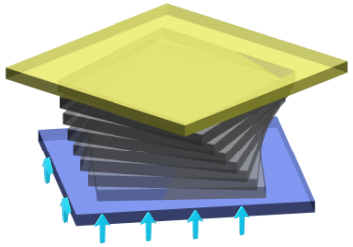


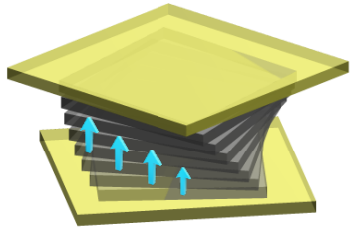
Optoelectronics

Outlook: Twisted vdW layers and chiral solids

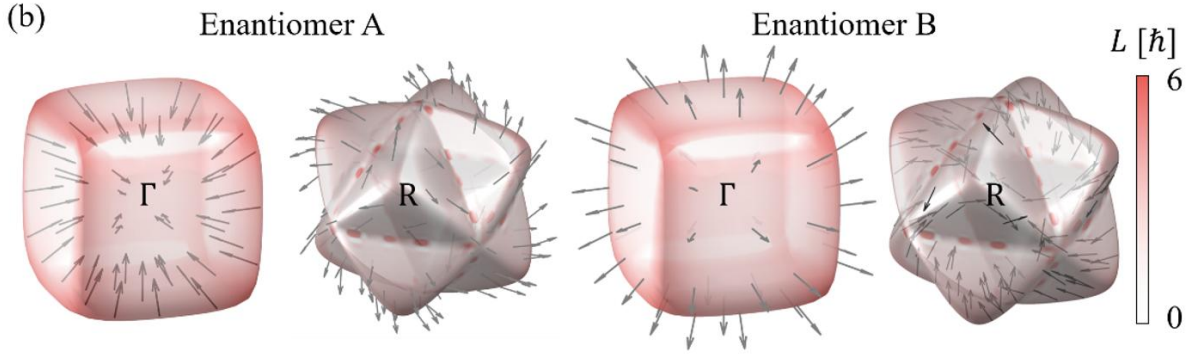


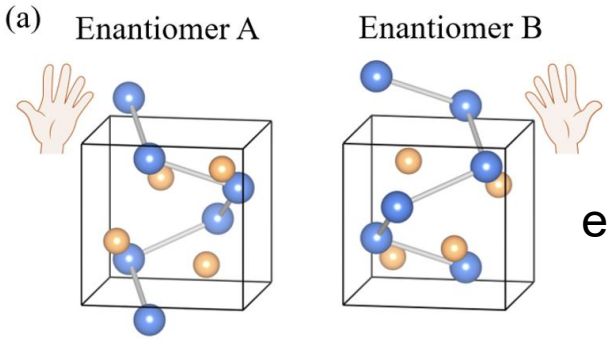






(a) (b)





e.g. RhSi and PdGa

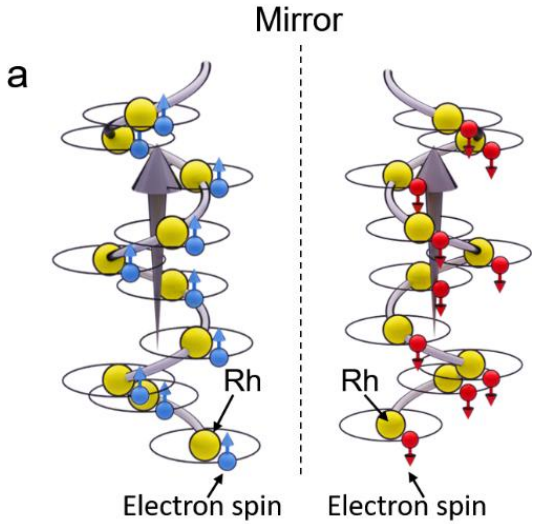
Y. Liu, T. Holder, B. Yan, The Innovation 2 (1), 100085 (2021)

J. Xiao, B. Yan, arXiv:2201.03623 (2022)

G. Menichetti, et al. arxiv:2312.09169 (2023)

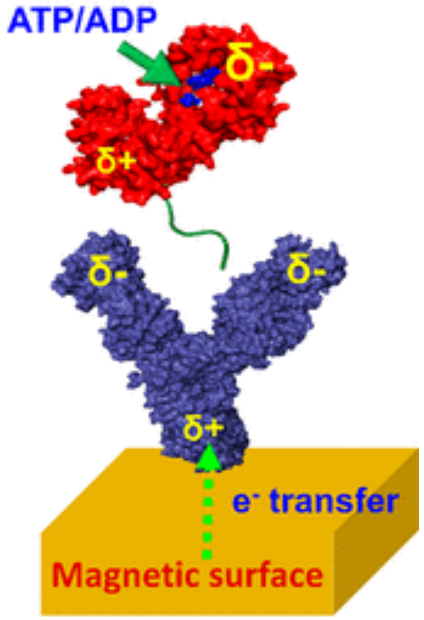
*Q. Yang, **B. Yan** et al PNAS (2023)*

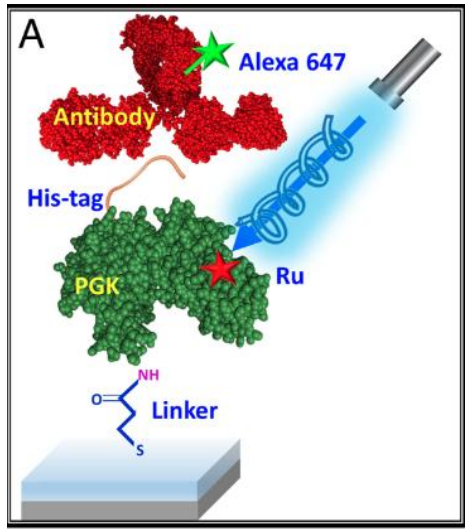
Outlook: chemistry and biology



Water splitting catalysis

Wang, **Yan**, et al. Nature Energy (under review)



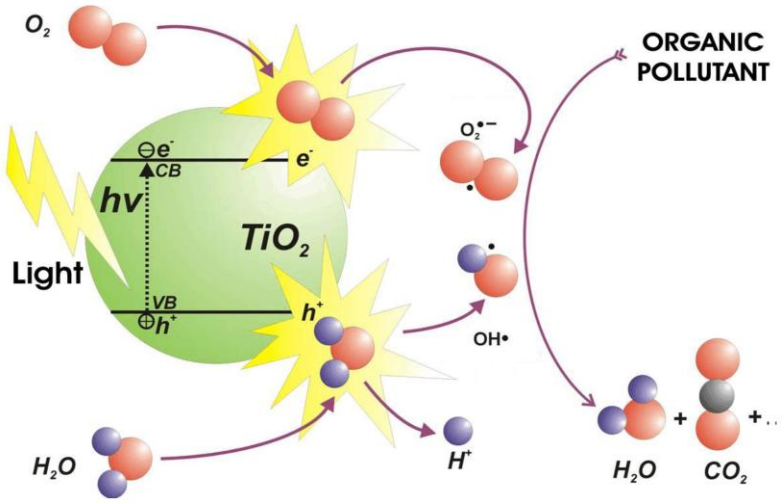


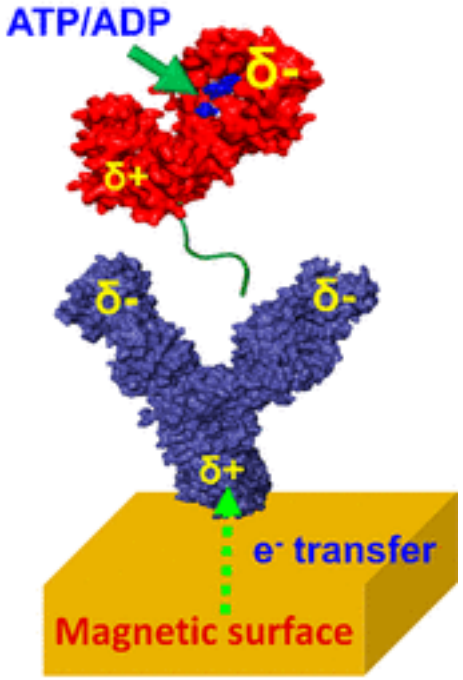
G. Haran, R. Namaan et al, PNAS (2022)

Control chemical/biological interactions by magnetism, or light.

Explore origin of life.

Dynamics in chemistry and biology





Control via magnetic field, magnetism, or CP light. Origin of life.

Acknowledgement

Experiment

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Theory

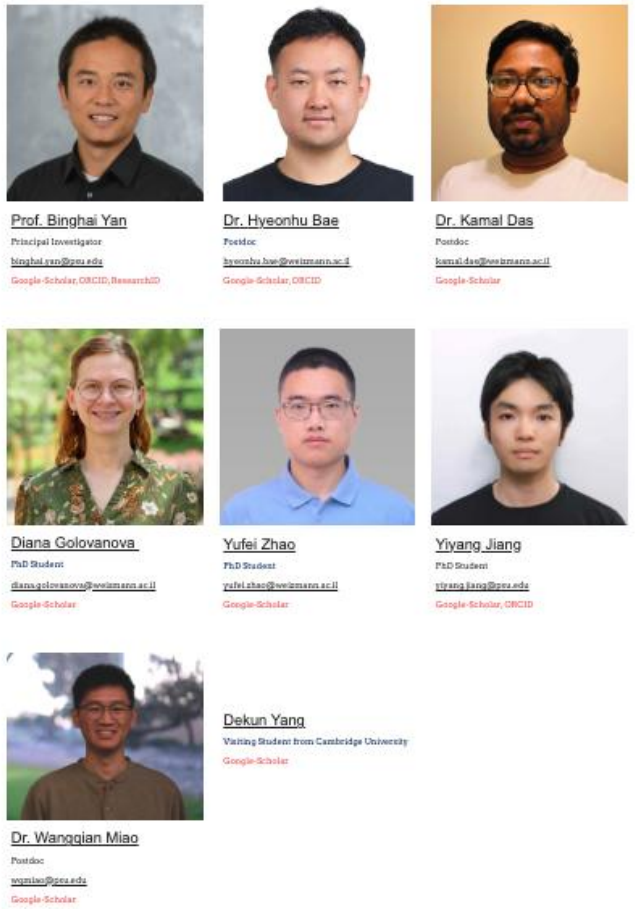
Noejung Park (UNIST)

Yuval Oreg (Weizmann)

Ady Stern (Weizmann)

Zhong Wang (Tsinghua)

Kai Sun (Michigan)



Thanks for your attention!

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