Ising superconductivity in gated MoS2

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17.12.15

Evidence for two-dimensional Ising superconductivity in gated MoS_2

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(Science **350**, 1353, Dec. 2015; Submitted Mar. 2015)

Ising pairing in superconducting $NbSe_2$ atomic layers

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(Nature Physics **12**, 139, Feb. 2016; Submitted Jul. 2015)

Superconductivity protected by spin–valley locking in ion-gated MoS_2

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(Nature Physics **12**, 144, Feb. 2016; Submitted Jun. 2015)

The group works on various kinds of two-dimensional materials and 2D interfaces. Briefly, we have three main research directions:

1) Quantum phase control and transport in 2D electronic systems

- J. M. Lu, O. Zheliuk, I. Leermakers, Noah F. Q. Yuan, U. Zeitler, K. T. Law, and J. T. Ye, "Two Dimensional Ising Superconductivity in Gated MoS2", ***Science*** DOI: 10.1126/science.aab2277 (express online, 2015)
- Y. Saito, Y. Nakamura, M. S. Bahramy, Y. Kohama, J. T. Ye, Y. Kasahara, et al. "Superconductivity protected by spin-valley locking in ion-gated MoS2", ***Nature Physics*** (in press)
- Y. Saito, Y. Kasahara*, J. T. Ye*, Y. Iwasa, T. Nojima, "Metallic Ground State in an Ion-gated Two-dimensional Superconductor", ***Science*** 350, 409 (2015). *equal contribution
- J. T. Ye, Y. J. Zhang, R. Akashi, etc. "Supercondcuting Dome in a Gate Tuned Band Insulator", ***Science*** 338 1193 (2012).
- J. T. Ye, S. Inoue, K. Kobayashi, etc. "Liquid-gated interface superconductivity on an atomically flat film", ***Nature Materials*** 9, 125 (2010).

2) Optical properties of 2D materials

- Y. J. Zhang, T. Oka, R. Suzuki, J. T. Ye, and Y. Iwasa, "Electrically Switchable Chiral Light-Emitting Transistor", ***Science*** 344, 725 (2014).
- Y. J. Zhang, J. T. Ye, Y. Yomogida, T. Takenobu, and Y. Iwasa "Formation of a Stable p–n Junction in a Liquid-Gated MoS2 Ambipolar Transistor", ***Nano Lett.*** 13 3023 (2013).
- Y. J. Zhang, J. T. Ye, Y. Matsuhashi, etc. "Ambipolar Transistor of thin flake MoS2", ***Nano Lett.*** 12 1136 (2012).

3) Field effect control of magnetism

- J. G. Checkelsky, J. T. Ye, Y. Onose, Y. Iwasa and Y. Tokura "Dirac-fermion-mediated ferromagnetism in a topological insulator", ***Nature Physics*** 8 729 (2012).

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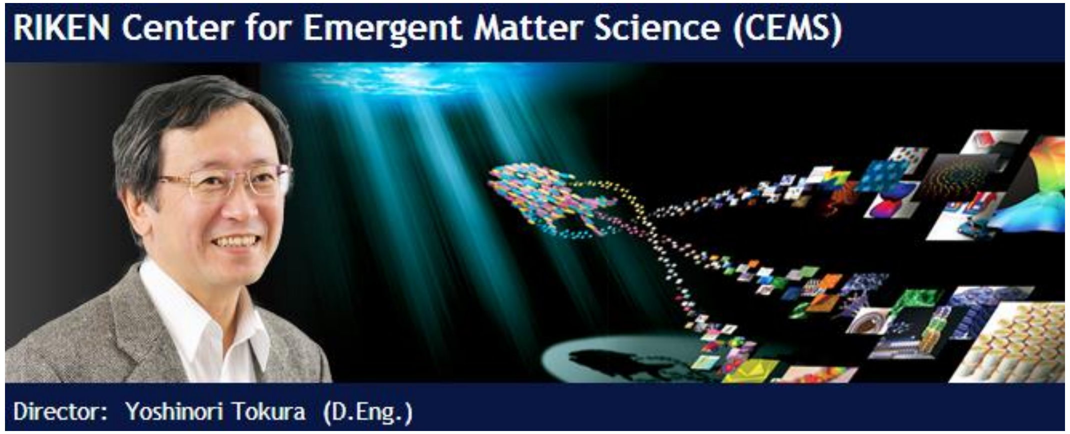

RIKEN Center for Emergent Matter Science

Emergent Device Research Team

Team Leader: Yoshihiro Iwasa (D.Eng.)

Main Research Field

Physics

Related Research Fields

Engineering / Materials Sciences

Research Subjects

- Field Effect Phase Control and its Applications
- Fabrication and Properties of Organic-Inorganic Interfaces
- Topological quantum transport

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"Evidence for two-dimensional Ising superconductivity in gated MoS2"
J. M. Lu, O. Zheliuk, I. Leermakers, N. F. Q. Yuan, U. Zeitler, K. T. Law, J. T. Ye, Science (2015), DOI:10.1126/science.aab2277.

"Ising pairing in superconducting NbSe2 atomic layers"
X. Xi, Z. Wang, W. Zhao, J-H Park, K. T. Law, H. Berger, L. Forró, J. Shan and K. F. Mak, Nature Physics (2015), DOI:10.1038/nphys3538.

"Possible Topological Superconducting Phases of MoS$_{2}$"
Noah F.Q. Yuan, Kin Fai Mak and K. T. Law, Phys. Rev. Lett. 113, 097001 (2014).

"Non-Abelian Majorana Doublets in Time-Reversal Invariant Topological Superconductor"
Xiong-Jun Liu, Chris L. M. Wong, K. T. Law, Phys. Rev. X **4**, 021018 (2014).

"Majorana Fermion Induced Selective Equal Spin Andreev Reflections"
James J. He, T. K. Ng, Patrick A. Lee and K. T. Law, Phys. Rev. Lett. **112**, 037001 (2014).

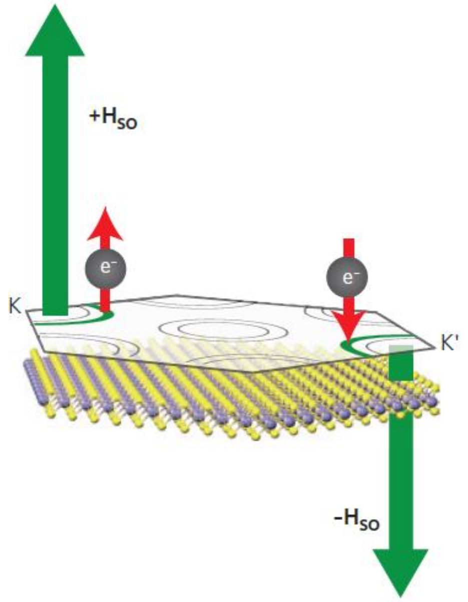
- **Background**

Ising superconductor (Zeeman-protected superconductor):

- Intrinsic spin-orbit coupling induced effective Zeeman field with opposite directions in opposite corners (K, -K) locks the spins of Cooper pairs in an Ising-like fashion.

- Effective Zeeman field prevents the alignment of the spin to in-plane magnetic fields and hence protects the superconducting state.

- In-plane critical field H_{c2} far beyond the Pauli paramagnetic limit.



Pauli limit:

- Pauli (spin) paramagnetic mechanisms
- Pauli limit (Clogston-Chandrasekhar limit, 1962): Consider the free energy of a BCS-type bulk superconductor and ignore the presence of any orbital paramagnetism. Compare the free energy decrease due to spin paramagnetism $\frac{1}{2}\chi_p H_0^2 = \mu_B^2 N(0) H_0^2$ (g factor is assumed to be 2 here), and that due to Cooper pairing $\frac{1}{2}N(0)\Delta^2(0)$. Finally, we get

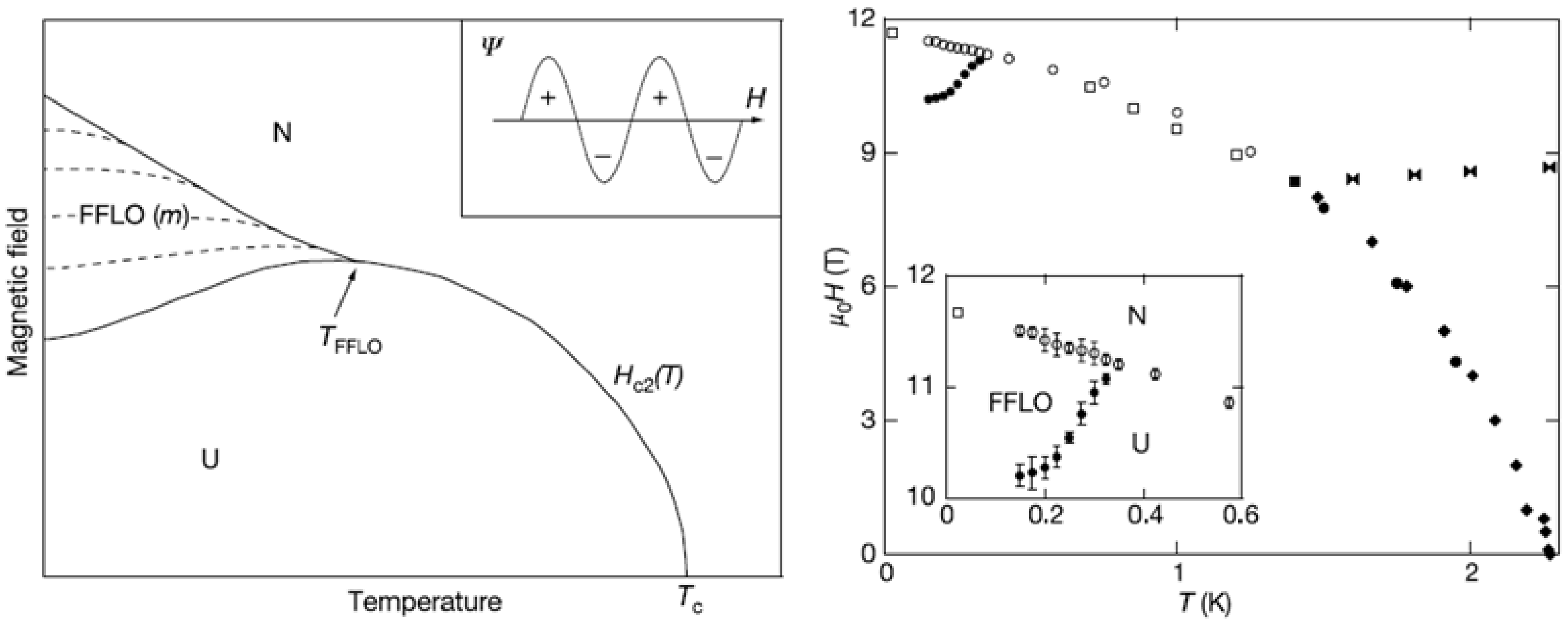
  $\mu_B H_0 = \frac{1}{\sqrt{2}}\Delta(0)$, or $H_0 = 1.84\ T_c$ (T).
- Kats (1970) suggested that for fields parallel to the layers, $H_{c2//}$ might be limited by the Pauli paramagnetic limit. However, Pauli limit can be surpassed in some superconducting systems.

In some superconductors, the Pauli limit can be surpassed.

$B_{c2} \Leftarrow B_p$

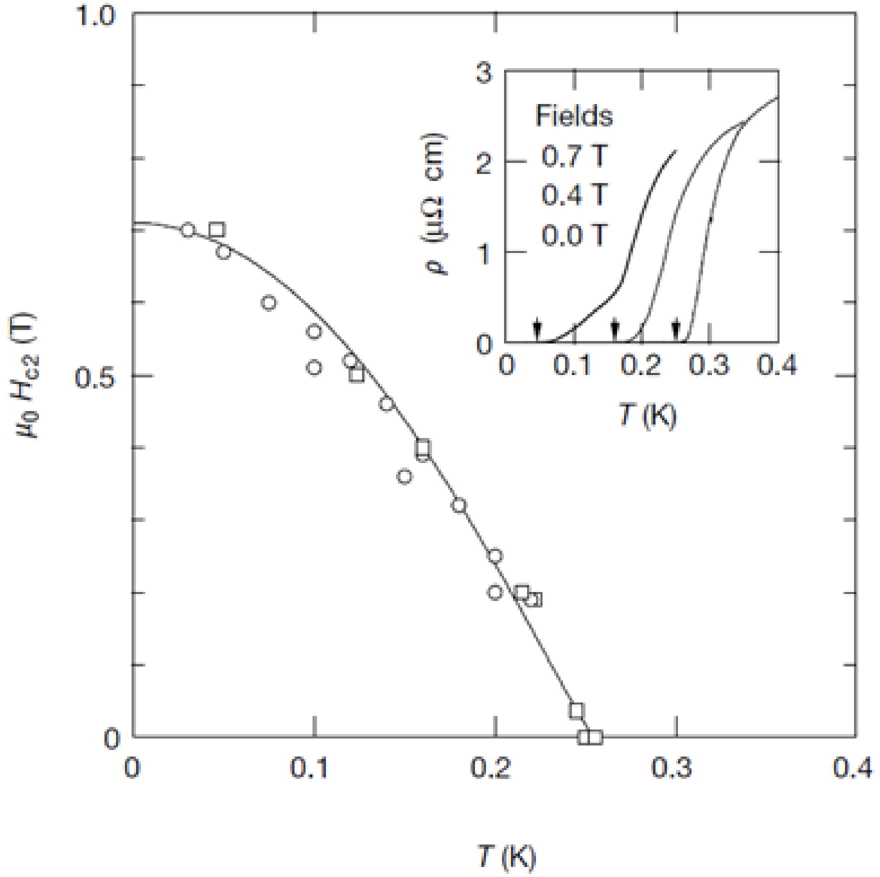
- Fulde-Ferrell-Larkin-Ovchinnikov state
- Spintriplet superconductor
- Spin-orbit scattering (SOS)
- Spin-orbit coupling (SOC)

- Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states (Cooper pairs are no longer formed by a pairing of spin-up and spin-down electrons carrying opposite momenta; instead, the superconducting order parameter carries a finite momentum, giving rise to an inhomogeneous superconducting state; Cooper pair density wave) (e.g., $CeCoIn_5$, Nature **425**, 51, 2003)



- Spin-triplet superconductors (e.g., URhGe, Nature **413**, 613, 2001)

the parallel-aligned spin configuration in Cooper pairs is not affected by Pauli paramagentism, and Bc2 can easily exceed Bp



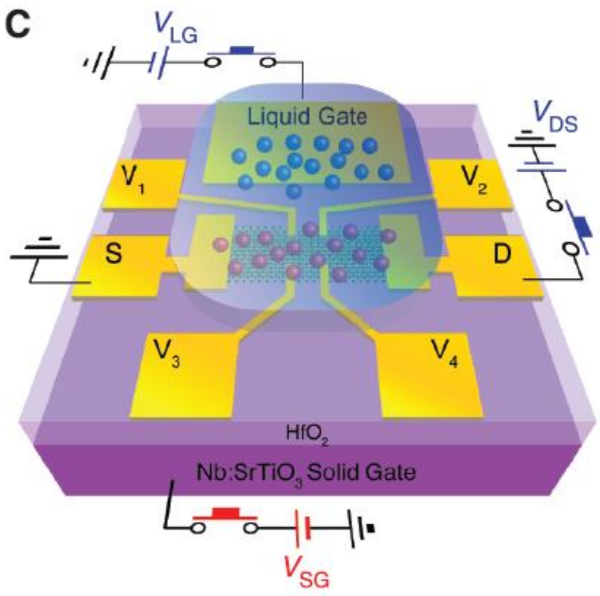
- Pauli limit may be greatly exceeded through spin-orbit scattering, which randomizes electron spins and thus weakens the spin paramagnetic effect.

- Several models have been developed to include the effects of Pauli spin paramagnetism and spin-orbit scattering, such as WHH theory and KLB theory.

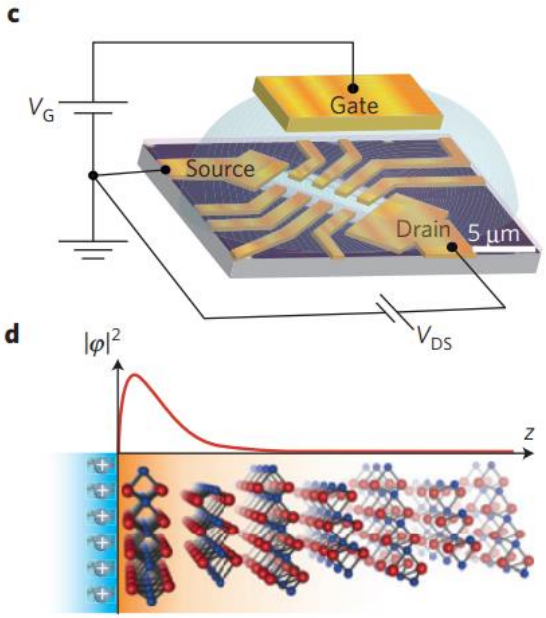
- **Device**

EDLT: electric double-layer transistors

- Ultra-high charge-carrier accumulation at the sample/electrolyte interface
- Carriers are induced electrostatically without introducing extrinsic disorder



Science **338**, 1193, 2012; Science **350**, 1353, 2015



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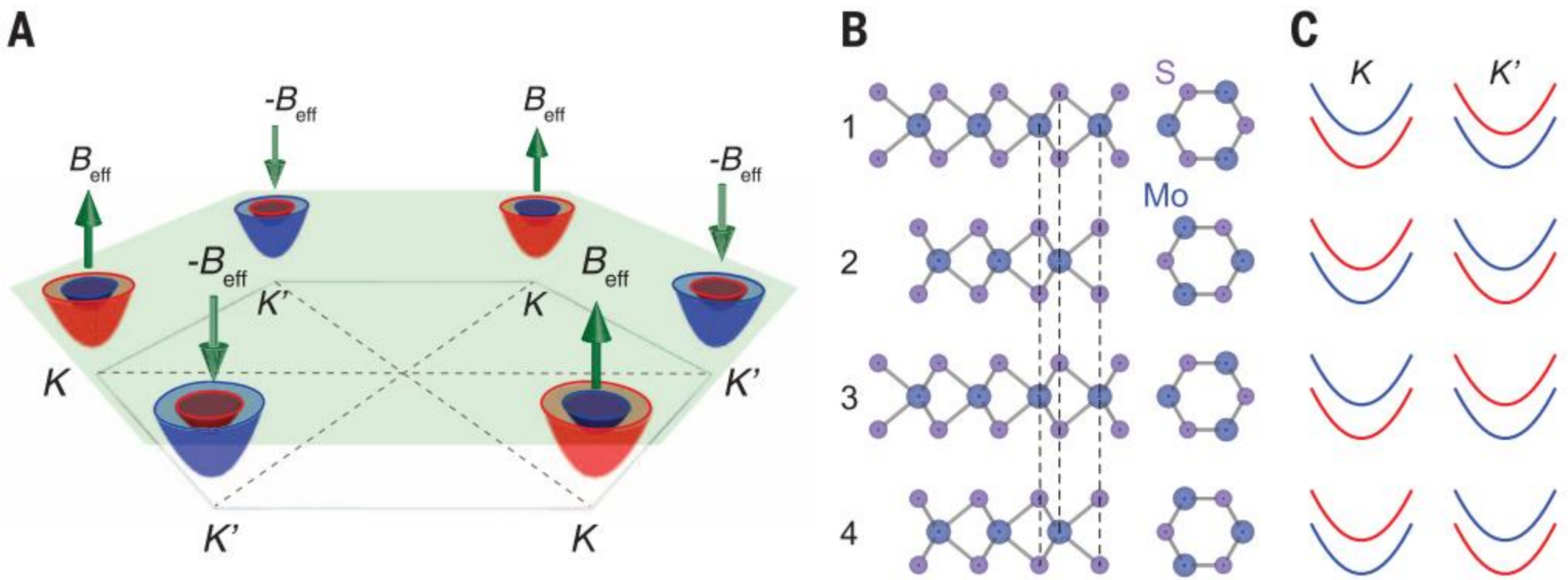
MoS_2

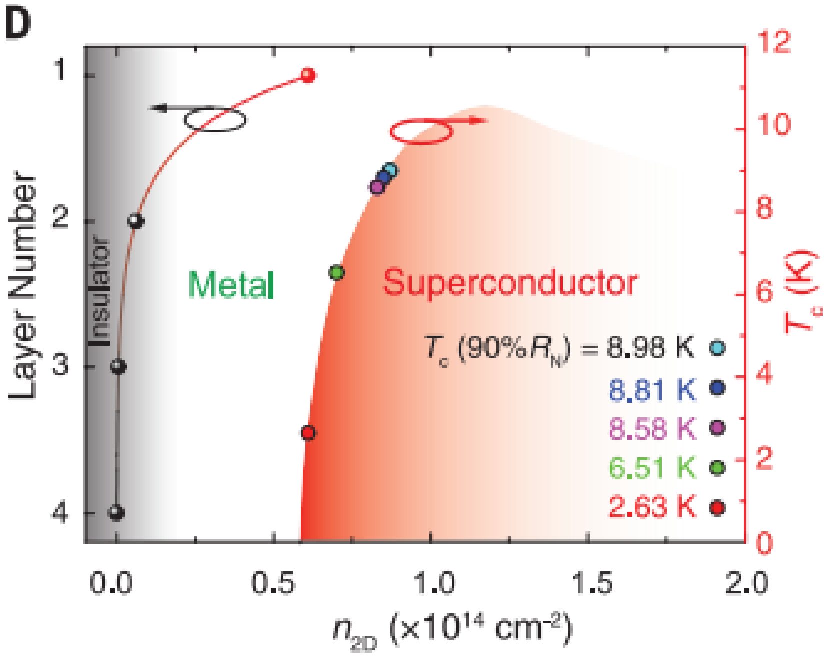


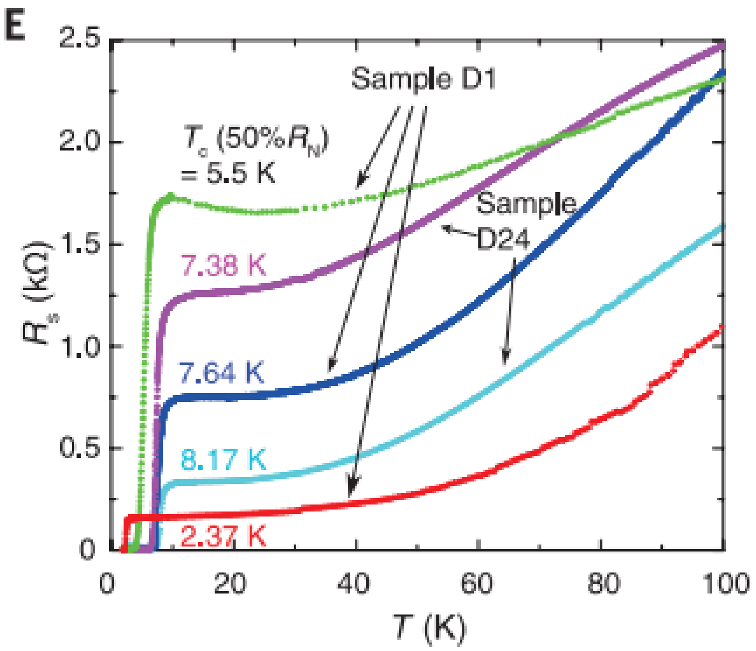
Science **338**, 1193, 2012; Science **350**, 1353, 2015

In-plane ISB in monolayer ⟹ SOC ⟹ B_{eff}

- **Measurement and Results**

n_{2D} of up to 10^{14} cm^{-2}





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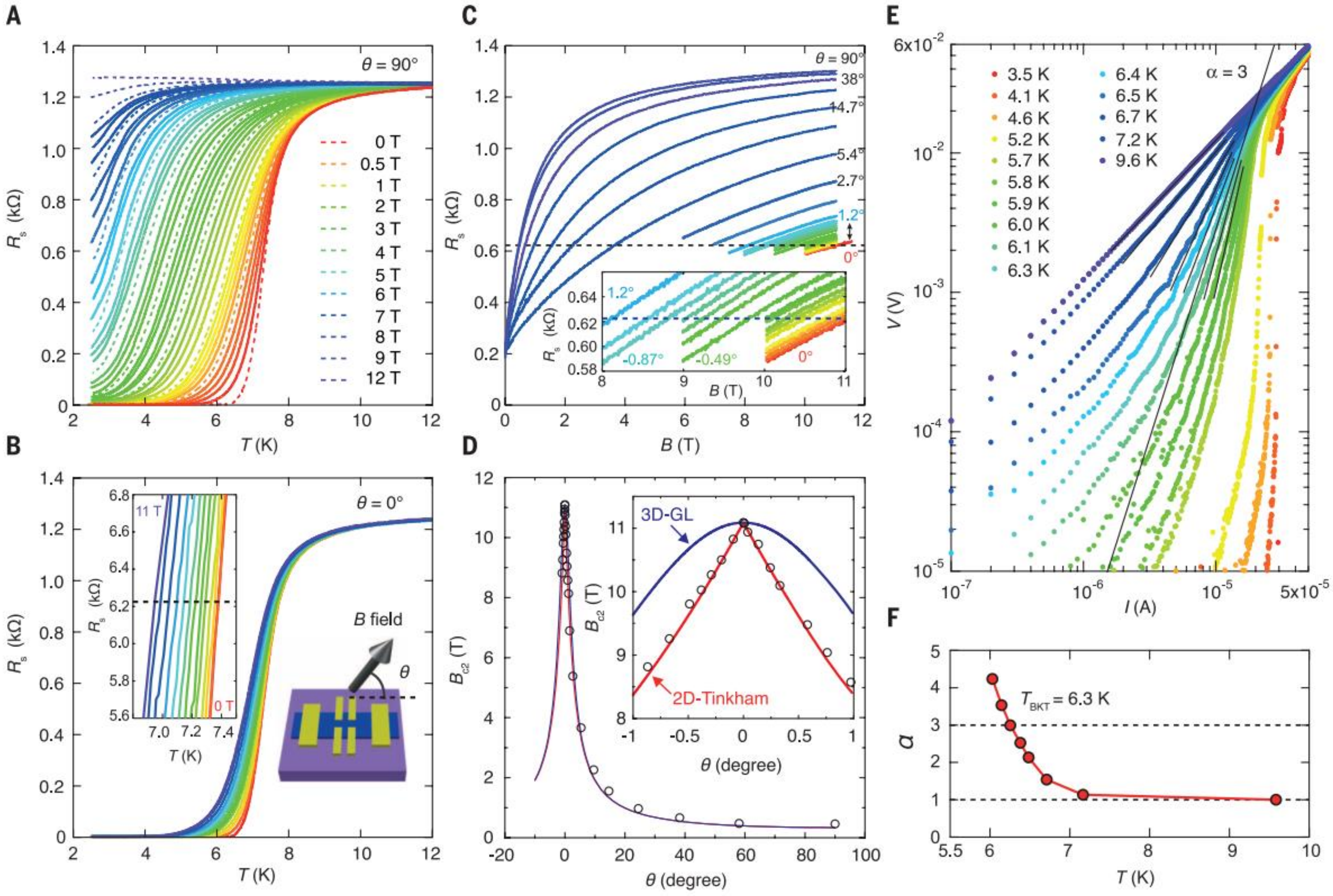


Science **338**, 1193, 2012; Science **350**, 1353, 2015

upper critical field of layered superconductors (or superconducting films)

- Orbital contributions: coupling between the magnetic field and the electron momentum (current loops, vortex)
- Anisotropic Ginzburg-Landau model (Lawrence and Doniach, 1970-71; adapted from M. Tinkham, Introduction to superconductivity)

Within the anisotropic GL approximation, the angular dependence interpolating H_{c2} between the limiting values given in (9.7) can be worked out by an anisotropic generalization of the harmonic oscillator calculation used in Sec. 4.8. The result is the simple ellipsoidal form:

$$\left(\frac{H_{c2}(\theta)\sin\theta}{H_{c2\|c}}\right)^2 + \left(\frac{H_{c2}(\theta)\cos\theta}{H_{c2\|ab}}\right)^2 = 1 \tag{9.9}$$

or, equivalently,

$$H_{c2}(\theta) = \frac{H_{c2\|ab}}{(\cos^2\theta + \gamma^2\sin^2\theta)^{1/2}} \tag{9.9a}$$

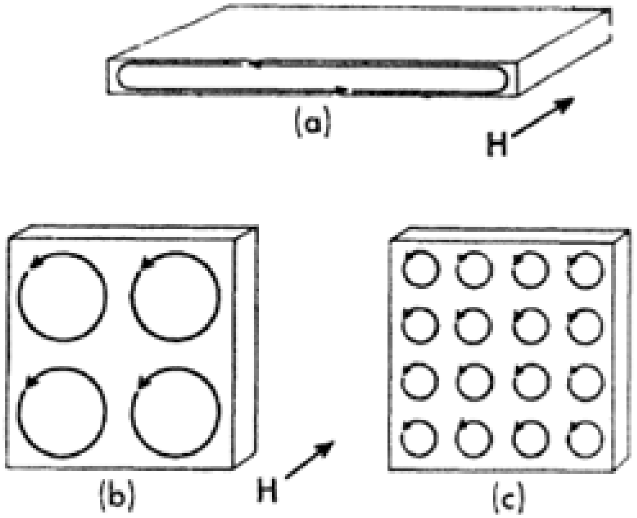
where θ is the angle between the magnetic field *and the ab plane.*

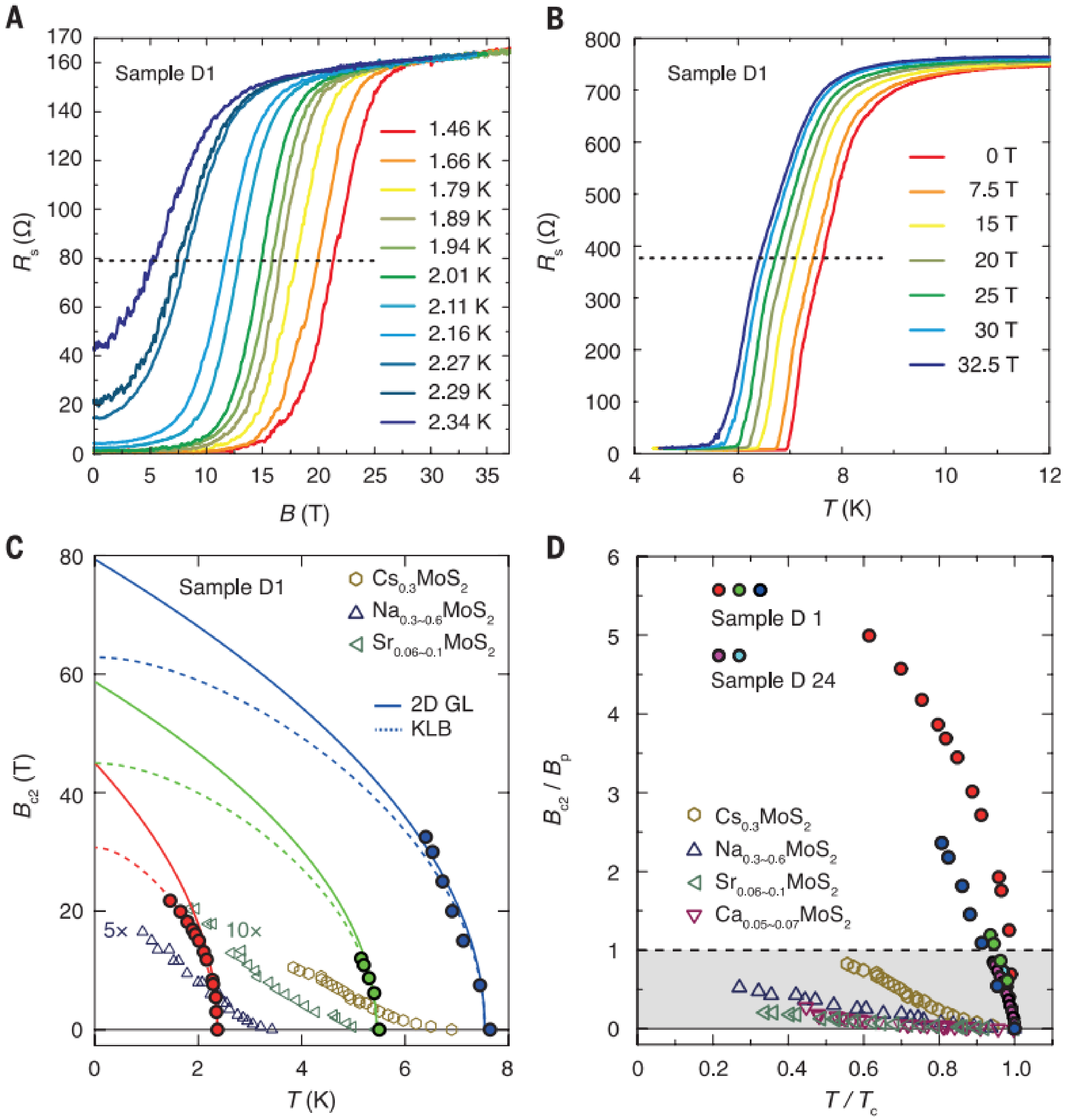
- 2D Tinkham model (Phys. Rev. **129**, 2413, 1963)
- Appliable condition for 2D Tinkham model: film thickness *d* < (This condition can be easily satisfied since ~ 500 Å)

From the free-energy expression, Eq. (19), we see that a perpendicular field component produces a contribution *linear* in the applied field to be balanced against the condensation energy. By contrast, a field component in the plane of the film produces a quadratic effect. The reason for this difference is evident from Fig. 1. In the parallel orientation the important dimension of the current loops is fixed by the film thickness, hence is constant, and the energy increases as H^2; on the other hand, in the perpendicular orientation, the size of the current loops scale down as H increases, leaving only a residual linear dependence. From this argument, we see that for thin films we expect a critical field vs angle relation of the form

$$H_T \sin\theta/H_{T\perp}+(H_T \cos\theta/H_{T\parallel})^2=1, \qquad (25)$$

FIG. 1. Schematic diagram of current configuration in parallel and perpendicular field cases. In parallel field geometry (a), the width of the loop is limited by film thickness. In perpendicular field geometry, size of vortex can adjust depending on field strength so as to minimize energy. Configuration (c) corresponds to higher field strength than (b), so that smaller vortices contain one flux quantum.





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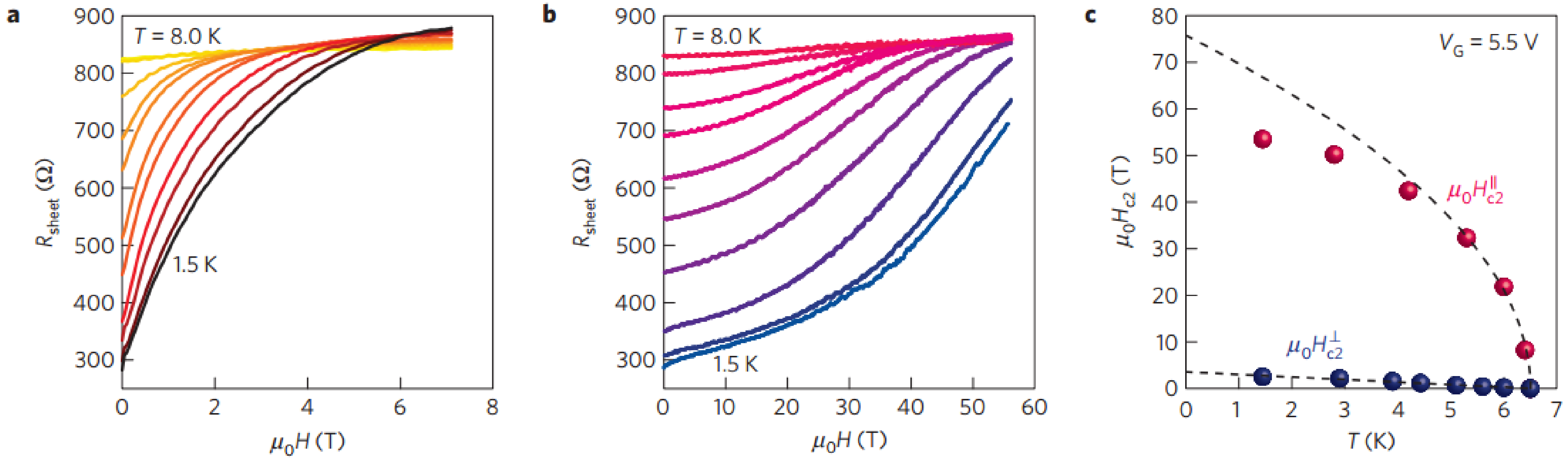

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- # Discussion

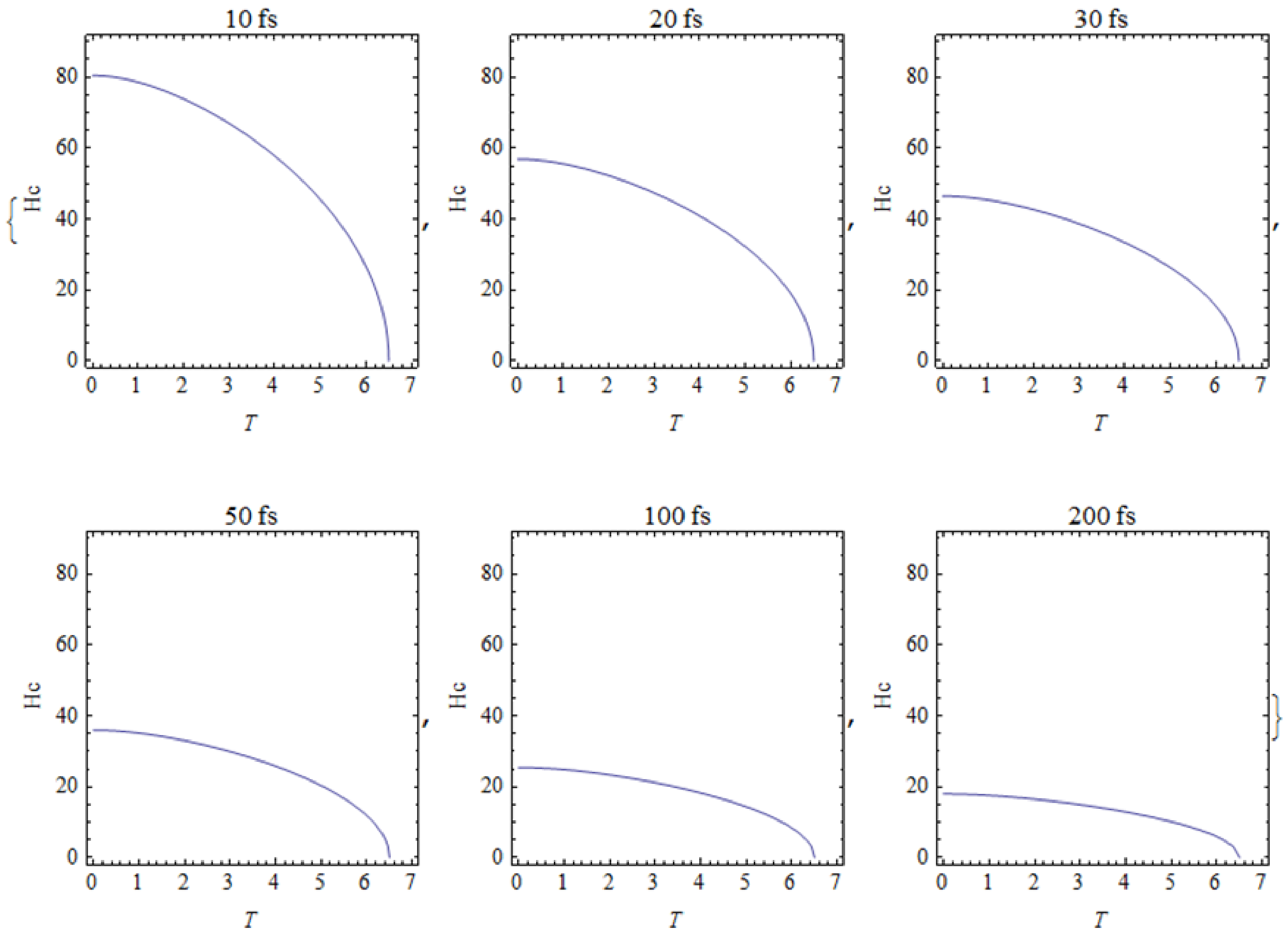
  - Klemm-Luther-Beasley theory (Phys. Rev. B **12**, 877, 1975): layered superconductors with weak interlayer Josephson tunnelling

The upper critical field H_{c2} in layered superconductors is calculated from a microscopic theory in which the electrons are assumed to propagate freely within the individual layers subject to scattering off impurities and to propagate via tunneling between the layers. For the magnetic field parallel to the layers, there is a temperature $T^* < T_c$ below which the normal cores of the vortices fit between the metallic layers, removing the orbital effects as a mechanism for the quenching of superconductivity in the individual layers. In this temperature regime, $H_{c2\parallel}$ is thus determined by the combined effects of Pauli paramagnetism and spin-orbit scattering, and for sufficiently strong spin-orbit scattering rates, $H_{c2\parallel}(T=0)$ can greatly exceed the Chandrasekhar-Clogston Pauli limiting field H_P. This unusual behavior is found to be most pronounced in the dirty limit for the electron propagation within the layers and when the electrons scatter many times in a given layer before tunneling to an adjacent layer. Our results are also discussed in light of the available experimental data.

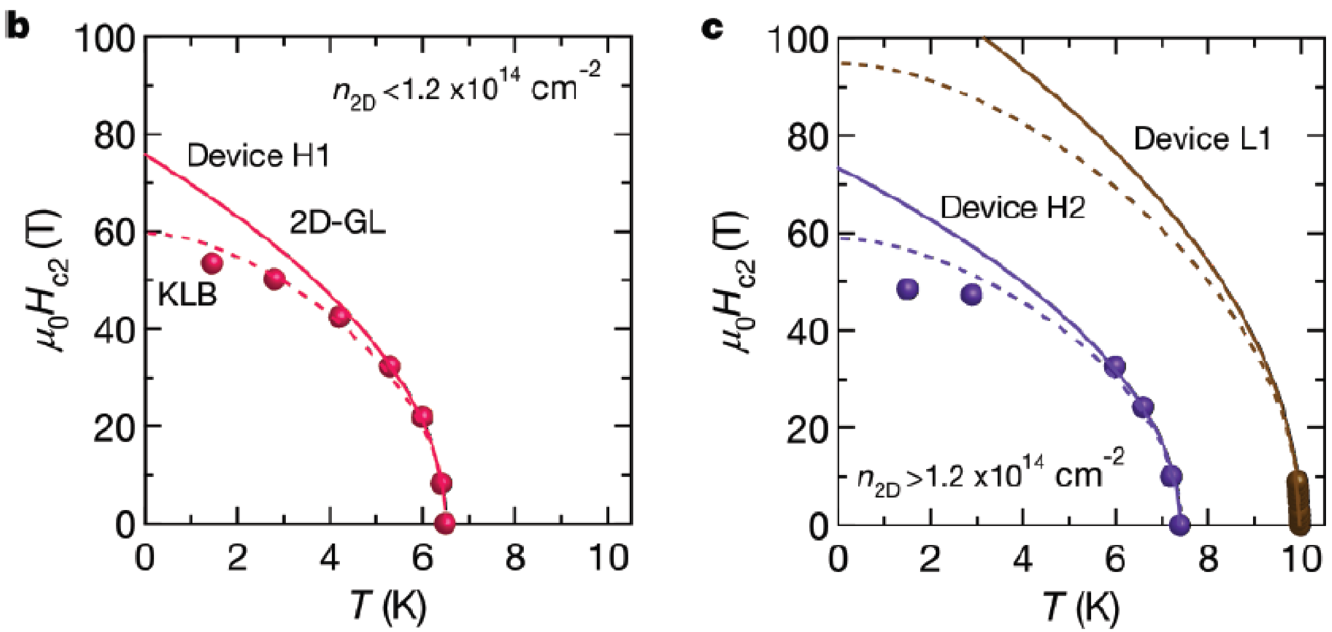
When considering superconductivity in the 2D limit, interlayer coupling is set to zero. For strong spin-orbit scattering, the KLB fitting reduces to

$$\ln\left(\frac{T}{T_c}\right)+\psi\left(\frac{1}{2}+\frac{(3\tau_{SO}/\hbar)(\mu_B H_{c2//})^2}{4\pi k_B T}\right)-\psi\left(\frac{1}{2}\right)=0$$

$$\ln\left(\frac{T}{T_c}\right)+\psi\left(\frac{1}{2}+\frac{(3\tau_{SO}/\hbar)(\mu_B H_{c2//})^2}{4\pi k_B T}\right)-\psi\left(\frac{1}{2}\right)=0$$



KLB theory yield avery short SOS time of ~24 fs , which is less than the total scattering time of 185 fs estimated from resistivity measurements at 15 K



- Failure of spin-orbit scattering effect to explain the enhancement of $H_{c2//}$

	T_c (K)	n_{2D} (cm^{-2})	μ_H (cm^2/Vs)	τ (fs)	τ_{SO} (fs)
Device L1	10.0	1.5×10^{14}	208	59.3	11.1
Device H1	6.5	0.85×10^{14}	86	25.5	17.9
Device H2	7.4	1.8×10^{14}	165	47.1	21.3

(gated MoS_2, Nature Physics **12**, 144, 2016)

In general, spin-orbit scattering (which results in spin flip) accounts for only a small fraction of total scatterting processes, that is $\tau_{so} >> \tau$.

Intrinsic mechanism: Ising superconductivity

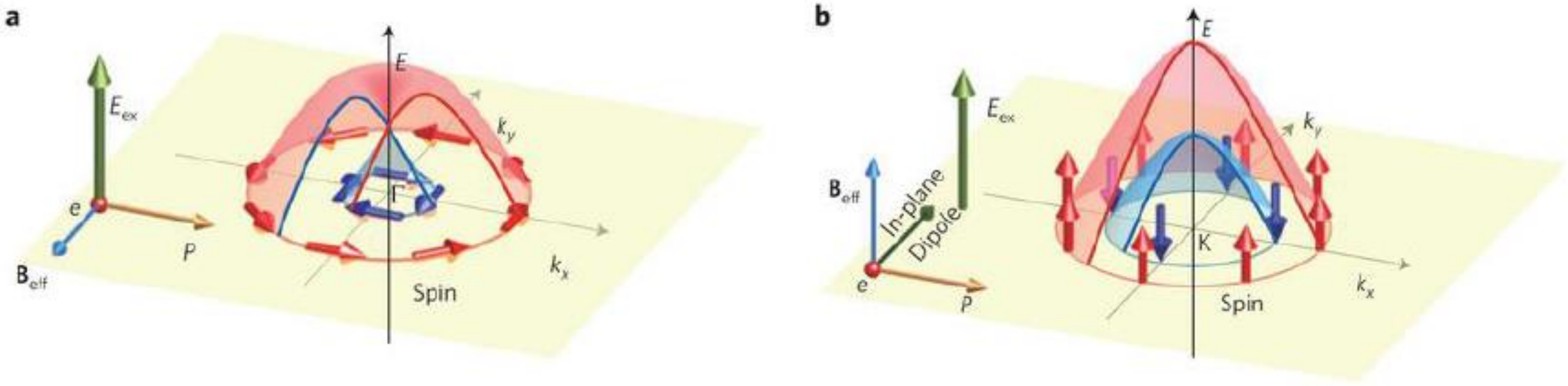
B_{c2} enhancement is mainly caused by the intrinsic spin-orbit coupling in MoS2.

- Zeeman type SOC
- Rashaba type SOC

$$H(\mathbf{k}+\epsilon\mathbf{K}) = \varepsilon_k + \epsilon\beta_{so}\sigma_z + \alpha_R \mathbf{g}_F \cdot \sigma + \mathbf{b} \cdot \sigma$$

Broken time or space reversal symmetry would result in spin splitting (polarization). e. g., applying magnetic field to broke time reversal symmetry; broken space reversal symmetry brings in effective crystalline field **ε** (effective Zeeman field -**k** × **ε**).

Rashba type SOC	Zeeman type SOC
Out-plane crystalline field **ε**	In-plane crystalline field **ε**
In-plane Zeeman field -**k** × **ε**	Out-plane Zeeman field -**k** × **ε**
In-plane helical spin polarization	Out-plane Ising fashion spin polarization



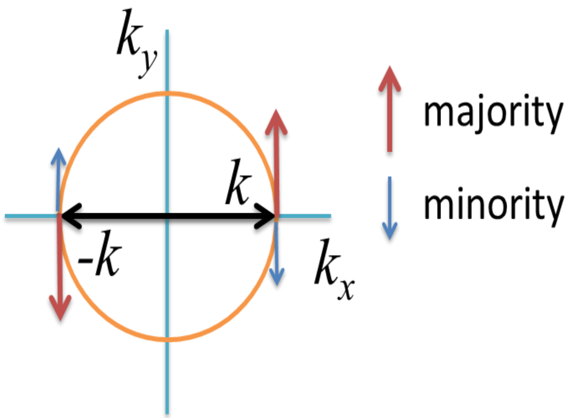
(Iwasa group, Nature Physics **9**, 563, 2013)

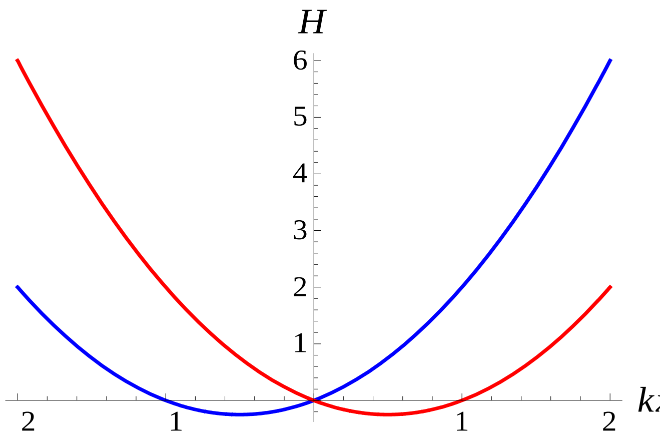
Rashba type SOC

$$H(k) = k^2/2m^* + \alpha_R g_F \cdot \sigma$$

$$g_F = (k_y, -k_x, 0)$$

Spin splitting between majority and minority $\alpha_R k$



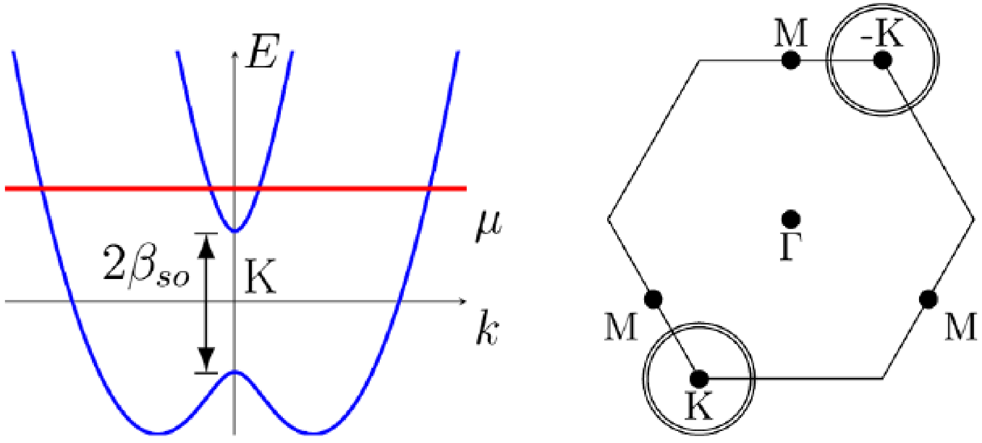


Zeeman type SOC

$$H(k) = k^2/2m^* + \varepsilon\beta_{so}\sigma_z$$

Spin splitting between majority and minority $2\beta_{so}$

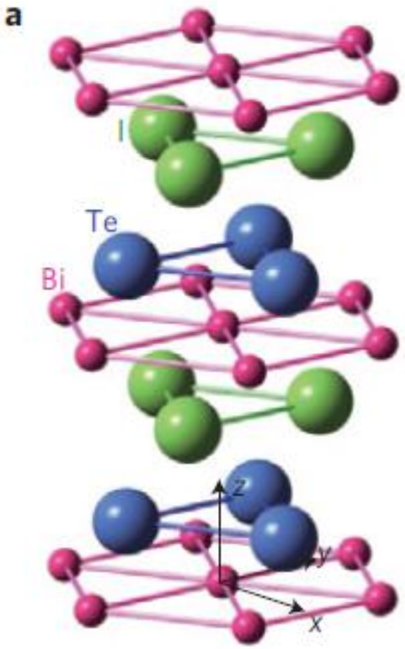
$$H_0(\boldsymbol{k} + \epsilon\boldsymbol{K}) = \frac{|\boldsymbol{k}|^2}{2m} - \mu + \alpha_R \boldsymbol{g}(\boldsymbol{k}) \cdot \boldsymbol{\sigma} + \epsilon\beta_{so}\sigma_z$$

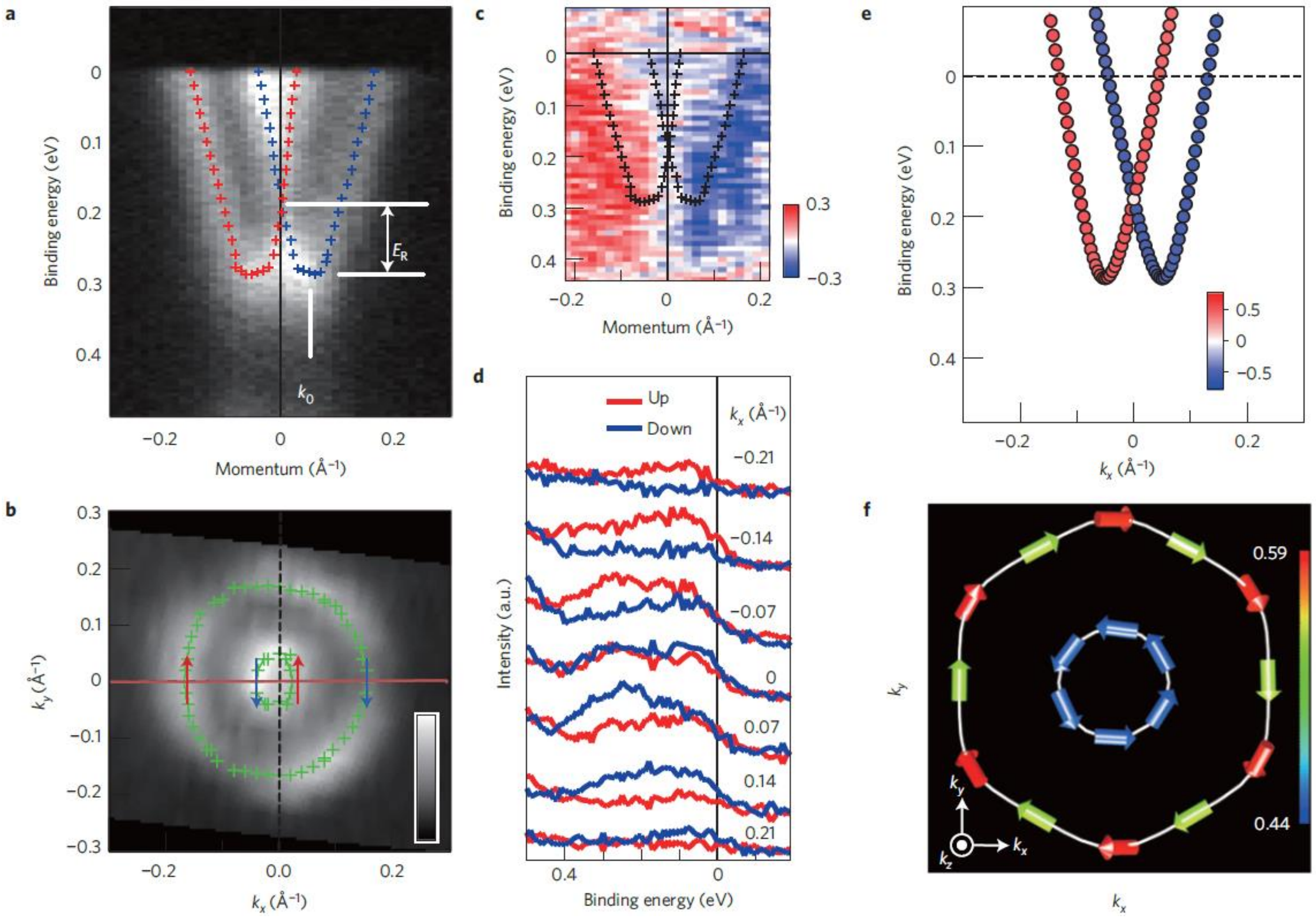


(a) (b)

Phys. Rev. Lett **113**, 097001 (2014)

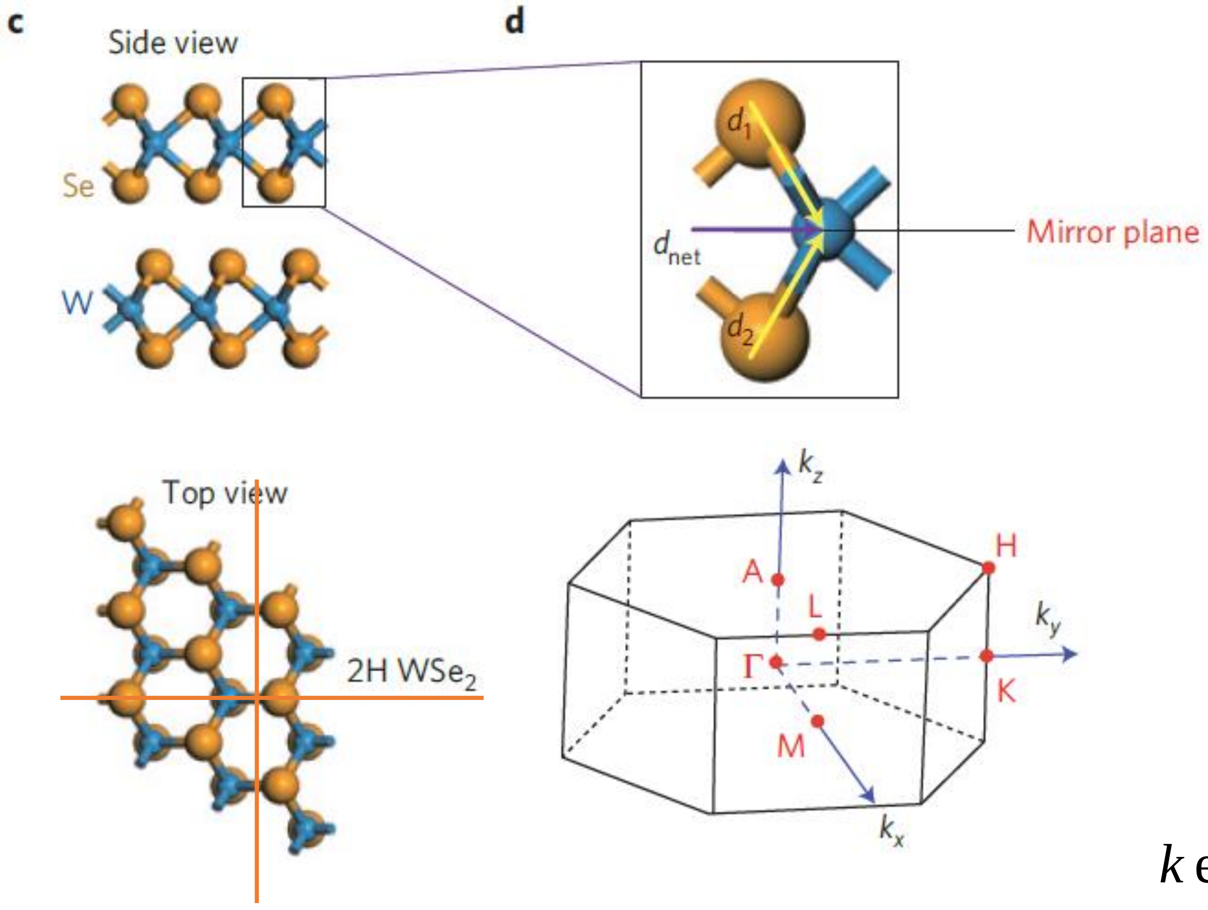
Typical example of Rashba type SOC:
Spin polarization of BiTeI by spin resolved ARPES





Nature Material **10**, 521, 2011

Typical example of Zeeman type SOC: TMDs



Crystalline field

Nature Physics **9**, 563, 2013

D_{3h}: M + C_{3v}

M symmetry suppresses the Rashba term, because it avoids any electric polarity along the z axis required for Rashba spin splitting. (M is broken by gating)

The Zeeman term:

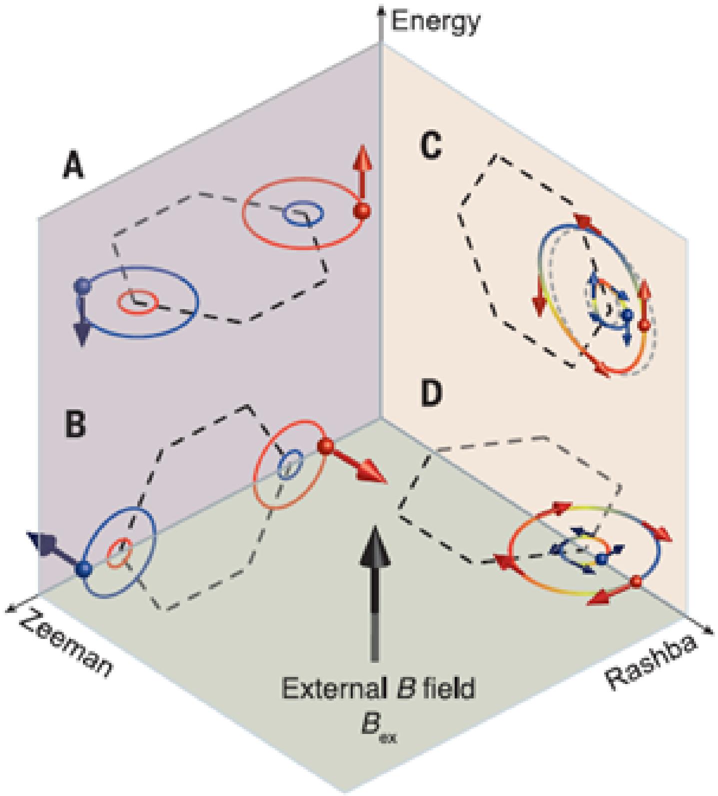
$$(3k_x^{\ 2} - k_y^{\ 2})k_y\sigma_z$$

Invariant under

$$k\exp(i\theta) \to k\exp[i(\theta + 2\pi/3)]$$

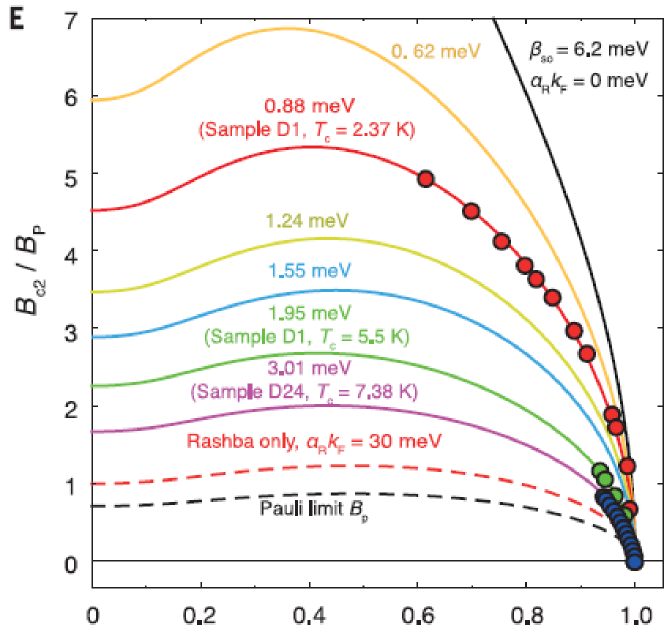
Spin polarization will be aligned along the z axis and becomes maximal/minimal along the -K directions.

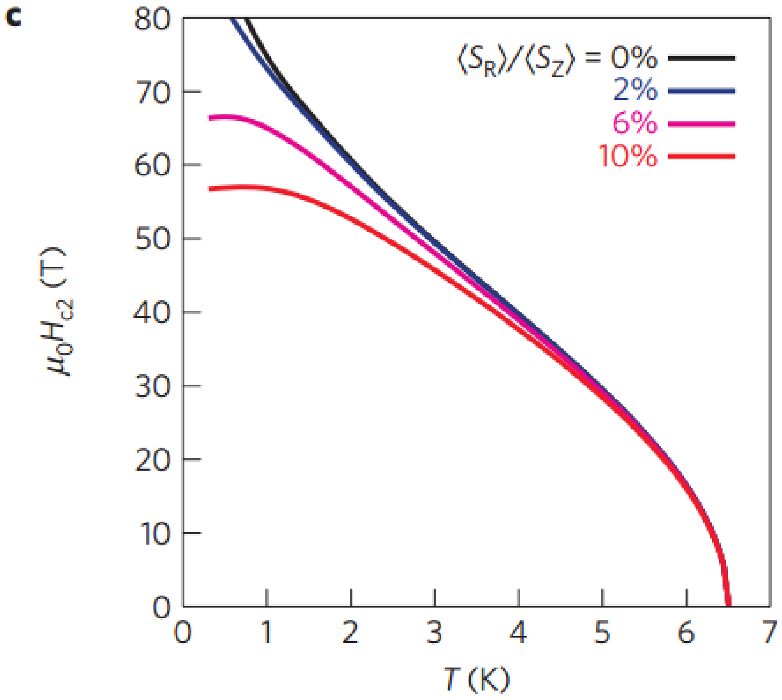
Effective Zeeman field protection:



The total energy in a magnetic field is schematically shown in Fig. 4, A to D. If the electron spin aligned by $\mathbf{B}_{eff}$ ($\mathbf{B}_{Ra}$) stays parallel to the external magnetic field $\mathbf{B}_{ex}$ (Fig. 4, A and C), the system gains energy through coupling between spin and external fields as $\mu_B \mathbf{B}_{ex}$. Therefore, B_{c2} is limited by B_p (Fig. 4A), or it can reach $\sqrt{2}\,B_p$ (Fig. 4C) when coupling is reduced in a Rashba-type spin configuration (*10*). When $\mathbf{B}_{eff}$ and $\mathbf{B}_{Ra}$ are perpendicular to $\mathbf{B}_{ex}$, as respectively shown in Fig. 4, B and D, the spin aligned by both effective fields is orthogonal to $\mathbf{B}_{ex}$. Hence, the coupling between spin and $\mathbf{B}_{ex}$ is minimized, and B_{c2} can easily surpass B_p in these two cases.

Science **350**, 1353, 2015





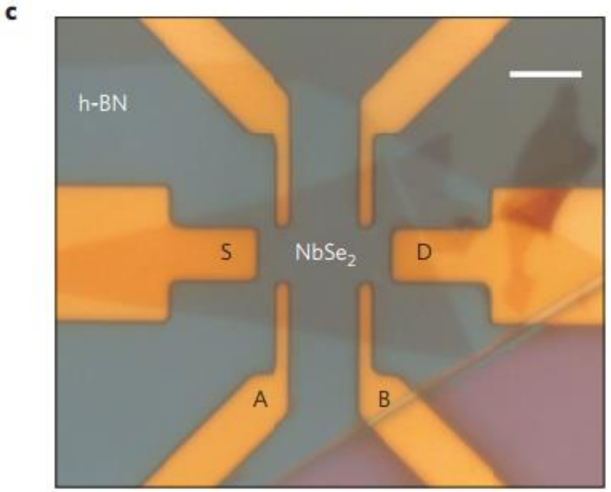
Competition between Rashba and Zeeman type SOC

$$H(k+\varepsilon K) = (\frac{k^2}{2m^*} - \mu) + \varepsilon\beta_{so}\sigma_z + \alpha_R(k_y, -k_x, 0)\cdot\sigma + \mu_B B\cdot\sigma$$

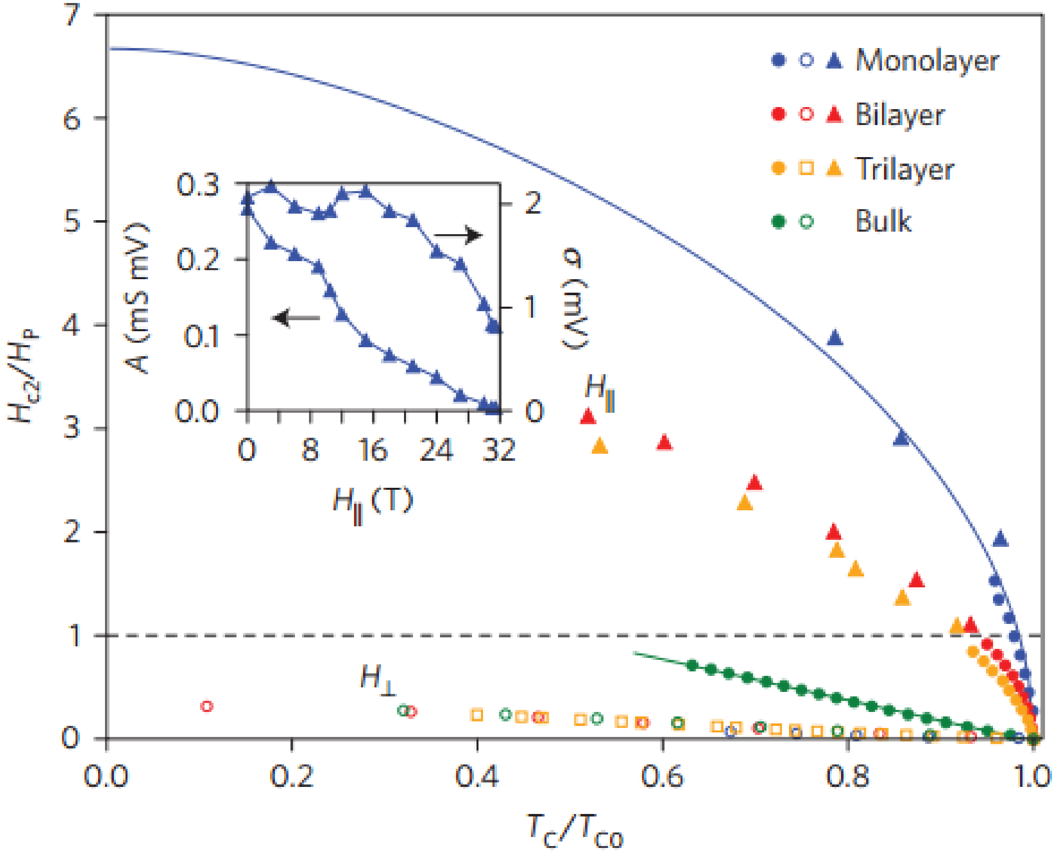
- Rashba SOC alone could only enhance $H_{c2//}$ slightly to 2 H_p.
- Out plane Zeeman protection would be weakened with stronger Rashba SOC (strong gating, higher T_c).

Science **350**, 1353, 2015;Nature Physics **12**, 144, 2016

- **Related works**



$$\mathbf{H}_{SO}(\mathbf{k}) = H_0\left[\sin(k_y a) - 2\cos\left(\frac{\sqrt{3}k_x a}{2}\right)\sin\left(\frac{k_y a}{2}\right)\right]\hat{z}$$



Nature Physics **12**, 139, 2016

- **Conclusion**

    - Ising Superconductor
    - MoS2
    - Other materials and possible mechanism

Thank you