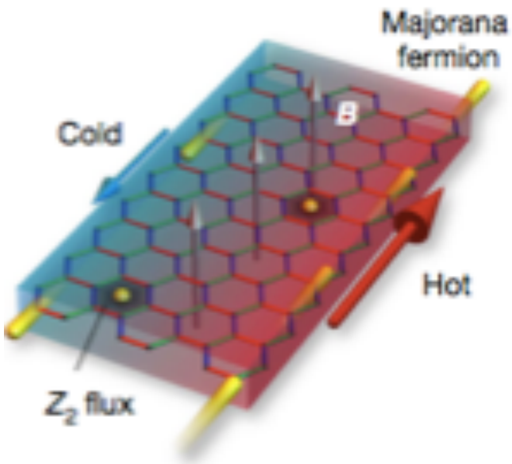
Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

Y. Kasahara[1], T. Ohnishi[1], Y. Mizukami[2], O. Tanaka[2], Sixiao Ma[1], K. Sugii[3], N. Kurita[4], H. Tanaka[4], J. Nasu[4], Y. Motome[5], T. Shibauchi[2] & Y. Matsuda[1]*

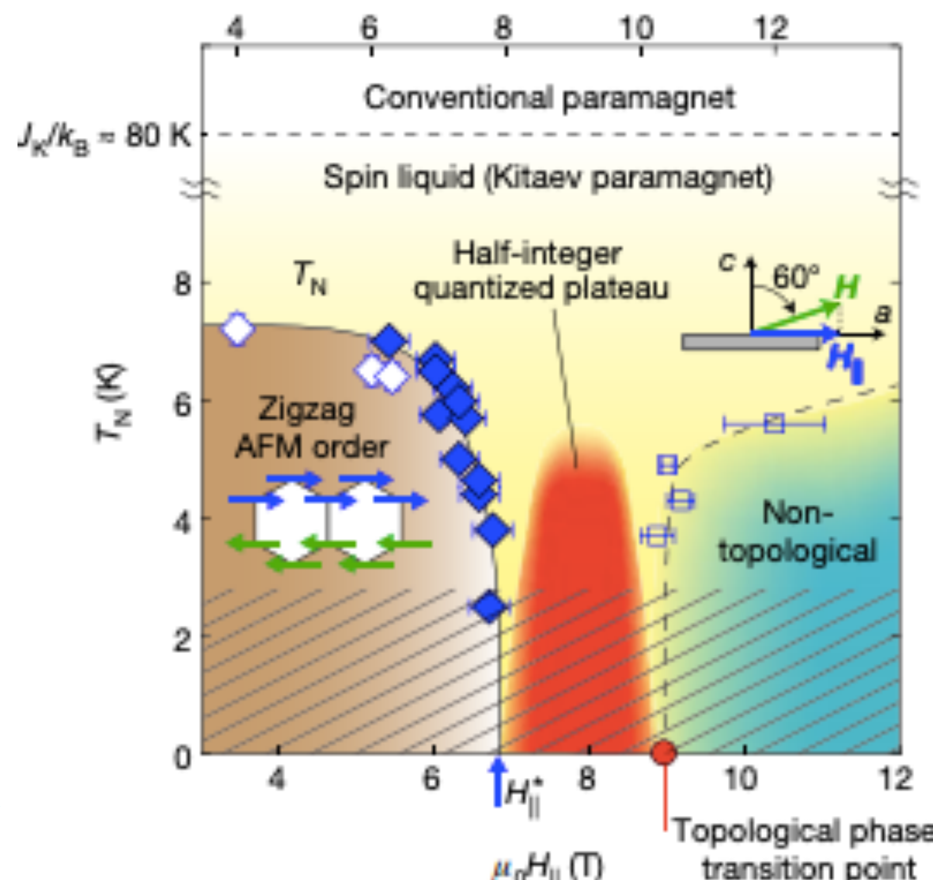


Recap

Results

Interpretation

Subsequent Work



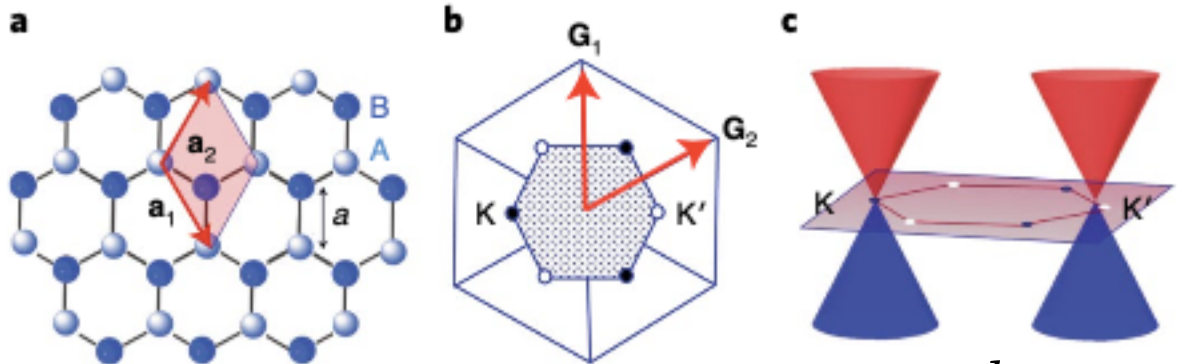
What ??s Would We Ask as Referees ??

Recap

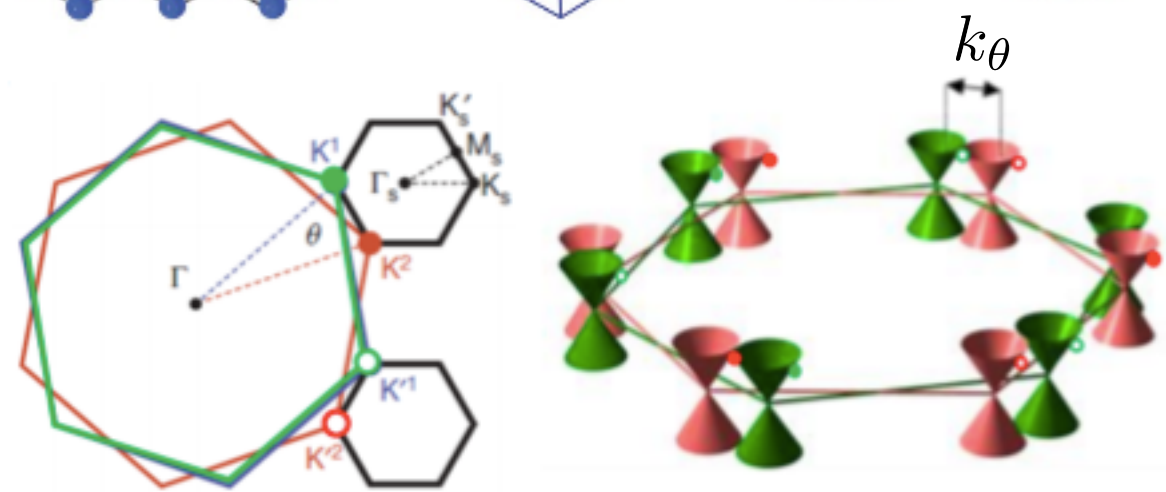
Questions from Last Class

Twisted Bilayer Graphene (Skanda's Talk)

Interference as Origin of Flat Bands??



single layer
of graphene



two independant
layers
of graphene

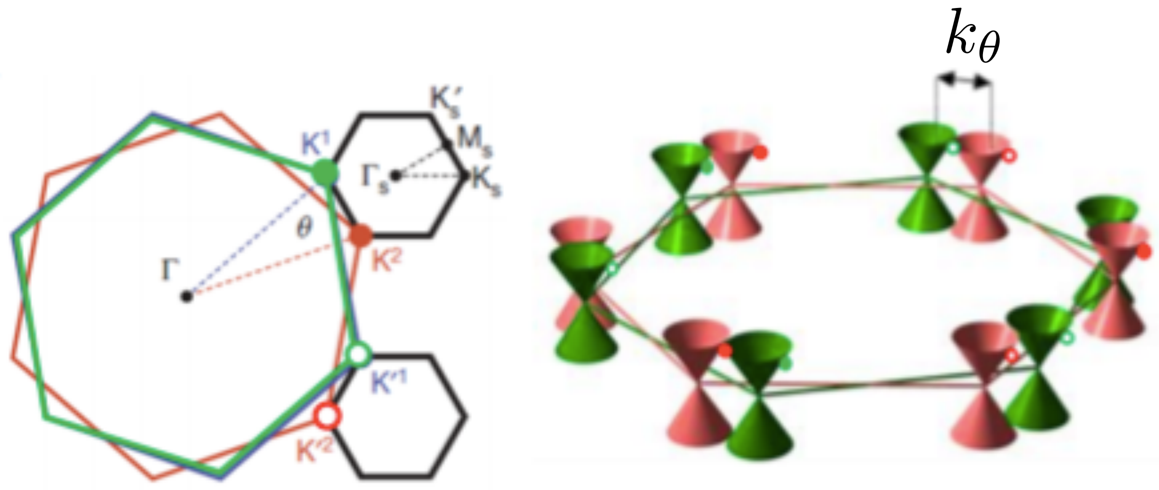
E. Y. Andei and A. MacDonald, *Graphene Bilayers with a Twist*

Recap

Questions from Last Class

Twisted Bilayer Graphene (Skanda's Talk)

Two Dirac cones intersect $\Delta E_0 \sim \hbar v_F k_\theta$



E. Y. Andei and A. MacDonald, *Graphene Bilayers with a Twist*

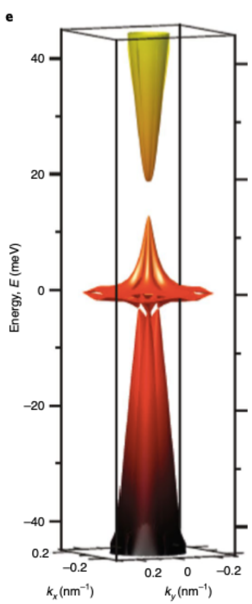
Recap

Questions from Last Class

Twisted Bilayer Graphene (Skanda's Talk)

Two Dirac cones intersect $\Delta E_0 \sim \hbar v_F k_\theta$

Interlayer Tunneling w leads to Avoided Band Crossings



$$\Delta E_0 \sim 2w$$

Strong Hybridization Between Layers

Reduction of Kinetic Energy in Flat Band

Recap

Questions from Last Class

Twisted Bilayer Graphene (Skanda's Talk)

Phonons ??

$$w_M < w_0$$

Small Width of Miniband (w_M)

Phonon Energy Scale (w_0)

Often used to motivate non-BCS superconductivity

What about (low frequency) shear modes ?

PHYSICAL REVIEW B **100**, 075416 (2019)

Moiré phonons in twisted bilayer graphene

Mikito Koshino[1,*] and Young-Woo Son[2]
[1]*Department of Physics, Osaka University, Toyonaka 560-0043, Japan*
[2]*Korea Institute for Advanced Study, Seoul 02455, Korea*

PHYSICAL REVIEW B **100**, 155426 (2019)

Moiré-pattern fluctuations and electron-phason coupling in twisted bilayer graphene

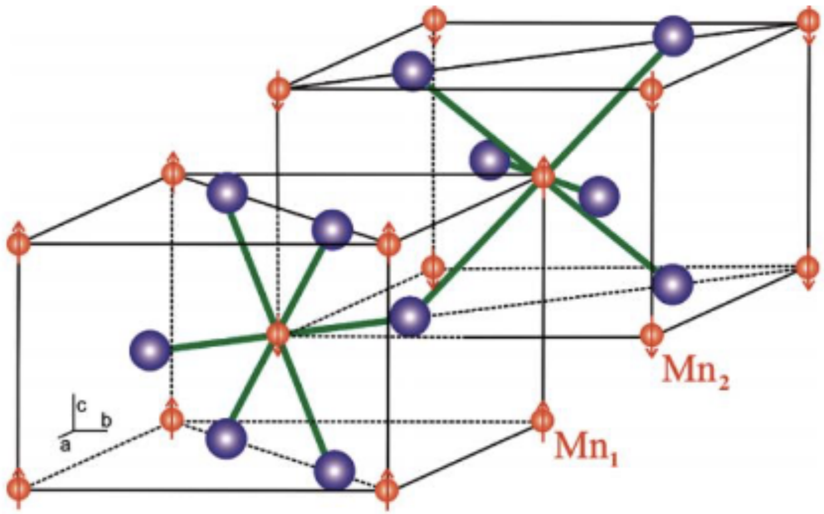
Héctor Ochoa
Department of Physics, Columbia University, New York, New York 10027, USA

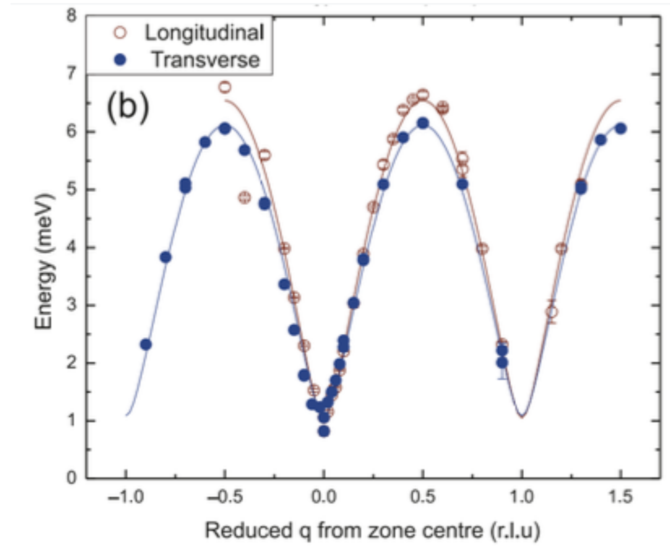
PHYSICAL REVIEW RESEARCH **2**, 013335 (2020)

Phonons in twisted transition-metal dichalcogenide bilayers: Ultrasoft phasons and a transition from a superlubric to a pinned phase

Indrajit Maity, Mit H. Naik, Prabal K. Maiti, H. R. Krishnamurthy, and Manish Jain[*]
Centre for Condensed Matter Theory, Department of Physics, Indian Institute of Science, Bangalore 560012, India

How to "Read" Neutron Plots for $\alpha - RuCl_3$



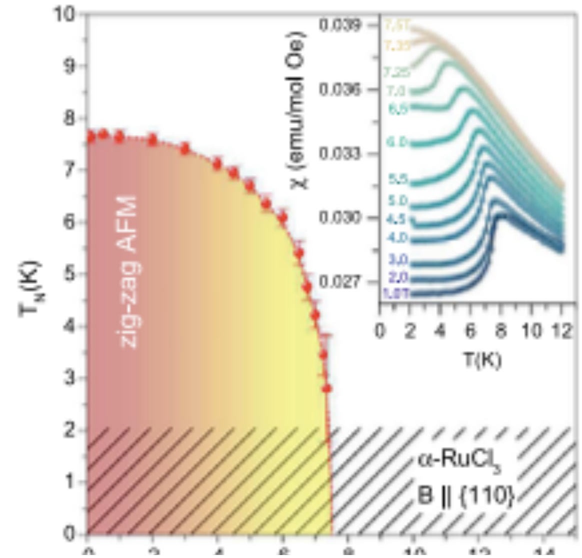


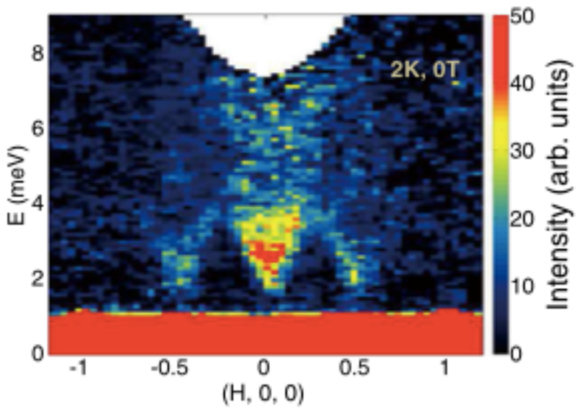
Textbook Classical Antiferromagnet

(from Cory's Talk)

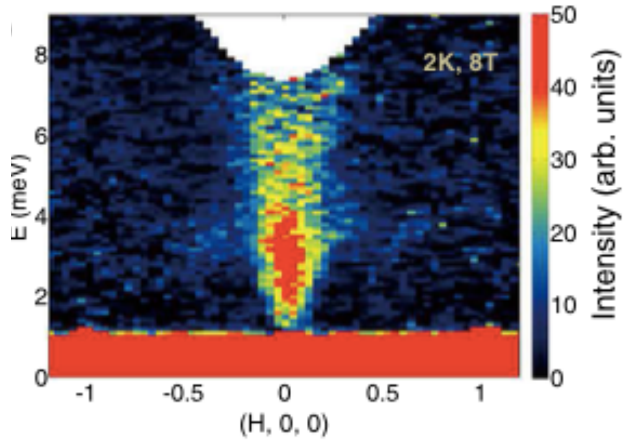
How to "Read" Neutron Plots for $\alpha - RuCl_3$

Inelastic Neutron Scattering
as a Function of Magnetic Field

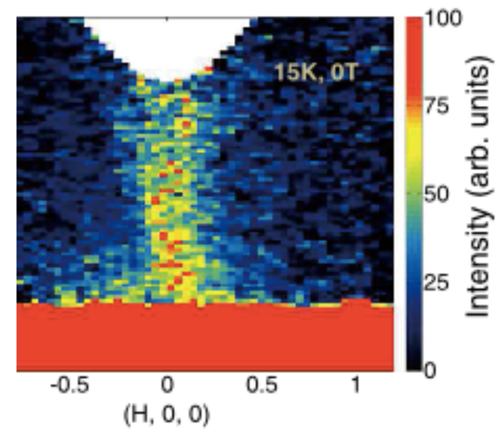




2K 0T

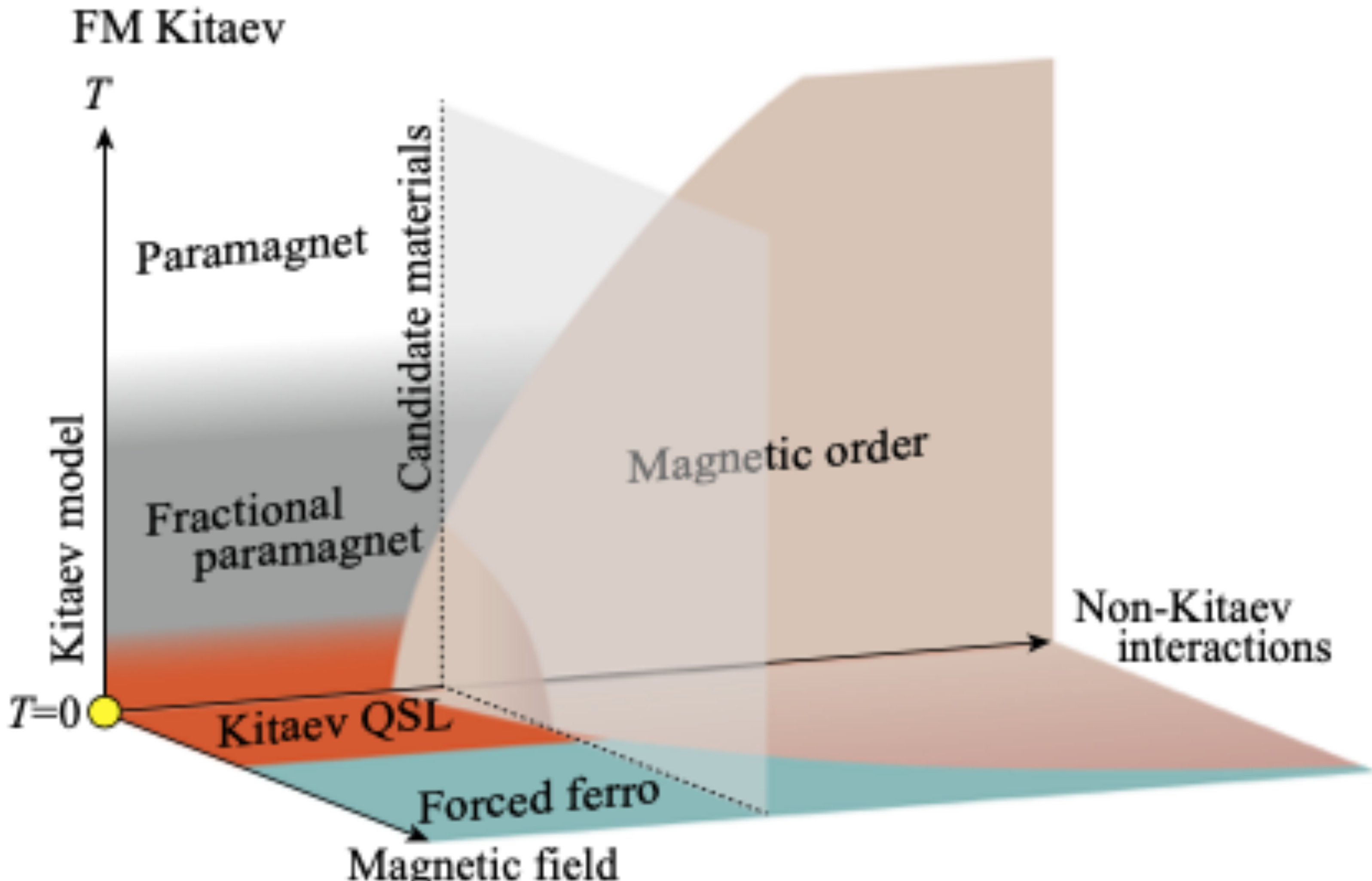


2K 8T

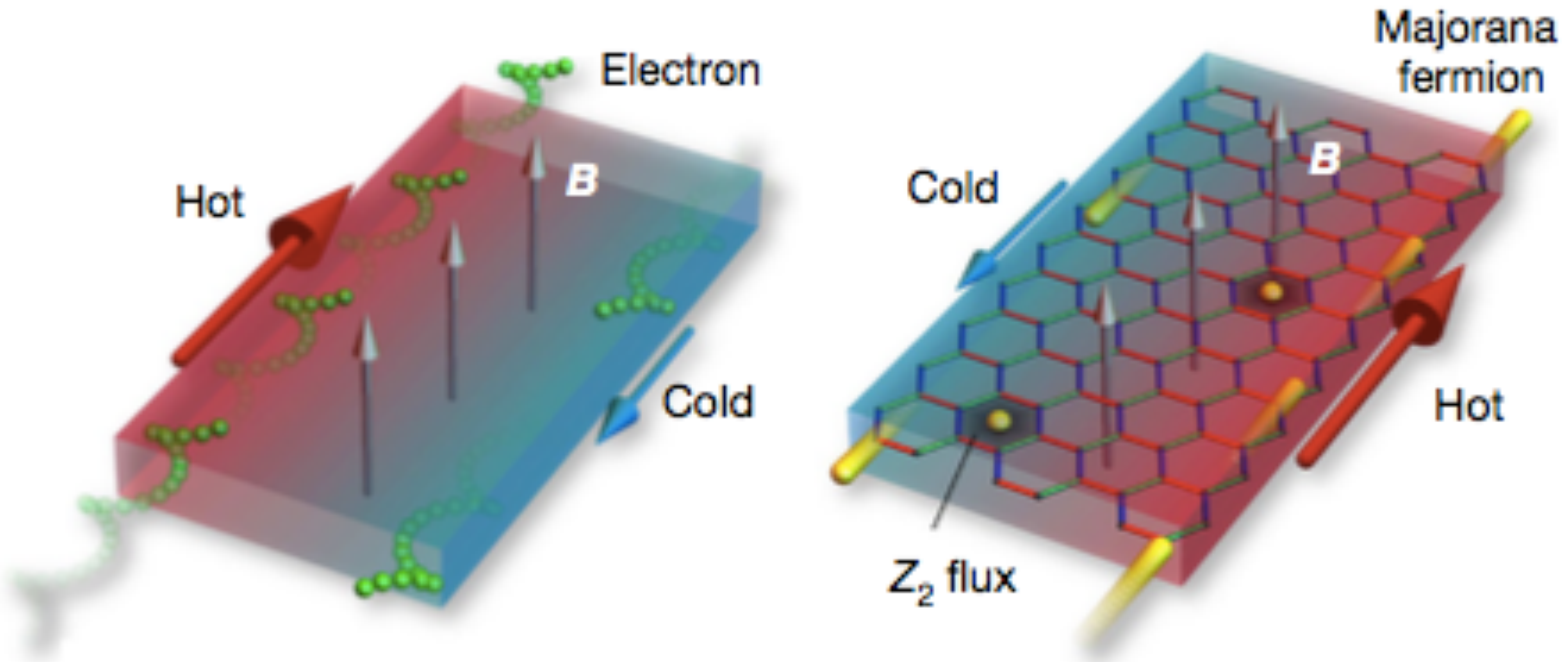


15K 0T

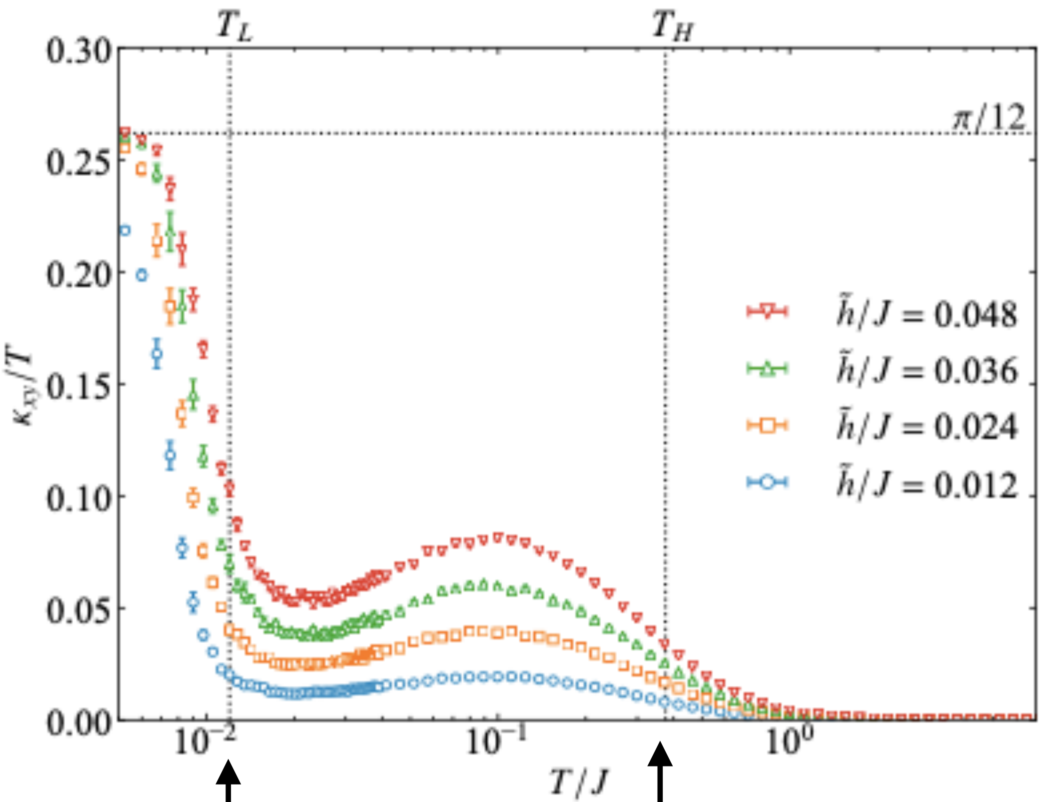
Schematic Phase Diagram



Thermal Hall Measurement



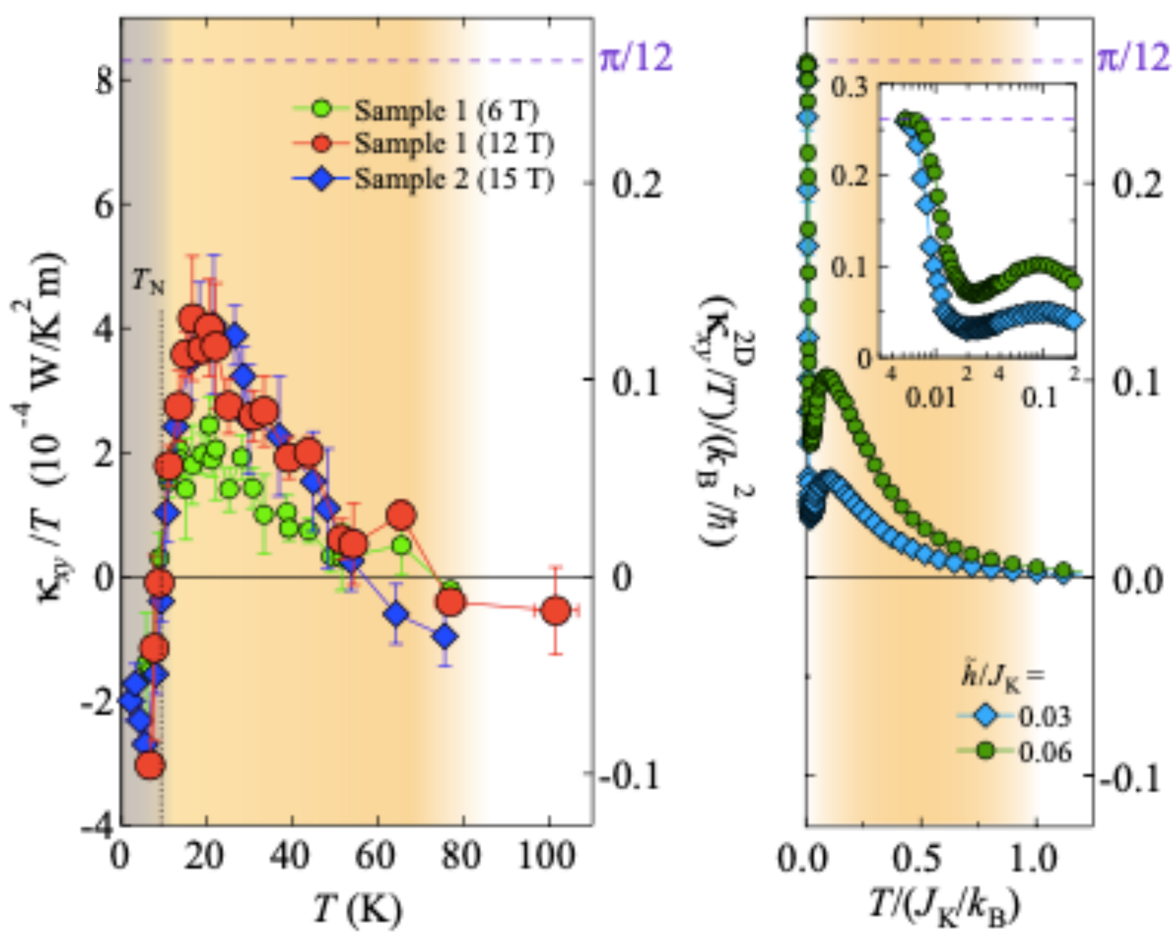
Finite-Temperature Simulations for Thermal Hall Effect



Excitation Gap for Z_2 Fluxes

Energy Scale of Itinerant Majorana Fermions

Theory-Experiment Comparison for $\alpha - RuCl_3$ (Magnetic Field Applied Perpendicular to the ab Plane)



$T_N \sim 7K$

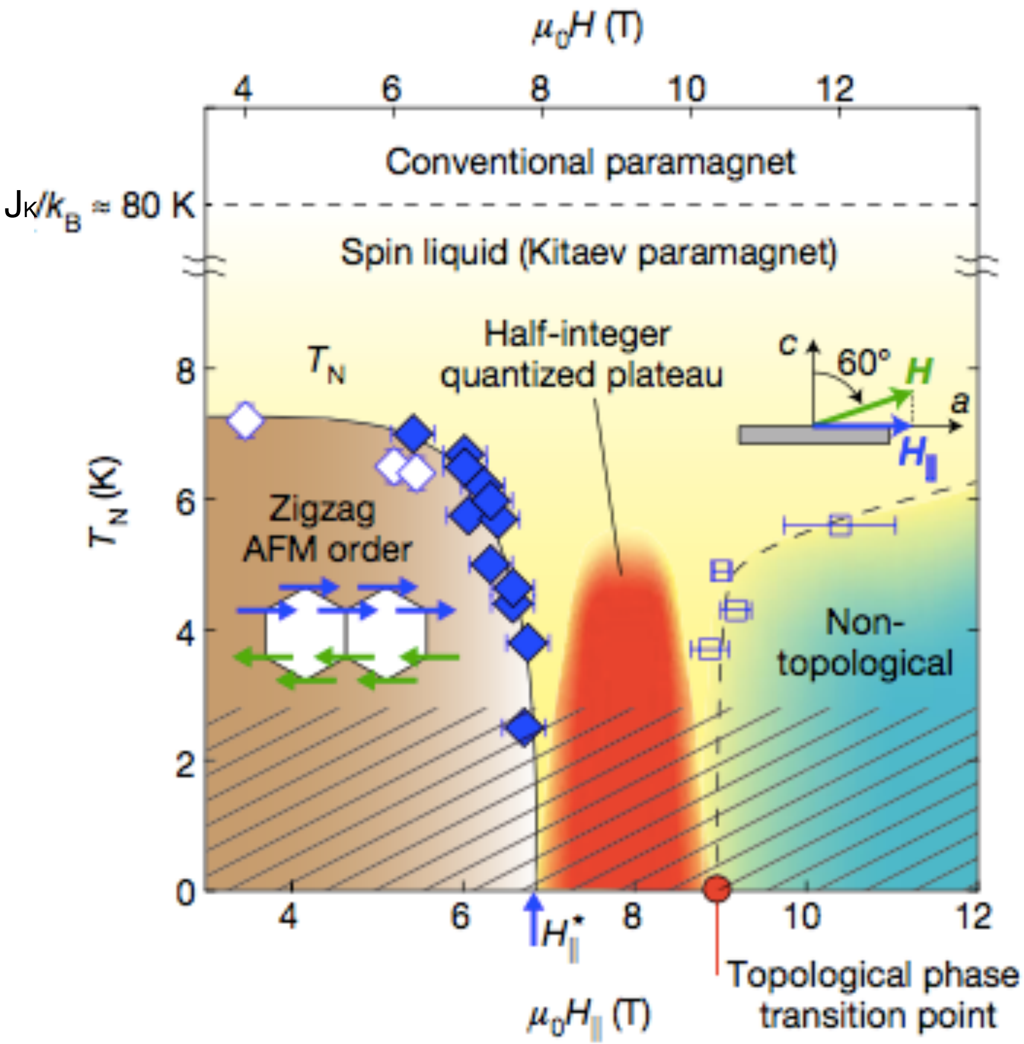
$J_K \sim 50 - 90K$

$H_{||} > 6.5T$

No AFM Order

Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

Y. Kasahara[1], T. Ohnishi[1], Y. Mizukami[2], O. Tanaka[2], Sixiao Ma[1], K. Sugii[3], N. Kurita[4], H. Tanaka[4], J. Nasu[4], Y. Motome[5], T. Shibauchi[2] & Y. Matsuda[1]*



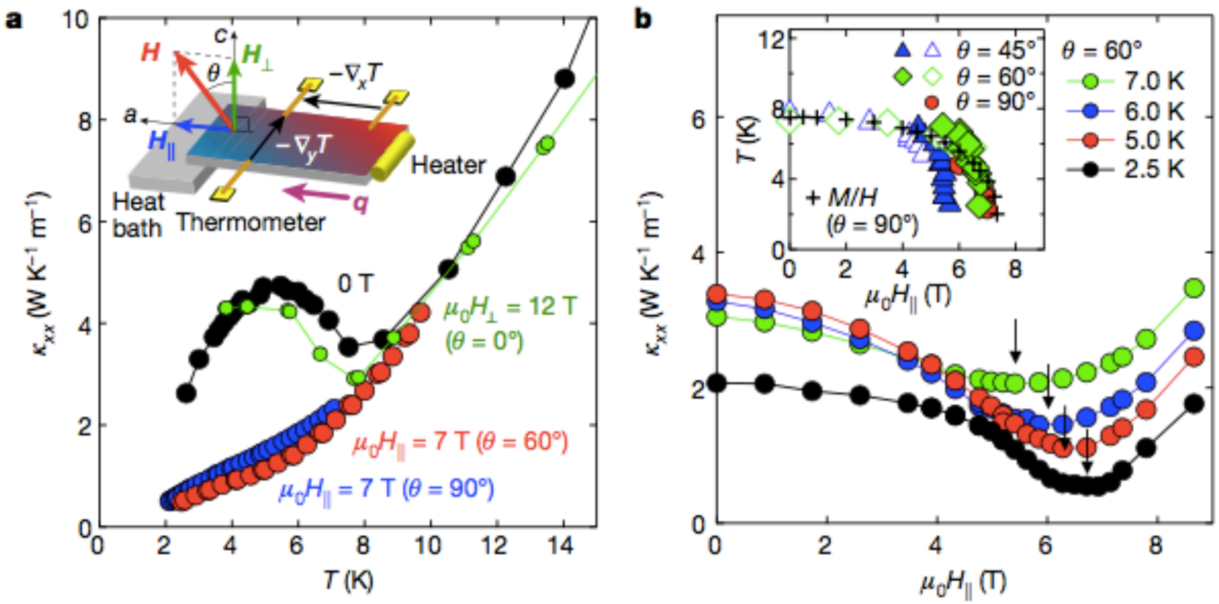
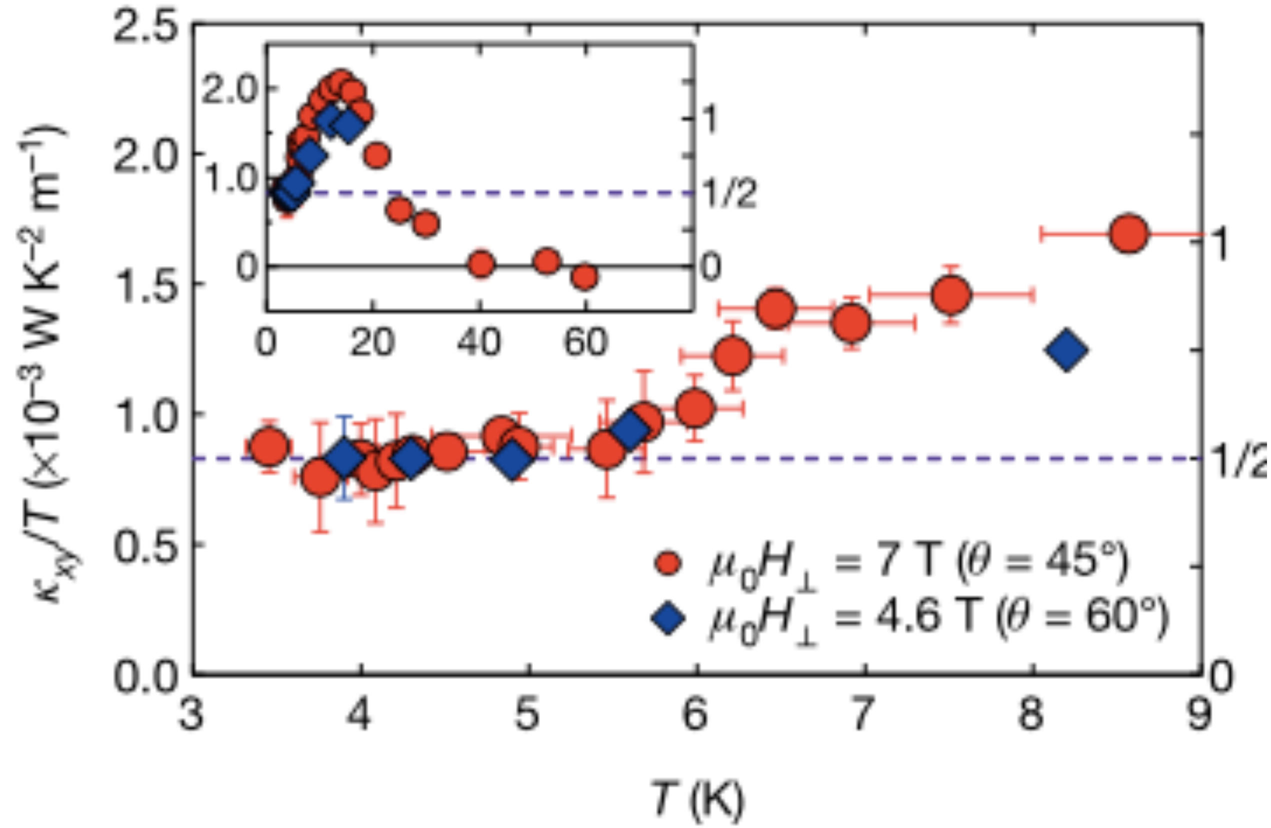
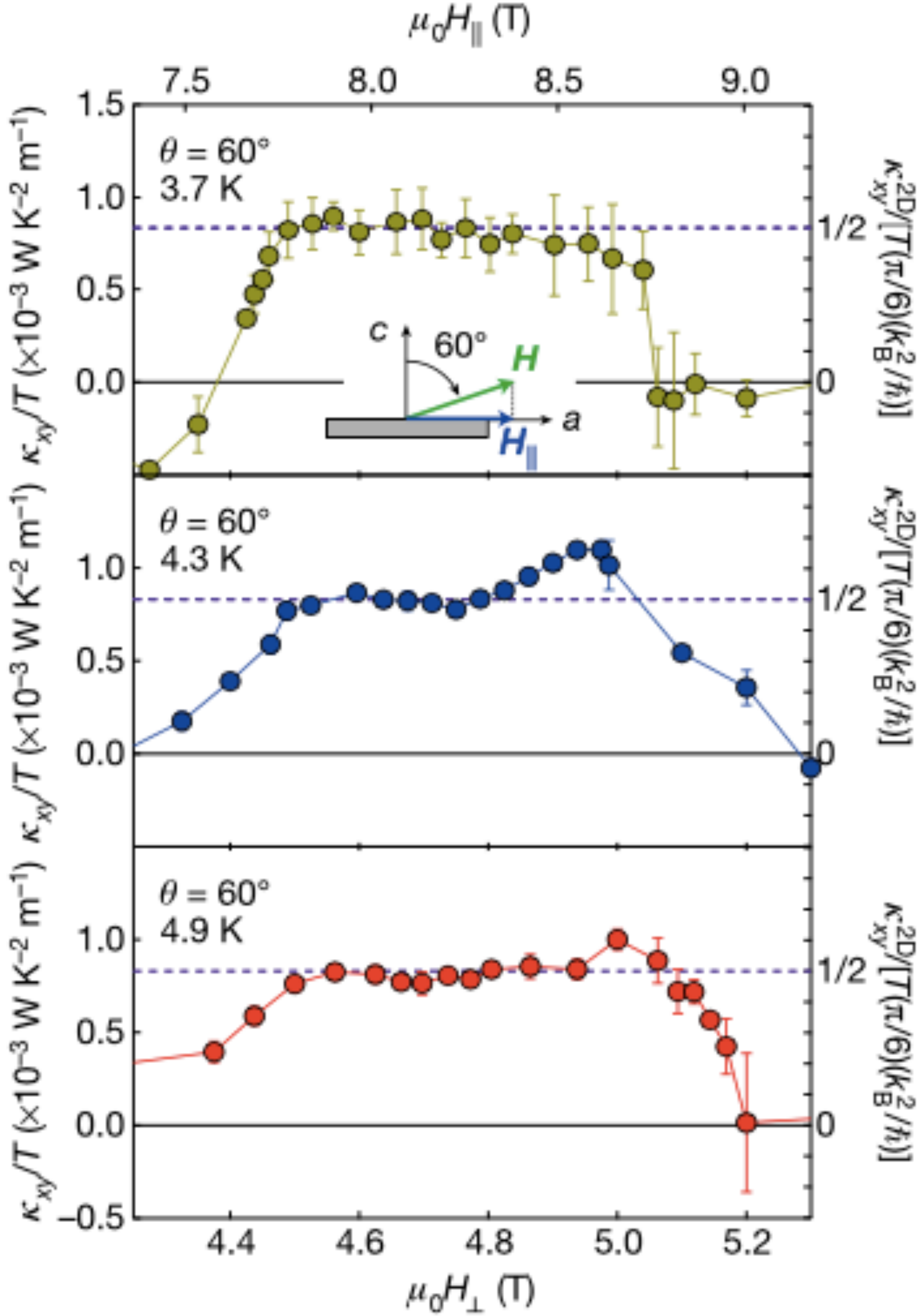


Fig. 2 | Longitudinal thermal conductivity in α-$RuCl_3$. a, Temperature dependence of κ_{xx} in a magnetic field ***H*** applied along various directions in the *a*–*c* plane. The inset illustrates a schematic of the measurement setup for κ_{xx} and κ_{xy} (see Methods for details). **b**, κ_{xx} at $\theta = 60°$, plotted as a function of the parallel field component, $H_{\parallel}$. The inset shows T_N versus $H_{\parallel}$ at different field directions. T_N is determined by the T dependence of κ_{xx} shown in **a** (open symbols) and by the minimum in the H dependence of κ_{xx} (filled symbols), shown by arrows in the main panel. Crosses show T_N for $\theta = 90°$, determined from magnetic susceptibility (M/H, where M is the magnetization) measurements[26].



2.5
2.0
1.5
1.0
0.5
0.0
3
4
5
6
7
8
9
T (K)
κ_{xy}/T ($\times 10^{-3}$ W K^{-2} m^{-1})
1
1/2
0
$\mu_0 H_\perp$ = 7 T (θ = 45°)
$\mu_0 H_\perp$ = 4.6 T (θ = 60°)
2.0
1.0
0
20
40
60
1/2



$\mu_0 H_\parallel$ (T)
7.5
8.0
8.5
9.0
1.5
1.0
0.5
0.0
−0.5
$\theta = 60°$
3.7 K
4.3 K
4.9 K
c
60°
H
a
$H_\parallel$
1/2
0
κ_{xy}/T ($\times 10^{-3}$ W K^{-2} m^{-1})
$\kappa_{xy}^{2D}/[T(\pi/6)(k_B^2/\hbar)]$
4.4
4.6
4.8
5.0
5.2
$\mu_0 H_\perp$ (T)

Interpretation

Temperature Scales ??

$$\kappa_{xx} \sim 10^3 \ \kappa_{xy}$$

$\sigma_{xx} >> \ \sigma_{xy}$ (Electrical Hall Effect quantization fails)

$$\theta_H = \tan^{-1}\left(\frac{\kappa_{xy}}{\kappa_{xx}}\right) = 10^{-3}$$

Phonons ??

Why quantization still observed ??

Quantization of the thermal Hall conductivity at small Hall angles

Mengxing Ye,[1,2] Gábor B. Halász,[2] Lucile Savary,[3] and Leon Balents[2]

[1]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[2]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[3]*Université de Lyon, École Normale Supérieure de Lyon, Université Claude Bernard Lyon I, CNRS, Laboratoire de physique, 46, allée d'Italie, 69007 Lyon, France*

(Dated: October 5, 2018)

Thermal Hall Quantization $L >> l$

Majorana-Phonon Exchange of Energy

Hall bar length Thermalization length

Majorana-Phonon Coupling $l \sim T^{-5}$

Observed Quantization of Thermal Hall Effect Should Break Down at the Temperature is Decreased !!

PHYSICAL REVIEW B **98**, 060412(R) (2018)

Rapid Communications

Spin-wave analysis of the low-temperature thermal Hall effect in the candidate Kitaev spin liquid α-$RuCl_3$

Jonathan Cookmeyer[1,*] and Joel E. Moore[1,2]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*

[2]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

Variational Monte Carlo of Proposed Hamiltonians ⟶ Spin Liquid Ground-States Not Preferred

$JK\Gamma$ Models

$K > 0$ ⟶ $\kappa \geq 0$ Inconsistent With Data!

Unusual Thermal Hall Effect in a Kitaev Spin Liquid Candidate α-$RuCl_3$

Y. Kasahara,[1] K. Sugii,[2] T. Ohnishi,[1] M. Shimozawa,[2] M. Yamashita,[2] N. Kurita,[3] H. Tanaka,[3] J. Nasu,[3] Y. Motome,[4] T. Shibauchi,[5] and Y. Matsuda[1]
[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*
[3]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[4]*Department of Applied Physics, University of Tokyo, Bunkyo, Tokyo 113-8656, Japan*
[5]*Department of Advanced Materials Science, University of Tokyo, Chiba 277-8561, Japan*

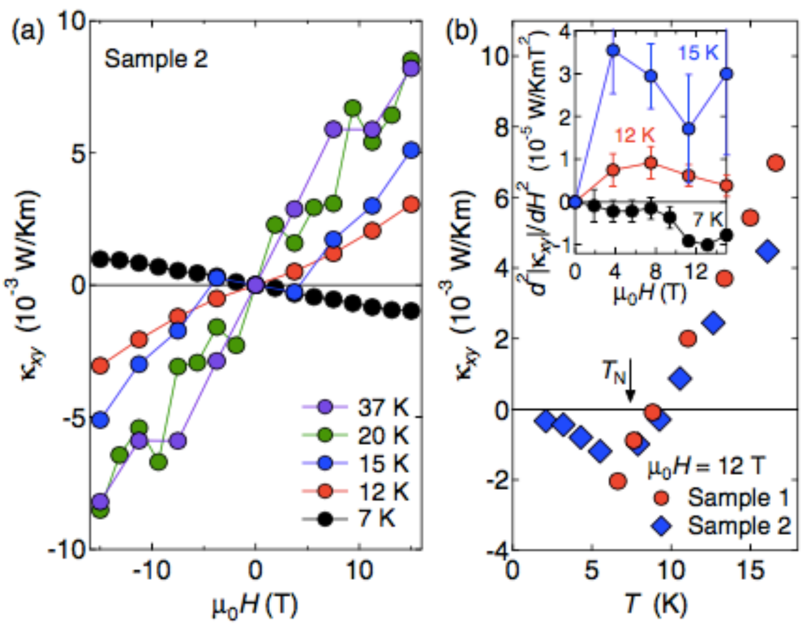


FIG. 3. (a) Field dependence of κ_{xy} for sample 2. (b) Temperature dependence of κ_{xy} near T_N. Inset shows the field dependence of $d^2|\kappa_{xy}(H)|/dH^2$ below and above T_N.

PHYSICAL REVIEW B **98**, 060412(R) (2018)

Rapid Communications

Spin-wave analysis of the low-temperature thermal Hall effect in the candidate Kitaev spin liquid α-$RuCl_3$

Jonathan Cookmeyer[1,*] and Joel E. Moore[1,2]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*

[2]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

Variational Monte Carlo of Proposed Hamiltonians → Spin Liquid Ground-States Not Preferred

$JK\Gamma$ Models

$K > 0$ → $\kappa \geq 0$ Inconsistent With Data!

Berry Curvature of Magnon Bands → κ_{xy}

Thermal Hall Effect of Magnons

Shuichi Murakami[1,2,3]* and Akihiro Okamoto[1]

[1]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[2]*TIES, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[3]*CREST, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*

(Received September 7, 2016; accepted October 21, 2016; published online December 8, 2016)

We review recent developments in theories and experiments on the magnon Hall effect. We derive the thermal Hall conductivity of magnons in terms of the Berry curvature of magnonic bands. In addition to the Dzyaloshinskii–Moriya interaction, we show that the dipolar interaction can make the Berry curvature nonzero. We mainly discuss theoretical aspects of the magnon Hall effect and related theoretical works. Experimental progress in this field is also mentioned.

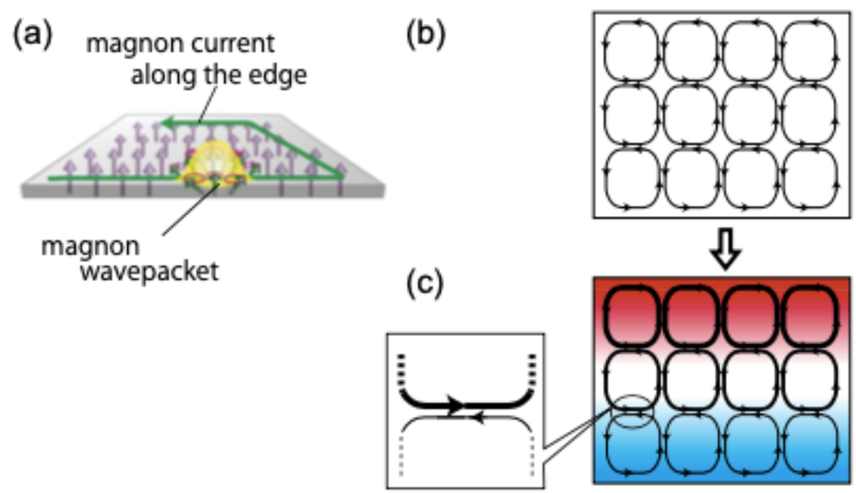


Fig. 2. (Color online) (a) Schematic of the magnon edge current. (b) Magnet in equilibrium, which is divided into small regions. The magnon edge currents within the neighboring regions cancel each other. (c) Magnet with the temperature gradient. The magnon edge currents in the small regions do not cancel, leading to a net transverse current.

PHYSICAL REVIEW B **98**, 060412(R) (2018)

Rapid Communications

Spin-wave analysis of the low-temperature thermal Hall effect in the candidate Kitaev spin liquid α-$RuCl_3$

Jonathan Cookmeyer[1,*] and Joel E. Moore[1,2]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*

[2]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

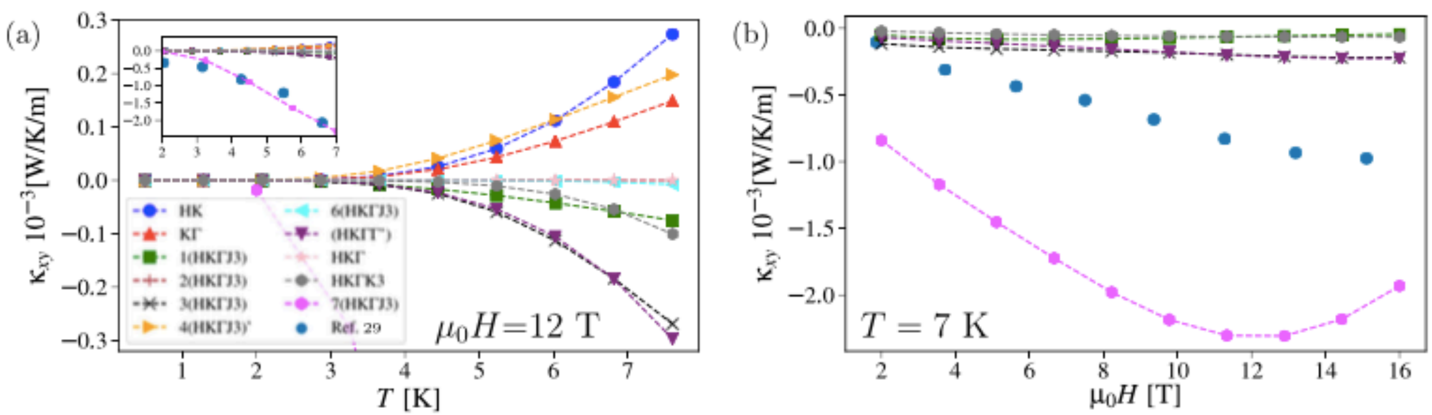


FIG. 2. We plot κ_{xy} as computed from Eq. (4) for the various models in Table I as a function of (a) temperature and (b) magnetic field. We also plot the data from Ref. [29] as blue dots. The inset of (a) shows a zoomed-out version of the same graph. In (b), models with $\kappa_{xy} \gtrsim 0$ were removed. Our model, which agrees well with the data in (a), does not agree with the data in (b). Since the data of Ref. [29] shows $\kappa_{xy} > 0$ at $T > T_N$ and excitations in the pure Kitaev model contribute to $\kappa_{xy} > 0$ [28], it is expected that at $T \approx T_N \approx 7$ K the contribution from just the magnons should be *below* the experimental data, as is true for our model. We do not plot $5(HK\Gamma J3)$ or $HK\Gamma J2$ since the zigzag spin-wave solution becomes unstable for some critical magnetic field $\mu_0 H < 10$ T. Our proposed model $7(HK\Gamma J3)$ has a large spin reduction $\Delta S_0/S \sim 0.9$ at $T = 7$ K.

www.sciencemag.org SCIENCE VOL 329 16 JULY 2010

Observation of the Magnon Hall Effect

Y. Onose,[1,2]* T. Ideue,[1] H. Katsura,[3] Y. Shiomi,[1,4] N. Nagaosa,[1,4] Y. Tokura[1,2,4]

The Hall effect usually occurs in conductors when the Lorentz force acts on a charge current in the presence of a perpendicular magnetic field. Neutral quasi-particles such as phonons and spins can, however, carry heat current and potentially exhibit the thermal Hall effect without resorting to the Lorentz force. We report experimental evidence for the anomalous thermal Hall effect caused by spin excitations (magnons) in an insulating ferromagnet with a pyrochlore lattice structure. Our theoretical analysis indicates that the propagation of the spin waves is influenced by the Dzyaloshinskii-Moriya spin-orbit interaction, which plays the role of the vector potential, much as in the intrinsic anomalous Hall effect in metallic ferromagnets.

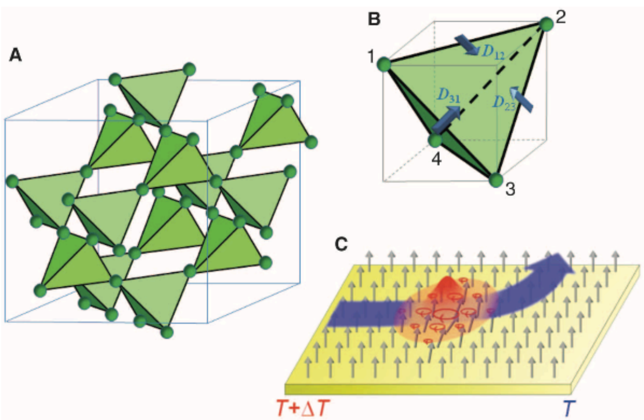
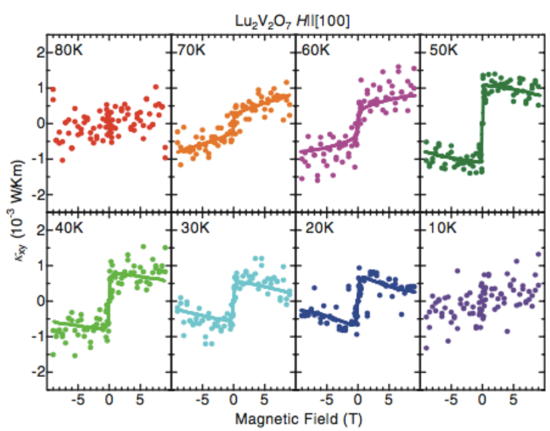


Fig. 1. The crystal structure of $Lu_2V_2O_7$ and the magnon Hall effect. **(A)** The V sublattice of $Lu_2V_2O_7$, which is composed of corner-sharing tetrahedra. **(B)** The direction of the Dzyaloshinskii-Moriya vector $\vec{D}_{ij}$ on each bond of the tetrahedron. The Dzyaloshinskii-Moriya interaction $\vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$ acts between the i and j sites. **(C)** The magnon Hall effect. A wave packet of magnon (a quantum of spin precession) moving from the hot to the cold side is deflected by the Dzyaloshinskii-Moriya interaction playing the role of a vector potential.

Fig. 3. Magnetic field variation of the thermal Hall conductivity of $Lu_2V_2O_7$ at various temperatures. The magnetic field is applied along the [100] direction. The solid lines are guides to the eye.



www.sciencemag.org SCIENCE VOL 329 16 JULY 2010

Observation of the Magnon Hall Effect

Y. Onose,[1,2]* T. Ideue,[1] H. Katsura,[3] Y. Shiomi,[1,4] N. Nagaosa,[1,4] Y. Tokura[1,2,4]

The Hall effect usually occurs in conductors when the Lorentz force acts on a charge current in the presence of a perpendicular magnetic field. Neutral quasi-particles such as phonons and spins can, however, carry heat current and potentially exhibit the thermal Hall effect without resorting to the Lorentz force. We report experimental evidence for the anomalous thermal Hall effect caused by spin excitations (magnons) in an insulating ferromagnet with a pyrochlore lattice structure. Our theoretical analysis indicates that the propagation of the spin waves is influenced by the Dzyaloshinskii-Moriya spin-orbit interaction, which plays the role of the vector potential, much as in the intrinsic anomalous Hall effect in metallic ferromagnets.

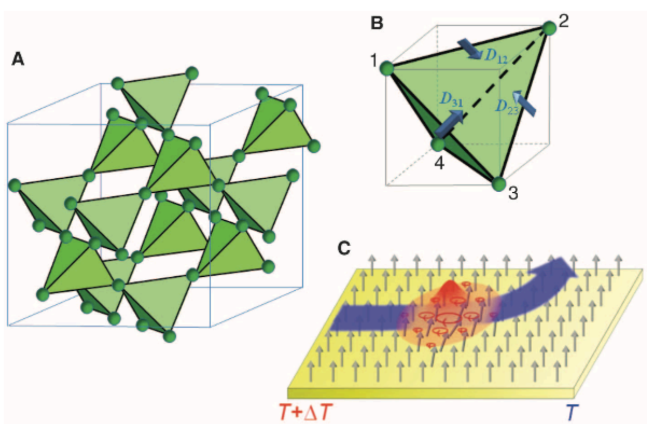


Fig. 1. The crystal structure of $Lu_2V_2O_7$ and the magnon Hall effect. **(A)** The *V* sublattice of $Lu_2V_2O_7$, which is composed of corner-sharing tetrahedra. **(B)** The direction of the Dzyaloshinskii-Moriya vector $\vec{D}_{ij}$ on each bond of the tetrahedron. The Dzyaloshinskii-Moriya interaction $\vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$ acts between the *i* and *j* sites. **(C)** The magnon Hall effect. A wave packet of magnon (a quantum of spin precession) moving from the hot to the cold side is deflected by the Dzyaloshinskii-Moriya interaction playing the role of a vector potential.

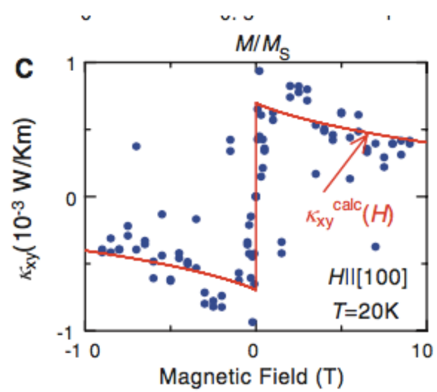


Fig. 4. **(A)** Temperature dependence of the spontaneous thermal Hall conductivity (the thermal Hall conductivity just above the saturation field) for *H* || [100], *H* || [110], and *H* || [111]. The thick dashed line is a guide to the eye. **(B)** The thermal Hall angle κ_{xy}/κ_{xx} plotted against the magnetization (*M*). For $Tb_3Ga_5O_{12}$ (dashed line), the value of κ_{xy}/κ_{xx} divided by the magnetic field *H* is taken from (*7*), and the magnetic susceptibility (*M/H*) is estimated from the magnetization curves in (*18*). The thick solid line is a guide to the eye. **(C)** Magnetic field variation of the thermal Hall conductivity at 20 K for *H* || [100]. The red solid line indicates the magnetic field dependence given by the theory (Eq. 4) that is based on the Dzyaloshinskii-Moriya interaction.

PHYSICAL REVIEW B **85**, 134411 (2012)

Effect of lattice geometry on magnon Hall effect in ferromagnetic insulators

T. Ideue,[1] Y. Onose,[1,2] H. Katsura,[3] Y. Shiomi,[1] S. Ishiwata,[1] N. Nagaosa,[1,4] and Y. Tokura[1,2,4]

[1]*Department of Applied Physics, University of Tokyo, Tokyo 113-8656, Japan*

[2]*Multiferroics Project, ERATO, Japan Science and Technology Agency (JST), Tokyo 113-8656, Japan*

[3]*Department of Physics, Gakushuin University, Tokyo 171-8588, Japan*

[4]*Cross-Correlated Materials Research Group (CMRG) and Correlated Electron Research Group (CERG), RIKEN Advanced Science Institute, Wako 351-0198, Japan*

(Received 5 January 2012; published 4 April 2012)

We have investigated the thermal Hall effect of magnons for various ferromagnetic insulators. For pyrochlore ferromagnetic insulators $Lu_2V_2O_7$, $Ho_2V_2O_7$, and $In_2Mn_2O_7$, finite thermal Hall conductivities have been observed below the Curie temperature T_C. From the temperature and magnetic-field dependencies, it is concluded that magnons are responsible for the thermal Hall effect. The Hall effect of magnons can be well explained by the theory based on the Berry curvature in momentum space induced by the Dzyaloshinskii-Moriya (DM) interaction. The analysis has been extended to the transition-metal (TM) oxides with perovskite structure. The thermal Hall signal was absent or far smaller in La_2NiMnO_6 and $YTiO_3$, which have the distorted perovskite structure with four TM ions in the unit cell. On the other hand, a finite thermal Hall response is discernible below T_C in another ferromagentic perovskite oxide $BiMnO_3$, which shows orbital ordering with a larger unit cell. The presence or absence of the thermal Hall effect in insulating pyrochlore and perovskite systems reflect the geometric and topological aspect of DM-induced magnon Hall effect.

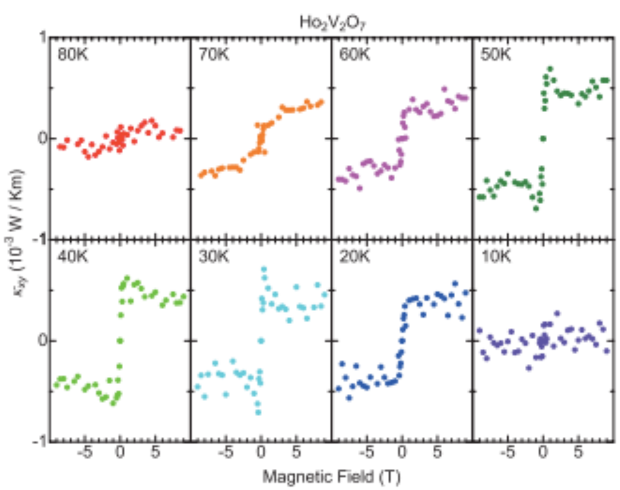


FIG. 5. (Color online) Magnetic-field variation of the thermal Hall conductivity for $Ho_2V_2O_7$ at various temperatures.

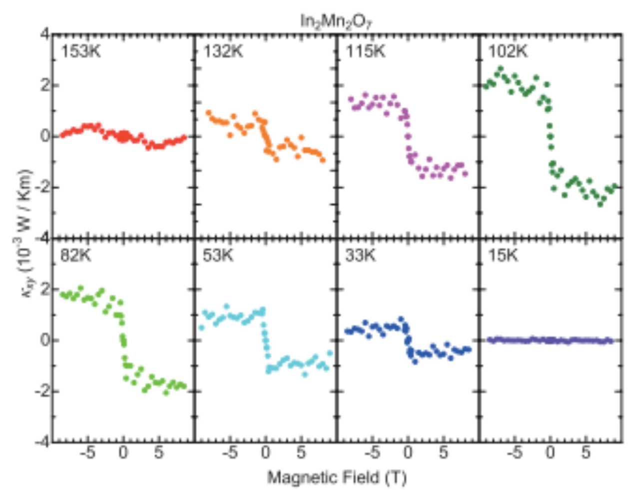


FIG. 6. (Color online) Magnetic-field variation of the thermal Hall conductivity for $In_2Mn_2O_7$ at various temperatures.

PHYSICAL REVIEW B **102**, 220404(R) (2020)

Rapid Communications

Sample dependence of half-integer quantized thermal Hall effect in the Kitaev spin-liquid candidate α-$RuCl_3$

M. Yamashita[1,*] J. Gouchi,[1] Y. Uwatoko,[1] N. Kurita,[2] and H. Tanaka[2]

[1]*Institute for Solid State Physics, The University of Tokyo, Kashiwa, 277-8581, Japan*

[2]*Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*

(Received 27 April 2020; revised 13 November 2020; accepted 23 November 2020; published 7 December 2020)

We have investigated the sample dependence of the half-integer thermal Hall effect in α-$RuCl_3$ under a magnetic field tilted 45° from the *c* axis to the *a* axis. We find that the sample with the largest longitudinal thermal conductivity κ_{xx} shows the half-integer quantized thermal Hall effect expected in the Kitaev model. On the other hand, the quantized thermal Hall effect was not observed in the samples with smaller κ_{xx}. We suggest that suppressing the magnetic scattering effects on the phonon thermal conduction, which broaden the field-induced gap protecting the chiral edge current of the Majorana fermions, is important to observe the quantized thermal Hall effect.

???

Have a Good Spring Break!