New Kitaev Materials

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Gordon and Betty Moore Foundation

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Long Term Collaborators on Kitaev Materials

Growth and Characterization

Jiaqiang Yan
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Scattering

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Arnab Banerjee
Matt Stone
Mark Lumsden
Alan Tennant
Paige Kelley
Christian Balz

Theory and Modeling

Roderich Moessner
Johannes Knolle
Cristian Batista

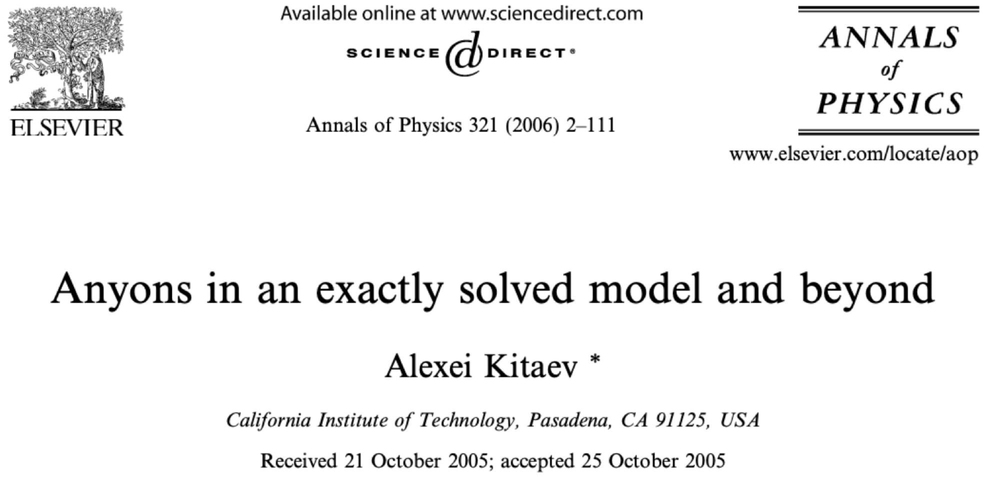
“Everything not forbidden is compulsory.”

--Murry Gell-Mann

Among baryons, antibaryons, and mesons, any process which is not forbidden by a conservation law actually does take place with appreciable probability. We have made liberal and tacit use of this assumption…

If a state of matter is allowed by physics,
it exists and we can find it.

Alexei Kitaev



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Anyons in an exactly solved model and beyond

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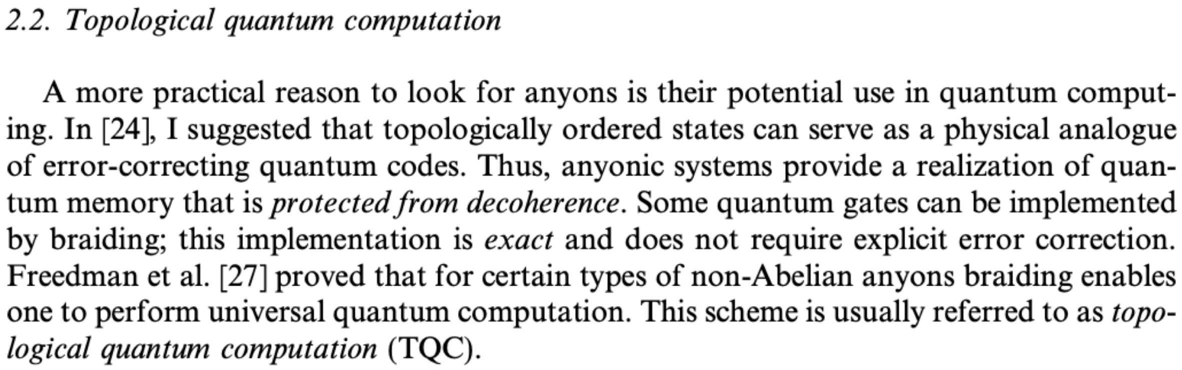
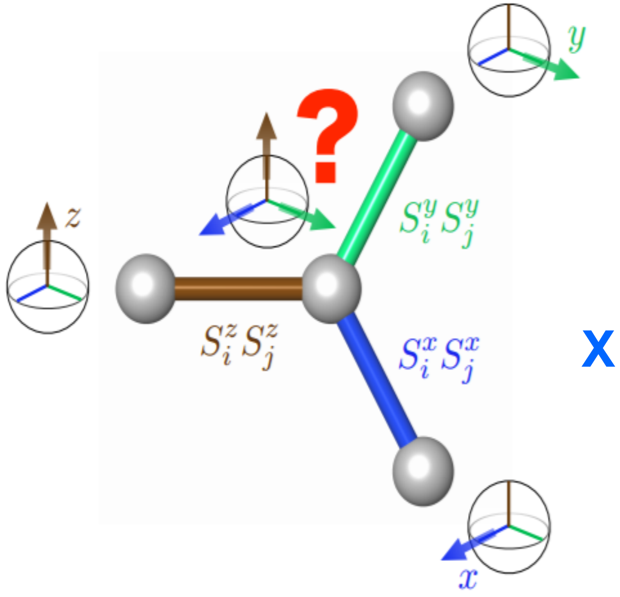


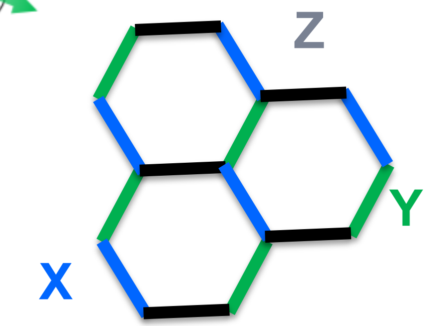
2.2. Topological quantum computation

A more practical reason to look for anyons is their potential use in quantum computing. In [24], I suggested that topologically ordered states can serve as a physical analogue of error-correcting quantum codes. Thus, anyonic systems provide a realization of quantum memory that is *protected from decoherence*. Some quantum gates can be implemented by braiding; this implementation is *exact* and does not require explicit error correction. Freedman et al. [27] proved that for certain types of non-Abelian anyons braiding enables one to perform universal quantum computation. This scheme is usually referred to as *topological quantum computation* (TQC).

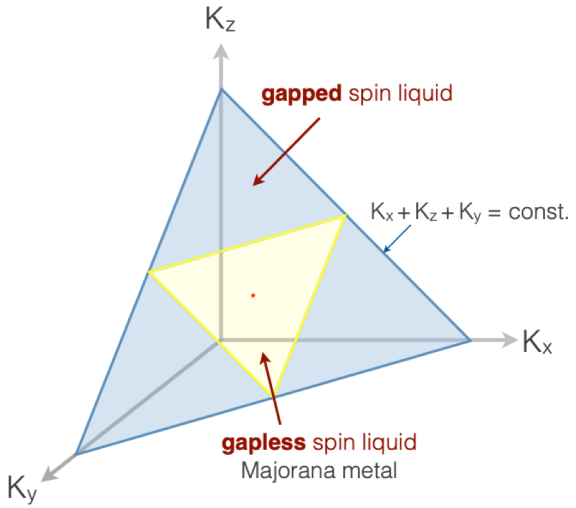
Kitaev model

- Bond-directional dependent Ising coupling → exchange frustration
- Ground state for S=1/2 moments on a 2D honeycomb lattice is an exactly solvable quantum spin liquid (QSL)
- Fractionalized spin excitations in the QSL are topologically protected gauge flux and Majorana fermion pairs





Trebst, arXiv:1701.07056



Two types of excitations in Kitaev spin liquid

Fractionalization of quantum spins

Spin 1/2 → Itinerant Majorana fermion

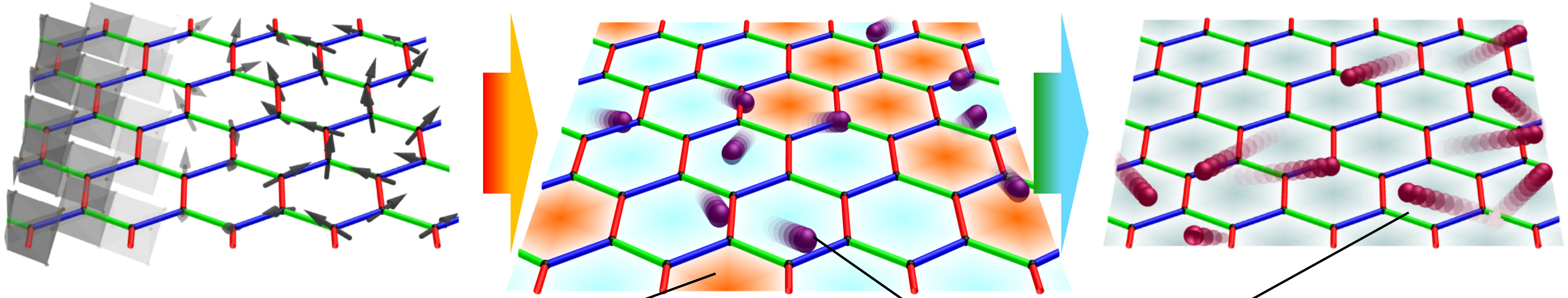
Spin 1/2 → Localized Majorana fermion

→ Z_2 fluxes (Vison)

$T > J_K$
Paramagnetic

$T < J_K$
Spin fractionalization

$T \ll J_K$
Quantum spin liquid



Z_2 flux

Itinerant Majorana fermions

Slide from Y. Matsuda

PRL **102,** 017205 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

Mott Insulators in the Strong Spin-Orbit Coupling Limit: From Heisenberg to a Quantum Compass and Kitaev Models

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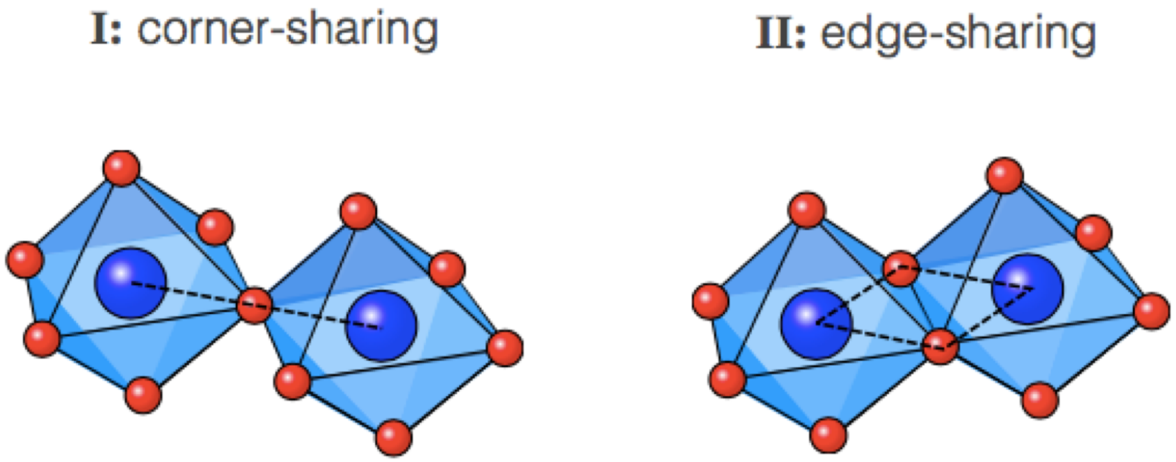


Image from Trebst

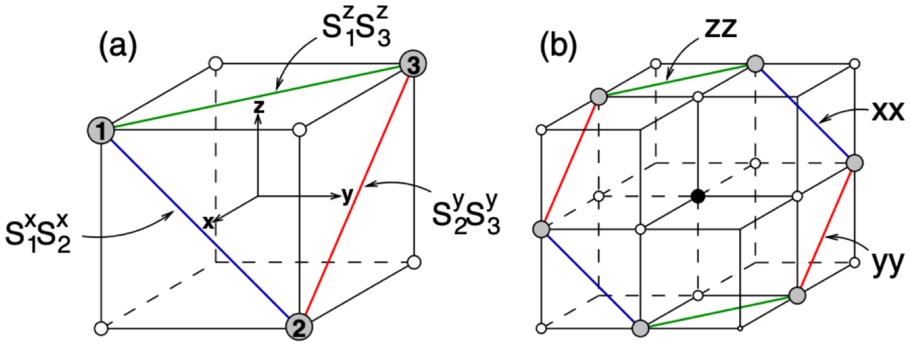


Image from Jackeli and G. Khaliullin

Proposed physical realization: Edge-sharing octahedra in honeycomb J_{eff} = ½ Mott insulators leads to bond directional, Kitaev-like exchange

How do you make a J_{eff} = ½ Mott Insulator?

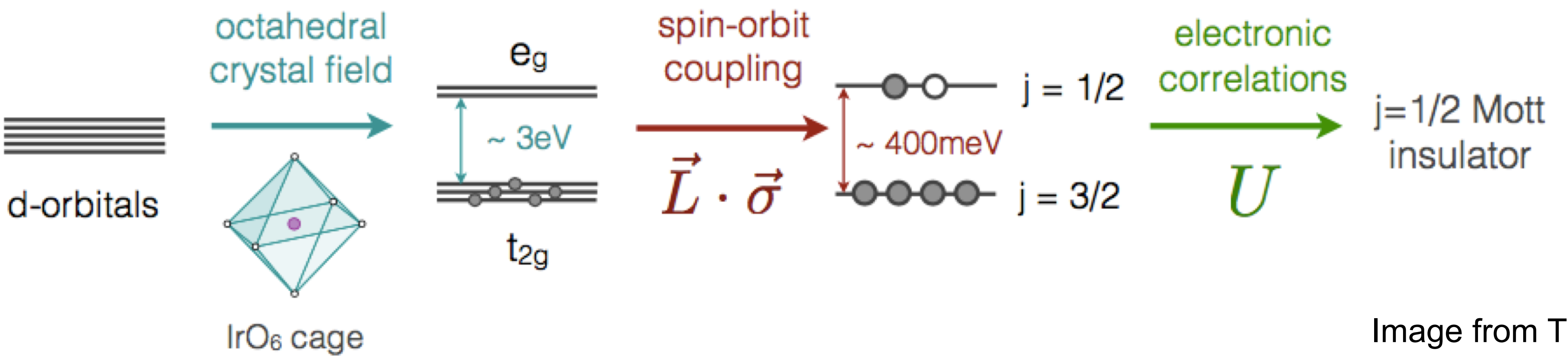


Image from Trebst

Available 4*d*/5*d* ions include: Re^{2+}, Ru^{3+}, Os^{3+}, Rh^{4+}, and Ir^{4+} .

More Realistic Hamiltonians

Generic Hamiltonian

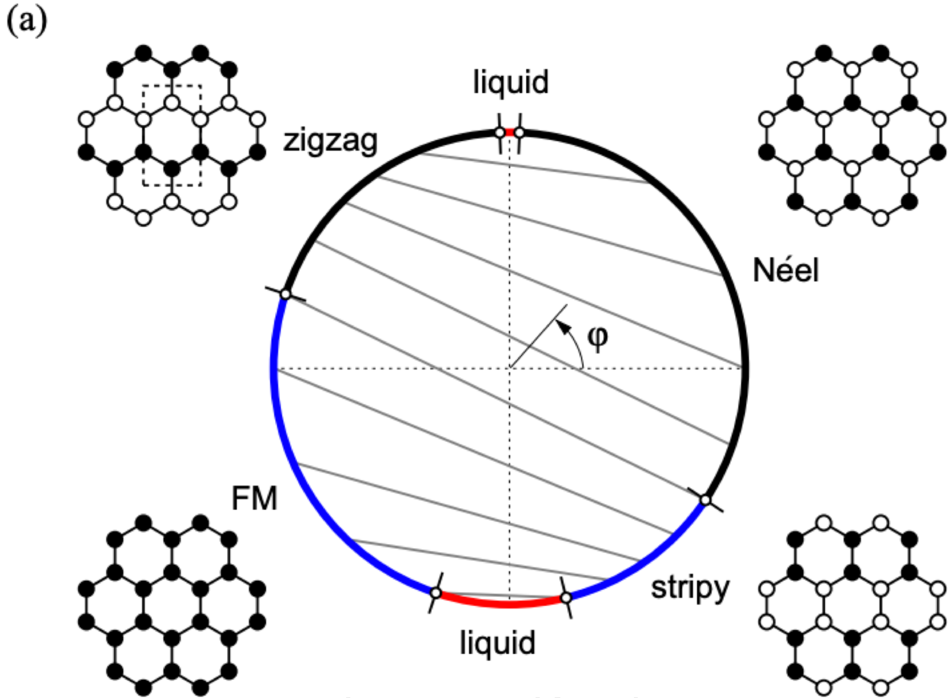
$$H = - \sum_{\gamma-\text{bonds}} J\, \mathbf{S}_i \mathbf{S}_j + K\ S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right) ,$$

J is the isotropic Heisenberg coupling

K is the Kitaev coupling

Γ is a symmetric off-diagonal exchange that couples the two orthogonal spin components α, β ⊥ Ɣ for a bond along the Ɣ = x, y, z direction.

Heisenberg Kitaev model (Γ = 0)

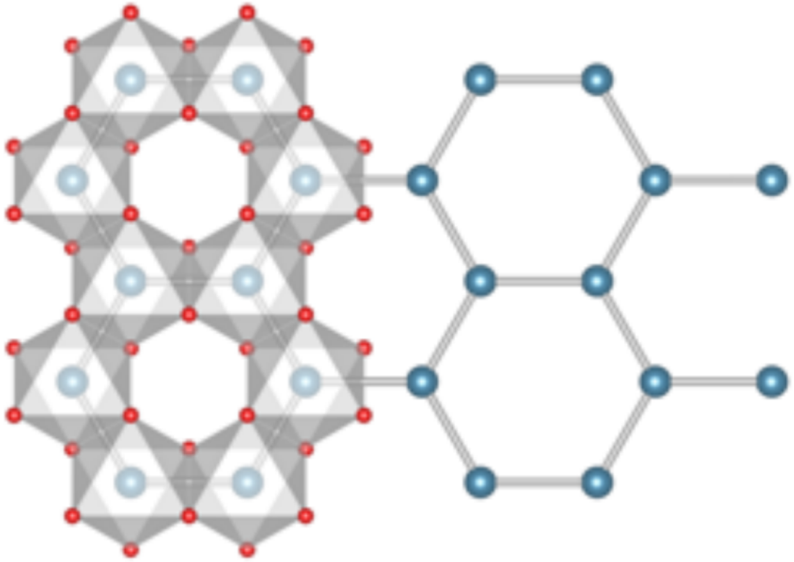


J = cos φ, K = sin φ

$$H = - \sum_{\gamma-\text{bonds}} J\, \mathbf{S}_i \mathbf{S}_j + K\ S_i^\gamma S_j^\gamma$$

Chaloupka, Jackeli, and Khaliullin

Na_2IrO_3 – the first Kitaev material



LETTERS

PUBLISHED ONLINE: 11 MAY 2015 | DOI: 10.1038/NPHYS3322

nature physics

Direct evidence for dominant bond-directional interactions in a honeycomb lattice iridate Na_2IrO_3

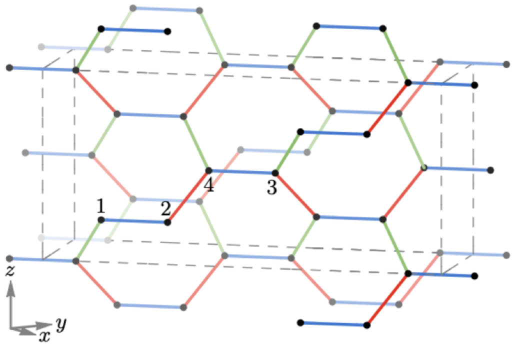
Sae Hwan Chun[1], Jong-Woo Kim[2], Jungho Kim[2], H. Zheng[1], Constantinos C. Stoumpos[1], C. D. Malliakas[1], J. F. Mitchell[1], Kavita Mehlawat[3], Yogesh Singh[3], Y. Choi[2], T. Gog[2], A. Al-Zein[4], M. Moretti Sala[4], M. Krisch[4], J. Chaloupka[5], G. Jackeli[6,7], G. Khaliullin[6] and B. J. Kim[6]*

Honeycomb lattice
J_{eff} = ½ Mott Insulator
Zig-zag magnetic order, T_N=15 K
Small trigonal distortion of the IrO_6 octahedra

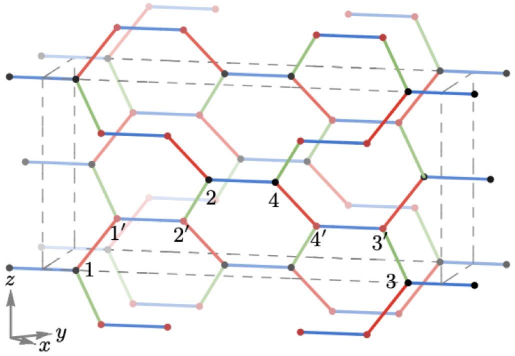
Idea: if Na is replaced by Li we can move closer to ideal Kitaev model

α-Li_2IrO_3

Work on Li_2IrO_3 led to the discovery of hyper-honeycomb β-Li_2IrO_3 (Takagi) and stripy-honeycomb γ-Li_2IrO_3 (Analytis).



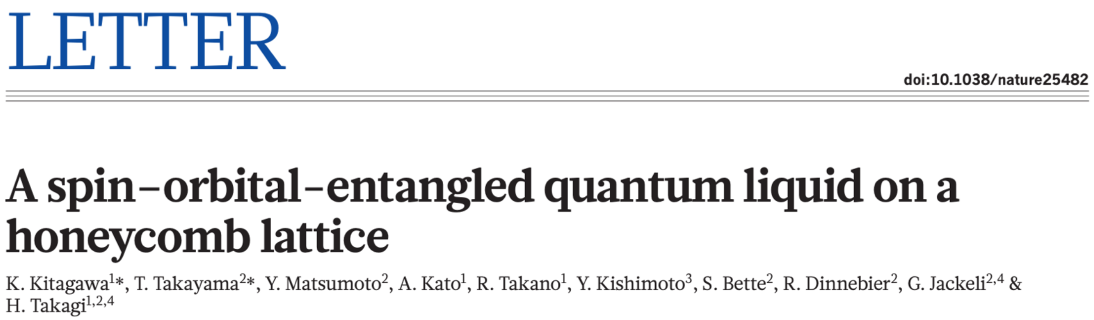
(a) Hyper-honeycomb lattice



(b) Stripy-honeycomb lattice

Image from Lee, Rau, and Kim

- α-Li_2IrO_3 is isostructural to Na_2IrO_3
- Difficult to grow large crystals
- Iridium is not neutron friendly
- T_N = 15 K
- Unusual incommensurate magnetic order with counterrotating moments on NN Ir sites
- Similar counter-rotating spiral magnetism in all polymorphs
- Kitaev interactions in α-Li_2IrO_3 are enhanced compared to Na_2IrO_3
- Is it possible to go smaller than Li?



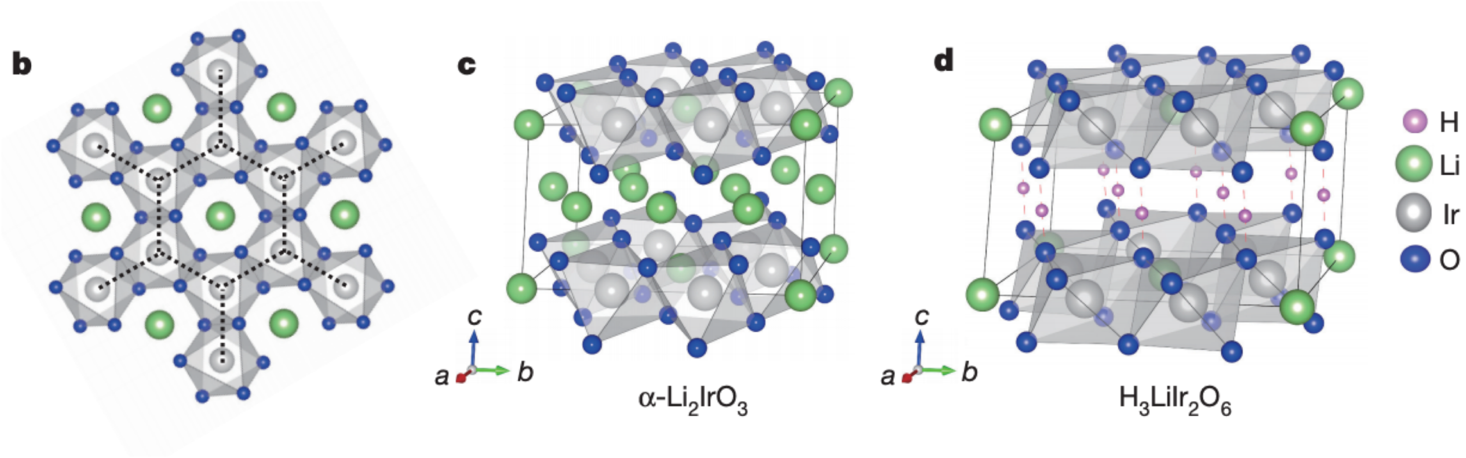
LETTER

doi:10.1038/nature25482

A spin–orbital-entangled quantum liquid on a honeycomb lattice

K. Kitagawa[1]*, T. Takayama[2]*, Y. Matsumoto[2], A. Kato[1], R. Takano[1], Y. Kishimoto[3], S. Bette[2], R. Dinnebier[2], G. Jackeli[2,4] & H. Takagi[1,2,4]

Use ion exchange to replace Li with H



α-Li_2IrO_3

$H_3LiIr_2O_6$

All of the interlayer Li+ ions of α-Li2IrO3 are replaced with H^+ ions but the $LiIr_2O_6$ honeycomb plane remains as it was.

"We therefore conclude that $H_3LiIr_2O_6$ is a quantum spin liquid."

N.B. The authors have not yet claimed $H_3LiIr_2O_6$ is a Kitaev QSL

$H_3LiIr_2O_6$

$LiIr_2O_6$ layers have very strong Kitaev interactions.

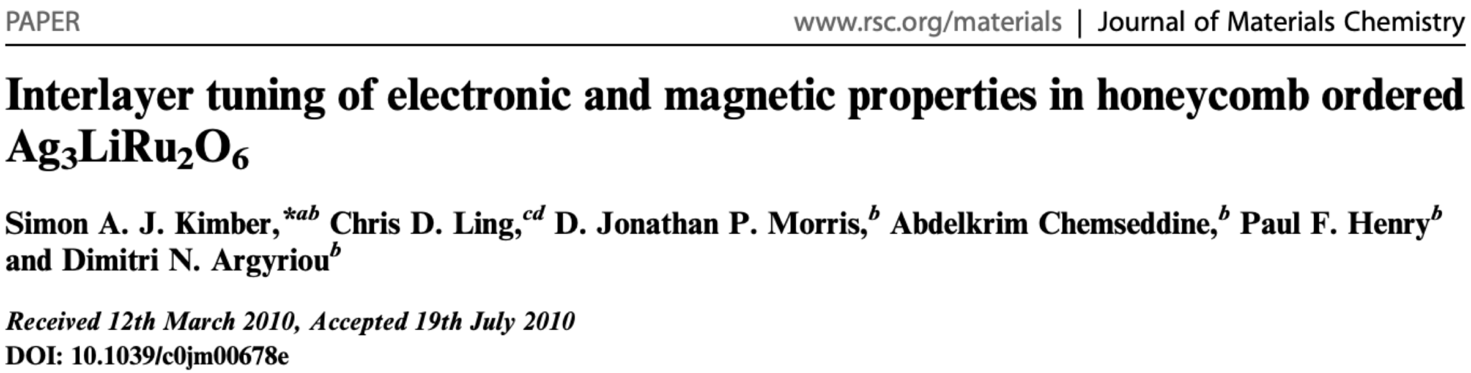
No magnetic order down to 50 mK.

Caveats:

i) the specific heat displays a low-temperature divergence of $C/T \propto T^{-1/2}$; however the Kitaev model has vanishing specific heat.

ii) only a small fraction of the total magnetic entropy is released experimentally; however the Kitaev model releases half its entropy at low T.

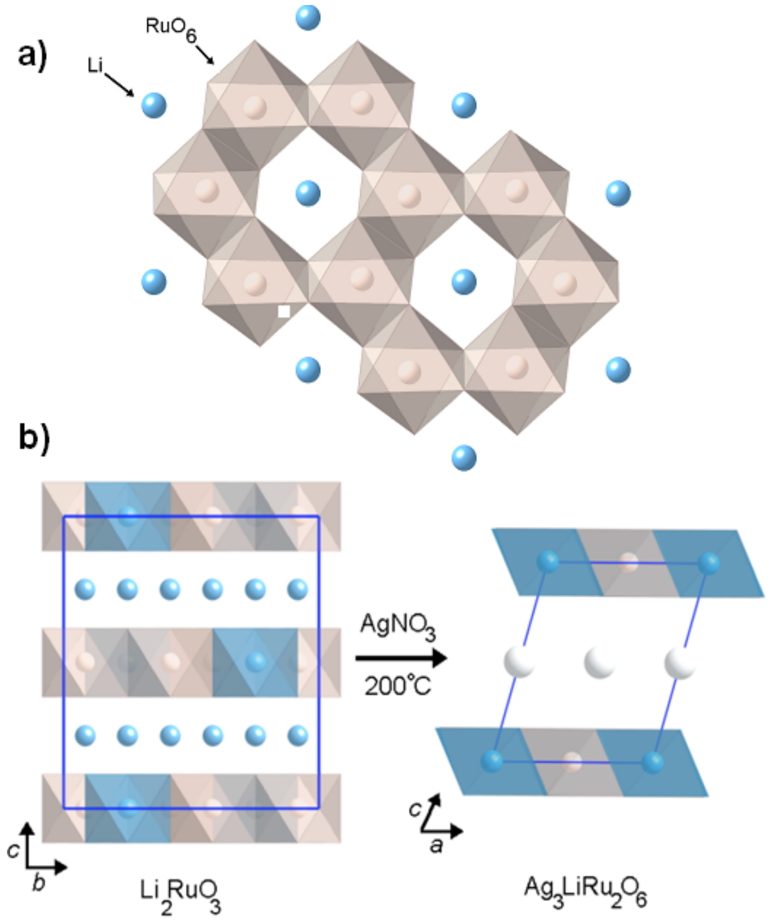
Ion Exchange Reactions



Interlayer tuning of electronic and magnetic properties in honeycomb ordered $Ag_3LiRu_2O_6$

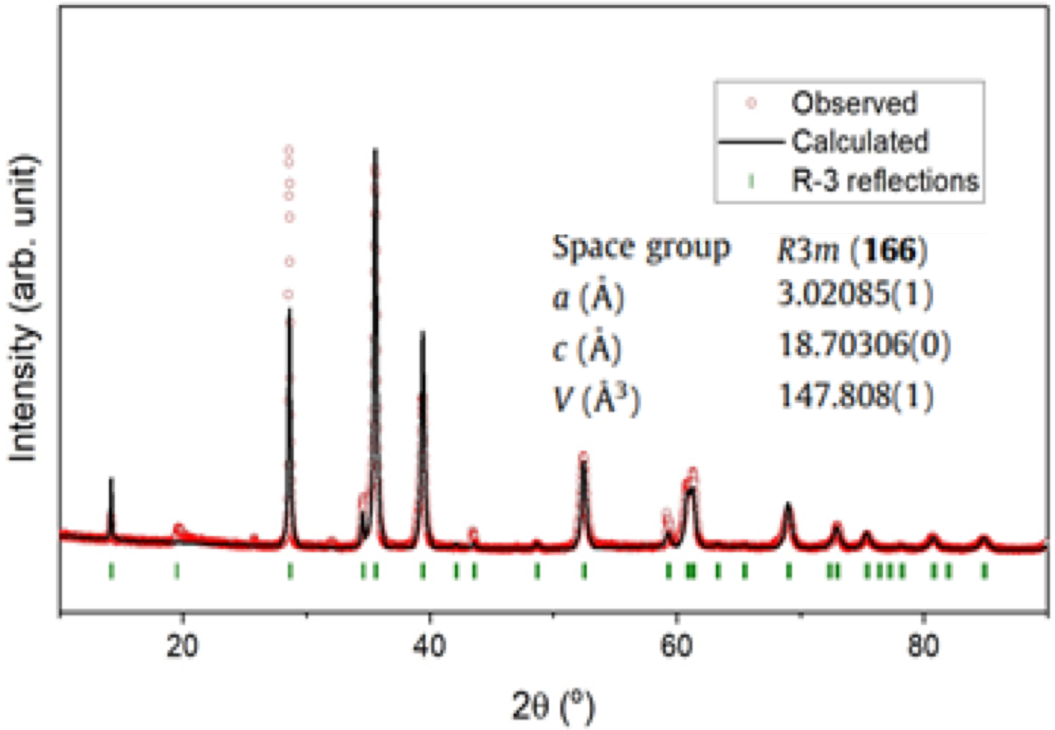
Simon A. J. Kimber,[*ab] **Chris D. Ling,**[cd] **D. Jonathan P. Morris,**[b] **Abdelkrim Chemseddine,**[b] **Paul F. Henry**[b] **and Dimitri N. Argyriou**[b]

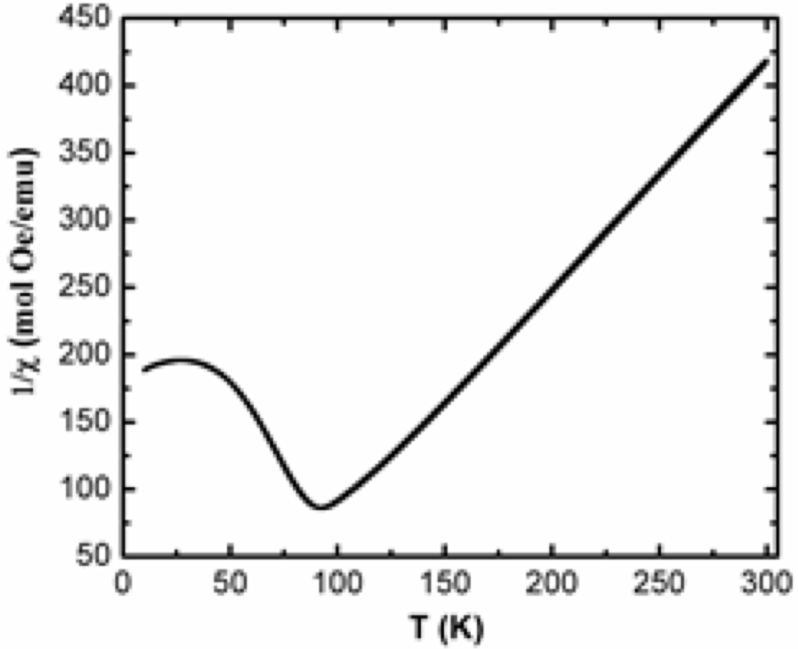
Received 12th March 2010, Accepted 19th July 2010
DOI: 10.1039/c0jm00678e



Starting compound	$AgNO_3$ exchange targets	CuCl exchange targets
Li_2RhO_3	$Ag_3LiRh_2O_6$	$Cu_3LiRh_2O_6$
Na_2RhO_3	$Ag_3NaRh_2O_6$	$Cu_3NaRh_2O_6$
Li_2IrO_3	$Ag_3LiIr_2O_6$	$Cu_3LiIr_2O_6$
Na_2IrO_3	$Ag_3NaIr_2O_6$	$Cu_3NaIr_2O_6$

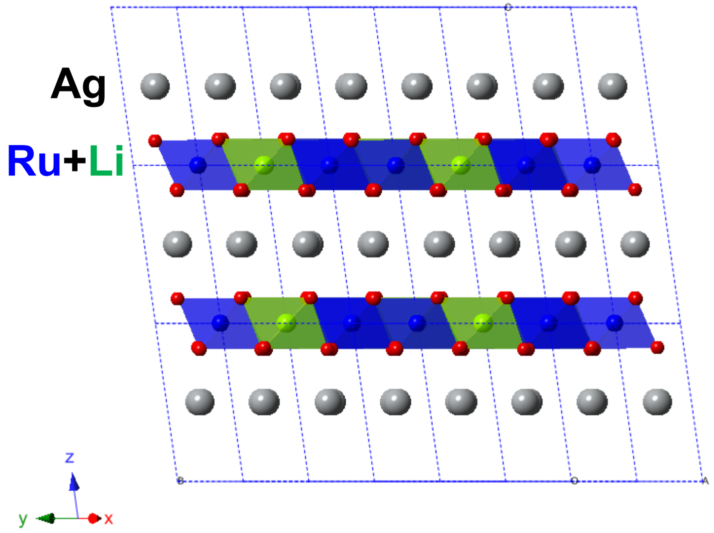
Ag3LiRh2O6


Observed
Calculated
R-3 reflections
Space group R3m (166)
a (Å) 3.02085(1)
c (Å) 18.70306(0)
V (Å³) 147.808(1)
Intensity (arb. unit)
20
40
60
80
2θ (°)

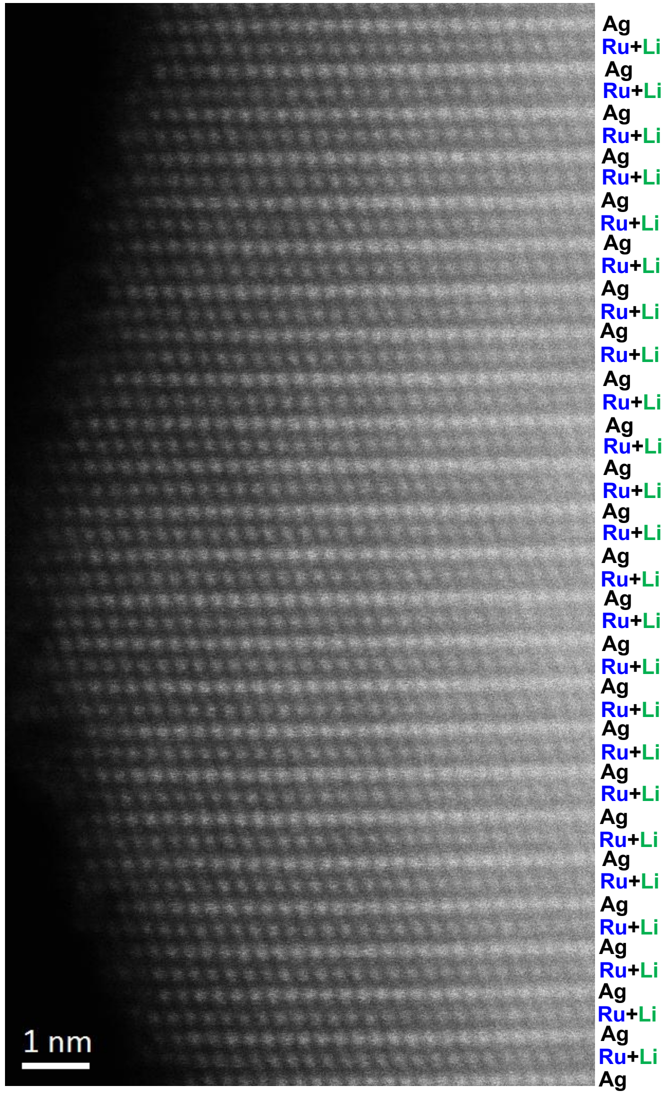

1/χ (mol Oe/emu)
450
400
350
300
250
200
150
100
50
0
50
100
150
200
250
300
T (K)

Ag3LiRu2O6: *C*12/*m*1
a = 5.2259(6) Å, b = 9.0356(10) Å, c = 6.5267(6) Å, b = 105.716(10) Å

Along [310]



HAADF-STEM (Z-contrast) image along [310]



No obvious Ag vacancy was observed.

Ru also distributes homogenously.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Article

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Cu_2IrO_3: A New Magnetically Frustrated Honeycomb Iridate

Mykola Abramchuk,[†] Cigdem Ozsoy-Keskinbora,[‡] Jason W. Krizan,[†] Kenneth R. Metz,[§] David C. Bell,[‡,⊥] and Fazel Tafti*[,†]

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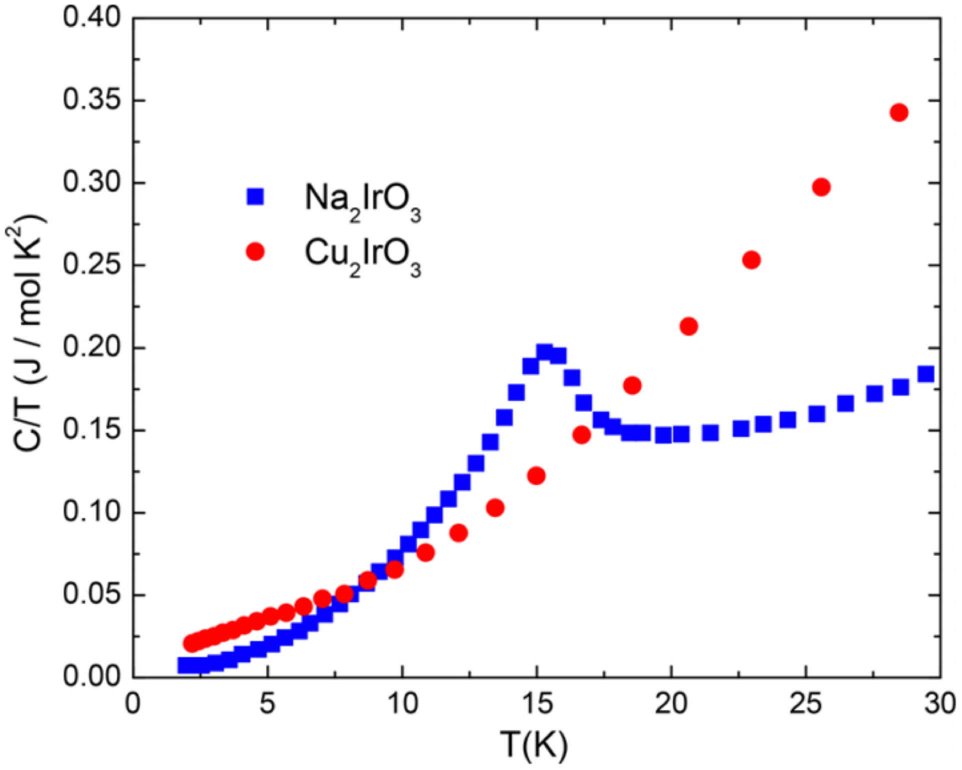
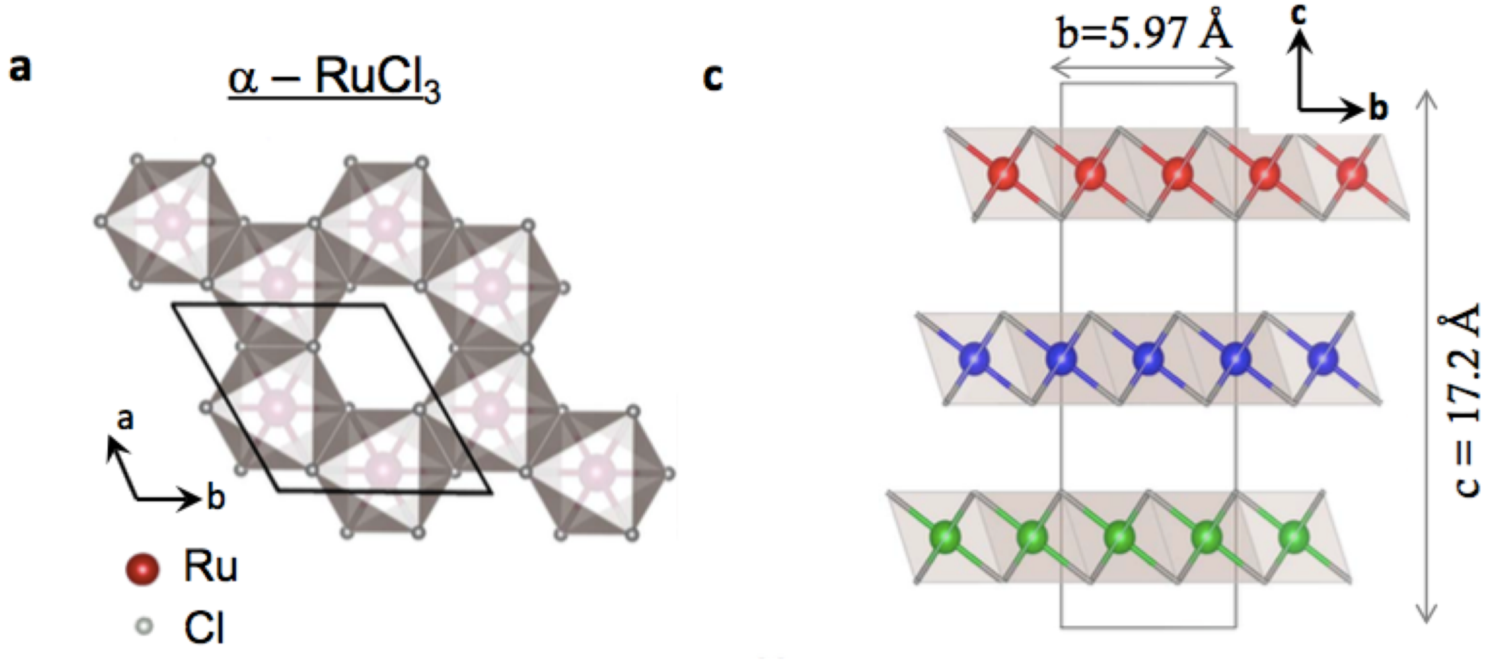
[‡]Harvard John A. Paulson School of Engineering and Applied Sciences and [⊥]Center for Nanoscale Systems, Harvard University, Cambridge, Massachusetts 02138, United States

Cu_2IrO_3 was synthesized using a topotactic cation exchange reaction according to $Na_2IrO_3 + 2CuCl \rightarrow Cu_2IrO_3 + 2NaCl$ under mild conditions (350 °C and 16 h).

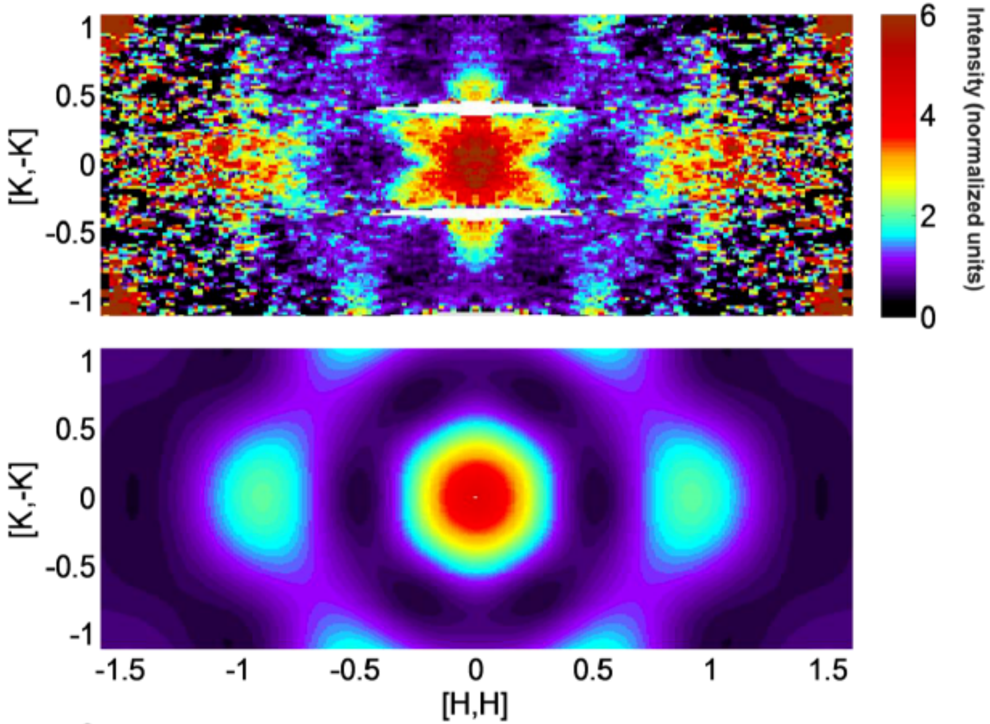


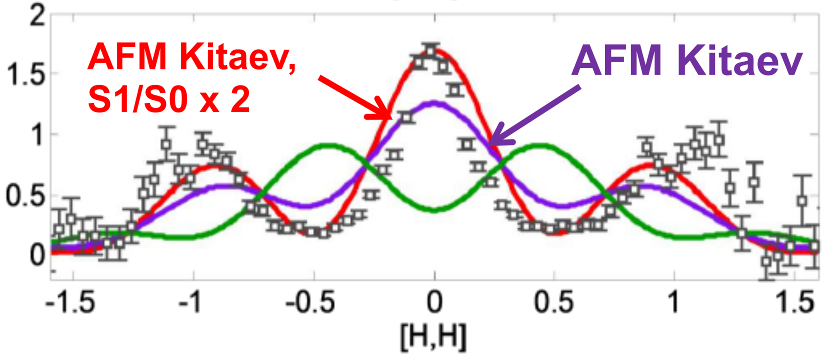
Moving away from Ir – $RuCl_3$



- Quasi-2D system with a van der Waals gap
- Honeycomb lattice
- Jeff = ½ Mott Insulator
- Orders magnetically at 7 K

RuCl$_3$ comparison with Kitaev model calculation

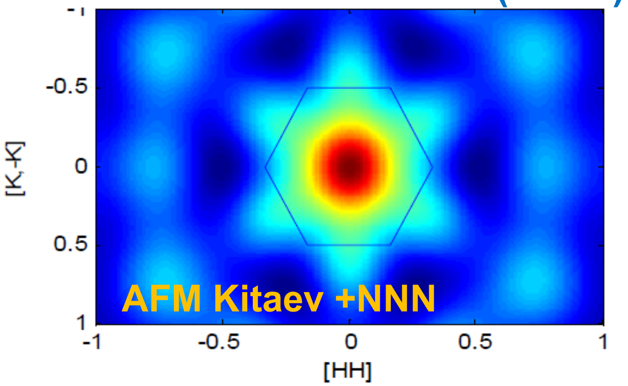




- Form factor and instrumental resolution included for comparison with experiment
- Central part of the scattering is described well by Kitaev Majorana mode

Kitaev QSL only depends on self- (S0) and NN (S1) correlations. Nearly quantitative agreement is found for:

- Enhanced S1/S0 (~2x)
- NNN correlations (~10%)



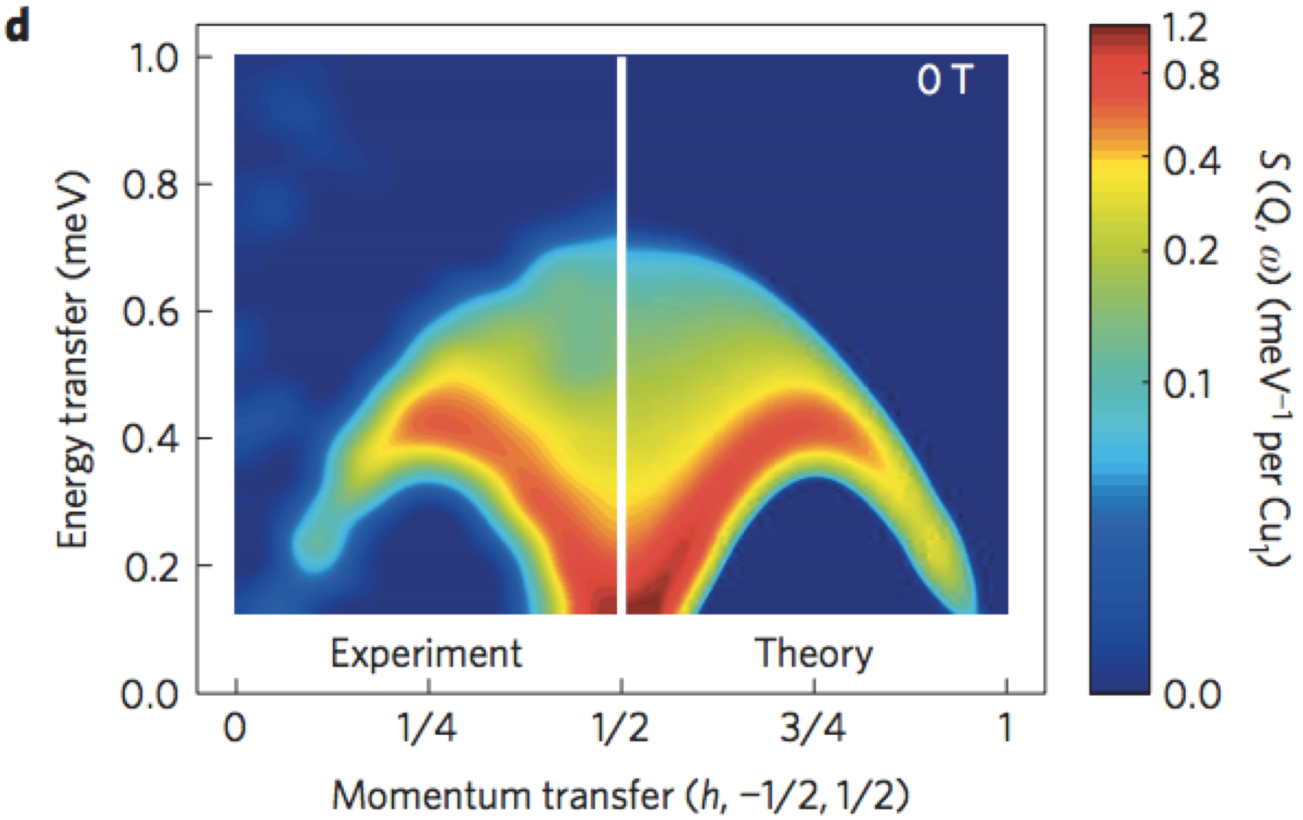
nature physics

ARTICLES
PUBLISHED ONLINE: 16 JUNE 2013 | DOI:10.1038/NPHYS2652

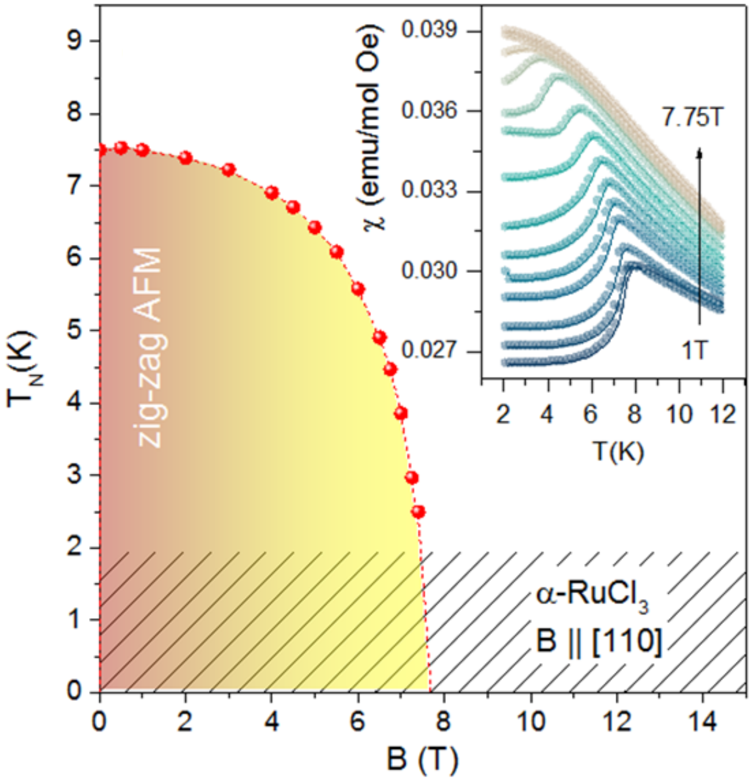
Fractional spinon excitations in the quantum Heisenberg antiferromagnetic chain

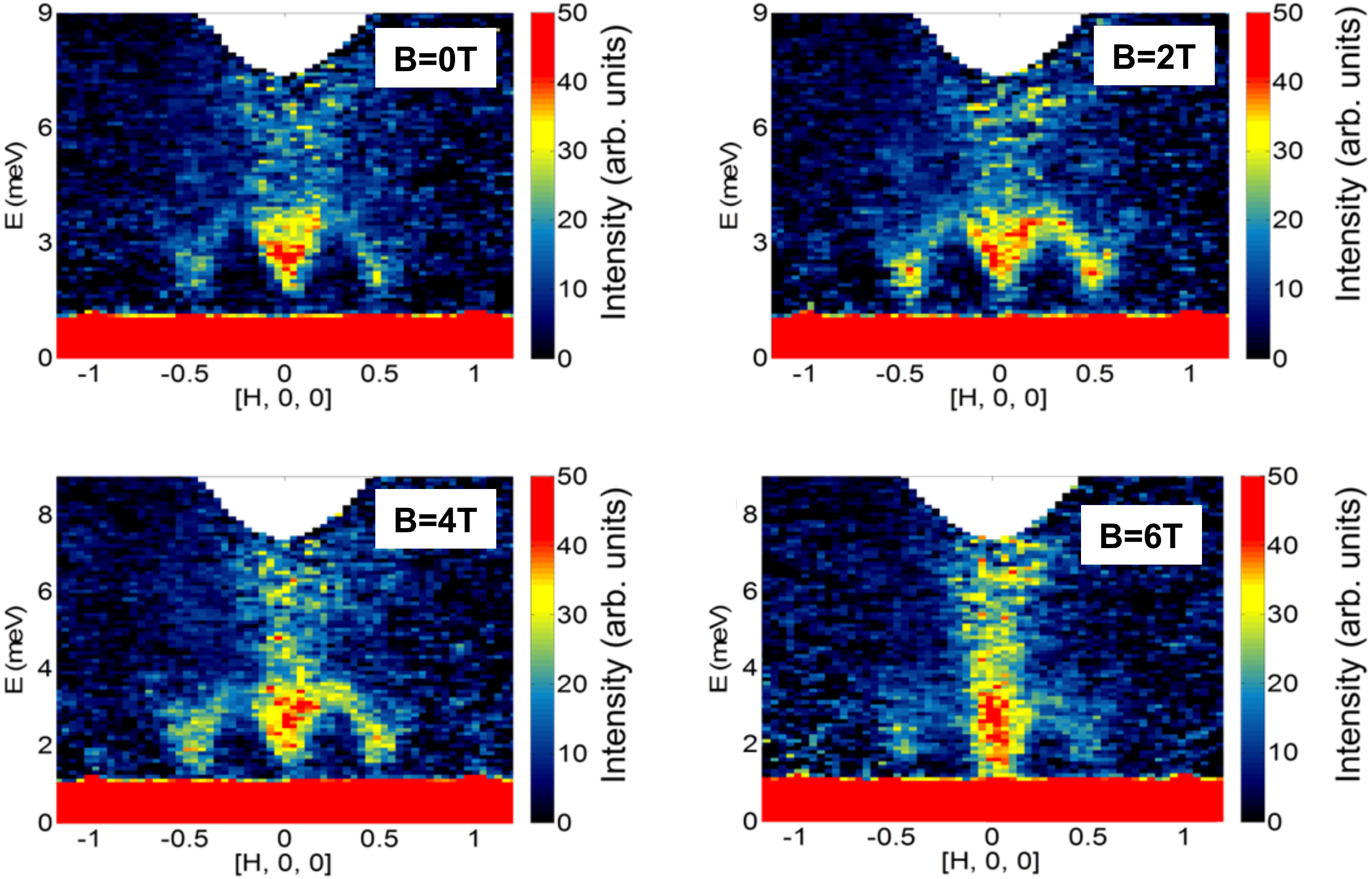
Martin Mourigal[1,2,3]★, Mechthild Enderle[1], Axel Klöpperpieper[4], Jean-Sébastien Caux[5], Anne Stunault[1] and Henrik M. Rønnow[2]

$CuSO_4{\cdot}5D_2O$.

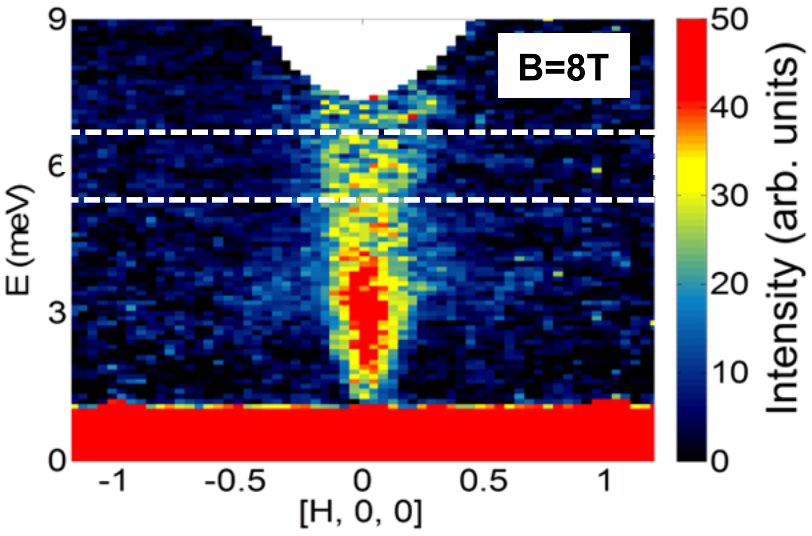


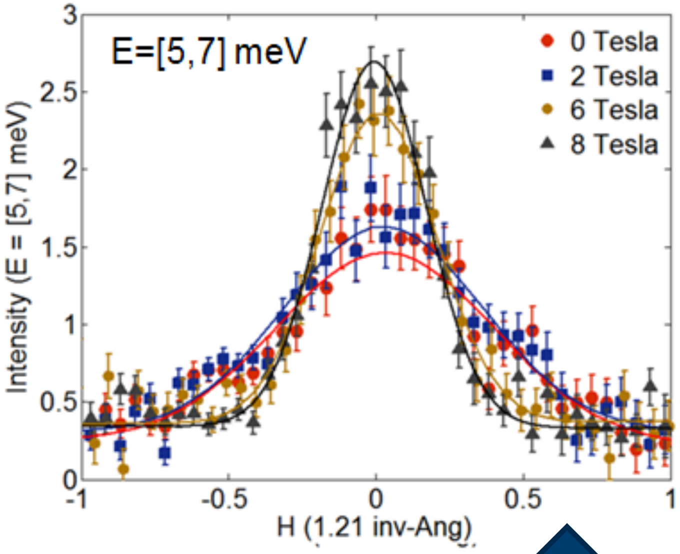
In-plane magnetic field suppresses magnetic order in RuCl3

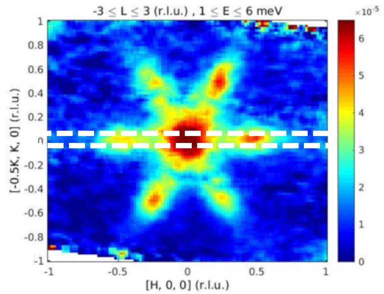




Spin wave intensity fades with increasing field, spectral weight shifts to the continuum scattering







- **At 8T spin waves are suppressed leaving only intense continuum scattering with a polarization gap at the Γ-point**
- **Cut along [H,0,0] traverses the arm of the zero-field star pattern that arises from further-neighbor correlations**
- **Narrowing peak indicates that further-neighbor correlations are diminished by a field**

High-field state is a gapped spin liquid with short-range correlations, may be connected to the Kitaev QSL (investigation ongoing)

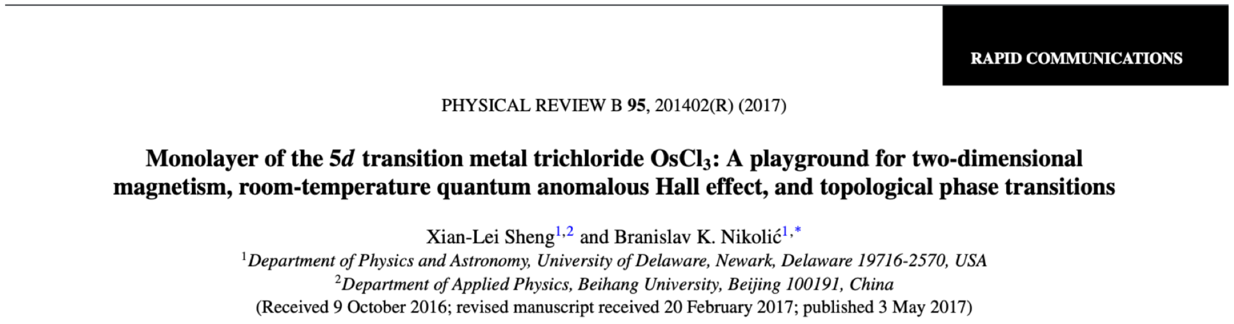
$OsCl_3$—*5d* analog of $RuCl_3$

The *5d* transition metal ion Os^{3+} is subject to an enhanced spin orbit coupling compared to Ru^{3+}

Reports of the synthesis and basic properties of $OsCl_3$ circa 1960-70 found the compound to be isostructural to $RuCl_3$, with a room-temperature effective magnetic moment $\mu_{eff} = 1.77\ \mu_B$.

This observation provides strong evidence that $5d^5$ Os^{3+} ions are in the low spin ground state with $J_{eff} = ½$, as is the case for Ru^{3+} in α-$RuCl_3$.

A recent DFT calculation for a monolayer of $OsCl_3$ suggest that the system may exhibit exotic phenomena apart from Kitaev physics, including a quantum anomalous Hall effect and topological phase transitions.



RAPID COMMUNICATIONS

PHYSICAL REVIEW B **95**, 201402(R) (2017)

Monolayer of the *5d* transition metal trichloride $OsCl_3$: A playground for two-dimensional magnetism, room-temperature quantum anomalous Hall effect, and topological phase transitions

Xian-Lei Sheng[1,2] and Branislav K. Nikolić[1,*]

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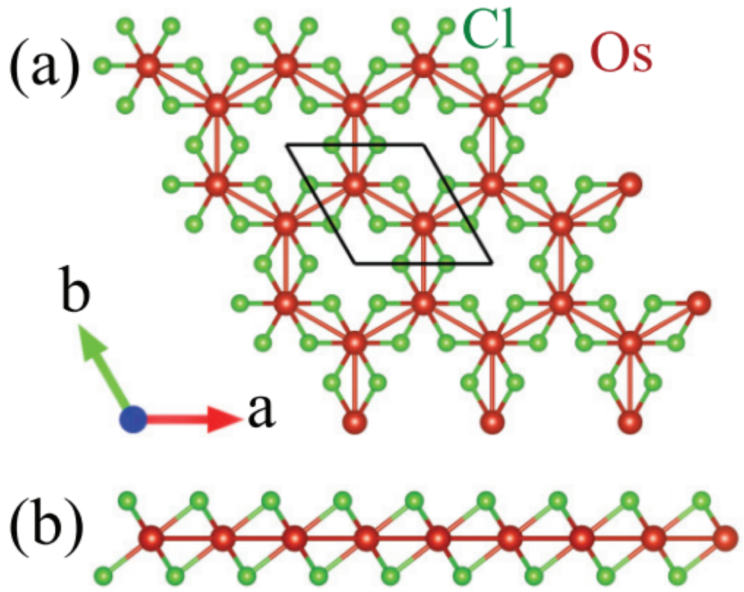
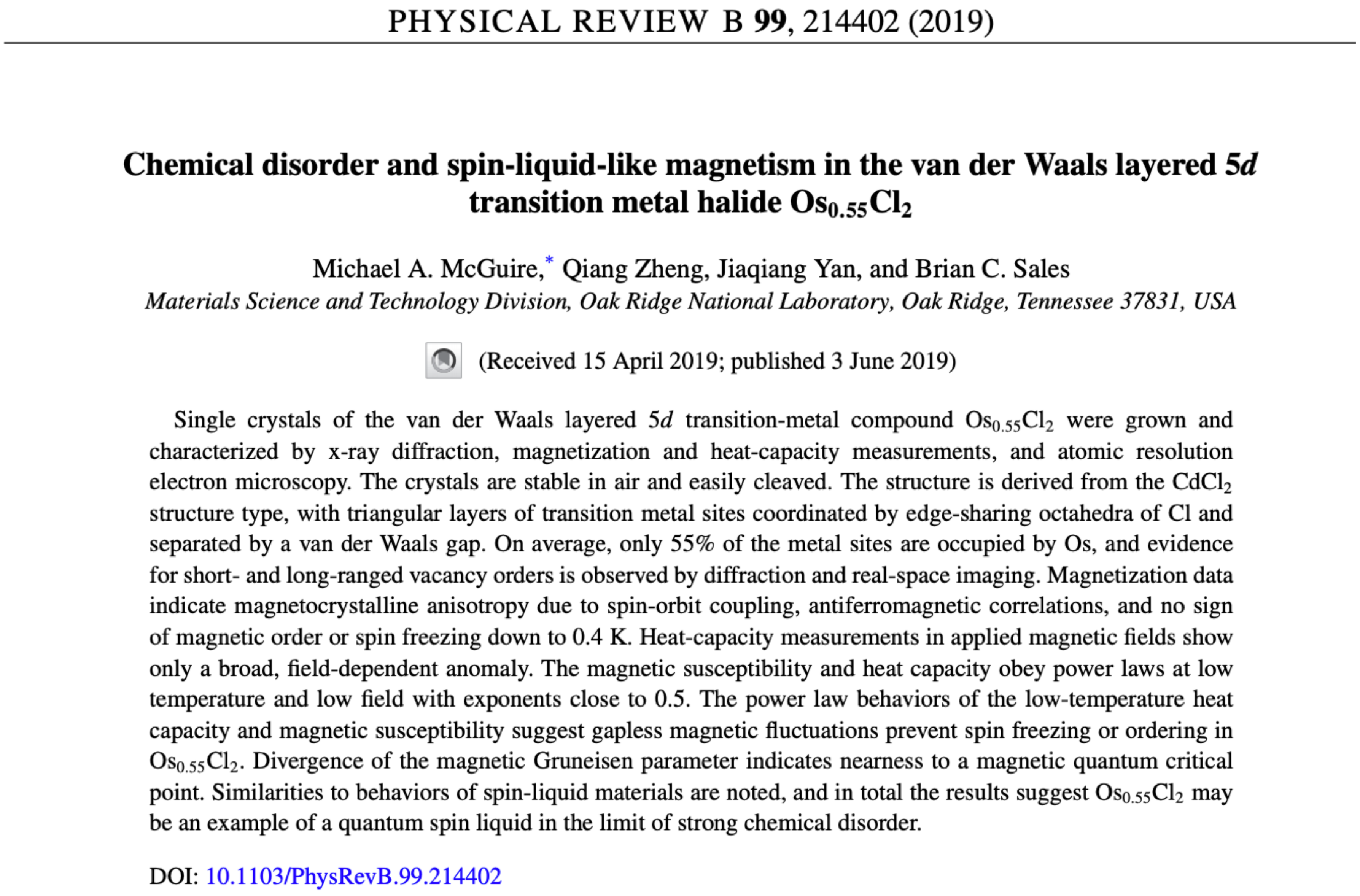
(Received 9 October 2016; revised manuscript received 20 February 2017; published 3 May 2017)





PHYSICAL REVIEW B **99**, 214402 (2019)

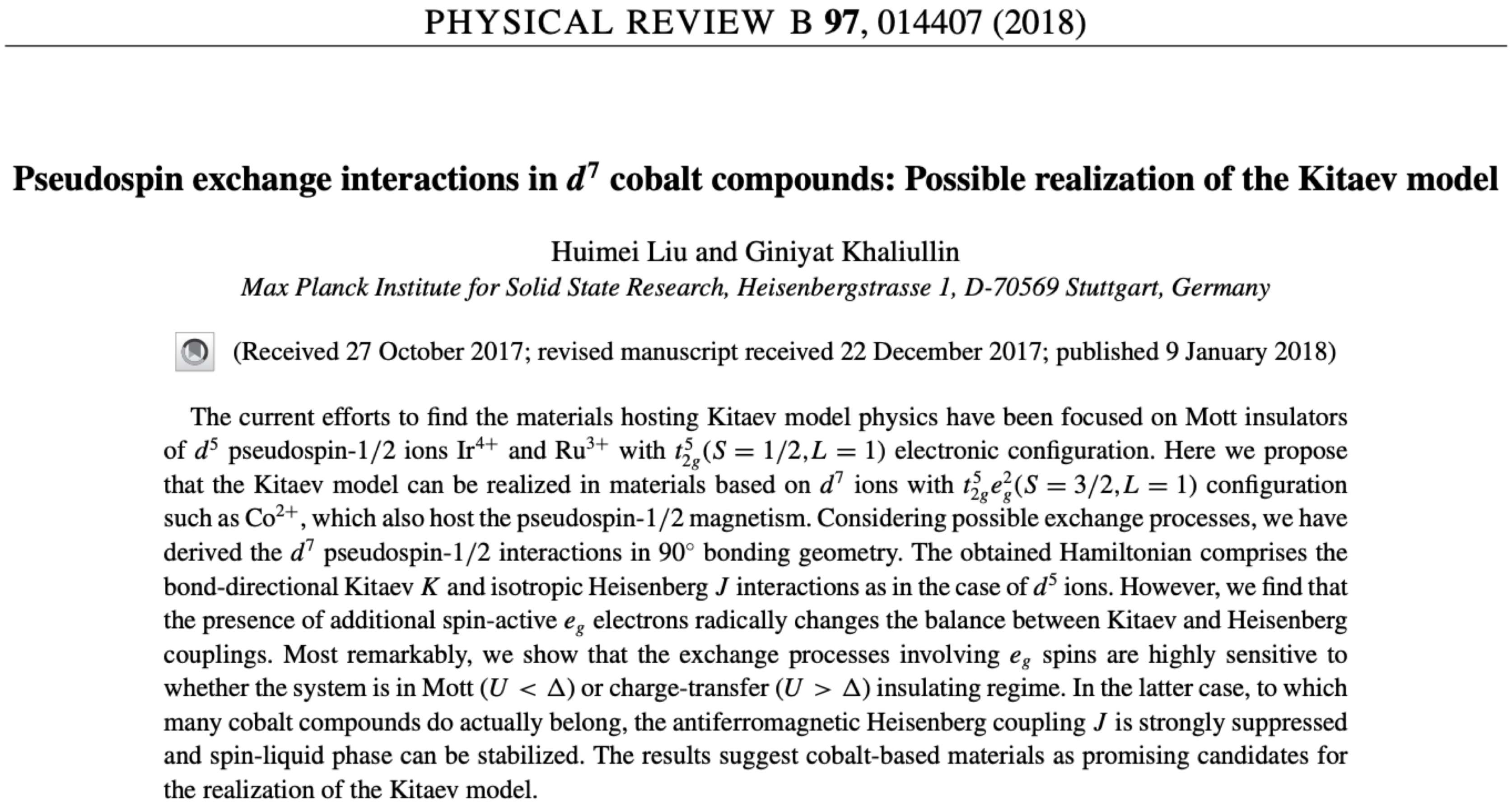
Chemical disorder and spin-liquid-like magnetism in the van der Waals layered 5*d* transition metal halide $Os_{0.55}Cl_2$

Michael A. McGuire,[*] Qiang Zheng, Jiaqiang Yan, and Brian C. Sales
Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

(Received 15 April 2019; published 3 June 2019)

Single crystals of the van der Waals layered 5*d* transition-metal compound $Os_{0.55}Cl_2$ were grown and characterized by x-ray diffraction, magnetization and heat-capacity measurements, and atomic resolution electron microscopy. The crystals are stable in air and easily cleaved. The structure is derived from the $CdCl_2$ structure type, with triangular layers of transition metal sites coordinated by edge-sharing octahedra of Cl and separated by a van der Waals gap. On average, only 55% of the metal sites are occupied by Os, and evidence for short- and long-ranged vacancy orders is observed by diffraction and real-space imaging. Magnetization data indicate magnetocrystalline anisotropy due to spin-orbit coupling, antiferromagnetic correlations, and no sign of magnetic order or spin freezing down to 0.4 K. Heat-capacity measurements in applied magnetic fields show only a broad, field-dependent anomaly. The magnetic susceptibility and heat capacity obey power laws at low temperature and low field with exponents close to 0.5. The power law behaviors of the low-temperature heat capacity and magnetic susceptibility suggest gapless magnetic fluctuations prevent spin freezing or ordering in $Os_{0.55}Cl_2$. Divergence of the magnetic Gruneisen parameter indicates nearness to a magnetic quantum critical point. Similarities to behaviors of spin-liquid materials are noted, and in total the results suggest $Os_{0.55}Cl_2$ may be an example of a quantum spin liquid in the limit of strong chemical disorder.

DOI: 10.1103/PhysRevB.99.214402



PHYSICAL REVIEW B **97**, 014407 (2018)

Pseudospin exchange interactions in d^7 cobalt compounds: Possible realization of the Kitaev model

Huimei Liu and Giniyat Khaliullin
Max Planck Institute for Solid State Research, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

(Received 27 October 2017; revised manuscript received 22 December 2017; published 9 January 2018)

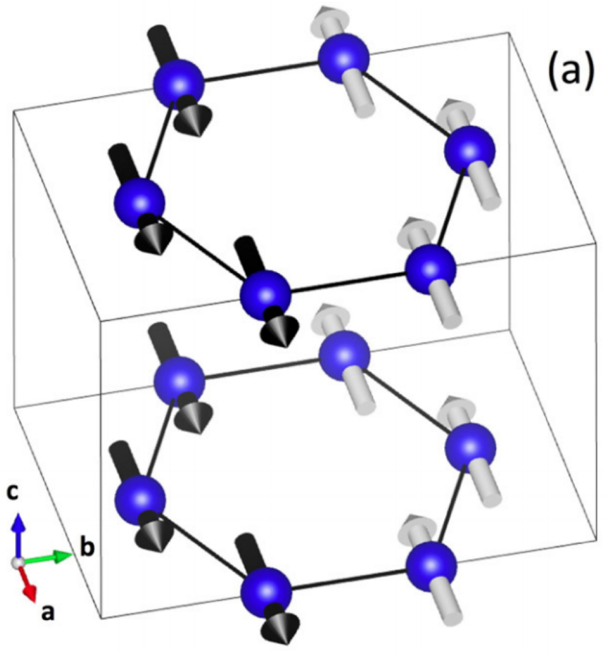
The current efforts to find the materials hosting Kitaev model physics have been focused on Mott insulators of d^5 pseudospin-1/2 ions Ir^{4+} and Ru^{3+} with $t_{2g}^5(S = 1/2, L = 1)$ electronic configuration. Here we propose that the Kitaev model can be realized in materials based on d^7 ions with $t_{2g}^5 e_g^2(S = 3/2, L = 1)$ configuration such as Co^{2+}, which also host the pseudospin-1/2 magnetism. Considering possible exchange processes, we have derived the d^7 pseudospin-1/2 interactions in 90° bonding geometry. The obtained Hamiltonian comprises the bond-directional Kitaev K and isotropic Heisenberg J interactions as in the case of d^5 ions. However, we find that the presence of additional spin-active e_g electrons radically changes the balance between Kitaev and Heisenberg couplings. Most remarkably, we show that the exchange processes involving e_g spins are highly sensitive to whether the system is in Mott ($U < \Delta$) or charge-transfer ($U > \Delta$) insulating regime. In the latter case, to which many cobalt compounds do actually belong, the antiferromagnetic Heisenberg coupling J is strongly suppressed and spin-liquid phase can be stabilized. The results suggest cobalt-based materials as promising candidates for the realization of the Kitaev model.

Our study is partially motivated by the recent experiments on cobalt compounds $Na_2Co_2TeO_6$ and $Na_3Co_2SbO_6$ with a layered hexagonal structure. In both systems, the d^7 ions Co^{2+} form a nearly perfect honeycomb lattice and develop a zigzag-type antiferromagnetic order at low temperatures, analogous to that observed in d^5 pseudospin-1/2 materials $RuCl_3$ and Na_2IrO_3. This similarity may not be accidental, and the results presented in this work suggest that d^7 cobalt compounds may indeed harbor pseudospin-1/2 Kitaev-Heisenberg model and related physics.

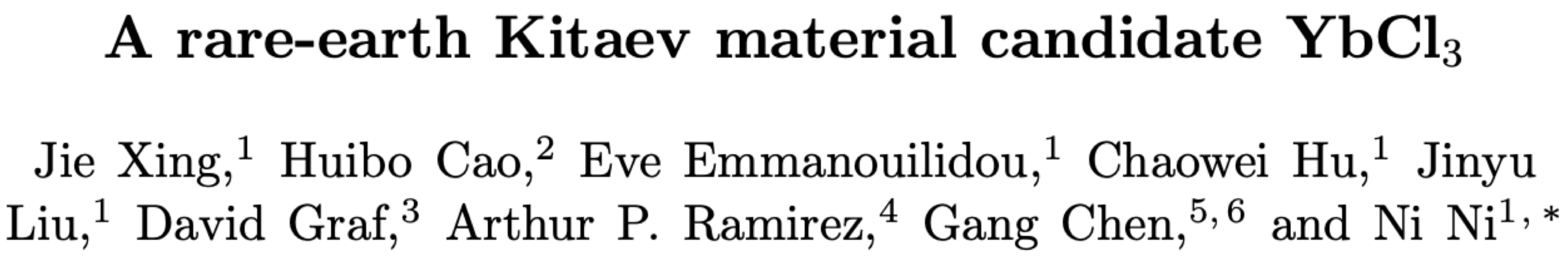
IOP Publishing
Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **29** (2017) 455801 (9pp)
https://doi.org/10.1088/1361-648X/aa8a43

The magnetic properties and structure of the quasi-two-dimensional antiferromagnet $CoPS_3$

A R Wildes[1,5], **V Simonet**[2], **E Ressouche**[3], **R Ballou**[2] **and G J McIntyre**[4]



T_N = 122 K

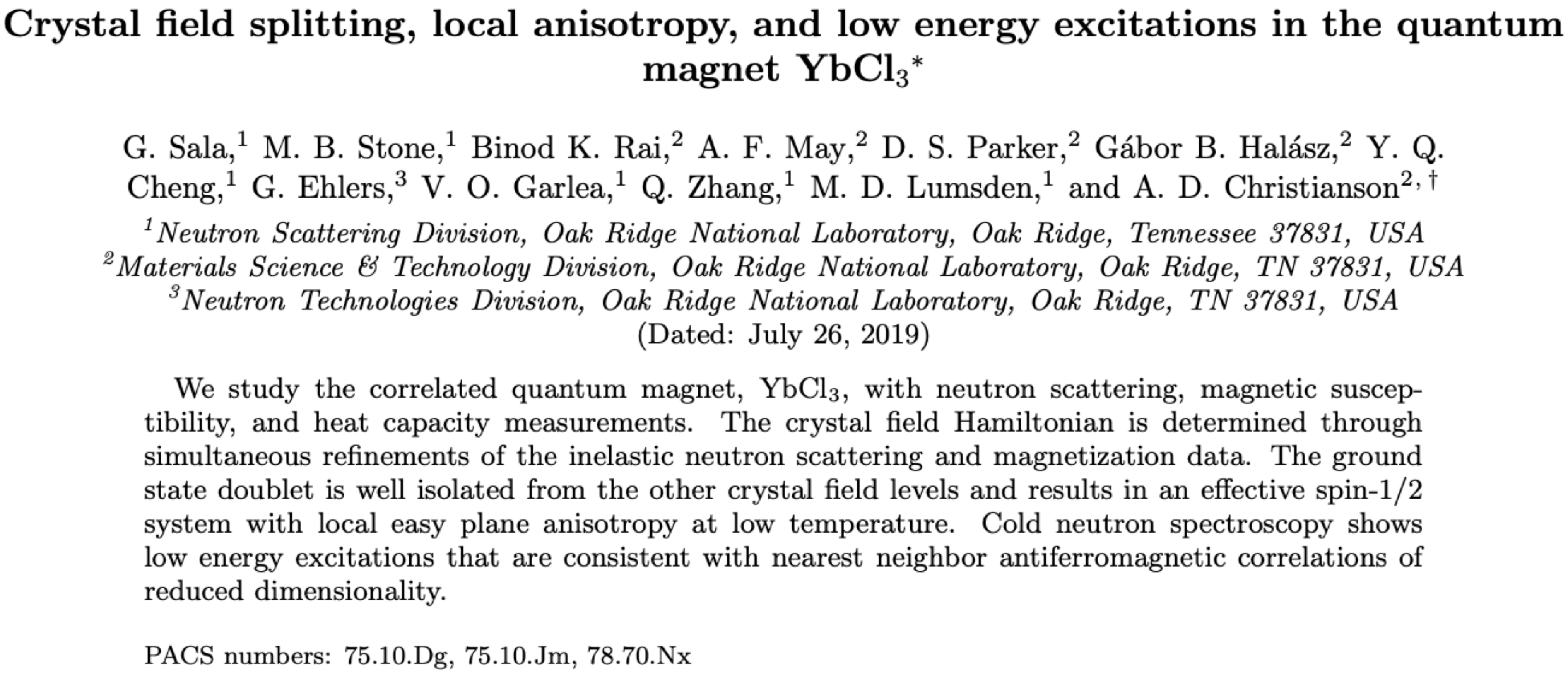


A rare-earth Kitaev material candidate $YbCl_3$

Jie Xing,[1] Huibo Cao,[2] Eve Emmanouilidou,[1] Chaowei Hu,[1] Jinyu Liu,[1] David Graf,[3] Arthur P. Ramirez,[4] Gang Chen,[5,6] and Ni Ni[1,*]

ArXiv: 1903.03615

In conclusion, we propose YbCl3 as a 2D Kitaev material candidate with Jeff = 1/2 local moments and strong bond-dependent in-plane anisotropy. This compound exhibits SRO at 1.20 K and LRO at 0.60 K with spins likely in the ab plane. The application of external magnetic fields can suppress these orders at around 6 T (in plane field) and 10 T (out-of-plane field), resulting in a QCP. Further investigation in the quantum critical region where quantum fluctuation dominates may lead to the discovery of a Kitaev QSL state.



Crystal field splitting, local anisotropy, and low energy excitations in the quantum magnet $YbCl_3$*

G. Sala,[1] M. B. Stone,[1] Binod K. Rai,[2] A. F. May,[2] D. S. Parker,[2] Gábor B. Halász,[2] Y. Q. Cheng,[1] G. Ehlers,[3] V. O. Garlea,[1] Q. Zhang,[1] M. D. Lumsden,[1] and A. D. Christianson[2,†]

[1]*Neutron Scattering Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Materials Science & Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[3]*Neutron Technologies Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

(Dated: July 26, 2019)

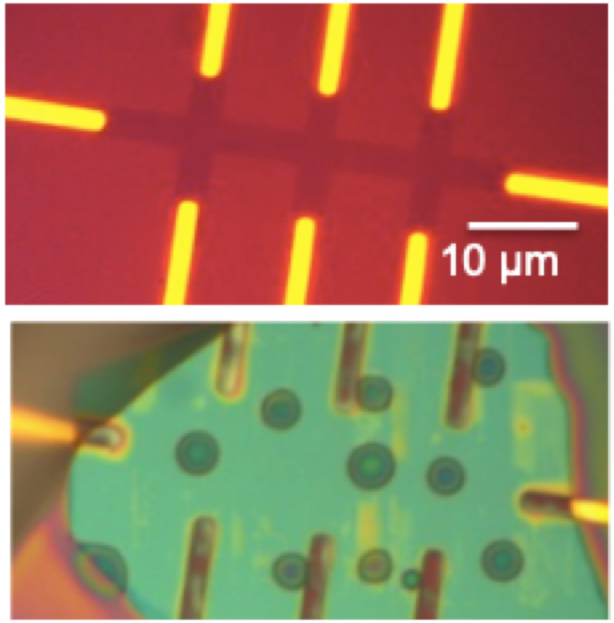
We study the correlated quantum magnet, $YbCl_3$, with neutron scattering, magnetic susceptibility, and heat capacity measurements. The crystal field Hamiltonian is determined through simultaneous refinements of the inelastic neutron scattering and magnetization data. The ground state doublet is well isolated from the other crystal field levels and results in an effective spin-1/2 system with local easy plane anisotropy at low temperature. Cold neutron spectroscopy shows low energy excitations that are consistent with nearest neighbor antiferromagnetic correlations of reduced dimensionality.

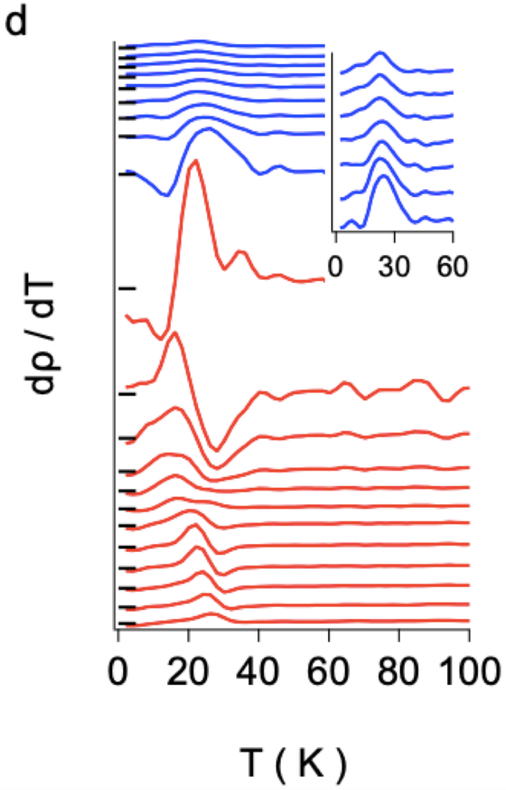
PACS numbers: 75.10.Dg, 75.10.Jm, 78.70.Nx

arXiv:1907.10627v1

Some recent developments on RuCl3

Metallizing $RuCl_3$ by charge transfer from graphene arXiv:1811.04838v1





Erik Henriksen
Washington University, St. Louis

- Exfoliated α-RuCl3 flakes stacked on monolayer graphene
- Devices exhibit an anomalously large conductivity along with signatures of multi-band transport strongly implying the α-RuCl3 has become charge-doped
- Temperature derivative of the resistivity contains clear signatures of magnetic phase transitions.

Electronic properties of α-RuCl$_3$ in proximity to graphene

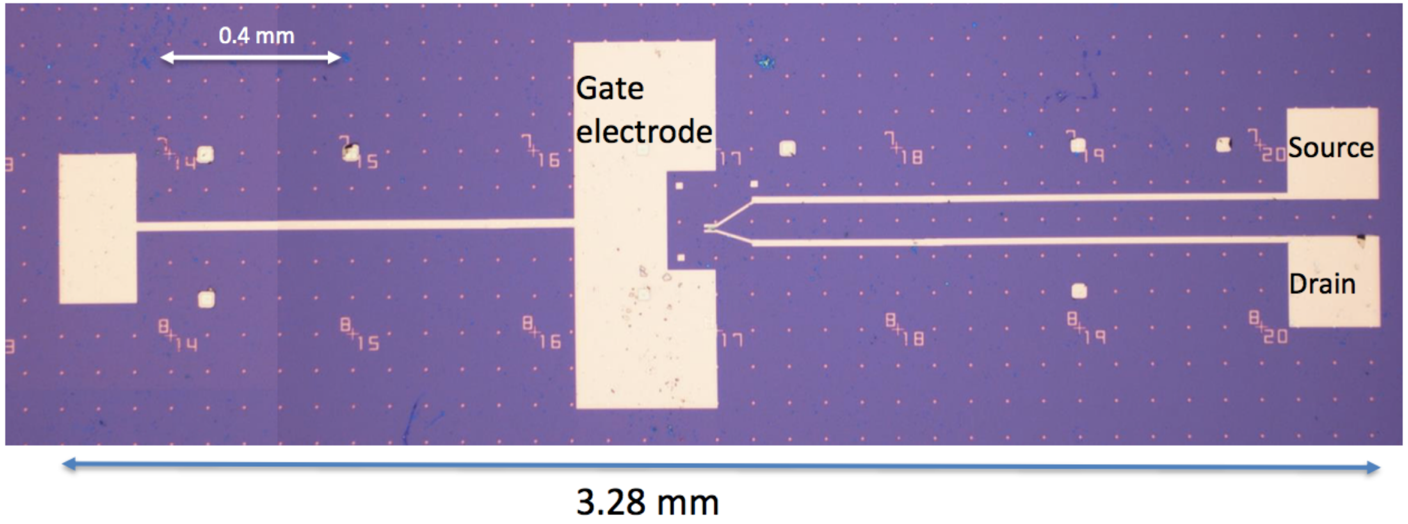
Sananda Biswas,[1] Ying Li,[1,2] Stephen M. Winter,[1] Johannes Knolle,[3,4,5] and Roser Valentí[1]

[1]*Institut für Theoretische Physik, Goethe-Universität Frankfurt, 60438 Frankfurt am Main, Germany*
[2]*Department of Applied Physics and MOE Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter, School of Science, Xi'an Jiaotong University, Xi'an 710049, China*
[3]*Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*
[4]*Department of Physics, T33, Technische Universität München, 85748 Garching, Germany*
[5]*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*

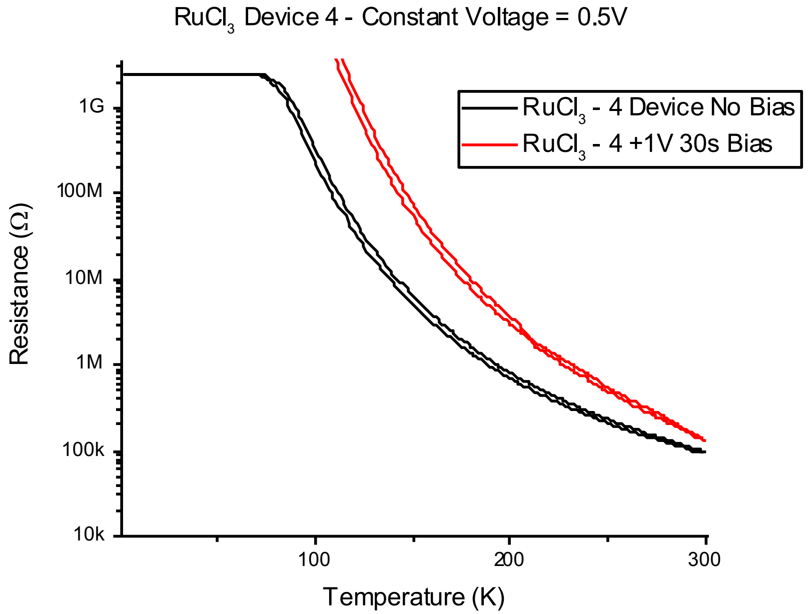
(Dated: August 27, 2019)

In the pursuit of developing routes to enhance magnetic Kitaev interactions in α-RuCl$_3$, as well as probing doping effects, we investigate the electronic properties of α-RuCl$_3$ in proximity to graphene. We study α-RuCl$_3$/graphene heterostructures via *ab initio* density functional theory calculations, Wannier projection and non-perturbative exact diagonalization methods. We show that α-RuCl$_3$ becomes strained when placed on graphene and charge transfer occurs between the two layers, making α-RuCl$_3$ (graphene) lightly electron-doped (hole-doped). This gives rise to an insulator to metal transition in α-RuCl$_3$ with the Fermi energy located close to the bottom of the upper Hubbard band of the t_{2g} manifold. These results suggest the possibility of realizing metallic and even exotic superconducting states. Moreover, we show that in the strained α-RuCl$_3$ monolayer the Kitaev interactions are enhanced by more than 50% compared to the unstrained bulk structure. Finally, we discuss scenarios related to transport experiments in α-RuCl$_3$/graphene heterostructures.

Failure to metallize a QSL--Ionic Liquid gating of RuCl3



In collaboration with Philip Rack and Zac Ward

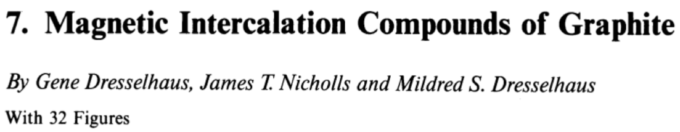


We made it more insulating!

1) Gating experiments on atomically thin magnets have mostly failed

2) Gating a VdW heterostructure of graphene/vdW magnet should work much better

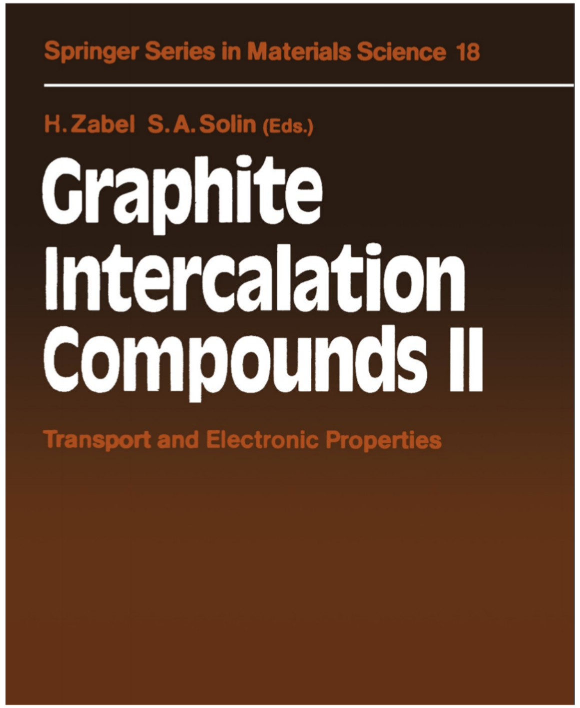
3) Graphite-Intercalated magnets are interesting again!



7. Magnetic Intercalation Compounds of Graphite

By Gene Dresselhaus, James T. Nicholls and Mildred S. Dresselhaus

With 32 Figures



Springer Series in Materials Science 18

H. Zabel S. A. Solin (Eds.)

Graphite Intercalation Compounds II

Transport and Electronic Properties

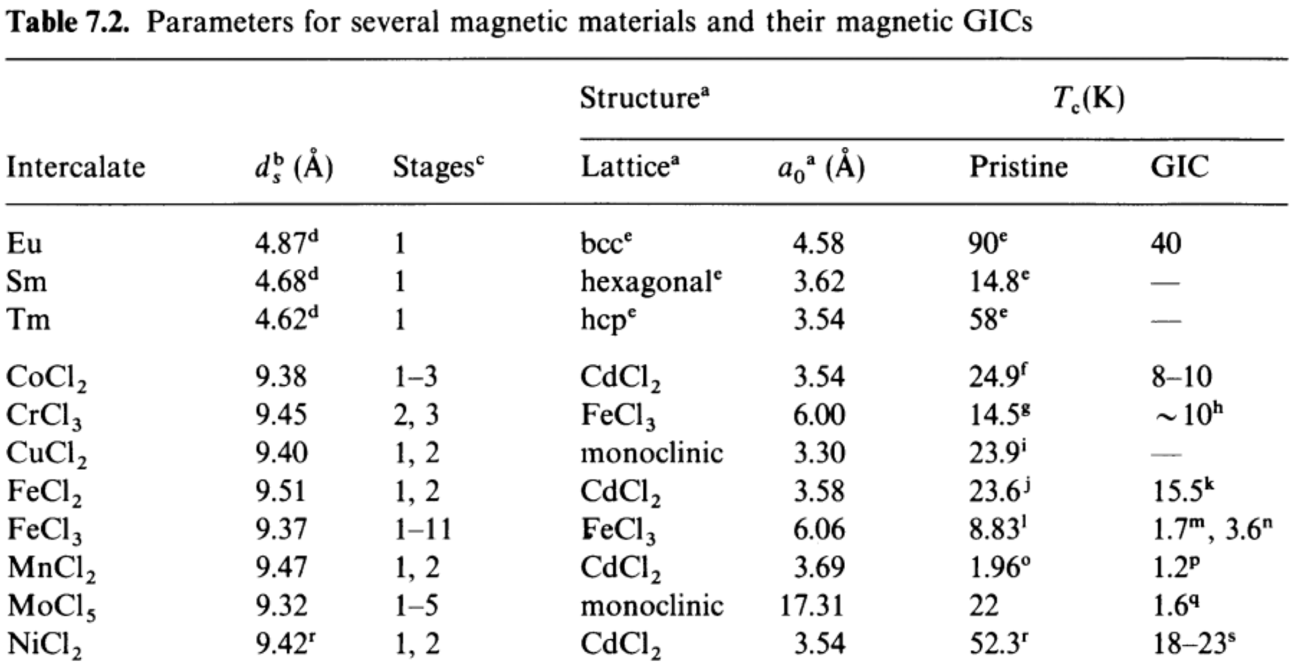
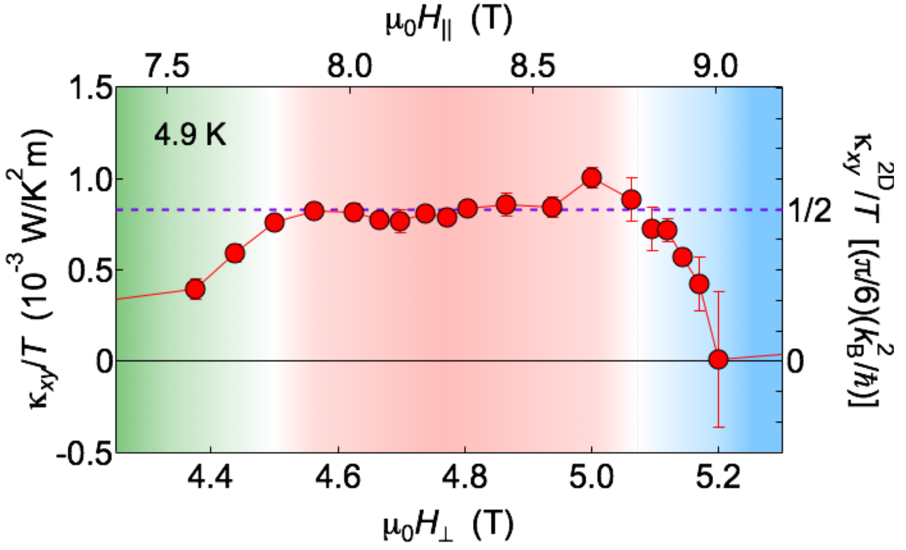
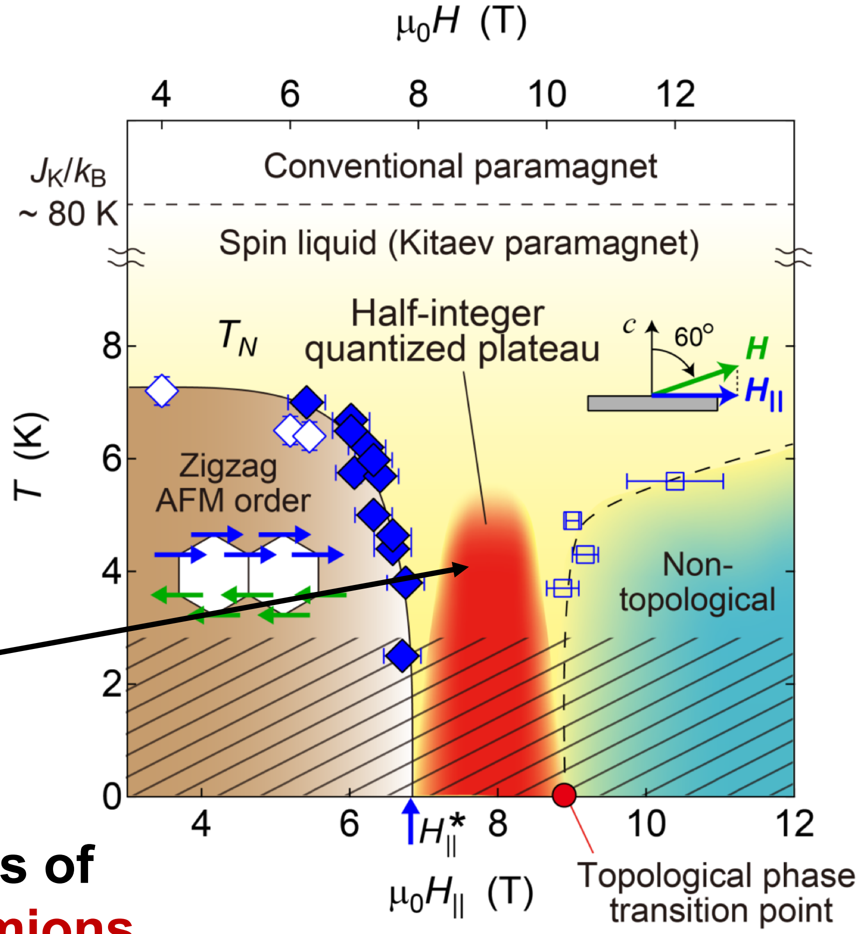


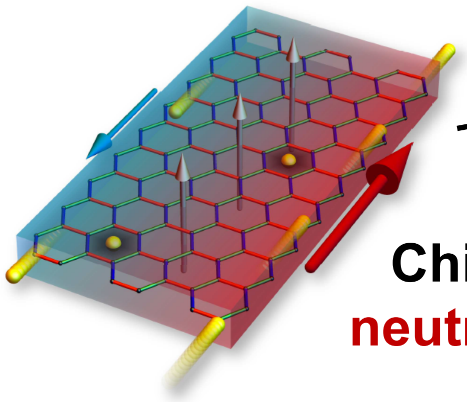
Table 7.2. Parameters for several magnetic materials and their magnetic GICs

			Structure[a]		T_c(K)	
Intercalate	d_s[b] (Å)	Stages[c]	Lattice[a]	a_0[a] (Å)	Pristine	GIC
Eu	4.87[d]	1	bcc[e]	4.58	90[e]	40
Sm	4.68[d]	1	hexagonal[e]	3.62	14.8[e]	—
Tm	4.62[d]	1	hcp[e]	3.54	58[e]	—
$CoCl_2$	9.38	1–3	$CdCl_2$	3.54	24.9[f]	8–10
$CrCl_3$	9.45	2, 3	$FeCl_3$	6.00	14.5[g]	~10[h]
$CuCl_2$	9.40	1, 2	monoclinic	3.30	23.9[i]	—
$FeCl_2$	9.51	1, 2	$CdCl_2$	3.58	23.6[j]	15.5[k]
$FeCl_3$	9.37	1–11	$FeCl_3$	6.06	8.83[l]	1.7[m], 3.6[n]
$MnCl_2$	9.47	1, 2	$CdCl_2$	3.69	1.96[o]	1.2[p]
$MoCl_5$	9.32	1–5	monoclinic	17.31	22	1.6[q]
$NiCl_2$	9.42[r]	1, 2	$CdCl_2$	3.54	52.3[r]	18–23[s]

Half integer thermal quantum Hall conductance





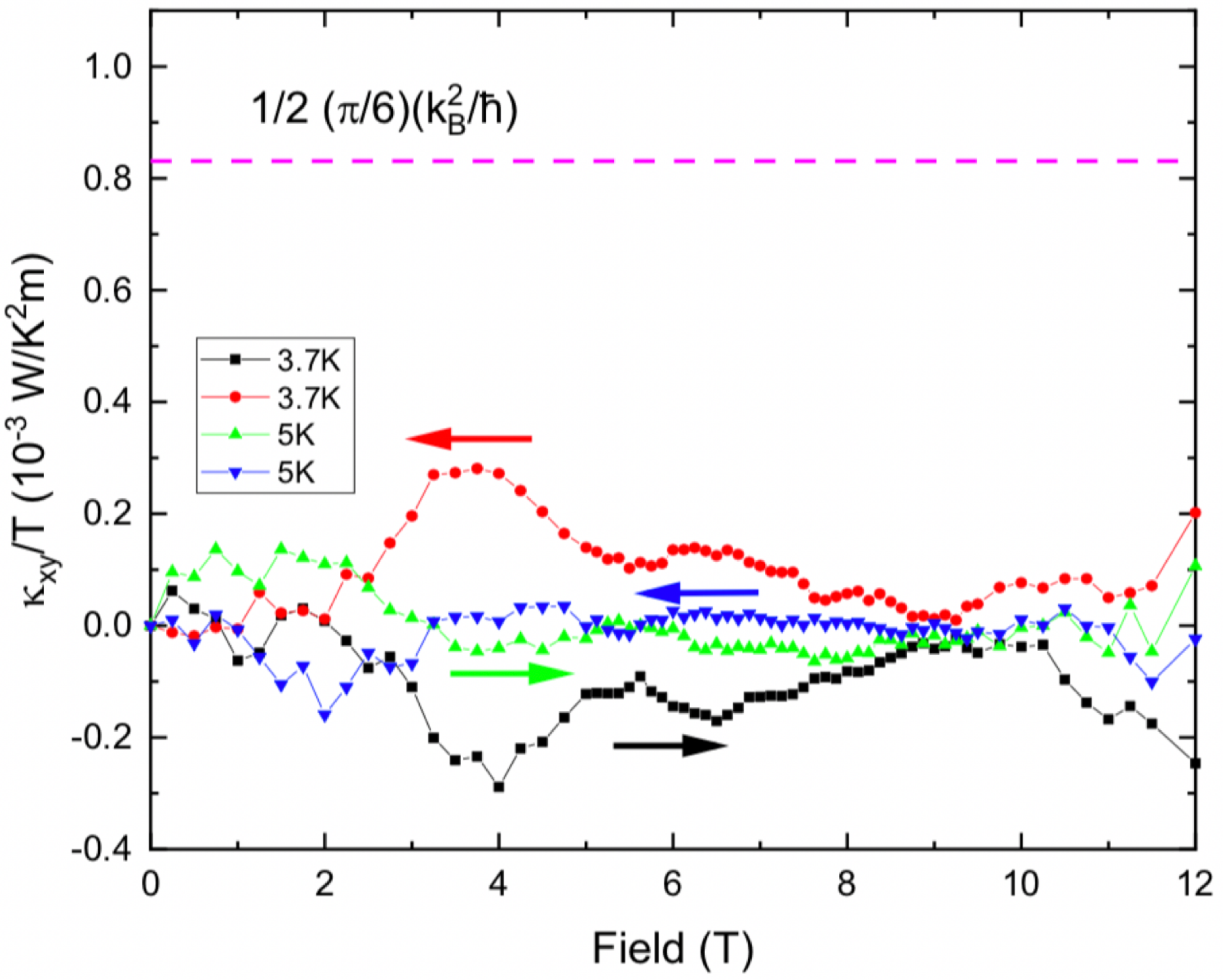


Chiral edge currents of
neutral Majorana fermions

$$\frac{\kappa_{xy}^{2D}}{T} = \frac{1}{2}\left(\frac{\pi}{6}\frac{k_B^2}{\hbar}\right)$$

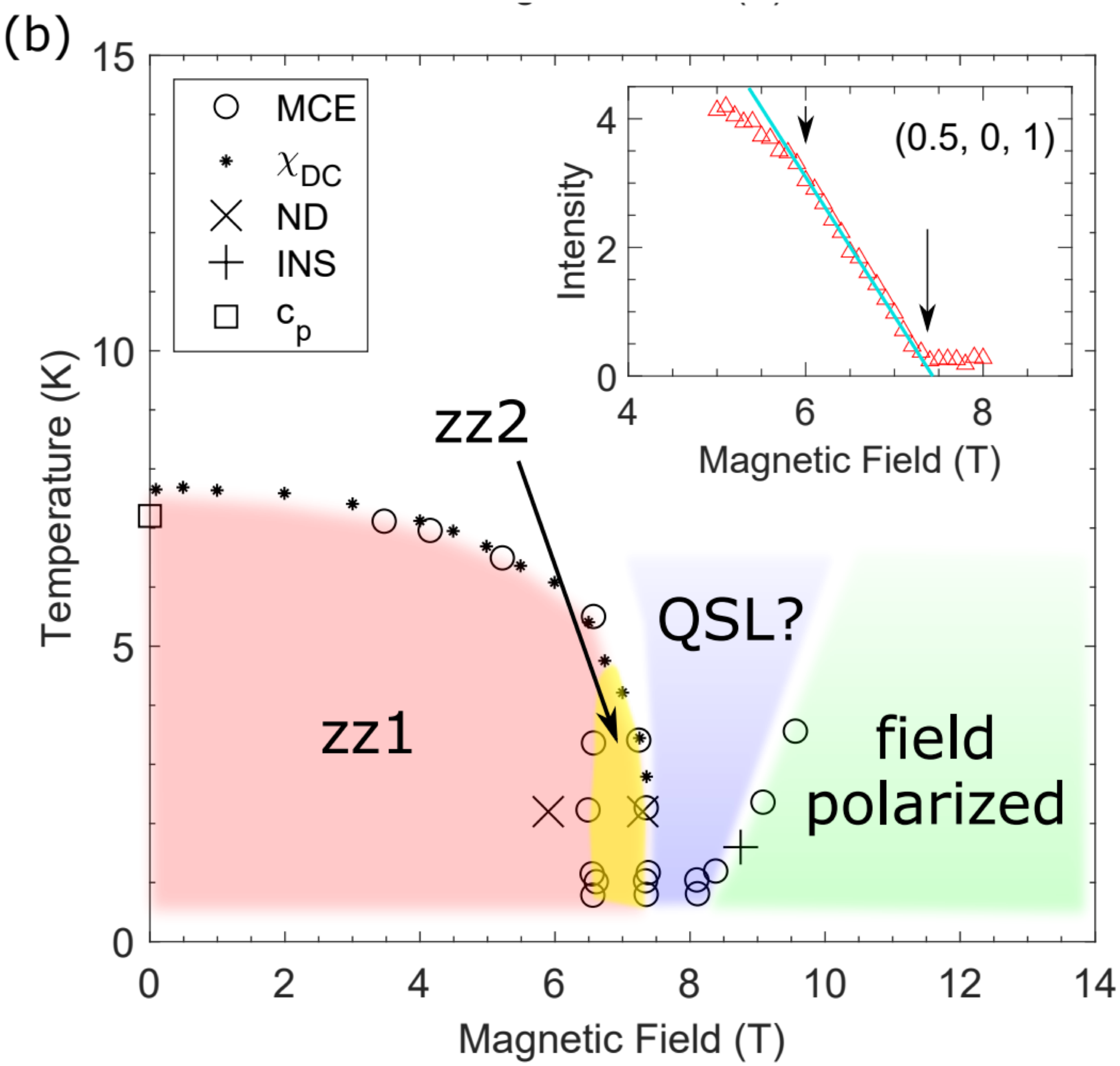
Y. Kasahara *et al*, Nature (2018).

Ong's group has not yet been able to reproduce the Kasahara result on our samples

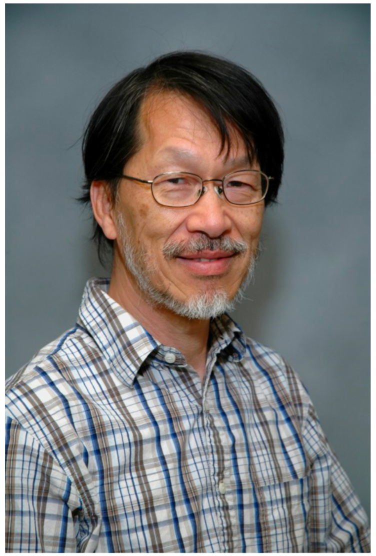


Paige Kelley

Zz2 -- arXiv:1807.06192



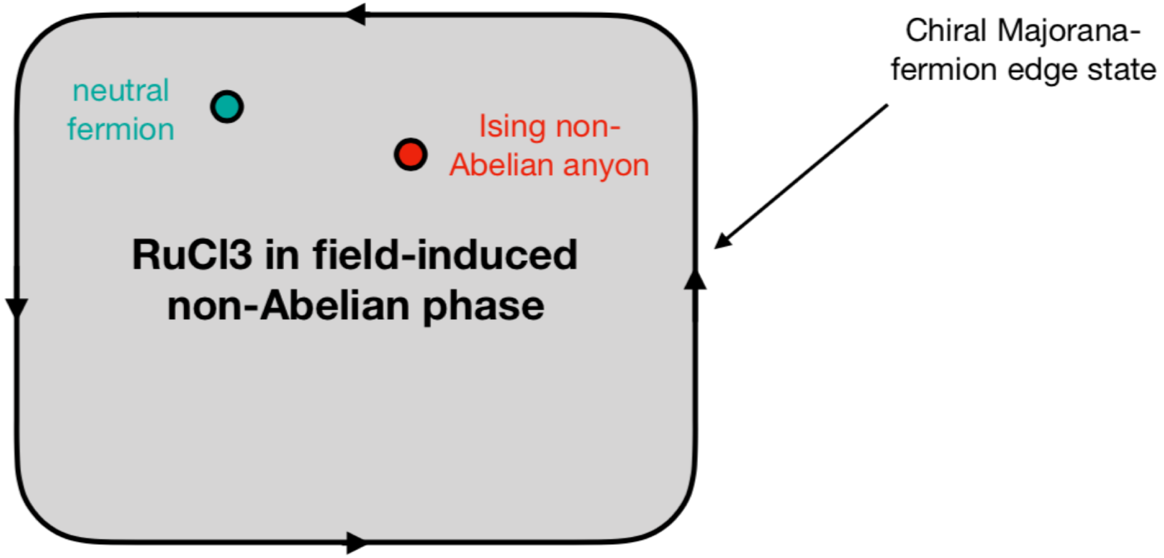
Christian Balz --INS



Yasu Takano--MCE

Electrical probes of non-Abelian spin liquids

Jason Alicea and Dave Aasen

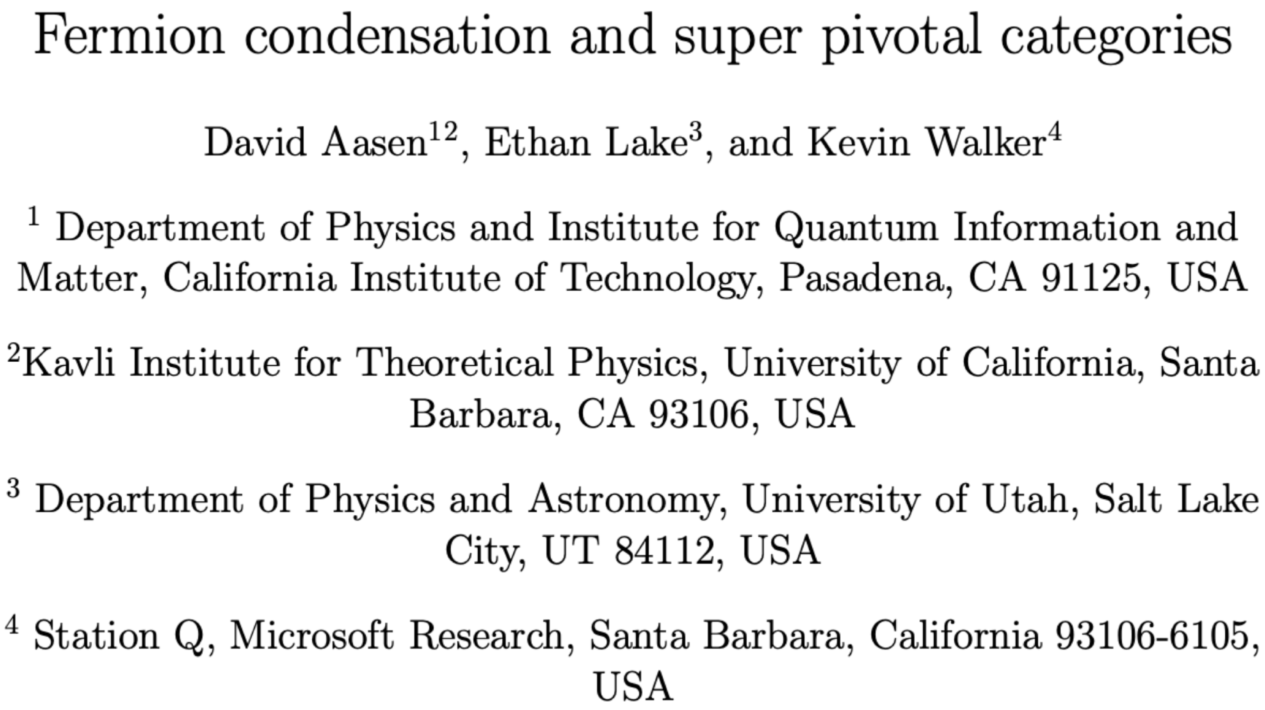


Goal: detect Ising anyons

Challenge: edge states, anyons are all electrically neutral, so do not naturally couple to leads

Basic idea: use “fermion condensation” to allow conversion between electrons <-> neutral fermions, then use familiar interferometry techniques

arXiv:1709.01941



Fermion condensation and super pivotal categories

David Aasen[1][2], Ethan Lake[3], and Kevin Walker[4]

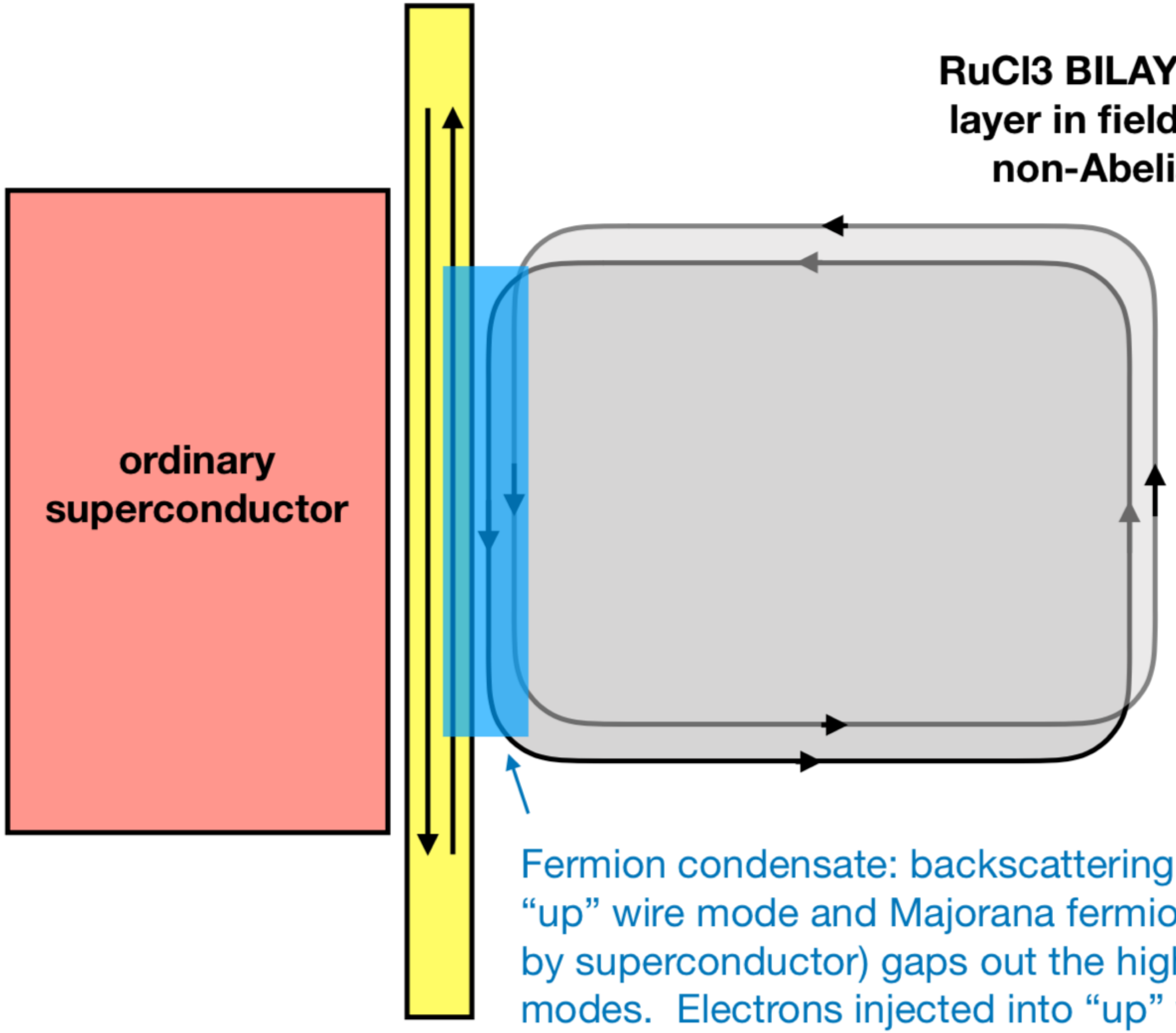
[1] Department of Physics and Institute for Quantum Information and
Matter, California Institute of Technology, Pasadena, CA 91125, USA

[2] Kavli Institute for Theoretical Physics, University of California, Santa
Barbara, CA 93106, USA

[3] Department of Physics and Astronomy, University of Utah, Salt Lake
City, UT 84112, USA

[4] Station Q, Microsoft Research, Santa Barbara, California 93106-6105,
USA

Due to their nontrivial spin and statistics, condensing fermions is not a straightforward business. From a mathematical perspective, in order to perform the condensation it is necessary to equip the configuration space of Ψ worldline endpoints with a certain complex line bundle. Physically, the construction of this bundle amounts to attaching a phase of physical (not emergent) fermions f to the parent bosonic theory. Fermion condensation then heuristically proceeds by coupling the Ψ fermions to the f fermions, and condensing Ψ f bound states.

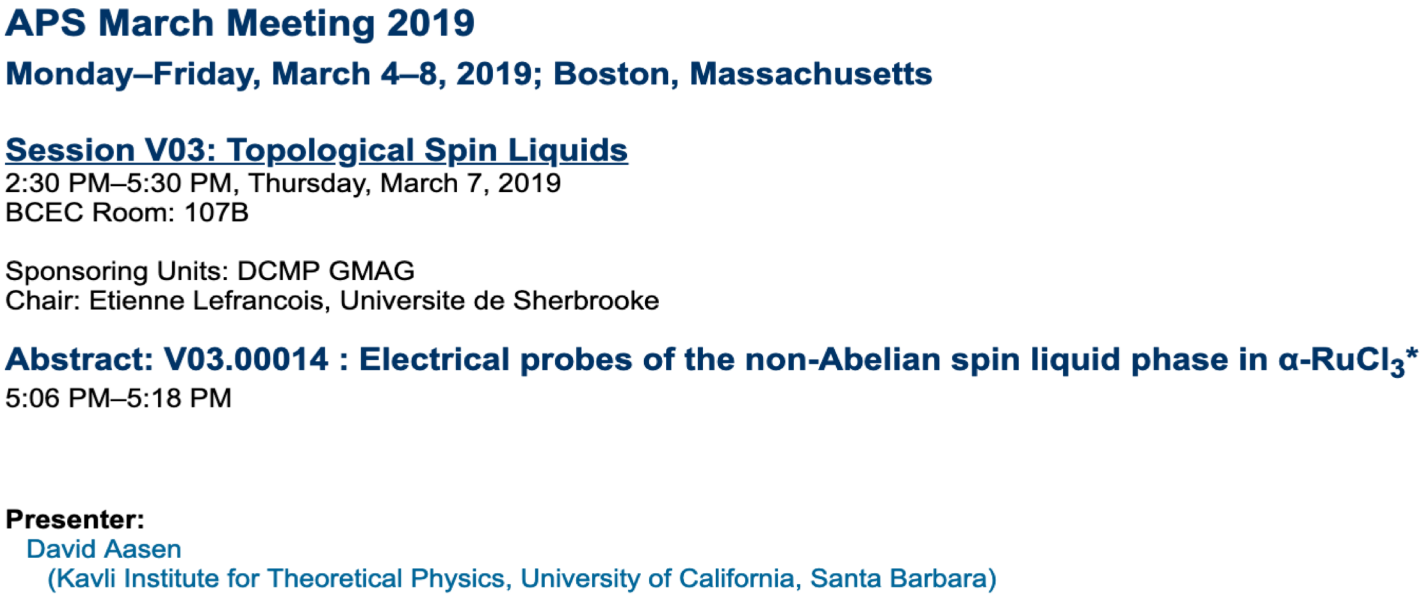


1D wire

RuCl3 BILAYER, each layer in field-induced non-Abelian phase

ordinary superconductor

Fermion condensate: backscattering between “up” wire mode and Majorana fermions (facilitated by superconductor) gaps out the highlighted modes. Electrons injected into “up” wire mode then get efficiently converted into neutral fermions and traverse the RuCl3 boundary.



APS March Meeting 2019

Monday–Friday, March 4–8, 2019; Boston, Massachusetts

Session V03: Topological Spin Liquids
2:30 PM–5:30 PM, Thursday, March 7, 2019
BCEC Room: 107B

Sponsoring Units: DCMP GMAG
Chair: Etienne Lefrancois, Universite de Sherbrooke

Abstract: V03.00014 : Electrical probes of the non-Abelian spin liquid phase in α-$RuCl_3$*

5:06 PM–5:18 PM

Presenter:
David Aasen
(Kavli Institute for Theoretical Physics, University of California, Santa Barbara)

Recent thermal-transport experiments indicate that the Kitaev material α-$RuCl_3$ realizes a non-Abelian spin liquid with Ising topological order over a range of magnetic fields. We propose a series of measurements for *electrically* detecting the hallmark chiral Majorana edge states and bulk anyons in the spin-liquid phase -- despite the fact that α-$RuCl_3$ is a good Mott insulator. In particular, we introduce circuits that exploit interfaces between electronic systems and α-$RuCl_3$ to convert physical fermions into emergent fermions, thus enabling analogues of transport probes of non-Abelian-anyon physics in topological superconductors. We further propose detection of individual bulk neutral fermions via a spin counterpart of charge sensing. Our results illuminate a partial pathway towards using Kitaev materials for topological quantum computation.

Conclusions

1) Kitaev materials are a great story of how theory, synthesis, and characterization intertwine to advance science.

2) New Kitaev materials are urgently needed and can have a huge scientific impact.

3) Soft chemistry approaches to new Kitaev materials are promising.

4) One needs to be careful when claiming a “Kitaev” QSL.

5) Discovery of charge transfer at RuCl3/graphene interfaces will lead to major advances in spintronics.

6) Prospects for someday using Kitaev materials in quantum computing are looking considerably brighter.

Thank you!

Quantum spin liquids (QSLs)

Topological

Gapped QSL	*Spinon, Anyon*	**Kagome** Herbertsmithite · · ·
U(1) QSL	*E-monopole* *M-monopole* *Photon*	**Pyrochlore** $Yb_2Ti_2O_7$ $Pr_2Zr_2O_7$ · · ·
Kitaev QSL	*Majorana* *Z_2-flux (Vison)*	**Honeycomb** α-$RuCl_3$ Na_2IrO_3, α-Li_2IrO_3 $A_3LiIr_2O_6$ (A = H, Cu, Ag)

Non-topological

Gapless QSL	*Spinon* *(Fermi surface)*	**Triangular** TaS_2 $EtMe_3Sb[Pd(dmit)_2]_2$ ·

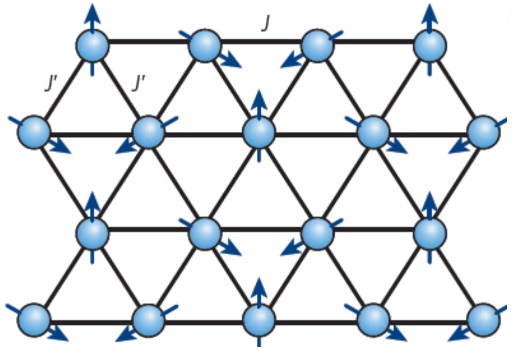
Why study Quantum Spin Liquids?

“Theoretically richer than the FQHE.” -- Leon Balents

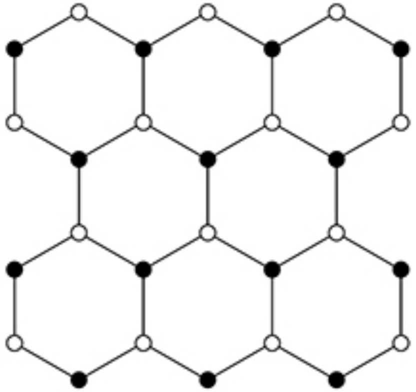
Doping QSL’s may be a path to new superconductors

Possibly a path to topologically protected quantum computing

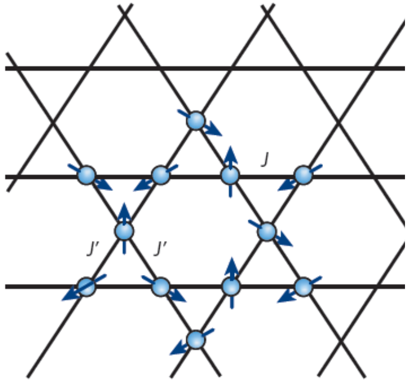
Triangular



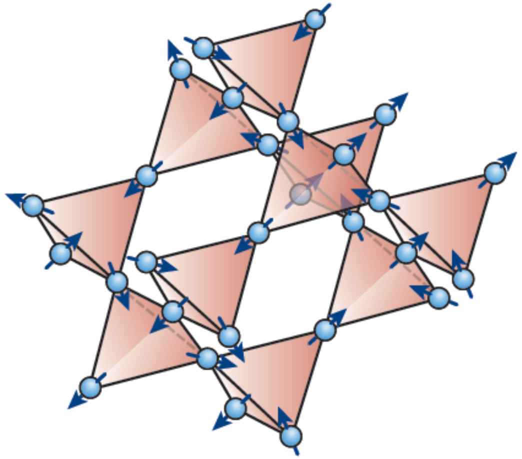
Honeycomb



Kagome

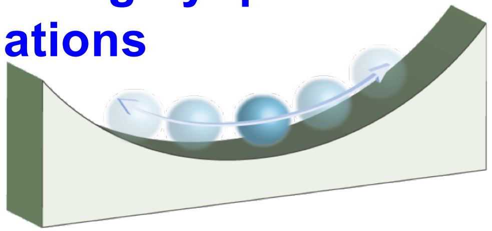


Pyrochlore



Quantum Liquids

No freezing by quantum fluctuations

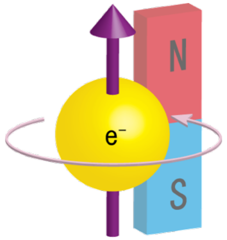


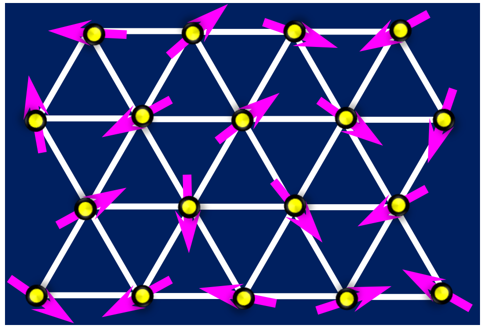
Zero point oscillation
> Interaction

Superfluid ^{3}He, ^{4}He

Quantum Spin Liquids

A state of matter where strong quantum fluctuations melt the long-range magnetic order even at absolute zero temperature.





Why are QSLs interesting?

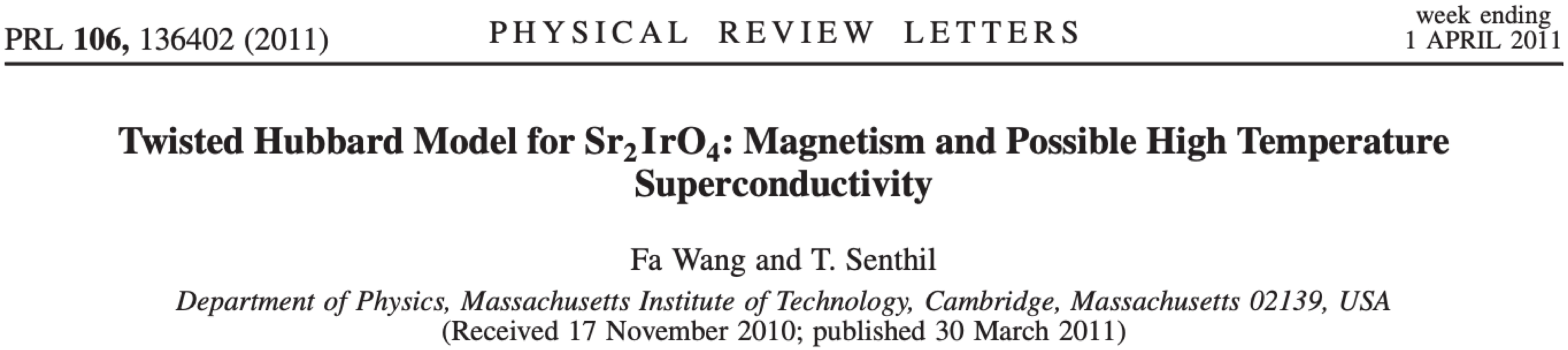
QSLs are states which do not break any simple symmetry.

P.W. Anderson, Mater. Res. Bull (73), Science (87)

Quasiparticle fractionalization and topological order

X.G. Wen, Phys. Rev. B 65, 165443 (2002).
S. Sachdev, Nat. Phys. 4, 173 (2008).

Recent review L. Savary and L. Balents, Rep. Prog. Phys. 80, 016502 (2017).
Y. Zhou, K. Kanoda, and T-. K. Ng, Rev. Mod. Phys. 80, 025003 (2017).



PRL **106,** 136402 (2011) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2011

Twisted Hubbard Model for Sr_2IrO_4: Magnetism and Possible High Temperature Superconductivity

Fa Wang and T. Senthil

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 17 November 2010; published 30 March 2011)

In particular, we propose that (electron-)doping Sr2IrO4 can potentially realize high-temperature superconductivity.

Take away message for those who have to leave:

1) There are reasons to be optimistic that Kitaev materials will work for quantum computation

1) New Kitaev materials are urgently needed!