October 1 ~ 5, 2018

Abstract Book

Workshop on Spin-orbit Coupled Topological States

apctp

아시아태평양이론물리센터

Contents

Organizers

Jeehoon Kim (POSTECH, Pohang)
Alireza Akbari (APCTP, Pohang)
Sungdae Ji (MPK, Pohang)
Yunkyu Bang (POSTECH)
Jae-Hoon Park (POSTECH)
Hyun-Woo Lee (POSTECH)
Kwon Park (KIAS)
Ki-Seok Kim (POSTECH)
Tae-Hwan Kim (POSTECH)
Eun-Gook Moon (KAIST)
Suk Bum Chung (University Of Seoul)
Keun Su Kim (Yonsei University)
Jungdae Kim (Ulsan University)
Gil-Ho Lee (POSTECH)
Gil Young Cho (POSTECH)

Invited Speakers

Ilya Eremin (Ruhr University Bochum)
Matteo Minola (MPI-FKF)
Gang Chen (Fudan University)
Hae-Young Kee (Toronto University)
Shik Shin (Tokyo University)
Tanmoy Das (Indian Institute of Science)
Yuki Motome (Tokyo University)
Ludovic Jaubert (CNRS, LOMA, University of Bordeaux)
Tien-Ming Chuang (SINICA)
Hyunsoo Kim (University of Maryland)
Yuji Matsuda (Kyoto University)
Shun-Qing Shen (University of Hong Kong)
Tristan Cren (CNRS, Universite Pierre-et-Maire-Curie)
Yoshiteru Maeno (Kyoto University)
Takashi Oka (MPI-PKS)
Nic Shannon (Okinawa Institute of Science and Technology, OIST)
Ross Mcdonald (Los Alamos National Lab, LANL)
Seunghyun Khim (MPI-CPS)
Daniel Leykam (IBS)
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Tuson Park (Sung Kyun Kwan University)
SungBin Lee (KAIST)
Eun-Gook Moon (KAIST)
Bohm-Jung Yang (SNU)
Jae Hoon Kim (Yonsei University)
Mahn-Soo Choi (Korea University)
Bum Joon Kim (POSTECH)
Jeil Jung (University of Seoul)
Kuan-Wen Chen (National High Magnetic Field Lab, NHMFL)
Dirk Wulferding (TU Braunschweig)
Ki-Seok Kim (POSTECH)
Minhyea Lee (University of Colorado)
Kee Hoon Kim (SNU)
Gil Young Cho (POSTECH)
Hye Jung Chang (KIST)

Campus Map

Workshop Venue

M-16 POSCO International Center (PIC) - Main Venue
D-01 Jigok Community Center (JCC) - Cafeteria for Lunch and Dinner
E-01 Accelerator Laboratory (PAL)

Other Faucilities

M-03 Hogil Kim Memorial Hall - APCTP(5F)
M-02 Science Building 1 - Max Planck Korea
M-06 Student Union Building - Book Store, Convenient Store, Food Court, Cafe
D-07 POSPLEX - Convenience Store, Restaurants, Gym, Swimming Pool
S-01 Tae-Joon Park Digital Library

Overview

Title _ Workshop on Spin-orbit Coupled Topological States (SOCTS)
Date _ October 1 (Mon) ~ 5 (Fri), 2018
Venue _ Auditorium, POSCO International Center (PIC), Pohang
Organized _ Asia Pacific Center for Theoretical Physics (APCTP)
Sponsored _ Korea Foundation for Max Planck POSTECH (MPK)
POSTECH Advanced Materials Science & BrainKorea21 Plus
International Centre for Theoretical Physics (ICTP)
Applied Science Korea Corporation (ASK Corporation)
Seongwoo Instruments
Instruments & Automation Korea (INA Korea)

Program at a Glance

	October. 1 Monday	October. 2 Tuesday	October. 3 Wednesday	October. 4 Thursday	October. 5 Friday
8:00~8:40	**Registration**				
8:40~8:50	**Opening Remarks**				
8:50~9:30	Shik Shin Tokyo Univ.	Tristan Cren CNRS, UPMC	Yuki Motome Tokyo Univ.	Jae Hoon Kim Yonsei Univ.	Hae-Young Kee Toronto Univ.
9:30~10:10	Jae-Hoon Park POSTECH	Tien-Ming Chuang SINICA	Yuji Matsuda Kyoto Univ.	Daniel Leykam IBS	Ludovic Jaubert CNRS, Bordeaux
10:10~10:30	**Coffee Break**				
10:30~11:10	Ilya Eremin Ruhr Univ. Bochum	Eun-Gook Moon KAIST	Suk Bum Chung Univ. Of Seoul	Tuson Park SKKU	Ara Go IBS
11:10~11:50	Seunghyun Khim MPI-CPS	Tanmoy Das IISC	Gil Young Cho POSTECH	Kee Hoon Kim SNU	Chan-Ho Yang KAIST
11:50~12:30	SungBin Lee KAIST	Shun-Qing Shen HKU	Jeil Jung Univ. of Seoul	Han-Yong Choi SKKU	Hye Jung Chang KIST
12:30~14:00	**Lunch**				**Closing Remarks** (12:30~12:40)
14:00~14:40	Dirk Wulferding TU Braunschweig	Matteo Minola MPI-FKF	Excursion (14:00~)	**PAL tour** (13:30-14:30)	**Lunch** (12:40~14:00)
14:40~15:20	Takashi Oka MPI-PKS	Hyunsoo Kim Univ.of Marylaud		**Break**	
15:20~16:00	Ross Mcdonald LANL	**Coffee Break** (15:20-15:40) Yoshiteru Maeno Kyoto University. (15:40-16:20)		Mahn-Soo Choi Korea Univ.	
16:00~16:20	**Coffee Break**			Bohm-Jung Yang SNU (16:00-16:40)	
16:20~17:00	Gang Chen Fudan Univ.	Minhyea Lee Univ. of Colorado		**Coffee Break** (16:40-17:00)	
17:00~17:40	Nicholas Shannon OIST	**Poster session** (17:00 -19:00)		BumJoon Kim POSTECH	
17:40~18:20	Ki-Seok Kim POSTECH			Kuan-Wen Chen NHMFL	
18:30~20:00	**Dinner**	**Banquet** (19:00)	**Dinner**	**Dinner**	

DAY 1 - October 1, Monday

8:00~8:40	Registration
8:40~8:50	Opening Remarks Jae-Hoon Park, POSTECH
	[Session 1] Chair: Alireza Akbari
8:50~9:30	Multiple Topological States in Iron-Based Superconductors Shik Shin, Tokyo University
9:30~10:10	Novel Magnetic Behaviors in Quasi-2D Honeycomb Lattices Jae-Hoon Park, POSTECH
10:10~10:30	**Coffee Break**
	[Session 2] Chair: Hyun-woo Lee
10:30~11:10	BCS-BEC Crossover in Multiband Superconductors Ilya Eremin, Ruhr University Bochum
11:10~11:50	A New Heavy-Fermion $CeRh_2As_2$ Close to an Unconventional Quantum Critical Point Seunghyun Khim, MPI-CPS
11:50~12:30	Multipolar Order and Superconductivity in Pr Based Kondo Materials SungBin Lee, KAIST
12:30~14:00	**Lunch**
	[Session 3] Chair: Yuji Matsuda
14:00~14:40	Anomalous Scattering Processes, Phonon Anomalies, and Their Relation to Transport Anomalies in the Weyl Semimetal WP_2 Dirk Wulferding, TU Braunschweig
14:40~15:20	Floquet Engineering in Topological Semimetals Takashi Oka, MPI-PKS
15:20~16:00	Topological Metals in the Quantum Limit Ross McDonald, LANL
16:00~16:20	**Coffee Break**
	[Session 4] Chair: Sungdae Ji
16:20 – 17:00	Frustrated Metal $Pr_2Ir_2O_2$ and Some thought on Thermal Transport Gang Chen, Fudan University
17:00 – 17:40	Frustrating Quantum Spin Ice Nicholas Shannon, Okinawa Institute of Science and Technology Graduate University
17:40 – 18:20	Quantum Critical Scaling in The Spin Excitation Spectrum of α-$RuCl_3$ Ki-Seok Kim, POSTECH
18:30 – 20:00	**Dinner**

DAY 2 - October 2, Tuesday

	[Sessoin 5] Chair: Ki-Seok Kim
8:50 – 9:30	Experimental Hints of 2D Topological Superconductivity: Direct Imaging of Dispersive Edge States and Zero Energy Bound States in Vortex Cores Tristan Cren, CNRS, University Pierre and Marie Curie
9:30 – 10:10	Termination-Dependent Superconducting Topological Surface States in Non-centrosymmetric $PbTaSe_2$ Tien-Ming Chuang, SINICA
10:10 – 10:30	**Coffee Break** (Group Photo)
	[Session 6] Chair: Yuki Motome
10:30 – 11:10	Vestiges of Topological Quantum Phase Transitions in Kitaev Quantum Spin Liquids Eun-Gook Moon, KAIST
11:10 – 11:50	Symmetry-Broken Topological Phases Tanmoy Das, Indian Institute of Science
11:50 – 12:30	Quantum Transport in Topological Materials Shun-Qing Shen, University of Hong Kong
12:30 – 14:00	**Lunch**
	[Session 7] Chair: Ross McDonald
14:00 – 14:40	Recent Developments from X-Ray Scattering Studies on Charge Order in High-Tc Superconducting Cuprates Matteo Minola, MPI-FKF
14:40 – 15:20	Unconventional Superconductivity and Anomalous Quantum Oscillations Hyunsoo Kim, University of Maryland
15:20 – 15:40	Coffee Break
	[Session 8] Chair: Nicholas Shannon
15:40 – 16:20	Inducing Giant Diamagnetism by DC Current in the Mott System Ca_2RuO_4 Yoshiteru Maeno, Kyoto University
16:20 – 17:00	In-Plane Thermal Conductivity and Magnetic Torque Study in 2D Honeycomb Lattice Magnets Minhyea Lee, University of Colorado
17:00 –19:00	**Poster Session**
19:00 – 21:00	**Banquet**

DAY 3 - October 3, Wednesday

[Sessoin 9] Chair: Gil-Ho Lee	
8:50 – 9:30	Majorana and Flux Excitations in Kitaev Spin Liquids Yuki Motome, Tokyo University
9:30 – 10:10	Half Integer Thermal Quantum Hall Effect in a Quantum Spin Liquid Yuji Matsuda, Kyoto University
10:10 – 10:30	**Coffee Break**
[Session 10] Chair: Shun-Qing Shen	
10:30 – 11:10	Cooper Pair Spin Current in $SrRuO_3$ / Sr_2RuO_4 Heterostructure Suk Bum Chung, University of Seoul
11:10 – 11:50	Electric Responses and Many-Body Invariants of Higher-Order Topological Insulators Gil Young Cho, POSTECH
11:50 – 12:30	Moire Flatbands in Van Der Waals Heterostructures Jeil Jung, University of Seoul
12:30 – 14:00	**Lunch**
14:00 –	**Excursion** (Invited Speakers only)
18:30 – 20:00	**Dinner**

DAY 4 - October 4, Thursday

[Sessoin 11] Chair: Tien-Ming Chuang	
8:50 – 9:30	Terahertz Electrodynamics of Topological Surface States Jae Hoon Kim, Yonsei University
9:30 – 10:10	Probing Weyl Points in Optics Daniel Leykam, IBS
10:10 – 10:30	**Coffee Break**
[Session 12] Chair: Tae-Hwan Kim	
10:30 – 11:10	Emergent Superconductivity in the Helical Antiferromagnet CrAs Tuson Park, Sungkyunkwan University
11:10 – 11:50	Enhanced Superconductivity in the Vicinity of A Pressure Tuned Lifshitz Transition: Cases for Fe-Based and Chalcogenide Superconductors Kee Hoon Kim, Seoul National University
11:50 – 12:30	BCS-BEC Crossover in The Holstein Model: DMFT-NRG Study of Superconductivity Han-Yong Choi, Sungkyunkwan University
12:30 – 14:00	**Lunch**
13:30 -14:30	**PAL Tour** (Invited Speakers Only)
[Session 13] Chair: Gil Young Cho	
15:20 – 16:00	Topological Classification of Quantum States of Bosons Mahn-Soo Choi, Korea University
16:00 – 16:40	Band Topology and Topological Phases in Systems with Space-time Inversion Symmetry Bohm-Jung Yang, Seoul National University
16:40 – 17:00	**Coffee Break**
[Session 14] Chair: Keun Su Kim	
17:00 – 17:40	Pseudospin-Lattice Coupling in The Spin-Orbit Mott Insulator Sr_2IrO_4 Bum-Joon Kim, POSTECH
17:40 – 18:20	Uncovering the Bulk Fermi Surfaces of the Topological Semimetals via De Hass-Van Alphen Effect Kuan-Wen Chen, NHMFL
18:30 – 20:00	**Dinner**

DAY 5 - October 5, Friday

	[Session 15] Chair: Ilya Eremin
8:50 – 9:30	Kitaev Spin Liquids and Nearby Phases Hae-Young Kee, Toronto University
9:30 – 10:10	Reentrance Behaviour in the Vicinity of Classical Spin Liquids Ludovic Jaubert, CNRS, LOMA, Univeresity of Bordeaux
10:10 – 10:30	**Coffee Break**
	[Session 16] Chair: Yunkyu Bang
10:30 – 11:10	Correlated Weyl Phases in Pyrochlore Iridates Ara Go, IBS
11:10 – 11:50	Ferroelectric Topology Chan-Ho Yang, KAIST
11:50 – 12:30	Finding Skyrmion in a Strong Permenant Magnet Using Lorentz TEM Hye Jung Chang, KIST
12:30 – 12:40	Closing Remarks Yunkyu Bang, APCTP
12:40 – 14:00	**Lunch**

Abstract
Invited Presentations

Abstract
Book

Workshop on Spin-orbit
Coupled Topological States

Multiple topological states in iron-based superconductors

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Topological materials and unconventional iron-based superconductors are both significant areas of study but, to date, relatively little overlap has been identified between these two fields. However, the combination of topological bands and superconductivity promises the manifestation of exotic superconducting states including Majorana fermions, the central component of topological quantum computation. Here, using laser-based, spin-resolved and angle-resolved photoemission spectroscopy and density functional theory calculations, we have identified both topological insulator and Dirac semimetal states near the Fermi energy in different iron-based superconducting compounds. Carrier doping can tune these topologically non-trivial bands to the Fermi energy, potentially allowing access to several different superconducting topological states in the same material. These results reveal the generic coexistence of superconductivity and multiple topological states in iron-based superconductors, indicating that this broad class of materials is a promising platform for high-temperature topological superconductivity.

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[1] P. Zhang, Z. Wang, X. Wu, K. Yaji, Y. Ishida, Y. Kohama, G. Dai, Y. Sun, C. Bareille, K. Kuroda, T. Kondo, K. Okazaki, K. Kindo, X. Wang, C. Jin, J. Hu, R. Thomale, K. Sumida, S. Wu, K. Miyamoto, T. Okuda, H. Ding, G.D. Gu, T. Tamegai, T. Kawakami, M. Sato, and S. Shin, Nature Physics (2018), in press.

[2] P. Zhang, K. Yaji1, T. Hashimoto, Y. Ota, T. Kondo, K. Okazaki, Z. Wang, J. Wen, G. D. Gu, H. Ding, and S. Shin, Science **359**, 6381(2018).

Novel Magnetic Behaviors in Quasi-2D Honeycomb Lattices

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Large spin-orbit coupling makes the magnetic eigenstate of the total angular momentum state with an admixed spin state and induces unusual magnetic behaviors. In cooperation with the crystal field, it could introduce the Kramers doublet in the magnetic ion site. Then the magnetism is described with the so-called spin-orbit coupled isospin states, and the system often displays novel magnetism behaviors. On the other hand, the admixed spin states possibly introduce anisotropic spin-spin interactions involving the inter-site hopping. In this talk, I will discuss spin-orbit coupled isospin spin liquid behaviors in a layered Kitaev lattice α-$RuCl_3$ and giant magnetic anisotropy observed in layered Cr compounds, which has been puzzled for the Cr^{3+} (t_{2g}^3) magnetic ion with L = 0.

Fluctuation-induced magnetic skyrmions at topological insulator surfaces

Ilya Eremin[1], Flavio S. Nogueira[2], Ferhat Katmis[3,4], Jagadeesh S. Moodera[3], Jeroen van den Brink[1,5], and Volodymyr P. Kravchuk[2,6]

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Ferromagnets in contact with a topological insulator have become appealing candidates for spintronics due to the Dirac surface states, which exhibit spin-momentum locking. Bilayer Bi2Se3-EuS structures, for instance, show a finite magnetization at the interface at temperatures well exceeding the Curie temperature of bulk EuS. Here we determine theoretically the effective magnetic interactions at a topological insulator-ferromagnet interface {\it above} the magnetic ordering temperature. We show that by integrating out the Dirac fermion fluctuations an effective Dzyaloshinskii-Moriya interaction and magnetic charging interaction emerge. As a result individual magnetic skyrmions and extended skyrmion lattices can form at interfaces of ferromagnets and topological insulators, the first indications of which have been very recently observed experimentally.

A new heavy-fermion CeRh2As2 close to an unconventional quantum critical point

Seunghyun Khim[1], Jacintha Banda[1], Daniel Hafner[1], Ulrike Stockert[1], Dongjin Jang[1,2], Manuel Brando[1], and Christoph Geibel[1]

[1]*Max Planck Institut für Chemische Physik fester Stoffe, Germany*
[2]*Max Planck-POSTECH Center for Complex Phase Materials, Pohang 37673, Korea*

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We have grown $CeRh_2As_2$ single crystals and studied its physical properties. This system has localized Ce^{3+} moments in high T and forms a coherent Kondo state below 30 K. The Kondo temperature (T_K) is estimated to be 20-30 K. The specific heat C/T increases with decreasing T below 5 K and reaches to ~ 1J/mol K^2 at 0.5 K.

The specific-heat measurements revealed two successive transitions at T_1 ~ 0.25 K and T_2 ~ 0.4 K at zero field. T_1 and T_2 much smaller than T_K and the enhanced specific-heat value imply that this system is very close to a hybridization induced quantum critical point (QCP). For B||ab, T_1 is completely suppressed above 2 T while it slowly decreases but remains finite at 10 T for B||c. T_2 for H||ab remains unchanged up to 4 T but gradually increases to reach 1 K at 14 T. For H||c, T_2 is suppressed to 0.3 K at 3 T but broaden and not discernible in higher fields.

We suggest the positive slope with field of T_2 and its anisotropic character as evidence of quadrupolar order as e.g. in CeB_6. This is supported by the observation that the magnetic entropy of Ce^{3+} continuously increases and approaches to Rln4 at 60-80 K, suggesting a quasi-quartet crystal electric field (CEF) ground state carrying finite quadrupolar moments. We also discuss the influence of the absent of the inversion symmetry on the Ce sites given by the $CaBe_2Ge_2$-type structure. The rich and unique phase diagram indicates the new compound, $CeRh_2As_2$, as a candidate system with coexisting dipolar and quadrupolar Kondo interactions possibly in a vicinity of a multipolar QCP.

Multipolar order and superconductivity in Pr based Kondo materials

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We discuss the multipolar ordering in $Pr(TM)_2(Al,Zn)_{20}$ Kondo materials. In Pr ion site, interplay of spin orbit coupling and crystal field splitting leads to non Kramers doublet as a ground state, where magnetic dipole degrees of freedom are absent but quadrupolar and octupolar degrees of freedom exist. Focusing on such unique ground state, we discuss physical properties of multipolar ordering and their phase transitions. We also discuss emergence of superconductivity in this cage compounds and their relevance to multipolar ordering.

Anomalous scattering processes, phonon anomalies, and their relation to transport anomalies in the Weyl semimetal WP_2

Dirk Wulferding[1], Peter Lemmens[1], Yurii Pashkevich[2], Tanya Shevtsova[2], Chandra Shekhar[3], and Claudia Felser[3]

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In Weyl semimetals globally robust electronic states exist, which are related to the topology of the electronic band structure, and therefore protected against local defects and impurities. This can lead to strong and unusual electron-electron correlations. The title compound WP_2 is a Weyl semimetal candidate with an anomalously large mobility at low temperatures and a charge-carrier mean free path of ~0.5 mm, described by hydrodynamic behavior [1,2,3].

Our Raman scattering study on WP_2 uncovers phonon anomalies as the system transitions from the ohmic, diffusive regime at high temperatures into the hydrodynamic regime at low temperatures. We also address electronic and fluctuation-based scattering signals and compare our study to related topological systems [4].

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Floquet engineering: from control of topology to new electronics

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Realizing new quantum states in solid state materials is of fundamental interest. I will explain several ideas based on Floquet engineering, i.e., control of quantum states by time periodical external fields.

(1) Control of topology by circularly polarized laser (CPL)
By applying CPL to materials such as 2D, 3D Dirac semimetals and Mott insulators, one can transform them into Floquet Chern insulator, Floquet Weyl semimetal [1], and even induce scalar chirality [2].
(2) Heterodyne Hall effect and Landau quantization in oscillating magnetic fields [3].

We studied the one particle dynamics of non-relativistic electrons in oscillating magnetic fields. To our surprise, we found that the Floquet quasi-energy becomes flat, as in Landau quantization, when the ratio between the cyclotron and the field frequencies takes a magic number. We also found that the heterodyne response, i.e., frequency shifted linear relation between the input electric field and output current, becomes quantized for the Hall component.

This work has been done in collaboration with Leda Bucciantini, Sota Kitamura, and Sthitadhi Roy.

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[3] T. Oka, and L. Bucciantini, Phys. Rev. **B 94**, 155133 (2016).

Topological Metals in the Quantum Limit

B. J. Ramshaw,[1,2] K. A. Modic,[3] Arkady Shekhter,[4] Yi Zhang,[2] Eun-Ah Kim,[2]
Philip J. W. Moll,[3] Maja Bachmann,[3] M. K. Chan,[1] J. B. Betts,[1] F. Balakirev,[1]
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Extreme magnetic fields play a fundamental role in both identifying and inducing novel states of matter. Beyond Landau level spectroscopy of the Fermi surface morphology and topology, I will discuss recent examples of novel physics in the quantum limit – where the cyclotron energy not only approaches, but exceeds the Fermi energy – from Hall quantization in three-dimensional Dirac systems, to the realization of the chiral anomaly in Weyl semimetals and the distinct possibility of inducing new correlated states of matter in topologically non-trivial metals. Magnetic fields of 95 tesla drive the Weyl semimetal TaAs far into its quantum limit (QL), where only the purely chiral 0th Landau levels (LLs) belonging to the Weyl fermions are occupied and can be studied in isolation. Up to 50 tesla we find the electrical resistivity to be nearly independent of magnetic field: unusual for a conventional metal but consistent with the chiral anomaly for Weyl fermions. Above 50 tesla we observe a two-order-of-magnitude increase in resistivity, indicating that a gap opens and providing a bulk measure of the Weyl-node separation. Above 80 tesla we observe strong ultrasonic attenuation below 2 kelvin, suggesting a new mesoscopically-textured state of matter. These results [1] illustrate how high magnetic fields can be used to overcome material constraints and access a state composed purely of Weyl fermions, and point the way to inducing new correlated states of matter composed of these exotic quasiparticles [2].

REFERENCES:

[1] B.J. Ramshaw et.al. Nature Communications **9**, 2217 (2018).
[2] This work was performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1157490 and the State of Florida, by LANL LDRD-DR20160085 “Topology and Strong Correlations”, and the U.S. Department of Energy Office of Basic Energy Sciences “Science at 100 T program”.

Frustrated metal Pr2Ir2O7 and some thought on thermal transport

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Extreme A We study the band structure topology and engineering from the interplay between local moments and itinerant electrons in the context of pyrochlore iridates. For the metallic iridate $Pr_2Ir_2O_7$, the Ir 5d conduction electrons interact with the Pr 4f local moments via the f-d exchange. While the Ir electrons form a Luttinger semimetal, the Pr moments can be tuned into an ordered spin ice with a finite ordering wavevector, dubbed "Melko-Hertog-Gingras" state, by varying Ir and O contents. We point out that the ordered spin ice of the Pr local moments generates an internal magnetic field that reconstructs the band structure of the Luttinger semimetal. Besides the broad existence of Weyl nodes, we predict that the magnetic translation of the "Melko-Hertog-Gingras" state for the Pr moments protects the Dirac band touching at certain time reversal invariant momenta for the Ir conduction electrons. We propose the magnetic fields to control the Pr magnetic structure and thereby indirectly influence the topological and other properties of the Ir electrons. Our prediction may be immediately tested in the ordered $Pr_2Ir_2O_7$ samples. We expect our work to stimulate a detailed examination of the band structure, magneto-transport, and other properties of $Pr_2Ir_2O_7$. If time permits, I will explain some thoughts about thermal transports in spin liquids.

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[1] Xu-Ping Yao and Gang Chen, arxiv:1712.06534.
[2] Yong-Hao Gao and Gang Chen, in preparation.

Frustrating Quantum Spin Ice

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"Quantum spin ice" materials have been widely discussed in terms of an XXZ model on a pyrochlore lattice. For unfrustrated interactions, $J_\pm > 0$, this model is accessible to quantum Monte Carlo simulation and plays host to a celebrated example giving way to easy-plane antiferromagnetic order for larger values of $J_\pm$. These results have generated considerable excitement, not least because of the tantalising possibility of making a direct comparison with experiment. However, there is no a prioiri reason to expect a quantum spin ice material to possess unfrustrated interactions, with explicit calculations for Pr--based pyrochlores predicting $J_\pm < 0$ [1]. And at present, relatively little is known about what should happen in this case [2].

In this talk we argue that the properties of a quantum spin ice may become even more interesting once it is “frustrated”. Using a broad range of analytic and numerical techniques, we explore the new phases which arise in the XXZ model on the pyrochlore lattice for $J_\pm < 0$. At finite temperature, we find that the frustrated model supports not one, but three distinct forms of spin liquid : the easy-axis spin liquid spin ice; a U(1)xU(1)xU(1) spin-liquid governed by a point with SU(2) symmetry; and an entirely new form of easy-plane spin liquid described by a U(1)xU(1) gauge group. We present explicit predictions for inelastic neutron scattering in each of these cases [3]. Meanwhile, in the quantum limit, for T=0, we find that spin ice gives way to the expected U(1) QSL in its π-flux phase [2], while the easy--plane spin liquid transforms into a nematic QSL. We provide a variational argument which shows how these two different phases are connected at the SU(2) point [4].

These results offer a rare opportunity to explore how one spin liquid transforms into another and suggest that experimental studies of pyrochlore magnets may still have a great many more surprises in store.

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Quantum critical scaling in the spin excitation spectrum of $\alpha - RuCl_3$

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Symmetry breaking in the presence of topological order serves as a platform for novel quantum phases of matter beyond the Landau-Ginzburg theoretical framework. In the present study we propose the coexistence between the symmetry-breaking order and the topological order in $\alpha - RuCl_3$, showing the emergence of symmetry breaking quantum criticality in the Kitaev spin-liquid state. Recently, inelastic neutron scattering measurements for $\alpha - RuCl_3$ revealed $\mathrm{Im}\chi(\omega, \mathrm{T}) = T^{-\eta_\chi} f(\omega/T)$ quantum critical scaling at both Γ and M points not only above but also below the Neel temperature in the quantum critical regime of $\omega/T \gg 1$. Based on the renormalization group analysis for an effective field theory to describe the zigzag spin-ordering transition in the Kitaev spin liquid state, we find the anomalous critical exponent η_χ and the universal scaling function $f(\omega/T)$, which fits the neutron scattering data quantitatively well, identifying them with the continuum spectrum of fermionic spinons scattering with critical zigzag spin fluctuations. The existence of ω/T quantum critical scaling suggests that the nature of the zigzag ordering transition cannot belong to the classical (two-dimensional) Ising universality class, where the quantum (three-dimensional) Ising universality class should be modified by gapless Majorana fermion excitations. Our renormalization group analysis and the comparison with the inelastic neutron scattering data suggest that the zigzag ordering antiferromagnetic quantum criticality in $\alpha - RuCl_3$ belongs to a novel universality class beyond the Wilson-Fisher fixed point. Interplay between symmetry breaking and topological order is responsible for the emergence of novel universality classes.

Two-dimensional topological superconductivity in Pb/Co/Si(111)

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The examination of supposedly well-known condensed matter systems through the prism of topology has led to the discovery of new quantum phenomena that were previously overlooked. Just like insulators can present topological phases characterized by Dirac edge states, superconductors can exhibit topological phases characterized by Majorana edge states. In particular, one-dimensional topological superconductors are predicted to host zero energy Majorana fermions at their extremities. Zero bias anomalies localized at the edge of proximity induced superconducting wires were recently interpreted as fingerprints of the emergence of topological superconductivity [1,2].

By contrast, two-dimensional (2D) superconductors have a one-dimensional boundary which would naturally lead to propagating Majorana edge states characterized by a Dirac-like dispersion. We have recently observed some hint of dispersive Majorana edge states in a single atomic layer Pb superconductor. This material has strong triplet correlations but is not topological by itself [3]. We will show that by applying a Zeeman field with the help of a buried Co-Si nano-magnet one can provoke a transition to a topological state.

In addition to their dispersive edge states, 2D topological superconductors are also supposed to support localized Majorana bound states in their vortex cores. We will show that some recent measurements seem to support this theoretical prediction.

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Termination-dependent Superconducting Topological Surface States in Non-centrosymmetric $PbTaSe_2$

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The search for topological superconductors (TSCs) is one of the most exciting subjects in condensed matter physics. TSCs are characterized by a full superconducting gap in the bulk and topologically protected gapless surface or edge states. Within each vortex core of TSCs, there exist the zero energy Majorana bound states, which are predicted to exhibit non-Abelian statistics and to form the basis of the fault-tolerant quantum computation. So far, $PbTaSe_2$ is the only stoichiometric bulk material exhibits the required topological surface states at EF combined with fully gapped bulk superconductivity [1]. Interestingly, two distinct and stable cleaved surfaces have been identified to be Pb- and Se-termination by using spectroscopic imaging-scanning tunneling microscope. Two terminations exhibit striking difference in both atomic and electronic structure above Tc while both exhibit a full superconducting gap and zero energy bound state in the superconducting vortex core [2]. Our results show $PbTaSe_2$ is a great platform for the study of 2D TSC.

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Vestiges of Topological Quantum Phase Transitions in Kitaev Quantum Spin Liquids

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We investigate vestiges of topological quantum phase transitions (TQPTs) between the Z_2 quantum spin liquids (QSLs). In two spatial dimensions, Z_2 QSLs and their TQPTs are not well-defined at non-zero temperatures, and it is imperative to clarify their observable signatures at non-zero temperature. Here, we present the nonzero temperature signature of TQPTs between Z_2 QSLs with Majorana fermions by using path-integral and parton mean field analysis on a modified Kitaev model with next-nearest neighbor interactions. We discuss the implication of our results to the recent experiments in $RuCl_3$ [1].

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Symmetry-broken topological phases

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Phases are matter are often classified by either a broken symmetry quantum order, or a symmetry invariant topological number. There are however several exceptions such as axion insulators, Mobius insulators which exhibit a topological invariant despite the loss of its corresponding symmetry. To study the complex behavior arising from the interplay between the quantum and topological orders, we present a Ginzburg-Landau-Chern-Simons (GLCS) theory. We apply this method to the enigmatic $TlCuCl_3$ system which shows many distinct quantum phenomena such as resilience of a Higgs mode to the magnetic QCP, etc. Based on DFT calculation, we show that this material is a magnetic topological insulator where the topological axion term makes the Higgs mode remains massive at the QCP. Finally, we discuss many other distinct cases where topology emerges from various combined symmetries, despite the loss of individual symmetries. contents

Intrinsic Magnetoresistivity in Three-Dimensional Dirac Materials

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Recently, negative longitudinal and positive in-plane transverse magnetoresistance have been observed in most topological Dirac/Weyl semimetals, and some other topological materials. Here we present a quantum theory of intrinsic magnetoresistance for three-dimensional Dirac fermions at a finite and uniform magnetic field B. In a semi-classical regime, it is shown that the longitudinal magnetoresistance is negative and quadratic of a weak field B while the in-plane transverse magnetoresistance is positive and quadratic of B. The relative magnetoresistance is inversely quartic of the Fermi wave vector and only determined by the density of charge carriers, irrelevant to the external scatterings in the weak scattering limit. This intrinsic anisotropic magnetoresistance is measurable in systems with lower carrier density and high mobility. In the quantum oscillation regime a formula for the phase shift in Shubnikov-de Hass oscillation is present as a function of the mobility and the magnetic field, which is useful for experimental data analysis.

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Recent developments from X-ray scattering studies on Charge Order in high-Tc superconducting cuprates

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Incommensurate charge order (CO) has been identified as the leading competitor of high-temperature superconductivity in all major families of layered copper oxides, but the perplexing variety of CO states in different cuprates has confounded investigations of its impact on the transport and thermodynamic properties. The three-dimensional (3D) CO observed in $YBa_2Cu_3O_{6+x}$ in high magnetic fields is of particular interest, because quantum transport measurements have revealed detailed information about the corresponding Fermi surface.

Here, we report a high-resolution inelastic hard x-ray scattering study of the high-temperature superconductor $YBa_2Cu_3O_{6.67}$ under uniaxial stress and show that a three-dimensional long-range-ordered CDW state akin to that observed in field can be induced by pressure along the a-axis, in the absence of magnetic fields. The amplitude of the CDW is strongly suppressed below the superconducting transition temperature, indicating strong thermodynamic competition with superconductivity. We also show that a strong softening of an optical phonon mode is associated with the transition.

We also used resonant soft X-ray scattering to demonstrate 3D CO in $YBa_2Cu_3O_{6+x}$ films grown epitaxially on $SrTiO_3$ (STO) in the absence of magnetic fields. The resonance profiles indicate that Cu sites in the charge-reservoir layers participate in the CO state, and thus efficiently transmit CO correlations between adjacent CuO_2 bilayer units. These results offer fresh perspectives for experiments elucidating the influence of 3D-CO on the electronic properties of cuprates without the need to apply high magnetic fields.

Unconventional superconductivity and anomalous quantum oscillations in topological semimetal YPtBi

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Several theoretical studies had discovered the topological nature in the half-Heusler compounds, which is driven by strong spin-orbit coupling (SOC) [1]. The non-trivial topology in these compounds has revealed interesting phenomena including chiral anomaly [2] and anomalous Hall effect [3] in GdPtBi. Furthermore, a new series of magnetic superconductor RPdBi (R=rare earth) [4] was discovered, which offers excellent opportunities to investigate the interplay between a topologically ordered phase and symmetry-breaking ordered phase. The discovery of unconventional superconductivity in YPtBi [5] has boosted an intense study on possible exotic superconductivity in the half-Heusler compounds. In this talk, we will discuss recent developments in research on superconductivity in YPtBi and present experimental works on the quantum oscillation measurements. We performed measurements of the angle-dependent Shubnikov-de Haas (SdH) effect and observed smooth evolution of Berry's phase as a function of magnetic field orientation. We will explain the unprecedented angular variation in SdH effect within a semiclassical picture with extreme spin-orbit coupling in YPtBi. Among the long-predicted topological semimetal half-Heusler RPtBi, YPtBi explicitly manifests the non-trivial Berry's phase and is a model 3D topological system for SdH effect affected by SOC.

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Inducing giant diamagnetism by DC current in the Mott system Ca_2RuO_4

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DC current can be a powerful tuning parameter of the electronic states of strongly correlated electron systems in the vicinity of Mott transitions. In this presentation, we give a short review on the research progress on the novel phenomena in the layered perovskite Ca_2RuO_4 and related materials.

Under DC current, Ca_2RuO_4 with a small Mott gap (~ 0.4 eV) exhibits semimetallic transport behavior with giant diamagnetism at low temperatures [1]. We attribute this behavior to emergent “Mott semimetal” state, in which the upper and lower Hubbard bands become tiny electron and hole pockets with light quasiparticle mass responsible for the large diamagnetism.

It demonstrates that in a non-equilibrium steady state (NESS) introduced by DC current, a Mott insulator with a small gap can be readily driven into novel electronic states.

This work is done mainly in collaboration with T. Oka, S. Kitamura, K. Kuroki, D. Shibata, T. Yoshida, and N. Kikugawa. This work was supported by JSPS KAKENHI Nos. JP26247060, JP15H05852, and JP15K21717.

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In-plane thermal conductivity and magnetic torque study in 2D honeycomb lattice magnets

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Thermal transport properties have been one of key experimental probes to study insulating quantum magnets and their phase diagram because of its versatility under a wide range of experimental conditions and its unique sensitivity only to itinerant excitations, as opposed to localized excitations. In this talk, I will present the thermal conductivity and the torque magnetization on quasi 2D honey comb lattice magnets — $RuCl_3$, $CrCl_3$ and Na_2IrO_3. Different contributions to the complex temperature and magnetic field dependence of thermal conductivity will be discussed in the relation to the torque magnetization.

Majorana and flux excitations in Kitaev spin liquids

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In this talk, we overview our recent theoretical studies on thermodynamics and spin dynamics in the Kitaev spin model, in comparison with recent experimental results. In particular, we discuss the signatures of fractional excitations of Majorana fermions and Z_2 fluxes, comparing our theoretical results and recent experimental data for candidate materials. The topics will cover spin dynamics (Raman [1], inelastic neutron and NMR [2,3]), thermal transport [4-6], and topological transitions in a magnetic field [7]. We will also discuss new directions for the material exploration of Kitaev magnets [8,9].

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Half integer thermal quantum Hall effect in a quantum spin liquid

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The quantum Hall effect (QHE) in 2D electron gases involves the topologically protected dissipationless charge current flow along the edges of the sample. Integer or fractional electrical conductance are measured in units of $e^2/2\pi\hbar$, which is associated with edge currents of electrons or quasiparticles with fractional charges, respectively. Here we report a novel type of quantization of the Hall effect in an insulating 2D quantum magnet. In $RuCl_3$ with dominant Kitaev interaction on 2D honeycomb lattice, we observed a quantum plateau of the 2D thermal Hall conductance, which is exactly half of that expected in the integer QHE [1,2]. This half-integer thermal Hall conductance is a direct signature of topologically protected chiral edge currents of non-Abelian anyon, i.e. charge neutral Majorana fermions.

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Cooper pair spin current in $SrRuO_3$ / Sr_2RuO_4 heterostructure

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The spin-triplet superconductor by definition should involve spin ordering that gives rise to the spin collective phenomena such as the spin collective modes and the spin supercurrent. However, in the superconducting phase in the best-known candidate material, Sr_2RuO_4, only the latter has been observed just for the mesoscopic sample [1]. I will show how the recently fabricated heterostructure of bulk Sr_2RuO_4 and the ferromagnetic $SrRuO_3$ provides a particularly natural probe for detecting both types of spin collective phenomena. The spin supercurrent that can be injected naturally into Sr_2RuO_4 from $SrRuO_3$ can be used to obtain an exceptionally high-quality spin valve, while applying an AC bias on $SrRuO_3$ can drive the Sr_2RuO_4 spin collective modes [2].

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Electric Responses and Many-Body Invariants of Higher-Order Topological Insulators

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In this talk, we propose many-body invariants for so-called higher-order topological insulators by generalizing Resta's pioneering work on polarizations. The many-body invariants are designed to measure quantized multipole moments from the bulk ground state wave-functions of higher-order topological insulators. Finally, we make a connection of these invariants and electromagnetic responses of higher-order topological insulators, which will pave the way to experimentally measure the invariants

Moire Flatbands in van der Waals heterostructures

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In this presentation I will discuss the electronic structure of moire patterned van der Waals materials that can give rise to narrow bandwidth flatbands under appropriate conditions of interlayer coupling, twist angles and external electric fields. Firstly, we will show how the enhancement of interlayer coupling in twisted bilayer graphene can linearly shift to larger values the flatband magic angles where correlated phases can be expected. Secondly, we will show how the flatbands can arise in a rhombohedral trilayer graphene perturbed by moire patterns of nearly aligned hexagonal boron nitride substrate and an external electric field can lead to flatbands with finite values of valley resolved quantized Chern numbers. We expect that a rich variety of quantum Hall phases at zero magnetic field can arise depending on the specific configuration of the ground state driven by the interactions.

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Terahertz Electrodynamics of Topological Surface States

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The topological surface states (TSSs) are a hallmark signature of topological insulators and exhibit a number of unique characteristics derived directly from the nontrivial bulk topology. The detection and manipulation of the TSSs in ambient conditions are a formidable challenge due to a number of difficulties associated with the residual bulk states. Here, we show that, by employing ultrathin topological insulator films and terahertz time-domain spectroscopy (THz-TDS), the TSSs can be isolated and manipulated to the extent that a series of interesting quantum effects can be demonstrated in ambient conditions.

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Probing Weyl points in optics

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Weyl points are isolated degeneracies of three-dimensional band structures. Forming monopoles of Berry curvature, they are protected by a quantized topological charge and host novel "Fermi arc" surface states. They can appear in two forms: isotropic "type-I" Weyl points, which have a vanishing density of states at the degeneracy point, and strongly anisotropic "type-II" Weyl points which have a nonzero density of states [1].

I will discuss how the novel properties of "type-II" Weyl points can be explored using photonic lattices of evanescently coupled optical waveguides fabricated using the femtosecond laser writing technique [2]. We employ an analogy with two-dimensional Floquet topological insulators to efficiently calculate the band structure of our system and demonstrate the existence of isolated Weyl points [3]. We probe the lattice at various wavelengths (1450–1650nm), equivalent to tuning the Fermi level, and observe the emergence of the Fermi arc surface states from the Weyl point. We also probe the bulk states, which display a conical diffraction pattern characteristic of the type-II Weyl point's conical isofrequency surface. At higher probe beam powers, the waveguides' Kerr self-focusing nonlinearity can be used to probe the effect of attractive interactions on the Weyl point modes [4].

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Emergent superconductivity in the helical antiferromagnet CrAs

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Unconventional superconductivity commonly emerges in proximity to a magnetically ordered phase, raising the possibility that critical spin fluctuations may mediate the formation of superconducting Cooper pairs. CrAs is an interesting new example in which antiferromagnetic order is tuned to zero temperature at a pressure where a dome of superconductivity reaches a maximum T_c [1]. Unlike other classes of unconventional superconductors, however, the superconductivity is completely decoupled from tunable quantum critical points in the 0.7% Al-doped CrAs, suggesting that the Cooper pair formation is not mediated by critical magnetic fluctuations. These discoveries not only point to new understanding of superconductivity in CrAs but also indicate more broadly the power of using multiple non-thermal tuning parameters simultaneously to reveal the relationship between superconductivity and a hidden quantum critical point [2].

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Enhanced superconductivity in the vicinity of a pressure tuned Lifshitz transition: cases for Fe-based and chalcogenide superconductors

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High pressure has been an important physical parameter, of which applications to solids can lead to findings of e.g., unexplored exotic phases of various quantum matters or their putative quantum mechanical ground states. With such recent developments of techniques, one can now apply conventionally up to ~100 GPa in diamond anvil cells and high quality hydrostatic pressure up to ~15 GPa at high field and low temperature environment. In this talk, I'll present pressure induced optimization of superconductivitiy, particularly focusing on tuning of electronic states in Fe-based superconductors and chalcogenide superconductors. In the latter, I will point out a possibility that the interplay between charge density wave (CDW) and superconductivity (SC) can exhibit unexpected change of electronic structure to strengthen superconductivity via the increase of electronic density of states and electron-phonon coupling. The enhanced superconductivity obviously seems to involve a Liftshitz transition in one of Fermi surface pockets formed within the commensurate CDW state. In the former, I'll also show how pressure can tune a possible Lifshitz transition of a system and lead to unexpected increase of superconducting transition temperature up to ~ 52 K.

BCS-BEC crossover in the Holstein model: DMFT-NRG study of superconductivity

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We consider the Holstein model to investigate the interplay between phonon dynamical effects and superconductivity in the BCS-BEC crossover at zero temperature. The crossover problem was well studied based on the attractive Hubbard model in both continuum and lattice models. It has been established that the BCS picture at small onsite interaction U changes smoothly over to the BEC regime as U is increased. The pairing gap Δsc continues to increase but the critical temperature Tc increases initially but decreases $\sim t^2/U$ as U is further increased with a maximum at U=Uc1. Uc1 is the lower critical value of the metal-insulator transition in the normal state. Here, we study the dynamical effects on the BCS-BEC crossover where the superconducting pairing is mediated by the phonons. The model with the onsite phonon frequency ω0 and electron-phonon coupling g is solved at half-filling by employing the dynamical mean-field theory (DMFT) in combination with Wilson's numerical renormalization group (NRG) technique. The NRG arbitrary precision in the low energy region enables us to extend the BCS-BEC crossover to the Holstein model where phonon soft mode emerges at the phase boundary gc1 separating metal and local pair (bipolaron) insulating states in the normal state. We find, interestingly, that at the phase boundary gc1 appears the maximum Tc regardless of the phonon frequency just like the maximum Tc appears at Uc1 for the attractive Hubbard model. Coupled with this, beyond g>gc1 emerges the zero frequency Goldstone mode of local pair phase fluctuations in the superconducting state. The weight of this zero mode scales with the gap Δsc. Also interesting is that the gap does not continue to increase as g increases but has a broad maximum at gp and decreases, where gp is set by the phonon frequency ω0. gp equals gc1 for adiabatic cases (ω0«t) and increases monotonically as ω0 is increased.

Topological Classification of Quantum States of Bosons

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Recently, many-body ground states of non-interacting Fermions on various lattices have been classified in terms of their topological properties. Topological insulators, topological superconductors, and Weyl semimetals are popular examples.

Here we consider the topologically non-trivial quantum states of Bosons. Due to the commutation relation (compared with the anti-commutation relation for Fermions), the geometry underlying the Fock space for Bosons should be symplectic by nature. We study the effects of the symplectic geometry on the topological classification of the quantum states of Bosons.

Band topology and topological phases in systems with space-time inversion symmetry

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In this talk, I am going to talk about novel topological properties of spinless fermions systems with space time inversion IST symmetry, which is basically a combination of time-reversal symmetry with additional inversion or two-fold rotation symmetry. In three dimensions, the band topology of IST symmetric systems can support nodal lines with Z_2 monopole charges [1]. Here we show the intriguing linking structure of monopole nodal line and propose a general mechanism for pair-creation and pair-annihilation. In the case of two dimensional systems with IST symmetry, we show that the nontrivial band topology of two band systems can be characterized by Euler class. We prove that a two-band system with nontrivial Euler class has band crossing points with nonzero total vorticity, which naturally violates the well-known Nielsen-Ninomiya theorem. We propose that both the topological property of monopole nodal lines and the fragile topology of 2D insulators with nontrivial Euler class originate from the underlying mathematical structure of the IST symmetric real wave functions, dubbed the second Stiefel-Whitney class.

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Pseudospin-lattice coupling in the spin-orbit Mott insulator Sr_2IrO_4

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Spin-orbit entangled magnetic dipoles, often referred to as pseudospins, provide a new avenue to explore novel magnetism inconceivable in the weak spin-orbit coupling limit, but the nature of their low-energy interactions remains to be understood. In this talk, I will present a comprehensive study of the static magnetism and low-energy pseudospin dynamics in the archetypal spin-orbit Mott insulator Sr_2IrO_4. We find that in order to understand even basic magnetization measurements, a formerly overlooked in-plane anisotropy is fundamental. In addition to magnetometry, we use neutron diffraction, inelastic neutron scattering, and resonant elastic and inelastic x-ray scattering to identify and quantify the interactions that determine the global symmetry of the system and govern the linear responses of pseudospins to external magnetic fields and their low-energy dynamics. We find that a pseudospin-only Hamiltonian is insufficient for an accurate description of the magnetism in Sr_2IrO_4, and that pseudospin-lattice coupling is essential. This finding should be generally applicable to other pseudospin systems with sizable orbital moments sensitive to anisotropic crystalline environments.

Uncovering the bulk Fermi surfaces of the topological semimetals via de Hass-van Alphen effect

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The de Hass-van Alphen (dHvA) effect is a powerful tool that has been used to investigate the metallic band structures and Fermi surfaces of many different materials during the last 90 years. Recently, it gained new importance during efforts to uncover the novel band structures and Berry's phases in systems with topologically protected electronic states. In this talk, I will focus on the dHvA effect measured using torque magnetomery in the type II Dirac semimetal family of materials (V,Nb,Ta)Al_3. Our measurements reveal the existence of tilted Dirac cones with Dirac type-II nodes located at 100, 230 and 250 meV away from the Fermi surface for VAl_3, $NbAl_3$, $TaAl_3$ respectively. These results are consistent with earlier band structure calculations, which also predict a non-trivial electronic topology. However, for all three compounds we find that the cyclotron orbits on the Fermi surfaces, including an orbit nearly enclosing the Dirac type-II node, yield trivial Berry phases. We will show that in order to determine the Berry phases, the overall understanding of the topology of the Fermi surfaces and the g-factors are required.

Kitaev spin liquids and nearby phases

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The Kitaev spin liquid phase is one of the prominent strongly interacting topological phases of matter, which enables topological quantum computations. Despite intensive efforts on searching for Kitaev spin liquid materials, unambiguous confirmation is yet to be reached. One challenge is to identify candidate materials and formulate realistic theoretical models. I will present a generic spin model for the spin-orbit coupled honeycomb lattice, and its phase diagram including of an extended region of quantum spin liquid and unconventional magnetic phases. Experimental implications to honeycomb iridates and $RuCl_3$ will be discussed.

Reentrance behaviour in the vicinity of classical spin liquids

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Quantum critical points famously separate different phases at zero temperature via a continuous phase transition. Their effects are being felt over a broad temperature range, whose quantum critical fluctuations often support neighbouring exotic magnetic phases. In this poster, we will explore its classical analogue when one of the two neighbouring phases is a spin liquid. The enhancement of symmetry at this zero-temperature boundary would naively suggest a “more” disordered phase than the neighbouring spin liquid. However, this enhanced ground-state manifold may actually allow for critical fluctuations (soft modes) to concentrate on regions of the phase space that are otherwise inaccessible at low temperature. Order by disorder then plays its role, and the magnetic order of this high-symmetry point spreads like a fan at finite temperature. This fan gives rise to a reentrant behaviour above the spin liquid and is continuously connected to more traditional order on the other side of the phase diagram. When order by disorder is not possible, then an extension of the idea of reentrance is possible for the competition between disordered spin liquids at finite temperature.

Correlated Weyl phases in pyrochlore iridates

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Motivated by Weyl semimetal and axion insulator observed in a model Hamiltonian targeting pyrochlore iridates $R_2Ir_2O_7$ (R-227) [1], we conducted density functional theory plus dynamical mean-field theory (DFT+DMFT) calculations for R-227 (R=Lu, Y, and Eu) compounds [2]. Unlike in usual three-dimensional materials, the single-site DMFT fails to reproduce qualitative difference between metallicity of Lu-227 and Y-227. Subsequent cluster DMFT calculations show that intersite correlations are crucial not only to explain the difference but also to stabilize the Weyl phases: Weyl metal and semimetal. We analyze the spectral weights from the cluster DMFT by employing k.p theory. The effective Hamiltonian yields finite susceptibilities in the aforementioned Weyl phases, indicating that the phases are likely stable to beyond-DMFT interaction effects.

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Ferroelectric Topology

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Topological defects in matter are a topic of intense interest in contemporary condensed matter physics. In particular, vortices and skyrmions in ferroic materials have received considerable attention as topologically protected quasi-particles that carry energy and information. These energetically quantized and spatially confined excitations behave collectively to form highly non-trivial structures called topological textures that are characterized by conserved quantities such as the winding number. Despite the identification of electric vortex structures, electric switching of competing vortex textures in dielectrics with deterministic configurability of the topological number remains experimentally unconfirmed. Here, we show that an epitaxial ferroelectric square nanoplate of bismuth ferrite enables five discrete levels for the ferroelectric topological invariant of the entire system. The total winding number of the topological texture can be configured from −1 to 3 by selective non-local electric switching of the quadrant domains. By using angle-resolved piezoresponse force microscopy in conjunction with local winding number analysis, we directly identify the existence of vortices and anti-vortices, observe pair creation and annihilation, and manipulate the net number of vortices. Our findings offer a useful concept for the stabilization and control of ferroelectric vortices for multi-level topological defect memory.

Finding skyrmion in a strong permenant magnet using Lorentz TEM

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Lorentz Transmission electron microscopy (LTEM) is one of the powerful instruments to observe the nanoscale structural and the magnetic field features of materials simultaneously. Recently, topological-in-origin robust magnetic skyrmions have been reported in several materials systems utilizing LTEM, mostly in the noncentrosymmetric B20 crystal system at low temperature, which limits the practical application. Here, we report novel hard skyrmions in one of the strongest ferromagnets, which can be operated at high temperature above room temperature. This is of importance stepping stone since it paves the way for an immense application potential by providing a new approach to make skyrmions in hard magnet materials through appropriate field cooling. The control and visualization was performed in the LTEM (FEI; Titan80-300) equipped with heating holder. Various skyrmion like bubbles formed near the skyrmion window will be also discussed in the presentation.

Abstract
Poster Presentations

Abstract Book

Workshop on Spin-orbit Coupled Topological States

Drumhead surface states and their signatures in quasiparticle scattering interference

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We consider a two-orbital tight-binding model defined on a layered three-dimensional hexagonal lattice to investigate the properties of topological nodal lines and their associated drumhead surface states. We examine these surface states in centrosymmetric systems, where the bulk nodal lines are of Dirac type (i.e., fourfold degenerate), as well as in noncentrosymmetric systems with strong Rashba and/or Dresselhaus spin-orbit coupling, where the bulk nodal lines are of Weyl type (i.e., twofold degenerate). We find that in noncentrosymmetric systems the nodal lines and their corresponding drumhead surface states are fully spin polarized due to spin-orbit coupling. We show that unique signatures of the topologically nontrivial drumhead surface states can be measured by means of quasiparticle scattering interference, which we compute for both Dirac and Weyl nodal line semimetals.

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Edge currents as a probe of the strongly spin-polarized topological noncentrosymmetric superconductors

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Recently the influence of antisymmetric spin-orbit coupling has been studied in novel topological superconductors such as half-Heusler compounds and artificial heterostructures. We investigate the effect of Rashba and/or Dresselhaus spin-orbit couplings on the band structure and topological properties of a two-dimensional noncentrosymmetric superconductor. For this goal, the topological helical edge modes are analyzed for different spin-orbit couplings as well as for several superconducting pairing symmetries. To explore the transport properties, we examine the response of the spin-polarized edge states to an exchange field in a superconductor-ferromagnet heterostructure. The broken chiral symmetry causes the unidirectional currents at opposite edges.

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Mixed-pairing superconductivity in 5d Mott insulators with antisymmetric exchange: Application to Sr_2IrO_4

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We study the symmetry of the potential superconducting order parameter in 5d Mott insulators with an eye toward hole-doped Sr_2IrO_4. Using a mean-field method, a mixed singlet-triplet superconductivity, d+p, is observed due to the antisymmetric exchange originating from a quasi-spin-orbit coupling. Our calculation on ribbon geometry shows the possible existence of the topologically protected edge states, because of the nodal structure of the superconducting gap. These edge modes are spin polarized and emerge as zero-energy flat bands, supporting a symmetry-protected Majorana state, verified by evaluation of the winding number and Z_2 topological invariant. At the end, a possible experimental approach for observation of these edge states and determination of the superconducting gap symmetry is discussed based on the quasiparticle interference technique.

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Violation of Ohm`s law in a Weyl metal

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Weyl metal is one of the topological non-trivial materials holding Weyl fermions which are massless and have a chirality. The Weyl metal has been described in terms of axion electromagnetism rather than in Maxwell electromagnetism, and has peculiar properties such as chiral anomaly, the presence of magnetic monopole in the reciprocal lattice space and negative longitudinal magneto resistance. In this presentation, by transportation experiment besides negative longitudinal magneto resistance, we observed ohm’s law was broken in the Weyl metal and carried experimental and theoretical analysis of the violation of ohm`s law [1].

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Proximity-induced mixed odd- and even-frequency pairing in monolayer $NbSe_2$

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Monolayer superconducting transition-metal dichalcogenide $NbSe_2$ is a candidate for a nodal topological superconductor by magnetic field. Because of the so-called Ising spin-orbit coupling that strongly pins the electron spins to the out-of-plane direction, Cooper pairs in monolayer superconductor $NbSe_2$ are protected against an applied in-plane magnetic field much larger than the Pauli limit. In monolayer $NbSe_2$, in addition to the Fermi pockets at the corners of Brillouin zone with opposite crystal momentum similar to other semiconducting transition-metal dichalcogenids, there is an extra Fermi pocket around the Γ point with much smaller spin splitting, which could lead to an alternative strategy for pairing possibilities that are manipulable by a smaller magnetic field. By considering a monolayer $NbSe_2$-ferromagnet substrate junction, we explore the modified pairing correlations on the pocket at Γ point in hole-doped monolayer $NbSe_2$. The underlying physics is fascinating as there is a delicate interplay of the induced exchange field and the Ising spin-orbit coupling. We realize a mixed singlet-triplet superconductivity, s + f, due to the Ising spin-orbit coupling. Moreover, our results reveal the admixture state including both odd- and even-frequency components, associated with the ferromagnetic proximity effect. Different frequency symmetries of the induced pairing correlations can be realized by manipulating the magnitude and direction of the induced magnetization.

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Anomalous quantum interference effects in graphene SNS junctions due to strain-induced gauge fields

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We investigate the influence of gauge fields induced by strain on the supercurrent passing through the graphene-based Josephson junctions. We show in the presence of a constant pseudo-magnetic field Bs originated from an arc-shaped elastic deformation, the Josephson current is monotonically enhanced. This is in contrast with the oscillatory behavior of supercurrent (known as Fraunhofer pattern) caused by real magnetic fields passing through the junction. The absence of oscillatory supercurrent originates from the fact that strain-induced gauge fields have opposite directions at the two valleys due to the time-reversal symmetry. Subsequently, there is no net Aharonov-Bohm effect due to Bs in the current carried by the bound states composed of electrons and holes from different valleys. On the other hand, when both magnetic and pseudo-magnetic fields are present, Fraunhofer-like oscillations as a function of the real magnetic fields flux are found. We find that the Fraunhofer pattern and in particular its period slightly changes by varying the strain-induced gauge fields as well as the geometric aspect ratio of the junction. Intriguingly, the combination of two kinds of gauge fields results in two special fingerprints in the local current density prole: (i) strong localization of the Josephson current density with more intense maximum amplitudes; (ii) appearance of the inflated vortex cores - finite regions with almost diminishing Josephson currents - which their sizes increase by increasing Bs. These findings reveal unexpected interference signatures of strain induced gauge fields in graphene SNS junctions and provide unique tools for sensitive probing of the pseudo-magnetic fields.

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Tailoring electronic transport in graphene by time-dependent gauge fields

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We investigate the influence of time and space dependent gauge fields in transport properties of monolayer graphene originated from either strain or external electromagnetic fields. Using the well-established framework of Floquet theory besides Bloch theorem we find the wave-functions and quasi-energies induced by the spatiotemporal modulation of the magnetic and pseudo-magnetic fields. Provided that strain induces pseudo-magnetic fields which change signs in two valleys, using the combination of real and fictitious gauge fields we can almost independently modify and control both the quasi-band structure and the transport properties of the two valleys. Of particular interest when the two time-dependent fields are exactly the same in magnitude and have circular polarization, it is possible to create a gap in one valley where real and pseudo magnetic fields sum up with each other, while the other remains gapless due to the cancellation of two gauge fields. Furthermore, we expect very peculiar anisotropic and valley dependent transport aspects particularly in optical conductivity using linearly polarized time-dependent gauge fields.

Interaction effects on the Kane Mele model in the Hofstadter regime

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Considering interacting Kane-Mele model of honeycomb lattice in the Hofstadter regime, we realize that the orbital motion of electrons can induce versatile topological phases with spontaneously broken symmetries. In the Hofstadter regime without spin orbit coupling, the interactions lead to the breaking of translational and rotational symmetries of the system resulting in nematic and ferrielectric phases. Here, within the mean field framework, we extend the study and consider the onsite and nearest neighbor interactions in the Kane-Mele model and discuss possible phases in the absence and presence of magnetic field at each integer filling of electrons.

1. Interaction effect on Kane Mele model at zero magnetic field: At half filling, the interplay of intrinsic spin-orbit coupling and onsite interaction leads to the phase transition from quantum spin Hall insulator to an antiferromagnetic Mott insulator with magnetization in the xy-plane. At quarter filling, we study this interplay and show that the combined effect opens a wide region of ferromagnetic Chern insulating phase in between metal and normal insulator. We further discuss the experimental realization of these phases in series of transition metal trichalcogenides [1].

2. We extend our study to analyze the collaborative effect of magnetic field, spin orbit coupling and interactions. Focusing on 2pi/3 magnetic flux per plaquette, we realize numerous interesting phases like insulator with noncoplanar magnetic ordering, ferrimagnetic Chern insulator with nematic charge order, ferrimagnetic-ferrielectric Chern insulators etc. Many of these phase transitions are also accompanied with the change in the topology of the system. Our theoretical study broadens the field of topological phases accompanied with multiferroic like properties, as a consequence of the interplay of magnetic field, spin orbit coupling and interactions [2].

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Unconventional Superconductivity in Luttinger Semimetals : subdominant s-wave with various gap structure

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Nowadays, unconventional superconductivity in Luttinger semimetal with strong spin-orbit coupling has attracted much attention [1-4]. In particular, pairing of j=3/2 intrinsic low-energy fermions show qualitative differences from the conventional pairing of j=1/2 fermions. We focus on the system where chemical potential lies close to quadratic band touching point. For this system, on-site interaction can generate d-wave superconductivity with sub-dominant s-wave superconductivity. Remarkably, for time-reversal breaking phase, there occur novel Bogoliubov–de Gennes spectrum so called "Bogoliubov Fermi surface" [2]. This Fermi surface can be energetically stable, and cannot be removed by CP preserving perturbation. For energetics, we use the general form of Ginzburg-Landau free energy with the help of the invariant theory [1].

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Topological phases of non-symmorphic crystals: Shastry-Sutherland lattice at integer filling

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A possible realization of time-reversal invariant topological insulator in non-symmorphic crystals is studied. Particularly, we investigate the tight-binding model for a two-dimensional Shastry-Sutherland lattice at integer filling. The stability of the topological insulating phases as a function of microscopic parameters is examined with edge spectrum. Also we discuss a possible application to topological Kondo insulators in non-symmorphic crystals.

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Quantum Falaco solitons

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Exotic topological states are of major focus in modern condensed matter physics. A Falaco soliton as a U-shape tube demonstrated initially in the swimming pool is one of the fascinating topological defects [1,2]. Later on, it turns out that it is a universal phenomenon at all length scales. However, the nature of the Falaco soliton system and its underlying physics remain elusive owing to the lack of a controllable system despite the discovery of various Falaco soliton systems. In this poster we report quantum Falaco solitons (QFS) created as a quantum flux in a superconducting Nb film. The manipulation of a single QFS evidences the purported linear potential of the QFS. QFS opens the door for exploring the confinement-deconfinement 1D phase transition beyond the 2D Berezinskii-Kosterlitz-Thouless (BKT) transition mechanism.

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Construction of a low temperature magnetic force microscope

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Magnetic force microscope (MFM), one of the kind of SPM, has become a powerful tool to investigate unconventional magnetic domains of topological magnetic materials as well as the strong antiferromagnetic nature of superconductors on the submicron scale. We have built low-temperature MFM, which operates at temperature down to 4 K and in magnetic field up to 6 T. We adopted optical fiber interferometry for sensing cantilever motion [1] and employed an x-y-z walker for coarse approach, an x-z fiber walker, and an x-y-z scanner, all of which are home-built. Our MFM will be upgraded with combination of a vector magnet and dilution refrigerator to scrutinize superconducting pairing symmetry.

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Atomic-scale resolution of Scanning Probe Microscopy in air and liquid environment

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Atomic resolution of scanning probe microscopy (SPM) is essential for investigating atomically controlled surface or interface of liquid and crystal. By optimizing scanning conditions as well as hardware specifications, we are able to build a high resolution SPM, capable of atomic scale imaging. The compact size of the microscope allows to reduce mechanical vibration noise, and its reduced piezo scanner is suitable for imaging the structure of a crystal lattice. As a demonstration of the microscope, we show the crystal structure of mica and HOPG obtained in air, and the lattice structure of calcite in water. The optimized SPM can be useful for observing atomic-scale phenomena on two-dimensional topological insulators.

Construction of High Resolution Low Temperature Atomic Force Microscope for Local Point Contact Spectroscopy

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Point Contact Spectroscopy(PCS) [1] has been a remarkable tool to study the electronic gap structure of superconductor, such as pairing symmetry. However, PCS has been limited by geometrical and induced pressure problems of between sample and tip. To overcome geometrical problems of PCS, using High Resolution Atomic Force Microscopy(HR-AFM) at 4 K for local point contacts spectroscopy (local PCS) makes to approach the exact position of various type's superconducting structure, such as Josephson junction and hetero junction of superconductors. For Local PCS we design the probe which load HR-AFM using laser deflection system in the 2-2-9 T cryogenic vector magnet. In this poster, I will introduce our system of Local PSC to give us a chance to study the pairing symmetry of topological superconductor.

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Non-vanishing Fraunhofer Pattern in bulk WTe_2 Weyl semimetal Josephson Junction

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WTe_2 is predicted to host Weyl nodes at the contact of electron and hole pockets in a momentum space (Type-II Weyl semimetal) and exhibit novel transport properties.[1] We fabricated proximity Josephson junctions based on mechanically exfoliated WTe_2 layers of thickness around 10-20 nm and studied their Josephson effects under magnetic field or microwave radiation. Josephson critical current modulation as a function of perpendicular magnetic field, $I_C(B)$, (so-called Fraunhofer pattern) exhibited non-vanishing lobes up to ~300 Gauss when current direction is parallel to b-axis of WTe_2 crystal. This indicates that Josephson current through b-axis of WTe_2 layer has enhanced contribution from the edges of the flake. We will discuss about observed anisotropic quantum transport of WTe_2-Josephson junction in regard to the nature of Type-II Weyl semimetal.

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Towards realizing topological chiral 1D channel in high-quality bilayer graphene

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Previous studies reported that the topological chiral 1D states could be realized in the AB/BA tilt defect boundary in bilayer graphene [1-3]. Such chiral 1D channel is known to have a novel topological property, such as valley-polarized current flowing. Although the 1D chiral channel is expected to show the quantized conductance of $4e^2/h$, the recent experiment by J. Long et al. has shown a value deviated from $4e^2/h$. This is presumably due to the disorder of graphene introduced during the conventional fabrication process. Here, we present our progress on achieving high quality of bilayer graphene device embedding AB/BA tilt defect boundaries by encapsulating graphene with atomically flat hBN crystals.

AB/BA boundaries in bilayer graphene is located by using near field scanning optical microscope (NSOM). However, one of difficulties would be that the AB/BA boundary can be moved by the stress exerted during encapsulation process. To confirm the location of AB/BA boundary after Van der Waals stacking, we developed the stack-and-flip method with which graphene is exposed on top for NSOM. Another difficulty comes from the fact that top hBN covering the graphene may suppress the near field signal that is essential for locating AB/BA boundary. To overcome this problem, we found out that NSOM could still locate the AB/BA boundary with top hBN thinner than 5 nm. We will also discuss possible application of 1D chiral channel as a highly efficient Cooper pair splitter by contacting to the s-wave superconductors, by exploiting valley chiral nature of 1D channel [4].

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AC non-linear longitudinal transport coefficients in a Weyl metal phase and implication of third harmonic generation

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Based on Boltzmann transport theory with chiral anomaly, we investigate the AC response of a Weyl metal and reveal a non-liner term via a 3w channel of the applied ac electric field with the frequency w. Using axion electrodynamics, we also show the generation of a 3-omega light. This phenomenon shows that the oscillation of a dissipationless channel is responsible for the third harmonic generation.

Magnonic quantum spin Hall state in the zigzag and stripe phases of the antiferromagnetic honeycomb lattice

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We investigated the topological property of magnon bands in the collinear magnetic orders of zigzag and stripe phases for the antiferromagnetic honeycomb lattice and identified Berry curvature and symmetry constraints on the magnon band structure. Different symmetries of both zigzag and stripe phases lead to different topological properties, in particular, the magnon bands of the stripe phase being disentangled with a finite Dzyaloshinskii-Moriya (DM) term with nonzero spin Chern number. This is corroborated by calculating the spin Nernst effect. Our study establishes the existence of a nontrivial magnon band topology for all observed collinear antiferromagnetic honeycomb lattices in the presence of the DM term.

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Quench dynamics of long-range Kitaev wire in presence of disorder

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We study quench dynamics of Kitaev chain with long-range pairing interaction decaying as power law. The dynamics of Loschmidt echo exhibit periodic quantum revivals in finite size system. The first revival time are well captured by the quasi-particle group velocity at the boundary of Brillouin zone for short-range Kitaev chain (power law exponent $\alpha >> 1$) while it gives a good approximation for the long-range ($\alpha < 1$) case. On the otherhand the standard formula obtained by considering the maximum quasi-particle group velocity fails to predict the same for the the long-range chain. Analyzing the effect of disorder on the dynamics of Loschmidt echo reveals that the first revival time does not change from the clean case, asserting the robustness of the first revival time. Further, we examine the survival probability of the low-energy edge state, and found that it is robust under quenching for short-range pairing and fragile for long-range pairing. This observation is also valid in presence of box disorder in the chemical potential. Finally, we present dynamical phase transition in the disordered long-range Kitaev chain and analyze the singularity of the rate of return probability for increasing disorder strengths. Our study further shed light into the dynamics of long-range Kitaev chain in presence of disorder.

Disorder Induced Phase Transitions of Type-II Weyl Semimetal

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Weyl semimetals (WSM) can be classified into two types depending on the topology of their Fermi surface. The conventional type-I WSM possess ellipsoidal Fermi surfaces while the type-II WSM are characterized by hyperboloidal Fermi surfaces that break Lorentz invariance. Examining the topology of the Fermi surface fully characterizes these two different phases. However, the microscopic mechanisms that drive the transitions between the two phases are still unclear. In this vein, we show that Anderson disorder can drive quantum phase transitions between the type-I WSM and the type-II WSM [1]. We demonstrate that the renormalization of the Fermi velocity due to the Anderson disorder increases the tilt of the Weyl cone and eventually causes type-I to type-II transition.

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Design of an aberration-corrected new miniature energy analyzer for SEM

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We designed a new miniature energy analyzer consisting of a magnetic sector and corrector systems for measurement of electron energy loss spectra in a scanning electron microscope. The use of low energy conditions less than 30 keV in SEM can prevent low-Z materials such as graphene from being knock-on damaged by electron beam [1]. Also, low initial energy of 10 keV enables us to measure band gap of semiconductor materials without Cerenkov loss [2]. Additionally, delocalization effects can be decreased under low voltage condition, so more accurate measurement and spatial mapping can be possible [3]. For EELS measurement with high energy resolution, aberration correction is essential. To correct the geometrical aberration caused by a magnetic prism, we designed two new corrector systems using ray tracing simulations. One corrector system fully corrects second-order aberration and partially corrects third-order aberration with a simple structure. Another corrector system fully corrects third-order aberration in the x-direction. By aberration correction, energy resolution of ~10 meV at an initial angle of 5 mrad can be achieved with either of the two corrector systems. With this energy analyzer, observing various material properties such as not only elements, chemical status, band gap, and plasmons, and phonons are expected in low energy conditions [4,5].

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Emergent Non-Fermi Liquids

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Understanding correlation effects in topological phases and their transitions is a cutting-edge area of research in recent condensed matter physics. We study topological quantum phase transitions (TQPTs) between double-Weyl semimetals (DWSMs) and insulators and argue that a novel class of quantum criticality appears at the TQPT characterized by emergent *anisotropic* non-Fermi liquid behaviors, in which the interplay between the Coulomb interaction and electronic critical modes induces not only anisotropic renormalization of the Coulomb interaction but also strongly correlated electronic excitation. Using the standard renormalization group methods, large N_f theory and the $\epsilon=4-d$ method with fermion flavor number N_f and spatial dimension d, we obtain the anomalous dimensions of electrons ($\eta_f=0.366/N_f$) in large N_f theory and the associated anisotropic scaling relations of various physical observables. Our results may be observed in candidate materials for DWSMs such as $HgCr_2Se_4$ or $SrSi_2$ when the system undergoes a TQPT.

Hard skyrmions in a rare earth permanent magnet

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Magnetic skyrmions with the nontrivial topological spin configuration manifesting ultrahigh-efficiency manipulation current1 are of prime interest in modern magnetic device technology. Despite of the overwhelming advantages, however, the application potential of skyrmions has been hampered by a limited number of existing skyrmion materials and thus it is of exceeding importance to establish a variety of skyrmion systems. Here we present an entirely new class of skyrmions, called hard skyrmions, identified for the first time in $Nd_2Fe_{14}B$ which is one of the strongest permanent ferromagnets. In contrast to previously known skyrmions, the new class and its variant appear only via field-cool procedure due to a high thermomagnetic irreversibility 2-5 and show a high level of phase robustness.

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Large magnetoresistance and superconductivity in the candidate type-II Weyl semimetal $MoTe_2$

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Transition-metal dialcogenides (TMDs) have attracted great interest because of their potential technological applications as well as its novel electronic states. Electronic structure calculations suggest that TMDs with non-centrosymmetry are type-II Weyl semimtal candidates. Recently, an extremely large magnetoresistance (XMR) appears in the orthorhombic T_d phase of $MoTe_2$ and was ascribed to the characteristics of Type II Weyl semimetals. In addition, the pressure induced superconductivity in the T_d phase is proposed to be related with the topological nature. Here we discuss the dependence on pressure of the large magnetoresistance (MR) and superconductivity in $MoTe_2$. With increasing pressure, the monoclinic-to-orthorhombic (T'-to-T_d) structural phase transition temperature gradually decreases and extrapolates to 0 K at P_c between 1.1 and 1.4 GPa[1]. A pair of electron and hole bands play an important role in the low-pressure T_d phase ($P < P_c$), while additional pair of electrons and holes is needed to explain Hall conductivities in the high-pressure 1T' phase ($P > P_c$). XMR shows a peak at a specific hole-to-electron concentration ratio (n_c), which is rapidly reduced when the ratio deviates from n_c in the T_d phase, underlining that the balanced electron hole carrier concentration is the source of the XMR effect in $MoTe_2$[1]. The small SC volume fraction in the T_d phase indicates that bulk superconductivity resides in 1T' phase, and thus surface sensitive measurements under pressure are required

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Atomistic study on surface structure and intrinsic defect of Cu2O(111)

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Semiconducting oxides usually exhibit n-type behavior due to O vacancies dominantly generated during growth. It is important to have p-type oxides for device applications. Copper (I) oxide or cuprous oxide (Cu2O) has been intensively studied due to its p-type characteristic with direct band gap of ~ 2.1 eV. Although some theoretical studies reported about the origin of p-type nature in Cu2O, it is not confirmed experimentally, yet. In this study, we establish clear understanding on the atomic structure of Cu2O (111) (1x1) surface using home-built low temperature scanning tunneling microscope (STM). In addition, intrinsic defects in Cu2O such as O and Cu vacancies are observed.

Quasi-one Dimensional Nanostructures as Sign of Nematicity in Iron Pnictides and Chalcogenides

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Impurity scattering is found to lead to quasi-one dimensional nanoscale modulation of the local density of states in the iron pnictides and chalcogenides. This ‘quasiparticle interference’ feature is remarkably similar across a wide variety of pnictide and chalcogenide phases, suggesting a common origin. We show that a unified understanding of the experiments can be obtained by simply invoking a four-fold symmetry breaking dxz – dyz orbital splitting, of a magnitude already suggested by the experiments. This can explain the one-dimensional characteristics in the local density of states observed in the orthorhombic nematic, tetragonal paramagnetic, as well as the spin-density wave and superconducting states in these materials.

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Spin-lattice Coupling in U(1) Quantum Spin Liquids

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Quantum spin liquids (QSLs) are exotic phases with intrinsic massive entanglements. Instead of microscopic spins, fractionalized particles and gauge fluctuations are emergent, which is revealing QSLs' exotic natures. In the pyrochlore system with strong spin-orbit coupling, U(1) QSL phase are suggested to appear, which contain emergent photons, gapless excitations without breaking any symmetries, as well as electric and magnetic monopoles. Interplay between emergent degrees of freedom of QSLs and conventional degrees of freedom is one of the key issues in QSLs. In this presentation, we investigate this interplay by using spin-lattice couplings. In the U(1) QSLs, spin-lattice coupling is fundamentally different from one in magnetically ordered phases. We construct a general theory for spin-lattice coupling and characteristic interplay between phonons and emergent photons with a symmetry-argument. We show that emergent photons are qualitatively more stable than phonons at low temperature. We also propose mechanisms to detect emergent photons in experiments such as sound attenuation and thermal transport.

Metal-insulator transition and high temperature charge density waves in monolayer VSe2

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Emergent phenomena driven by electronic reconstructions in oxide heterostructures have been intensively discussed. However, the role of these phenomena in shaping the electronic properties in van der Waals heterointerfaces has hitherto not been established. By reducing the material thickness and forming a heterointerface, we find two types of charge-ordering transitions in monolayer VSe2 on graphene substrates. Angleresolved photoemission spectroscopy (ARPES) uncovers that Fermi-surface nesting becomes perfect in ML VSe2. Renormalization-group analysis confirms that imperfect nesting in three dimensions universally flows into perfect nesting in two dimensions. As a result, the charge-density wave-transition temperature is dramatically enhanced to a value of 350 K compared to the 105 K in bulk VSe2. More interestingly, ARPES and scanning tunneling microscopy measurements confirm an unexpected metal−insulator transition at 135 K that is driven by lattice distortions. The heterointerface plays an important role in driving this novel metal−insulator transition in the family of monolayer transition-metal dichalcogenides.

Unified theory on Rashba spin-orbit coupling at surface state

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Rashba spin-momentum coupling is an essential concept to describe spin physics at surfaces and interfaces of metal and semiconductor[1]. This interaction is not only important fundamentally, but also key idea to explain remarkable phenomena like spin transistor[2], spin-charge conversion[3] and Majorana fermion[4]. Despite the interaction is related to most of phenomena at surface state, the unveiled origin of the interaction makes difficult to decide size of interaction and depict spin quantities. We propose the mechanism of the coupling and compare with present studies on surface state. We construct unified theory incorporating several properties including charge distribution asymmetry[5], orbital angular momentum[6] and spin-orbital entanglement[7]. We will also reconsider some surface spin properties with our theory. This unified theory is expected to find giant Rashba material efficiently and analyze spin phenomena at surface and interface.

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Chiral pair of Fermi arcs, anomaly cancellation, and spin or valley Hall effects in Weyl metals with broken inversion symmetry

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Even though anomaly in theory is something we have to fix, existence of anomaly gives a hint that there should be something more we have to consider for the complete theory. It has been known that effective bulk theory of TRSB (Time Reversal Symmetry Broken) Weyl metal has perturbative gauge anomaly which has to be fixed. This anomaly in the bulk effective theory of TRSB Weyl metal can be canceled by other anomaly flown from the (1+1) chiral fermion theory of surface of TRSB Weyl metal [1]. This mechanism of anomaly cancelation is known as Callan-Harvey mechanism [2]. We apply the same mechanism to the ISB (Inversion Symmetry Broken) Weyl metal which should have even pairs of Weyl points because of Time reversal symmetry. Since time reversal symmetry is preserved in the ISB Weyl metal phase, there is no typical gauge anomaly. However, there is another anomaly which can be captured by introducing fictitious gauge field such as spin or valley gauge field. Additionally, we find that there is ambiguity in choosing which Weyl point is connected to other by Fermi arcs depending on the representation of action even for the same Hamiltonian. It tells us that low energy effective theory for ISB Weyl metal which have only linear dispersion does not contain enough information to decide the topological properties of ISB Weyl metal phase. It is very intuitive consequences but has not been issued yet. Here we prove this argument for general case of ISB Weyl metal phase and gives some sense that we need to know high energy information to decide the topological properties of the ISB Weyl metal phase.

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Transmission/reflection coefficients and Faraday/Kerr rotations as a function of applied magnetic fields in spin-orbit coupled Dirac metals

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We reveal the nature of propagation of light in spin-orbit coupled Dirac metals under external magnetic fields. Such applied magnetic fields split the four-fold degeneracy of a spin-orbit coupled Dirac metal state into a pair of a two-fold degeneracy along the direction of the applied magnetic field, resulting in a Weyl band structure. These Weyl metals turn out to play the role of a chiral prism, whose electromagnetic properties are described by axion electrodynamics: An incident monochromatic wave can split into three polarized modes, propagating with different wave numbers (i.e., propagating with different group velocities). In particular, the axion electrodynamics allows the longitudinal oscillating component inside the Weyl metal state which resembles propagation of a plasmon. The helicity of the propagating/reflected light is determined by the axion term given by the applied magnetic field. This implies that the direction of the external magnetic field controls the Faraday/Kerr rotation. We find several interesting optical properties of the Weyl metal phase. First, longitudinal oscillating charge-density fluctuations along the light propagating direction arise when the pair of Weyl nodes are aligned along the direction of the oscillating magnetic field, which give rise to the longitudinal component of the electromagnetic wave. Second, the Weyl metal phase becomes more reflective when the external magnetic field is enhanced due to the longitudinal negative magnetoresistivity, which is a fingerprint of the Weyl metal phase. Third, eigenmodes can have various structures, depending on a parameter , which corresponds to a ratio between the conventional Hall effect from normal electrons and the anomalous Hall effect from Weyl electrons. We propose these strong magnetic field dependencies of the optical response as the fingerprints of the axion electrodynamics

Effect of magnetic moments on Anderson transition

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In this work, we investigate non-ergodic (glassy) features exhibited in the vicinity of the Anderson-Mott transition such as an increasing magnetic susceptibility and specific-heat coefficient attributed to the formation of local moments. An important unresolved question of the issue is how the local moments interact with the conduction electrons that becomes localized at the metal-insulator transition, whose answer is of vital importance for the interpretation of transport experiments in doped semiconductors such as Si:P, Si:P,B, and Si:B.

In a theoretical point of view, it is a very difficult problem of constructing a self-consistent theory for the metal-insulator transition that takes into account the disordered conduction electrons, local moment formation and Kondo physics in disordered systems. We use a numerical diagonalization technique based on the Hartree-Fock/Ewald method to study the effect of interaction on the disordered, Coulomb interacting spin 1/2 fermions. Our results reveal that a ferromagnetic transition takes place at a critical interaction strength U=Uc2, which is distinct from the Anderson-Mott transition at U=Uc1.

Approaching the ferromagnetic transition from the paramagnetic side, we observe the formation of local moments whose position and the magnitude are dependent on the initial configuration of a disordered potential. We perform scaling analysis to clarify the fate of the local moments in thermodynamic limit.

Topological phase transitions in Bi_2Se_3 driven by magnetic proximity effect

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Recent study has demonstrated that the topological surface states of a 3-5 quintuple layer (QL) Bi_2Se_3 are hybridized. This condition provides us with an opportunity to control the surface states by using the magnetic proximity effect. Therefore, we investigated the terahertz electrodynamics of a topological insulator Bi_2Se_3 3 QL thin film grown on an oxygen-deficient metal oxide substrate, whose oxygen vacancy sites are filled with un-paired electrons that carry a magnetic moment. By modulating the oxygen defect density, we found a phase transition from the insulating phase under low oxygen defect density to the topological metallic phase of only G_0 longitudinal conductance under high oxygen defect density, which means that the topological surface states partially recover from hybridization. We analyzed the optical conductance of this metallic case with an electrical island model based on the variable range hopping. Our results demonstrate the possibility to modulate topological surface states and search for applications in spintronic devices and quantum computing.

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Metallic domain boundary of metastable charge-density-wave phases in thin 1*T*-TaS_2

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Two dimensional (2D) materials have fascinated researchers with emerging electronic states different from bulk ones due to reduced screening and quantum confinements [1, 2]. For example, 1T-TaS_2, one of the well-known transition metal dichalcogenides (TMDC), undergoes a series of charge-density wave (CDW) transitions as decreasing temperature in bulk: incommensurate CDW (IC-CDW) into nearly commensurate CDW (NC-CDW) at 350 K; NC-CDW into commensurate CDW (C-CDW) around 180 K [3]. Recent transport measurements revealed that the transition from NC-CDW into C-CDW is suppressed for super-cooled thin 1T-TaS_2 [4, 5], and suppressed C-CDW is recovered by a strong in-plane electric field through metastable CDW phases [5]. Up to date, those metastable CDW phases are not well characterized in real space because thin 1T-TaS_2 flakes having metastable CDW phases are usually much smaller than thicker ones [5, 6].

In this work, we have been trying to directly observe the metastable CDW phases in thin 1T-TaS_2 and manipulate them with voltage pulses. To access the metastable CDW phases with scanning tunneling microscopy (STM), we prepared thin 1T-TaS_2 on an epitaxially grown graphene/SiC substrate by mechanical exfoliation. We exfoliated 1T-TaS_2 in an Ar-filled glove-box and transferred it into UHV chamber using an UHV-suitcase. The thickness of 1T-TaS_2 flakes is controlled about 10-50 nm, and CDW ground states of the thin flakes at room temperature were found to be NC-CDW phase consistent with the previous transport results. By applying large voltage pulses between a STM tip and a thin flake, we could manipulate the CDW phases of thin 1T-TaS_2 from NC-CDW into IC-CDW at room temperature. After cooling down to 87 K at cooling rate of about 1 K/min, we observed metastable CDW phases of thin 1T-TaS_2, having insulating C-CDW domains and domain boundaries with in-gap states. Voltage pulses induce another phase having smaller domains and metallic domain boundaries. Our studies about metastable CDW phases and its controllability with voltage pulses would be helpful in understanding about phase transition in 2D materials and developing new-generation memory devices using various phase transitions.

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Bulk Electronic States in Proton-Beam Irradiated Bi_2Te_3 : A ^{125}Te NMR Study

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The 200 keV proton (H+)-beam with a high dose of 1015 cm-2 was irradiated on the Bi2Te3 polycrystalline powders. The beam may create defects in the penetration range, thus modifying the electronic structures which result in the Knight shifts. We find the proton beam broadens 125Te nuclear magnetic resonance (NMR) linewidth, undergoing motional narrowing upon increasing temperatures. We suggest that the free-carriers created by beam irradiation are thermally excited electrons, which show no appreciable change in the spin-orbit coupling in this topological insulator.

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Spin wave excitation in the Kitaev honeycomb magnet α-$RuCl_3$

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Recently, α-$RuCl_3$ has been hailed as a promising candidate for the 2D Kitaev honeycomb model [1]. Although the compound shows magnetically long-range ordered ground state due to non-Kitaev terms, the evident magnetic continuum excitation signifies the fractionalized excitation, indicating that the proximity to Kitaev quantum spin liquid [2,3]. In this presentation, we report a dynamic spin correlation of α-$RuCl_3$ by using inelastic neutron scattering measurement. Below ordering temperature (T_N~6.5 K), the magnetic excitation displays sharp spin wave excitation that coexists with a broad continuum excitation. Here our linear spin wave theory captures the spin wave excitations which describes the minimal Hamiltonian model of the system. Then, the spectral weight of the calculated multi-magnon excitation is estimated, where we describe the definite fractionalized excitation. Furthermore, we present the field-dependence of magnetic excitation, where it discusses the possible field-induced quantum spin liquid.

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Developing single photon detector with graphene-based Josephson junction

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Many researchers have been actively studying and developing the quantum devices for quantum information applications. As various kinds of quantum devices are developed, it would more needed to transfer quantum information from one quantum computer to the others. In order to use photons for quantum communications, we need a device that converts optical information into quantum information and vice versa. We propose to use graphene-based Josephson junctions (gJjs) to detect single photons of frequencies ranging from microwave for solid-state qubits to infrared for tele-communications.

While vanishingly small heat capacity and small electron-phonon coupling of monolayer graphene allow a single photon to heat up the graphene up to a few Kelvins, fast dynamics of Josephson junction enables immediate detection of photons before the graphene cools back. For microwave photons that has small energy of meV, sensitive change of Josephson coupling against temperature rise is demanded. We used titanium (Ti) of Tc~0.3 K to realize gJjs of which critical current (I_c) is very sensitive the temperature (T). High $|dI_c/dT|$~8 K/μA was achieved around T=100 mK, with which microwave single photon detection may be achievable according to the simulation [1]. We also report niobium nitride (NbN)-gJj that operates as a near-infrared (NIR) single photon detector of wavelength 1550 nm. We demonstrated NIR single photon detection with Poissonian distribution of the detection events and its linear dependence on NIR laser power. We will discuss how to achieve highly sensitive photon detection that is required for quantum information processing by exploiting extremely low electronic heat capacity and desirably small electron-phonon coupling of monolayer graphene [1].

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Magnetic structure of hexagonal ferrites in Indium substituted LuFeO3

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Hexagonal LuFeO3 has attracted much attention due to its possible room-temperature multiferroicity, which shows both ferroelectricity and magnetism in a single phase. However, most studies have been performed in a thin film form due to the instability of the hexagonal phase in pure LuFeO3. Herein, we report that a single-phase hexagonal structure of LuFeO3 stabilizes in a bulk form with a wide range of Indium substitution ($0.4 \leq \text{In} \leq 0.8$). Our neutron powder diffraction studies revealed that either undistorted or distorted hexagonal structures stabilizes depending on the Indium substitution ratio. The magnetic spin structures as well as their electric properties of bulk hexagonal (Lu,In)FeO3 will be presented.

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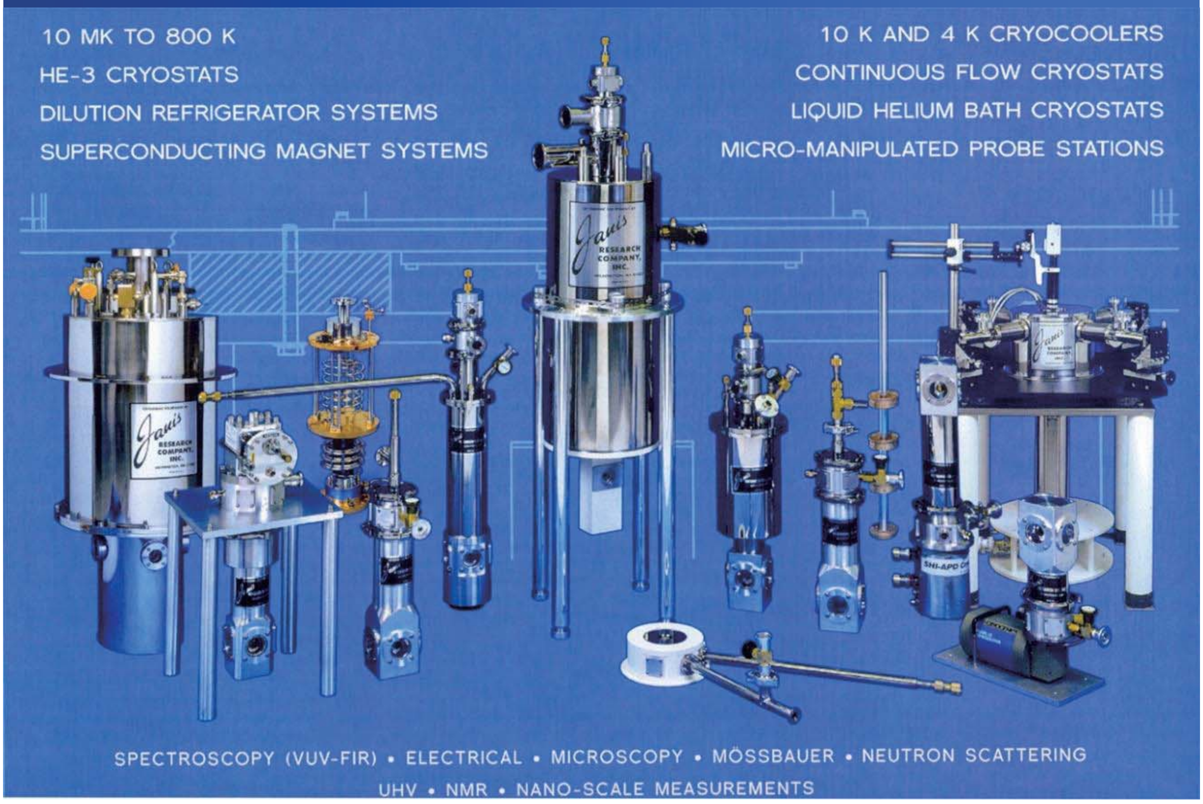

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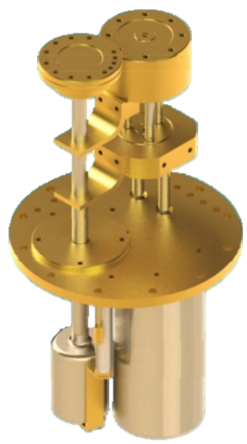

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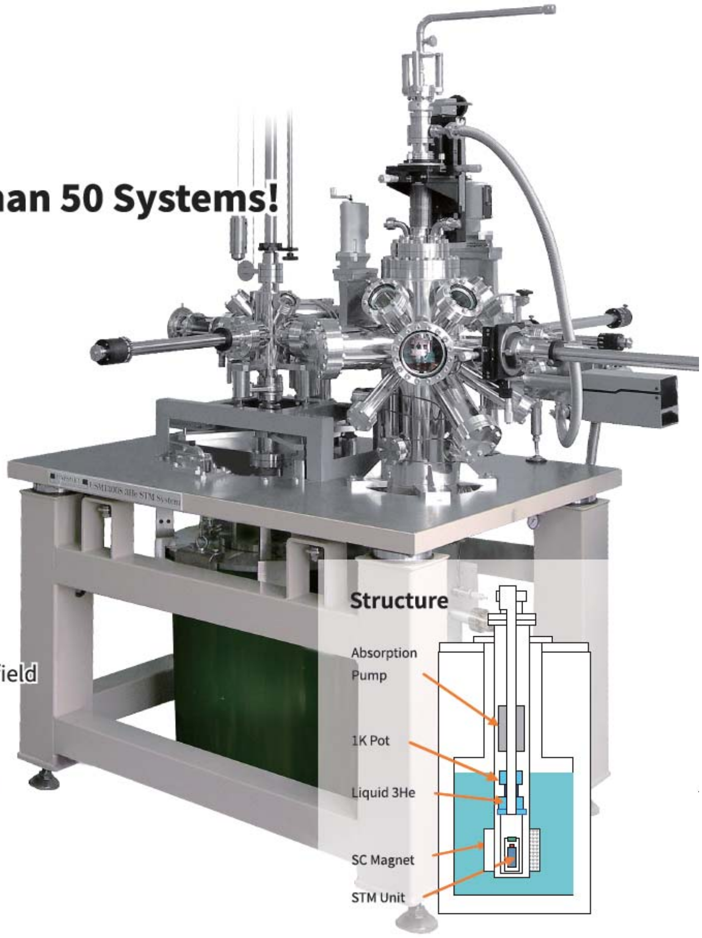

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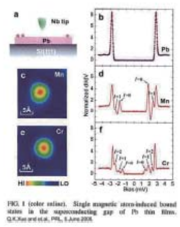

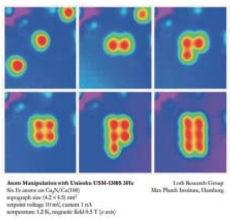

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