Majorana Fermions and Topological Materials Science

Edited by
Antonio Bianconi – Yoshiteru Maeno

superstripes press

science series

Science Series No.14

Title: Majorana Fermions and Topological Materials Science

Published on July 2018
by Superstripes Press, Rome, Italy

https://www.superstripes.net/superstripes-press

ISBN 978-88-6683-088-7
ISBN-A 10.978.886683/0887

Graphics: Paolo Alberti

Authors*:

D. Agterberg, J. Alicea, M.S. Anwar, Y. Asano, A. Bianconi, S. Borisenko, M. Cuoco, T. Dietl, M. Eschrig, S. Fujimoto, V. Hizhnyakov, Y. Kasahara, N. Kawakami, S. Komori, T. Kondo, A. Lanzara, G. Liu, Y. Maeno, D. Mandrus, Y. Matsuda, M.V. Mazziotti, T. Mizushima, L. Molenkamp, K. Muraki, H. Nakamura, F. Nogueira, K. Nomura, Y. Ominato, C. Ortix, G. Panaccione, D. Razmadze, H. Røising, M. Sato, M. Shi, S. Souma, S. Suetsugu, T. Takayama, C.X. Trang, M. Ueda, A. Vecchione, R. Yano, S. Yonezawa, S.C. Zhang.

*These authors presented the scientific reports collected in this book at the Majorana Fermions and Topological Materials Science Workshop – 75th Course of the Solid State Physics School, Erice, Italy on July 21-27, 2018

Papers presented at the
Majorana Fermions and Topological Materials Science Workshop –
75th Course of the Solid State Physics School

Erice, Italy on July 21-27, 2018

Organized by
«Ettore Majorana» Foundation and Centre for Scientific Culture
Topological Materials Science (TMS), Japan
Rome Int. Center Materials Science RICMASS SUPERSTRIPES

Chairmen
Antonio Bianconi – Yoshiteru Maeno

75th Course of the Solid State Physics School directed by
Giorgio Benedek

EMFCSC President
Antonino Zichichi

Index

22A-2

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

Yuichi Kasahara[1*].

[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

***Email**: *ykasahara@scphys.kyoto-u.ac.jp*

Key words: quantum spin liquid, Kitaev model, thermal Hall effect

Kitaev quantum spin liquid (QSL) displays the fractionalization of quantum spins into Majorana fermions [1]. In magnetic fields, the emergence of Majorana edge current is predicted to manifest itself in the form of a finite thermal Hall effect [1,2], a feature commonly discussed in topological superconductors. Here we report on thermal Hall conductivity κ_{xy} measurements in α-$RuCl_3$, a prime candidate for realizing Kitaev spin model on two-dimensional (2D) honeycomb lattice. α-$RuCl_3$ exhibits antiferromagnetic order at $T_N \sim 7$ K in zero field, but the application of a parallel magnetic field melts the AFM order, leading to a field-induced spin-liquid state at low temperatures. To study the thermal Hall effect in this field-induced spin liquid state, we measure κ_{xy} in magnetic fields tilted away from the *c* axis within the *ac*-plane. We find that κ_{xy}/T shows a plateau behavior as a function of applied magnetic field. The 2D thermal Hall conductance κ_{xy}^{2D}/T per honeycomb planes attains a quantization value of $(\pi/12)(k_B/\hbar)$, which is exactly half of κ_{xy}^{2D}/T in the integer quantum Hall effect. This half-integer thermal Hall conductance provides direct evidence of topologically protected chiral edge currents of charge-neutral Majorana fermions, which possess half degrees of freedom of conventional fermions. At high field, the quantization disappears and κ_{xy}^{2D}/T goes to zero rapidly, indicating a crossover from topologically non-trivial QSL to trivial high-field state. [3,4]

References

[1] A. Kitaev, *Ann. Phys.* **321**, 2 (2006).
[2] J. Nasu, J. Yoshitake, and Y. Motome, *Phys. Rev. Lett.* **119**, 127204 (2017).
[3] Y. Kasahara *et al*., *Phys. Rev. Lett.* **120**, 217205 (2018).
[4] Y. Kasahara *et al*., to be published in *Nature*.

to explicitly demonstrate the microscopic mechanisms that control the character of the quasiparticle spectrum [4].
Finally, I will review some quantum platforms marked spin-singlet or triplet pairing interfaced with non-trivial magnetic patterns and discuss the nature of the emerging topological superconductors [6,7,8].

References

1. P. Tang, Q. Zhou, G. Xu, and S.-C. Zhang, Nat. Phys. 12, 1100 (2016).
2. W. Brzezicki and M. Cuoco, Phys. Rev. B 95, 155108 (2017).
3. S. M. Young and B. J. Wieder, Phys. Rev. Lett. 118, 186401 (2017).
4. W. Brzezicki, C. Noce, A. Romano, and M. Cuoco, Phys. Rev. Lett. 114, 247002 (2015).
5. W. Brzezicki and M. Cuoco, Phys. Rev. B 97, 064513 (2018).
6. M. T. Mercaldo, M. Cuoco, P. Kotetes, Phys. Rev. B 94, 140503(R) (2016).
7. A. Romano, P. Gentile, C. Noce, I. Vekhter, M. Cuoco, Phys. Rev. Lett. 110, 267002 (2013).
8. M. T. Mercaldo, P. Kotetes, M. Cuoco, arXiv:1806.07140.

22P-2

Pair conversion through spin-glass interfaces in magnetic Josephson junctions

Sachio Komori, James Devine-Stoneman, Mark Blamire, and Jason Robinson

Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge CB3 0FS, United Kingdom

***Email**: sk891@cam.ac.uk

Key words: proximity effect, spin-triplet pairing, Josephson junction

Electron pairing at a superconductor / ferromagnet interface (S/F) is controllable through the alignment of the magnetic exchange field. Over the past decade, it has been established that a non-uniform magnetic exchange field at the S/F interface can convert spin-singlet pairs (antiparallel spins) to a triplet state in which the spins are parallel and triplet supercurrents are long-ranged in F metals. This has been demonstrated via the Josephson effect in S/F/S junctions [1-4] and through critical temperature measurements of superconducting spin-valves [5-7].

In this talk, I will present our group's latest results on triplet pair creation and will demonstrate singlet-to-triplet pair conversion in magnetic Josephson junctions via spin-glass Cr/Fe interfaces.

References

1. R. S. Keizer et al. *Nature* 439, 825 (2006).
2. T. S. Khaire et al. *Phys. Rev. Lett.* 104, 137002 (2010).
3. J. W. A. Robinson et al. *Science* 329, 59 (2010).
4. M. S. Anwar et al. *Appl. Phys. Lett.* 100, 52602 (2012).
5. A. Singh et al. *Phys. Rev. X* 5, 21019 (2015).
6. X. L. Wang et al. *Phys. Rev. B* 89, 140508 (2014).
7. A. Srivastava et al. *Phys. Rev. Appl.* 8, 44008 (2017).

22P-4

Emergence of massless Dirac and Weyl fermions in Semi-metals with broken Parity-Time symmetry

Ming Shi[1*].

[1] *Swiss Light Source, Paul Scherrer Institute, CH-5232 Villigen, Switzerland*

***Email**: ming.shi@psi.ch

Key words: topological semimetals, ARPES

The Weyl and Dirac semimetals are recently discovered topological quantum states of matter characterized by the unavoidable crossing of two non- or doubly-degenerate energy bands near the Fermi level, respectively. These crossing points (Weyl or Dirac nodes) are the source of exotic phenomena, including the realization of massless Dirac and Weyl fermions as quasiparticles in the bulk and the formation of Fermi arc states on the surfaces. I will show how the Weyl and Dirac semimetals are realized in systems with broken inversion and/or time-reversal symmetry and address the issue whether the band degeneracy can be retained when parity-time symmetry is broken, which is essential for the emergence of massless Dirac fermions as low-energy excitations in the system.

22P-5

Axial spin-momentum locking in a cubic Dirac material

Hiro Nakamura[1*].

[1]*Max Planck Institute for Solid State Research,
Heisenbergstr. 1, Stuttgart 70569, Germany*

***Email**: *h.nakamura@fkf.mpg.de*

Key words: Dirac/Weyl semimetal, transport, thin film

The presence of both inversion and time-reversal symmetries in solids leads to well-known double degeneracy of electronic bands. The lifting of degeneracy makes spin or chirality to manifest in the form of (pseudo)spin texture in momentum space. Non-trivial cases are when the double degeneracy remains in exotic materials. Three-dimensional (3D) Dirac material is a remarkable example of this case, in which potential spin-momentum locking is challenging to resolve because all the states are degenerate. Here, we use quantum interference effects in magnetoconductance to detect hidden entanglement of spin and momentum in antiperovskite-type 3D Dirac materials. We find dominant weak antilocalization (WAL) when the Fermi energy (E_F) is tuned close to the Dirac nodes, whereas clear signature of weak localization (WL) develops when E_F shifts by doping. Notably, the mixing of different Dirac valleys does not suppress WAL, pointing to contrasting interference physics compared to graphene. These results are explained by an axial spin-momentum locking of real spin at each Dirac pocket, which, via scattering among six Dirac valleys that originates from cubic symmetry, effectively rotates spin [1].

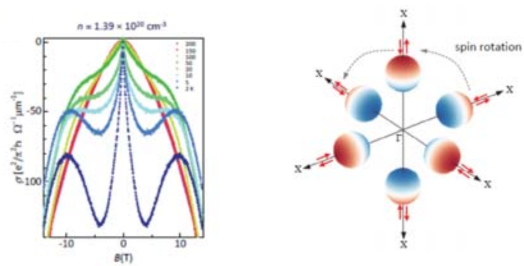


Figure 1: Antilocalization (left) and axial spin-momentum locking (right) in Sr_3SnO.

References

1. H. Nakamura *et al.*, submitted

23A-1

Topological Lifshitz transitions giving BEC condensate in unconventional superconductors driven by Fano resonance

Antonio Bianconi[1,2,3*]

[1]*Rome International Centre for Material Science Superstripes, RICMASS, via dei Sabelli 119A, 00185 Rome, Italy*
[2]*Institute of Crystallography, IC, CNR - via Salaria, Km 29.300, 00015 Monterotondo Roma, Italy*
[3]*National Research Nuclear University MEPhI 115409 Moscow Russia*

***Email**: *antonio.bianconi@ricmass.eu*
Key words: topological superconductivity, topological matter, Fano resonances

At the topological Lifshitz transition for the appearing of a new Fermi surface spot in a multi-valley superconducting material, the BPV (Bianconi-Perali-Valletta) theory [1-11] has predicted the emergence of Bose Einstein Condensation BEC. The BPV numerical solution of the self-consistent anisotropic energy gap equation joint with the chemical-potential density equation starting from the solution of the Schrödinger equation has predicted the unconventional superconducting state driven by the exchange interaction giving a Fano resonance between of localized and delocalized pairing channels.

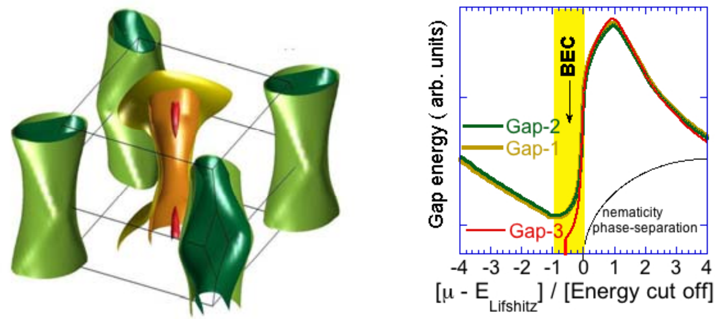


Figure 1: *Left panel*: The Fermi surface of $FeSe_{1-x} S_x$ at the Lifshitz transition where beyond the 1st d_{XZ} (green) and the 2nd d_{xy} (orange) there is a 3rd small Fe $3dz^2$, $ml=0$ (red) Fermi surface disappearing, at the topological Lifshitz transition at the end of nematicity phase (or phase separation). Right panel: The BPV (Bianconi Perali Valletta) theory giving the three gaps superconductivity by numerical solution of the gap equation joint with density equation, predicts the BEC in the range of the Lifshitz parameter $-1<Z<0$ where Z is given by the energy separation between the chemical potential and the energy $E_{Lifshitz}$ of the topological Lifshitz transition for the appearing of a new Fermi surface, normalized to the "energy cut off" of the pairing interaction. The BEC condensate is predicted to occur in the yellow range at the end point of the nanoscale phase separation called also by some authors "nematic phase".

23A-2

Nematic superconductivity in $Cu_xBi_2Se_3$ and other doped Bi_2Se_3 systems

Shingo Yonezawa[1*].

[1] *Department of Physics, Graduate School of Science, Kyoto University, 606-8502 Kyoto, Japan*

***Email**: *yonezawa@scphys.kyoto-u.ac.jp*

Key words: nematic superconductivity, specific heat, $Cu_xBi_2Se_3$

Doped Bi_2Se_3 systems with ion intercalations have been extensively studied as a leading candidate for topological superconductivity [1] hosting Majorana quasiparticle excitations. More recently, it has been proposed that this class of materials can host novel superconductivity with rotational-symmetry breaking in the gap amplitude or in the spin part of the order parameter [2]. Such superconductivity has been termed as "nematic superconductivity", in an analogy to the nematic liquid-crystal phases exhibiting spontaneous rotational-symmetry breaking without losing fluidity.

Nematic superconducting nature in $Cu_xBi_2Se_3$ has been first observed in the spin part of the superconducting order parameter by using the NMR technique [3], and subsequently in the superconducting gap amplitude by using the field-angle-resolved calorimetry [4]. Almost simultaneously to Ref. [4], nematicity in the upper-critical field of $Sr_xBi_2Se_3$ investigated by magnetoresistivity [5] and in vortex-pinning anisotropy of $Nb_xBi_2Se_3$ observed by torque magnetometory [6] has been also reported. More recently, nematic nature in these doped Bi_2Se_3 systems has been reported by other groups [7-11].

In this presentation, we explain our magneto-calorimetry study on the gap nematicity in the topological superconducting state of $Cu_xBi_2Se_3$ [4] and compare and discuss results reported by various groups.

References

[1] Y. S. Hor *et al.*, Phys. Rev. Lett. **104**, 057001 (2010).
[2] L. Fu and E. Berg, Phys. Rev. Lett. **105**, 097001 (2010); Y. Nagai *et al.*, Phys. Rev. B **86**, 094507 (2012); L. Fu, Phys. Rev. B. **90**, 100509R (2014).
[3] K. Matano *et al.*, Nature Phys. **12**, 852 (2016).
[4] S. Yonezawa *et al.*, Nature Phys. **13**, 123 (2017).
[5] Y. Pan *et al.*, Sci. Rep. **6**, 28632 (2016).
[6] T. Asaba *et al.*, Phys. Rev. X **7**, 011009 (2017).
[7] G. Du *et al.*, Sci. China-Phys. Mech. Astron. **60**, 037411 (2017).
[8] J. Shen *et al.*, npj Quantum Mater. **2**, 59 (2017).
[9] M. P. Smylie *et al.*, arXiv 1712.03215.
[10] A. Y. Kuntsevich *et al.*, arXiv 1801.09287.
[11] R. Tao *et al.*, arXiv:1804.09122.

23A-3

Chiral anomaly and chiral electromagnetism in Weyl/Dirac superconductors

Satoshi Fujimoto[1*].

[1]*Department of Materials Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan*

***Email**: *fuji@mp.es.osaka-u.ac.jp*

Key words: Weyl superconductors, Dirac superconductors, chiral anomaly

In Weyl/Dirac superconductors, Weyl/Dirac fermions are realized as nodal Bogoliubov quasiparticles. An important feature of Dirac and Weyl quasiparticles is that they have the chirality degrees of freedom, which give rise to chiral anomaly and also interactions with strain-induced chiral electromagnetic fields. We, here, discuss some intriguing phenomena associated with these effects. Firstly, we consider thermal transport of Weyl superconductors in the case with emergent magnetic fields generated by vortex textures or lattice strain. It is found that chiral anomaly of Weyl-Bogoliubov quasiparticles leads to negative thermal magnetoresistivity, when the emergent magnetic field is parallel to the temperature gradient. Furthermore, it is revealed that the chiral anomaly contribution of the thermal conductivity exhibits characteristic temperature dependence, which can be a smoking-gun signature of this effect. Secondly, we discuss effects of strain-induced chiral electromagnetic fields on Cooper pairs in Weyl/Dirac superconductors. It is found that although a chiral magnetic field is not screened by the Meissner effect because of the chiral character, it gives rise to a pseudo-Lorentz force acting on Cooper pairs, which induces charge/spin supercurrent flowing parallel to the chiral magnetic fields in Weyl/Dirac superconductors. This effect is akin to the chiral magnetic effect in Weyl metals. This result also implies that the Fulde-Ferrell state can be stabilized by the strain-induced chiral magnetic field, when the bulk current flow is prohibited by a boundary condition.

References

1. T. Kobayashi et al, arXiv: 1806.00993.
2. T. Matsuhsita et al., Phys. Rev. B97, 134519 (2018).

23A-4

Vortex electrodynamics of topological superconductors

Flavio S. Nogueira[1*].

[1]*Leibniz Institute for Solid State and Materials Research, IFW Dresden, Helmholtzstraße 20, 01069 Dresden, Germany*

***Email**: *f.de.souza.nogueira@ifw-dresden.de*

Key words: Axion electrodynamics, vortices, topological superconductors and insulators

We discuss the effects of the axion term on the electrodynamics of vortex lines in different realizations of topological superconductivity. In the case of heterostructures involving s-wave superconductors (SCs) proximate to three-dimensional topological insulators (TIs), the vortex becomes electrically polarized, featuring fractional electric charges at interfaces and a non-conventional angular momentum. The latter typically vanishes in ordinary superconductors, but exhibits anyon-like behavior in TI-SC structures. We also discuss the interplay of this result and the presence of Majorana zero modes bounded to the vortex. We also discuss the electrodynamics of vortex lines in intrinsic topological superconductors featuring two order parameters and an axion field given by the phase difference between these order parameters.

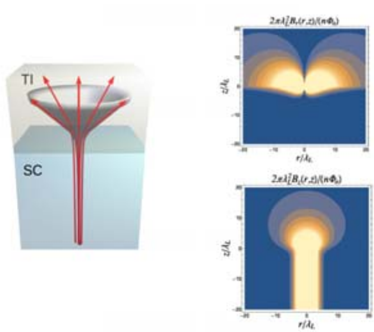


Figure 1: Vortex in a TI-SC heterostructure.

References

1. F. S. Nogueira, Z. Nussinov, and J. van den Brink, arXiv:1805.04359
2. F. S. Nogueira, Z. Nussinov, and J. van den Brink, Phys. Rev. Lett. 117, 167002 (2016)

23A-5

Topological Crystalline Insulators: Role of Magnetism and Superconductivity

Tomasz Dietl[1,2]

[1]*International Centre for Interfacing Magnetism and Superconductivity with Topological Matter - MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsawa, Poland*
[2]*WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
***Email**: *Tomasz.Dietl@MagTop.ifpan.edu.pl*

Key words: semiconductors, topological matter, Majorana excitations

As an introduction, a notion of topological crystalline insulators [1] will be presented together with experimental search for them in lead tellurides and lead tin selenides rock salt crystals [2,3], which gives evidence for the presence of 2D topological states adjacent to surfaces with certain crystallographic orientations [3] and of 1D topological states at specific surface atomic steps [4] in alloys with tin concentration sufficiently high to insure the inverted band structure at the *L* points of the Brillouin zone.

In the talk we will discuss recent results of point-contact spectroscopy in topological (Pb,Sn)Te and (Pb,Sn,Mn)Te. The data reveal the presence of zero-mode excitations superimposed onto an energy gap that shows a BCS-type critical behavior as a function of the magnetic field and temperature [5]. The origin of these Majorana-like excitations will be discussed taking into account the presence of 1D topological states at atomic steps.

References

1. 1. T. H. Hsieh, Hsin Lin, Junwei Liu, Wenhui Duan, A. Bansil, and Liang Fu, *Nat. Commun.* **3**, 982 (2012).
2. K. A. Kolwas, G. Grabecki, S. Trushkin, J. Wróbel, M. Aleszkiewicz, Ł. Cywiński, T. Dietl, G. Springholz, and G. Bauer, *phys. stat. sol. (b)* **250**, 37 (2013), arXiv:1111.2433.
3. P. Dziawa, B.J. Kowalski, K. Dybko, R. Buczko, A. Szczerbakow, M. Szot, E. Łusakowska, T. Balasubramanian, B.M. Wojek, M.H. Berntsen, O. Tjernberg, and T. Story, *Nat. Mater.* **11**, 1023 (2012).
4. P. Sessi, D. Di Sante, A. Szczerbakow, F. Glott, S. Wilfert, H. Schmidt, T. Bathon, P. Dziawa, M. Greiter, T. Neupert, G. Sangiovanni, T. Story, R. Thomale, M. Bode, *Science* **354**, 1269 (2016).
5. G.P. Mazur, K. Dybko, A. Szczerbakow, M. Zgirski, E. Łusakowska, S. Kret, J. Korczak, T. Story, M. Sawicki, and T. Dietl, *arXiv:1709.04000.*

23P-1

Intrinsic localized modes in anharmonic lattices

Vladimir Hizhnyakov.

Institute of Physics, University of Tartu, W. Ostwaldi Str 1, 50411, Tartu, Estonia

***Email**: *hizh@ut.ee*

Key words: anharmonic modes, localization, crystals, atomic chains, graphene

It is known that localized and moving stable vibrations can exist in perfect anharmonic lattices. Such vibrations are called intrinsic localized modes (ILMs), discrete breathers or discrete solitons. The realization that these excitations only require nonlinearity plus discreteness has expanded the subject in different directions, including ionic crystals, metals, magnetic solids, atomic plains (graphene), Josephson junctions, optical waveguide arrays, laser photonic crystals and micromechanical arrays.

Different pairs of potentials were used in ILM studies. All these potentials have a strong odd anharmonicity and show softening with increasing amplitude. Therefore, ILM fall from optical bands to phonon gaps. For example, graphene does not have a gap in the phonon spectrum. However, if we stretch it, a gap appears. Calculations show that in such a graphene there can actually be in-plane ILMs.

In many cases, a simple approach based on the approximation of pair potentials works well. However, we found that this approximation is insufficient for metals and covalent crystals (diamond); in these systems, ILM can exist over the phonon spectrum [1]. In addition, there are systems in which odd anharmonicity disappears because of the symmetry arguments [2]. Examples are given by atomic chains and planes (e.g. graphene). In these systems, odd anharmonicities disappear for out-of-chain/plane vibrations. Consequently, there may exist transverse/out-of-plane ILMs with a frequency higher than the maximum frequency of the corresponding phonons. This frequency is in resonance with longitudinal phonons, so ILM can decay. However, its interaction with mentioned phonons is weak. Therefore, the lifetime of such ILM is large. We performed analytical and numerical studies of these ILMs in the monoatomic chain and graphene, which fully confirm this conclusion. For example, transverse ILM in a chain, according to both theoretical calculations and numerical simulation, can exceed 10^{10} vibrational periods, i.e. these ILMs are practically stable.

References

1. M. Haas, V. Hizhnyakov, A. Shelkan, M. Klopov, A.J. Sievers, *Phys. Rev. B* **84**, 144303 (2011).
2. V. Hizhnyakov, M. Klopov, A. Shelkan, *Physics Letters A* **380**, 1075 (2016).

23P-2

Spin triplet proximity effect in Sr_2RuO_4/$SrRuO_3$ junctions

M. S. Anwar[1*], M. Kunieda, Y. Sugimoto, Y.J. Shin, S.J. Kang, Y. Tano, S.R. Lee, R. Ishiguro, S. Yonezawa, H. Takayanagi, T.W. Noh and Y. Maeno

[1]Cambridge University, UK, [2]Kyoto University, Japan [3]Seoul National University, Korea [4]Women's University, Tokyo, Japan [5]Tokyo University of Science, Japan [6]RIKEN, Saitama, Japan

***Email**: *msa60@cam.ac.uk*

Key words: spin-triplet superconductivity, *p*-wave proximity effect, Oxide interfaces, Strontium Ruthenates

Order parameters of spin-singlet superconductivity and ferromagnetism are antagonistic with each other. By bringing a ferromagnet (F) in contact with a spin-singlet superconductor (S) the Cooper pairs penetrate in an F but over a short range (a few nm) due to strong exchange field of F. If magnetic inhomogeneity such as ferromagnetic domain walls or non-collinear magnetization is present at S/T interface the spin-triplet correlation can also emerge that can induce over a long-range (~1 μm) [1]. On the other hand, using a spin-triplet superconductor (T) spin-triplet correlation can induce directly into a F. Theoretically, it has been predicted that spin-triplet proximity effect can be controlled by the relative orientations between the magnetization in the F and the Cooper pair spin in T [2].

We investigate the spin-triplet proximity effect in various Au/$SrRuO_3$/Sr_2RuO_4 junctions (Fig. a) [3] by measuring the differential conductance. Three distinguishable superconducting transitions reveal that the spin-triplet proximity effect is emerged over 15-nm thick $SrRuO_3$ layer [4]. The dimensions of our devices provide the evidence that induced correlation is dominated by *p*-wave even-frequency pair amplitude. Furthermore, the proximity effect exhibits anisotropic response to applied magnetic field (Fig. b). In this presentation, we also present the effect of barrier height on differential conductance to brobe the true nature of induced correlation at $SrRuO_3$/Sr_2RuO_4 interface.

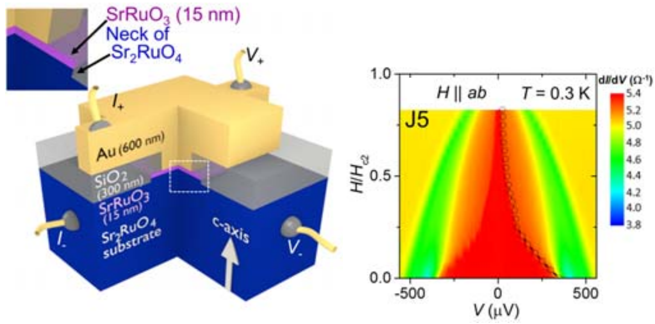


Figure 1: (a) Schematic 3D view of a $Au/SrRuO_3/Sr_2RuO_4$ junction. (b) Differential conductance as a function bias voltage and in-plane applied field.

References

1. J. Linder and J. W. A. Robinson, *Nat. Phys.* 11, 307 (2015).
2. P. M. R. Brydon et al., *Phys. Rev. B* 88, 054509 (2013).
3. M. S. Anwar et al., *Appl. Phys. Ex.* 8, 015502 (2015).
4. M. S. Anwar et al., *Nat. Commu.* 7, 13220 (2016).

23P-3

ARPES study of superconducting Pb thin film on topological insulator

C. X. Trang[1], N. Shimamura[1], K. Nakayama[1], K. Sugawara[2,3], S. Souma[2,3], T. Takahashi[1,3,4], K. Segawa[4], Y. Ando[5], and T. Sato[1,3]

[1]Dept. Physics, Tohoku University, [2]WPI-AIMR, Tohoku University,
[3]CSRN, Tohoku University, [4]Kyoto Sangyo University, and [5]University of Cologne.

***Email**: *c.trang@arpes.phys.tohoku.ac.jp*
Key words: spectroscopy, interface, topological superconductivity.

Three-dimensional topological insulators (3D TIs) represent a new state of quantum matter with an insulating bulk band and a conducting surface state. The discovery of TIs stimulated the search for a more exotic state of matter, the topological superconductors (TSCs). TSCs have currently attached significant attentions because of its ability to host Majorana fermions [1]. Theoretically, Majorana zero mode is predicted to occur in vortex cores of 3D TIs when they are close proximity to conventional *s*-wave superconductors. However, experimental identification of Majorana fermion has been a big challenge due to a limited number of candidate materials.

Here we have succeeded in fabricating a superconducting Pb thin film on a cleaved surface of TI $TlBiSe_2$ by molecular beam epitaxy (MBE), and performed angle-resolved photoemission spectroscopy. We have chosen $TlBiSe_2$ because it is non-trivial TI with a simple electronic structure. Figure 1(a) shows the valence-band structure of pristine $TlBiSe_2$, which has a sharp topological surface states (SS)

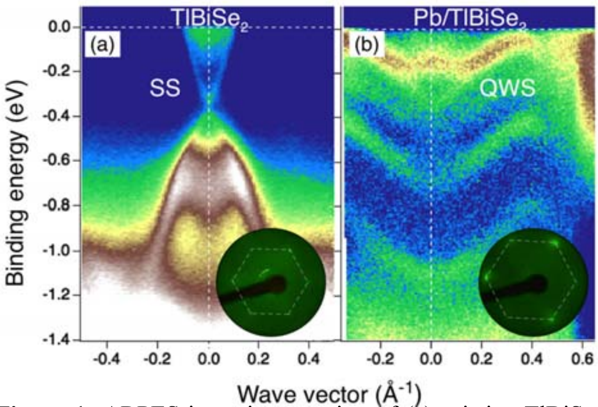


Figure 1: ARPES-intensity mapping of (a) pristine $TlBiSe_2$ and (b) $Pb/TlBiSe_2$. The LEED patterns (inset) also confirm a successful growth of Pb film on $TlBiSe_2$.

around the $\overline{\Gamma}$ point. Successful growth of Pb film is clearly seen from the quantum well states (QWSs) shown in Fig. 1(b). Moreover, we found that the $TlBiSe_2$-originated topological surface states are affected by the energy bands from the Pb thin film (Data not shown). In this presentation, we will discuss the electronic structure related to the occurrence of superconductivity in this hybrid, which is useful for realizing a possible TSC.

References

1. J. Alicea, Rep. Prog. Phys. **75**, 076501 (2012).

23P-4

Unconventional superconductivity near a topological Lifshitz transition in arrays of not connected wires

Maria Vittoria Mazziotti[1,2], Antonio Valletta[3], Andrea Perali[4], Antonio Bianconi[1,5,6]

[1] *RICMASS, Rome International Center for Materials Science Superstripes - Via dei Sabelli 119A, 00185 Rome, Italy*
[2] *Dept. of Mathematics and Physics, University of Rome III, Rome, Italy*
[3] *Institute for Microelectronics and Microsystems, IMM, Consiglio Nazionale delle Ricerche CNR Via del Fosso del Cavaliere 100, 00133 Roma, Italy*
[4] *School of Pharmacy, Physics Unit, University of Camerino - Camerino, Italy*
[5] *Institute of Crystallography, IC, Consiglio Nazionale delle Ricerche CNR - via Salaria, Km 29.300, 00015 Monterotondo Roma, Italy*
[6] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) 115409 Moscow Kashirskoe shosse 31, Russia*

corresponding author: Maria Vittoria Mazziotti

***Email:** *vittoria.mazziotti@gmail.com*

Key words: Lifshitz transition, Fano resonance, Shape resonance, Feshbach resonance unconventional superconductivity, BPV Theory

Recently interest is growing on unconventional high-temperature superconductivity in 2D anisotropic organic conductors made of non connected but weakly interacting quantum wires [1–7]. In a recent work [8], we have proposed a driving mechanism for high Tc based on the control of the Fano resonance between a first superconducting gap in a first condensate where the Fermi energy is near a topological Lifshitz transition and the superconducting gaps in other bands with high Fermi energy. In this scenario the maximum critical temperature occurs at a shape resonance where a first condensate in the appearing new small Fermi surface pocket is in the BCS-BEC crossover while the other condensates are in the BCS regime. Here we have studied the tuning of the strength of the pairing interaction in the new appearing band to establish to optimal state in the hot condensate in the BCS-BEC crossover regime. To this end we have studied the multi-gaps superconductivity by increasing the pairing coupling term in the hot band near the Lifshitz transition. We have found that the BCS-BEC regime occurs where the ratio between the superconducting gap and the Fermi energy is close to 0.5. The maximum of the Tc occurs in the range where the ratio of the Fermi energy on the pairing energy

24A-1

Discovery of the chiral Majorana fermion and its application to topological quantum computing

Shoucheng Zhang

Department of Physics, Stanford University,
Stanford, CA 94305-4045

***Email**: *sczhang@stanford.edu*

Key words:

Majorana fermion is a hypothetical fermionic particle which is its own anti-particle. Intense research efforts focus on its experimental observation as a fundamental particle in high energy physics and as a quasi-particle in condensed matter systems.
We have theoretically predicted the chiral Majorana fermion in a hybrid structure of quantum anomalous Hall thin film coupled with a conventional superconductor, and have proposed the half-integer quantized conductance plateau as its compelling signature. Recently, this theoretical prediction has been experimentally realized in magnetically doped topological insulator coupled with Nb superconductor and the half plateau quantization has been observed. I shall discuss a new proposal to braid the chiral Majorana fermion in a Corbino device geometry. The discovery of the chiral Majorana fermion leads to new avenues towards topological quantum computing, which could be much faster compared to Majorana zero modes.

References

24A-2

Topological Physics in HgTe-based Quantum Devices

Laurens Molenkamp[1*].

[1]*University of Wuerzburg, Physics Institute, EP3 ,*
Am Hubland, 97074 Wuerzburg, Germany

***Email**: laurens.molenkamp@physik.uni-wuerzburg.de*

Key words: topological superconductivity, Josephson junctions, virtual substrates

Suitably structured HgTe is a topological insulator in both 2- (a quantum well wider than some 6.3 nm) and 3 (an epilayer grown under tensile strain) dimensions.

The material has favorable properties for quantum transport studies, i.e. a good mobility and a complete absence of bulk carriers, which allowed us to demonstrate variety of novel transport effects.

One aspect of these studies is topological superconductivity, which can be achieved by inducing superconductivity in the topological surface states of these materials. Special emphasis will be given to recent results on the ac Josephson effect. We will present data on Shapiro step behavior that is a very strong indication for the presence of a gapless Andreev mode in our Josephson junctions, both in 2- and in 3-dimensional structure. An additional and very direct evidence for the presence of a zero mode is our observation of Josephson radiation at an energy equal to half the superconducting gap.

Controlling the strain of the HgTe layers strain opens up yet another line a research. We have recently optimized MBE growth of so-called virtual substrates ((Cd,Zn)Te superlattices as a buffer on a GaAs substrate), that allow us to vary the strain from 0.4% tensile to 1.5% compressive. While tensile strain turns 3-dimensional HgTe into a narrow gap insulator, compressive strain turns the material into a topological (Weyl) semimetal, exhibiting clear signs of the Adler-Bell-Jackiw anomaly in its magnetoresistance. In quantum wells, compressive strain allows inverted energy gaps up to 60 meV.

24A-3

Probing the spin-orbit interaction in the bulk of a two-dimensional topological insulator

Koji Muraki[1*], Y. Takahashi, T. Akiho, and H. Irie

[1]*NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan*

***Email**: *muraki.koji@lab.ntt.co.jp*

Key words: spin-orbit interaction, inversion symmetry, zero-field spin splitting, quantum spin Hall insulator, topological matter, semiconductor heterostructure

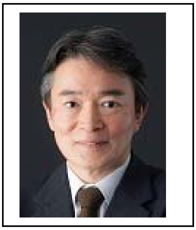
We report capacitance measurements probing the spin-orbit interaction and the resultant zero-field spin splitting in the bulk of a two-dimensional (2D) topological insulator formed in InAs/$In_xGa_{1-x}Sb$ quantum wells [1-3]. The measured capacitance between the quantum wells and the front gate contains a contribution from the quantum capacitance that reflects the density of states (DOS) at the Fermi level of the 2D system. As the Fermi level is swept using a gate voltage, the capacitance showed a dip at the charge neutrality, reflecting the reduced DOS in the gap. Most strikingly, we observed additional features in the capacitance vs gate volrage; on moving away from the charge neutrality, the capacitance suddenly increased in a steplike manner on both *p*- and *n*-type sides. We show that these steps correspond to changes in the number of spin-split bands crossing the Fermi level and are evidence for the full spin-orbit polarization at zero field. Whereas the measured spin splitting in the valence band agrees well with the 8-band k·p calculation, that in the conduction band is significantly greater than the calculation. The unexpectedly large spin splitting suggests that the spin-orbit interaction terms associated with the bulk inversion asymmetry, usually neglected in k·p calculations for heterostructures, are playing an important role. We also demonstrate that the capacitance measurement is useful to probe the residual DOS of disorder-induced in-gap states and the electric-field driven topological phase transition. The quantitative knowledge of the spin-orbit interactions in the bulk band structure allows us to discuss their impacts on the edge states and the topological phase transition. This work was supported by JSPS KAKENHI Grant No. JP15H05854.

References

1. C. Liu *et al*., *Physical Review Letters 100*, 236601 (2008).
2. T. Akiho *et al*., *Applied Physics Letters 109*, 192105 (2016).
3. L. Du et al., *Physical Review Letters 119*, 056803 (2017).

24A-4

Zeno Hall effect and many-body spin Hall effect with space-inversion symmetry



Masahito Ueda[1,2]

[1]Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan [2]RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan

***Email**: *ueda@phys.s.u-tokyo.ac.jp*

Key words: Zeno effect, spin Hall effect, Berry phase

We present two Hall effects arising from long-range interactions. First, we show that the quantum Zeno effect gives rise to the anomalous Hall effect by tailoring the Hilbert space of a two-dimensional lattice system into a single Bloch band with a nontrivial Berry curvature. In particular, we find retroreflection at the edge of the system due to an interplay between the band flatness and the nontrivial Berry curvature [1]. Second, we argue that the spin Hall effect can arise in systems with space inversion symmetry by invoking the dipole-dipole interaction (DDI). The DDI-induced spin Hall effect can serve as a complementary tool to generate spin currents and may be realized in ultracold atomic and molecular systems [2].

References

1. Z. Gong, et al., Phys. Rev. Lett. **118**, 200401 (2017).
2. G. T. Phuc and M. Ueda, Phys. Rev. A**97**, 061608 (R) (2018)

24A-5

Laser induced topological phases in correlated systems

Norio Kawakami[1*].

[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

***Email**: *norio@scphys.kyoto-u.ac.jp*

Key words: topological phases, nonequilibrium, correlated systems

We discuss emergent topological phases induced by laser irradiation in correlated electron (fermion) systems.

We first address a possible way to realize topological superconductivity with application of laser light to superconducting cuprate thin films. Applying Floquet theory to a model of d-wave superconductors with Rashba spin-orbit coupling, we derive an effective model and discuss its topological nature. Interplay of the Rashba spin-orbit coupling and the laser light effect induces the synthetic magnetic fields, thus leading to a topological superconductor characterized by a Chern number. The effective magnetic fields do not create the vortices in superconductors, and thus the proposed scheme provides a promising way to realize a topological superconductor in cuprates [1].

We then study the nature of laser-irradiated Kondo insulators. We find two generic effects induced by laser light. One is the dynamical localization, which suppresses hopping and hybridization, and the other is the laser-induced hopping and hybridization, which can be interpreted as a synthetic spin-orbit coupling or magnetic field. In topological Kondo insulators, linearly polarized laser light realizes phase transitions between trivial, weak topological and strong topological Kondo insulators, whereas circularly polarized laser light breaks time-reversal symmetry, thereby inducing Weyl semimetallic phases [2].

If time allows, we also address topological phase transitions in correlated fermions in optical lattices. Laser induced Kondo effect newly proposed for cold atoms can be used for discussing symmetry-protected Kondo insulating phases and topological phase transitions among them [3].

References

1. K. Takasan, A. Daido, N. Kawakami, Y. Yanase. *Phys. Rev. B95*, 134508 (2017).
2. K. Takasan, M. Nakagawa, N. Kawakami, *Phys. Rev. B96*, 115120 (2017).
3. M. Nakagawa and N. Kawakami, Phys. Rev. Lett. **115**, 165303 (2015);
   Phys. Rev. **B 96**, 155133 (2017)

25A-1

Symmetry-enriched Majorana modes

Jason Alicea[1*].

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

***Email**: *aliceaj@caltech.edu*

Key words: Majorana modes, parafermions, topological quantum computation

The pursuit of non-Abelian anyons promises to reveal novel facets of quantum mechanics that can, in turn, be exploited for topological quantum computation. In one-dimensional wires, rigorous classifications show that non-Abelian-anyon physics can only originate from Majorana zero modes, which are the focus of an intense experimental enterprise. Two-dimensional materials, by contrast, can in principle host an infinite variety of non-Abelian anyons that offer greater utility for quantum computing. In this talk I will show that Majorana modes in quantum wires can be enriched by symmetries, leading to novel behavior that intimately relates to anyons unique to the two-dimensional world. This surprising connection follows from an exact mapping between ordinary electrons in wires and systems of "parafermions". I will highlight new, experimentally relevant horizons in the Majorana problem that arise from this work.

25A-2

Evidence for magnetic Weyl fermions in a correlated metal

Takeshi Kondo
Institute for Solid State Physics, University of Tokyo

***Email**: kondo1215@issp.u-tokyo.ac.jp

Key words: angle-resolved photoemission spectroscopy, magnetic topological material, anomalous Hall effect

The recent Berry phase formulation of the transport properties has uncovered that a large anomalous Hall effect (AHE) can arise not only in ferromagnets, but also in antiferromagnets. Mn_3Sn, a non-collinear antiferromagnet, has been found to exhibit a large AHE even at room temperature [1], and possibility of the Weyl metallic state in it has been proposed.

In my talk, I will introduce the fascinating properties of Mn_3Sn yielded by a large fictitious field due to Berry phase in momentum space, and present the expected experimental evidence for magnetic Weyl fermions in this material [3]. Detailed comparison between angle-resolved photoemission spectroscopy (ARPES) measurements and density functional theory (DFT) calculations reveals significant bandwidth renormalization and damping effect due to the strong correlation among Mn *3d* electrons (Fig.1). Magnetotransport measurements indicate chiral anomaly of Weyl fermions: the emergence of positive magneto conductance only in the presence of parallel electric and magnetic fields. The magnetic Weyl state has a fascinating functionality beyond weakly correlated, space-symmetry-breaking Weyl semimetals; that is, weak magnetic fields (about 10 mT) can control the distribution of Weyl points, thus the large fictitious fields (equivalent to approximately a few hundred T) produced by them in momentum space.

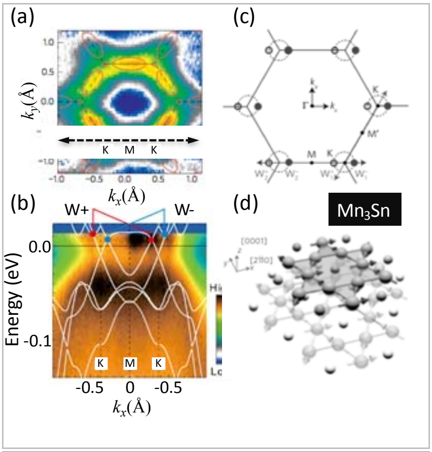


Figure 1: (a) ARPES intensity at E_F and the calculated Fermi surface. (b) Energy dispersion along K-M-K (ARPES and calculation): (left) the original ARPES intensities, and (right) those divided by Fermi function at the measured temperature of 60 K. (c) Distribution of the Weyl points in the bands on k_x-k_y plane at $k_z = 0$ near E_F for the magnetic texture shown in d. (d) Magnetic texture in the kagome lattice.

This discovery will lay the foundation for a new field of science and technology involving the magnetic Weyl excitations of strongly correlated electron systems.

References

1. S. Nakatsuji, et al., Nature **527**, 212 (2015).
2. H. Yang, et al. New J. Phys. 19, 015008 (2017).
3. K. Kuroda, et al., Nature Materials **16**, 1090 (2017).

25A-3

ARPES studies of Weyl state in non-centrosymmetric $TaIrTe_4$ and other materials

Sergey Borisenko[1*].

[1]*IFW-Dresden, 01069 Dresden, Germany*

***Email**: *s.borisenko@ifw-dresden.de*

Key words: ARPES, Dirac and Weyl semimetals, topological matter

Recent breakthrough in search for the analogs of fundamental particles in condensed matter systems lead to experimental realizations of 3D Dirac and Weyl semimetals. Weyl state can be hosted either by non-centrosymmetric or magnetic materials and can be of the first or the second type. Several non-centrosymmetric materials have been proposed to be type-II Weyl semimetals, but in all of them the Fermi arcs between projections of multiple Weyl points either have not been observed directly or they were hardly distinguishable from the trivial surface states which significantly hinders the practical application of these materials. In this talk we present experimental evidence for type-II non-centrosymmetric Weyl state in TaIrTe4 where it has been predicted theoretically. We find direct correspondence between ARPES spectra and calculated electronic structure both in the bulk and the surface and clearly observe the exotic surface states which support the quasi-1D Fermi arcs connecting only four Weyl points. Remarkably, these electronic states are spin-polarized in the direction along the arcs, thus highlighting TaIrTe4
as a novel material with promising application potential.

25A-4

Three-dimensional topological point- and line-node semimetals

Seigo Souma[1,2]

[1]*Center for Spintronics Research Network (CSRN), Tohoku Universyty, Sendai 980-8577, Japan*
[2]*WPI-Advanced Institute of Materials Reserach (WPI-AIMR), Tohoku Universyty, Sendai 980-8577, Japan*

***Email**: s.souma @arpes.phys.tohoku.ac.jp*

Key words: photoemission, ARPES, topological matter, Weyl semimetal, line node

Topological semimetals (TSM) are recently becoming a leading platform for realizing exciting topological phases of matter. In contrast to conventional semimetals with a finite band overlap between valence band (VB) and conduction band (CB), topological semimetals are categorized by the band contacting nature between the VB and CB in the Brillouin zone; point-contact (Dirac/Weyl semimetals) or line contact (line-node semimetals; LNSMs).

TSM shows a singularity of Berry curvature around such nodal electronic states, giving rise to various quantum phenomena like chiral anomaly, anomalous Hall effect, and large negative magnetoresistance. In this talk, we show our recent ARPES results on the candidates of such TSM's [1-4]. Figure 1a shows a quasi-two-dimensional Fermi surface hosting bulk nodal lines of HfSiS [2]. Most notably, we discovered an unexpected Dirac-like dispersion extending one-dimensionally in *k* space – the Dirac-node arc – near the bulk node at the zone diagonal as schematically depicted in Fig. 1b [2]. These Dirac states reside on the surface and could be related to hybridizations of bulk states, but currently we have no explanation for its origin. This discovery poses an intriguing challenge to the theoretical understanding of line-node semimetals. In this talk, we also present our data on various TMS and discuss a connection to the expected quantum phenomena.

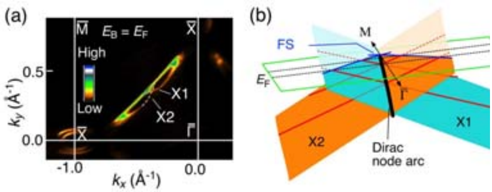


Fig. 1(a) ARPES-intensity mapping at Fermi level of HfSiS. (b) Schematic band dispersion in 3D E-*k* space for the new surface states X1 and X2. Black line indicates the Dirac-node arc.

References

1. S. Souma *et al*., *Phys. Rev. B* **93**, 161112R (2016).
2. D. Takane *et al*., *Phys. Rev. B* **94**, 121108R (2016).
3. K. Nakayama *et al*., *Phys. Rev. B* **95**, 125204 (2017).
4. D. Takane *et al*., *Npj Quantum Mater*. **3**, 1 (2018).

25A-5

Non-Equilibrium momentum and spin dependent dynamics of Topological insulators and Weyl semimetals

Alessandra Lanzara[1,2]

[1]Physics Department, University of California, Berkeley
[2]Materials Science Division, Lawrence Berkeley National Laboratory

***Email**: ALanzara@lbl.gov

Key words:

The helical spin texture of surface electrons in topological insulators and Weyl semimetals has attracted a great deal of interest in the past few years, as being source of exotic phenomena.

Here, we use angle resolved photoemission spectroscopy with time and spin resolution to directly access the topological surface states and the full band structure above the Fermi level in topological insulators and Weyl semimetal. The Fermi surface topology and full spin texture is measured. Time resolved measurements reveal presence of long decay process in addition to coevolution of surface states through a topological phase transition. Importance of these results and their implication for devices applications will be discussed.

References

25P-1

Weyl Fermions and Spintronics

Kentaro Nomura[1,2*].

[1]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

[2] *Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan*

***Email**: *nomura@imr.tohoku.ac.jp*

Key words: Weyl semimetal, Spin torque, magnetic domain wall, charge configuration

The electrical control of spin magnetization aims to be used in next-generation magnetic devices, allowing information to be written electronically. Recently, spintronics phenomena in topological materials have been drawn interests for achieving novel electrical manipulation of the magnetization, and generation of spin currents. In this presentation, we discuss magnetotransport and magnetization dynamics in magnetic Weyl semimetals. A Weyl semimetal is a topologically protected gapless quantum state with either time-reversal or spatial inversion symmetries broken in three dimensions. Weyl semimetals with broken time-reversal symmetry are more interesting and promising for spintronics applications. We derive an effective free energy functional of magnetization which describes electromagnetic responses of a Weyl semimetal with ferromagnetic order[1]. We theoretically demonstrate that Weyl electrons in a magnetic Weyl semimetal exert a spin torque on the local magnetization, without a flowing current, when the chemical potential is modulated in a magnetic field. The spin torque is proportional to the anomalous Hall conductivity, and its effective field strength may overcome the Zeeman field. Using this effect, the direction of the local magnetization is switched by gate control in a thin film. Dynamics of local magnetization is analyzed by solving the Landau-Lifshitz-Gilbert equation[2]. We also discuss magnetic textures such as domain walls in magnetic Weyl semimetals and show that the charge density and the current density are generated near the domain walls, which might be used to manipulate the motion of domain walls electrically.[3,4,5]

.

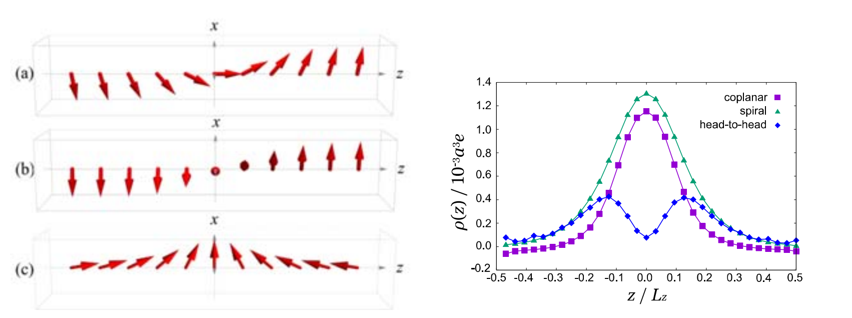


Figure 1: (Left) Domain wall configurations in magnetic Weyl semimetals. (a) coplanar (Neel) type, (b) spiral (Bloch) type, and (c) head-to-head type. (right) The charge density accumulated around the domain walls.

References

1. K. Nomura and D. Kurebayashi, Phys. Rev. Lett. **115**, 127201(2015) .
2. D. Kurebayashi and K. Nomura, Phys. Rev. Applied. **6**, 044013 (2016).
3. Y. Araki, A. Yoshida, and K. Nomura, Phys. Rev. B **94**, 115312 (2016).
4. Y. Araki and K. Nomura, to appear in Phys. Rev. Applied. (2018).
5. Y. Araki, A. Yoshida, and K. Nomura, arXiv:1805.00383 (2018).

25P-2

Topological phases in nanoscale shaped spin-orbit coupled nanostructures

Carmine Ortix[1,2].

[1]Institute for Theoretical Physics, Center for Extreme Matter and Emergent Phenomena, Utrecht University, Princetonplein 5, 3584 CC Utrecht, Netherlands
[2]Dipartimento di Fisica ``E. R. Caianiello", Universita' di Salerno, IT-84084 Fisciano, Italy

***Email**: *c.ortix@uu.nl*

Key words: Topological insulators, Thouless charge pumps, Hofstadter butterfly, curvature effects

I will discuss the possible interplay between curvature effects on the electronic properties and the topological properties of the quantum states in low-dimensional nanomaterials[1]. In particular, I will present the intricate twist between spin textures and spin transport in shape deformed nanostructures. Non-uniform Rashba spin-orbit coupling in shape deformed quantum rings leads to spin textures with a tunable topological character. These topologically non-trivial spin patterns affect the electron spin interference, thereby resulting in different geometry-driven electronic transport behavior[2]. I will also show how semiconducting narrow channels patterned in a mesoscale serpentine shape can operate as a topological charge pump with a rotating planar magnetic field serving as the external ac perturbation[3].

References

1. P. Gentile et al., *Phys. Rev. Lett. 115*, 256801 (2015).
2. Z.-J. Ying et al. *Phys. Rev. B 94*, 081406 (R) (2016).
3. S. Pandey et al. *Phys. Rev. B 97*, 241103 (R) (2018).

26A-1

Topologically protected Bogoliubov Fermi surfaces

Daniel F. Agterberg[1], Philip M.R. Brydon[2], Henri Menke[2], and Carsten Timm[3]
[1]*Department of Physics, University of Wisconsin – Milwaukee, WI 53201, USA*
[2]*Department of Physics, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand*
[3]*Institute of Theoretical Physics, Technical University Dresden, 01062 Dresden, Germany*

***Email**: *agterber@uwm.edu*
Key words: superconductivity, topological matter

It is commonly believed that, in the absence of disorder or an external magnetic field, there are three possible types of superconducting excitation gaps: The gap is nodeless, it has point nodes, or it has line nodes. Here, we show that, for an even-parity nodal superconducting state which spontaneously breaks time-reversal symmetry, the low-energy excitation spectrum generally does not belong to any of these categories; instead, it has extended Bogoliubov Fermi surfaces [1,2]. These Fermi surfaces are topologically protected from being gapped by a non-trivial Z_2 invariant. In this talk, I will discuss the physical origin, topological protection, and energetic stability of these Bogoliubov Fermi surfaces, using superconductivity in j=3/2 fermions as a representative example.

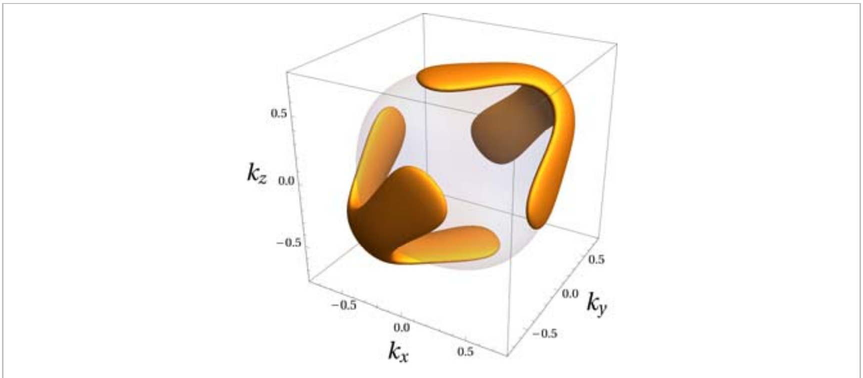


Figure 1: Representative Bogoliubov Fermi surface (solid gold) and normal state Fermi surface (translucent grey).

References

1. D.F. Agterberg, P.M.R. Brydon, and C. Timm, Phys. Rev. Lett. **118**, 127001 (2017) .
2. P. M. R. Brydon, D. F. Agterberg, H. Menke, and C. Timm, arXiv:1806.03773.

26A-2

Topological Superconductivity in Non-Centrosymmetric Materials

Matthias Eschrig[1*]

[1]*Royal Holloway, University of London, Egham, Surrey, TW200EX, United Kingdom*

***Email**: *matthias.eschrig@rhul.ac.uk*

Key words: topological superconductivity, non-centrosymmetric materials

We study non-centrosymmetric superconductors with various point group symmetries. For self-consistent order parameter profiles the surface density of states is calculated showing intricate structure of the Andreev bound states as well as spin polarization. The topology's effect on the surface states and the tunnel conductance is thoroughly investigated, and a topological phase diagram is constructed for open and closed Fermi surfaces showing a sharp transition between the two for the cubic point group O.

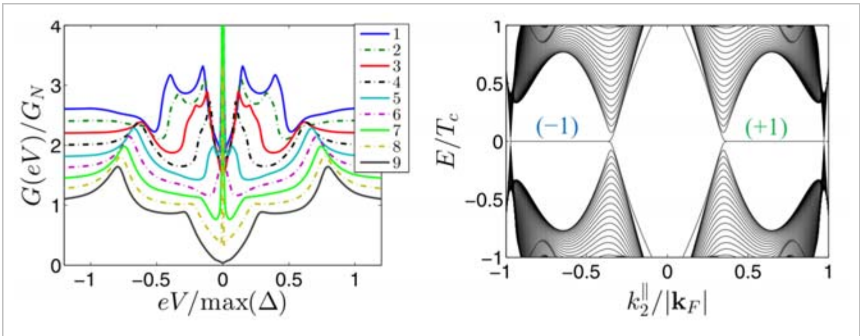


Figure 1: Tunnel conductance (for various ratios between singlet and triplet component of the superconducting order parameter) and surface band structure along the (111) diagonal for a non-centrosymmetric superconductor with cubic point group symmetry [1].

References

[1] N. Wennerdal and M. Eschrig, *Physical Review B* **95,** 024513 (2017).

26A-4

Strain-Enhanced Superconductivity in Sr_2RuO_4

Yoshiteru Maeno

Department of Physics, Kyoto Univerity, Sakyo, Kyoto 606-8502, Japan

Email: *maeno@scphys.kyoto-u.ac.jp*

Key words: strain, topological superconductivity, Sr_2RuO_4

Recently, strain engineering is used as a powerful approach to induce or elucidate topological superconductivity. Capability of controlling the crystalline point-group symmetry by uniaxial strains is particularly attractive, as exemplified by the doubling of T_c from 1.5 K to 3.4 K in Sr_2RuO_4 using a piezo device [1-4]. Such enhanced-T_c state shares the properties of the "3-K" phase in the Sr_2RuO_4-Ru eutectics [5] as well as of the superconductivity in Ru-free Sr_2RuO_4 enhanced with a conventional uniaxial-pressure cell [6]. We also present closely-related facts to consider concerning the topological nature, such as the multicomponent order parameter characteristics of the intrinsic "1.5-K phase" [7, 8].

Although a most probable superconducting state of Sr_2RuO_4 is a topological superconducting state with spin-triplet chiral *p*-wave symmetry, there are important unresolved issues on the behaviour under magnetic fields. Nevertheless, there does not seem to be an alternative spin-singlet scenario at present capable of explaining some key experiments [9]. Strain-engineering is expected to help resolving some of these longstanding issues on the topological superconductivity of Sr_2RuO_4.

This talk is based on the collaborations and discussions mainly with S. Yonezawa, A.P. Mackenzie, C. Hicks, Y. Yasui, M.S. Anwar, K. Lahabi, J. Aarts, M. Sato, and S. Kashiwaya.

References

[1] C. Hicks *et al.*, Science **344**, 283 (2014).
[2] C. Hicks *et al*., Rev. Sci. Instrum. **85**, 065003 (2014).
[3] A. Steppke et al., Science **355**, eaaf9398 (2017).
[4] M.E. Barber et al., Phys. Rev. Lett. **120**, 076602 (2018).
[5] Y. Maeno *et al.*, Phys. Rev. Lett. **81**, 3765 (1998).
[6] S. Kittaka *et al.,* Phys. Rev. B **81**, 180510(R) (2010).
[7] M. S. Anwar *et al.*, Phys. Rev. B **95**, 224509 (2017).
[8] Y. Yasui *et al*., Phys. Rev. B **96**, 180507(R) (2017).
[9] A. P. Mackenzie *et al.*, npj Quantum Materials (2017) **2**:40.

26A-5

Flat Andreev bound states and odd-frequency Cooper pairs

Yasuhiro Asano[1].

[1]*Department of Applied Physics, Hokkaido University, 060-8628, Sapporo, Japan*

***Email**: *asano@eng.hokudai.ac.jp*

Key words: Andreev bound state, conductance quantization, odd-frequency Cooper pairs, index theorem

The quantization of an observable value in physics is closely related some of the time to an invariant in mathematics. We focus on the minimum value of the zero-bias differential conductance G_{min} in a junction consisting of a dirty normal metal and a nodal superconductor preserving time-reversal symmetry. Our analytical results based on the quasiclassical Green function method show that G_{min} is quantized at $(4e^2/h)N_{ZES}$ in the limit of strong impurity scatterings in the normal metal at zero temperature [1,2]. The integer N_{ZES} represents the number of Andreev bound states at zero energy which assist the perfect transmission through the dirty normal metal. An analysis of the chiral symmetry of the Hamiltonian indicates that N_{ZES} corresponds to the Atiyah-Singer index in mathematics[3] and describes number of Majorana fermion appearing at the junction interface.

We have discussed that odd-frequency Cooper pairs play an essential role in such unusual proximity effect[4]. In the presentation, we will demonstrate the stable paramagnetic superconducting states due to odd-frequency pairs in a small nodal superconductor. [5]

.

References

1. S. Ikegaya, Y. Asano, and Y. Tanaka, Phys. Rev. B **91**,174511 (2015);
   S. Ikegaya, S.-I. Suzuki, Y. Tanaka, and Y. Asano, Phys. Rev. B **94**, 054512 (2016).
2. S. Ikegaya and Y. Asano, Phys. Rev. B **95**, 214503 (2017).
3. S. Ikegaya, S. Kobayashi, and Y. Asano, Phys. Rev. B **97** 174501 (2018)
4. Y. Asano and Y. Tanaka, Phys. Rev. B **87**, 104513 (2013).
5. S.-I. Suzuki and Y. Asano, Phys. Rev. B **89**, 184508 (2014); **91**, 214510 (2015).

26P-1

Quantum Oscillations and Neutral Fermions in an Insulator

Yuji Matsuda

Department of Physics, Kyoto University, Kyoto 606-8502, Japan

***Email**: *matsuda@scphys.kyoto-u.ac.jp*

Key words: Topological Kondo insulator, Quantum Oscillations, Neutral Fermions

Solid-state materials can be classified into two groups; insulators and metals. Insulators do not conduct the electric charge and exhibit diverging resistivity at low temperatures, whereas metals sustain conduction electrons which continue to conduct electricity well all the way down to zero temperature. Here we have discovered that the Kondo insulator YbB_{12}, which is a long-known material, belongs to neither categories. The most significant results are

1) The quantum oscillations of the resistivity in an insulating state.
2) The presence of highly mobile and gapless neutral fermions in the bulk, implying that YbB_{12} is an electrical insulator but thermal metal.

References

1. Z. Xiang et al. a preprint.
2. Y. Sato et al. a preprint

26P-2

Topogical materials

Antonio Vecchione[1].

[1]CNR-SPIN, c/o Università di Salerno- Via Giovanni Paolo II, 132 - 84084 - Fisciano (SA), Italy

***Email**: *vecchione@sa.infn.it*

Key words: topological materials, preparation, crystal growth

Properties and preparation of topological materials such as topological insulators, topological crystalline insulators, topological superconductors, Dirac and Weyl semimetals and beyond are introduced. In particular, preparation and doping of topological materials are assessed and some results are listed.

Although various preparation methods are used to improve the crystal quality of the topological materials, it cannot reach the industrialization at the present stage. In this regard, the topical task of materials science of these systems is to expand significantly the range of materials studied by searching for and designing new compounds, solid solutions, and doped phase. Here, it will be given a panorama on the state of art of the preparation techniques of these fascinating materials.

P-1

Topological Nature and Temperature-Induced Lifshitz Transition in $ZrTe_5$ and $HfTe_5$

Guodong Liu[1*].

[1] *Beijing National Laboratory for Condensed Matter Physics,, Institute of Physics,Chinese Academy of Sciences, Beijing 100190, China*

***Email**: *GDLiu_ARPES@iphy.ac.cn*

Key words: angle-resolved photoemission spectroscopy (ARPES), Lifshitz transition, electronic structure, $ZrTe_5$, $HfTe_5$

The topological quantum materials have attracted much attention because they represent new states of matter with unique electronic structures, spin textures, and associated novel physical properties. It opens up the possibility for these materials to become prominent candidates of new devices in future electronics and spintronics. In this poster, we report a high-resolution angle-resolved photoemission spectroscopy study on the topological nature and temperature-induced Lifshitz transition in $ZrTe_5$ and $HfTe_5$, by using a self-developed and 4-Dimensional laser-based ARPES system.

The transition metal pentatellurides $ZrTe_5$ and $HfTe_5$ have drawn considerable attention, due to a recent theoretical proposal of possible topological phase transition from 2D to 3D topological insulator and their unusual transport properties discovered for many decades. By measuring the electronic structure and its detailed temperature evolution, we observed clear gaps from the bulk state and one dimensional-like electronic features from the edge state of two-dimensional $ZrTe_5$ and $HfTe_5$ sheets. It indicates that the bulk $ZrTe_5$ and $HfTe_5$ are weak topological insulators and they exhibit a tendency of weak-to-strong topological insulator transition at low temperature. In addition, we found direct electronic evidence on the temperature-induced Lifshitz transition in $ZrTe_5$ and $HfTe_5$, which provides a natural understanding on underlying origin of the long-standing transport anomaly.

.

References

1. Yan Zhang et al., *Nature Communications* 8, 15512 (2017)
2. Yan Zhang et al., *Science Bulletin* 62(13), 950-956 (2017)

* This work is done in collaboration with Yan Zhang, Chenlu Wang, Li Yu, Simin Nie, Hongming Weng, Lingxiao Zhao, Genfu Chen, Xi Dai, Zhong Fang, Zuyan Xu, Chuangtian Chen and Xingjiang Zhou.

P-2

Electronic polarization in topological nodal semimetal thin film

Yuya Ominato[1*] and Kentaro Nomura[1,2*].

[1]Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[2]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan
***Email**: yuya@imr.tohoku.ac.jp*

Key words: topological nodal semimetal, electronic polarization, thin film, screening effect

Topological nodal semimetals are characterized by the topology of the electronic band structures. They are categorized into nodal point semimetals and nodal line semimetals. Famous examples of the nodal point semimetals are Dirac/Weyl semimetals. In the Dirac/Weyl semimetals, there are many physical properties which are closely related to the topology of their band structures. Recently, the nodal line semimetals also attract many researchers and there are many theoretical and experimental papers. One of the interesting physical response of the nodal line semimetals is the electronic polarization. The electronic polarization in the nodal line semimetals is theoretically studied, and they are closely related to the Berry phase of the nodal line semimetals. These studies, however, are applicable to only insulating phase.

In this work, we calculate electronic polarization in a nodal line semimetal thin film. We consider screening effect and our calculation is applicable to the metallic phase. We find the nodal line semimetals are characterized by the step of the polarization as a function of the external E-filed. This feature is observed even in the Fermi energy off the nodal line, and not observed in the Weyl semimetals.

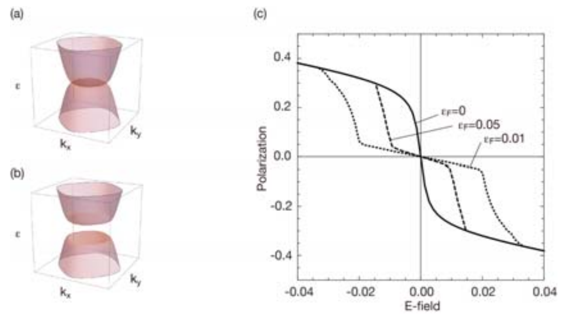


Figure 1:(a)/(b) Electronic band structure in the absence/presence of E-field.
(c) Electronic polarization as a function of E-field.

Charge sensing of Topological Nanowire Devices

Davydas Razmadze[1*], Deividas Sabonis[1], Filip K. Malinowski[1], Gerbold C. Menard[1], Sebastian Pauka[2], Hung Nguyen[1], Peter Krogstrup[1], Ferdinand Kuemmeth[1], Charles M. Marcus[1]
[1]*Center for Quantum Devices and Microsoft Quantum Lab–Copenhagen, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[2]*RC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, Australia.*
***Email**[*]: d.razmadze@nbi.ku.dk

Key words: Charge sensing, nanowires, Majorana devices,

Reported observations of Majorana zero modes in condensed matter system has lead to interest in realizing Majorana-based topological qubits [1]. Key to realizing Majorana qubits is implementing fast readout [2, 3] that would be capable of measuring charge parity of the Majorana devices.

In this work, we investigate a Majorana device made from a semiconducting nanowire (InAs) with epitaxially grown superconductor (Al). In addition, two InAs nanowires (without Al) placed near the Majorana wire, coupled via floating gates, are used as a charge detectors, following the readout scheme in [1]. Signal to noise ratios > 5 are with 1 µs integration time in fields up to 1 T are reported.

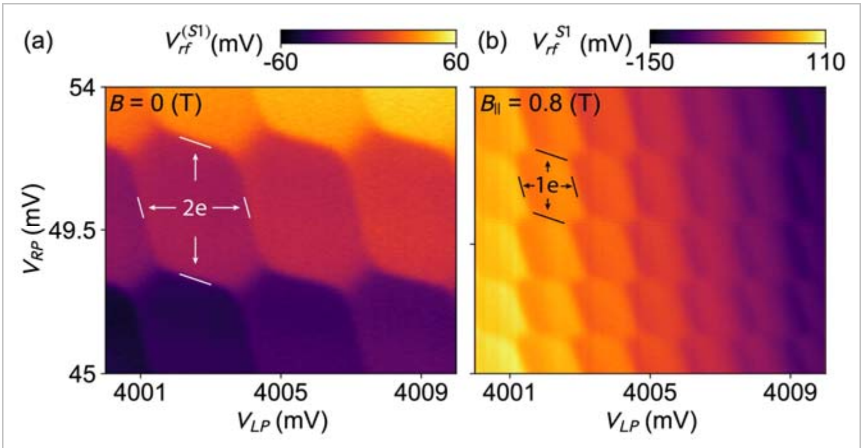


Figure 1: a) Charge sensing of the Majorana device in the double-quantum-dot regime at B = 0. b) Charge sensing signal of the same device in the *1e* charge regime with in axial magnetic field of 0.8 T.

P-4

Size Constraints on Majorana Beamsplitter Interferometer: Majorana Coupling and Surface-Bulk Scattering

Henrik Schou Røising[1]

[1]*Rudolf Peierls Center for Theoretical Physics, Oxford OX1 3PU, United Kingdom*

***Email**: henrik.roising@physics.ox.ac.uk
Key words: Aharonov-Bohm effect, Majorana fermions, topological materials

Topological insulator surfaces in proximity to superconductors have been proposed as a way to produce Majorana fermions in condensed matter physics. One of the simplest proposed experiments with such a system is Majorana interferometry. Here we consider two possibly conflicting constraints on the size of such an interferometer. Coupling of a Majorana mode from the edge (the arms) of the interferometer to vortices in the center of the device sets a lower bound on the size of the device. On the other hand, scattering to the usually imperfectly insulating bulk sets an upper bound. From estimates of experimental parameters, we find that typical samples may have no size window in which the Majorana interferometer can operate, implying that a new generation of more highly insulating samples must be explored.

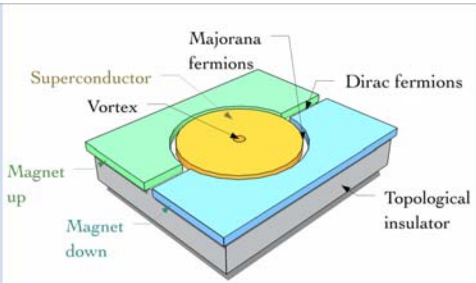


Figure 1: A Majorana interferometer. The size of the device is limited from below by vortex-edge coupling and from above by surface-bulk scattering.

References
1. H. Røising and S.H. Simon. *Physical Review B* **97**, 115424 (2018).

P-5

Three-dimensional Dirac electrons in antiperovskite Sr_3PbO

S. Suetsugu[1*], K. Kitagawa[1], K. Hayama[1], A. W. Rost[2], J. Nuss[2], C. Mühle[2], H. Takagi[1,2]

[1]*Department of Physics, The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Max Planck Institute for Solid State Research, Heisenbergstrasse 1, 70569 Stuttgart, Germany*

***Email**: suetsugu@qmat.phys.s.u-tokyo.ac.jp*

Key words: 3D Dirac semimetal

Three-dimensional (3D) Dirac semimetals with 3D linear dispersion in bulk have been attracting considerable interest because of their expected unconventional properties such as linear magnetoresistance (MR) and chiral anomaly on quasi 1D conducting states in the quantum limit. Recently, a family of cubic antiperovskite A_3TtO (A=Ca,Sr,Ba; Tt=Sn,Pb) was theoretically proposed as a candidate system for 3D massive Dirac electrons [1] with giant orbital diamagnetism [2].

Magneto-transport and NMR measurements were conducted on single crystals of Sr_3PbO. The presence of light mass carriers of only a few percent of free electron and the linear MR (Fig.1) are indicated by magneto-transport measurements at low temperatures. NMR spin lattice relaxation rate $1/T_1$ shows a crossover from T-linear to T^3 dependence, which reflects the density of states $D(E) \sim E^2$ expected for 3D Dirac electrons. Combining the bulk susceptibility, the NMR Knight shift (Fig.2) and $1/T_1$, a giant orbital diamagnetism can be identified, magnitude of which depends critically on the carrier density. All those results are consistent with the presence of 3D Dirac electrons in Sr_3PbO.

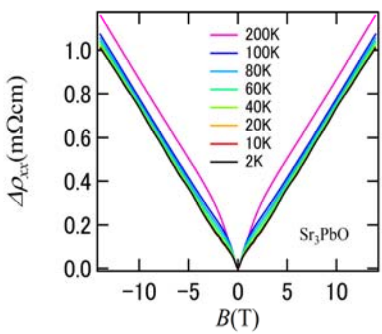


Figure 1: Linear MR

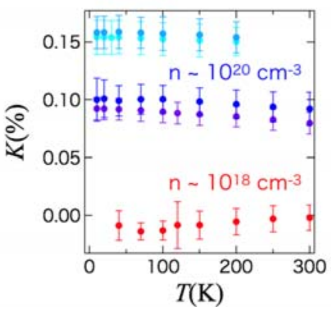


Figure 2: Knight shift

References
1. T. Kariyado and M. Ogata, J. Phys. Soc. Jpn. **80**, 083704 (2011).
2. H. Fukuyama and R. Kubo, J. Phys. Soc. Jpn. **28**, 570 (1970).