Abstract

Symposium Oral Presentation

June 10-12, 2015

New effects in spintronics derived from the symmetry of response functions

Hubert Ebert, Diemo Ködderitzsch, Marten Seemann, Kristina Chadova, and Sebastian Wimmer

Department Chemie, Ludwig-Maximilians-Universität München, Butenandtstr. 5-13
81377 München, Germany

Kubo's linear response formalism allows to determine the response of a property of a solid to a perturbation in a very general way. A prominent example of application is the evaluation of charge, spin and heat transport coefficients of solid state systems. The scheme of Kleiner [1] to investigate the symmetry of conventional transport coefficients has been extended to describe the symmetry of various response tensors appearing in the field of spintronics. Implications for the appearance of interesting effects described by non-zero elements of these response tensors are reviewed. As a first example the occurrence of the anomalous Hall effect (AHE) in materials having nontrivial spin structures, such as non-collinear antiferromagnets, will be discussed on the basis of the shape of the conventional conductivity tensor. As observed by other authors [2,3] the AHE might even occur for a system with zero net magnetization. We revisit and extend these studies employing a combined group theoretical and first principles approach. Based exclusively on symmetry considerations the occurrence of transverse transport and related optical effects for a given magnetic order of a solid can be predicted. Numerical studies using a first principles electronic structure method in combination with Kubo's linear response formalism are performed on the Hall effect, the magnetic circular dichroism in X-ray absorption (XMCD) and magneto-optical Kerr effect (MOKE) to independently cross-check the group theoretical predictions. As a second example the symmetry properties of the spin conductivity tensor are reviewed. It is shown that only the magnetic Laue group has to be considered in this context. In this case non-vanishing transverse elements, found without making reference to the two-current model, give rise to the spin Hall effect in non-magnetic as well as magnetic solids. In the latter case non-vanishing longitudinal elements cause among others the spin-dependent Seebeck effect. For non-magnetic solids having low symmetry non-vanishing longitudinal elements are shown to exist as well. These give rise to spin-orbit induced longitudinal spin transport [4] that has not been considered before. Numerical studies confirm these findings and demonstrate that the longitudinal spin conductivity may be in the same order of magnitude as the conventional transverse one. Finally, the use of symmetry when dealing with the spin-orbit torque [5], Gilbert damping [6] as well as the Edelstein effect [7] is sketched.

References

[1] Kleiner, Phys. Rev. **142**, 318 (1966).
[2] Chen, Niu, and MacDonald, PRL **112**, 017205 (2014).
[3] Kübler and Felser, EPL **108**, 67001 (2014).
[4] Wimmer, Seemann, Chadova, Ködderitzsch, and Ebert, arXiv:1502.04947 [cond-mat.mtrl-sci] (2015).
[5] Manchon and Zhang, PRB **78**, 212405 (2008).
[6] Gilbert, IEEE Trans. Magn. **40**, 3443 (2004).
[7] Edelstein, Solid State Commun. **73**, 233 (1990).

Detection of spin fluctuations in spin glass via spin Hall effect

Y. Niimi[1,*], M. Kimata[1], Y. Omori[1], B. Gu[2,3],
T. Ziman[4], S. Maekawa[2,3], A. Fert[5], and Y. Otani,[1,6]

[1]*Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa 277-8581, Japan*
[2]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[3]*CREST, Japan Science and Technology Agency, Sanbancho, Tokyo 102-0075, Japan*
[4]*CNRS and Institut Laue Langevin, Boîte Postale 156, F-38042 Grenoble Cedex 9, France*
[5]*Unité Mixte de Physique CNRS/Thales, 91767 Palaiseau France*
[6]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 351-0198*
**Present address: Department of Physics, Osaka University, 1-1 Machikaneyama Toyonaka, Japan 560-0043*

Pure spin current, flow of spin angular momentum with no flow of charge, is a key physical quantity to realize low-power spintronic devices. The spin Hall effect (SHE) enables one to convert charge current into pure spin current via spin-orbit interaction. Unlike most work, that has focused primarily on the magnitude of the spin Hall angle, the conversion yield between charge and spin currents, we here demonstrate an example of employing the SHE as a probe of a fundamental response of the spin current to the random spin configurations in spin glass systems.

For this purpose, we chose CuMnBi ternary alloys [1]. When there is no Bi impurity in CuMn, it shows no SHE in the spin transport but shows a typical cusp structure at the spin glass temperature T_g in the thermo-magnetic curves. Once a small concentration of Bi was added in CuMn, a large SHE was observed as shown in our previous work on Bi-doped Cu [2]. Most remarkable is that the SHE of $Cu_{98}Mn_{1.5}Bi_{0.5}$ starts to decrease at T^* (= 40 K = $4T_g$) and becomes as little as seven times smaller at $0.5T_g$, as shown in Fig. 1(a). With decreasing the Mn concentration from 1.5% to 0, T^* is systematically shifted to the lower temperature side. A similar temperature dependence was also observed in anomalous Hall effects in the ternary alloys. These experimental results clearly show that a pure spin current induced by skew scattering at the Bi sites is strongly suppressed by fluctuating spins at the Mn sites even far above T_g (see Fig. 2), and can be qualitatively explained by the relative dynamics between the localized moment and the conduction electron spin.

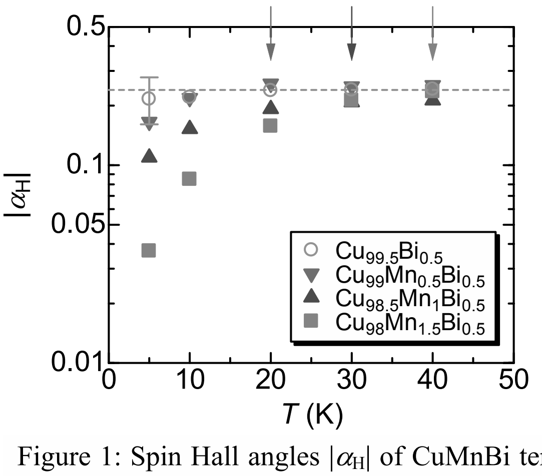

Figure 1: Spin Hall angles $|\alpha_H|$ of CuMnBi ternary alloys as a function of temperature. The arrows indicate T^* where $|\alpha_H|$ start to decrease. The broken line in the figure shows $|\alpha_H|$ of $Cu_{99.5}Bi_{0.5}$.

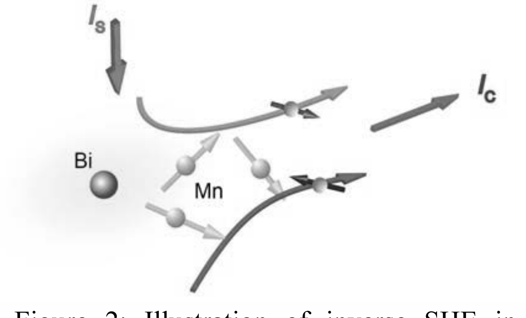

Figure 2: Illustration of inverse SHE in CuMnBi spin glass system. The pure spin current I_S is converted into the charge current I_C at the Bi site. I_S is also affected by fluctuating spins at the Mn sites. Red and blue arrows with green spheres are spins of conduction electrons (|*e*|) and the curved arrows indicate the motions of spin-up and spin-down electrons.

References
[1] A. Fert *et al.*, J. Magn. Magn. Mater. **24**, 231 (1981).
[2] Y. Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012).

Spin transport through antiferromagnets

Yaroslav Tserkovnyak and So Takei

Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA

Antiferromagnetic insulators appear as a promising medium for low-dissipation transmission of spin currents. In the absence of charge carriers, the spin is transmitted collectively, either by thermal cloud of magnons or by a coherent precessional dynamics of the Néel order. The latter can be understood as an instance of spin superfluidity, which is operative even at absolute zero temperature. In this talk, I will discuss two experimental geometries where such spin currents can be probed: (1) Easy-plane antiferromagnet contacted by two heavy metals for injecting (detecting) spin currents by the direct (inverse) spin Hall effect. In such systems, the spin superfluidity can be manifested as a long-ranged negative drag between charge currents in the metals. (2) Easy-axis antiferromagnet sandwiched between a heavy metal and ferromagnetic insulator. The spin Hall effect at the metal/antiferromagnet interface and exchange coupling at the antiferromagnet/ferromagnet interface allow for the spin currents (carried by both coherent dynamics and thermal magnons) to be transmitted across the trilayer. This establishes reciprocal coupling between charge currents in the metal with magnetic dynamics in the ferromagnet, which can be readily accessed with the state-of-the-art experimental tools.

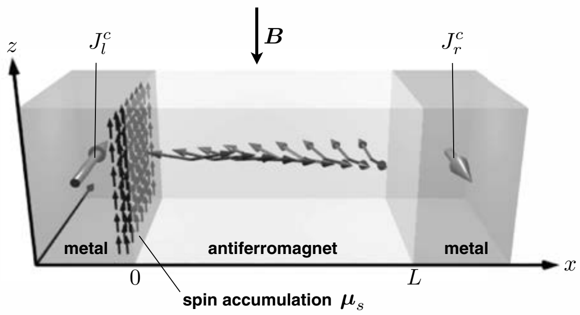

Figure 1: Antiferromagnetic spin superfluid mediating negative drag between metallic leads.

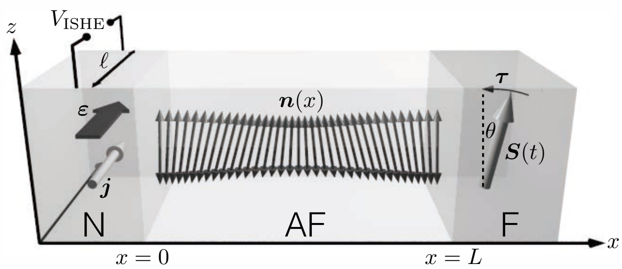

Figure 2: Antiferromagnetic spin waves (either evanescent or thermal) mediating spin-charge coupling between a heavy metal and ferromagnetic insulator.

References

[1] S. Takei and Y. Tserkovnyak, Phys. Rev. Lett. **112**, 227201 (2014).

[2] S. Takei, B. I. Halperin, A. Yacoby, and Y. Tserkovnyak, Phys. Rev. B **90**, 094408 (2014).

[3] S. Takei, T. Moriyama, T. Ono, and Y. Tserkovnyak, arXiv:1502.04128.

S10-4

Spin torque ferromagnetic resonance measurements in antiferromagnetic multilayers.

T. Moriyama and T. Ono

Institute for Chemical Research, Kyoto University, Japan.

Since antiferromagnets (AFMs) have no spontaneous magnetization unlike ferromagnetic materials, it is not easy to manipulate the magnetic moments in AFMs by external magnetic field. However, recent theoretical studies [1] suggest that it is possible to manipulate the magnetization in AFMs by spin-transfer-torque in a similar manner to ferromagnetic materials. In this study, we perform spin-toque ferromagnetic resonance (ST-FMR) measurements [2] on FeCoB/IrMn/Pt multilayers to experimentally investigate the interaction between the spin current and the magnetic moments of antiferromagnetic IrMn.

We fabricate FeCoB 4nm/IrMn t_{IrMn}=0~25 nm/Pt 4nm multilayers on thermally oxidized Si substrate by magnetron sputtering. The film is then patterned into 5~20um wide strips with a coplanar waveguide facilitating both the rf and dc current injection into the strip. The dc electric current I_{dc} flowing in Pt layer invokes spin Hall effect and injects a pure spin current into the neighboring IrMn layer. By using ST-FMR technique, we investigate the linewidth modification of the FeCoB/IrMn resonant spectra under the spin current injection from Pt. Since the spectral linewidth is a direct indication of the magnetic damping in the FeCoB/IrMn bilayer, change in the linewidth due to the spin current is a probe of how much the anti-damping torque is exerted on the FeCoB through the IrMn layer. It is found that the linewidths are varied by the spin current even with $t_{IrMn} \neq$ 0nm. Assuming that IrMn is not transparent for the electron spins [3], the results suggest that the anti-damping torque due to the spin current is exerted on the IrMn magnetic moments and it modifies the effective damping of the FeCoB layer through the interfacial magnetic coupling between FeCoB/IrMn. In the presentation, I will also discuss the recent results obtained with various antiferromagnets including NiO and FeMn.

[1] A. H. MacDonald and M. Tsoi, *Phil. Trans. R. Soc. A* **369**, 3098 (2011)

[2] L. Liu, T. Moriyama, D.C. Ralph, and R.A. Buhrman, *Phys. Rev. Lett.* **106**, 036601 (2011)

[3] R. Acharyya, H. Y. T. Nguyen, W. P. Pratt, Jr., and J. Bass, *J. Appl. Phys.* **109**, 07C503 (2011)

Spin Hall angle dispersion driven anomalous Hall effect

Dazhi Hou,[1] Z. Qiu[1], G. E. W. Bauer[1,2] and E. Saitoh,[1,2]

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

The anomalous Hall effect (AHE) is a manifestation of the breaking of the time reversal symmetry due to the magnetization. Despite decades of controversy in the microscopic mechanisms, the phenomenological explanation of the AHE is in a broad consensus: conduction electrons of up and down spins are equally deflected to opposite directions transversely, and the unbalance in their numbers causes the anomalous Hall current. Here we show that there can be another scenario of the AHE: the difference in the strength of the transverse deflections for the up and down spin electrons, which is induced by a spin accumulation, causes an anomalous Hall current with negligibly small spin polarization in normal metals(Fig. 1) [1]. Experiment results show that this spin Hall angle energy derivative governed contribution can be hundreds of times larger than that of the old AHE picture. Our findings reveal the hidden utility of the spin Hall angle dispersion in the detection of the spin accumulation and will inspire new designs for the spintronics devices.

In addition, I would like to briefly share our recent progress in the temperature dependence of the spin current transport in antiferromagnetic insultors.

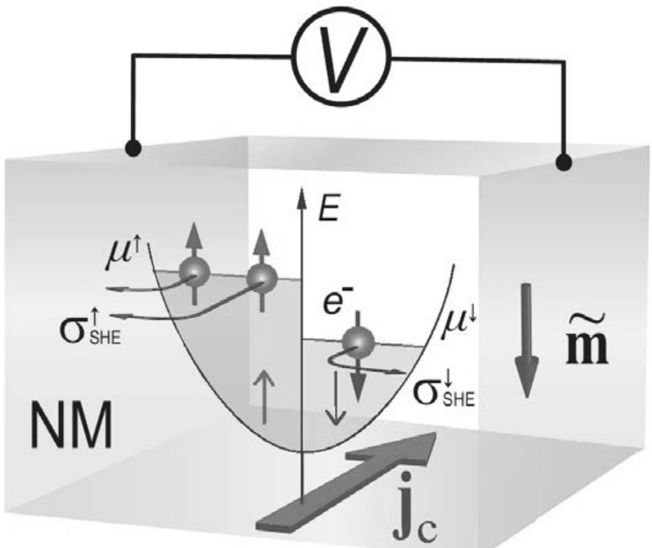

Figure 1: The anomalous Hall effect when there is a spin accumulation in a normal metal, which origins from the difference between the spin Hall conductivities of the up- and down-spin eletrons.

References:
[1] Dazhi Hou, Z. Qiu, R. Iguchi, K. Sato, K. Uchida, G. E. W. Bauer, E. Saitoh, arXiv:1503.00816

Bidirectional conversion between microwave and light via ferromagnetic magnons

R. Hisatomi,[1] A. Osada,[1] S. Ishino,[1] A. Noguchi,[1] Y. Tabuchi,[1]
T. Ishikawa,[1] R. Yamazaki,[1] K. Usami,[1] and Y. Nakamura,[1,2]
[1]*Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan 153-8904*
[2]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 351-0198*

Understanding and exploiting the interactions between well-controlled quantum systems can be a key to building a large-scale artificial many-body quantum system. We are pursuing the architecture where superconducting artificial atoms are connected by light via quantum transducers. The quantum transducer is a device by which an electromagnetic field in microwave domain and that in optical domain can be coherently converted. Here we report such conversions using ferromagnetic magnon mode, or more specifically, the uniform magnetization oscillation mode, i.e., the Kittel mode. The sample is a ferromagnetic sphere of yttrium iron garnet (YIG) crystal, which is positioned in a microwave cavity to enhance the coupling between the microwave mode and the Kittel mode. Microwave response of the coupled system can be probed by microwave reflection spectroscopy [**Fig.1 (a)**] as well as by optical measurement in which the polarization of a travelling optical field through the YIG crystal oscillating at the resonant frequency of the Kittel mode, i.e., the Faraday effect [**Fig.1 (b)**]. By driving the coupled system, on the other hand, with two optical fields at frequencies differed by the Kittel mode frequency we excite the Kittel mode. Due to the large cooperativity, the driven Kittel mode predominantly decays into the microwave cavity mode leading to the coherent microwave generation. We thus demonstrate the bidirectional conversion between microwave and light via the Kittel mode, paving the road to use the Kittel mode as a quantum transducer.

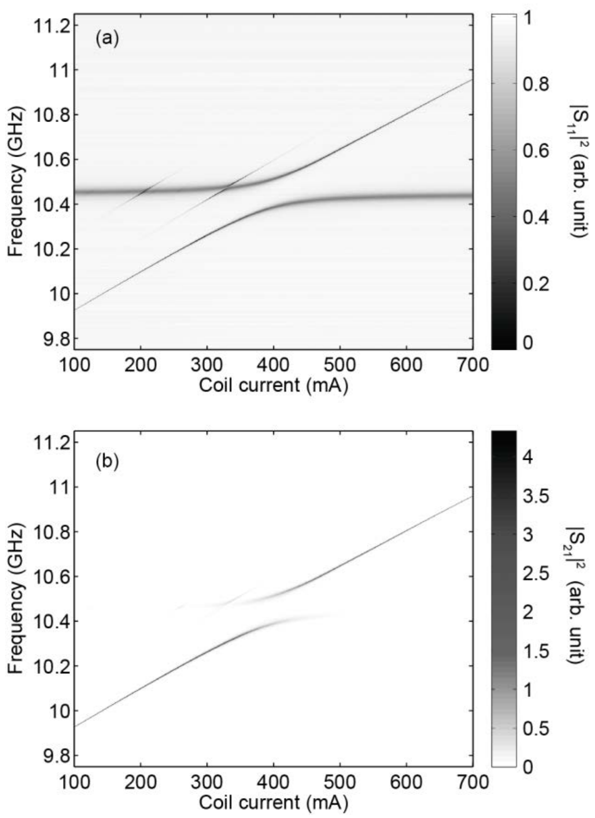

Figure 1: Spectroscopy of the coupled system consisting of the microwave cavity and the Kittel mode coupled system. (a) Spectrum probed by microwave reflection, and (b) those probed via Faraday effect.

Conversion from single photons to single electron spins using GaAs-based double quantum dots

Akira Oiwa[1], Takafumi Fujita[2,3], and Seigo Tarucha[2,4]

[1]*The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka, Japan 567-0047*

[2] *Department of Applied Physics. The University of Tokyo, 3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-8656*

[3]*Kavli Institute of Nanoscience Delft, Quantum Transport, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*

[4]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 361-0198*

Electrical controllability of gate-defined quantum dots (QDs) has brought significant developments in the coherent manipulation of electron spins and two-qubit gate operation toward scalable qubits for quantum computations. Such suitability of gate-defined QDs to quantum information technologies would be considerably enhanced if spin states in the QDs could couple to photon states coherently. Here we show that the photon polarization can couple to the spin degree of freedom in gate-defined GaAs QDs.

Double QDs were fabricated in AlGaAs/GaAs quantum wells [1]. First we show that the resonant inter-dot tunneling can offer a robust detection scheme of the single photoelectron trapping in the double QDs [2,3]. In the two-electron regime, the inter-dot tunneling of the photoelectrons strongly depends on the relative spin orientation (parallel or anti-parallel) of the two QDs. Therefore by combining the resonant inter-dot tunneling scheme with the Pauli spin effect, we have realized the detection of single photoelectron spins. Finally, we demonstrate the angular momentum conversion from single photons to single electron spins in the double QD from the dependence of the detected spins on the incident photon polarization [4].

Authors acknowledge the collaborations with K. Kuroyama, H. Kiyama, G. Allison, M. Larsson, K. Morimoto, S. Teraoka, S. Haffouz, D. G. Austing, A. Ludwig, and A. D. Wieck. This work was supported by Grants-in-Aid for Scientific Research A (No. 25246005), S (No.26220710), Innovative Area "Nano Spin Conversion Science" (No. 26103004), ImPACT Program of Council for Science, Technology and Innovation and SCOPE of MIC.

References

[1] G. Allion *et al*., Phys. Rev. B **90**, 235310 (2014).
[2] T. Fujita *et al*., Phys. Rev. Lett. **110**, 266803 (2013).
[3] K. Morimoto *et al*., Phys. Rev. B **90**, 085306 (2014).
[4] T. Fujita *et al*., submitted.

Single spin, photon, and charge manipulation of NV center in diamond

Norikazu MIZUOCHI, [1,2]

[1]Graduate School of Engineering Science, Osaka University 1-3, Machikane-yama, Toyonaka-city, Osaka, 560-8531, JAPAN
[2]JST-CREST

NV center in diamond has been extensively interested because the single spin of it can be manipulated and detected at room temperature (RT). Furthermore, coherence time (T_2) of the NV center is very long. T_2 is the time to retain coherence (superposition state) and directly relates to the sensitivity of magnetic sensor. Therefore, the unique and excellent properties are expected to be applied for quantum computing, quantum communication and high-sensitive magnetic sensor with nano-scale resolution. By using the NV center, we previously investigated the quantum entanglement generation [1], spin coherence properties [2], and quantum coupling with a flux-qubit [3], and electrically driven single photon source at RT [4].

Recently, we realized deterministic electrical charge-state control of single NV- center [5] by using a p-i-n diode that facilitates the delivery of charge carriers to the defect for charge state switching. A homebuilt confocal microscope was used to observe the single NV centers. By developing this technique for the decoupling of nuclear spins from the NV electron spin, realization of quantum memory of nuclear spin with very long T_2 can be expected. In addition, we also realized nearly perfect alignment (more than 99 %) of the NV axis along the [111]-axis [6]. This result enables a fourfold improvement of optical detection efficiency for spin information in quantum device and a fourfold improvement in magnetic-field sensitivity. These achievements are considered to be a crucial step towards elaborated diamond-based quantum spintronics devices.

These researches are supported SCOPE program, NICT program, Kakenhi, and JST CREST program. The p-i-n diode was produced by AIST in Japan.

[1] P. Neumann, & NM, et al., Science, 320, 1326 (2008).
[2] N. Mizuochi, et al., Phys. Rev. B, 80, 041201(R) (2009).
[3] X. Zhu, & NM, et al., Nature, 478, 221 (2011).
[4] N. Mizuochi et al., Nature Photon. 6, 299 (2012).
[5] Y. Doi, & NM, et al., Phys. Rev. X. 4, 01107 (2014).
[6] T. Fukui, & NM, et al., Appl. Phys. Express 7, 055201 (2014).

Teaching Nanomagnets New Tricks

Igor Žutić
Department of Physics, University at Buffalo

Semiconductor nanostrcutures doped with magnetic impurities provide an intriguing playground to control magnetic ordering. An important manifestation of such ordering is the formation of a magnetic polaron (MP). It can be viewed as a cloud of localized magnetic ion spins, aligned through an exchange interaction with a confined carrier spin and is typically considered a low-temperature phenomenon in bulk semiconductors. However, recent experimental advances in colloidal nanocrystals and epitaxially grown quantum dots (QDs) show robust signatures of MPs that can persist up to room temperature and lead to effective internal fields up to 100 tesla [1]. These highly tunable semiconductor nanostructures, allowing versatile control of the number of carriers, their spin, and the effects of quantum confinement, offer novel possibilities for magnetism, inaccessible to bulk structures. We suggest how magnetic ordering can be controlled even at a fixed number of carriers [2] and enhanced by heating [3]. In a closed-shell system a pseudosinglet spin configuration is responsible for magnetic ordering [4], shown in Fig. 1. We expect that doping quantum dots with magnetic impurities (typically, Mn) may open unexplored opportunities to study the nanoscale correlations [5]. Through Mn-carrier exchange interaction, molecular-like correlations can be enhanced, imprinted on Mn spins, and thus observed. We propose experiments to verify our predictions.

[1] R. Beaulac et al., Science **325**, 973 (2009); S. T. Ochsenbein et al., Nature Nanotech. **4**, 681 (2009); I. R. Sellers et al., Phys. Rev. B **82**, 195320 (2010), F. Xiu et al., Nature Mater. 9, 337 (2010).
[2] R. M. Abolfath, A. G. Petukhov, and I. Žutić, Phys. Rev. Lett. **101**, 207202 (2008).
[3] J. M. Pientka et al., Phys. Rev. B **86**, 161403(R) (2012).
[4] R. Oszwaldowski, I. Žutić, A. G. Petukhov, Phys. Rev. Lett. **106**, 177201 (2011).
[5] R. Oszwaldowski, et al., Phys. Rev. B **86** 201408 (R) (2012); J. Pientka et al., preprint.

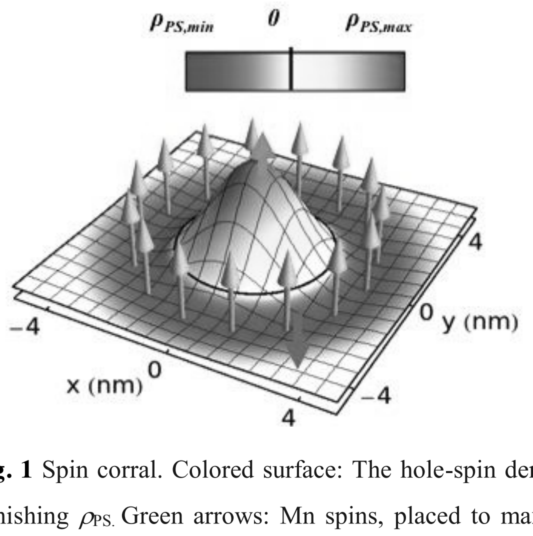

Fig. 1 Spin corral. Colored surface: The hole-spin density ρ_{PS} of the pseudosinglet. Black circle indicates vanishing ρ_{PS}. Green arrows: Mn spins, placed to maximize the stability of the ferromagnetic alignment. Red and blue arrows: The more probable hole-spin projections at two positions [4].

Quantum Hall effects at oxide interfaces

Yusuke Kozuka[1]

[1]*Department of Applied Physics and Quantum-Phase Electronics Center (QPEC), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-8656*

Semiconductor interfaces have provided a variety of opportunities for physics of condensed matters particularly in mesoscopic physics as represented by the quantum Hall effect. As the physics are mostly described in terms of material-independent forms with appropriate renormalization of material parameters, the quantum Hall effect has been primarily studied in the cleanest material, i.e. GaAs. Currently, the electron mobility of the state-of-the-art GaAs heterostructure exceeds 10 million cm^2/Vs, leading to a regime where electron correlation determines its ground state.

Such high-mobility electrons are now available at oxide interfaces as well. Particularly, we have developed the growth technique of ZnO thin films [1]. While the mobility reaches one million cm^2/Vs, the quantum scattering time, which reflects total rate of the scattering, is now comparable to that of the best-quality GaAs as shown in Fig. 1. This enabled recent observation of even-denominator fractional quantum Hall state at $\nu = 3/2$ for the first time [2]. Although $\nu = 3/2$ may be understood in a similar manner to $\nu = 5/2$ state of GaAs, ZnO possesses much stronger electron interaction than that of GaAs, which would leads to a completely new ground state in this material.

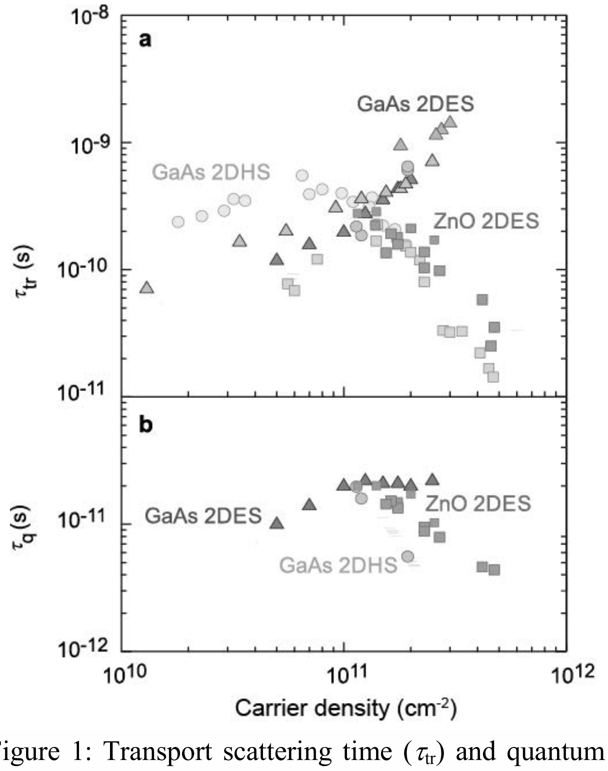

Figure 1: Transport scattering time (τ_{tr}) and quantum scattering time (τ_q) as a function of carrier density for high-mobility carriers in GaAs and ZnO

References
[1] Y. Kozuka, A. Tsukazaki, M. Kawasaki, Appl. Phys. Rev. **1**, 011303 (2014).
[2] J. Falson, D. Maryenko, B. Friess, D. Zhang, Y. Kozuka, A. Tsukazaki, J. H. Smet, M. Kawasaki, Nature Phys. **11**, 347 (2015).

S10-11

Local Currents in a Two-Dimensional Topological Insulator

Xiaoqian Dang, J. D. Burton, and Evgeny Y. Tsymbal

Department of Physics and Astronomy, University of Nebraska, Lincoln, NE, USA

Symmetry protected edge states in a two-dimensional topological insulator are interesting both from the fundamental point of view as well as from the point of view of potential applications in nanoelectronics. Here using a simple tight-binding model and the Landauer-Büttiker formalism we explore local current distributions in a two-dimensional topological insulator focusing on effects of impurities as well as finite size effects. For an isolated edge state, we show that the local conductance decays into the bulk in an oscillatory fashion as explained by the complex band structure of the bulk topological insulator. We demonstrate that although the net conductance of the edge state is topologically protected, impurity scattering leads to intricate local current patterns involving vortex currents of certain chirality. For finite size strips of a topological insulator we observe the formation of an oscillatory band gap in the spectrum of the edge states, the emergence of Friedel oscillations caused by an open channel for backscattering from impurity, and antiresonances in conductance when the Fermi energy matches the energy of the localized state created by impurity.

Theory of Spin Mechatronics

Mamoru Matsuo[1,2]

[1]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki, Japan 319-1195,
[2]ERATO, Japan Science and Technology Agency, Sendai, Japan, 980-8577

Spin current, a flow of spins, is a key concept in the field of spintronics[1]. It is generated by using angular momentum conversion between magnetization, photon and electric current and so on. On the other hand, mechanical angular momentum due to mechanical motion has not been utilized for spin-current generation, which might be useful in nano-electromechanical systems.

In this talk, we discuss spin-current generation from mechanical motion such as rigid rotation[2], vibration[3], elastic deformations[4], and spin-manipulation by mechanical rotation[5]. Conventionally, the Pauli equation for spinor is derived from the special relativistic Dirac equation that cannot describe inertial effects induced by acceleration of a body. We use the general relativistic Dirac equation to describe spin transport phenomena with inertial effects, and show that mechanical generation of spin current and mechanical manipulation of spins stem from the inertial effects on spins that have been ignored in conventional condensed matter theory.

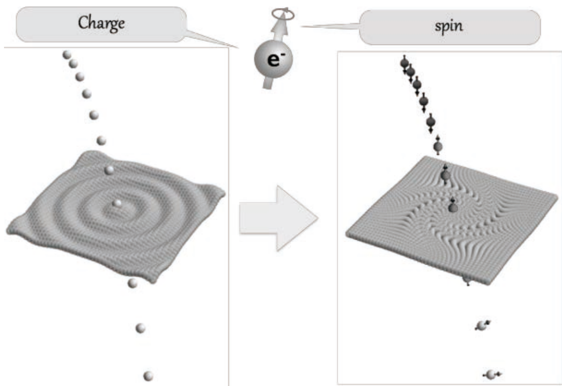

Figure 1: Concept of spin-mechatronics. *Left:* The coupling between charge current and mechanical motion has yielded electro-mechanical systems. *Right*: The coupling between spin current and mechanical motion will open up a new field of spintronics.

This work has been done in collaboration with J. Ieda and S. Maekawa.

References

[1] S. Maekawa, S. O. Valenzuela, E. Saitoh, and T. Kimura ed. “Spin Current”, Oxford University Press (2012).
[2] M. Matsuo et al., Phys. Rev. Lett 106, 076601 (2011).
[3] M. Matsuo et al., Phys. Rev. B 84, 104410 (2011).
[4] M. Matsuo et al., Phys. Rev. B87, 180402(R) (2013); Phys. Rev. B87, 115301 (2013).
[5] H. Chudo et al., Appl. Phys. Express 7, 063004 (2014); J. Phys. Soc. Jpn. 84, 043601 (2015); K. Harii et al., Jpn. J. Appl. Phys. 54, 050302 (2015).

Stability of skyrmion lattices and symmetries of Dzyaloshinskii-Moriya magnets

Alexey Kovalev,[1]

[1]*Department of Physics and Astronomy and Nebraska Center for Materials and Nanoscience, University of Nebraska-Lincoln, NE 68588, USA*

The form of Dzyaloshinskii-Moriya interaction is defined by the symmetries of the underlying crystal, e.g. non-centrosymmetric systems or systems with structural asymmetry. By the direct Free energy minimization and Monte-Carlo simulations we study the phase diagram of Dzyaloshinskii-Moriya magnets with different symmetries of the crystal structure. We observe that the skyrmion lattice can be deformed, e.g., losing its six fold symmetry in favor of four fold symmetry. In some instances, we observe the appearance of merons – topological objects with half of the topological charge. This behavior largely depends on the balance of anisotropies and Dzyaloshinskii-Moriya interactions as well as on the form of Dzyaloshinskii-Moriya interactions. We also discuss various strategies for manipulating such magnetic textures.

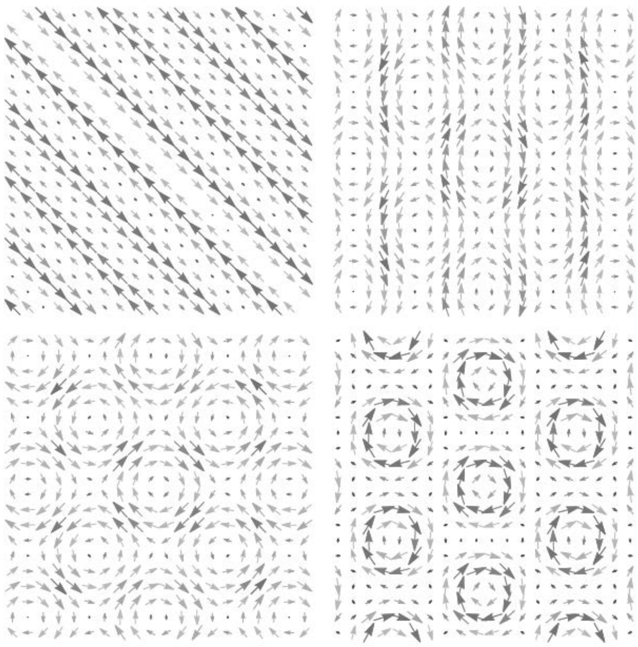

Figure 1: Possible magnetic textures in systems with DMI. Upper plots: helix state and SC1 skyrmion state with a two-fold rotational symmetry. Lower plots: SC2 skyrmion state with a four-fold rotational symmetry and SCh with a six-fold symmetry.

Chirality and Ferromagnetism

Shinichiro Seki[1,2]

[1]RIKEN Center for Emergent Matter Science (CEMS), Wako, Japan, 351-0198
[2]PRESTO, Japan Science and Technology Agency (JST), Tokyo, Japan, 113-8656

Recently, the interplay between the chirality and ferromagnetism has attracted much attention as the source of unique emergent phenomena.

One example is the formation of magnetic skyrmion, i.e. nanometer-scale vortex-like swirling spin texture with particle nature (Fig. 1(a)). Skyrmions in metallic materials can be manipulated by electric current through the spin-transfer torque. Such electric controllability, along with their small size and particle nature, are a promising advantage for potential spintronic device applications. Recently, we discovered that skyrmions appear also in an insulating chiral-lattice magnet Cu_2OSeO_3 [1-3]. Skyrmions in insulator can magnetically induce electric polarization through the relativistic spin-orbit interaction, which enables the manipulation of the skyrmion by external electric field without loss of joule heating.

We have also investigated the spin-dynamics in such chiral-lattice ferromagnets[4-7], and found that the propagation character of the light and spin wave in these compounds show clear nonreciprocal nature (Fig. 1(b)). In general, any (quasi-)particle flow along the magnetic field direction should hold the chiral symmetry, and the above nonreciprocal propagation character originates from the interference of chirality between the propagating entity and crystallographic lattice. The present finding indicates that the chiral-lattice ferromagnets can be utilized as the efficient diode for microwave light and spin wave.

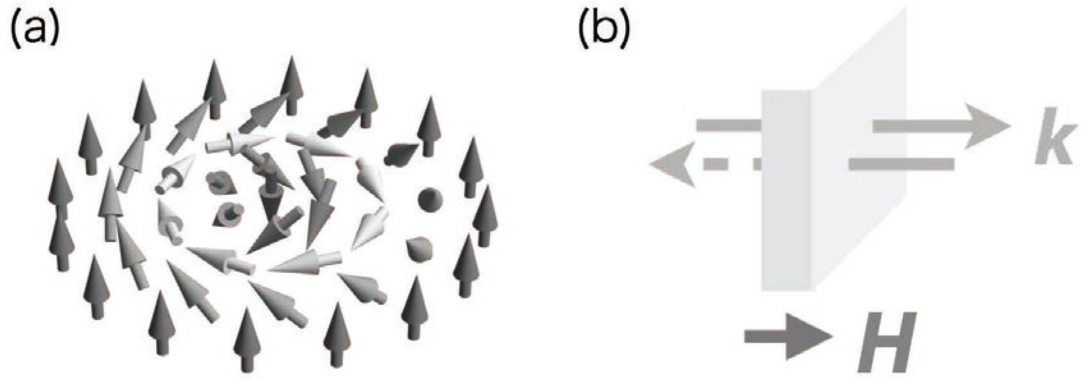

Fig. 1: Two emergent phenomena in chiral-lattice ferromagnets. (a) Formation of skyrmion spin texture, and (b) nonreciprocal propagation of (quasi)-particle flow along magnetic field direction.

References
[1] S. Seki *et al*., Science **336**, 198 (2012).
[2] S. Seki *et al*., Phys. Rev. B **85**, 220406(R) (2012).
[3] S. Seki *et al*., Phys. Rev. B **86**, 060403(R) (2012).
[4] Y. Onose *et al*., Phys. Rev. Lett. **109**, 037603 (2012).
[5] Y. Okamura *et al*., Nature Comm. **4**, 2391 (2013).
[6] M. Mochizuki and S. Seki, Phys. Rev. B **87**, 174403 (2013).
[7] Y. Okamura *et al*., Phys. Rev. Lett. (in press)

Complex Spin States by Interfacial Dzyaloshinskii-Moriya Interactions: From Single Atoms to Thin Films

Roland Wiesendanger*

Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, D-20355 Hamburg, Germany

Localized magnetic moments in a metal are coupled by indirect exchange interactions, which are mediated by the conduction electrons of the nonmagnetic host. For hosts with weak spin-orbit coupling, this exchange can be described by a Ruderman-Kittel-Kasuya-Yoshida (RKKY)-interaction. The damped oscillation of this interaction as a function of distance between ferromagnetic and antiferromagnetic coupling has already been observed in real space by spin-polarized scanning tunneling microscopy (SP-STM) [1,2]. However, for materials with strong spin-orbit coupling, such as platinum or iridium, an additional anisotropic Dzyaloshinskii-Moriya (DM) type term has to be considered [3].

Here, we report on a detailed study of the distance dependency of this DM term in pairs of an Fe-H_2 Kondo complex and an Fe atom adsorbed on Pt(111). We have built several pairs of various distances by STM-induced single-atom manipulation and performed inelastic scanning tunneling spectroscopy (ISTS) above each atom in such pairs. This reveals a splitting of the Kondo resonance, dependent on the strength of the isotropic RKKY and anisotropic DM components of the interaction for the specific distance. By comparison with theory, we were able to extract the strength of both components and find that in our system the DM term is of similar magnitude as the isotropic exchange.

The importance of these interfacial DM interactions for determining the magnetic ground state in low-dimensional systems has been revealed by observing spin spirals with a unique rotational sense in atomic Fe chains on Ir(001) [4] as well as ultrathin transition metal films on W(110) and W(001) substrates using SP-STM [5-7]. Moreover, we have discovered nanoskyrmion lattices in ultrathin layers of transition metals, such as monolayer Fe films on Ir(111) [8,9]. In this case, skyrmionic lattices with a periodicity of only one nanometer can be stabilized even in zero external field by interfacial DM interactions.

More recently, we have made use of multiple interface engineering in bilayer and multilayer systems in order to demonstrate the direct observation and manipulation of individual skyrmions of single-digit nanometer-scale size [10]. By locally injecting spin-polarized electrons from an atomically sharp SP-STM tip, we were able to write and delete individual skyrmions one-by-one, making use of spin-transfer torque exerted by the injected high-energy spin-polarized electrons. The creation and annihilation of individual magnetic skyrmions demonstrates their great potential for future nanospintronic devices making use of individual topological charges as information carriers [11].

References

[1] F. Meier et al., Science **320**, 82 (2008).
[2] L. Zhou et al., Nature Physics **6**, 187 (2010).
[3] A. Fert et al., Phys. Rev. Lett. **44**, 1538 (1980).
[4] M. Menzel et al., Phys. Rev. Lett. **108**, 197204 (2012).
[5] M. Bode et al., Nature **447**, 190 (2007).
[6] P. Ferriani et al., Phys. Rev. Lett. **101**, 027201 (2008).
[7] Y. Yoshida et al., Phys. Rev. Lett. **108**, 087205 (2012).
[8] S. Heinze et al., Nature Physics **7**, 713 (2011).
[9] J. Brede et al., Nature Nanotechnology **9**, 1018 (2014).
[10] N. Romming et al., Science **341**, 6146 (2013).
[11] A. Fert et al., Nature Nanotechnology **8**, 152 (2013).

Coherence by elevated temperature

Volker Meden

Institut für Theorie der Statistischen Physik, RWTH Aachen University, 52056 Aachen, Germany

We reveal several distinct regimes of the relaxation dynamics of a small quantum system coupled to an environment within the plane of the dissipation strength and the reservoir temperature. This is achieved by discriminating between coherent dynamics with damped oscillatory behavior on all time scales, partially coherent behavior being nonmonotonic at intermediate times but monotonic at large ones, and purely monotonic incoherent decay. Surprisingly, elevated temperature can render the system "more coherent" by inducing a transition from the partially coherent to the coherent regime. This provides a refined view on the relaxation dynamics of open quantum systems.

References

[1] D. M. Kennes, O. Kashuba, and V. Meden, Phys. Rev. B **88**, 241110(R).
[2] D. M. Kennes, O. Kashuba, M. Pletyukhov, H. Schoeller, and V. Meden, Phys. Rev. Lett. **110**, 100405 (2013).

S11-5

Shot noise monitoring of the cross-over between SU(4) and SU(2) symmetry of the Kondo effect in a carbon nanotube quantum dot.

M. Ferrier[1,2], T. Arakawa[1], T. Hata[1], R. Fujiwara[1], R. Delagrange[2], R. Weil[2], R. Deblock[2], R. Sakano[3], A. Oguri[4] and K. Kobayashi[1]

[1]*Department of Physics, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, 560-0043 Osaka, Japan,*

[2]*LPS, Université Paris-Sud, CNRS, UMR 8502, F-91405 Orsay Cedex, France*

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

[4]*Department of Physics, Osaka City University, Sumiyoshi-ku, Osaka 558-8585, Japan*

In a quantum dot, Kondo effect occurs when the spin of the confined electron is entangled with the electrons of the leads forming locally a strongly correlated Fermi-liquid. Our experiments were performed in such a dot formed in a single carbon nanotube, where Kondo effect with different symmetry groups, namely SU(2) and SU(4), shows up. In the latter case, as spin and orbital degrees of freedom are degenerate, two channels contribute to transport and Kondo resonance emerges for odd and even number of electrons. With our sample it was possible to investigate both symmetries near the unitary limit.
It is predicted that, in the Kondo regime, strong interaction creates a peculiar two-particle scattering which appears as an effective charge e^* for the quasi-particles [1,2]. We have extracted the signature of this effective charge in the shot noise for both symmetry in good agreement with theory [3,4]. This result demonstrates that theory of the Kondo effect can be safely extended out of equilibrium even in the unconventional SU(4) symmetry[5].
Surprisingly, the SU(4) Kondo effect for 2 electrons persists until very high perpendicular magnetic field (13 T). We have measured this evolution in the conductance and shot noise. Our results show that only one perfect channel persists and the effective charge increases up to the SU(2) value. It suggests that the symmetry of the Kondo effect changes from SU(4) to the so called singlet-triplet SU(2) at high field.

References

[1] E. Sela et al, *Phys. Rev. Lett.* **97**, 086601 (2006)
[2] A. O. Gogolin and A. Komnik, *Phys. Rev. Lett.* **97**, 16602 (2006)
[3] C. Mora *et al*. Phys. Rev. B **80,** 125304 (2009)
[4] R. Sakano *et al*, Phys. Rev. B **83,** 075440 (2011)
[5] M. Ferrier *et al*. (submitted)

Universal Fermi liquid crossover and quantum criticality in a mesoscopic system

G. Zarand[1], A. J. Keller[2], L. Peeters[2], C. P. Moca[1,3], I. Weymann[4], D. Mahalu[5], V. Umansky[5], and D. Goldhaber-Gordon[2]

[1]BME-MTA Exotic Quantum Phases “Momentum” Group, Institute of Physics, Budapest University of Technology and Economics, H-1521 Budapest, Hungary
[2]Geballe Laboratory for Advanced Materials, Stanford University, Stanford, CA 94305, USA
[3]Department of Physics, University of Oradea, 410087, Romania
[4]Faculty of Physics, Adam Mickiewicz University, Poznan´, Poland 5Department of Condensed Matter Physics,
[5]Weizmann Institute of Science, Rehovot 96100, Israel

The microscopic origins of quantum phase transitions (QPTs) in complex materials and the fate of the Fermi liquid state at quantum criticality are often debated. Quantum dots and mesoscopic circuits provide an experimental framework for realizing known quantum impurity Hamiltonians that can feature tunable second-order QPTs. Here we investigate experimentally and theoretically in unprecedented detail the quantum phase transitions occurring in a mesoscopic system, a quantum dot coupled to a metallic grain and to lead electrodes [1,2]. We establish theoretically the complex phase diagram of this device through detailed numerical renormalization group calculations and resolve a former controversy: We show that, counter-intuitively, stable lines of non-Fermi liquid spin and charge two-channel Kondo states [3,4] emerge and coexist with SU(4) physics in this simple device [5]. We demonstrate experimentally, with support from numerical computations, a universal crossover from a quantum critical non-Fermi liquid behavior to distinct Fermi liquid ground states in a regime, where our device realizes a spin-1/2 impurity exchange-coupled equally to two independent electronic reservoirs. Arbitrarily small detuning of the exchange couplings results in conventional screening of the spin by the more strongly coupled channel for energies below a Fermi liquid scale T*. We extract a quadratic dependence of T* on gate voltage close to criticality and validate an asymptotically exact conformal field theory description of the universal crossover between strongly correlated non-Fermi liquid and Fermi liquid states [6].

References

[1] Potok, R. M., Rau, I. G., Shtrikman, H., Oreg, Y. & Goldhaber-Gordon, D. Nature **446**, 167–171 (2007).
[2] Keller, A.J., Peeters, L., Moca, C.P., Weymann, I., Mahalu, D., Umansky, V., Zarand, G. & Goldhaber-Gordon, D. (unpublished).
[3] Oreg, Y. & Goldhaber-Gordon, D. Phys. Rev. Lett. **90**, 136602 (2003).
[4] Matveev, K. A., Sov. Phys. JETP **72**, 892 (1991).
[5] Le Hur, K., Simon, P. & Loss, D., Phys. Rev. B **75**, 035332 (2007).
[6] Sela, E., Mitchell, A. K. & Fritz, L., Phys. Rev. Lett. **106**, 147202 (2011).

S11-7

Topological Valley Currents in Gapped Dirac Materials

Leonid Levitov

Physics Department, Massachusetts Institute of Technology, 6C-345, 77 Massachusetts Ave, Cambridge MA02139, USA

Gapped 2D Dirac materials, in which inversion symmetry is broken by a gap-opening perturbation, feature a unique valley transport regime. The system ground state hosts dissipationless persistent valley currents existing even when topologically protected edge modes are absent or when they are localized due to edge roughness. Topological valley currents in such materials are dominated by bulk currents produced by electronic states just beneath the gap rather than by edge modes. Dissipationless currents induced by an external bias are characterized by a quantized half-integer valley Hall conductivity. The under-gap currents dominate magnetization and the charge Hall effect in a light-induced valley-polarized state.

Chiral electroluminescence from 2D material based transistors

Y. J. Zhang[1], M. Onga[1], R. Suzuki[1], and Y. Iwasa[1,2]
[1] Department of Applied Physics and Quantum-Phase Electronics Center,
University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan
[2] RIKEN, Center for Emergent Matter Science (CEMS), Wako 351-0198, Japan

Layered Transition metal dichalcogenides (TMDs) are fruitful platform for electronics, spintronics, and opto-valleytronics. The monolayer TMDs have a similar crystal structure as staggered graphene and thus various physics predicted for inversion asymmetric graphene also inheres in monolayer TMDs. Especially, valley related physics are of particular importance. The broken inversion symmetry splits six Fermi pockets, locating at the first Brillouin zone edges, into two inequivalent groups (±K). The existence of valley degree of freedom is the base requirement for valleytronics. The broken inversion symmetry also lead to finite and valley-depended Berry curvature, which leads to valley-depended optical selection rule (valley circular dichroism), Zeeman-type spin splitting, and valley Hall effect [1]. After the fundamental investigation of valley circular dichroism in TMDs by polarization-resolved photoluminescence, valley-dependent spin splitting [2] and light-induced valley Hall effect [3] were experimentally observed.

We have investigated *p-n* junctions embedded in TMDs, in terms of opto-electronic applications. Taking advantage of the ambipolar transport characteristics, *p-n* junctions can be electrostatically formed in channel TMD materials using field effect transistor (FET) geometry [4]. Among various FETs, electric double layer transistor (EDLT), a FET using liquid dielectrics, have been manifested their potentials upon TMDs by field-induced superconductivity [5] or control of spin relaxation [6]. For opto-electronic devices, we observed electrically controllable helical electroluminescence from TMD *p-n* junction formed by EDLTs [7]. In a stark contrast, such a functionality is absent in junctions formed by conventional FETs [8]. The origin of this phenomenon lies in the anisotropic band dispersion (trigonal warping) that, under in-plane electric field, leads to valley-depending carrier transport and electron-hole recombination. Within the conventional FETs, the in-plane electric field is expected to be too small to induce these effects, implying the potential of EDLTs.

References

[1] D. Xiao, G. Liu, W. Feng, X. Xu, and W. Yao, Phys. Rev. Lett. **108**, 196802 (2012).
[2] R. Suzuki *et al*., Nat. Nanotechnol. **9**, 611 (2014).
[3] K. F. Mak, K. L. McGill, J. Park, and P. L. McEuen, Science **344**, 1489 (2014).
[4] Y. J. Zhang, J. T. Ye, Y. Yomogida, T. Takenobu, and Y. Iwasa, Nano Lett. **13**, 3023 (2013).
[5] J. T. Ye *et al*., Science **338**, 1193 (2012).
[6] H. T. Yuan *et al*., Nat. Phys. **9**, 563 (2013).
[7] Y. J. Zhang, T. Oka, R. Suzuki, J. T. Ye, and Y. Iwasa, Science **344**, 725 (2014).
[8] A. Pospischil, M. M. Furchi, and T. Mueller, Nat. Nanotechnol. **9**, 257 (2014).

Quantum transport in van der Waals heterostructures of graphene and 2D materials

Tomoki Machida,[1,2] Satoru Masubuchi,[1] Sei Morikawa,[1] Yohta Sata,[1] Naoto Yabuki,[1] Naoko Inoue,[1] Miho Arai,[1] Rai Moriya,[1] Kenji Watanabe,[3] and Takashi Taniguchi [3]

[1] Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, Japan
[2] INQIE, University of Tokyo, Tokyo 153-8505, Japan
[3] National Institute for Materials Science, Ibaraki 305-0044, Japan

Recent advances in transfer techniques of atomic layers have enabled one to fabricate van der Waals heterostructures of two-dimensional (2D) crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs). In this talk, we study carrier transport in high-mobility dual-gated h-BN/graphene/h-BN devices. The resistance across the npn junctions shows an oscillatory behavior, suggesing that the co-propagating p and n quantum Hall edge channels traveling along the pn interface functions as a built-in Aharanov-Bohm-type interferometer. The trajectories of peak and dip in the observed resistance oscillation are well reproduced by our numerical calculation that assumes magnetic flux quantization in the area enclosed by the co-propagating edge channels. Coherent nature of the co-propagating edge channels are confirmed by the checkerboard-like pattern in the dc-bias and magnetic-field dependences of the resistance oscillations. We will also present our recent experiments on quantum transport in various van der Waals junctions of 2D materials.

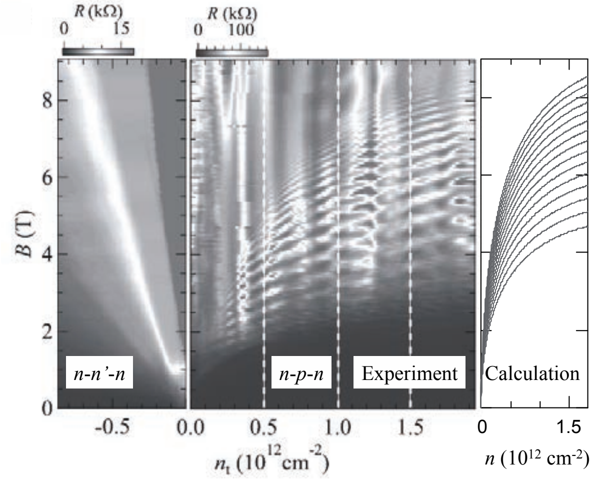

Fig. 1 Color-plot of two-terminal magnetoresistance of graphene nnn (left) and npn (center) junctions. Simulated peak positions of carrier transmission between the counter-circulating quantum Hall edge channels at the pn interface (right).

References

[1] S. Morikawa, S. Masubuchi, R. Moriya, K. Watanabe, T. Taniguchi, and T. Machida, Appl. Phys. Lett. **106**, 183101 (2015).

[2] S. Masubuchi, M. Onuki, M. Arai, T. Yamaguchi, K. Watanabe, T. Taniguchi, and T. Machida, Phys. Rev. B **88**, 121402 (2013).

[3] S. Masubuchi, K. Iguchi, T. Yamaguchi, M. Onuki, M. Arai, K. Watanabe, T. Taniguchi, and T. Machida, Phys. Rev. Lett. **109**, 036601 (2012).

[4] R. Moriya, T. Yamaguchi, Y. Inoue, S. Morikawa, Y. Sata, S. Masubuchi, and T. Machida, Appl. Phys. Lett. **105**, 083119 (2014).

[5] Y. Sata, R. Moriya, T. Yamaguchi, Y. Inoue, S. Morikawa, N. Yabuki, S. Masubuchi, and T. Machida, Jpn. J. Appl. Phys. **54**, 04DJ04 (2015).

[6] T. Yamaguchi, R. Moriya, Y. Inoue, S. Morikawa, S. Masubuchi, K. Watanabe, T. Taniguchi, and T. Machida, Appl. Phys. Lett. **105**, 223109 (2014)

Valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene

Yuya Shimazaiki,[1] Michihisa Yamamoto,[1,2] Ivan V. Borzenets,[1] Kenji Watanabe,[3] Takashi Taniguchi,[3] and Seigo Tarucha[1,4]

[1]*Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan, 113-8656*
[2]*PRESTO, JST, 4-1-8 Hon-cho, Kawaguchi-shi, Saitama, Japan, 332-0012*
[3]*National Institute for Materials Science, 1-1 Namiki, Tsukuba-shi, Ibaraki, Japan, 305-0044*
[4]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 361-0198*

We report on the observation of the valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene [1, 2]. Certain specific crystal structuers result in degenerate local minima (conduction band) or maxima (valence band) called "valleys" in the band structure. "Valleytronics" is a newly developed concept for electronics utilizing the occupation degree of freedom of valleys as an information carrier. Honeycomb lattice systems such as graphene and transitional metal dichalcogenides (TMDCs) are ideal materials for valleytronics. These systems have K and K′ valleys that have opposite electron chiralities. When spatial inversion symmetry is broken in these systems, valley contrasting Berry curvature emerges. This results in valley Hall effect [3] and inverse valley Hall effect, which enable generation and detection of a pure valley current. Valley Hall effect was demonstrated in structurally spatial inversion symmetry broken systems such as monolayer MoS_2 [4] and monolayer graphene/h-BN superlattice [5]. For the case of bilayer graphene, however, a perpendicular electric field called displacement field can be used to break spatial inversion symmetry. The tunable displacement field allows for further controllability of the valley Hall effect and unambiguous detection of the pure valley current.

Here we used dual-gated bilayer graphene to break the spatial inversion symmetry electrically as well as to tune the carrier density. We employed nonlocal resistance measurement to prove existence of the valley Hall effect. Fig. 1 shows the schematic image of the nonlocal transport mediated by the pure valley current. The spatial inversion symmetry is broken by the displacement field (D). Pure valley current is generated at the left side via the valley Hall effect, and detected as a voltage signal at the right side after being converted via the inverse valley Hall effect. At 70K, around charge neutrality point, we found that large nonlocal resistance emerges under displacement field and it scales cubically with the local resistivity by tuning the displacement field. This is an evidence of the pure valley current mediating the nonlocal transport and the valley Hall effect in spatial inversion symmetry broken bilayer graphene. The worth noting point is the observation of valley Hall effect in insulating regime. In the ideal zero conductivity limit, energy non-dissipative conversion of an electric field to a pure valley current will be enabled.

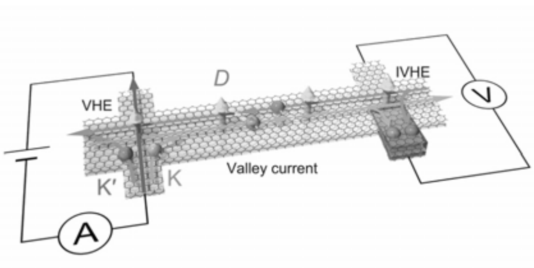

Figure 1: Schematic image of the pure valley current mediated nonlocal transport

References
[1] Y. Shimazaki, *et al.,* arXiv:1501.04776 (2015)
[2] M. Sui, *et al.,* arXiv:1501.04685 (2015)
[3] D. Xiao, *et al., Phys. Rev. Lett.* **99**, 236809 (2007)
[4] K. F. Mak, *et al., Science* **344**, 1489–1492 (2014)
[5] R. V. Gorbachev, *et al., Science* **346**, 448–451 (2014)

Singularity of the spectrum of Andreev levels in multi-terminal Josephson junction

Tomohiro Yokoyama,[1,2] and Yuli V. Nazarov,[1]

[1]*Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, Delft, The Netherlands, 2628CJ*
[2]*Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan, 361-0198*

We study theoretically a short multi-terminal Josephson junction. It can be realized with crossed InSb/As nanowires [1], where spin-orbit (SO) interaction is strong. In short Josephson junctions, quasiparticle Andreev bound states with discrete energy-levels are formed in the superconducting gap region, $|E| < \Delta$. The Andreev levels depend on the phase differences between superconductors. All phases have a 2π-periodicity. We consider a four-terminal junction, where three phase differences are defined and the Andreev levels form the band (like) structure, $E_n(\varphi_1, \varphi_2, \varphi_3)$. We investigate the spectrum of Andreev levels and the presence of singular points in the spectrum at $E = 0$ and $|E| = \Delta$, which are associated with the Weyl physics in a 3D solid [2].

The Andreev levels, $E_n(\varphi_1, \varphi_2, \varphi_3)$, are determined from the Beenakker's equation [3]. By the time-reversal symmetry, the change of sign of all phases results in the same energy-level, $E_n(-\varphi_1, -\varphi_2, -\varphi_3) = E_n(\varphi_1, \varphi_2, \varphi_3)$. The Andreev levels come in pair of positive and negative energy. For some junctions, accidental band touching is found at $E = 0$. In the absence of SO interaction, the Andreev levels are doubly degenerate. The conical points at $E = 0$ come in groups of four, as shown in Fig. 1(a). The SO interaction splits the conical points to upward and downward [Fig. 1(b)]. When the S-matrix is changed continuously, the conical points move but keep the groups of four. If the points meet with each other, we find a pair annihilation. These indicate topological protection of the Weyl point.

The Andreev level touches the gap edge in the absence of SO interaction. The gap edge touching point forms a 2D surface in the 3D phase space. The SO interaction generally removes the levels from $|E| = \Delta$. We establish the effective Hamiltonian from the Beenakker's equation and find the conditions of the gap edge touching in the presence of SO interaction.

References
[1] S. R. Plissard *et al.*, Nature Nanotech. **8**, 859 (2013).
[2] S. Murakami, New J. Phys. **9**, 356 (2007).
[3] C. W. J. Beenakker, Phys. Rev. Lett. **67**, 3836 (1991).

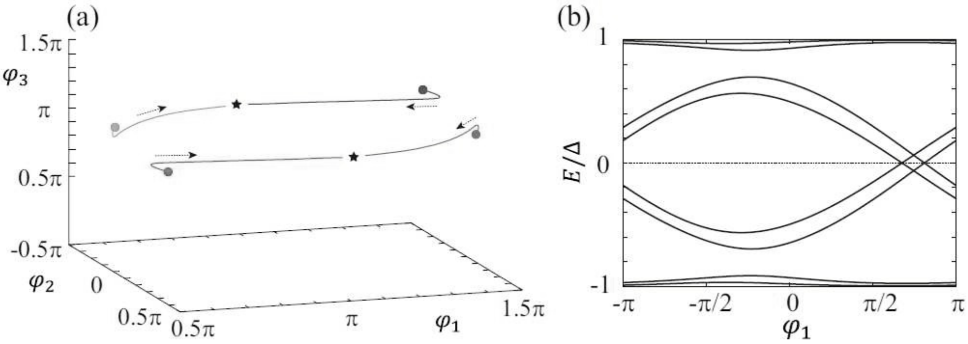

Figure 1: (a)Position of Weyl points in 3D phase space. Dots mean no SO interaction. Lines are the trajectory when the SO interaction is tuned continuously. The pair annihilation happens at star marks. (b)Andreev level with conical point, which is split by the SO interaction to upward ($E > 0$) and downward ($E < 0$).

S12-2

Superconducting hybrid structures based on quantum spin Hall systems

Björn Trauzettel

Institute for Theoretical Physics, Physics Department, Würzburg University, 97074 Würzburg, Germany

We will discuss transport properties of helical edge states at the boundary of quantum spin Hall (QSH) systems in proximity to superconductors (S) and/or ferromagnets (F). For a single helical edge state, we argue that an unconventional triplet order parameter can be directly identified in an F-QSH-S setup by looking at crossed Andreev reflections [1]. In the case of two helical edge states coupled to two super-conducting electrodes in a SQUID-like geometry, we show how a Doppler shift -- due to an external magnetic field -- can significantly affect the Josephson current through the junction [2].

References

[1] F. Crépin, P. Burset, and B. Trauzettel, *Odd-frequency triplet superconductivity at the helical edge of a topological insulator*, arXiv:1503.07784.

[2] G. Tkachov, P. Burset, B. Trauzettel, and E.M. Hankiewicz, Quantum interference of edge supercurrents in a two-dimensional topological insulator, arXiv:1409.7301.

Mode Mixing in Graphene *p-n* Junctions Investigated by Shot Noise Measurement

Norio Kumada,[1,2] F. D. Parmentier,[2] H. Hibino,[1] D. C. Glattli,[2] and P. Roulleau,[2]

[1] *NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Japan 243-0198*
[2] *Nanoelectronics Group, Service de Physique de l'Etat Condensé, IRAMIS/DSM (CNRS URA 2464), CEA Saclay, F-91191 Gif-sur-Yvette, France.*

Because of linear and gapless band structure, graphene offers unique *p-n* junctions (PNJs) at which symmetric *p* and *n* regions adjoin without a gap in between. In quantum Hall effect regime, counter circulating edge modes in the *p* and *n* regions mix in the PNJ, leading to quantized conductance at unusual fractional values. In this work, we investigate the mode mixing process by shot noise measurement and suggest that the graphene PNJ can serve as a beam splitter.

We prepared graphene by thermal decomposition of SiC. We used five samples with different PNJ length between L = 5 and 100 μm. When a bias V_{sd} is applied between the edge modes in the *p* and *n* regions, the mode mixing in the PNJ leads to non-equilibrium energy distribution. Partitioning of the mixed modes at the exit of PNJ generates shot noise [Fig. 1(a)]. Since the amplitude of the noise represented by Fano factor F depends on the energy distribution in the PNJ, shot noise measurement provides information on the mode mixing process. We show that, for short PNJs, F is consistent with the value expected for quasi-elastic mode mixing. As L is increased, F becomes smaller; this is due to energy loss towards external degrees of freedom. The energy relaxation length deduced from the L dependence of F is 16 μm. We suggest that the mixing and subsequent partitioning of the modes without energy loss which are provided by a short PNJ (L << 16 μm) suggest that it can serve as a beam splitter. Since 16 μm is much larger than the typical size of mesoscopic devices, our results encourage using graphene for electron quantum optics experiment.

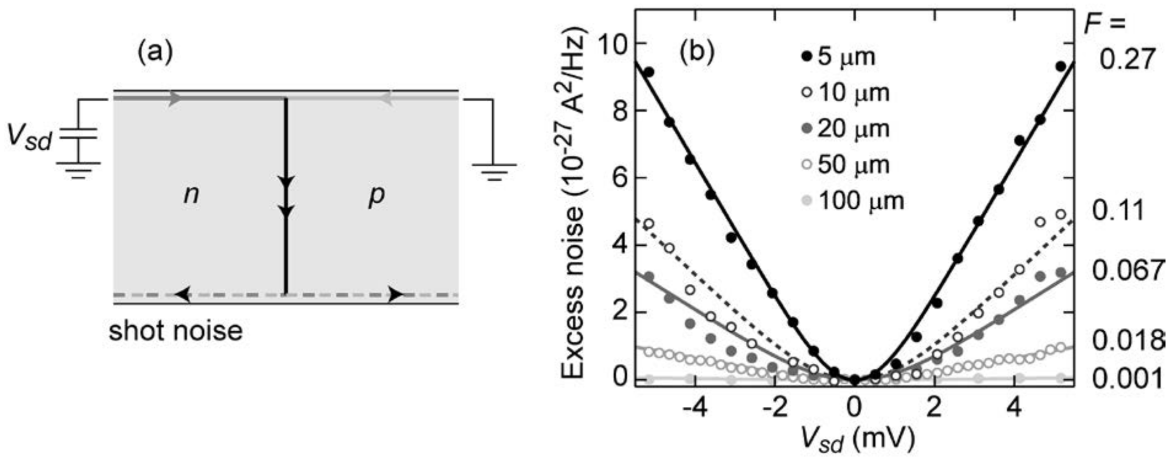

Figure 1: (a) Mode mixing and partitioning in a graphene *p-n* junction in quantum Hall effect regime. (b) Shot noise as a function of V_{sd} for five samples with different length of the *p-n* junction. The filling factors in the *p* and *n* regions are ν = -2 and 2, respectively. The magnetic field is 10 T and the temperature is 4 K.

S12-4

Josephson like effect and Cooper pair transfer in multi-terminal superconducting devices

Thierry Martin

Aix Marseille Université, Université de Toulon, CNRS, CPT, UMR 7332, 13288 Marseille, France

I will summarize the ongoing efforts of my team and my collaborators on the transfer of multiple Cooper pairs between hybrid circuits containing more than two superconductors and where non local crossed Andreev reflection operates. This can be studied with biased superconductors, where strikingly a DC Josephson signal can be obtained when the voltage biases imposed on the superconductors are commensurate. The DC current which are generated depend then on the combination of phases of the superconductors, which is unusual in non-equilibrium superconductivity. This DC signal can be optimized by tuning the energy level of the dots which separate the superconducting leads. Furthermore, we exhibit novel multiple Andreev reflection processes which depend again of these phases. Alternatively, we can also study such multiple Cooper pair resonances in an equilibrium setting in a setup containing two coupled SQUIDS (the biSQUID): a magnetic field piercing the loops of this device can be used to study its current phase response, and careful Fourier analysis reveals the signal of multiple Cooper pair transfers which are identical to those observed off equilibrium. Further extensions of this work using the circuit theory of superconductivity might be discussed.

S12-5

Fractional charge tunneling through a local fractional quantum Hall system measured using cross-correlation noise measurements

Masayuki Hashisaka

Department of Physics, Tokyo Institute of Technology, 2-12-1-H81, Ookayama, Meguro, Tokyo, Japan 152-8551

While an electron cannot divide into fractions, a fractional quasiparticle can be exited in fractional quantum Hall (FQH) systems. Fractional quasiparticles have been investigated by measuring shot noise, which reflects charge of tunneling quasiparticles [1,2]. Here, I demonstrate a shot-noise evidence of the creation of fractional quasiparticles in a local FQH system, which is sandwiched between integer quantum Hall (IQH) systems [3]. After a brief introduction of our cross-correlation noise measurements [4], I show that a fractional quasiparticle emerges from the IQH system, when a charge tunnels through the local FQH state.

Figure 1 shows a schematic of the device and the measurement setup. The measurements were performed at 80 mK in a high magnetic field (8.0 T) perpendicular to the two dimensional electron system. The local FQH state (filling factor ν_{QPC}) is formed at the quantum point contact (QPC), which is embedded in the $\nu_B = 1$ IQH system. A dc current I_1 injected from ohmic contact Ω_1 flows along the chiral quantum Hall edge channel, and is partitioned at the QPC. We evaluated the shot noise generated at the QPC by measuring the cross correlation $S_{35} = \langle \Delta I_3 \Delta I_5 \rangle$. The charge of tunneling quasiparticles is extracted from the shot-noise power. The obtained S_{35} is plotted in Fig. 2 as a function of the transmission probability T of the QPC. The data follows the theoretical curve of $S_{35} \propto -e^* \times T(1-T)$ calculated assuming the quasiparticle charge $e^* = e/3$ (dotted line), rather than that assuming $e^* = e$ (solid line), over the wide range of T. What is important to note is that T is the transmission probability between IQH systems through the local FQH system. This indicates that the fractional quasiparticles emerge from the IQH system to tunnel through the FQH system.

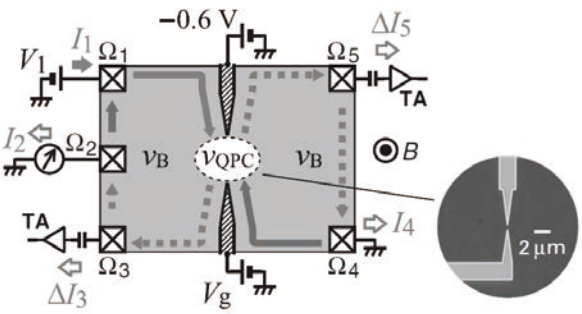

Figure 1: Schematic of a local FQH state (ν_{QPC}) sandwiched between bulk IQH systems (ν_B) and the measurement setup.

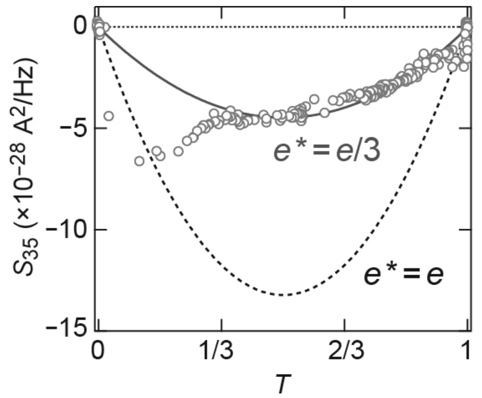

Figure 2: S_{35} measured as a function of T.

References
[1] R. de-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Mahalu, Nature **389**, 162 (1997).
[2] L. Saminadayar, D. C. Glattli, Y. Jin, and B. Etienne, Phys. Rev. Lett. **79**, 2526 (1997).
[3] M. Hashisaka, T. Ota, K. Muraki, and T. Fujisawa, Phys. Rev. Lett. **114**, 056802 (2015).
[4] M. Hashisaka, T. Ota, M. Yamagishi, K. Muraki, and T. Fujisawa, Rev. Sci. Instrum. **85**, 054704 (2014).

Fluctuation Theorem for a Small Engine and Magnetization Switching by Spin Torque

Yasuhiro Utsumi,[1] and Tomohiro Taniguchi,[2]

[1]Department of Physics Engineering, Faculty of Engineering, Mie University, Tsu, Mie, 514-8507, Japan
[2]National Institute of Advanced Industrial Science and Technology (AIST),
Spintronics Research Center, 1-1-1 Umezono, Tsukuba 305-8568, Japan

We consider a reversal of the magnetic moment of a nano-magnet by the fluctuating spin-torque induced by a non-equilibrium current of electron spins [Fig. 1 (a)]. This is an example of the problem of the escape of a particle from a metastable state subjected to a fluctuating non-conservative force. The spin-torque is the non-conservative force and its fluctuations are beyond the description of the fluctuation-dissipation theorem. We estimate the joint probability distribution of work done by the spin torque and the Joule heat generated by the current, which satisfies the fluctuation theorem for a small engine [Fig. 1 (b)]. We predict a threshold voltage above which the spin-torque shot noise induces probabilistic switching events and below which such events are blocked. We adopt the theory of the full-counting statistics under the adiabatic pumping of spin angular momentum. This enables us to account for the back-action effect, which is crucial to maintain consistency with the fluctuation theorem.

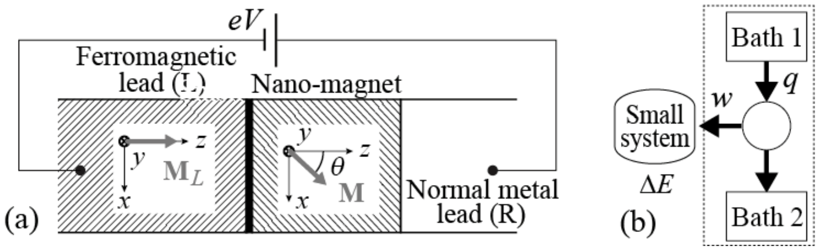

Figure 1: (a) A nano-magnet coupled to the left ferromagnetic lead and the right normal metal lead. The directions of magnetic moments of the ferromagnetic lead and the nano-magnet are $\mathbf{e}_z = (0,0,1)$ and $\mathbf{m} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$. (b) Schematic picture of a small engine. The input heat q and the output work w fluctuate.

References

[1] Yasuhiro Utsumi, Tomohiro Taniguchi, arXiv:1408.6588, PRL in press.

S12-7

Spin-dependent thermoelectric effects and spin-triplet-supercurrent in mesoscopic superconductors

Wolfgang Belzig,[1] Peter Machon, [1] and Matthias Eschrig,[2]

[1]*Department of Physics, University of Konstanz,78457 Konstanz, Germany*
[2]*Department of Physics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom*

The usually negligibly small thermoelectric effects in superconducting heterostructures can be boosted dramatically due to the simultaneous effect of spin splitting and spin filtering. Building on an idea we published in [1], we propose realistic mesoscopic setups to observe thermoelectric effects in superconductor heterostructures with ferromagnetic interfaces or terminals. We focus on the Seebeck effect being a direct measure of the local thermoelectric response and find that a thermopower of the order of ~250 μV/K can be achieved in a transistor-like structure. A measurement of the thermopower can furthermore be used to determine quantitatively the spin-dependent interface parameters that induce the spin splitting. For applications in nanoscale cooling we discuss the figure of merit for which we find values exceeding 1.5 for temperatures ≲1K. In the talk I will explain the quasiclassical circuit theory behind the prediction, which takes into account the usually present diffusive scattering at interfaces and surfaces. A crucial ingredient are spin-dependent boundary conditions for the diffusive Greens functions, which need to take into account the microscopic details of the spin-dependent interface scattering and are a long-standing problem for the quasiclassical theory. The relevance for possible spin-triplet supercurrents are discussed.

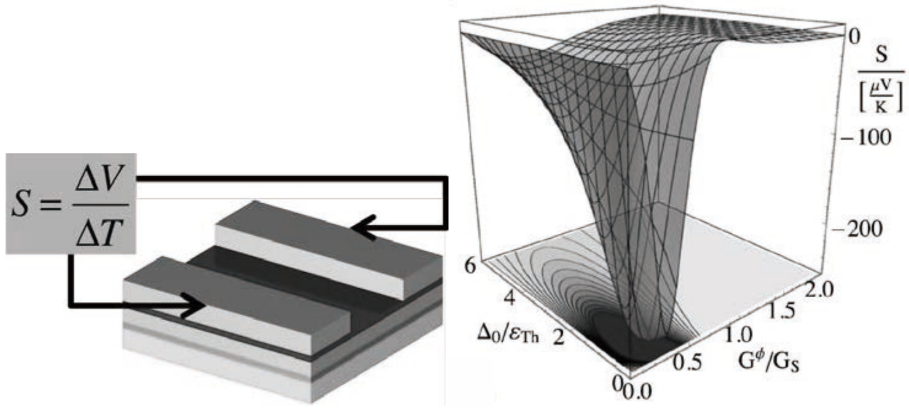

Figure 1: The left panel shows a setup to observe the predicted thermoelectric effect. The structure consists of a superconducting substrate (green), coupled to normal metal film (yellow) covered by ferromagnetic insulating film (blue). Current is injected and extracted by two normal contacts on top. By applying a temperature difference ΔT a thermovoltage ΔV can be measured (at zero current). The resulting Seebeck coefficient $S = \Delta V/\Delta T$ is plotted on the right. [2]

References

[1] P. Machon, M. Eschrig, and W. Belzig, Phys. Rev. Lett. **110**, 047002 (2013).
[2] P. Machon, M. Eschrig, and W. Belzig, New J Phys **16**, 073002 (2014).

S12-8

Waiting for rare entropic fluctuations in mesoscopic physics

Keiji Saito[1]

[1]Department of Physics, Keio University, Yokohama 223-8522, Japan

Non-equilibrium fluctuations of various stochastic variables, such as work and entropy production, have bee widely discussed recently in the context of large deviations, cumulants and fluctuation relations. Typically, one looks at the distribution of these observables, at large fixed time. To characterize the precise stochastic nature of the process, we here address the distribution in the time domain. In particular, we focus on the first passage time distribution (FPTD) of entropy production, in several realistic models. We find that the fluctuation relation symmetry plays a crucial role in getting the typical asymptotic behavior. Similarities and differences to the simple random walk picture are discussed. For a driven particle in the ring geometry, the mean residence time is connected to the particle current and the steady state distribution, and it leads to a fluctuation relation-like symmetry in terms of the FPTD

References

[1] Keiji Saito and Abhishek Dhar, arXiv:1504.02187

S12-9

Coupled Charge and Magnetization in a Weyl Semimetal

Kentaro Nomura[1]

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

We theoretically investigate ferromagnetic ordering in magnetically doped solid-solution narrow-gap semiconductors with the strong spin-orbit interaction such as Cr-doped $Bi_2(Se_xTe_{1-x})_3$. We compute the spontaneous magnetization of impurities and itinerant electrons, and estimate the critical temperature as a function of the concentration of magnetic dopants and the strength of the spin-orbit interaction. It is found that the critical temperature is proportional to the concentration of dopants and enhanced with the strong spin-orbit interaction. When the original band gap is suppressed, the ferromagnetic transition could make the system turn to the Weyl semimetal which possesses a pair of Weyl points separating in momentum space. We discuss coupled spin and charge dynamical effect realized in this type of material. We propose a magnetically induced current with temporal varying chiral vector potential. Applying field theoretical methods we derive the expression of the current induced by the dynamics of magnetic collective excitations. Furthermore, we also conduct the numerical calculation for the lattice model, and obtain the results which agree with the analytical result. This work was done in collaboration with Daich Kurebayashi.

Imaging the wave functions of Dirac–Landau levels in the topological surface state

Tetsuo Hanaguri,[1] Ying-Shuang Fu,[1,2] Minoru Kawamura,[1] Kyushiro Igarashi,[3] Hidenori Takagi,[4,5] and Takao Sasagawa,[3]

[1]*RIKEN Center for Emergent Matter Science, 2-1 Hirosawa, Wako, Saitama, Japan, 361-0198*
[2]*School of Physics, Huazhong University of Science & Technology, 1037 Luoyu Road, Wuhan 430074, China*
[3]*Materials and Structures Laboratory, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan*
[4]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[5]*Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, 70569 Stuttgart, Germany*

Topological insulators are characterized by a metallic surface state where electrons behave as massless Dirac particles described by the two-component wave function. In topological insulators, these two components are associated with the spin degrees of freedom, thereby governing the magnetic properties. Thus, it is highly desirable for spintronics applications to elucidate where and how the two-component nature emerges.

We found that the two-component nature manifests itself in the internal structures of Landau orbits formed in a magnetic field [1]. Using spectroscopic-imaging scanning tunneling microscopy, we directly image the local density-of-states (LDOS) distributions associated with the Landau orbits in the topological surface state of Bi_2Se_3. In the presence of the potential variation, Landau orbits drift along the equipotential lines. The energy-dependent ring-like structures shown in Fig. 1 represent such drift states surrounding the potential minimum. The LDOS variation across the ring includes the information of the internal structure of the wave function. With increasing Landau-level index *n*, width of the ring increases and two concentric rings become evident. We found that the observed internal structures are qualitatively different from those of conventional massive electrons [2] but are well reproduced by the calculation based on a two-component model Dirac Hamiltonian. Our model further predicts non-trivial energy-dependent spin-magnetization textures around the potential minimum. This is originated from the interplay between the two components and may provide a clue to manipulate spins in the topological surface state.

References
[1] Ying-Shuang Fu, M. Kawamura, K. Igarashi, H. Takagi, T. Hanaguri, and T. Sasagawa, Nature Phys. **10**, 815 (2014).
[2] K. Hashimoto, T. Champel, S. Florens, C. Sohrmann, J. Wiebe, Y. Hirayama, R. A. Römer, R. Wiesendanger, and M. Morgenstern, Phys. Rev. Lett. **109**, 116805 (2012).

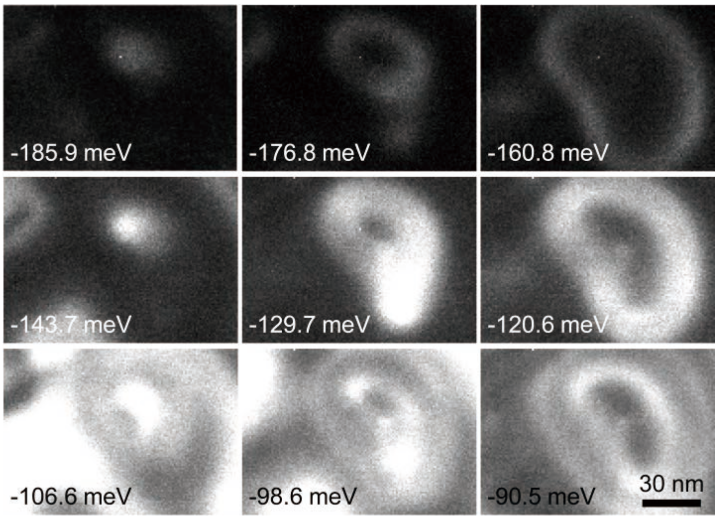

Figure 1: LDOS distributions in the topological surface state of Bi_2Se_3 at 11 T, showing the Landau orbits drifting around the potential minimum. Top, middle and bottom rows correspond to $n = 0$, 1 and 2 states, respectively [1].

Helical transport in helical crystals

Taiki Yoda[1], Takehito Yokoyama[1], and Shuichi Murakami[1,2]

[1]*Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
[2]*TIES, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*

Tellurium (Te) and selenium (Se) crystals consist of helices, and they are classified by their handedness. This unique crystal structure and its low crystalline symmetry gives rise to a radial spin texture, as is found by first-principle calculation [1].

Such a helical structure is reminiscent of a solenoid, and it may lead to new possibilities for electromagnetic transport. As is known, a current flowing along a solenoid induces a magnetic field along its axis, depending on its handedness. In this presentation, we pursue an analog of a "solenoid" in three-dimensional helical crystals. In a 3D metallic crystal with helical crystal structure, we expect that a current will induce a magnetization. We theoretically demonstrate it with a simple 3D tight-binding model with a helical crystal structure (Fig. 1). It turns out that an orbital magnetization is induced when a current flows along the helical axis (Fig.2(a)). Moreover, when the spin-orbit coupling is included, the spin polarization is also induced by a current (Fig. 2(c)). When the current is along the helical axis, the induced magnetization is also along the helical axis, with its sign dependent on the handedness of the crystal. This current-induced spin polarization comes from the radial spin texture (Fig. 2(b)), which is different from the tangential spin texture in typical Rashba spin-orbit coupling.

This chiral transport is nontrivial, because the lattice structure itself is a three-dimensional network, and the current flows in the whole crystal, unlike a solenoid. These results can be generalized to any helical crystals.

References

[1] M. Hirayama, R. Okugawa, S. Ishibashi, S. Murakami and T. Miyake, arXiv: 1409.7517, to appear in Phys. Rev. Lett.
[2] T. Yoda, T. Yokoyama, S. Murakami, preprint (2015).

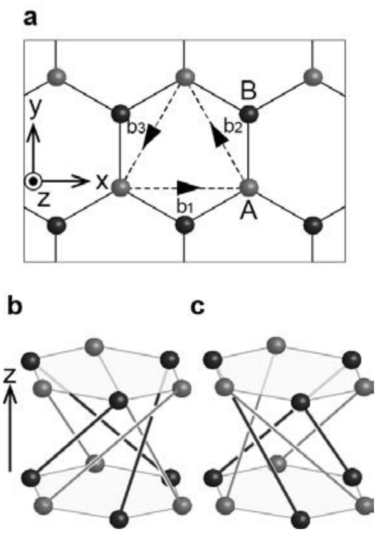

Figure 1: Helical lattice structure for the model. **a:** Structure within *xy* plane. Right-handed (**b**) and left-handed (**c**) helical structure.

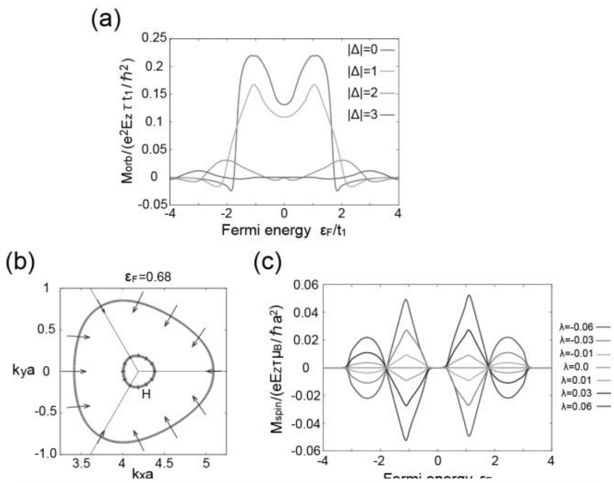

Figure 2: Numerical results for the helical model. (a) Current-induced orbital magnetization, (b) spin texture, and (c) current-induced spin magnetization.

S12-12

Conversion from a charge current into a spin polarized current in the surface state of three-dimensional topological insulator

Yuichiro Ando[1], Satoshi Sasaki[2], Kouji Segawa[2], Yoichi Ando[2], and Masashi Shiraishi[1]

[1] *Department of Electronic Science and Engineering, Kyoto University, Kyoto, Japan, 615-8510*
[2] *Institute of Scientific and Industrial Research, Osaka University, Ibaraki, Osaka, Japan, 567-0047*

Conversion from a charge current into a spin current and vice versa i.e., charge-spin conversion attracts tremendous amount of attention. A charge current through a ferromagnetic material/nonmagnetic material interfaces is one of the fundamental ways to realize the charge-spin conversion [1,2]. Surface state of the three-dimensional (3D) topological insulators (TIs), which is classified in terms of Z_2 topological invariant, has been expected to represent a novel charge-spin conversion.[3] The topological surface state presents a single Dirac cone with a helical spin polarization. Therefore it is expected that spin quantization axis of the conduction electron in the TI surface state is perpendicularly locked to the carrier momentum i.e., spin-momentum locking [3-5]. Due to the spin-momentum locking, it is expected that charge current naturally induces spin polarized current, whose axis and the sign can be controlled by the direction of the charge flow and the Fermi level. Therefore, magnetoresistance at an interface between ferromagnetic metal and TI, caused by a spin polarized current in TI surface state has been expected.[7]

In this presentation, we report conversion from a charge current into spin polarized current due to the spin-momentum locking of a bulk-insulating TI, $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ (BSTS) surface, BSTS. The surface-dominated transport has been demonstrated in this compound,[8] and the angle-resolved photoemisison spectroscopy study has confirmed its Fermi level to be located in a bulk band gap,[9] realizing the intrinsic insulating state. In the magnetoresistance measurement of a ferromagnetic $Ni_{80}Fe_{20}$(Py) film/BSTS structures, we observed a rectangular hysteresis behavior which is governed by the resistance at the interface between BSTS and the Py electrode. The interface resistance changed both with the magnetization direction of the Py electrode and with the current direction as shown in Fig. 1. [9]

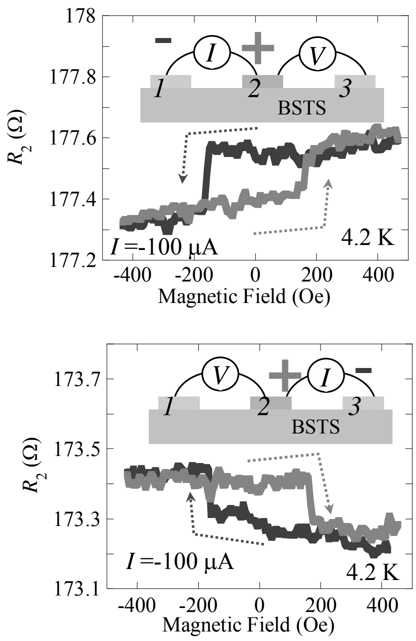

Fig. 1 Results of magnetoresistance measurement in Py/BSTS devices measured at 4.2 K .

References

[1] M. Johnson and R. H. Silsbee, PRL **55**, 1790(1985).
[2] F. J. Jedema *et. al.*, Nature **410**, 345(2001).
[3]Y, Ando, J. Phys. Soc. Jpn. **82**, 102001(2013).
[4] C. H. Li, *et al.*, Nature Nanotech. **9**, 5 (2014).
[5] Y. Shiomi *et al.*, PRL **113**, 196601(2014).
[6] A. A. Burkov and D. G. Hawthorn, PRL **105**, 066802 (2010).
[7] A. A. Taskin, *et al.*, PRL **107**, 016801 (2011).
[8] T. Arakane et al., Nat. Comm. **3**, 636(2012).
[9] Y. Ando *et al.*, Nano Lett. **14**, 6226(2014).