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CEMS

Center for Emergent Matter Science

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CEMS

RIKEN

Building a sustainable society that can co-exist in harmony with the environment

Message From the Director

RIKEN Center for Emergent Matter Science (CEMS) was established in 2013 as a research center which bound the basics of physics, chemistry, and electronics, where top leaders and young researchers collaborate with each other. Here, 'emergence' means that an aggregate system composed of many elements may exhibit qualitatively different behaviors beyond just the sum of each element's behaviors.

We aim to design novel material functions and to realize them by producing materials and devices as their stage. The basic research fields of CEMS are 'strong correlation physics', 'supramolecular chemistry', and 'quantum information electronics'. Researchers in each field aim to create new knowledge based on their own interests, which are combined to contribute to the sustainability of the earth's environment and the future development of the human beings.

CEMS has been dealing with developing energy functions of electrons in condensed matters which open the door to 'the third energy revolution'. The industry revolution in the late 18th century replaced manual and animal labor with machines powered by energy from coal. In 19th century, humans began harnessing electrical energy, a discovery that was rooted in the newly understood principles of electromagnetism. Most of the electrical energy today is still obtained from coal, oil, natural gas, nuclear power, water flow and wind through electromagnetic induction. However, the realization of carbon neutral requires the direct transformation from light, heat, etc. to the electrical energy. CEMS keeps trying to construct new electromagnetism based on the emergence in condensed matters, looking back the fact that the electrical energy originates from electrons in materials.

We must also be conscious about the fact that the rapid information revolution today is accelerating the global boiling. Energy consumption in acquisition, storage, calculation, and communication of information is steeply growing. The storage and conversion of information are essentially equivalent to those of energy in condensed matters. The emergent electromagnetism should contribute to the realization of information society with suppressed energy consumption.

CEMS keeps exploring innovative principles and new materials that cannot be approached by any extension of conventional technology but only by basic material science.

Taka-hisa Arima
Director, RIKEN Center for Emergent Matter Science

RIKEN Center for Emergent Matter Science

The Center for Emergent Matter Science (CEMS) brings together leading scientists in three areas—physics, chemistry, and electronics—to elaborate the principles of emergent phenomena and to open the path to potential applications.

CEMS carries out research in three areas: strongly-correlated materials, supramolecular functional chemistry, and quantum information electronics. It incorporates about 200 researchers from around the world, organized into about 40 research groups and teams.

There are other leading centers around the world working in each of the three areas covered by CEMS, but nowhere in the world is there a center that brings the three together in one place. In order to create a sustainable society that can co-exist with the natural environment, cooperation between the fields of physics, chemistry, and electronics is critical.

Bringing these three areas together allows “emergent phenomena” to take place within the center' s research as well, making possible breakthroughs in research that could not be predicted from the outset.

The goal of CEMS is not to develop technologies that can be immediately put into application. It is not to push existing technologies forward, but rather to pursue radical new technological principles that will contribute to human society in five decades or even a century in the future. To do this, it focuses on basic research and the development of new theories.

Researchers who have pioneered these three fields have been brought together along with young scientists who are not held back by existing theories, to work as a team to take on this truly challenging research. This is the real work of CEMS.

Introduction to EMS

“Emergence” refers to the phenomenon in which a number of elements that are brought together gain properties that could not be predicted from the individual elements. For example, when a large number of electrons become strongly correlated, they can give rise to extremely strong electrical and magnetic action that could not be predicted from the actions of a single electron.

Additionally, by linking together a large number of molecules, it is possible to create materials with new functionalities that were not possessed by the individual molecules. In this way, when particles such as electrons or molecules gather together, they can give rise to surprising materials and functions that could not be predicted simply as an aggregation of the original constituent elements.

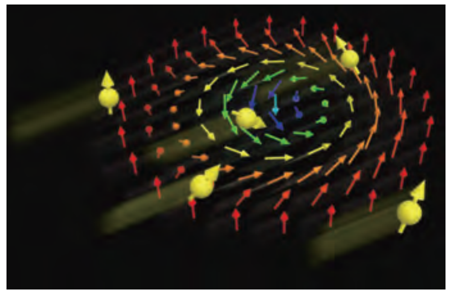
The science that attempts to elucidate the principles of emergent phenomena and create new materials and functions based on these principles is known as emergent matter science. For example, the phenomenon of superconductivity, where metals and other compounds suddenly lose all their electrical resistance when cooled to a certain degree, is a phenomenon that arises from the mutual interactions between electrons. Normally, superconductivity appears at very low temperatures, but if we are able to design and develop materials that are high-temperature superconductors, it will become possible to transmit electricity without any loss.

In that way, emergent matter science has the potential to trigger a major revolution in our lifestyles, and contribute to the achievement of a sustainable society that can co-exist in harmony with the environment.

Strong Correlation Physics Research Group

Topological spin textures and emergent electromagnetic functions

Nanometric spin texture called "skyrmion". The skyrmion is the idea coined by Tony Skyrme, a nuclear physicist, to describe a state of nucleon as the topological soliton. It has recently been demonstrated that such a kind of topological particle should exist widely in ubiquitous magnetic solids. The arrows in the figure represent the directions of the spin (electron's magnetic moment); the spins direct up at the peripheral, swirl in going to the inside, and direct down at the core. This topology cannot be reached via continuous deformation from the conventional spin orders, meaning that the skyrmion can be viewed by a topologically protected particle. The skyrmion can carry a fictitious (emergent) magnetic field working on moving conduction electrons (represented by yellow balls), and hence causes the topological Hall effect (transverse drift of the current). Furthermore, the electric current itself can drive the skyrmion. The critical current density for the drive of skyrmions is around 100 A/cm^2, by five orders of magnitude smaller than the conventional value for the drive of magnetic domain walls. These features may favor the application of skyrmions to innovative spintronics, i.e. toward "skyrmionics".



Skyrmion and conduction electron motion

Publications

1. K. Ueda, T. Yu, M. Hirayama, R. Kurokawa, T. Nakajima, H. Saito, M. Kriener, M. Hoshino, D. Hashizume, T.-h. Arima, R. Arita, and Y. Tokura, "Colossal negative magnetoresistance in field-induced Weyl semimetal of magnetic half-Heusler compound", *Nat. Commun.* 14, 6339 (2023).
2. T. Hori, N. Kanazawa, M. Hirayama, K. Fujiwara, A. Tsukazaki, M. Ichikawa, M. Kawasaki, and Y. Tokura, "A Noble-Metal-Free Spintronic System with Proximity-Enhanced Ferromagnetic Topological Surface State of FeSi above Room Temperature", *Adv. Mater.* 35, 2206801 (2022).
3. A. Kitaori, N. Kanazawa, T. Yokouchi, F. Kagawa, N. Nagaosa, and Y. Tokura, "Emergent electromagnetic induction beyond room temperature", *Proc. Natl. Acad. Sci. U.S.A.* 118, e2105422118 (2021).
4. T. Yokouchi, F. Kagawa, M. Hirschberger, Y. Otani, N. Nagaosa, and Y. Tokura, "Emergent electromagnetic induction in a helical-spin magnet", *Nature*, 586, 232 (2020).
5. T. Kurumaji, T. Nakajima, M. Hirschberger, A. Kikkawa, Y. Yamasaki, H. Sagayama, H. Nakao, Y. Taguchi, T. Arima, Y. Tokura, "Skyrmion lattice with a giant topological Hall effect in a frustrated triangular-lattice magnet", *Science*, 365, 914 (2019).

Yoshinori Tokura (D.Eng.), Group Director
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Research field

Physics, Engineering, Materials Science

Keywords

Strongly correlated electron system, Topological insulators, Spin-orbit interaction, Berry phase physics, Multiferroics, Skyrmion

Brief resume

- 1981 D. Eng., University of Tokyo
- 1986 Associate Professor, University of Tokyo
- 1994 Professor, Department of Physics, University of Tokyo
- 1995 Professor, Department of Applied Physics, University of Tokyo
- 2001 Director, Correlated Electron Research Center, AIST
- 2007 Group Director, Cross-Correlated Materials Research Group, RIKEN
- 2008 AIST Fellow, National Institute of Advanced Industrial Science and Technology (-present)
- 2010 Director, Emergent Materials Department, RIKEN
- 2010 Group Director, Correlated Electron Research Group, RIKEN
- 2013 Director, RIKEN Center for Emergent Matter Science (CEMS)
- 2013 Group Director, Strong Correlation Physics Research Group, Strong Correlation Physics Division, RIKEN CEMS (-present)
- 2014 Team Leader, Strong Correlation Quantum Transport Research Team, RIKEN CEMS (-present)
- 2017 Distinguished University Professor, University of Tokyo (-present)
- 2019 Special University Professor, University of Tokyo
- 2024 Special Advisor to the President, RIKEN (-present)

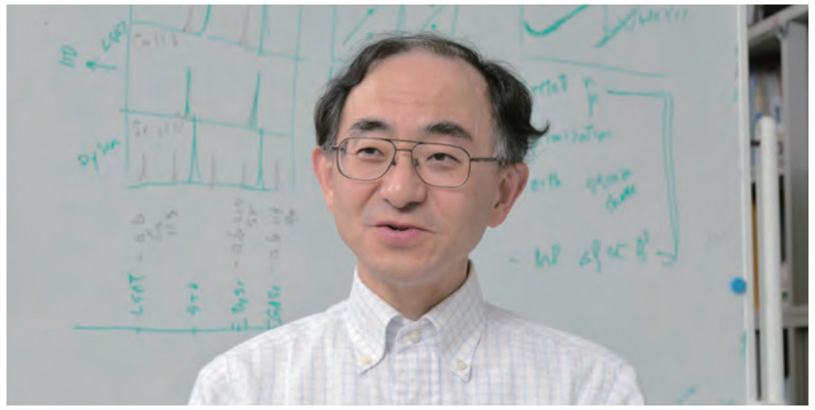
Outline

Our group investigates a variety of emergent phenomena in strongly correlated electron systems, which cannot be understood within the framework of conventional semiconductor/metal physics, to construct a new scheme of science and technology. In particular, we focus on transport, dielectric and optical properties in non-trivial spin/orbital structures, aiming at clarifying the correlation between the response and the spin/orbital state. In addition, we investigate electron systems with strong relativistic spin-orbit interaction, unraveling its impact on transport phenomena and other electronic properties. Target materials include high-temperature superconductors, colossal magnetoresistance systems, multiferroics, topological insulators, and skyrmion materials.

Core members

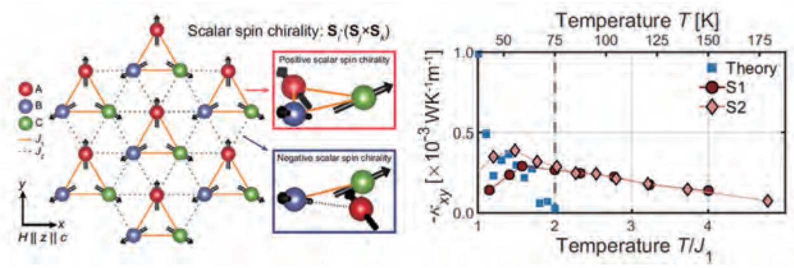
(Senior Research Scientist) Masamichi Nakajima
(Special Postdoctoral Researcher) Hinako Murayama
(Senior Technical Scientist) Chieko Terakura

Strong Correlation Theory Research Group



Thermal Hall effects due to topological spin fluctuations in $YMnO_3$

The thermal Hall effect in magnetic insulators has been considered a powerful tool to study the topological nature of charge-neutral quasiparticles such as phonons and magnons. Yet, unlike the kagome system, the triangular lattice has received less attention for studying the thermal Hall effect because the scalar spin chirality cancels out between adjacent triangles. However, such cancellation is violated when the triangular lattice is distorted, i.e., trimerized triangular lattice. We report that the trimerized triangular lattice of multiferroic hexagonal manganite $YMnO_3$ produces a highly unusual thermal Hall effect under an applied magnetic field. Our theoretical calculations demonstrate that the thermal Hall conductivity is related to the splitting of the otherwise degenerate two fluctuating chiralities of its 120° magnetic structure. Our result is one of the most unusual cases of topological physics due to this broken Z_2 symmetry of the chirality in the supposedly paramagnetic state of $YMnO_3$, due to strong topological spin fluctuations with the Dzyaloshinskii-Moriya interaction.



(Left) Crystal structure and spin structure of magnetic ferroelectrics $YMnO_3$. (Right) Comparison of the calculation results of the thermal Hall effect by numerical simulation for the spin Hamiltonian and the experimental results. Theories are shown in blue, and experiments are shown in red and persimmon. Ha-Leem Kim et al., "Thermal Hall effects due to topological spin fluctuations in $YMnO_3$", Nature Communications 15, 243 (2024). https://doi.org/10.1038/s41467-023-44448-9

Publications

1. Ha-Leem Kim, Takuma Saito, Heejun Yang, Hiroaki Ishizuka, Matthew John Coak, Jun Han Lee, Hasung Sim, Yoon Seok Oh, Naoto Nagaosa, Je-Geun Park, "Thermal Hall effects due to topological spin fluctuations in YMnO3", *Nat. Commun.*, 15, 243 (2024).
2. J. Ahn, G.Y. Guo, N.Nagaosa, A. Vishwanath, "Riemannian geometry of resonant optical responses", *Nat. Phys.* 18, 290 (2022).
3. N. Nagaosa, "Emergent inductor by spiral magnets", *JJAP* 58, 12909 (2019).
4. R. Wakatsuki, Y. Saito, S. Hoshino, Y. M. Itahashi, T. Ideue, M. Ezawa, Y. Iwasa, and N. Nagaosa, "Nonreciprocal charge transport in noncentrosymmetric superconductors", *Sci. Adv.*, 3, e1602390 (2017).
5. T. Morimoto, and N. Nagaosa, "Topological nature of nonlinear optical effects in solids", *Sci. Adv.*, 2, e1501524 (2016).

Naoto Nagaosa (D.Sci.), Group Director
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Research field

Physics, Engineering, Materials Sciences

Keywords

Emergent electromagnetism, Magnetoelectric effect, Shift current, Non-reciprocal effect, Spin Hall effect, Interface electrons, Superconductivity

Brief resume

- 1983 Research Associate, University of Tokyo
- 1986 D.Sci., University of Tokyo
- 1998 Professor, University of Tokyo (-present)
- 2001 Team Leader, Theory Team, Correlated Electron Research Center, National Institute of Advanced Industrial Science and Technology
- 2007 Team Leader, Theoretical Design Team, RIKEN
- 2010 Team Leader, Strong-Correlation Theory Research Team, RIKEN
- 2013 Deputy Director, RIKEN Center for Emergent Matter Science (CEMS)
- 2013 Group Director, Strong Correlation Theory Research Group, Division Director, Strong Correlation Physics Division, RIKEN CEMS (-present)
- 2024 Director, Fundamental Quantum Science Program (-present)

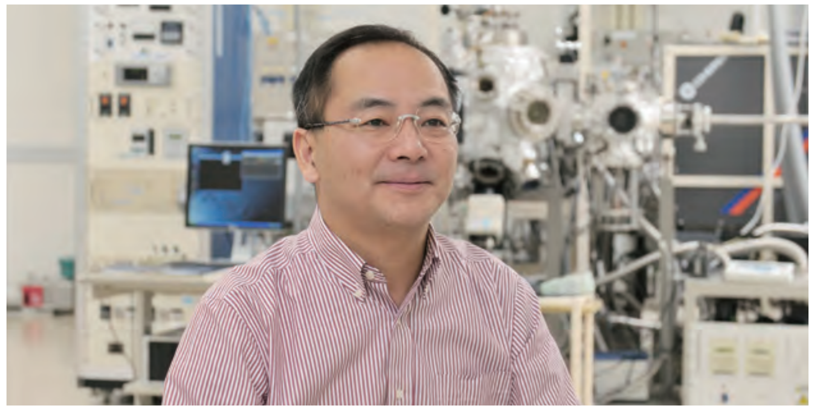
Outline

We study theoretically the electronic states in solids from the viewpoint of topology and explore new functions with non-dissipative currents. Combining first-principles calculations, quantum field theory, and numerical analysis, we predict and design magnetic, optical, transport and thermal properties of correlated electrons focusing on their internal degrees of freedom such as spin and orbital. In particular, we study extensively the nontrivial interplay between these various properties, i.e., cross-correlation, and develop new concepts such as electron fractionalization and non-dissipative quantum operation by considering the topology given by the relativistic spin-orbit interaction and/or spin textures.

Core members

(Senior Research Scientist) Wataru Koshibae
(Research Scientist) Hiroki Isobe
(Postdoctoral Researcher) Taekoo Oh
(Special Postdoctoral Researcher) Yingming Xie

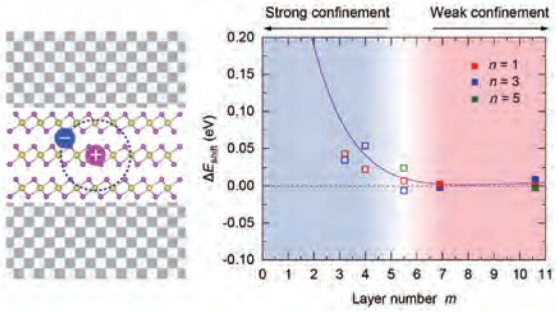
Strong Correlation Interface Research Group



Detection of exciton confinement crossover in two-dimensional quantum wells of a layered semiconductor

An exciton, a bound state of an electron and a hole, confined in a low-dimensional system exhibits a distinct state from that in three-dimensional bulk materials. Especially in two-dimensional quantum wells, it is known that two types of confinement effects appear depending on the well layer width: an increase in exciton binding energy (strong confinement) and quantization of exciton center-of-mass motion (weak confinement). However, the transition between these two has not been systematically investigated.

In this study, we have employed a molecular beam epitaxy (MBE) to fabricate samples with systematically varied well widths at the atomic layer level for lead iodide (PbI_2), a typical two-dimensional semiconductor that exhibits a large excitonic response. The optical absorption spectra of the obtained high-quality quantum-well structures show sharp exciton absorption near the band edge and vibrational structure due to the quantization of exciton center-of-mass motion. The quantization energy is well explained by the tight-binding model when the well width is thick, but when the well width is less than 5 atomic layers, there is a marked shift to the high energy side, indicating a strong confinement effect. This is the first clear detection of the crossover between strong and weak exciton confinement regimes.



Transition in exciton confinement state observed in quantum-well structures of a layered semiconductor PbI_2

Publications

1. M. Ohno, T. C. Fujita, and M. Kawasaki "Proximity effect of emergent field from spin ice in an oxide heterostructure", *Sci. Adv.* 10, eadk6308 (2024).
2. K. S. Takahashi, J. Iguchi, Y. Tokura, and M. Kawasaki "Metal-insulator transitions in strained single quantum wells of $Sr_{1-x}La_xVO_3$", *Phys. Rev. B* 109, 035158 (2024).
3. D. Maryenko, I. V. Maznichenko, S. Ostanin, M. Kawamura, K. S. Takahashi, M. Nakamura, V. K. Dugaev, E. Ya. Sherman, A. Ernst, and M. Kawasaki "Superconductivity at epitaxial $LaTiO_3$-$KTaO_3$ interfaces", *APL Mater.* 11, 061102 (2023).
4. M. Nakamura, R. Namba, T. Yasunami, N. Ogawa, Y. Tokura, and M. Kawasaki "Crossover from strong to weak exciton confinement in thickness-controlled epitaxial PbI_2 thin films", *Appl. Phys. Lett.* 122, 073101 (2023).
5. N. Takahara, K. S. Takahashi, Y. Tokura, and M. Kawasaki "Evolution of ferromagnetism and electron correlation in $Eu_{1-x}Gd_xTiO_3$ thin films with 4f7 configuration", *Phys. Rev B* 108, 125138 (2023).

Masashi Kawasaki (D.Eng.), Group Director
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Research field

Physics, Engineering, Chemistry, Materials Sciences

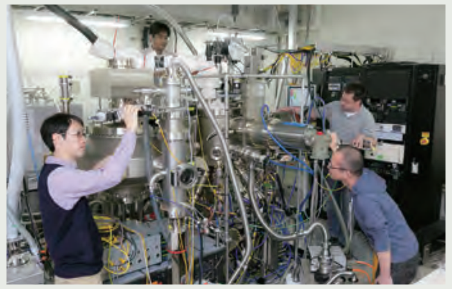
Keywords

Topological electronics, Thin films and interfaces, Topological materials, Unconventional photovoltaic effect, Unconventional Hall effect

Brief resume

1989 D.Eng., University of Tokyo
1989 Postdoctoral Fellow, Japan Society for the Promotion of Science
1989 Postdoctoral Fellow, T. J. Watson Research Center, IBM, USA
1991 Research Associate, Tokyo Institute of Technology
1997 Associate Professor, Tokyo Institute of Technology
2001 Professor, Tohoku University
2007 Team Leader, Functional Superstructure Team, RIKEN
2010 Team Leader, Strong-Correlation Interfacial Device Research Team, RIKEN
2011 Professor, University of Tokyo
2013 Deputy Director, RIKEN Center for Emergent Matter Science (CEMS)
2013 Group Director, Strong Correlation Interface Research Group, Strong Correlation Physics Division, RIKEN CEMS (-present)
2023 Research Strategy Advisor, RIKEN (-present)

Outline



Thin films and interfaces of topological materials are the playground of our research. Chiral spin textures in real space and magnetic monopoles in momentum space are the sources of non-trivial Hall effect. Photo-excited polar crystals generate unconventional photocurrent. Not classical mechanics but quantum mechanics is needed to understand those examples. We will design and demonstrate possible devices that utilize expectedly dissipationless electron flow exemplified as above. The device physics study will open a new avenue towards topological electronics that manage flow of information and energy carried by such topological current.

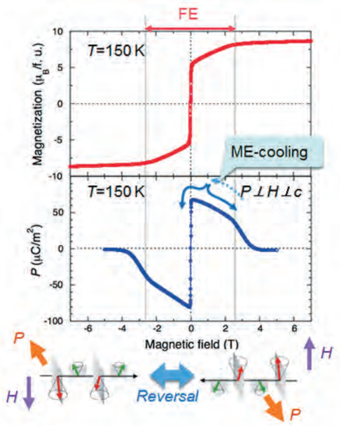
Core members

(Senior Research Scientist) Kei Takahashi, Masao Nakamura, Denis Maryenko
(Junior Research Associate) Noriyuki Takahara

Strong Correlation Quantum Structure Research Group

Spin-driven ferroelectricity and electromagnon in multiferroic Y-type hexaferrite compounds

Y-type hexaferrite compounds are composed of an alternate stacking of spinel block layers and hexagonal perovskite block layers. The magnetic anisotropy of each layer and effective exchange interaction are dependent on the composition. As a consequence, various magnetic orders appears in the temperature-magnetic field plane. It is predicted that two kinds of magnetic orders, transverse cone and double fan, can host electric polarization via the inverse Dzyalloshinsky-Moriya interaction. We performed measurements of magnetization, electric polarization, and spin-polarized neutron scattering in $BaSrCo_2Fe_{11}AlO_{22}$. It has been found that the alternate longitudinal cone first appears by cooling from a high temperature at zero magnetic field. If a magnetic field is once applied perpendicular to the c-axis at low temperatures, the double fan replaces and survives even after the magnetic field is turned off. The electric polarization is also induced along the axis perpendicular both to the c-axis and to the magnetic field. The electric polarization is reversed by switching the magnetic field direction. Inelastic spin-polarized neutron scattering has predicted that both the double fan and alternative longitudinal cone may host an electromagnon (magnon excited by THz electric field).



Magnetic-field induced reversal of electric polarization and possible change in magnetic structure in a Y-type hexaferrite $BaSrCo_2Fe_{11}AlO_{22}$.

Publications

1. M. Gen, H. Ishikawa, A. Miyake, T. Yajima, H. O. Jeschke, H. Sagayama, A. Ikeda, Y. H. Matsuda, K. Kindo, M. Tokunaga, Y. Kohama, T. Kurumaji, Y. Tokunaga, T. Arima, "Breathing pyrochlore magnet $CuGaCr_4S_8$: Magnetic, thermodynamic, and dielectric properties", *Phys. Rev. Materials*, 7, 104404 (2023).
2. S. Kitou, M. Gen, Y. Nakamura, K. Sugimoto, Y. Tokunaga, S. Ishiwata, T. Arima, "Real-Space Observation of Ligand Hole State in Cubic Perovskite $SrFeO_3$", *Adv. Sci.*, 10, 2302839 (2023).
3. T. Nakajima, T. Oda, M. Hino, H. Endo, K. Ohishi, K. Kakurai, A. Kikkawa, Y. Taguchi, Y. Tokura, T. Arima, "Crystallization of magnetic skyrmions in MnSi investigated by neutron spin echo spectroscopy", *Phys. Rev. Research* 2, 043393 (2020).
4. V. Ukleev, Y. Yamasaki, O., Utesov, K. Shibata, N. Kanazawa, N. Jaouen, H. Nakao, Y. Tokura, T. Arima, "Metastable solitonic states in the strained itinerant helimagnet FeGe", *Phys. Rev. B* 102, 014416 (2020).
5. S. Gao, D. Hirai, H. Sagayama, H. Ohsumi, Z. Hiroi, T. Arima, "Antiferromagnetic long-range order in the 5d1 double-perovskite Sr_2MgReO_6", *Phys. Rev. B* 101, 220412R (2020).

Taka-hisa Arima (Ph.D.), Group Director
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Research field

Materials Science, Physics

Keywords

X-ray scattering, Neutron scattering, Electron diffraction, Structure science, Imaging

Brief resume

1988 TORAY Co. Ltd.
1991 Research Associate, Faculty of Science, University of Tokyo
1994 Ph.D. (Science), University of Tokyo
1995 Research Associate, Graduate School of Engineering, University of Tokyo
1995 Associate Professor, Institute of Materials Science, University of Tsukuba (2001-2006 Group Leader, ERATO Tokura Spin Super Structure Project)
2004 Professor, Institute of Multidisciplinary Research for Advanced Materials, Tohoku University
2011 Professor, Graduate School of Frontier Sciences, University of Tokyo (-present)
2007 Team Leader, Spin Order Research Team, RIKEN SPring-8 Center
2013 Team Leader, Strong Correlation Quantum Structure Research Team, RIKEN Center for Emergent Matter Science
2023 Deputy Director, RIKEN Center for Emergent Matter Science (CEMS)
2023 Group Director, Strong Correlation Quantum Structure Research Group, RIKEN Center for Emergent Matter Science (-present)
2024 Director, RIKEN Center for Emergent Matter Science (CEMS) (-present)

Outline

Strongly correlated electron systems may exhibit various interesting emergent phenomena such as superconductivity, colossal magneto-resistance, and giant magneto-electric effects. These emergent phenomena are directly associated with the spatial distributions as well as the spatial and temporal fluctuations of atoms, electron density, and spin density. To reveal these phenomena, we perform crystallographic and magnetic structure analyses, spectroscopies, and microscopies by using synchrotron x-rays, neutrons, and high-energy electron beams.

Core members

(Special Postdoctoral Researcher) Masaki Gen
(Postdoctoral Researcher) Kamini Gautam

Strong Correlation Materials Research Group

Yasujiro Taguchi (D.Eng.), Group Director
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Research field

Physics, Engineering, Materials Science

Keywords

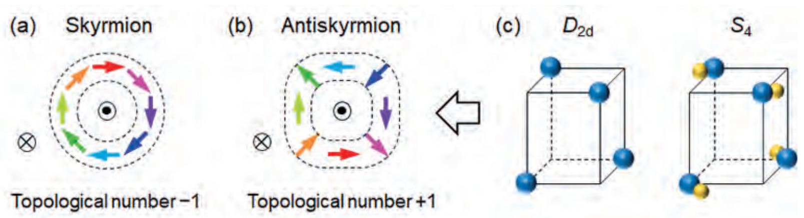
Strongly correlated electron system, Skyrmion, Multiferroics, Thermoelectric effect

Brief resume

1993 Researcher, SONY Corporation
1997 Research Associate, University of Tokyo
2002 D.Eng., University of Tokyo
2002 Associate Professor, Institute for Materials Research, Tohoku University
2007 Team Leader, Exploratory Materials Team, RIKEN
2010 Team Leader, Strong-Correlation Materials Research Team, RIKEN
2013 Team Leader, Strong Correlation Materials Research Team, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science
2018 Group Director, Strong Correlation Materials Research Group, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (-present)
2018 Director, Office of the Center Director, RIKEN Center for Emergent Matter Science
2024 Deputy Director, RIKEN Center for Emergent Matter Science (-present)

Discovery of new magnet hosting antiskyrmions at room temperature

Skyrmion is a nanometric magnetic vortex characterized by an integer topological number, which behaves as a stable particle, and anticipated to be applied to high-performance magnetic memory devices. Recently, a new magnetic vortex, antiskyrmion, with the opposite sign of the topological number has attracted much attention. However, antiskyrmions have thus far been observed only in Heusler compounds with D_{2d} symmetry. This limitation has prevented intensive studies of topological properties of antiskyrmions and their applications. Our group discovered a Pd-doped Schreibersite, $Fe_{1.9}Ni_{0.9}Pd_{0.2}P$, with S_4 symmetry to host antiskyrmions over a wide temperature range including room temperature. It was also found that antiskyrmions and skyrmions are interconverted to each other by changing magnetic fields or sample thickness. Furthermore, sawtooth-like novel magnetic domain patterns with S_4 symmetry were observed near the surface of thick crystals.



Schematics of (a) skyrmion, (b)antiskyrmion, and (c) symmetry of the crystal structures hosting antiskyrmions.

Publications

1. D. Nakamura, K. Karube, K. Matsuuara, F. Kagawa, X.Z. Yu, Y. Tokura, and Y. Taguchi, "Transport signatures of magnetic texture evolution in a microfabricated thin plate of antiskyrmion-hosting $(Fe,Ni,Pd)_3P$", *Phys. Rev. B*, 108, 104403 (2023).
2. K. Karube, L. C. Peng, J. Masell, M. Hemmida, H.-A. Krug von Nidda, I. Kézsmárki, X. Z. Yu, Y. Tokura, and Y. Taguchi, "Doping control of magnetic anisotropy for stable antiskyrmion formation in schreibersite $(Fe,Ni)_3P$ with S_4 symmetry", *Adv. Mater.,* 34, 2108770 (2022).
3. K. Karube, L. C. Peng, J. Masell, X. Z. Yu, F. Kagawa, Y. Tokura, and Y. Taguchi, "Room-temperature antiskyrmions and sawtooth surface textures in a non-centrosymmetric magnet with S_4 symmetry", *Nat. Mater.,* 20, 335 (2021).
4. M. Kriener, M. Sakano, M. Kamitani, M. S. Bahramy, R. Yukawa, K. Horiba, H. Kumigashira, K. Ishizaka, Y. Tokura, and Y. Taguchi, "Evolution of Electronic States and Emergence of Superconductivity in the Polar Semiconductor GeTe by Doping Valence-Skipping Indium", *Phys. Rev. Lett.*, 124, 047002 (2020).
5. V. Kocsis, T. Nakajima, M. Matsuda, A. Kikkawa, Y. Kaneko, J. Takashima, K. Kakurai, T. Arima, F. Kagawa, Y. Tokunaga, Y. Tokura, and Y. Taguchi, "Magnetization-polarization cross-control near room temperature in hexaferrite single crystals", *Nat. Commun.*, 10, 1247 (2019).

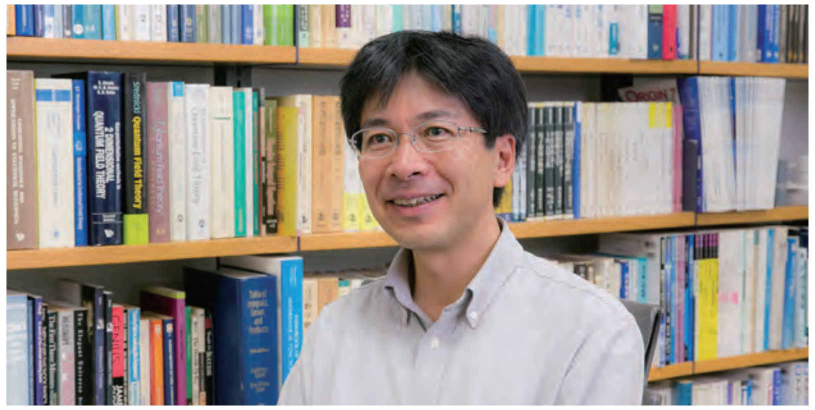
Outline

Our group aims at obtaining gigantic cross-correlation responses, understanding their mechanisms, and developing new functions in strongly-correlated-electron bulk materials, such as transition-metal oxides. To this end, we try to synthesize a wide range of materials using various methods, including high-pressure techniques, and investigate their physical properties. Specific targets are: (1) exploration of new skyrmion materials; (2) obtaining gigantic magnetoelectric responses in mutiferroic materials at high temperatures; (3) exploration of new magnetic materials; (4) exploration of new thermoelectric materials.

Core members

(Senior Research Scientist) Markus Kriener, Daisuke Nakamura
(Senior Technical Scientist) Akiko Kikkawa
(Postdoctral Researcher) Zhehong Liu
(Technical Staff I) Gurvan Bosser

Quantum Matter Theory Research Group



Akira Furusaki (D.Sci.), Group Director
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Research field

Physics, Materials Science

Keywords

Electron correlation, Frustrated quantum magnets, Topological insulators, Topological superconductivity

Brief resume

1991 Research Associate, Department of Applied Physics, University of Tokyo
1993 Ph.D., University of Tokyo
1993 Postdoctoral Associate, Massachusetts Institute of Technology, USA
1995 Research Associate, Department of Applied Physics, University of Tokyo
1996 Associate Professor, Yukawa Institute for Theoretical Physics, Kyoto University
2003 Chief Scientist, Condensed Matter Theory Laboratory, RIKEN (-present)
2013 Team Leader, Quantum Matter Theory Research Team, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science
2024 Group Director, Quantum Matter Theory Research Group, RIKEN Center for Emergent Matter Science (-present)
2024 Deputy Director,RIKEN Center for Emergent Matter Science (-present)

Classifying topological insulators and topological superconductors

Modern electronics is based on the band theory that describes quantum mechanical motion of electrons in a solid. The band theory can explain properties of metals, insulators and semiconductors, and led to the invention of transistors. However, recent studies revealed some important physics which was missed in the standard band theory. Namely, electron wave functions can have a nontrivial topological structure in momentum space, and this leads to a topological insulator. In addition, superconductors with gapped quasiparticle excitations can be a topological superconductor. In principle there are various types of topological insulators (TIs) and topological superconductors (TSCs) in nature.

We constructed a general theory that can classify TIs and TSCs in terms of generic symmetries. This theory shows that in every spatial dimension there are three types of TIs/TSCs with an integer topological index and two types of TIs/TSCs with a binary topological index. We extend our theory to understand the effect of crystalline symmetry and electron correlation.

A coffee mug and a donut are equivalent in topology because they can be continuously deformed from one to the other. The wave functions of electrons in insulators can be topologically lassified.

Publications

1. S. Kobayashi, S. Sumita, M. Hirayama, and A. Furusaki, "Crystal symmetry protected gapless vortex-line phases in superconducting Dirac semimetals", *Phys. Rev. B* 107, 214518 (2023).
2. K. Yoshimi, T. Misawa, T. Tsumuraya, and H. Seo, "Comprehensive ab initio investigation of the phase diagram of quasi-one-dimensional molecular solids", *Phys. Rev. Lett.*, 131, 036401 (2023).
3. Y. Yao, M. Oshikawa, and A. Furusaki, "Gappability index for quantum many-body systems", *Phys. Rev. Lett.*, 129, 017204 (2022).
4. M. Naka, Y. Motome, and H. Seo, "Anomalous Hall effect in antiferromagnetic perovskites", *Phys. Rev. B*, 106, 195149 (2022).
5. S. Kobayashi and A. Furusaki, "Fragile topological insulators protected by rotation symmetry without spin-orbit coupling", *Phys. Rev. B*, 104, 195114 (2021).

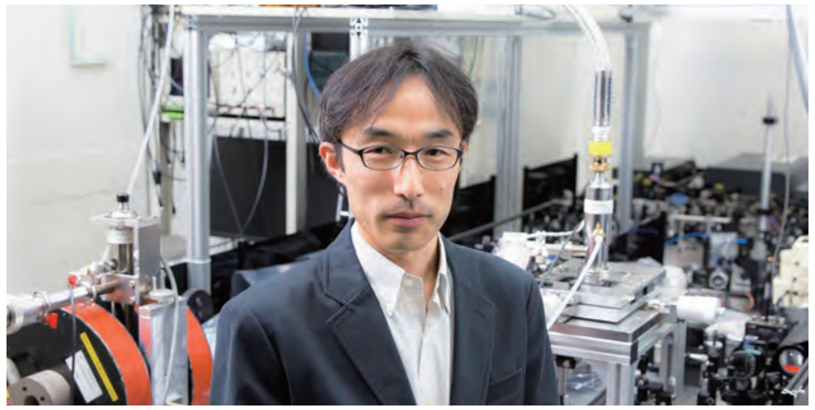
Outline

We investigate novel quantum phases of many-electron systems in solids which emerge as a result of strong electron correlation and quantum effects. We theoretically study electronic properties of these new phases (such as transport and magnetism) and critical phenomena at phase transitions. Specifically, we study topological insulators and superconductors, frustrated quantum magnets, and other strongly correlated electron systems in transition metal oxides and molecular conductors, etc. We construct effective models for electrons in these materials and unveil their various emergent phases by solving quantum statistical mechanics of these models using both analytical and numerical methods.

Core members

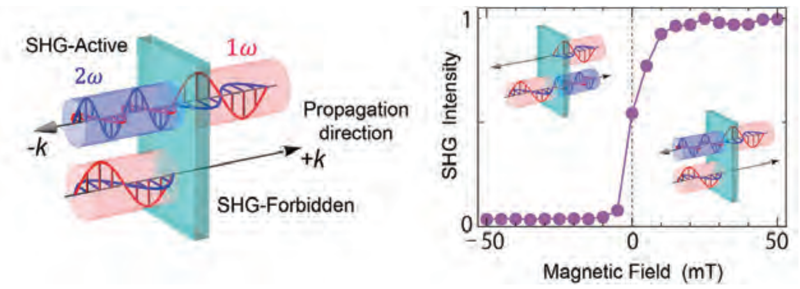
(Senior Research Scientist) Tsutomu Momoi, Shigeki Onoda, Hitoshi Seo
(Research Scientist) Shingo Kobayashi
(Special Postdoctoral Researcher) Shuhei Ohyama, Yutaro Tanaka
(Postdoctoral Researcher) Keisuke Kitayama
(Visiting Researcher) Moritz Hirschmann
(Junior Research Associate) Lingzhi Zhang

Emergent Photodynamics Research Group



Optical diode effect in second harmonic generation

In multiferroic materials where spatial-inversion and time-reversal symmetries are simultaneously broken, optical responses can change by reversing the direction of light propagation. This nonreciprocal effect has been realized in various linear optical responses, such as transmission, emission, scattering, and refraction. We investigate the nonreciprocal effects in nonlinear optical processes, specifically second harmonic generation (SHG) in CuB_2O_4. Generally, nonreciprocal effects are negligibly small, because their origin is an interference between magnetic and electric dipole transitions, where the former is intrinsically much smaller than the latter. We found that the magnetic dipole transition in CuB_2O_4 can be enhanced extremely due to optical resonance, leading to the magnitude comparable to that of the electric dipole one under the non-resonant condition. As a result, these two transitions interfere with each other in the same phase and amplitude, resulting in an almost perfect nonlinear nonreciprocal effect with 97% change in the SHG intensity. We also demonstrated that the light direction with the larger SHG intensity can be controlled by reversing a magnetic field of only 10 mT.



(Left) Schematic illustration of nonreciprocal SHG.
(Right) Magnetic field dependence of SHG intensity.

Publications

1. Z. Wang, X.-X. Zhang, Y. Shiomi, T. Arima, N. Nagaosa, Y. Tokura, and N. Ogawa, "Exciton-magnon splitting in van der Waals antiferromagnet $MnPS_3$ unveiled by second-harmonic generation", *Phys. Rev. Res.* 5, L042032 (2023).
2. S. Toyoda, J.-C. Liao, G.-Y. Guo, Y. Tokunaga, T. Arima, Y. Tokura, and N. Ogawa, "Magnetic-field switching of second harmonic generation in noncentrosymmetric magnet $Eu_2MnSi_2O_7$", *Phys. Rev. Mater.* 7, 024403 (2023)
3. S. Toyoda, M. Fiebig, L. Forster, T. Arima, Y. Tokura, and N. Ogawa, "Writing of strain-controlled multiferroic ribbons into $MnWO_4$", *Nature Commun.* 12, 6199 (2021).
4. S. Toyoda, M. Fiebig, T. Arima, Y. Tokura, and N. Ogawa, "Nonreciprocal second harmonic generation in a magnetoelectric material", *Sci. Adv.* 7, eabe2793 (2021).
5. M. Sotome, M. Nakamura, J. Fujioka, M. Ogino, Y. Kaneko, T. Morimoto, Y. Zhang, M. Kawasaki, N. Nagaosa, Y. Tokura, and N. Ogawa, "Spectral dynamics of shift-current in ferroelectric semiconductor SbSI", *Proc. Natl. Acad. Sci.*, 116, 1929 (2019).

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Research field

Physics, Materials Science, Engineering

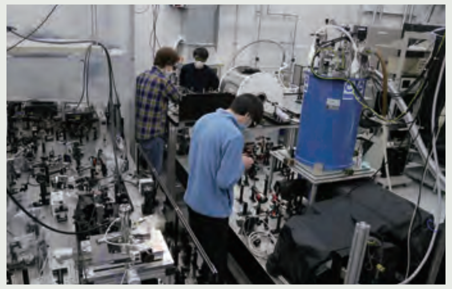
Keywords

Strongly correlated electron systems, Quantum materials, Ultrafast/broadband optical spectroscopy, Photocurrent spectroscopy, Opto-spintronics

Brief resume

2004 D. Eng., University of Tokyo
2004 Postdoctoral Associate, University of California at Irvine
2004 Research Fellow of the Japan Society for the Promotion of Science
2006 Project Assistant Professor, University of Tokyo
2008 Assistant Professor, University of Tokyo
2012 ASI Research Scientist, RIKEN
2013 Senior Research Scientist, RIKEN Center for Emergent Matter Science
2015 Unit Leader, Emergent Photodynamics Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science
2017 JST PRESTO Researcher
2018 Team Leader, Emergent Photodynamics Research Team, RIKEN Center for Emergent Matter Science
2020 Guest Professor, University of Tokyo
2024 Director, Office of the Center Director, RIKEN Center for Emergent Matter Science (-present)
2024 Group Director, Emergent Photodynamics Research Group, RIKEN Center for Emergent Matter Science (-present)

Outline



Our group explores novel photodynamics of electron/spin/lattice in bulk crystals and at thin-film interfaces emerging via electron-correlation, strong spin-orbit interaction, and topology. Examples are ultrafast spectroscopy of shift/injection current, generation of spin current mediated by Dirac/Weyl electrons, and manipulation of topological magnetic textures. With a strong command of photons, we try to realize new photo-electric/magnetic effects in solids, and visualize spatiotemporal propagation of various elemental excitations at the sub-diffraction limit.

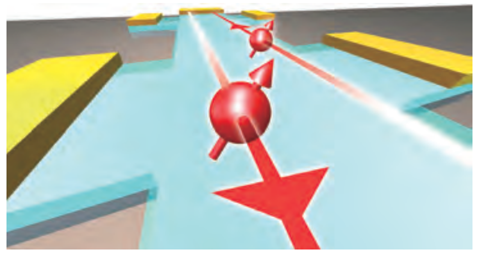
Core members

(Research Scientist) Shingo Toyoda

Strong Correlation Quantum Transport Research Team

Quantum transport phenomena of surface Dirac states in thin film superstructures

The topological insulator is a new state of matter, whose bulk is a three-dimensional charge-gapped insulator but whose surface hosts a two-dimensional Dirac electron state. Surface Dirac states are characterized by massless electrons and holes whose spins are polarized perpendicular to their crystal momentum. As a result, the quantum transport phenomena stemming from their charge and spin degrees of freedom are promising for the applications to low-power consumption electronic devices. The well-known example for this is the quantum anomalous Hall effect (QAHE) in which one-dimensional conducting channel without any dissipation emerges at zero magnetic field. We established the growth of high quality thin film superstructure of topological insulator $(Bi_xSb_{1-x})_2Te_3$ sandwiched by ferromagnetic insulator (Zn,Cr)Te, by means of molecular beam epitaxy (MBE) method. We cooled down to cryogenic temperature, and successfully observed QAHE. We will make full use of the thin film superstructure to add functionality to topological materials. In particular, we now embark on the observation or control of the Majorana quasiparticle, which is expected to be applied to quantum computers.



Schematic of the quantum Hall effect on the surface of a topological insulator

Publications

1. M. Kawamura, M. Mogi, R. Yoshimi, T. Morimoto, K. S. Takahashi, A. Tsukazaki, N. Nagaosa, M. Kawasaki, and Y. Tokura, "Laughlin charge pumping in a quantum anomalous Hall insulator", *Nat. Phys.* 19, 333–337 (2023).
2. M. Mogi, Y. Okamura, M. Kawamura, R. Yoshimi, K. Yasuda, A. Tsukazaki, K. S. Takahashi, T. Morimoto, N. Nagaosa, M. Kawasaki, Y. Takahashi, and Y. Tokura, "Experimental signature of the parity anomaly in a semi-magnetic topological insulator", *Nat. Phys.*, 18, 390 (2022).
3. K. Yasuda, T. Morimoto, R. Yoshimi, M. Mogi, A. Tsukazaki, M. Kawamura, K. S. Takahashi, M. Kawasaki, N. Nagaosa and Y. Tokura, "Large non-reciprocal charge transport mediated by quantum anomalous Hall edge states", *Nat. Nanotechnol.*, 15, 831 (2020).
4. K. Yasuda, H. Yasuda, T. Liang, R. Yoshimi, A. Tsukazaki, K. S. Takahashi, N. Nagaosa, M. Kawasaki, and Y. Tokura, "Nonreciprocal charge transport at topological insulator/superconductor interface", *Nat. Commun.*, 10, 2734 (2019).
5. R. Yoshimi, K. Yasuda, A. Tsukazaki, K. S. Takahashi, M. Kawasaki, and Y. Tokura, "Current-driven magnetization switching in ferromagnetic bulk Rashba semiconductor (Ge, Mn) Te", *Sci. Adv.*, 4, eaat9989 (2018).

Yoshinori Tokura (D.Eng.), Team Leader
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Research field

Physics, Engineering, Materials Science

Keywords

Strongly correlated electron system, High-temperature superconductor, Spin-orbit interaction, Topological insulators, Interface electronic structure

Brief resume

1981 D. Eng., University of Tokyo
1986 Associate Professor, University of Tokyo
1994 Professor, Department of Physics, University of Tokyo
1995 Professor, Department of Applied Physics, University of Tokyo
2001 Director, Correlated Electron Research Center, AIST
2007 Group Director, Cross-Correlated Materials Research Group, RIKEN
2008 AIST Fellow, National Institute of Advanced Industrial Science and Technology (-present)
2010 Director, Emergent Materials Department, RIKEN
2010 Group Director, Correlated Electron Research Group, RIKEN
2013 Director, RIKEN Center for Emergent Matter Science (CEMS)
2013 Group Director, Strong Correlation Physics Research Group, Strong Correlation Physics Division, RIKEN CEMS (-present)
2014 Team Leader, Strong Correlation Quantum Transport Research Team, RIKEN CEMS (-present)
2017 Distinguished University Professor, University of Tokyo (-present)
2019 Special University Professor, University of Tokyo
2024 Special Advisor to the President, RIKEN (-present)

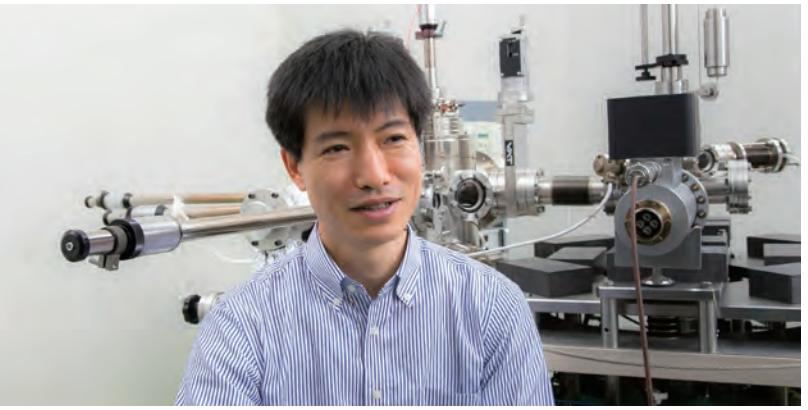
Outline

We study various kinds of quantum transport phenomena which emerge in bulk materials and at hetero-interfaces of thin films, focusing on electron systems with strong correlation and/or strong spin-orbit interactions. Specifically, we try to clarify quantum states of Dirac electrons at surface/interfaces of topological insulators as well as in bulk Rashba system with broken inversion symmetry, by observing Landau level formation, quantum (anomalous) Hall effect, and various quantum oscillation phenomena at low temperatures and in high magnetic fields. Also, we synthesize high-temperature superconducting cuprates in bulk forms and various transition-metal oxides thin films, and measure transport properties under high pressure or high magnetic-field, aiming at increasing superconducting transition temperature and at finding novel magneto-transport properties.

Core members

(Research Scientist) Ilya Belopolski
(Postdoctoral Researcher) Yuki Sato, Lixuan Tai
(Special Postdoctoral Researcher) Max Birch

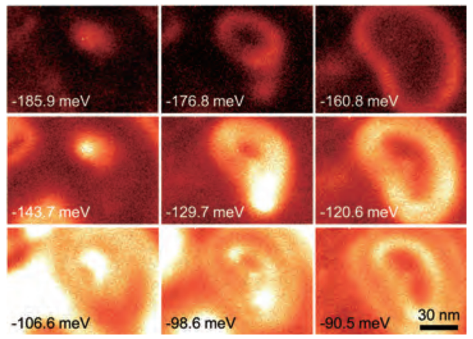
Emergent Phenomena Measurement Research Team



Direct imaging of massless electrons at the surface of a topological insulator

Topological insulators are a new phase of matter which was discovered recently. Although it is an insulator in the bulk, a topological insulator possesses a metallic surface where electrons lose their mass. The surface state is expected to serve as a base of spintronics application, because spins of massless electrons can be used to handle information. However, the experimental understanding of massless electrons is still elusive.

Using scanning tunneling microscope, our team succeeded in imaging the nano-scale spatial structure of massless electrons at the surface of a topological insulator Bi_2Se_3. We focus on imaging in a magnetic field, where electrons exhibit cyclotron motion. The center of the cyclotron motion drifts around the charged defect, resulting in an "electron ring". We found that the unique character of massless electrons manifests itself in the internal structure of the electron ring. The observed internal structure is related to the spin distribution and will give us an important clue for future spintronics applications.



"Electron rings" at different energies

Publications

1. C. J. Butler, M. Yoshida, T. Hanaguri, and Y. Iwasa, "Behavior under magnetic field of resonance at the edge of the upper Hubbard band in 1T-TaS_2", *Phys. Rev. B*, 107, L161107 (2023).
2. C. J. Butler, Y. Kohsaka, Y. Yamakawa, M. S. Bahramy, S. Onari, H. Kontani, T. Hanaguri, and S. Shamoto, "Correlation-driven electronic nematicity in the Dirac semimetal $BaNiS_2$", *Proc. Natl. Acad. Sci. USA*, 119, e2212730119 (2022).
3. T. Machida, Y. Nagai, and T. Hanaguri, "Zeeman effects on Yu-Shiba-Rusinov states", *Phys. Rev. Res.*, 4, 033182 (2022).
4. T. Machida, Y. Yoshimura, T. Nakamura, Y. Kohsaka, T. Hanaguri, C.-R. Hsing, C.-M. Wei, Y. Hasegawa, S. Hasegawa, and A. Takayama, "Superconductivity near the saddle point in the two-dimensional Rashba system Si(111)$\sqrt{3}\times\sqrt{3}$-(Tl,Pb)", *Phys. Rev. B*, 105, 064507 (2022).
5. S. Kasahara, H. Suzuki, T. Machida, Y. Sato, Y. Ukai, H. Murayama, S. Suetsugu, Y. Kasahara, T. Shibauchi, T. Hanaguri, and Y. Matsuda, "Quasiparticle Nodal Plane in the Fulde-Ferrell-Larkin-Ovchinnikov State of FeSe", *Phys. Rev. Lett.*, 127, 257001 (2021).

Tetsuo Hanaguri (D.Eng.), Team Leader
hanaguri@riken.jp

Research field

Physics, Engineering, Materials Sciences

Keywords

Scanning tunneling microscopy, Superconductivity, Topological insulators

Brief resume

- 1993 D.Eng., Tohoku University
- 1993 Research Associate, Department of Basic Science, The University of Tokyo
- 1999 Associate Professor, Department of Advanced Materials Science, The University of Tokyo
- 2004 Senior Research Scientist, Magnetic Materials Laboratory, RIKEN
- 2013 Team Leader, Emergent Phenomena Measurement Research Team, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

We experimentally study electronic states related to emergent phenomena in electron systems, such as high-temperature superconductivity and topological quantum phenomena. For this purpose, we use scanning tunneling microscopes working under combined extreme conditions of very low temperatures, high magnetic fields and ultra-high vacuum. Modern scanning-tunneling-microscopy technology enables us to obtain a "map of the electronic state" with atomic-scale spatial resolution. We make and analyze the maps of various materials and establish the relationships between material properties and electronic states. We also pursue the development of novel measurement techniques to discover new emergent phenomena in condensed matter.

Core members

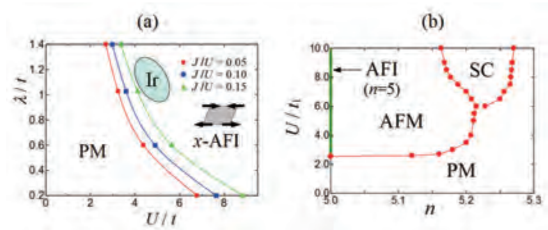
(Senior Research Scientist) Tadashi Machida
(Research Scientist) Christopher John Butler
(Special Postdoctoral Researcher)
Masahiro Naritsuka, Katsuki Nihongi

Computational Quantum Matter Research Team

Mechanism of novel insulating state and possible superconductivity induced by a spin-orbit coupling

Electrons in solids are moving around, affected by the Coulomb interaction, electron-lattice interaction, and spin-orbit interaction, which induces different behaviors characteristic of each material. Recently, the study for the spin-orbit coupling has greatly progressed and attracted much attention. In the 5d transition metal oxide Sr_2IrO_4, the spin and orbital degrees of freedom are strongly entangled due to the large spin-orbit coupling and the novel quantum state is formed. Sr_2IrO_4 is also expected to be a possible superconducting material with a great deal of similarities to the parent compound of cuprate high-temperature superconductivity.

We have studied the detailed electronic properties of a 3-orbital Hubbard model for Sr_2IrO_4 with several computational methods. Our calculations have clearly shown that the ground state of this material is an effective total angular momentum J_{eff}=1/2 antiferromagnetic insulator, where J_{eff} is "pseudospin",formed by spin and orbital degrees of freedom due to the strong spin-orbit coupling (x-AFI in Fig. (a)). We have also proposed that the $d_{x^2-y^2}$-wave "pseudospin singlet" superconductivity (SC in Fig. (b)) is induced by electron doping into the J_{eff}=1/2 antiferromagnetic insulator Sr_2IrO_4.



Ground state phase diagram of 3-orbital Hubbard model with a spin-orbit coupling. (a) Electron density n=5, (b) n>5.

Publications

1. K. Shinjo, S. Sota, S. yunoki, and T. Tohyama, "Controlling inversion and time-reversal symmetries by subcycle pules in the one-dimensional extended Hubbard model", *Phys. Rev. B* 107, 195103 (2023).
2. H. Watanabe, T. Shirakawa, K. Seki, H. Sakakibara, T. Kotani, H. Ikeda, and S. Yunoki, "Monte Carlo study of cuprate superconductors in a four-band d-p model: role of orbital degrees of freedom", *J. Phys.: Condens. Matter* 35, 195601 (2023).
3. F. Lange, S. Ejima, J. Fujimoto, T. Shirakawa, H. Fehske, S. Yunoki, and S. Maekawa, "Generation of current vortex by spin current in Rashba systems", *Phys. Rev. Lett.* 126, 157202 (2021).
4. H. Watanabe, T. Shirakawa, K. Seki, H. Sakakibara, T. Kotani, H. Ikeda, and S. Yunoki, "Unified description of cuprate superconductors suing a four-band d-p model", *Phys. Rev. Research* 3, 033157 (2021).
5. T. Kaneko, T. Shirakawa, S. Sorella, and S. Yunoki, "Photoinduced eta pairing in the Hubbard model", *Phys. Rev. Lett.* 122, 077002 (2019).

Seiji Yunoki (D.Eng.), Team Leader
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Research field

Physics, Materials Science

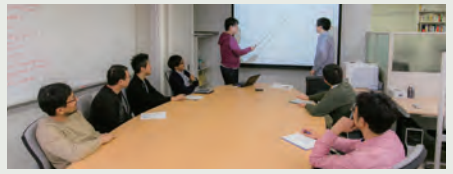
Keywords

Strongly correlated electron system, Magnetism, Superconductivity, Computational condensed matter physics

Brief resume

- 1996 D.Eng., Nagoya University
- 1996 Postdoctoral Researcher, National High Magnetic Field Laboratory, USA
- 1999 Postdoctoral Researcher, Materials Science Center, Groningen University, Netherlands
- 2001 Postdoctoral Researcher, International School for Advanced Studies, Italy
- 2006 Long-Term Researcher and Research Assistant Professor, Oak Ridge National Laboratory and University of Tennessee, USA
- 2008 Associate Chief Scientist, Computational Condensed Matter Physics Laboratory, RIKEN
- 2010 Team Leader, Computational Materials Science Research Team, RIKEN Advance Institute for Computational Science
- 2013 Team Leader, Computational Quantum Matter Research Team, RIKEN Center for Emergent Matter Science (-present)
- 2017 Chief Scientist, Computational Condensed Matter Physics Laboratory, RIKEN (-present)
- 2018 Team Leader, Computational Materials Science Research Team, RIKEN Center for Computational Science (-present)
- 2021 Team Leader, Quantum Computational Science Research Team, RIKEN Center for Quantum Computing (-present)

Outline



Electrons in solids are in motion within the energy band reflecting the lattice structure of each material. The Coulomb interaction, electron-lattice interaction, and spin-orbit interaction have nontrivial effects on the motion of electrons and induce various interesting phenomena. Our aim is to elucidate the emergent quantum phenomena induced by cooperation or competition of these interactions, using state-of-the-art computational methods for condensed matter physics. Our current focus is on various functional transition metal oxides, topological materials, and heterostructures made of these materials. Our research will lead not only to clarify the mechanism of quantum phenomena in existent materials but also to propose novel materials.

Core members

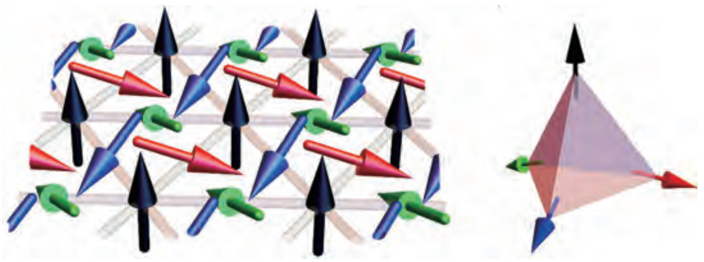
(Reseach Scientist) Kazuya Shinjo

First-Principles Materials Science Research Team

Classification of emergent responses of magnetic materials based on spin crystallographic groups

The spin, an intrinsic degree of freedom of electrons, brings about diverse physical properties through its ordering (magnetism). In particular, when there is the spin-orbit interaction (SOI), which links the spin and orbital degrees of freedom, magnetism is associated with the physical properties of materials, such as electrical conductivity and elasticity. This is evident in phenomena like the anomalous Hall effect and magnetostriction. However, the impact of SOI is limited in elements such as Fe and Mn due to its relativistic nature, which constrains material exploration. On the other hand, thanks to their non-trivial magnetic structures, some antiferromagnets show emergent electromagnetic responses independent of SOI.

When exploring the properties of such antiferromagnetic materials, analyzing the symmetry of magnetic structures plays a crucial role. Magnetic space groups are commonly used for this purpose, but they implicitly assume the presence of spin-orbit interaction, making them unsuitable for the symmetry analysis of emergent electromagnetic phenomena. We have focused on spin space groups that do not consider the constraints of spin-orbit interaction. We developed a method to conveniently identify magnetism-driven properties. This method serves as a guideline for understanding and predicting emergent properties.



Example of a non-coplanar spin structure with nontrivial spin space group symmetry.

Publications

1. Y. Nomura, S. Sakai, and R. Arita, “Fermi surface expansion above critical temperature in a Hund ferromagnet”, *Phys. Rev. Lett.*, 128, 206401 (2022)
2. Y. Nomura, R. Arita, “Superconductivity in infinite-layer nickelates”, *Rep. Prog. Phys.*, 85 052501 (2022).
3. M.-T. Huebsch, T. Nomoto, M.-T. Suzuki, R.Arita, “Benchmark for *Ab Initio* Prediction of Magnetic Structures Based on Cluster-Multipole Theory”, *Phys. Rev. X* 11, 011031 (2021).
4. T. Nomoto, T. Koretsune, R. Arita, “Formation Mechanism of the Helical Q Structure in Gd-Based Skyrmion Materials”, *Phys. Rev. Lett.* 125, 117204 (2020).
5. J. A. Flores-Livas, L. Boeri, A. Sanna, G. Profeta, R. Arita, M. Eremets, “A perspective on conventional high-temperature superconductors at high pressure: Methods and materials”, *Phys. Rep.* 856, 1-78 (2020).

Ryotaro Arita (D.Sci.), Team Leader
arita@riken.jp

Research field

Physics, Materials Science

Keywords

First-principles calculations, Theoretical materials design, Strongly correlated electron systems

Brief resume

- 2000 D.Sci., University of Tokyo
- 2000 Research Associate, Department of Physics, University of Tokyo
- 2004 Postdoctoral Researcher, Max Planck Institute for Solid State Research
- 2006 Research Scientist/Senior Research Scientist, Condensed Matter Theory Laboratory, RIKEN
- 2008 Associate Professor, Department of Applied Physics, University of Tokyo
- 2011 PRESTO, Japan Science and Technology Agency
- 2014 Team Leader, First-Principles Materials Science Research Team, RIKEN Center for Emergent Matter Science (-present)
- 2018 Professor, Department of Applied Physics, University of Tokyo
- 2022 Professor, Research Center for Advanced Science and Technology, University of Tokyo (-present)

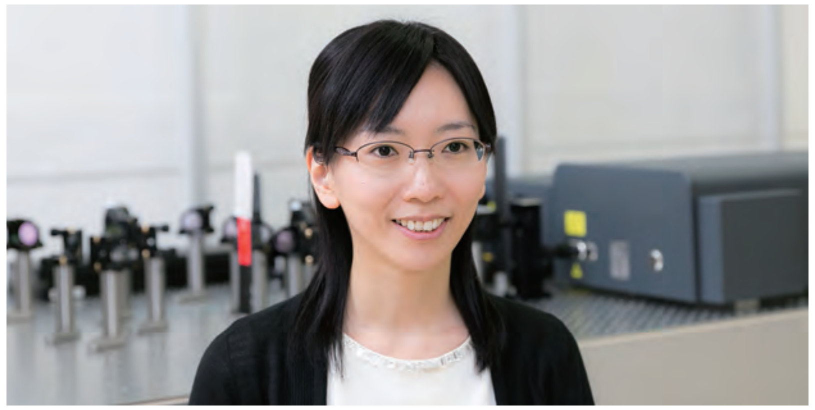
Outline

By means of first-principles methods, our team studies non-trivial electronic properties of materials which lead to new ideas/notions in condensed matter physics or those which have potential possibilities as unique functional materials. Especially, we are currently interested in strongly correlated/topological materials such as high T_c cuprates, iron-based superconductors, organic superconductors, carbon-based superconductors, 5d transition metal compounds, heavy fermions, giant Rashba systems, topological insulators, zeolites, and so on. We aim at predicting unexpected phenomena originating from many-body correlations and establishing new guiding principles for materials design. We are also interested in the development of new methods for *ab initio* electronic structure calculation.

Core members

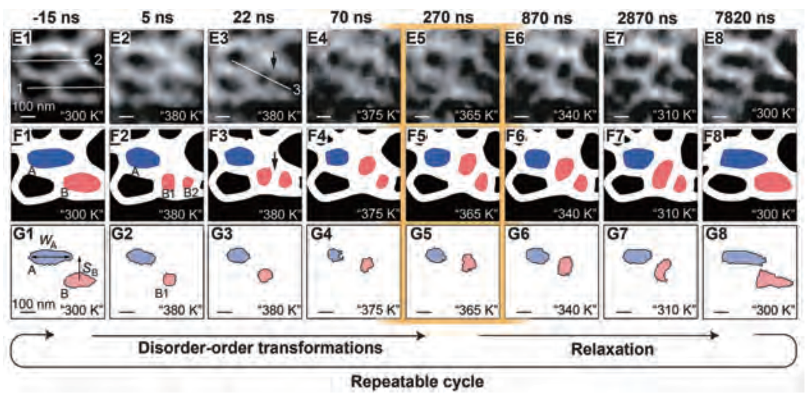
(Senior Research Scientist) Shiro Sakai
(Research Scientist) Yuta Murakami
(Special Postdoctoral Researcher)
Hsiao-Yi Chen, Rikuto Oiwa, Jean B.P.G. Moree, Kotaro Shimizu, Kosuke Nogaki
(International Program Associate) Ming-Chun Jiang

Electronic State Spectroscopy Research Team



Nano-to-micro spatiotemporal imaging of magnetic skyrmions

Magnetic skyrmions are self-organized topological spin textures that behave like particles. Because of their fast creation and typically long lifetime, experimental verification of skyrmion’ s creation/annihilation processes has been challenging. Our team successfully tracked skyrmion dynamics in a room-temperature chiral magnet by using pump-probe Lorentz transmission electron microscope. Following the nanosecond photothermal excitation, we resolved 160-nm skyrmion’ s proliferation at <1 ns, contraction at 5 ns, drift from 10 ns to 4 µs, and coalescence at ~5 µs. These motions relay the multiscale arrangement and relaxation of skyrmion clusters in a repeatable cycle. Such repeatable dynamics of skyrmions, arising from the weakened but still persistent topological protection around defects, enables us to visualize the whole life of the skyrmions and demonstrates the possible high-frequency manipulations of topological charges brought by skyrmions.



Spatiotemporal imaging of magnetic skyrmions recorded by ultrafast Lorentz electron microscope.
Copyright: https://www.science.org/doi/10.1126/sciadv.abg1322

Publications

1. A. Nakamura, T. Shimojima, K. Ishizaka, “Characterizing an Optically Induced Sub-micrometer Gigahertz Acoustic Wave in a Silicon Thin Plate”, *Nano Lett.* 23, 2490–2495 (2023).
2. T. Shimojima, A. Nakamura, X. Z. Yu, K. Karube, Y. Taguchi, Y. Tokura, K. Ishizaka,“Nano-to-micro spatiotemporal imaging of magnetic skyrmion’s life cycle”, *Sci. Adv.* 7, eabg1322/1-8 (2021).
3. A. Nakamura, T. Shimojima, Y. Chiashi, M. Kamitani, H. Sakai, S. Ishiwata, H. Li, and K. Ishizaka, “Nanoscale Imaging of Unusual Photoacoustic Waves in Thin Flake VTe_2”, *Nano Lett.* 20, 7, 4932 (2020).
4. N. Mitsuishi, T. Shimojima, K. Ishizaka et al., “Switching of band inversion and topological surface states by charge density wave”, *Nature Commun.* 11, 2466 (2020).
5. T. Shimojima, Y. Suzuki, A. Nakamura, N. Mitsuishi, S. Kasahara, T. Shibauchi, Y. Matsuda, Y. Ishida, S. Shin and K. Ishizaka, “Ultrafast nematic-orbital excitation in FeSe”, *Nature Commun.* 10, 1946 (2019).

Kyoko Ishizaka (Ph.D.), Team Leader
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Research field

Physics, Materials Science

Keywords

Ultrafast time-resolved TEM, Photoelectron Spectroscopy, Strongly Correlated Electron System, Superconductivity, Topological Materials

Brief resume

- 2004 Ph.D., Engineering, University of Tokyo
- 2004 Research Associate, Institute for Solid State Physics, University of Tokyo
- 2010 Associate Professor, Department of Applied Physics, School of Engineering, University of Tokyo
- 2014 Associate Professor, Quantum-Phase Electronics Center, School of Engineering, University of Tokyo
- 2016 Team Leader, Electronic States Spectroscopy Research Team, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (-present)
- 2018 Professor, Quantum-Phase Electronics Center, School of Engineering, University of Tokyo (-present)

Outline

We investigate the electronic states of materials showing a variety of physical properties, functions, and quantum phenomena. By utilizing spin- and angle-resolved photoemission spectroscopy, which can probe the energy, momentum, and spin of electrons, we investigate new materials, topological quantum states, and many-body effects in strongly correlated systems. We are also developing the pulsed-laser based ultrafast transmission electron microscopy, aiming for probing the dynamical states of nanoscale spin/lattice/charge textures, materials, and devices.

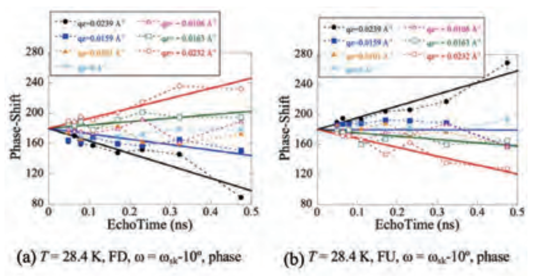
Core members

(Research Scientist) Asuka Nakamura
(Postdoctoral Researcher) Natsuki Mitsuishi

Strongly Correlated Spin Research Team

Asymmetric Dynamics in the Skyrmion lattice confirmed in neutron-scattering experiments

The skyrmion structure found in the topological magnet MnSi is actively investigated in the field of spintronics, a new technology considered an alternative to traditional electronics. The key feature of the skyrmion structure is its ability to respond to external fields at the very small energy scale of μeV. Moreover, it was theoretically predicted that the skyrmion structure would show an asymmetric behavior (dynamics) when subjected to magnetic fields applied in parallel and antiparallel directions. Normally, observing fluctuations of magnetic moments in reciprocal space is suited for neutron inelastic scattering experiments using a three-axis spectrometer with a thermal neutron source, but this method cannot be used in the μeV energy range. For this, we succeeded in observing the low-energy excitations in the skyrmion state of MnSi in detail using the world's highest performance spin echo spectrometer installed at ILL in France.



Magnetic field direction dependence of the phase shift observed in MnSi

Publications

1. M. Soda, E. M. Forgan, E. Blackburn, E. Campillo, V. Ryukhtin, I. Hoffmann, A. Kikkawa, Y. Taguchi, H. Yoshizawa, and H. Kawano-Furukawa, "Asymmetric slow dynamics of the skyrmion lattice in MnSi", *Nat. Phys.*, 19, 1476–1481 (2023)
2. M. Soda, N. Kagamida, S.Mühlbauer, E. Campillo, E. M Forgan,M. Kriener, H. Yoshizawa, H. Kawano-Furukawa, Penetration Depth and Coherence Length in the Superconductor β-PdBi$_2$, *J. Phys. Soc. Japan*, 91 (3), 034706 (2022).
3. M. Soda, N. Kagamida, S.Mühlbauer, E. M Forgan, E. Campillo, M. Kriener, H. Yoshizawa, H. Kawano-Furukawa, Field Dependence of Superfluid Density in β-PdBi$_2$, *J. Phys. Soc. Japan*, 90 (10), 104710, (2021).

Hazuki Furukawa (Ph.D.), Team Leader
hazuki.furukawa@riken.jp

Research field

Physics, Materials Science

Keywords

Strongly correlated electron system, Magnetism, Superconductivity, Skyrmion, Neutron scattering

Brief resume

- 1995 Ph. D. in Physics, University of Tokyo
- 1995 Special researcher on Basic Science, The Institute of Physical and Chemical Research (RIKEN)
- 1998 Research Associate, Oak Ridge National Lab.
- 1999 Associate Professor, Dep. of Physics, Faculty of Science, Ochanomizu Univ.
- 1999 PRESTO, Japan Science and Technology Agency
- 2003 Full Professor, Dep. of Physics, Faculty of Science, Ochanomizu Univ.
- 2007 Full Professor, Division of Natural/Applied Science, Graduate School of Humanities and Sciences, Ochanomizu University
- 2015 Full Professor, Faculty of Core Research Natural Science Division, Ochanomizu University (-present)
- 2016 Team Leader, Strongly Correlated Spin Research Team, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

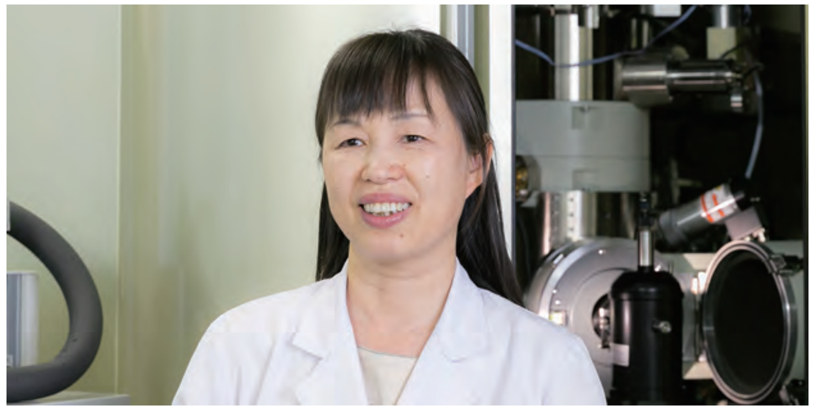
Our team studies the static and dynamic magnetic and atomic structure of strongly correlated electron systems using various neutron scattering techniques. We are working to verify the relevance of physical characteristics in controlling and enhancing the behavior of these systems.

Research topics include; (1) Elucidation of the role of spin-orbit interactions in quantum states of newly discovered exotic superconductors, (2) Verification of FFLO phase and/or helical vortex phase, and (3) Study of the dynamics of skyrmions in topological magnetic materials.

Core members

(Technical Scientist) Edward Foley

Electronic States Microscopy Research Team

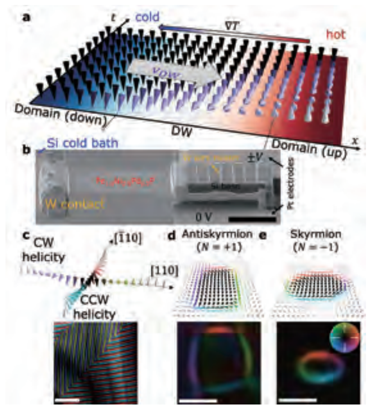


Control of q-vector and mutual conversion between skyrmions and antiskyrmions via thermal currents

As an antiparticle of skyrmion, the antiskyrmion exhibits opposite topological charge and unique spin texture composed of the alternating Bloch- and Néel-type spirals. In this study, we observed the dynamic behavior of helical structures, skyrmions (e) and antiskyrmions (d) under a temperature gradient ∇T in a magnetic material $Fe_{1.9}Ni_{0.9}Pd_{0.2}P$ (FNPP).

First, a 150nm-thick FNPP plate was fabricated, and Pt heater wires were attached to a silica (SiO_2) substrate, connected to one end of the FNPP plate. Then, an insulating material, TEOS, was coated onto the SiO_2 substrate (as shown in b). By passing a current through the heater wires, a lateral ∇T was induced within the FNPP. Upon applying ∇T to the helical structure with two q-vector (c) within the FNPP, the helical structure transformed into a single-q-vector helices. Furthermore, by applying a perpendicular magnetic field of 450 mT (mT) to the FNPP, followed by gradual reduction the field to zero, skyrmions were generated within the FNPP (e). The applying of ∇T causes the transformation of skyrmions into antiskyrmions (d).

These results demonstrate successful control over the helical magnetic structure, skyrmions, and antiskyrmions in FNPP using thermal currents.



a, Schematic of a magnetic domain structure. b, A scanning electron microscopy image of the $Fe_{1.9}Ni_{0.9}Pd_{0.2}P$ device exhibiting a heater at the right site. c, Stripe domain structure at zero magnetic field (upper panel, schematic; downer, experimental). d, An antiskyrmion (N=+1). e, A metastable skyrmion (N=-1). Scalebars 1 μm in (b) and 0.1 μm in (c-e).

Publications

1. F. S. Yasin, J. Masell, K. Karube, D. Shindo, Y. Taguchi, Y. Tokura, X. Yu, "Heat current-driven topological spin texture transformations and helical q-vector switching", *Nat. Commun.*, 14, 7094 (2023).
2. X. Yu, N. Kanazawa, X. Zhang, Y. Takahashi, K. V. Iakoubovskii, K. Nakajima, T. Tanigaki, M. Mochizuki, Y. Tokura, "Spontaneous vortex-antivortex pairs and their topological transitions in a chiral-lattice magnet", *Adv. Mater.* 2306441 (2023).
3. X. Z. Yu, F. Kagawa, S. Seki, M. Kubota, J. Masell, F. S. Yasin, K. Nakajima, M. Nakamura, M. Kawasaki, N. Nagaosa and Y. Tokura, "Real-space observations of 60-nm skyrmion dynamics in an insulating magnet under low heat flow", *Nat. Commun.*, 12, 5079 (2021).
4. N. D. Khanh, T. Nakajima, X. Z. Yu, S. Gao, K. Shibata, M. Hirschberger, Y. Yamasaki, H. Sagayama, H. Nakao, L. Peng, K. Nakajima, R. Takagi, T. Arima, Y. Tokura, S. Seki, "Nanometric square skyrmion lattice in a centrosymmetric tetragonal magnet", *Nat. Nanotechnol.*, 15, 444 (2020).
5. X. Z. Yu, W. Koshibae, Y. Tokunaga, K. Shibata, Y. Taguchi, N. Nagaosa and Y. Tokura, "Transformation between meron and skyrmion topological spin textures in a chiral magnet", *Nature*, 564, 95 (2018).

Xiuzhen Yu (D.Sci.), Team Leader
yu_x@riken.jp

Research field

Physics, Engineering, Materials Science

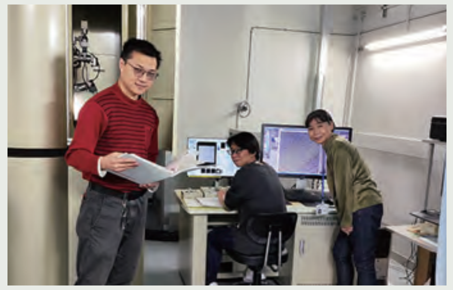
Keywords

Electronic states, Lorentz microscopy, Analytical electron microscopy, High-resolution electron microscopy, Differential phase-contrast microscopy, 3D magnetic imaging

Brief resume

- 1990 Master, Department of Semiconductor, Jilin University
- 2002 Technician, Tokura Spin Superstructure Project, ERATO, Japan Science and Technology Agency
- 2006 Engineer, Advanced Electron Microscopy Group, Advanced Nano Characterization Center, NIMS
- 2008 Doctor of Science, Department of Physics, Tohoku University
- 2008 Researcher, Advanced Electron Microscopy Group, Advanced Nano Characterization Center, NIMS
- 2010 Researcher, Tokura Multiferroic Project, ERATO, Japan Science and Technology Agency
- 2011 Postdoctoral Researcher, Quantum Science on Strong Correlation Group, Advanced Science Institute, RIKEN
- 2013 Senior Research Scientist, Strong Correlation Physics Research Group, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (CEMS)
- 2017 Team Leader, Electronic States Microscopy Research Team, RIKEN CEMS (-present)

Outline

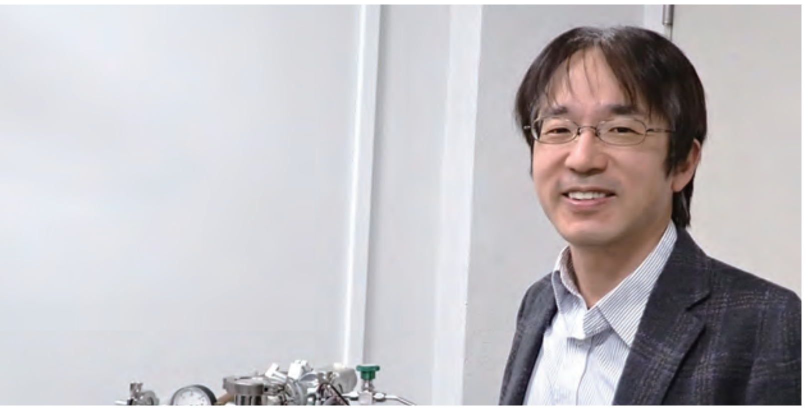


Our team is working on the real-space observation of electron structures or topological electron-spin textures (skyrmion) and their dynamics in strong-correlation systems by means of atomic-resolution electron microscopy. We use various microscopies, such as the in-situ imaging technique, differential phase-contrast microscopy, 3D magnetic imaging, electron energy-loss spectroscopy, and energy dispersive spectroscopy, etc., to explore the electronic structures and their dynamical phase transitions with external stimuli. We also use these powerful tools to quantitatively characterize the nanometric magnetic and electric fields in topological matters to exploit emergent phenomena and hence their possible applications in the spintronics.

Core members

(Technical Staff II) Kiyomi Nakajima
(Postdoctoral Researcher) Yao Guang
(Technical Scientist) Yi Ling Chiew

Dynamic Emergent Phenomena Research Team



Fumitaka Kagawa (D.Eng.), Team Leader
fumitaka.kagawa@riken.jp

Research field

Materials Science, Physics

Keywords

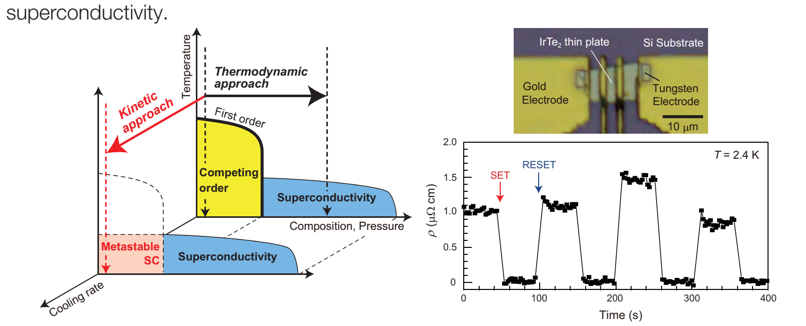
Strongly correlated electron system, Phase control, Scanning probe microscopy, Spectroscopy

Brief resume

- 2006 D.Eng., University of Tokyo
- 2006 Research fellowship for young scientists
- 2007 Researcher, JST-ERATO Multiferroic project
- 2010 Project Lecturer, Quantum-Phase Electronics Center, University of Tokyo
- 2012 Lecturer, Department of Applied Physics, University of Tokyo
- 2013 Unit Leader, Dynamic Emergent Phenomena Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science
- 2017 Associate Professor, Department of Applied Physics, University of Tokyo
- 2022 Professor, Department of Physics, Tokyo Institute of Technology (-present)
- 2022 Team Leader, Dynamic Emergent Phenomena Research Team, RIKEN Center for Emergent Matter Science (-present)

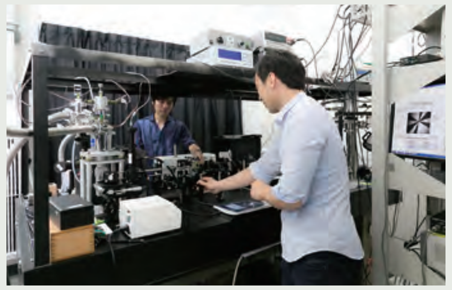
Kinetic approach to superconductivity hidden behind a competing order

In strongly correlated electron systems, the emergence of superconductivity is often inhibited by the formation of a thermodynamically more stable magnetic/charge order. Nevertheless, by changing thermodynamic parameters, such as the physical/chemical pressure and carrier density, the free-energy balance between the superconductivity and the competing order can be varied, thus enabling the superconductivity to develop as the thermodynamically most stable state. We demonstrate a new kinetic approach to avoiding the competing order and thereby inducing persistent superconductivity. In the transition-metal dichalcogenide $IrTe_2$ as an example, by utilizing current-pulse-based rapid cooling up to ~10^7 K s^{-1}, we successfully kinetically avoid a first-order phase transition to a competing charge order and uncover metastable superconductivity hidden behind. The present method also enables non-volatile and reversible switching of the metastable superconductivity with electric pulse applications, a unique advantage of the kinetic approach. Thus, our findings provide a new approach to developing and controlling superconductivity.



Conceptual phase diagram of superconductivity with ultra-rapid cooling (left), the thin-plate sample used in the experiments (top right) and non-volatile switching between superconducting and non-superconducting states demonstrated by resistivity measurements (bottom right)

Outline



Our team explores dynamic emergent phenomena exhibited by strongly correlated electron systems in both bulk and device structures to construct a new scheme for scientific investigation. In particular, we study external-field-driven dynamic phenomena exhibited by sub-micron-scale structures, such as topological spin textures and domain walls, using spectroscopy of dielectric responses and resistance fluctuations from the millihertz to gigahertz region. We also pursue real-space observations and measurements of local physical properties using scanning probe microscopy as a complementary approach. We are aiming to control novel physical properties exhibited by topological structures in condensed matter systems on the basis of knowledge obtained from these methods.

Publications

1. M. Wang, K. Tanaka, S. Sakai, Z. Wang, K. Deng, Y. Lyu, C. Li, D. Tian, S. Sheng, N. Ogawa, N. Kanazawa, P. Yu, R. Arita, and F. Kagawa, "Emergent zero-field anomalous Hall effect in a reconstructed rutile antiferromagnetic metal", *Nat. Commun.* 14, 8240 (2023).
2. S. Furuta, S. H. Moody, K. Kado, W. Koshibae, and F. Kagawa, "Energetic perspective on emergent inductance exhibited by magnetic textures in the pinned regime", *npj Spintronics* 1, 1 (2023).
3. K. Matsuura, Y. Nishizawa, Y. Kinoshita, T. Kurumaji, A. Miyaka, H. Oike, M. Tokunaga, Y. Tokura, and F. Kagawa, "Low-temperature hysteresis broadening emerging from domain-wall creep dynamics in a two-phase competing system", *Commun. Mat.* 4, 71 (2023).
4. T. Sato, W. Koshibae, A. Kikkawa, Y. Taguchi, N. Nagaosa, Y. Tokura, and F. Kagawa, "Nonthermal current-induced transition from skyrmion lattice to nontopological magnetic phase in spatially confined MnSi", *Phys. Rev. B* 106, 144425 (2022).
5. H. Oike, M. Kamitani, Y. Tokura, and F. Kagawa, "Kinetic approach to superconductivity hidden behind a competing order", *Sci. Adv.* 4, eaau3489 (2018).

Core members

(Postdoctoral Researcher) Tetsuya Nomoto
(Visiting Scientist)
Hiroshi Oike, Takuro Sato, Keisuke Matsuura

Emergent Soft Matter Function Research Group

Takuzo Aida (D.Eng.), Group Director
takuzo.aida@riken.jp

Research field

Chemistry, Materials Science

Keywords

Soft material, Molecular design, Self-assembly, Energy conversion, Biomimetics, Stimuli-responsive material, Electronic material, Photoelectric conversion material, Environmentally friendly material

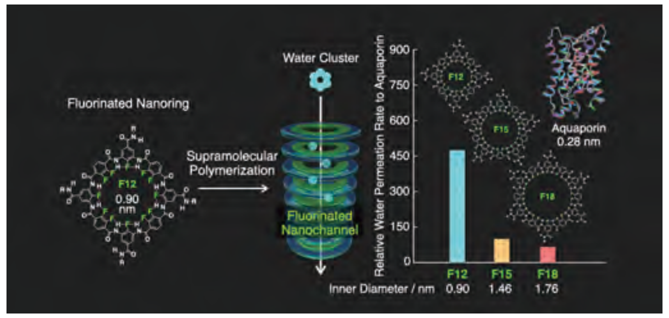
Brief resume

- 1984 D.Eng., University of Tokyo
- 1984 Research Assistant / Lecturer, University of Tokyo
- 1991 Associate Professor, University of Tokyo
- 1996 Professor, University of Tokyo (-present)
- 2000 Project Leader, ERATO Aida Nanospace Project, Japan Science and Technology Corporation
- 2007 Group Director, Responsive Matter Chemistry & Engineering Research Group, RIKEN
- 2010 Group Director, Functional Soft Matter Research Group, RIKEN
- 2011 Team Leader, Photoelectric Conversion Research Team, RIKEN
- 2013 Deputy Director, RIKEN Center for Emergent Matter Science (CEMS)
- 2013 Group Director, Emergent Soft Matter Function Research Group, Division Director, Supramolecular Chemistry Division, RIKEN CEMS (-present)
- 2022 Distinguished University Professor, University of Tokyo (-present)

Fluorinated nanotubes that allow water to pass through at very high speed but not salt

Desalination of seawater is an essential issue for realizing a sustainable society, and various water treatment membranes have been developed. The development of technology to desalinate seawater at high speed is one of the Sustainable Development Goals (SDGs) adopted at the UN Summit in 2015, but to solve the global shortage of drinking water, it is necessary to dramatically increase the capacity of the water treatment membranes currently in use. In basic research to increase the capacity of water treatment membranes, "aquaporins" have been the focus of attention. Inspired by the structure and performance of aquaporins, various nanotubes that mimic aquaporins, such as carbon nanotubes, have been reported, but nothing has been reported that significantly exceeds the performance of aquaporins.

In this study, the group obtained fluorinated nanotubes whose inner walls are densely covered with fluorine like Teflon by layering macrocyclic compounds with fluorine atoms densely bonded to the inner surface in a row by a method called supramolecular polymerization. Evaluation of the water permeability and salt removal ability of these nanotubes revealed that they are 4,500 times more permeable to water than aquaporins, but impervious to salt.



Fluorinated Nanotubes for Ultra-Fast Water Permeation and Their Inner Diameter Dependence

Outline

With world's focus on environment and energy issues, our group aims to establish a novel principle of material sciences addressing these problems, through the development of unprecedented functional materials with precisely controlled structure and properties at molecular to nanoscale levels. The main research subjects include (1) the development of novel organic catalysts consisting only of ubiquitous elements for high efficient water photolysis, (2) the development of the solution-processable organic ferroelectric materials for the application to memory devices, and (3) the development of precise supramolecular polymerizations.

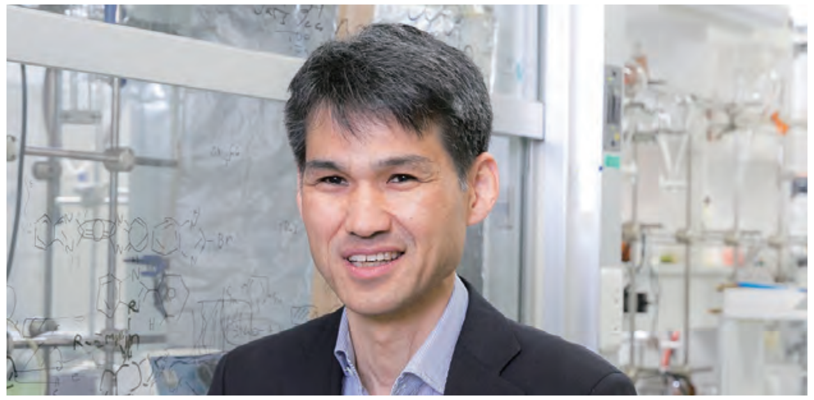
Publications

1. Y. Zhao, H. Kawano, H. Yamagishi, S. Otake, Y. Itoh, H. Huang, E. W. Meijer, and T. Aida, "Pathway Complexity in Nanotubular Supramolecular Polymerization: Metal–Organic Nanotubes with a Planar-Chiral Monomer", *J. Am. Chem. Soc.*, 145, 13920 (2023).
2. Y. Itoh, S. Chen, R. Hirahara, T. Aoki, T. Ueda, I. Shimada, J. J. Cannon, C. Shao, J. Shiomi, K. V. Tabata, H. Noji, K. Sato, and T. Aida, "Ultrafast water permeation through nanochannels with a densely fluorous interior surface", *Science*, 376, 738 (2022).
3. Z. Chen, Y. Suzuki, A. Imayoshi, X. Ji, K. V. Rao, Y. Omata, D. Miyajima, E. Sato, A. Nihonyanagi, and T. Aida, "Solvent-free autocatalytic supramolecular polymerization", *Nature Mater.*, 21, 253 (2022).
4. W. Meng, S. Kondo, T. Ito, K. Komatsu, J. Pirillo, Y. Hijikata, Y. Ikuhara, T. Aida, and H. Sato, "An elastic metal-organic crystal with densely catenated backbone", *Nature*, 598, 298 (2021).
5. Y. Yanagisawa, Y. Nan, K. Okuro, and T. Aida, "Mechanically robust, readily repairable polymers via tailored noncovalent cross-linking", *Science*, 359, 72 (2018).

Core members

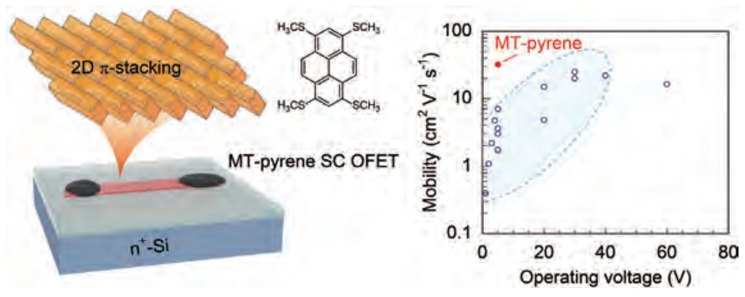
(Research Scientist) Nobuhiko Mitoma, Hubiao Huang
(Special Postdoctoral Researcher) Abir Goswami
(Technical Staff)
Motonobu Kuwayama, Hiroyuki Inuzuka
(Research Part-Time Worker) Sei Obuse, Yiren Cheng
(Junior Research Associate)
Gangfeng Chen, Yang Hong, Jinxu Liu

Emergent Molecular Function Research Group



Development of high-mobility organic semiconductors by controlling molecular arrangement

Solid-state properties of organic semiconductors, e.g., carrier mobility, are largely dependent not only on the molecular structure but also packing structure and molecular orientation in the solid state. However, it is very difficult to predict and control the crystal structure at the stage of molecular design, and the development of methodologies for controlling the crystal structure of organic semiconductors is an important issue. We have found that it is possible to lead to a crystal structure suitable for high mobility by introducing a simple substituent such as a methylthio group at an appropriate position in the organic semiconductor skeleton. For example, When four methylthio groups were regio-selectively introduced into pyrene that crystalizes into a sandwich herringbone structure, the crystal structure changes dramatically into a brickwork structure, which enables two-dimensional conduction. The carrier mobility evaluated by using single-crystal field-effect transistors was higher than 30 $cm^2 V^{-1} s^{-1}$, which was among the highest for organic semiconductors.



Development of high-mobility organic semiconductors by controlling molecular arrangement

Publications

1. K. Takimiya, K. Bulgarevich, K. Kawabata, "Crystal-structure control of molecular semiconductors by methylthiolation: towards ultrahigh mobility", *Acc. Chem. Res.*, 34, 884 (2024).
2. T. Matsuo, K. Kawabata, K. Takimiya, "A novel n-type molecular dopant with a closed-shell electronic structure applicable to the vacuum-deposition process", *Adv. Mater.*, 36, 2311047 (2024).
3. K. Bulgarevich, S. Horiuchi, K. Takimiya, "Crystal-structure simulation of methylthiolated peri-condensed polycyclic aromatic hydrocarbons for identifying promising molecular semiconductors: discovery of 1,3,8,10-tetrakis(methylthio)peropyrene showing ultrahigh mobility", *Adv. Mater.*, 355, 2305548 (2023).
4. K. Takimiya, Kirill Bulgarevich, M. Abbas, S. Horiuchi, T. Ogaki, K. Kawabata, A. Ablat,""Manipulation" of crystal structure by methylthiolation enabling ultrahigh mobility in a pyrene-based molecular semiconductor", *Adv. Mater.*, 33, 2102914 (2021).
5. Y. Wang, K. Takimiya, "Naphthodithiophenediimide–Bithiopheneimide Copolymers for High-Performance n-Type Organic Thermoelectrics: Significant Impact of Backbone Orientation on Conductivity and Thermoelectric Performance", *Adv. Mater.*, 32, 2002060 (2020).

Kazuo Takimiya (D.Eng.), Group Director
takimiya@riken.jp

Research field

Chemistry, Engineering, Materials Science

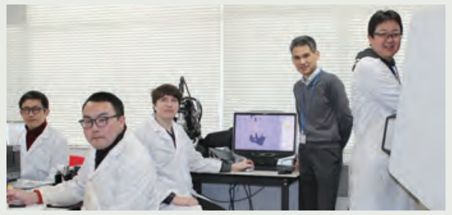
Keywords

Organic semiconductor, Pi-electronic compound, Organic Synthesis, Organic field-effect transistor, Organic solar cells, Organic thermoelectric materials

Brief resume

- 1994 Ph.D., Hiroshima University
- 1994 Research Associate, Hiroshima University
- 1997 Visiting Researcher, Odense University, Denmark
- 2003 Associate Professor, Hiroshima University
- 2007 Professor, Hiroshima University
- 2012 Team Leader, Emergent Molecular Function Research Team, RIKEN
- 2013 Group Director, Emergent Molecular Function Research Group, Supramolecular Chemistry Division, RIKEN CEMS
- 2017 Professor, Tohoku University (-present)
- 2018 Team Leader, Emergent Molecular Function Research Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science
- 2024 Group Director, Emergent Molecular Function Research Group, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)
- 2024 Deputy Director, RIKEN Center for Emergent Matter Science (-present)

Outline



Our research activity is based upon organic synthesis that can afford new organic materials utilized in optoelectronic devices, such as organic field-effect transistors (OFETs), organic solar cells (organic photovoltaics, OPVs), and organic thermoelectric devices (OTE). To this end, our team develops new organic materials, which can be designed and synthesized in order to have appropriate molecular and electronic structures for target functionalities. Our recent achievements are: 1) high-performance molecular semiconductors applicable to OFETs with the high mobilities, 2) new non-fullerene acceptors and their OPVs showing high power conversion efficiencies, and 3) new molecular design strategies to control packing structures of organic semiconductors.

Core members

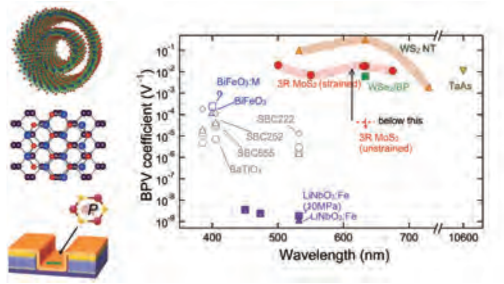
(Researcher) Barun Dhara
(Postdoctoral Researcher) Masanori Sawamoto, Kirill Bulgarevich, Haruki Sanematsu
(Visiting Scientist) Kohsuke Kawabata

Emergent Device Research Group

Bulk photovoltaic effect induced by symmetry control of two-dimensional materials

Our team is studying nonreciprocal transport in semiconductors and superconductors. One of them is a bulk photovoltaic effect, where the photoelectric conversion occurs without PN junctions.

Monolayer transition metal dichalcogenides (TMDs) are two-dimensional materials with three-fold symmetry, which are known not to exhibit bulk photovoltaics. However, such a nanomaterial is capable of changing symmetry either by deforming or creating heterojunctions. This is a unique and important feature of nanomaterials that distinguishes them from bulk. Specifically, we have found strong bulk photovoltaic effects in the visible to infrared region in WS_2 nanotubes, WSe_2/black phosphorus van Waals heterojunctions, and strained MoS_2 (Refs. Nature 570, 349 (2019), 3, 5). We found that the shift current mechanism plays an important role in this photovoltaic effect. Symmetry-controlled nanomaterials showing such large photovoltaic effects will be a promising new platform for high-efficiency photovoltaics and sensors.



Left: Symmetry controlled TMDs. From the top, TMD nanotube, van der Waals heterostructure, and strained device. Copylight: Adapted from "Nature Nanotechnology 18, 36 (2023)." Right: Wave length dependence of bulk photovoltaic coefficient for nano TMDs.

Publications

1. H. Matsuoka, S. Kajihara, Y. Wang, Y. Iwasa, M. Nakano, " Band-driven switching of magnetism in a van der Waals magnetic semimetal", *Sci. Adv.*10, eadk1415 (2024).
2. R. D. Septianto, R. Miranti, T. Kikitsu, T. Hlkima, D. Hashizume, N. Matsushita, Y. Iwasa, S. Z. Bisri . "Enabling metallic behaviour in two-dimensional superlattice of semiconductor colloidal quantum dots", *Nat. Commun.*, 14, 2670 (2023).
3. Y. Dong, M. -M. Yang, M. Yoshii, S. Matsuoka, S. Kitamura, T. Hasegawa, N. Ogawa, T. Morimoto, T. Ideue, Y. Iwasa, "Giant bulk piezophotovoltaic effect in 3*R*-MoS_2", *Nat. Nanotechnol.* 18, 36-41(2023).
4. Y. Nakagawa, Y. Kasahara, T. Nomoto, R. Arita, T. Nojima, Y. Iwasa, "Gate-controlled BCS-BEC crossover in a two-dimensional superconductor", *Science*, 372, 190 (2021).
5. T. Akamatsu, T. Ideue, L. Zhou, Y Dong, S. Kitamura, M. Yoshii, D. Yang, M. Onga, Y. Nakagawa, K. Watanabe, T. Taniguchi, J. Laurienzo, J. Huang, Z. Ye, T. Morimoto, H. Yuan, Y. Iwasa, "A van der Waals interface that creates in-plane polarization and a spontaneous photovoltaic effect", *Science*, 372, 68-72 (2021).

Yoshihiro Iwasa (D.Eng.), Group Director
iwasay@riken.jp

Research field

Physics, Engineering, Chemistry, Materials Science

Keywords

2D materials, Nanotubes, Quantum dots, Superconductivity, Thermoelectric effect, Nonreciprocal transport, Anomalous photovoltaic effect

Brief resume

- 1986 Ph. D., University of Tokyo
- 1986 Research Associate, Department of Applied Physics, University of Tokyo
- 1991 Lecturer, Department of Applied Physics, University of Tokyo
- 1994 Associate Professor, School of Materials Science, Japan Advanced Institute of Science and Technology
- 2001 Professor, Institute for Materials Research, Tohoku University
- 2010 Professor, Quantum-Phase Electronics Center, University of Tokyo
- 2010 Team Leader, Strong-Correlation Hybrid Materials Research Team, RIKEN
- 2013 Team Leader, Emergent Device Research Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science
- 2024 Group Director, Emergent Device Research Group, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)
- 2024 Deputy Director, RIKEN Center for Emergent Matter Science (-present)

Outline

The purpose of our team is to discover novel properties and create revolutionary functions, based on nanodevices of two-dimensional (2D) materials, 1D nanotubes, and 0D quantum dots (QD) of various oxides and chalcogenides. Our focus is superconductivity, phase transitions, and nonreciprocal transport, using 2D materials and their van der Waals heterostructures, and a wide range of carrier density tuning using electric double layer transistors. We also develop several novel solution-processable QDs, assemble them into various arrangements, and realize various functionalities including thermoelectricity, photovoltaics, and charge storage.

Core members

(Special Postdoctoral Researcher) Yuki Itahashi
(Postdoctoral Researcher) Ricky Dwi Septianto, Takashi Shitaokoshi, Dong Li
(International Program Associate) Retno Dwi Wulandari, Thanyarat Phutthaphongloet, Alec Paul Romagosa

Emergent Bioinspired Soft Matter Research Team

Mechanically polar gel for rectifying materials, energies, and creatures against the increase of entropy

Materials that respond to external stimuli in a polar fashion, i.e. they respond differently to stimuli applied from the left or right, have attracted increasing attention. While materials that exhibit polar response to electrical, magnetic, and optical stimuli have been studied for many years, those exhibiting polar response to mechanical force have not even been imagined. As a first example, we have developed a composite gel composed of obliquely oriented graphene-oxide nanosheets embedded in a three-dimensional polymer network. When the gel is subjected to leftward shear, the nanosheets immediately buckle and lose their reinforcing ability, causing the gel to deform easily. In contrast, under rightward shear, the nanosheets do not buckle and continue to reinforce the gel. There is a 67-fold difference in stiffness between the left and right shear, and the gel behaves like a one-way door. As a result, the gel can perform a variety of functions against the increase of entropy, such as generating asymmetric vibrations from symmetric or random vibrations, transporting contacting objects in one direction, asymmetrically bouncing colliding objects, and causing a group of small worms to migrate in one direction.

Mechanically polar gel for rectifying materials, energies, and creatures

Publications

1. X. Wang, Z. Li, S. Wang, K. Sano, Z. Sun, Z. Shao, A. Takeishi, S. Matsubara, D. Okumura, N. Sakai, T. Sasaki, T. Aida, and Y. Ishida, "Mechanical non-reciprocity in a uniform composite material", *Science*, 380, 192 (2023).
2. K. Sano, N. Igarashi, Y. Ebina, T. Sasaki, T. Hikima, T. Aida, and Y. Ishida, "A mechanically adaptive hydrogel with a reconfigurable network consisting entirely of inorganic nanosheets and water", *Nat. Commun.*, 11, 6026 (2020).
3. K. Salikolimi, V. K. Praveen, A. A. Sudhakar, K. Yamada, N. N. Horimoto, and Y. Ishida, "Helical supramolecular polymers with rationally designed binding sites for chiral guest recognition", *Nat. Commun.*, 11, 2311 (2020).
4. Y. S. Kim, M. Liu, Y. Ishida, Y. Ebina, M. Osada, T. Sasaki, T. Hikima, M. Takata, and T. Aida, "Thermoresponsive actuation enabled by permittivity switching in an electrostatically anisotropic hydrogel", *Nat. Mater.*, 14, 1002 (2015).
5. M. Liu, Y. Ishida, Y. Ebina, T. Sasaki, T. Hikima, M. Takata, and T. Aida, "An anisotropic hydrogel with electrostatic repulsion between cofacially aligned nanosheets", *Nature*, 517, 68 (2015).

Yasuhiro Ishida (D.Eng.), Team Leader
y-ishida@riken.jp

Research field

Chemistry, Materials Science

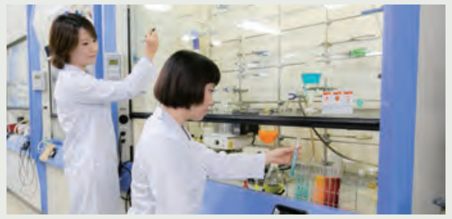
Keywords

Biomimetics, Soft material, Anisotropy, Autonomy, Polarity, Hierarchy

Brief resume

- 2001 D.Eng., University of Tokyo
- 2001 Assistant Professor, Graduate School of Frontier Sciences, University of Tokyo
- 2002 Assistant Professor, Graduate School of Engineering, University of Tokyo
- 2007 Lecturer, Graduate School of Engineering, University of Tokyo
- 2007 Researcher, PRESTO, Japan Science and Technology Agency
- 2009 Team Leader, Nanocomposite Soft Materials Engineering Team, RIKEN
- 2010 Team Leader, Bioinspired Material Research Team, RIKEN
- 2013 Team Leader, Emergent Bioinspired Soft Matter Research Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)

Outline



Owing to intrinsic similarity to living organisms, such as lightweight, softness, and biocompatibility, soft materials have attracted increasing attention for biomedical applications, including artificial organs. However, in terms of structure, there is a significant difference between synthetic soft materials and living organisms; most synthetic soft materials are of isotropic structures, while living tissues are anisotropic. As seen in muscular, bone, and nerval textures, such anisotropic structures play critical roles for exhibiting their superb functions. By using external fields for orienting constituents, we have developed various anisotropic soft materials with highly oriented structure and unprecedented unique functions reminiscent of living organisms.

Core members

(Expert Technician) Kuniyo Yamada
(Research Scientist) Xiang Wang
(Postdoctoral Researcher) Qifeng Mu, Yunlei Zhang
(Technical Staff) Hayato Kanai
(International Program Associate) Chia-Hsin Lin
(Student Trainee) Xiaoyao Wei, Yitong Xie

Emergent Soft System Research Team

Ultraflexible, high-performance and stable organic solar cells

One of the requirements of the Internet of Things—referring to a world where devices of all sorts are connected to the Internet—is the development of power sources for a host of devices, including devices that can be worn on the body. These could include sensors that record heartbeats and body temperature, for example, providing early warning of medical problems. In the past, attempts have been made to create photovoltaics that could be incorporated into textiles, but typically they lacked at least one of the important properties—long-term stability in both air and water, energy efficiency, and robustness including resistance to deformation—that are key to successful devices.

We have developed an ultraflexible organic photovoltaic (OPV) that achieves sufficient thermal stability of up to 120 °C and a high power conversion efficiency of 13% with a total thickness of 3 μm. Additionally, our ultraflexible organic solar cells exhibit prolonged device storage lifetime to >3,000 h at room temperature. Our ultraflexible OPVs possessing extraordinary thermal durability allow a facile bonding onto textiles through the hot-melt adhesive technology.

(Left) Ultraflexible organic solar cells manufactured on a 1 μm-thick plastic film.
(Right) Photograph of the washing process for the devices conforming to a dress shirt.

Publications

1. S. Xiong, K. Fukuda, K. Nakano, S. Lee, Y. Sumi, M. Takakuwa, D. Inoue, D. Hashizume, B. Du, T. Yokota, Yi. Zhou, K. Tajima, and T. Someya*, "Waterproof and ultraflexible organic photovoltaics with improved interface adhesion", *Nat. Commun.*, 15, 681 (2024).
2. Z. Jiang, N. Chen, Z. Yi, J. Zhong, F. Zhang, S. Ji, R. Liao, Y. Wang, H. Li, Z. Liu, Y. Wang, T. Yokota, X. Liu, K. Fukuda, X. Chen, and T. Someya, "A 1.3-micrometre-thick elastic conductor for seamless on-skin and implantable sensors", *Nat. Electron.*, 5, 784-793 (2022).
3. Y. Kakei, S. Katayama, S. Lee, M. Takakuwa, K. Furusawa, S. Umezu, H. Sato, K. Fukuda, and T. Someya, "Integration of body-mounted ultrasoft organic solar cell on cyborg insects with intact mobility", *npj Flex. Electron.*, 6, 78 (2022).
4. M. Takakuwa, K. Fukuda, T. Yokota, D. Inoue, D. Hashizume, S. Umezu, T. Someya, "Direct gold bonding for flexible integrated electronics", *Sci. Adv.*, 7, eabl6228 (2021).
5. S. Park, S.-W. Heo, W. Lee, D. Inoue, Z. Jiang, K. Yu, H. Jinno, D. Hashizume, M. Sekino, T. Yokota, K. Fukuda, K. Tajima, and T. Someya "Self-powered ultra-flexible electronics via nano-grating-patterned organic photovoltaics", *Nature*, 551, 516-521 (2018).

Takao Someya (Ph.D.), Team Leader
takao.someya@riken.jp

Research field

Electronic Engineering, Materials Science

Keywords

Organic electronics, Organic field-effect transistor, Organic light emitting devices, Organic solar cells, Organic sensors

Brief resume

- 1997 Ph.D., Electronic Engineering, University of Tokyo
- 1997 Research Associate, University of Tokyo
- 1998 Lecturer, University of Tokyo
- 2001 JSPS Postdoctoral Fellowship for Research Abroad (Columbia University)
- 2002 Associate Professor, University of Tokyo
- 2009 Professor, University of Tokyo (-present)
- 2015 Chief Scientist, Thin-film deice lab, RIKEN (-present)
- 2015 Team Leader, Emergent Soft System Research Team, Supramolecular Chemistry Division, RIKEN CEMS (-present)
- 2020 Dean, School of Engineering, University of Tokyo (-2023)
- 2023 Executive Director and Vice President, University of Tokyo (-present)

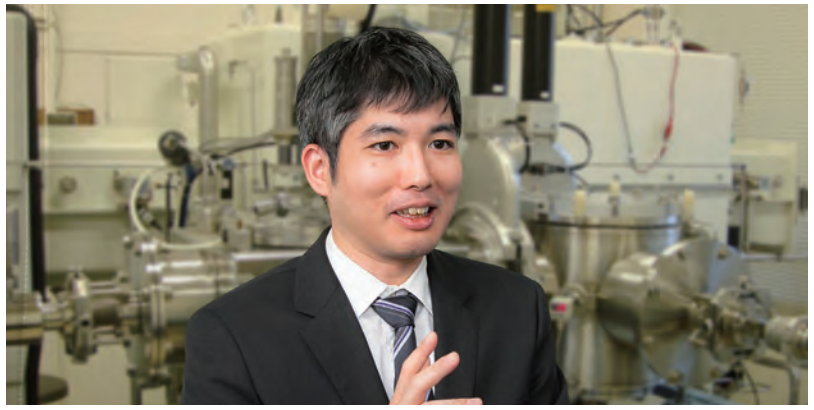
Outline

Electronics is expected to support the foundation of highly develop ICT such as Internet of Things (IoT), artificial intelligence (AI), and robotics. In addition to improve the computing speed and storage capacity, it is required to minimize negative impact of machines on environment and simultaneously to realize the harmony between human and machines. We make full use of the novel soft electronic materials such as novel organic semiconductors in order to fabricate emergent thin-film devices and, subsequently, to realize emergent soft systems that exhibit super-high efficiency and harmonization with humans. The new soft systems have excellent features such as lightweight and large area, which are complimentary to inorganic semiconductors, are expected to open up new eco-friendly applications.

Core members

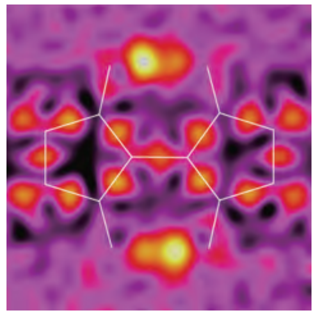
(Senior Research Scientist) Kenjiro Fukuda
(Research Scientist) Sunghoon Lee
(Postdoctoral Researcher) Sixing Xiong, Ruiqi Guo
(Visiting Scientist) Younguk Cho
(Visiting Researcher) Wang Shuxu
(Senior Technical Staff) Shin Young Lee
(Student Trainee) Baocai Du, Wenqing Wang, Karin Iwa
(Junior Research Associate) Shumpei Katayama

Emergent Functional Polymers Research Team



Organic semiconductors exhibiting intramolecular double proton transfer

To investigate potential applications of the 3,3′ -dihydroxy-2,2′ -biindan-1,1′ -dione (BIT) structure as an organic semiconductor with intramolecular hydrogen bonds, a new synthetic route under mild conditions is developed based on the addition reaction of 1,3-dione to ninhydrin and the subsequent hydrogenation of the hydroxyl group. This route affords several new BIT derivatives, including asymmetrically substituted structures that are difficult to access by conventional high-temperature synthesis. The BIT derivatives exhibit rapid tautomerization by intramolecular double proton transfer in solution. The tautomerizations are also observed in the solid state by variable temperature measurements of X-ray diffractometry and magic angle spinning 13C solid-state NMR. Possible interplay between the double proton transfer and the charge transport is suggested by quantum chemical calculations. The monoalkylated BIT derivative with a lamellar packing structure suitable for lateral charge transport in films shows a hole mobility of up to 0.012 $cm^2 V^{-1} s^{-1}$ with a weak temperature dependence in an organic field effect transistor.



Electron density difference analysis of X-ray structure analysis has observed protons exchanging between two positions in the center of the molecule.

Publications

1. K. Nakano, Y. Kaji, and K. Tajima, "Origin of electric field-dependent charge generation in organic photovoltaics with planar and bulk heterojunctions", *J. Mater. Chem. A*, 11, 26499 (2023).
2. K. Nakano, I-W. Leong, D. Hashizume, K. Bulgarevich, K. Takimiya, Y. Nishiyama, T. Yamazaki, and K. Tajima, "Synthesis of 3,3'-dihydroxy-2,2'-diindan-1,1'-dione derivatives for tautomeric organic semiconductors exhibiting intramolecular double proton transfer", *Chemical Science*, 14, 12205 (2023).
3. W.-C. Wang, K. Nakano, Y. Tanaka, K. Kurihara, H. Ishii, K. Adachi, D. Hashizume, C.-S. Hsu, and K. Tajima, "Stable spontaneous orientation polarization by widening the optical band gap with 1,3,5,7-tetrakis (1-phenyl-1H-benzo[d]imidazol-2-yl)adamantane", *J. Mater. Chem. C*, 11, 13039 (2023).
4. R. Suzuki, Y. Ochiai, K. Nakano, M. Miyasaka, and K. Tajima, "Detrimental Effects of "Universal" Singlet Photocrosslinkers in Organic Photovoltaics", *ACS Appl. Energy Mater.*, 6, 9, 4982 (2023).
5. W.-C. Wang, K. Nakano, C.-S. Hsu, and K. Tajima, "Synthesis of 2,5,8-Tris(1-phenyl-1H-benzo [d]imidazol-2-yl)benzo[1,2-b:3,4-b':5,6-b"] Trithiophenes and Their Spontaneous Orientation Polarization in Thin Films", *ACS Appl. Mater. Interface*, 15, 16, 20294 (2023).

Keisuke Tajima (Ph.D.), Team Leader
keisuke.tajima@riken.jp

Research field

Chemistry, Engineering, Materials Science

Keywords

Organic electronics, Organic solar cells, Polymer synthesis, Self-assembly, Nanostructure control

Brief resume

2002 Ph.D., The University of Tokyo
2002 Postdoctoral Researcher, Northwestern University
2004 Research Associate, The University of Tokyo
2009 Lecturer, The University of Tokyo
2011 Associate Professor, The University of Tokyo
2011 PRESTO Researcher, Japan Science and Technology Agency (-2017)
2012 Team Leader, Emergent Functional Polymers Research Team, RIKEN
2013 Team Leader, Emergent Functional Polymers Research Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)

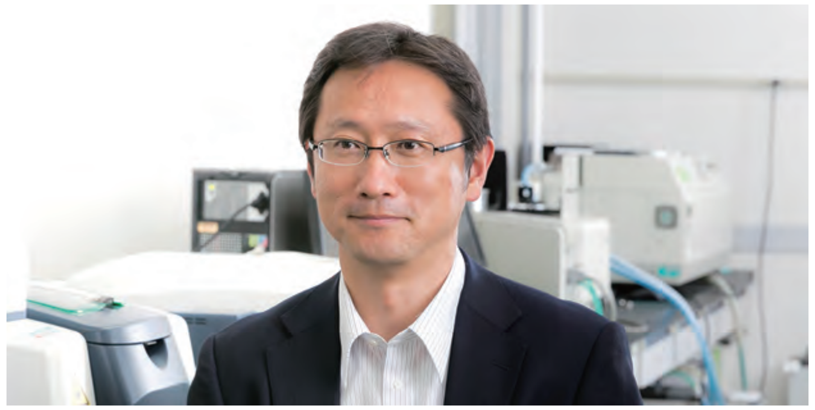
Outline

We work on the development of new organic semiconducting polymer materials and their application to organic electronic devices. Specifically, relying on the basic chemistry of the intermolecular interactions during the film forming process from the solutions, we seek the methodology and the molecular design to control the precise structures in molecular- and nano-scale at our will, and try to find breakthroughs to drastically enhance the performance of the organic electronic devices. Targets of our research are not only the conventional organic solar cells and field-effect transistors, but also the organic electronic devices with new functions based on the structure controls.

Core members

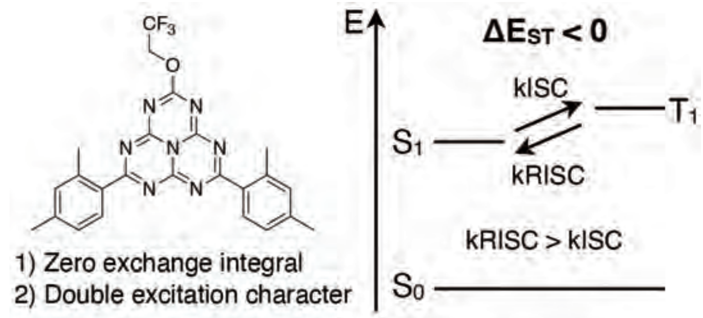
(Research Scientist) Kyohei Nakano
(Special Postdoctoral Researcher) Hitoshi Saito
(Postdoctoral Researcher) Takaho Yokoyama
(Technical Staff) Yumiko Kaji
(Junior Research Associate) Ryo Suzuki

Emergent Supramolecular Materials Research Team



Luminescence and excited states of the molecules with double excitation character

In molecular excited states, the energy level of S1 is higher than that of T1, because of the exchange energy of two electrons in the excited state derived from the Fermionic nature of electrons and the Pauli exclusion principle. Cyclazine and heptazine derivative have been reported to have un-overlapped HOMO and LUMO and to possibly show negative ΔEST (E(S1) – E(T1)) (Leupin et al., JACS 1980; Ehrmaier et al., J. Phys. Chem. A 2019). We designed and synthesized the substituted heptazine molecule and experimentally proved its negative ΔEST of −11 meV by the temperature dependence of delayed fluorescence and transient absorption. Conventional DFT quantum chemical calculation with one-electron description gave the positive ΔEST, while wavefunction-based quantum chemical calculation gave the negative ΔEST, indicating the double excitation character of the molecule. The reverse intersystem crossing rate was faster than the intersystem crossing rate, and much shorter delayed fluorescence and transient EL lifetime were exhibited. These results are the demonstration of unique luminescence from the molecule with inverted S1 and T1 derived from double excitation character in the excited state.



Molecules showing the inverted singlet and triplet excited state and energy diagram

Publications

1. Y.-J. Pu, D. Valverde, J.-C. Sancho-García, Y. Olivier, "Computational Design of Multiple Resonance–Type BN Molecules for Inverted Singlet and Triplet Excited States", *J. Phys. Chem. A*, 127, 10189 (2023).
2. N. Aizawa, Y.-J. Pu, Y. Harabuchi, A. Nihonyanagi, R. Ibuka, H. Inuzuka, B. Dhara, Y. Koyama, K. Nakayama, S. Maeda, F. Araoka, D. Miyajima, "Delayed fluorescence from inverted singlet and triplet excited states", *Nature*, 609, 502 (2022).
3. J. Liu, K. Enomoto, K. Takeda, D. Inoue, Y.-J. Pu, "Simple Cubic Self-Assembly of PbS Quantum Dots by Finely Controlled Ligand Removal through Gel Permeation Chromatography", *Chem. Sci.*, 12, 10354 (2021).
4. T. Lee, K. Enomoto, K. Ohshiro, D. Inoue, T. Kikitsu, H.-D. Kim, Y.-J. Pu, D. Kim, "Controlling the Dimension of the Quantum Resonance in CdTe Quantum Dot Superlattices Fabricated via Layer-by-Layer Assembly", *Nat. Commun.*, 11, 5471 (2020).
5. K. Enomoto, D. Inoue, Y.-J. Pu, "Controllable 1D patterned assembly of colloidal quantum dots on $PbSO_4$ nanoribbons", *Adv. Funct. Mater.*, 29, 1905175 (2019).

Yong-Jin Pu (D.Eng.), Team Leader
yongjin.pu@riken.jp

Research field

Chemistry, Materials Science

Keywords

Excited State, Interstate Transition, Organic Semiconductor, Semiconductor Nanoparticle, Colloidal Quantum Dot

Brief resume

2002 D. Eng., Waseda University
2002 Research associate, Waseda University
2004 JSPS Postdoctoral Fellowship for Research Abroad (University of Oxford)
2006 Research associate, Yamagata University
2010 Associate Professor, Yamagata University
2013 PRESTO Researcher, Japan Science and Technology Agency
2017 Team Leader, Emergent Supramolecular Materials Research Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)

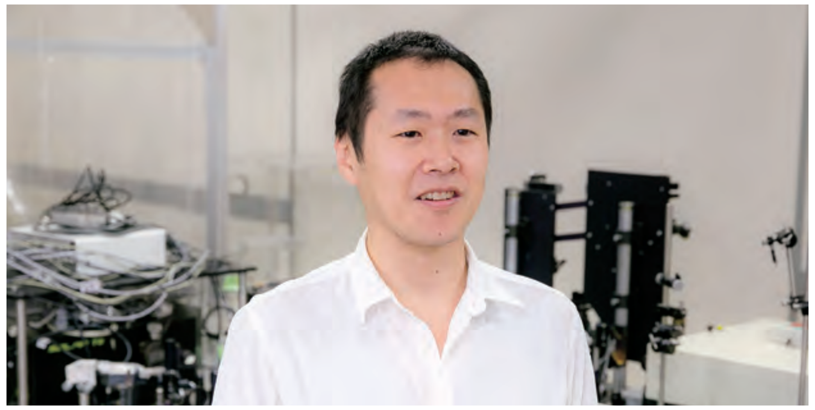
Outline

We precisely control the energy levels, interstate transition rate, luminescence efficiency, spin multiplicity etc. of organic/inorganic semiconductors and nanoparticles by their dynamic and static molecular structure, shape/size, chemical composition, and assembly pattern, for creating innovative energy-related technologies.

Core members

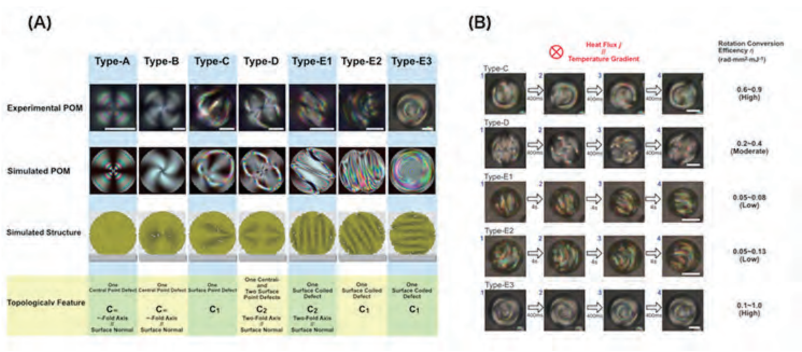
(Research Scientist)
Kazushi Enomoto, Ryutaro Komatsu
(Special Postdoctoral Researcher) Retno Miranti
(Postdoctoral Researcher) Rahul Singh, Guanhao Liu

Physicochemical Soft Matter Research Team



Topology-dependent lehmann rotation in chiral nematic emulsions

Lehmann rotation is a 'heat flow' -to- 'motion' energy conversion effect in liquid crystals, which was found in the end of the 19th century. In spite of the huge effort by physicists for more than 100 years, its physical mechanism has not been clear yet. On the other hand, topology is ubiquitous in liquid crystals which can be treated as continua to understand many other complex physical systems. In this research, it was proven that highly efficient Lehmann rotation is realizable even in emulsion states of a chiral liquid crystal dispersed in a fluorinated oligomer, in which topological diversity is confirmed depending on the droplet size and the strength of chirality. Interestingly, the estimated heat-rotation conversion rate therein significantly depends on these inner topological states of the droplets. This result is not merely important as a key to solve the long-persistent physical problem in Lehmann rotation, but also interesting for fundamental sciences related to topology.



(A) Topological diversity in a chiral nematic emulsion, (B) Lehmann rotation depending on the topological states.

Publications

1. H. Nishikawa, K. Sano and F. Araoka, "Anisotropic fluid with phototunable dielectric permittivity", *Nat. Commun.*, 13, 1142 (2022).
2. H. Nishikawa and F. Araoka, "A New Class of Chiral Nematic Phase with Helical Polar Order", *Adv. Mater.*, 33, 2101305 (2021).
3. S. Aya and F. Araoka, "Kinetics of motile solitons in nematic liquid crystals", *Nat. Commun.*, 11, 3248 (2020).
4. J. Yoshioka and F. Araoka, "Topology-dependent self-structure mediation and efficient energy conversion in heat-flux-driven rotors of cholesteric droplets", *Nat. Commun.*, 9, 432 (2018).
5. K. V. Le, H. Takezoe, and F. Araoka, "Chiral Superstructure Mesophases of Achiral Bent-Shaped Molecules – Hierarchical Chirality Amplification and Physical Properties", *Adv. Mater.*, 29, 1602737 (2017).

Fumito Araoka (D.Eng.), Team Leader
fumito.araoka@riken.jp

Research field

Physical and Structural Properties of Functional Organic Materials

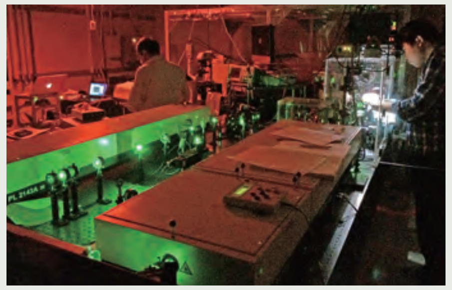
Keywords

Liquid crystals, Polymeric materials, Soft-matter physics, Optical properties, Organic nonlinear optics, Organic ferroelectrics

Brief resume

2003 Ph.D. in Engineering, Tokyo Institute of Technology, Japan
2003 Postdoctoral Researcher, Catholic University of Leuven, Belgium
2005 Postdoctoral Researcher, The University of Tokyo
2006 Postdoctoral Researcher, Tokyo Institute of Technology
2007 Assistant Professor, Tokyo Institute of Technology
2013 Unit Leader, Physicochemical Soft-Matter Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science
2018 Team Leader, Physicochemical Soft-Matter Research Team, RIKEN Center for Emergent Matter Science (-present)

Outline



Our team is mainly working on functionality of soft-matter systems from the viewpoints of physical experiments and analyses. In our research unit, particular attention is paid to liquid crystals due to their self-organizability leading to multifarious structures in which many interesting physical phenomena emerge. Our interest also covers potential applications of such soft-matter systems towards optical/electronic or chemical devices. For example, 1. Ferroelectric interactions and switching mechanisms in novel liquid crystalline ferroelectric materials, 2. Chirality related phenomena - origin and control of emergence, as well as applications of superstructure chirality in self-organized soft-matter systems, 3. Novel optical/electronic devices based on self-organized soft-matter systems.

Core members

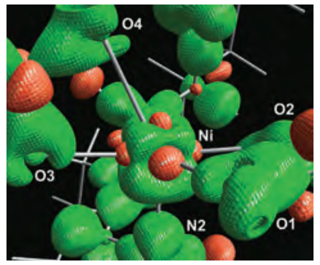
(Special Postdoctoral Researcher) Hiroya Nishikawa
(Researcher) Taishi Noma
(Postdoctoral Researcher) Daichi Okada
(JSPS PD Researcher) Keita Saito

Materials Characterization Support Team

Visualization of chemical bonds by accurate X-ray analysis

Our team has investigated the nature of molecules, which have unusual chemical bonds and show less stability, in the crystalline state by analyzing the distribution of valence electrons derived from accurate and precise single-crystal X-ray crystal structure analysis.

The conventional X-ray diffraction method clarifies the arrangement of atoms in the crystalline state by modeling total electron density distribution using spherical atom (isolated atom) models. As widely recognized, the resulting structures give important information on the nature of molecules. However, valence density distribution, which plays a critical role in the chemistry of molecules, is not included in the resulting models. For a deeper understanding of the nature and chemistry of the analyzed molecule, in particular, reactivity, charge separation, bonding mode, and intermolecular interaction, the valence densities should be analyzed. In this study, the valence densities are analyzed by applying multipole models instead of the spherical atom models to gain much direct information on the electronic structure of molecules.



Distribution of 3d-electrons in Ni(II) complex and bonding electrons
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Publications

1. S. Xiong, K. Fukuda, K. Nakano, S. Lee, Y. Sumi, M. Takakuwa, D. Inoue, D. Hashizume, B. Du, T. Yokota, Y. Zhou, K. Tajima, and T. Someya, "Waterproof and ultraflexible organic photovoltaics with improved interface adhesion", *Nat. Commun.*, 15, 681 (2024).
2. S. Kong, A. Li, J. Long, K. Adachi, D. Hashizume, Q. Jiang, K. Fushimi, H. Ooka, J. Xiao, and R. Nakamura, "Acid-stable manganese oxides for proton exchange membrane water electrolysis", *Nat. Catal.*, 7, 252 (2024).
3. K. Ueda, T. Yu, M. Hirayama, R. Kurokawa, T. Nakajima, H. Saito, M. Kriener, M. Hoshino, D. Hashizume, T. Arima, R. Arita, and Y. Tokura, "Colossal negative magnetoresistance in field-induced Weyl semimetal of magnetic half-Heusler compound", *Nat. Commun.*, 14, 6339 (2023).
4. H. Takagi, R. Takagi, S. Minami, T. Nomoto, K. Ohishi, M.-T. Suzuki, Y. Yanagi, M. Hirayama, N. D. Khanh, K. Karube, H. Saito, D. Hashizume, R. Kiyanagi, Y. Tokura, R. Arita, T. Nakajima, and S. Seki, "Spontaneous topological Hall effect induced by non-coplanar antiferromagnetic order in intercalated van der Waals materials", *Nat. Phys.*, 19, 961 (2023).
5. J. Nogami, D. Hashizume, Y. Nagashima, K. Miyamoto, M. Uchiyama, and K. Tanaka, "Catalytic stereoselective synthesis of doubly, triply and quadruply twisted aromatic belts", *Nat. Synth.*, 2, 888 (2023).

Daisuke Hashizume (D.Sci.), Team Leader
hashi@riken.jp

Research field

Structural Chemistry, Analytical Chemistry, Materials Science

Keywords

X-ray crystal structure analysis, Electron microscopy, Chemical analysis

Brief resume

1997 Tokyo Institute of Technology, PhD in Chemistry
1997 Research Associate, Department of Applied Physics and Chemistry, Univ. of Electro-Communications
2002 Research Scientist, Molecular Characterization Team, Advanced Development and Support Center, RIKEN
2011 Senior Research Scientist, Materials Characterization Team, Advanced Technology Support Division, RIKEN
2013 Unit Leader, Materials Characterization Support Unit, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science
2018 Team Leader, Materials Characterization Support Team, Supramolecular Chemistry Division, RIKEN Center for Emergent Matter Science (-present)

Outline

Our team provides research support using X-ray diffractometry, electron microscopy, and elemental analysis. In addition to supporting the individual method, we propose multifaceted research support by combining these methods. To keep our support at the highest quality in the world, we always update our knowledge and technical skills. We make tight and deep collaborations with researchers to achieve their scientific purposes and to propose new insights into the research from an analytical point of view, in addition to providing routine analysis. Beyond routine analysis, we explore and develop new measurement methods directed to more advanced and sophisticated analyses.

Core members

(Senior Technical Scientist) Keiko Suzuki
(Expert Technician) Daishi Inoue
(Technical Staff) Kiyohiro Adachi

Quantum Functional System Research Group

Quantum error correction with silicon spin qubits

Silicon-based spin qubits offer an outstanding nanofabrication capability for scaling up. Here we demonstrate a basic quantum error correction using silicon spin qubits. We implement a Toffoli-class three-qubit gate by a single pulse under simultaneous exchange coupling. We then synthesize a three-qubit repetition code to demonstrate the correction of a phase flip error on one of the three qubits.

We accurately control the three-spin system defined in a triple quantum dot of silicon/silicon-germanium by electric-dipole spin resonance and adiabatic pulsing of exchange coupling. We combine the single-qubit and two-qubit gates to encode a spin qubit state to a three-qubit entangled state. Then we implement a three-qubit Toffoli gate by a single rotation pulse under simultaneous nearest-neighbor exchange interaction.

We intentonally introduce a phase error with various error angles in one of the three qubits and measure the process fidelity of the data qubit with and without error correction. The measured fidelity decreases monotoniclly with increasing error angle withou error correciton,whereas well recovered with error correction, indicating the errror correciton protocol works well.

This is the first proof-of-principle experiment of error correciton in the spin qubit system, and will encourage development of scalable multi-qubit devices in silicon.

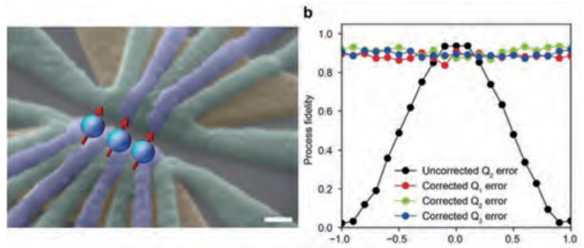


Figure (Left) Silicon three quantum bit device used for the experiment. (Right) Result of quantum phase error correction (Error recovery for the data qubit Q2).

Publications

1. J. Yoneda, J. S. Rojas-Arias, P. Stano, K. Takeda, A.Noiri, T. Nakajima, D. Loss, and S. Tarucha, "Noise-correlation spectrum for a pair of spin qubits in silicon", *Nat. Phys.* 19, 1793 (2023).
2. S. Matsuo, T. Imoto, T. Yokoyama, Y. Sato, T. Lindemann, S. Gronin, G.C. Gardner, M.J. Manfra, and S. Tarucha, "Josephson diode effect derived from short-range coherent coupling", *Nat. Phys.* 19, 1636 (2023).
3. K. Takeda, A. Noiri, T. Nakajima, T. Kobayashi, and S. Tarucha, "Quantum error correction with silicon spin qubits", *Nature* 608, 682-686 (2022).
4. A. Noiri, K. Takeda, T. Nakajima, T. Kobayashi, A. Sammak, G. Scappucci, and S. Tarucha, "Fast universal quantum gate above the fault-tolerance threshold in silicon", *Nature* 601, 338 (2022).
5. T. Nakajima, A. Noiri, K. Kawasaki, J. Yoneda, P. Stano, S. Amaha, T. Otsuka, K. Takeda, M.R. Delbecq, G. Allison, A. Ludwig, A. D. Wieck, D. Loss, and S. Tarucha, "Coherence of a driven electron spin qubit actively decoupled from quasi-static noise", *Phys. Rev. X* 10, 011060 (2020).

Seigo Tarucha (D.Eng.), Group Director
tarucha@riken.jp

Research field

Physics, Engineering

Keywords

Quantum information devices, Quantum entanglement, Quantum coherence, Topological particles

Brief resume

- 1978 Staff member at the Basic Research Laboratories of Nippon Tel. & Tel. Corp.
- 1990 Leader, Research Program on Electron Transport in Low-Dimensional Semiconductor Structures, NTT Basic Research Laboratories(-1998)
- 1998 Professor, Department of Physics, University of Tokyo
- 2004 Professor, Department of Applied Physics, University of Tokyo (-present)
- 2013 Group Director, Quantum Functional System Research Group, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
- 2018 Deputy Director, RIKEN Center for Emergent Matter Science
- 2020 Team Leader, Semiconductor Quantum Information Device Research Team, RIKEN Center for Quantum Computing (-present)
- 2024 Team Leader, Emergent Phenomena Observation Technology Research Team, RIKEN Center for Emergent Matter Science (-present)

Outline

Quantum information processing is an ideal information technology whose operation accompanies low-energy dissipation and high information security. We aim at demonstrating the ability of the solid-state information processing, and finally paving the way for the realization with innovative concepts and technology. The specific research targets are implementation of small-scale quantum processing circuits with spins in silicon, development of control methods of quantum coherence and entanglement in the circuits, and development of innovative quantum information devices, and in addition development of control methods of topological particles providing new concepts of quantum information.

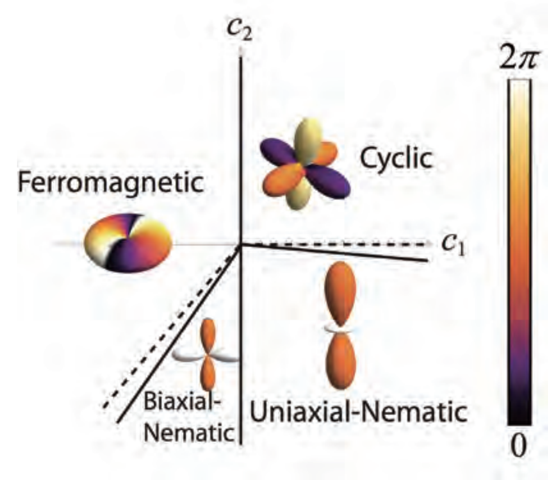
Core members

(Senior Research Scientist)
Takashi Nakajima, Kenta Takeda
(Research Scientist) Akito Noiri, Leon Camenzind
(Postdoctoral Researcher)
Ikkyeong Jin, Oliver Kurtossy Csaba
(Visiting Researcher) Jacob Francis Chittock-wood
(Senior Visiting Scientist) Michael Desmond Fraser
(Visiting Scientist) Tomohiro Otsuka, Sadashige Matsuo, Raisei Mizokuchi
(Technical Staff I) Soichiro Teraoka
(International Program Associate) Yi-Hsien Wu
(Junior Research Associate) Chutian Wen
(Student Trainee) Shohei Kobayashi, Ryutaro Matsuoka, Yuto Arakawa, Ai Hirade

Quantum Condensate Research Team

Topological excitations in Bose-Einstein condensates

Bose-Einstein condensates offer a cornucopia of symmetry breaking because a rich variety of internal degrees of freedom are available depending on the atomic species. We have used these degrees of freedom to explore various aspects of symmetry breaking and topological excitations. Among them are the so-called Kibble-Zurek mechanism in which the order parameter develops singularities after some parameter of the system is suddenly quenched. Ordinary vortices and spin vortices are found to emerge. We also investigate novel topological phenomena such as knot excitations in an antiferromagnetic Bose-Einstein condensate.



Ground-state phase diagram of a spin-2 Bose-Einstein condensate (BEC). Depending on the phase, different topological excitations appear.

Publications

1. L. Dabelow and M. Ueda, Three learning stages and accuracy-efficiency tradeoff of restricted Boltzmann machines, *Nat. Commun.* 13, 5474 (2022)
2. E. Yukawa and M. Ueda, "Mophological Superfluid in a Nonmagnetic Spin-2 Bose-Einstein Condensate", *Phys. Rev. Lett.*, 124, 105301 (2020).
3. K. Kawabata, K. Shiozaki, M. Ueda and M. Sato, "Symmetry and Topology in Non-Hermitian Physics", *Phys. Rev. X*, 9, 041015 (2019).
4. K. Kawabata, S. Higashikawa, Z. Gong, Y. Ashida, and M. Ueda, "Topological unification of time-reversal and particle-hole symmetries in non-Hermitian physics", *Nat. Commun.*, 10, 297 (2019). [selected as Editors' Highlights]
5. Z. Gong, Y. Ashida, K. Kawabata, K. Takasan, S. Higashikawa, and M. Ueda, "Topological Phases of Non-Hermitian Systems", *Phys. Rev. X*, 8, 031079 (2018). [Viewpoint was published in "Miguel A. Bandres and Mordechai Segev, Physics, 11, 96 (2018)"]

Masahito Ueda (Ph.D.), Team Leader
masahito.ueda@riken.jp

Research field

Physics, Engineering, Mathematics, Multidisciplinary

Keywords

Cold atoms, Bose-Einstein condensates, Nonequilibrium open quantum systems, Quantum thermodynamics

Brief resume

- 1988 Resercher, NTT Basic Research Laboratories
- 1994 Associate Professor, Hiroshima University
- 2000 Professor, Tokyo Institute of Technology
- 2008 Professor, University of Tokyo (-present)
- 2014 Team Leader, Quantum Condensate Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

We aim to explore physics frontiers that lie at the boarderlines between quantum physics, quantum measurement, information, thermodynamics, and machine learning. In particular, we exploit nonequilib-rium open quantum physics and quantum thermody-namics by using ultracold atoms in which almost all parameters such as the interparticle interaction are tunable.

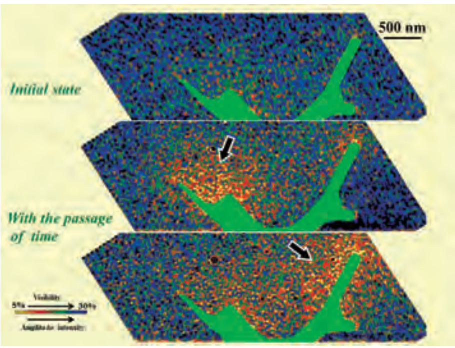
Core members

(Postdoctoral Researcher) Kai Li
(Visiting Scientist) Xingyuan Zhang

Emergent Phenomena Observation Technology Research Team

In situ observation of accumulation and collective motion of electrons

Comprehensive understanding of electromagnetic fields requires their visualization both inside and outside of materials. Since electromagnetic fields originate from various motions of electrons, comprehensive study of motions of electrons is of vital importance as well as of significant interest for understanding various emergent phenomena. The purpose of this study is to extend electron holography technology to visualize motions of electrons. By detecting electric field variations through amplitude reconstruction processes for holograms, we have succeeded in visualizing collective motions of electrons around various insulating materials. The lower right figures below show one of our experimental results of visualization of the collective motions of electrons around microfibrils of sciatic nerve tissue. In these reconstructed amplitude images, the bright yellow regions indicate the area where electric field fluctuates due to the motions of electrons. At the initial state (top figure),the electric field variations are not prominent. When the electron irradiation continues, however, bright yellow regions appear and the position of the regions changes gradually between the two branches as indicated by black arrows in the lower figures. These results indicate that the collective motions of electrons can be detected through electric field variation and can be visualized through amplitude reconstruction process for holograms.



Reconstructed amplitude images around microfibrils of sciatic nerve tissue (green).The bright yellow regions indicate the area where electric field fluctuates due to the motions of electrons.

Publications

1. K. Niitsu, Y. Liu, A. C. Booth, X. Yu, N. Mathur, M. J. Stolt, D. Shindo, S. Jin, J. Zang, N. Nagaosa and Y. Tokura "Geometrically stabilized skyrmionic vortex in FeGe tetrahedral nanoparticles", *Nat. Mater.*, 21,305 (2022).
2. H. Idzuchi, F.Pientka, K.-F. Huang, K. Harada, Ö. Gül, Y. J. Shin, L. T. Nguyen,N.H.Jo,D. Shindo, R. J. Cava, P. C. Canfield, and P. Kim,"Unconventional supercurrent phase in Ising superconductor Josephson junction with atomically thin magnetic insulator", *Nat. Commun.*,12, 5332,1 (2021).
3. D. Shindo, Z. Akase "Direct observation of electric and magnetic fields of functional materials", *Materials Science and Engineering: R.*, 142, 100564,1 (2020).
4. D. Shindo, T. Tanigaki, and H. S. Park, "Advanced electron holography applied to electromagnetic field study in materials science", *Adv. Mater.*, 29,1602216,1 (2017).
5. M. Nakamura, F. Kagawa, T. Tanigaki, H. S. Park, T. Matsuda, D. Shindo, Y. Tokura, and M. Kawasaki, "Spontaneous polarization and bulk photovoltaic effect driven by polar discontinuity in $LaFeO_3/SrTiO_3$ heterojunctions", *Phys. Rev. Lett.*, 116(15), 156801,1 (2016).

Seigo Tarucha (D.Eng), Team Leader
tarucha@riken.jp

Research field

Physics, Engineering, Materials Science

Keywords

Imaging, Electron microscopy, Lorentz microscopy, Flux quantum, Electron holography, Nanomagnetism

Brief resume

- 1978 Staff member at the Basic Research Laboratories of Nippon Tel. & Tel. Corp.
- 1990 Leader, Research Program on Electron Transport in Low-Dimensional Semiconductor Structures, NTT Basic Research Laboratories(-1998)
- 1998 Professor, Department of Physics, University of Tokyo
- 2004 Professor, Department of Applied Physics, University of Tokyo (-present)
- 2013 Group Director, Quantum Functional System Research Group, Division Director, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
- 2018 Deputy Director, RIKEN Center for Emergent Matter Science
- 2020 Team Leader, Semiconductor Quantum Information Device Research Team, RIKEN Center for Quantum Computing (-present)
- 2024 Team Leader, Emergent Phenomena Observation Technology Research Team, RIKEN Center for Emergent Matter Science (-present)

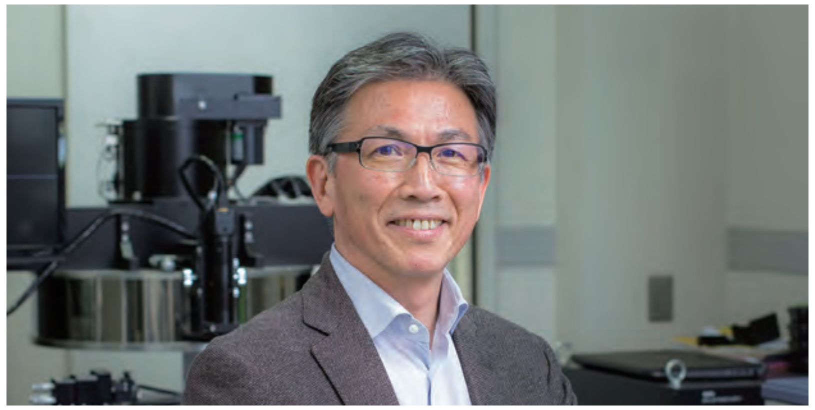
Outline

For observing and analyzing emergent matter phenomena, we use advanced electron microscopy, especially electron holography. Electron holography is a leading-edge observation technology that utilizes interference effects of electron waves and visualizes electromagnetic fields on the nanometer scale. By developing multifunctional transmission electron microscope-specimen holders equipped with plural probes, changes in the electromagnetic fields in and around specimens under applied voltages and magnetic fields are quantitatively investigated. By improving resolutions and precisions of these observation technologies, we can extensively study mechanisms of emergent matter phenomena in newly designed specimens for investigating many-body systems with multiple degrees of freedom.

Core members

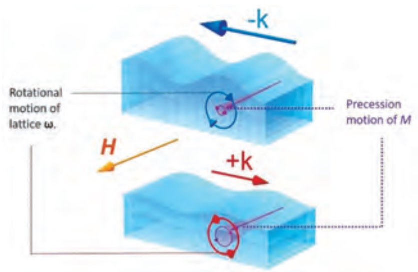
(Senior Research Scientist) Ken Harada
(Technical Scientist) Yoh Iwasaki
(Technical Staff) Keiko Shimada

Quantum Nano-Scale Magnetism Research Team



Towards the new vision of Spintronics Devices: Spin to charge conversion induced by mechanical oscillation.

Spin conversion, the key concept of Spintronics, describes various intriguing spin-mediated interconversion phenomena at the nanoscale between electricity, light, sound, vibration, and heat. The interaction between spin and mechanical oscillation prevails not well explored among the above. Our group has demonstrated the feasibility of a novel hybrid device's spin-mediated conversion of mechanical oscillation to electrical charge current. Surface acoustic waves (SAWs) across ferromagnetic layers induce periodic elastic deformation that drives precession magnetization dynamics such as ferromagnetic resonance (FMR), generating spin current flow into adjacent nonmagnetic layers. Interestingly, the coupling of SAWs with magnetic layers has more to offer. Our group has also demonstrated the nonreciprocal attenuation of SAWs via magneto-rotation coupling, a mechanism in which the magnetization couples to the rotational lattice motion (see figure). The achieved nonreciprocity values up to 100% opens up the route to application developments such as magneto-acoustic rectifiers. Beyond nonreciprocity, we are also exploring the enhancements of magnon-phonon coupling towards the strong coupling regime by using carefully designed acoustic cavities.



Schematics of the magneto-rotation coupling. Depending on the propagation direction, SAWs rotate the lattice in opposite directions (as indicted by the blue and red oriented cycles in the figure). This rotational lattice motion couples with the magnetization via magnetic anisotropies, giving rise to a circularly polarized effective field, which suppresses or enhances the magnetization precession (purple cone). In this way, it induces a nonreciprocal attenuation on the SAWs.

Publications

1. Y. Hwang, J. Puebla, K. Kondou, C. Gonzalez-Ballestero, H. Isshiki, C. S Sánchez Muñoz, L. Liao, F. Chen, W. Luo, S. Maekawa, and Y. Otani, "Strongly coupled spin waves and surface acoustic waves at room temperature", *Phys. Rev. Lett.,* 132, 056704 (2024).
2. J. Kim, J. Uzuhashi, M. Horio, T. Senoo, D. Go, D. Jo, T. Sumi, T. Wada, I. Matsuda, T. Ohkubo, S. Mitani, H-W. Lee, and Y. Otani, "Oxide layer dependent orbital torque efficiency in ferromagnet/Cu/oxide heterostructures", *Phys. Rev. Mater.* 7, L111401 (2023).
3. T. Lyons, J. Puebla, K. Yamamoto, R. Deacon, Y. Hwang, K. Ishibashi, S. Maekawa, and Y. Otani, "Acoustically driven magnon-phonon coupling in a layered antiferromagnet", (Editors selection), *Phys. Rev. Lett.* 131, 196701 (2023).
4. L. Liao, J. Puebla, K. Yamamoto, J. Kim, S. Maekawa, Y. Hwang, Y. Ba, and Y. Otani, "Valley-selective phonon-magnon scattering in magnetoelastic superlattices", *Phys. Rev. Lett.* 131, 176701 (2023).
5. N. Budai, H. Isshiki, R. Uesugi, Z. Zhu, T. Higo, S. Nakatsuji, & Y. Otani, "High-resolution magnetic imaging by mapping the locally induced anomalous Nernst effect using atomic force microscopy", Appl. Phys. Lett. 122, 102401 (2023).

Yoshichika Otani (D.Sci.), Team Leader
yotani@riken.jp

Research field

Physics, Engineering, Materials Science

Keywords

Nanomagnetism, Spintronics, Spin current, Spin Hall effect, Edelstein effect, Magnon-phonon coupling

Brief resume

- 1989 D.Sci.,Department of Physics, Keio University
- 1989 Research Fellow, Trinity College University of Dublin, Ireland
- 1991 Postdoctoral Researcher, Laboratoire Louis Néel, CNRS, France
- 1992 Research Instructor, Keio University
- 1995 Associate Professor, Tohoku University
- 2001 Team Leader, Quantum Nano-Scale Magnetics Team, RIKEN
- 2004 Professor, ISSP University of Tokyo (-present)
- 2013 Team Leader, Quantum Nano-Scale Magnetism Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

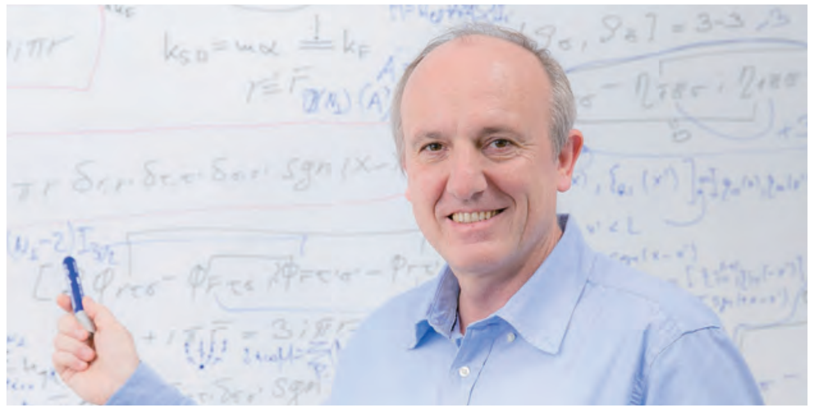
Outline

The Quantum Nano-Scale Magnetism Team fabricates ferromagnetic/nonmagnetic hybrid nanostructures from metals, semiconductors, insulators, and molecules to study quantum behaviors in domain wall displacement and magnetization dynamics mediated by spin current, a flow of spin angular momentum, and orbital current, a flow of orbital angular momentum. We focus our research on the fundamental process of interconversion and coupling between quasi-particles such as electron spin, magnon, phonon, and photon. In addition, we hope to develop a new technique for controlling spin conversion based on underlying exchange and spin-orbit interactions and a new class of low-power spintronic devices for novel energy harvesting.

Core members

(Senior Research Scientist) Kouta Kondou
(Research Scientist) Jorge Luis Puebla Nunez
(Postdoctoral Researcher) You Ba
(Student Trainee)
Liyang Liao, Sosuke Hori, Jiacheng Liu

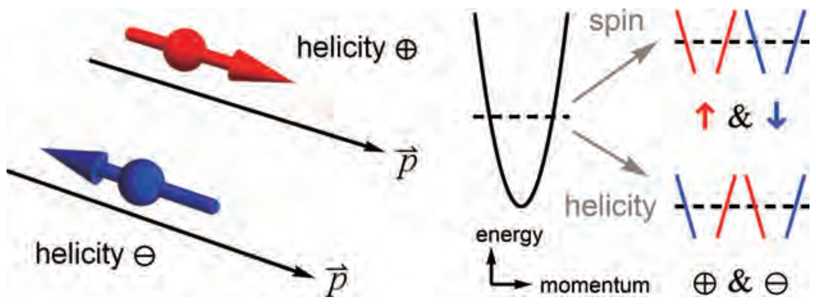
Quantum System Theory Research Team



Helical Liquids in Semiconductors

One-dimensional helical liquids can appear at boundaries of certain condensed matter systems. Two prime examples are the edge of a quantum spin Hall insulator, also known as a two-dimensional topological insulator, and the hinge of a three-dimensional second-order topological insulator. The presence of such states serves as a signature of their nontrivial bulk topology.

We investigate various aspects of helical liquids, such as their realization, topological protection and stability, or possible experimental characterization. We focus especially on proximity-induced topological superconductivity, allowing for exciting applications towards topological quantum computation with the resulting Majorana bound states.



Helicity. (Left) In particle physics, the helicity of a particle is defined through the relative orientation between its spin and momentum. (Right) In a condensed matter system hosting spin-1/2 fermions with quadratic dispersion, we can label the degenerate states near the Fermi level either by their spins or by their helicities. Unlike the spin, the states with opposite helicities can be split in a time-reversal-invariant system.
Chen-Hsuan Hsu, Peter Stano, Jelena Klinovaja, and Daniel Loss, "Helical Liquids in Semiconductors", Semicond. Sci. Technol. 36, 123003 (2021).© IOP Publishing

Publications

1. O. Malkoc, P. Stano, D. Loss, "Charge-noise induced dephasing in silicon hole-spin qubits", *Phys. Rev. Lett.* 129, 247701 (2022).
2. Ch.-H. Hsu, P. Stano, J. Klinovaja, D. Loss, "Helical Liquids in Semiconductors", *Semicond. Sci. Technol.* 36, 123003 (2021).
3. C.-H. Hsu, F. Ronetti, P. Stano, J. Klinovaja, and D. Loss, "Universal conductance dips and fractional excitations in a two-subband quantum wire", *Phys. Rev. Research* 2, 043208 (2020).
4. P. Aseev, P. Marra, P. Stano, J. Klinovaja, D. Loss, "Degeneracy lifting of Majorana bound states due to electron-phonon interactions", *Phys. Rev. B,* 99, 205435 (2019).
5. Ch.-H. Hsu, P. Stano, J. Klinovaja, D. Loss, "Majorana Kramers pairs in higher-order topological insulators", *Phys. Rev. Lett.,* 121, 196801 (2018).

Daniel Loss (Ph.D.), Team Leader
loss.daniel@riken.jp

Research field

Theoretical Physics,
Quantum Theory of Condensed Matter

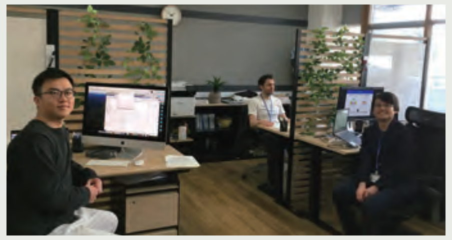
Keywords

Strongly correlated electron system, Nanodevice, Spin-orbit interaction, Topological quantum matter, Majorana fermions and parafermions

Brief resume

- 1985 Ph.D. in Theoretical Physics, University of Zurich, Switzerland
- 1985 Postdoctoral Research Associate, University of Zurich, Switzerland
- 1989 Postdoctoral Research Fellow, University of Illinois at Urbana-Champaign, USA
- 1991 Research Scientist, IBM T. J. Watson Research Center, USA
- 1993 Assistant Professor, Simon Fraser University, Canada
- 1995 Associate Professor, Simon Fraser University, Canada
- 1996 Professor, Department of Physics, University of Basel, Switzerland (-present)
- 2012 Team Leader, Emergent Quantum System Research Team, RIKEN
- 2013 Team Leader, Quantum System Theory Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
- 2021 Team Leader, Semiconductor Quantum Information Device Theory Research Team, RIKEN Center for Quantum Computing (-present)

Outline

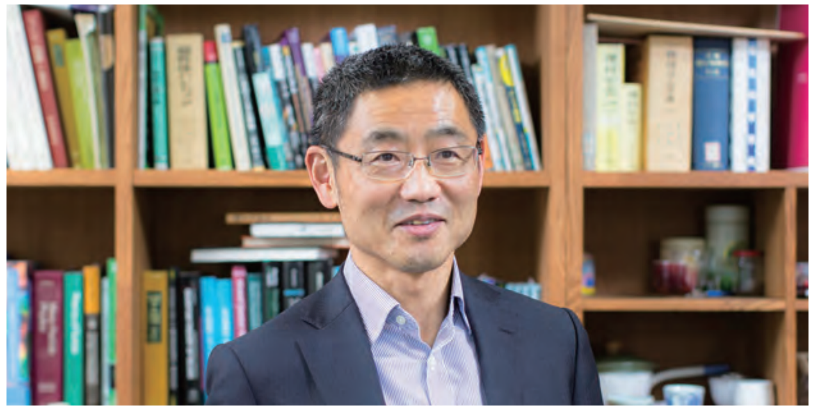


Our team works on the quantum theory of condensed matter with a focus on spin and topological phenomena in semiconducting and magnetic nanostructures. In particular, we investigate novel mechanisms and seek new platforms hosting topological or spin phases in solid-state systems, including helical spin texture, topological insulators and topological superconductors, which have potential hosting topological quantum states, such as Majorana fermions and parafermions. Moreover, we also investigate (quasi-)one-dimensional Tomonaga-Luttinger liquid, nuclear spins in semiconductors, many-body effects in low-dimensional systems, (fractional) quantum Hall effect, strongly correlated electron systems, spin-orbit interaction, and quantum transport phenomena.

Core members

(Senior Research Scientist) Peter Stano
(Research Scientist) Kazuki Nakazawa
(Postdoctoral Researcher) Guanxiong Qu

Spin Physics Theory Research Team



Microscopic theory of spintronics

Spin-charge conversion effects in spintronics have been conventionally argued based on the concept of spin current, which has a fundamental ambiguity that cannot be avoided arising from its non-conservation. We have presented a linear response theory formulation to describe the effects in terms of response functions between physical observable, free from ambiguity. Our formalism without phenomenological constants like spin mixing conductance is expected to be important for trustable predictions and designs of spintronics devices.

Theoretical description of spintronics effects in analogy with electromagnetism has also been carried out. The results would be useful for integration of spintronics into electronics.

In ferromagnetic metals, spin of electrons traveling through a magnetization structure follows the local spin and acquires a quantum phase. This phase acts as an effective electromagnetic fields that couples to electron spin.

Publications

1. H. Funaki, and G. Tatara, "Hydrodynamic theory of chiral angular momentum generation in metals", *Phys. Rev. Research*, 3, 023160(9) (2021).
2. G. Tatara, C. A. Akosa, and R. M. Otxoa de Zuazola, "Magnon pair emission from a relativistic domain wall in antiferromagnets", *Phys. Rev. Research*, 2, 043226(17) (2020).
3. G. Tatara, "Effective gauge field theory of spintronics", *Physica E: Low-dimensional Systems and Nanostructures*, 106, 208-238 (2019).
4. C. A. Akosa, O. A.Tretiakov, G. Tatara, and A. Manchon, "Theory of the Topological Spin Hall Effect in Antiferromagnetic Skyrmions: Impact on Current-Induced Motion", *Phys. Rev. Lett.*, 121, 097204(5) (2018).
5. T. Kikuchi, T. Koretsune, R. Arita, and G. Tatara, "Dzyaloshinskii-Moriya Interaction as a Consequence of a Doppler Shift due to Spin-Orbit-Induced Intrinsic Spin Current", *Phys. Rev. Lett.*,116, 247201 (1-6) (2016). (PRL Editors'Suggestion).

Gen Tatara (D.Sci.), Team Leader
gen.tatara@riken.jp

Research field

Physics, Engineering, Materials Science

Keywords

Spintronics, Spin-orbit interaction, Domain wall, Monopole, Spin current, Metamaterial

Brief resume

- 1992 Doctor of Science, Department of Physics, Faculty of Science, University of Tokyo
- 1992 Postdoctoral Fellow, The Department of Physics, Faculty of Science, University of Tokyo
- 1994 Postdoctoral Fellow, The Institute of Physical and Chemical Research, RIKEN
- 1996 Assistant Professor, Graduate School of Science, Osaka University
- 2004 PRESTO, Japan Science and Technology Agency
- 2005 Associate Professor, Graduate School of Science and Engineering, Tokyo Metropolitan University
- 2012 Team Leader, Emergent Spintronics Theory Research Team, RIKEN
- 2013 Team Leader, Spin Physics Theory Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

Our aim is to explore novel spin-related effects with extremely high efficiency in condensed matters. We thus contributes to development of spintronics, a technology using spin as well as charge of electrons, and to realization of ultrafast and high-density information technology with low energy consumption. Our particular interest is at present in a strong quantum relativistic effect in solids, which is applicable to very strong magnets and efficient conversion of spin information to an electric signal. Our main method is a field theory.

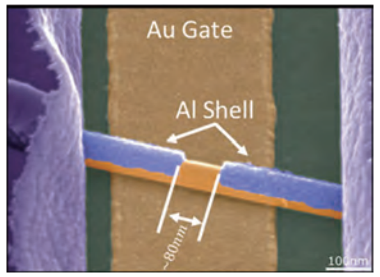
Core members

(Research Scientist)
Mohammad Hussein Naseef Al Assadi
(Postdoctoral Researcher) Terufumi Yamaguti
(Visiting Scientist) Collins Ashu Akosa

Quantum Effect Device Research Team

Towards Majorana qubit with superconductor/InAs nanowire hybrid structures

To maintain quantum coherence is an essential requirement for the quantum computer. But, it is really a tough requirement because of decoherence and noise that could easily induce error in the computing processes. Majorana zeromodes (MZMs), simply mentioned as Majorana fermion, could help to solve this difficulty as it is predicted to be robust against such local disturbance. Although Majorana fermion has not convincingly been demonstrated, we are trying to search for it in the superconductor/semiconductor nanowire and/or superconductor/topological insulator hybrid structures, in order to realize the "Majorana qubit". The figure shows a SNS (Super-Normal-Super) type Josephson junction with a InAs nanowire grown by molecular beam epitaxy (MBE) technique followed by the in-situ deposition of the Al contacts. We are trying to measure the energy spectrum of the MZMs by fabricating the RF-SQUID with the nanowire JJ and coupling it to the microwave resonator. This work has been carried out in collaboration with Prof. Thomas Schäpers in Julich Research Center in Germany.



Scanning electron microscope image of the InAs nanowire Josephson junction with Al contacts

Publications

1. M. D. Randle, M. Hosoda, R. S. Deacon, M. Ohtomo, P. Zellekens, K. Watanabe, T. Taniguchi, S. Okazaki, T. Sasagawa, K. Kawaguchi, S. Sato, and K. Ishibashi, "Gate-defined Josephson Weak-Links in Monolayer WTe_2," *Adv. Mater.*, 35, 2301683 (2023).
2. P. Zellekens, R. Deacon, P. Perla, D. Grützmacher, M. Lepsa, T. Schäpers, and K. Ishibashi, "Microwave spectroscopy of Andreev states in InAs nanowire-based hybrid junctions using a flip-chip layout", *Commun. Phys.*, 5, 267 (2022).
3. A. Hida and K. Ishibashi, "Exciton Controlled-NOT Gate Using Coupled Quantum Dots in Carbon Nanotube", *ACS Photonics*, 9, 3398 (2022).
4. R. Wang, R. S. Deacon, J. Sun, J. Yao, C. M. Lieber, K. Ishibashi, "Gate Tunable Hole Charge Qubit Formed in a Ge/Si Nanowire Double Quantum Dot Coupled to Microwave Photons", *Nano Lett.* 19, 1052 (2019).
5. R. S. Deacon, J. Wiedenmann, E. Bocquillon, T. M. Klapwijk, P. Leubner, C. Brüne, S. Tarucha, K. Ishibashi, H. Buhmann, L. W. Molenkamp, "Josephson radiation from gapless Andreev bound states in HgTe-based topological junctions", *Phys. Rev. X*, 7, 021011 (2017).

Koji Ishibashi (D.Eng.), Team Leader
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Research field

Engineering, Physics

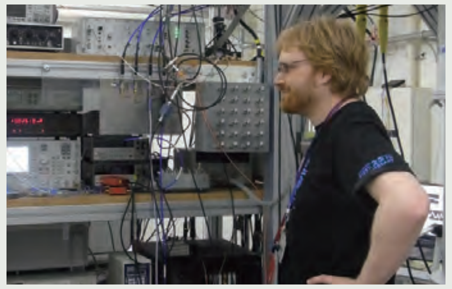
Keywords

Carbon nanotube, Semiconductor nanowire, Quantum dots, Topological superconductor, Quantum information devices

Brief resume

- 1988 D.Eng., Graduate School of Electrical Engineering, Osaka University
- 1988 Researcher, Frontier Research Program, RIKEN
- 1991 Researcher, Semiconductor Laboratory, RIKEN
- 1996 Visiting Researcher, Delft University of Technology, The Netherlands
- 2003 Chief Scientist, Advanced Device Laboratory, RIKEN (-present)
- 2003 Adjunct Professor, Chiba University (-current)
- 2005 Adjunct Professor, Tokyo University of Science (-present)
- 2013 Team Leader, Quantum Effect Device Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

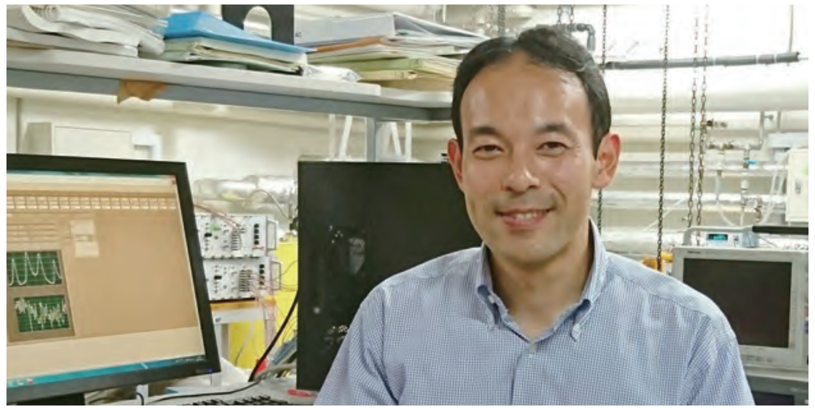


We study quantum effects that appear in nanoscale structures and apply them to functional nanodevice. We focus on hybrid nanostructures, such as carbon nanotube/molecule heterostructures and topological insulator or nanostructures/superconductor hybrid nanostructures as well as nanoscale Si transistors, to study quantum effects and to realize unique functionalities that enable us to control electrons, photons, excitons, and Cooper pairs on a single quantum level. With those, we develop quantum information devices and study physics behind them for future low-power nanoelectronics.

Core members

(Senior Research Scientist) Keiji Ono, Russell S. Deacon
(Special Post-Doctoral Researcher) Patrick Zellekens

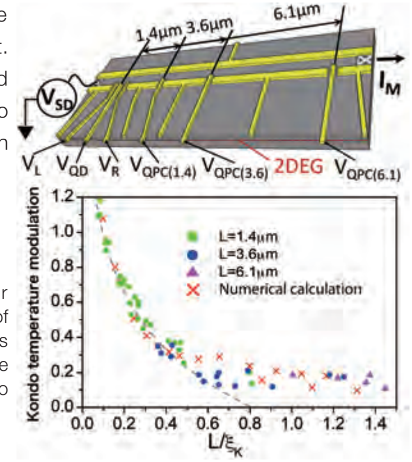
Quantum Electron Device Research Team



Electrical control and quantum simulation of the Kondo screening cloud

The Kondo effect, an archetype of many-body correlations, arises from the interaction between a localized spin and surrounding conducting electrons. Since conducting electrons form a spin cloud to screen the localized spin, the Kondo state is also called as the Kondo screening cloud. The size of the Kondo cloud is inverse proportional to the Kondo temperature and the cloud has the universal shape.

The Kondo cloud is formed by confining a localized spin in a semiconductor artificial atom coupled to conducting electrons. Our recent experiment has revealed that the quantum interference can deform the cloud and modulate the entanglement between the localized spin and conducting electron spins. We are now investigating systems, where multiple Kondo clouds overlap with one another. Such strongly correlated systems are quantum many-body states, where quantitative calculation of physical quantities is difficult. Precise control of quantum systems based on the tunable Kondo cloud is expected to enable quantum simulations of systems with long-range spin coupling.



Schematic illustration of the device used for observation of the Kondo cloud and real shape of the Kondo cloud. The Kondo cloud shape was obtained by quantifying the Kondo temperature modulation by the gate voltage VQPC applied to the quantum point contacts.

Figure taken from Nature 579, 210 (2020).

Publications

1. M. Tanaka, K. Watanabe, T. Taniguchi, K. Nomura, S. Tarucha, and M. Yamamoto, "Temperature-induced phase transitions in the correlated quantum Hall state of bilayer graphene", *Phys. Rev. B*, 105, 075427 (2022).
2. R. Ito, S. Takada, A. Ludwig, A. D. Wieck, S. Tarucha, and M. Yamamoto, "Coherent beam splitting of flying electrons driven by a surface acoustic wave", *Phys. Rev. Lett.*, 126, 070501 (2021).
3. M. Tanaka, Y. Shimazaki, I. V. Borzenets, K. Watanabe, T. Taniguchi, S. Tarucha, and M. Yamamoto, "Charge Neutral Current Generation in a Spontaneous Quantum Hall Antiferromagnet", *Phys. Rev. Lett.*, 126, 016801 (2021).
4. I. V. Borzenets, J. Shim, J. C. H. Chen, A. Ludwig, A. D. Wieck, S. Tarucha, H.-S. Sim, and M. Yamamoto, "Observation of the Kondo screening cloud", *Nature*, 579, 210 (2020).
5. Y. Shimazaki, M. Yamamoto, I. V. Borzenets, K. Watanabe, T. Taniguchi, and S. Tarucha, "Generation and detection of pure valley current by electrically induced Berry curvature in bilayer graphene", *Nat. Phys.*, 11, 1032 (2015).

Michihisa Yamamoto (D.Sci.), Team Leader
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Research field

Physics, Engineering

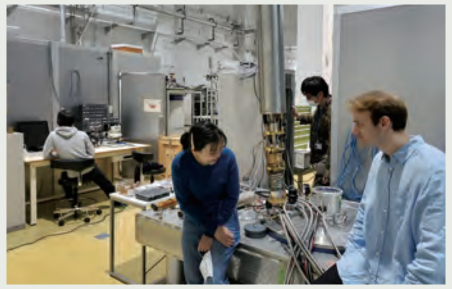
Keywords

Two-dimensional electron systems, Single electron manipulation, Nanodevices, Quantum coherence, Quantum correlations

Brief resume

- 2004 Ph. D. in Physics, The University of Tokyo, Japan
- 2004 Research Associate, Department of Applied Physics, The University of Tokyo
- 2014 Lecturer, Department of Applied Physics, The University of Tokyo
- 2017 Associate Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo
- 2017 Unit Leader, Quantum Electron Device Research Unit, RIKEN Center for Emergent Matter Science
- 2020 Team Leader, Quantum Electron Device Research Team, RIKEN Center for Emergent Matter Science (-present)
- 2023 Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo (-present)

Outline



We develop quantum electron devices based on manipulation and transfer of quantum degrees of freedom in solids. We employ quantum electron optics, where quantum states of propagating electrons are manipulated in a single electron unit, and experiments on transfer and manipulation of novel quantum degrees of freedom in atomic-layer materials. These experiments aim to reveal physics of quantum coherence, quantum correlations, and quantum conversions, as guiding principles for quantum electron devices. We also employ state of the art quantum technologies to solve long-standing problems in condensed matter physics from microscopic points of view.

Core members

(Research Scientist) Yuya Shimazaki
(Postdoctoral Researcher) Ngoc Han Tu
(Visiting Scientist) David Pomaranski

Emergent Spintronics Research Team

Eiji Saitoh (Ph.D.), Team Leader
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Research field

Physics, Engineering, Materials Sciences

Keywords

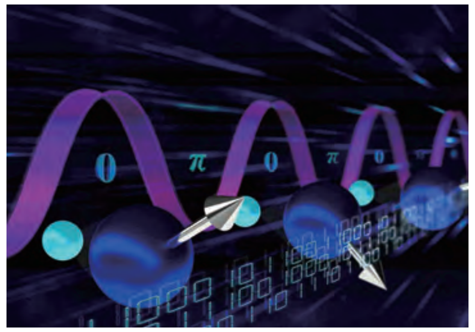
Spintronics, Energy conversion, Quantum device, Quantum information, Machine learning physics

Brief resume

- 2001 Ph.D., Engineering, University of Tokyo
- 2001 Research Associate, Department of Physics, Keio University
- 2006 Senior Lecturer, Department of Applied Physics, Keio University
- 2009 Professor, Institute for Materials Research, Tohoku University
- 2012 Professor, Principal Investigator at WPI-AIMR, Tohoku University
- 2018 Professor, Department of Applied Physics, University of Tokyo (-present)
- 2023 Team Leader, Emergent Spintronics Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

Creating the principles of future quantum devices with spintronics

Quantum spintronics provides essential guiding principles for achieving innovative devices. It explores the physics of the interaction between the spin degrees of freedom of electrons and the diverse ordering in condensed matter, bridging the way to practical applications. Spin dynamics exhibiting strong nonlinearity due to the shape effects of nano magnets demonstrate exotic responses such as squeezing and nonlinear bifurcation phenomena, which can be controlled by spin and electric currents. Research on prominent nonlinear parametric processes in nano magnets is conducted, paving the way for nonlinear and quantum regimes in collective spin excitations. In particular, quantum squeezed magnons (spin waves) associated with strong nonlinearity and high coherence serve as promising magnetic quantum information carriers, offering potential applications in quantum information electronics and quantum sensors (e.g., magnetic field sensors, thermal and thermal fluctuation sensors). Furthermore, thermally squeezed magnons hold promise for applications in thermal control and power generation devices. Additionally, beyond ferromagnetic order, various ordered phases exist in condensed matter, and their coupling with electric and spin currents can yield exciting results. Leveraging the spintronics measurement techniques in our group, we also explore new realms of material science that this coupling can bring.



Parametron in nano magnets

Outline

Our research team is conducting research on various quantum spintronics phenomena in nanoscale shape-controlled composite structures of magnetic materials, inorganic and organic semiconductors, and superconductors. Focusing on quantum spin dynamics, spin transport, and the interaction between spin and macroscopic order parameters, we are conducting experiments using methods such as transport measurements, optical measurements, and ultra low temperature microwave spectroscopy. Through this research, we aim to extend spintronics to the quantum domain, construct a fundamental physics system, and apply it to information processing and energy conversion.

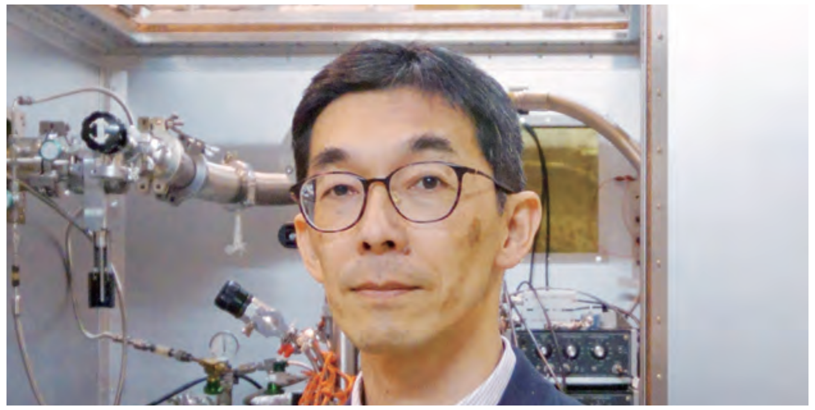
Core members

(Research Scientist) Takahiko Makiuchi
(Visiting Scientist)
Tomosato Hioki, Naoto Yokoi, Hiroki Arisawa

Publications

1. T. Makiuchi, T. Hioki, H. Shimizu, K. Hoshi, M. Elyasi, K. Yamamoto, N. Yokoi, A. A. Serga, B. Hillebrands, G. E. W. Bauer and, E. Saitoh,"Persistent magnetic coherence in magnets", *Nat. Mater.* (2024).
2. H. Arisawa, H. Shim, S. Daimon, T. Kikkawa, Y. Oikawa, S. Takahashi, T. Ono and, E. Saitoh, "Observation of spin-current striction in a magnet", *Nat. Commun.* 13, 2440 (2022).
3. S. Daimon, K. Tsunekawa, S. Kawakami, T. Kikkawa, R. Ramos, K. Oyanagi, T. Ohtsuki, and E. Saitoh, "Deciphering quantum fingerprints in electric conductance", *Nat. Commun.* 13, 3160 (2022).
4. T. Kikkawa, D. Reitz, H. Ito, T. Makiuchi, T. Sugimoto, K. Tsunekawa, S. Daimon, K. Oyanagi, R. Ramos, S. Takahashi, Y. Shiomi, Y. Tserkovnyak, and E. Saitoh, "Observation of nuclear-spin Seebeck effect", *Nat. Commun.* 12, 4356 (2021).
5. Y. Shiomi, J. Lustikova, S. Watanabe, D. Hirobe, S. Takahashi, and E. Saitoh, "Spin pumping from nuclear spin waves", *Nat. Phys.* 15, 22 (2019).
6. K. Uchida, S. Daimon, R. Iguchi, and E. Saitoh, "Observation of anisotropic magneto-Peltier effect in nickel", *Nature* 558, 95 (2018).

Topological Electronics Research Team



Minoru Kawamura (Ph. D.), Team Leader
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Research field

Physics, Engineering, Materials Sciences

Keywords

Topological insulators, Topological superconductors, Thin films and interfaces, Quantum transport phenomena, Anomalous Hall effect

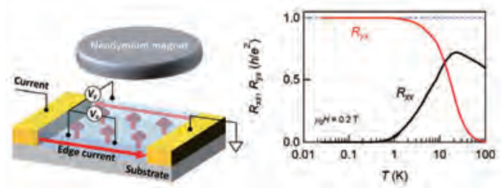
Brief resume

- 2001 Ph. D., The University of Tokyo
- 2001 Research Associate, NTT Basic Research Laboratories
- 2003 Special Postdoctoral Researcher, Low Temperature Physics Laboratory, RIKEN
- 2006 Assistant Professor, Institute of Industrial Science, The University of Tokyo
- 2008 Research Scientist, Low Temperature Physics Laboratory, RIKEN
- 2015 Senior Research Scientist, Strong Correlation Quantum Transport Research Team, RIKEN Center for Emergent Matter Science
- 2024 Team Leader, Topological Electronics Research Team, RIKEN Center for Emergent Matter Science (-present)

Development of quantum resistance standard devices using magnetic topological insulators

Topological insulators are a group of materials that have insulating interiors and metallic surface states. In magnetic topological insulators doped with magnetic elements, the resistance perpendicular to the current (Hall resistance) becomes the quantum unit of electrical resistance, the von Klitzing constant (h/e^2, where h is Planck's constant and e is the elementary charge). This phenomenon known as the quantum anomalous Hall effect occurs even in the absence of an external magnetic field. Therefore, it is expected to work as a new type of quantum resistance standard that does not require a strong magnetic field.

In this study, we synthesized magnetic heterostructure films of topological insulators using molecular beam epitaxy. In collaboration with a research team of the National Institute of Advanced Industrial Science and Technology, we measured the accuracy of the quantum anomalous Hall effect by using a small permanent magnet to align the magnetic domains. We found that the quantum anomalous Hall resistance has an accuracy of ten parts per billion, which is close to the level of the national metrology standard.



(Left) Schematic illustration of the quantum anomalous Hall effect device with a small permanent magnet. (Right) Temperature dependence of the longitudinal (R_{xx}) and Hall (R_{yx}) resistance.

Outline

We study various quantum transport phenomena in electronic systems in solids. In particular, we focus on thin film crystals and heterostructures of materials with non-trivial band structure topology and strong spin-orbit interactions, and study phenomena in which electronic correlation and/or geometrical phase play an important role. Through these studies, we aim to discover new quantum phenomena that will advance our understanding of condensed matter physics, and to explore electronic and spintronic functions using these phenomena, opening the door to new technologies.

Publications

1. M. Kawamura, M. Mogi, R. Yoshimi, T. Morimoto, K. S. Takahashi, A. Tsukazaki, N. Nagaosa, M. Kawasaki, and Y. Tokura "Laughlin charge pumping in a quantum anomalous Hall insulator", *Nat. Phys.*, 19, 333 (2023).
2. M. Mogi, Y. Okamura, M. Kawamura, R. Yoshimi, K. Yasuda, A. Tsukazaki, K. S. Takahashi, T. Morimoto, N. Nagaosa, M. Kawasaki, Y. Takahashi, and Y. Tokura "Experimental signature of the parity anomaly in a semi-magnetic topological insulator", *Nat. Phys.* 18, 390 (2022).
3. Y. Okazaki, T. Oe, M. Kawamura, R. Yoshimi, S. Nakamura, S. Takada, M. Mogi, K. S. Takahashi, A. Tsukazaki, M. Kawasaki, Y. Tokura, and N. –H. Kaneko"Quantum anomalous Hall effect with a permanent magnet defines a quantum resistance standard", *Nat. Phys.* 18, 25 (2022).
4. M. Kawamura, M. Mogi, R. Yoshimi, A. Tsukazaki, Y. Kozuka, K. S. Takahashi, M. Kawasaki, and Y. Tokura "Topological quantum phase transition in magnetic topological insulator upon magnetization rotation", *Phys. Rev. B* 98, 140404 (2018).
5. M. Mogi, M. Kawamura, R. Yoshimi, A. Tsukazaki, Y. Kozuka, N. Shirakawa, K. S. Takahashi, M. Kawasaki, and Y. Tokura "A magnetic heterostructure of topological insulators as a candidate for an axion insulator", *Nat. Mater.* 16, 516 (2017).

Semiconductor Science Research Support Team

Fumihiro Matsukura (D.Sci.), Team Leader
fumihiro.matsukura@riken.jp

Research field

Physics, Materials Science

Keywords

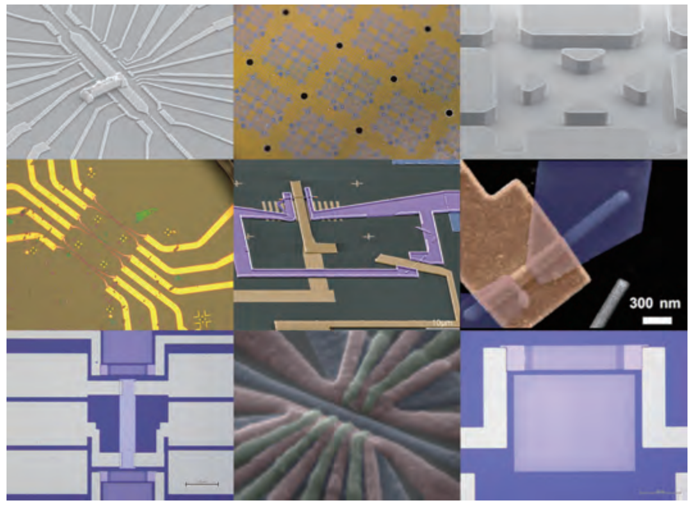
Nano-device fabrication, Device characterization, User education

Brief resume

2012 Professor, AIMR, Tohoku University
2018 Professor, CIES, Tohoku University
2023 Team Leader, Semiconductor Science Research Support Team, RIKEN Center for Emergent Matter Science (-present)

Supporting nano-device fabrication

To build a sustainable society, it is essential to realize devices with low power consumption and high-speed operation based on nanotechnologies. In Center for Emergent Matter Science, researchers are developing quantum and spin devices by using state-of-the-art equipment with its best condition Our team is established to support the researcher' s activity by providing skillful expertise. We are responsible for the operation of equipment like lithography systems including electron-beam lithography systems, maskless UV photolithography systems, deposition systems like evaporators and sputters, dry and wet etching systems and observation system like scanning electron microscopy. We instruct users in the usage of equipment and provide technical information in fabrication. With our effort, the researchers are now able to fabricate and characterize various devices in the range of 10 nm – 10 μm routinely.



Devices fabricated in the cleanroom.

Outline

Our mission is to develop novel technologies in nanoscience and nanotechnology and to support the users in RIKEN for the fabrication and characterization of nanoscale devices. We are responsible for the operation of the facilities including the cleanroom (ISO class 5) and the chemical rooms with suitable safety measures by educating the users.

Core members

(Technical Staff)
Reiko Nakatomi, Yoshio Taguchi, Hideaki Oyama

Emergent Molecular Assembly Research Unit

Hiroshi Sato (Ph.D.), Unit Leader
hiroshi.sato@riken.jp

Research field

Chemistry, Materials Science

Keywords

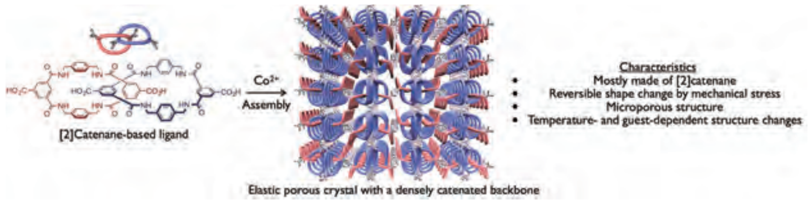
Self-assembly, Crystal engineering, Porous materials, Surface/Interface

Brief resume

2008 Ph. D., The University of Tokyo
2008 Researcher, JST-ERATO Kitagawas Integrated Pores Project
2010 Project Assistant Professor, Institute for Integrated Cell-Material Sciences, Kyoto University
2012 Assistant Professor, Institute for Integrated Cell-Material Sciences, Kyoto University
2014 Lecturer, Department of Chemistry and Biotechnology, University of Tokyo
2020 Associate Professor, Department of Chemistry and Biotechnology, University of Tokyo
2020 Researcher, PRESTO, Japan Science and Technology Agency
2021 Unit Leader, Emergent Molecular Assembly Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)
2023 Specially Appointed Professor, International Institute for Sustainability with Knotted Chiral Meta Matter (-present)

Topological bonds assemble to form porous crystals

Our unit succeeded for the first time in synthesizing crystals by precisely arranging catenane molecules (topological bonds), which are chains of two ring-shaped molecules, and metal ions three dimensionally through coordination bonds. The crystal structure was examined using single crystal X-ray structural analysis, and it was found that more than 90% of the crystal is composed of catenane molecules, that it has a structure with micropores, and that it changes its structure with changes in temperature. Furthermore, it was revealed that the crystal changes its shape when force is applied from the outside and recovers its original shape when the force is removed, showing rubber-like properties despite its crystalline nature. This is expected to lead to the application of innovative porous materials that can absorb and desorb gas molecules, such as carbon dioxide, by pinching and releasing them with a finger.



An elastic porous crystal with a Densely Catenated Backbone

Outline

The aim of this unit is to unleash the potential of molecules by controlling their assembly and arrangement patterns, and to create novel functions that are impossible to achieve with single molecules. Our specific research themes are as follows.
(1) Creation of materials by precise arrangement of topological bonds: By periodically arranging topological bonds such as catenanes, we will realize new materials.
(2) Sequence control in supramolecular polymerization: In supramolecular polymerization, it is still challenging to control the monomer sequence, and we are trying to control the sequence in coordination polymers.

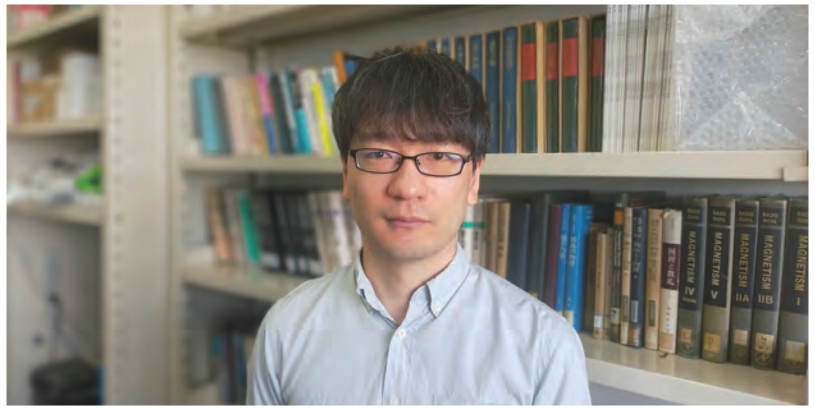
Core members

(Visiting Scientist) Naeimeh Bahrilaleh
(Student Trainee) Wei Yuan

Publications

1. K. Leng, H. Sato, Z. Chen, W. Yuan, and T. Aida ."Photochemical Surgery" of 1D Metal–Organic Frameworks with a Site-Selective Solubilization/Crystallization Strategy", *J. Am. Chem. Soc.*, 145, 23416 (2023).
2. W. Meng, S. Kondo, T. Itoh, K. Komatsu, J. Pirillo, Y. Hijikata, Y. Ikuhara, T. Aida, and H. Sato "An Elastic Metal–Organic Crystal with a Densely Catenated Backbone", *Nature*, 598, 298 (2021).
3. H. Huang, H. Sato, J. Pirillo, Y. Hijikata, Y. S. Zhao, S. Z. D. Cheng, and T. Aida "Accumulated Lattice Strain as an Internal Trigger for Spontaneous Pathway Selection", *J. Am. Chem. Soc.*, 143, 15319 (2021).
4. H. Sato, T. Matsui, Z. Chen, J. Pirillo, Y. Hijikata, and T. Aida "Photochemically Crushable and Regenerative Metal–Organic Framework", *J. Am. Chem. Soc.*, 142, 14069 (2020).
5. J.-M. Lee and H. Sato "Photoswitching to the Core", *Nat. Chem.*, 12, 584 (2020).

Emergent Quantum Spintronics Research Unit



Tomoyuki Yokouchi (D. Eng.), Unit Leader
tomoyuki.yokouchi@riken.jp

Research field

Physics, Engineering, Materials Sciences

Keywords

Spintronics, Artificial intelligence, Magnetic skyrmions, Spin dynamics, Spin Hall effect

Brief resume

2018 D. Eng., University of Tokyo
2018 Special Postdoctoral Researcher, RIKEN Center for Emergent Matter Science
2020 Assistant Professor, Graduate School of Arts and Sciences, The University of Tokyo
2023 Unit Leader, Emergent Quantum Spintronics Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

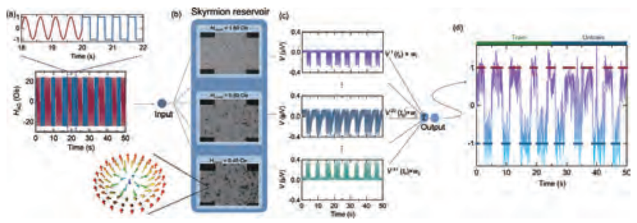
Outline

The aim of our unit is to understand the quantum and emergent properties in spintronics, which aims to utilize both the charge and spin of electrons, and to construct a new scheme for them. In particular, by employing microfabrication techniques, we will develop novel quantum spintronic and quantum transport phenomena in various magnetic materials. Our goal is to elucidate the mechanisms driving their emergence. Furthermore, by focusing on the classical and quantum dynamics of topological spin structures, we will also work to establish a new scheme for emergent computational techniques, such as physical reservoir computing.

Physical reservoir computing using skyrmions

Recently, artificial intelligence (AI), which is machine learning inspired by the design of the human brain, has been rapidly developing, leading to innovative technologies and services. However, addressing the substantial power consumption when executing AI with conventional computational devices has become an urgent issue. Consequently, the study of "neuromorphic devices", which mimic the brain's behavior at the device level aiming for higher performance and energy-efficient artificial intelligence, has become crucial.

We have demonstrated that a topological spin structure called a skyrmion can be used for "physical reservoir computing", a category of neuromorphic devices. First, we revealed that the skyrmion dynamics induced by a magnetic field satisfy the properties required for physical reservoir computing. Then, by fabricating skyrmion-based physical reservoir devices and conducting several benchmark tests, we found that the formation of skyrmions is vital for improving the performance. This discovery reveals the potential to improve the performance and energy efficiency of neuromorphic devices using skyrmions.



Schematics of the benchmark test for the skyrmion physical reservoir. (a) Waveform of the input signal. For the benchmark test, we input a combination of sine waves and square waves, and executed a problem that outputs 1 if the input is a sine wave and -1 if it is a square wave. (b) Schematic of the skyrmion physical reservoir device. The skyrmion physical reservoir device was constructed by connecting cross-shape devices in parallel. (c) Output waveforms from each cross-shape device. (d) Final output of the skyrmion physical reservoir computer. The red and blue horizontal lines indicate the correct output.

Publications

1. T. Yokouchi, Y. Ikeda, T. Morimoto, and Y. Shiomi, "Giant Magnetochiral Anisotropy in Weyl-semimetal WTe_2 Induced by Diverging Berry Curvature" *Phys. Rev. Lett.* 130, 136301 (2023).
2. T. Yokouchi, S. Sugimoto, B. Rana, S. Seki, N. Ogawa, Y. Shiomi S. Kasai, and Y. Otani "Pattern recognition with neuromorphic computing using magnetic-field induced dynamics of skyrmions" *Sci. Adv.* 8, abq5652 (2022).
3. T. Yokouchi, F. Kagawa, M. Hirschberger, Y. Otani, N. Nagaosa, and Y. Tokura "Emergent electromagnetic induction in a helical-spin magnet" *Nature* 586, 232 (2020).
4. T. Yokouchi, F. Kagawa, M. Hirschberger, Y. Otani, N. Nagaosa, and Y. Tokura "Creation of magnetic skyrmions by surface acoustic waves" *Nat. Nanotechnol.* 15, 361 (2020).
5. T. Yokouchi, S. Hoshino, N. Kanazawa, A. Kikkawa, D. Morikawa, K. Shibata, T. Arima, Y. Taguchi, F. Kagawa, N. Nagaosa, Y. Tokura, "Current-induced dynamics of skyrmion strings" *Sci. Adv.* 4, eaat1115 (2018).

Emergent Functional Magnetic Materials Research Unit

Kosuke Karube (Ph.D.), Unit Leader
kosuke.karube@riken.jp

Research field

Materials Sciences, Physics, Engineering

Keywords

Strongly correlated electron systems, Topological magnetism

Brief resume

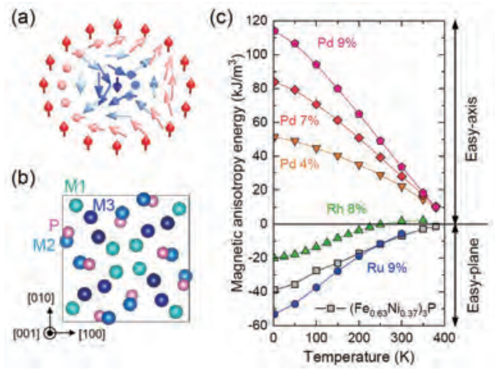
2015 Ph.D., Kyoto University
2015 Postdoctoral Researcher, Strong-Correlation Materials Research Group, RIKEN Center for Emergent Matter Science
2019 Research Scientist, Strong-Correlation Materials Research Group, RIKEN Center for Emergent Matter Science
2023 Senior Research Scientist, Strong-Correlation Materials Research Group, RIKEN Center for Emergent Matter Science
2023 Unit Leader, Emergent Functional Magnetic Materials Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

Outline

The aim of this unit is to unleash the potential of molecules by controlling their assembly and arrangement patterns, and to create novel functions that are impossible to achieve with single molecules. Our specific research themes are as follows.
(1) Creation of materials by precise arrangement of topological bonds: By periodically arranging topological bonds such as catenanes, we will realize new materials.
(2) Sequence control in supramolecular polymerization: In supramolecular polymerization, it is still challenging to control the monomer sequence, so we are trying to control the sequence in coordination polymers.

Development of new room-temperature antiskyrmion materials

Skyrmions are vortex-like topological spin textures and anticipated to be used for spintronics devices. Antiskyrmions are anti-vortex topological spin textures with topological numbers of opposite sign to those of skyrmions. While antiskyrmions have been expected to form in magnets with D_{2d} or S_4 symmetry, they have only been observed in Heusler alloys with D_{2d} symmetry. We focused on room-temperature ferromagnets $(Fe,Ni)_3P$ with S_4 symmetry. Our systematic material syntheses and magnetic measurements have revealed that the magnetic anisotropy is dramatically changed by doping with 4*d* transition metals. In particular, Pd-doping changes the magnetic anisotropy from easy-plane to easy-axis and leads to the formation of stable antiskyrmions above room temperature.

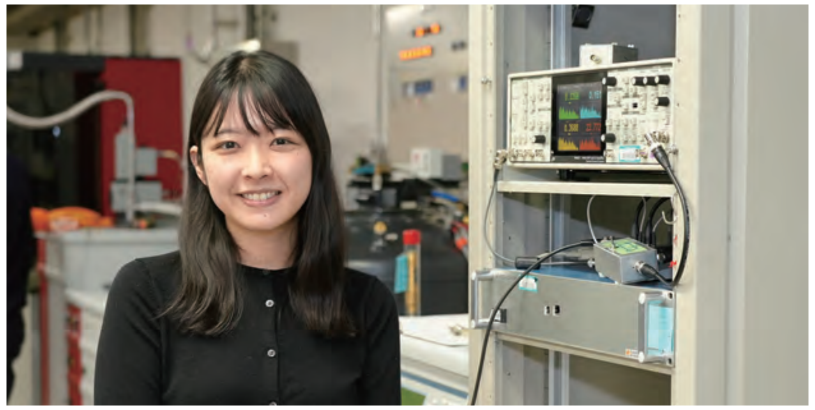


(a) Schematic spin texture of an antiskyrmion. (b) Schematic crystal structure of M_3P (M: transition metals) with S_4 symmetry. (c) Temperature dependence of magnetic anisotropy energy for various compositions of $(Fe,Ni)_3P$ doped with 4*d* transition metals.

Publications

1. K. Karube, V. Ukleev, F. Kagawa, Y. Tokura, Y. Taguchi, and J. S. White, "Unveiling the anisotropic fractal magnetic domain structure in bulk crystals of antiskyrmion host $(Fe,Ni,Pd)_3P$ by small-angle neutron scattering", *J. Appl. Cryst.*, 55, 1392 (2022).
2. K. Karube, L. C. Peng, J. Masell, M. Hemmida, H.-A. Krug von Nidda, I. Kézsmárki, X. Z. Yu, Y. Tokura, and Y. Taguchi, "Doping Control of Magnetic Anisotropy for Stable Antiskyrmion Formation in Schreibersite $(Fe,Ni)_3P$ with S_4 symmetry", *Adv. Mater.*, 34, 2108770 (2022).
3. K. Karube, L. C. Peng, J. Masell, X. Z. Yu, F. Kagawa, Y. Tokura, and Y. Taguchi, "Room-temperature antiskyrmions and sawtooth surface textures in a non-centrosymmetric magnet with S_4 symmetry", *Nat. Mater.*, 20, 335 (2021).
4. K. Karube, J. S. White, V. Ukleev, C. D. Dewhurst, R. Cubitt, A. Kikkawa, Y. Tokunaga, H. M. Rønnow, Y. Tokura, and Y. Taguchi, "Metastable skyrmion lattices governed by magnetic disorder and anisotropy in β-Mn-type chiral magnets", *Phys. Rev. B*, 102, 064408 (2020).
5. K. Karube, J. S. White, N. Reynolds, J. L. Gavilano, H. Oike, A. Kikkawa, F. Kagawa, Y. Tokunaga, H. M. Rønnow, Y. Tokura, and Y. Taguchi, "Robust metastable skyrmions and their triangular-square lattice structural transition in a high-temperature chiral magnet", *Nat. Mater.*, 15, 1237 (2016).

Extreme Quantum Matter Physics RIKEN ECL Research Unit

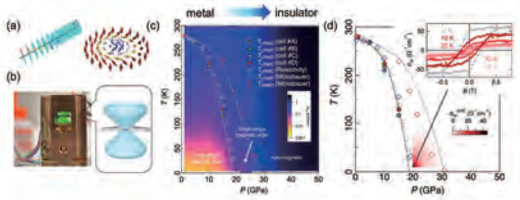


Topological magnetic phase transitions explored under ultra-high pressure

Investigating new quantum phases stands as a pivotal subject in condensed matter physics. Specifically, the quantum phase transition, characterized by the suppression of long-range magnetic order at zero-temperature, reveals a variety of novel quantum phase. These include non-Fermi liquid states, high-temperature superconductivity driven by antiferromagnetic fluctuations, and unconventional superconductivity mediated by ferromagnetic fluctuations.

In this research, we focused on the quantum phase transition of helical spin textures and magnetic skyrmions. We applied ultra-high pressure (~50 GPa) in a chiral magnet FeGe and unveiled an exotic quantum phase. In specific, we observed a metal-to-insulator transition induced by dramatic changes in the band structure, as well as the emergence of spontaneous anomalous Hall effect induced by the short-range magnetic order above the quantum phase transition. This unconventional anomalous Hall effect, which cannot be explained by conventional mechanisms, seems to be related to the quantum fluctuations in chiral systems.

Experimentally, the precise magneto-transport study under ultra-high pressure was enabled by our innovative technique using FIB method. We anticipate that this method will significantly contribute to the discovery of new quantum phases in the high-pressure regime.



(a) Schematic illustration of helical spin texture and magnetic skyrmion in a chiral magnet FeGe. (b) Optical picture and schematic illustration of diamond anvil cell used in the experiment. (c) Contour map of resistivity in the temperature-pressure phase diagram. (d) Contour map of Hall conductivity of the unconventional spontaneous anomalous Hall effect enhanced around the quantum phase transition.

Publications

1. Y. Fujishiro, C. Terakura, A. Miyake, N. Kanazawa, K. Nakazawa, N. Ogawa, H. Kadobayashi, S. Kawaguchi, T. Kagayama, M. Tokunaga, Y. Kato, Y. Motome, K. Shimizu, and Y. Tokura "Anomalous charge transport upon quantum melting of chiral spin order", arXiv:2310.04823
2. H. Matsuoka, Y. Fujishiro, S. Minami, T. Koretsune, R. Arita, T. Tokura, and Y. Iwasa "Electron-doped magnetic Weyl semimetal LixCo3Sn2S2 by bulk-gating", arXiv:2312.17547
3. Y. Fujishiro, N. Kanazawa, R. Kurihara, H. Ishizuka, T. Hori, F. S. Yasin, X. Z. Yu, A. Tsukazaki, M. Ichikawa, M. Kawasaki, N. Nagaosa, M. Tokunaga, and Y. Tokura "Giant anomalous Hall effect from spin-chirality scattering in a chiral magnet", *Nat. Commun.* 12, 317 (2021).
4. Y. Fujishiro, N. Kanazawa, and Y. Tokura "Engineering skyrmions and emergent monopoles in topological spin crystals", *Appl. Phys. Lett.* 116, 090501 (2020).
5. M. Tanaka, Y. Fujishiro, M. Mogi, Y. Kaneko, T. Yokosawa, N. Kanazawa, S. Minami, T. Koretsune, R. Arita, S. Tarucha, M. Yamamoto, and Y. Tokura "Topological kagome magnet Co3Sn2S2 thin flakes with high electron mobility and large anomalous Hall effect", *Nano Lett.* 20, 10, 7476–7481 (2020).

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Research field

Physics, Engineering, Materials Sciences

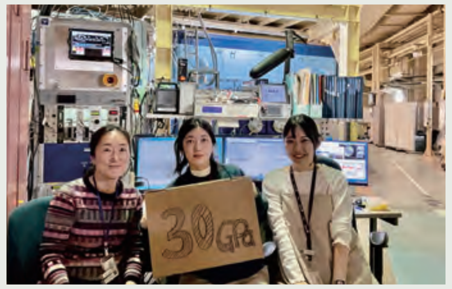
Keywords

Magnetic topological material, strongly correlated electron system, charge transport phenomena, intercalation, ultra-high pressure

Brief resume

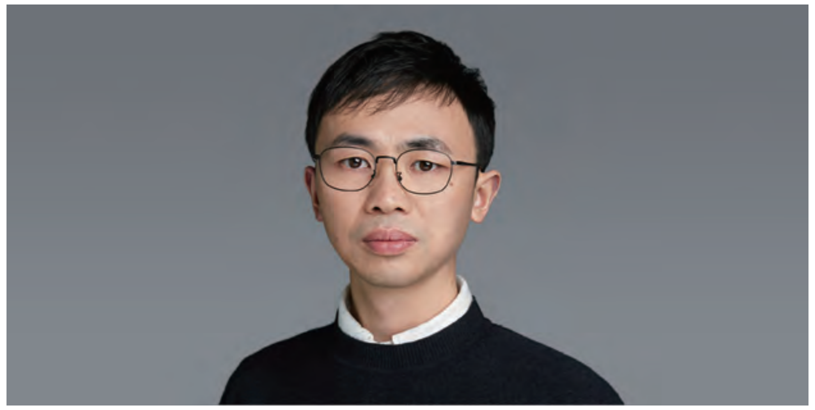
- 2021 D. Eng., The University of Tokyo
- 2021 Special Postdoctoral Researcher, RIKEN Center for Emergent Matter Science
- 2024 RIKEN ECL Unit Leader, Extreme Quantum Matter Physics RIKEN ECL Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (–present)
- 2024 RIKEN ECL Unit Leader, Extreme Quantum Matter Physics RIKEN ECL Research Unit, RIKEN Cluster for Pioneering Research (–present)

Outline



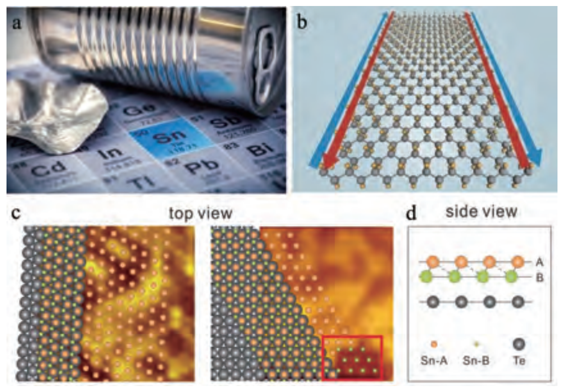
In our unit, we aim to investigate intriguing emergent phenomena in magnetic topological materials and strongly correlated electron system, with a particular emphasis on "extreme" conditions previously unattainable in earlier experiments. For instance, we employ microfabrication techniques on single crystalline quantum materials using focused ion beams (FIB). This enables us to (i) perform precise magneto-transport study under ultra-high pressure, (ii) explore magnetization dynamics in spin textures under high-density currents, and (iii) manipulate carrier densities in bulk layered materials through ion intercalation. Through these innovative approaches, we aim to reveal new quantum phases and elucidate their electronic functionalities.

Computational Materials Function Research Unit



Discovery of graphene's latest cousin: stanene

One of the grand challenges in condensed matter physics and material science is to develop room-temperature electron conduction without dissipation. Based on first-principles calculations, we predicted a new material class of stanene (i.e., the latest cousin of graphene) that is promising for the purpose. Stanene (from the Latin stannum meaning tin) is a 2D layer of tin atoms in a buckled honeycomb lattice. One intriguing feature of stanene and its derivatives is that the materials support large-gap quantum spin Hall (QSH) states, enabling conducting electricity without heat loss. Moreover, many other exotic characteristics were also proposed theoretically for stanene-related materials, including enhanced thermoelectric performance, topological superconductivity and the near-room-temperature quantum anomalous Hall effect. Very recently we have successfully fabricated the monolayer stanene structure by molecular beam epitaxy. This will stimulate great experimental effort to observe the unusual electronic properties of stanene.



(a) An element familiar as the coating for tin cans: tin (chemical symbol Sn).
(b) A 2D layer of tin, named stanene, when decorated by halogen atoms, is able to conduct electricity perfectly along its edges (blue and red arrows) at room temperature.
(c) The atomic structure model (top view) superimposed on the measured STM images for the 2D stanene on Bi_2Te_3(111). (d) Side view.

Publications

1. H. Li, Z. Tang, J. Fu, W.-H. Dong, N. Zou, X. Gong, W. Duan, and Y. Xu "Deep-learning density functional perturbation theory", *Phys. Rev. Lett.* 132, 096401 (2024).
2. H. Li, Z. Tang, X. Gong, N. Zou, W. Duan, and Y. Xu "Deep-learning electronic-structure calculation of magnetic superstructures", *Nat. Comput.* Sci. 3, 321 (2023).
3. H. Li, Z. Wang, N. Zou, M. Ye, R. Xu, X. Gong, W. Duan, and Y. Xu "Deep Neural Network Representation of Density Functional Theory Hamiltonian", *Nat. Comput. Sci.*, 2, 367 (2022).
4. C. Wang, B. Lian, X. Guo, J. Mao, Z. Zhang, D. Zhang, B.-L. Gu, Y. Xu, and W. Duan, "Type-II Ising superconductivity in two-dimensional materials with spin-orbit coupling", *Phys. Rev. Lett.* 123, 126402 (2019).
5. J. Li, Y. Li, S. Du, Z. Wang, B.-L. Gu, S.-C. Zhang, K. He, W. Duan, and Y. Xu, "Intrinsic magnetic topological insulators in van der Waals layered $MnBi_2Te_4$-family materials", *Sci. Adv.* 5, eaaw5685 (2019).

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Research field

Condensed Matter Physics, Materials Science

Keywords

First-principles calculations, Artificial intelligence for science, Topological quantum matters, Theoretical materials design

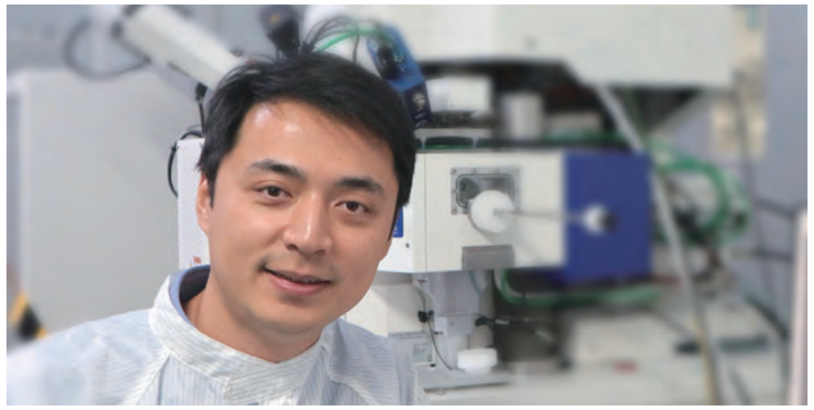
Brief resume

- 2010 Ph.D., Condensed Matter Physics, Tsinghua University, Beijing, China
- 2013 Alexander von Humboldt Fellow, Fritz Haber Institute, Berlin, Germany
- 2015 Research Scholar, Stanford University, USA
- 2015 Assistant Professor, Tsinghua University, Beijing, China
- 2015 Unit Leader, Computational Materials Function Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)
- 2018 Associate Professor, Tsinghua University, Beijing, China
- 2021 Professor, Tsinghua University, Beijing, China (-present)

Outline

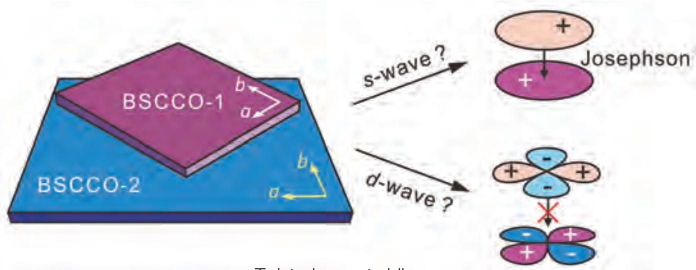
We are a research group on theoretical and computational condensed-matter and materials physics. Our main research interest is to understand/predict unusual quantum phenomena and novel material properties, based on first-principles electronic structure calculations. In particular, we focus on exploring the electronic, thermal, optical and magnetic properties of low-dimensional systems (e.g. layered materials, materials surfaces and interfaces) as well as materials with non-trivial topological order. The primary goal of our research is to design advanced functional materials that can be used for low-dissipation electronics, high-performance thermoelectricity and high-efficiency solar cell. We are also interested in developing theoretical methods for studying quantum thermal, electronic, and thermoelectric transport at the mesoscopic scale.

Low-Dimensional Transport Research Unit



Josephson tunneling in twisted bilayer cuprates

Superconductivity is one of the macroscopic quantum phenomena. The superconducting state can be described by quantum mechanical wave functions categorized as s-, p-, d-wave, etc., similar to the wave functions of a hydrogen atom. Conventional superconductors such as tin or aluminum host s-wave pairing symmetry, and although it remains debatable, most researchers believe that copper oxides are d-wave superconductors instead. Theoretically, if two d-wave superconductors are stacked vertically, the Josephson coupling strength starts to change once one superconductor is twisted against the other one. It monotonically drops to zero when the rotation angle increases up to 45 degrees. By contrast, the s-wave superconductors show constant Josephson coupling, irrespective of the rotation angles. Recently, we successfully fabricated high-quality c-axis twisted Josephson junctions with accurate control over the twist angle. Junctions at various twist angles all exhibit a single tunneling branch behavior, suggesting that only the first half of a unit cell on both sides of the twisted flakes is involved in the Josephson tunneling process. Interestingly, we found that when one cuprate flake is rotated by 45° against the other, Josephson coupling still exists, and the coupling strength of 45° and 0° are comparable. This behavior is consistent with s-wave pairing symmetry.



Twisted cuprate bilayer.

Publications

1. H. Wang, Y. Zhu, Z. Bai, Z. Wang, S. Hu, H.-Y. Xie, X. Hu, J. Cui, M. Huang, J. Chen, Y. Ding, L. Zhao, X. Li, Q. Zhang, L. Gu, X.J. Zhou, J. Zhu, D. Zhang, and Q.-K. Xue, "Prominent Josephson tunneling between twisted single copper oxide planes of $Bi_2Sr_{2-x}La_xCuO_{6+y}$", *Nat. Commun.* 14, 5201 (2023).
2. M. Liao, Y. Zhu, S. Hu, R. Zhong, J. Schneeloch, G. Gu, D. Zhang, and Q.-K. Xue, "Little-Parks like oscillations in lightly doped cuprate superconductors", *Nat. Commun.* 13, 1316 (2022).
3. Y. Zhu, M. Liao, Q. Zhang, H.-Y. Xie, F. Meng, Y. Liu, Z. Bai, S. Ji, J. Zhang, K. Jiang, R. Zhong, J. Schneeloch, G. Gu, L. Gu, X. Ma, D. Zhang, and Q.-K. Xue, "Presence of s-wave pairing in Josephson junctions made of twisted ultrathin $Bi_2Sr_2CaCu_2O_{8+x}$ flakes", *Phys. Rev. X* 11, 031011 (2021).
4. M. Liao, H. Wang, Y. Zhu, R. Shang, M. Rafique, L. Yang, H. Zhang, D. Zhang, and Q.-K. Xue, "Coexistence of resistance oscillations and the anomalous metal phase in a lithium intercalated $TiSe_2$ superconductor", *Nat. Commun.* 12, 5342 (2021).
5. J. Falson, Y. Xu, M. Liao, Y. Zang, K. Zhu, C. Wang, Z. Zhang, Ho. Liu, W. Duan, K. He, Ha. Liu, J. H. Smet, D. Zhang, and Q.-K. Xue, "Type-II Ising pairing in few-layer stanene", *Science* 367, 1454 (2020).

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Research field

Physics

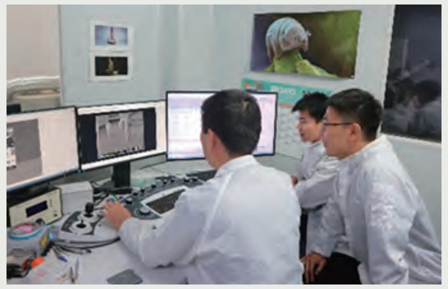
Keywords

Condensed matter physics, High-temperature superconductor, Josephson effect, Low dimensional superconductors, Van der Waals epitaxy

Brief resume

2014 PhD in physics, Max Planck Institute for Solid State Research, Stuttgart, Germany
2014 PhD in physics, University of Stuttgart, Stuttgart, Germany
2014 Post-doctor, Tsinghua University, Beijing, China.
2016 Assistant Professor, Tsinghua University, Beijing, China.
2018 Associate Professor, Tsinghua University, Beijing, China (-present)
2021 Unit Leader, Low-Dimensional Transport Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

Outline

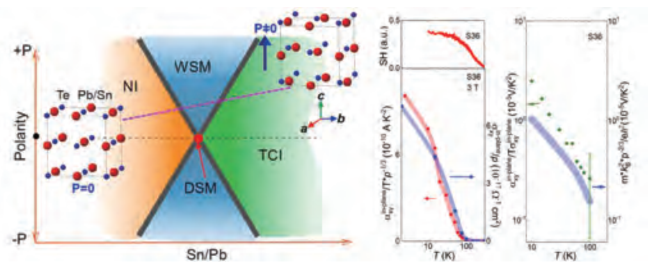


Our research unit studies a variety of low-dimensional electronic systems that undergo Cooper pairing. We aim at addressing some of the basic properties such as the pairing mechanism and the pairing symmetry. Furthermore, we look for novel quantum phenomena in reduced dimensions under specially designed conditions. The experimental knobs include stacking van der Waals heterostructures, injecting lithium/hydrogen/fluoride ions, varying the magnetic field orientations at ultralow temperatures, and ramping up the magnetic field to an extremely high value. By collaborating closely with experimental and theoretical experts in the field, we hope to gain a comprehensive understanding of those exotic phenomena.

Topological Quantum Phenomenon Research Unit

Berry curvature generation detected by Nernst responses in ferroelectric Weyl semimetal

The quest for non-magnetic Weyl semimetals with high tunability of phase has remained a demanding challenge. As the symmetry-breaking control parameter, the ferroelectric order can be steered to turn on/off the Weyl semimetals phase, adjust the band structures around the Fermi level, and enlarge/shrink the momentum separation of Weyl nodes which generate the Berry curvature as the emergent magnetic field. Here, we report the realization of a ferroelectric non-magnetic Weyl semimetal based on indium-doped $Pb_{1-x}Sn_xTe$ alloy where the underlying inversion symmetry as well as mirror symmetries are broken with the strength of ferroelectricity adjustable via tuning indium doping level and Sn/Pb ratio. The transverse thermoelectric effect, i.e., Nernst effect, both for out-of-plane and in-plane magnetic-field geometry, is exploited as a Berry-curvature-sensitive experimental probe to manifest the generation of Berry curvature via the re-distribution of Weyl nodes under magnetic fields. The results demonstrate a clean non-magnetic Weyl semimetal coupled with highly tunable ferroelectric order, providing an ideal platform for manipulating the Weyl fermions in non-magnetic system.



The left panel shows the topological phase transition in the system of In-PbSnTe. Since the spatial inversion symmetry is broken by ferroelectricity, a Weyl semimetal phase appears. The right panel shows anomalous Hall and thermoelectric Hall effect, which originates from the Berry curvature generated by the Weyl nodes.

Publications

1. CL. Zhang, T. Liang, Y. Kaneko, N. Nagaosa, Y. Tokura, "Giant Berry curvature dipole density in a ferroelectric Weyl semimetal", *npj Quantum Materials*, 7, 1-6 (2022).
2. C. Zhang, T. Liang, M. S. Bahramy, N. Ogawa, V. Kocsis, K. Ueda, Y. Kaneko, M. Kriener, and Y. Tokura "Berry curvature generation detected by Nernst responses in ferroelectric Weyl semimetal", *PNAS*, 118, e2111855118 (2021).
3. C. Zhang, T. Liang, N. Ogawa, Y. Kaneko, M. Kriener, T. Nakajima, Y. Taguchi, and Y. Tokura "Highly tunable topological system based on PbTe-SnTe binary alloy", *Phys. Rev. Materials*, 4, 091201 (2020).
4. J.J. He, T. Liang, Y. Tanaka, and N. Nagaosa "Platform of chiral Majorana edge modes and its quantum transport phenomena", *Commun. Phys.*, 2, 149 (2019).
5. K. Yasuda, H. Yasuda, T. Liang, R. Yoshimi, A. Tsukazaki, K. Takahashi, N. Nagaosa, M. Kawasaki, Y. Tokura, "Nonreciprocal charge transport at topological insulator/superconductor interface", *Nat. Commun.* 10, 2734 (2019).

Tian Liang (Ph.D.), Unit Leader
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Research field

Physics

Keywords

Condensed matter physics, Topological quantum matters, Berry phase physics, Thermoelectric effect, Strongly Correlated electron system

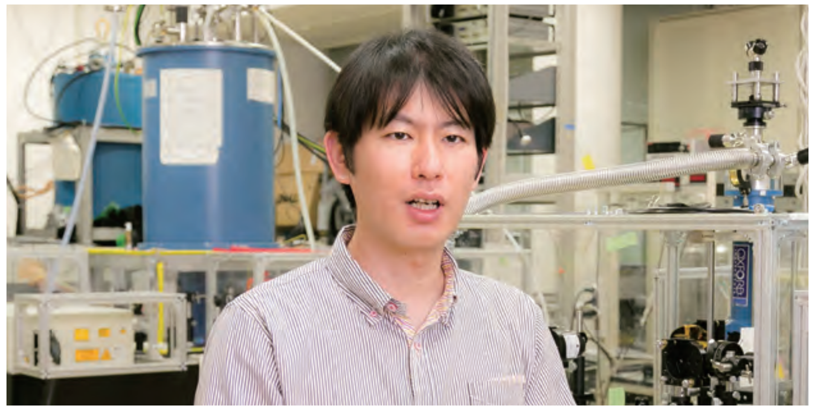
Brief resume

2016 Ph.D. in physics, Princeton University, USA
2016 Postdoctoral associate, Stanford University, USA
2018 Postdoctoral Researcher, Strong Correlation Quantum Transport Research Team, RIKEN Center for Emergent Matter Science
2021 Assistant Professor, Tsinghua University, China
2021 Unit Leader, Topological Quantum Phenomenon Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)
2023 Associate Professor, Tsinghua University, China (-present)

Outline

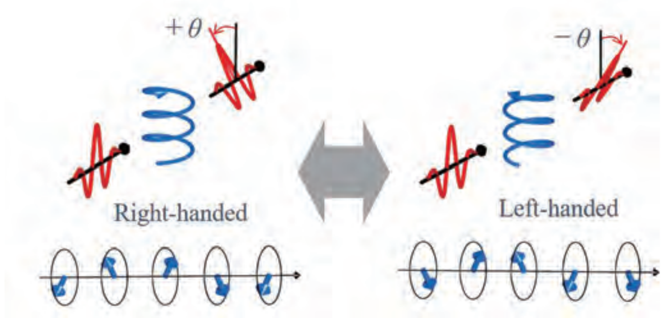
In our unit, we aim to investigate the intriguing physical properties in topological phases of matter and strongly correlated electron system, through the research based on the condensed matter experiment. First, from fundamental physics point of view, we pay attention to the nontrivial geometrical properties of the band structure, and aim to measure the novel electrical, thermal, and magnetic quantum effect on the system. In addition, from application point of view, we work on the design of high quality thermoelectric material and devices with low dissipation. In order to achieve the above mentioned goals, we will collaborate with the researchers all over the world and enhance the understanding of physics both from the fundamental and application aspects.

Emergent Spectroscopy Research Unit



Magnetoelectric optical effect with electromagnons in helimagnet

Helical spin orders exhibit the magnetically induced ferroelectricity, resulting in the concept of multiferroics with strong magnetoelectric coupling. In addition to the ferroelectric polarization, the helical spin orders possess the chirality; the right-handed and left-handed spin habits are distinguished in terms of chirality. The strong magnetoelectric coupling generates the novel spin excitation referred to as electromagnon, which is the magnon endowed with the electric activity, in terahertz region. We clarified that the strong magnetoelectric coupling of the electromagnon resonance causes the nonreciprocal optical effect in general. We also demonstrated the electric field control of chirality by using the helical spin order with ferroelectricity and chirality. On the electromagnon resonance, the reversal of the natural optical activity, which is most fundamental nature of chiral matter, is observed. The control of optical activity may lead to the novel chiral optics.



Control of natural optical activity induced by helical spin-order

Publications

1. K. Shoriki, K. Moriishi, Y. Okamura, K. Yokoi, H. Usui, H. Murakawa, H. Sakai, N. Hanasaki, Y. Tokura, Y. Takahashi, "Large nonlinear optical magnetoelectric response in a noncentrosymmetric magnetic Weyl semimetal", *Proc. Natl. Acad. Sci. USA*, 121, e2316910121 (2024).
2. Y. D. Kato, Y. Okamura, M. Hirschberger, Y. Tokura, and Y. Takahashi, "Topological magneto-optical effect from skyrmion lattice", *Nat. Commun.* 14, 5416 (2023).
3. Y. Okamura, T. Morimoto, N. Ogawa, Y. Kaneko, G-Y. Guo, M. Kawasaki, N. Naogaosa, Y. Tokura, and Y. Takahashi, "Photovoltaic effect by soft phonon excitation", *PNAS* 119, e2122313119 (2022).
4. S. Iguchi, R. Masuda, S. Seki, Y. Tokura and Y. Takahashi, "Enhanced gyrotropic birefringence and natural optical activity on electromagnon resonance in a helimagnet", *Nat. Commun.* 12, 6674 (2021).
5. R. Masuda, Y. Kaneko, Y. Tokura and Y. Takahashi, "Electric field control of natural optical activity in a multiferroic helimagnet", *Science* 372, 496 (2021).

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Research field

Physics, Materials Science

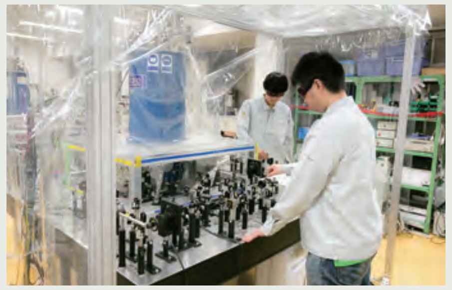
Keywords

Strongly correlated electron system, Multiferroics, Terahertz spectroscopy, Ultrafast spectroscopy, Non-reciprocal effect

Brief resume

- 2007 Ph.D, The University of Tokyo
- 2007 Researcher, Tokura Multiferroic Project, ERATO, Japan Science and Technology Agency
- 2011 Lecturer, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo
- 2014 Associate Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo
- 2014 Unit Leader, Emergent Spectroscopy Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science(-present)
- 2016 Associate Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo (-present)

Outline

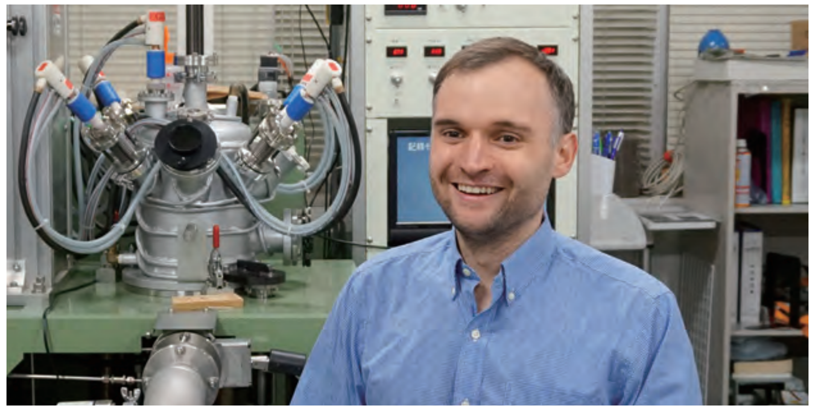


Light-matter interaction has been a fundamental issue for the condensed matter physics. Optical spectroscopy plays an important role for the various researches, and the emergent phenomena in condensed matter provide novel optical responses. Our unit focuses on the light-matter interaction on the strongly correlated electron systems as listed below. (1) Magnetoelectric optical effect driven by the cross-coupling between the magnetism and dielectric properties in matter. (2) Optical control of the magnetism and dielectric properties. (3) Novel optical responses derived from the topology in condensed matter. We are pushing forward scientific and technological developments with these researches.

Core members

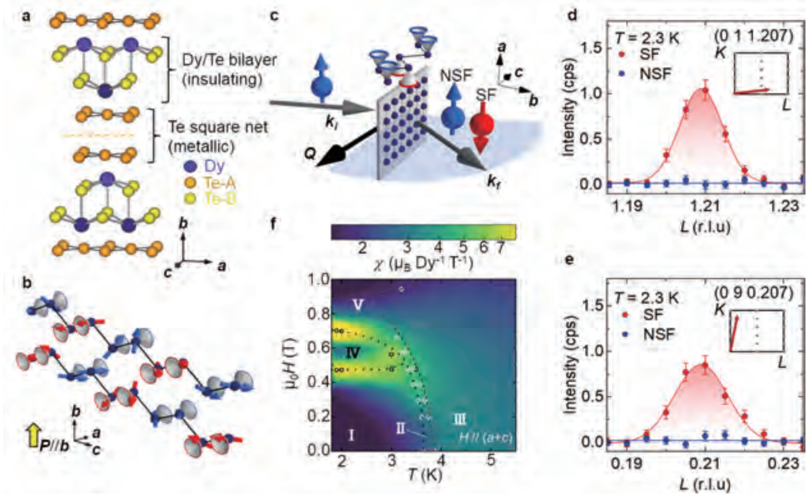
(Visiting Researcher) Yoshihiro Okamura

Topological Quantum Matter Research Unit



Non-coplanar helimagnetism in the layered van-der-Waals metal $DyTe_3$

There are various theoretical proposals for on-demand creation of complex spin textures by twisting sheets of layered helimagnets. The materials needed for these proposals, helimagnets with weak chemical bonding between layers, are exceedingly rare. Here we use polarized neutron scattering to reveal a helimagnetic texture, directly coupled to a charge-density wave order, in the layered van-der-Waals magnet $DyTe_3$.



Non-coplanar helimagnetism in the layered van-der-Waals metal $DyTe_3$. a, Crystallographic unit cell. b, Zigzag chain illustration of the non-coplanar magnetic ground state. c, Experimental geometry for polarized neutron scattering. d,e, Polarization analysis for the incommensurate cycloidal reflection. f, Magnetic phase diagram.

Publications

1. S. Akatsuka, S. Esser, S. Okumura, R. Yambe, R. Yamada, M. M. Hirschmann, S. Aji J.S. White, S. Gao, Y. Onuki, T.-h. Arima, T. Nakajima, and M. Hirschberger, Non-coplanar helimagnetism in the layered van-der-Waals metal $DyTe_3$, Nat. Commun. (in press)
2. M. Hirschberger, L. Spitz, T. Nomoto, T. Kurumaji, S. Gao, J. Masell, T. Nakajima, A. Kikkawa, Y. Yamasaki, H. Sagayama, H. Nakao, Y. Taguchi, R. Arita, T.-h. Arima, and Y. Tokura, "Topological Nernst Effect of the Two-Dimensional Skyrmion Lattice", *Phys. Rev. Lett.* 125, 076602 (2020).
3. M. Hirschberger, T. Nakajima, S. Gao, L. Peng, A. Kikkawa, T. Kurumaji, M. Kriener, Y. Yamasaki, H. Sagayama, H. Nakao, K. Ohishi, Kakurai, Y. Taguchi, X. Yu, T.-h. Arima, and Y. Tokura, "Skyrmion phase and competing magnetic orders on a breathing kagome lattice", *Nat. Commun.*, 10, 5831 (2019).
4. M. Hirschberger, S. Kushwaha, Z. Wang, Q. Gibson, S. Liang, C.A. Belvin, B.A. Bernevig, R.J. Cava, and N.P. Ong, "The chiral anomaly and thermopower of Weyl fermions in the half-Heusler GdPtBi", *Nat. Mater.*, 15, 1161 (2016).
5. M. Hirschberger, R. Chisnell, Y.S. Lee, and N.P. Ong, "Thermal Hall effect of spin excitations in a kagome magnet", *Phys. Rev. Lett.*, 115, 106603 (2015).

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Research field

Physics, Materials Science

Keywords

Strongly Correlated electron system, Magnetism, Skyrmion, Spin-orbit interaction, Emergent electromagnetism, Topological materials, Frustrated quantum magnets, Berry phase physics

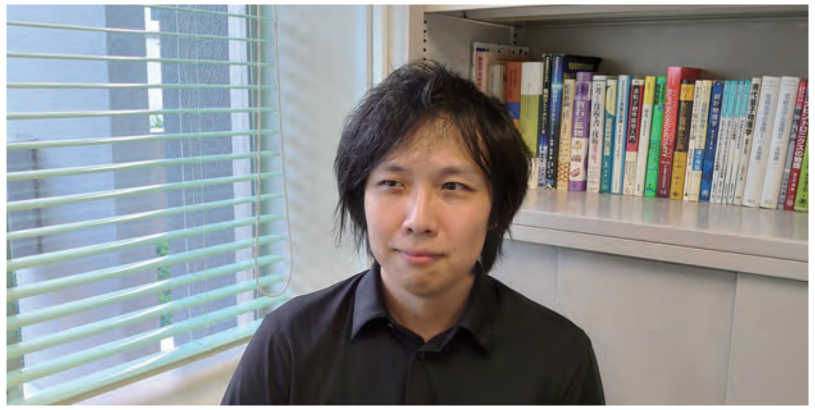
Brief resume

- 2011 Dipl. Phys., Department of Physics, Technical University of Munich, Munich, Germany
- 2017 Ph.D., Department of Physics, Princeton University, Princeton, NJ, USA
- 2017 Postdoctoral Researcher, RIKEN Center for Emergent Matter Science (CEMS)
- 2018 Alexander von Humboldt / JSPS Research Fellow and Visiting Researcher at RIKEN CEMS
- 2019 Project Lecturer, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo
- 2019 Unit Leader, Topological Quantum Matter Research Unit, Cross-Divisional Materials Research Program, RIKEN CEMS (-present)
- 2021 Associate Professor, Department of Applied Physics, School of Engineering, The University of Tokyo (-present)
- 2021 Project Associate Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo (-present)

Outline

We study the interplay between magnetic order, in particular non-coplanar spin arrangements such as magnetic skyrmions, and the electronic band structure in solids. Particular emphasis is put on compounds with the potential to be grown in thin-film form and on realizing new types of protected surface states in correlated materials. Methods include materials search guided by density functional theory calculations, crystal synthesis using a variety of solid state techniques, and ultra-high resolution transport measurements (up to very high magnetic fields). We collaborate closely with other researchers at RIKEN and beyond to resolve the magnetic structure of new materials using scattering and imaging experiments.

Topological Materials Design Research Unit



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Research field

Physics, Materials Science

Keywords

First-principles calculations, Theoretical materials design, Topological materials, Majorana fermions and parafermions, Spin-orbit interaction

Brief resume

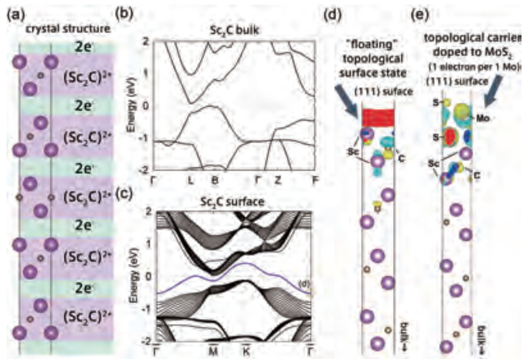
- 2013 Ph.D., Department of Applied Physics, University of Tokyo
- 2013 Postdoctoral Researcher, Nanosystem Research Institute, AIST
- 2015 Project Assistant Professor, Department of Physics, Tokyo Institute of Technology
- 2017 Research Scientist, First-Principles Materials Science Research Team, RIKEN Center for Emergent Matter Science
- 2020 Unit Leader, Topological Materials Design Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)
- 2020 Project Associate Professor, Quantum-Phase Electronics Center, The University of Tokyo (-present)

Outline

In our unit, we explore novel materials and their properties using first-principles calculations, which are numerical methods for realistic materials. In particular, we focus on the topological properties of the electronic band structure and search for topological materials with non-trivial properties. We investigate the properties and applications of these unique electronic states. We also include superconducting states and propose the emergence of Majorana fermions. In addition, we develop ab initio methods to treat correlation effects and design a wide range of materials including strongly correlated systems and magnetic systems. We design materials across a wide range of fields, including in the chemical and materials fields, such as electrides.

Electrides as a new platform of topological materials

Our unit propose e lectrides as a new platform of topological materials. Electrides are a group of materials in which electron e^- exists in the interstitial region and stabilizes the structure as an anion. Electrides are being studied in the field of catalysis because of their small work function. For example, in the layered material Sc_2C (Fig. (a)), electrons enter the cavities between the layers and exhibit insulating properties as shown in Fig. (b). The charge density of $[Sc_2C]^{2+}2e^-$ extends to interlayer positions that are significantly displaced from the Sc_2C layer due to the anionic electrons $2e^-$, resulting in a non-trivial system with a quantized large polarization. Reflecting the bulk topology, a topologically-protected metallic state appears on the Sc_2C surface (Fig. (c)). The metallic surface state originates from the interstitial electron, and therefore floats above the Sc_2C surface (Fig. (d)). This electron cloud has a small work function, making it possible to use Sc_2C as a topological substrate for high-density electron doping. For example, one electron per Mo site can be doped for MoS_2 (Fig. (e)). We have discovered a variety of topological electrides including relativistic systems, which will lead to the development of topological properties across scientific fields.

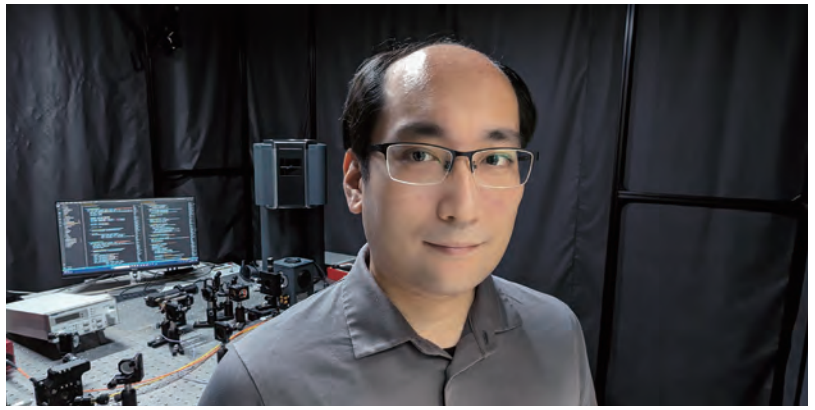


(a) Crystal structure of the topological electride $[Sc_2C]^{2+}2e^-$, (b) band structure of Sc_2C, (c) band structure of the Sc_2C (111) surface, (d) floating topological surface state, (e) topological carrier doped to MoS_2

Publications

1. T. Yu, R. Arita, and M. Hirayama, "Interstitial-Electron-Induced Topological Molecular Crystals", *Adv. Phys. Res.*, 2200041 (2023).
2. Y. Ohtsuka, N. Kanazawa, M. Hirayama, A. Matsui, T. Nomoto, R. Arita, T. Nakajima, T. Hanashima, V. Ukleev, H. Aoki, M. Mogi, K. Fujiwara, A. Tsukazaki, M. Ichikawa, M. Kawasaki, Y. Tokura, "Emergence of spin-orbit coupled ferromagnetic surface state derived from Zak phase in a nonmagnetic insulator FeSi", *Sci. Adv.*, 7, eabj0498 (2021).
3. M. Hirayama, T. Tadano, Y. Nomura, and R. Arita "Materials design of dynamically stable d^9 layered nickelates", *Phys. Rev. B*, 101, 075107 (2020).
4. M. Hirayama, S. Matsuishi, H. Hosono, and S. Murakami, "Electrides as a New Platform of Topological Materials", *Phys. Rev. X*, 8, 031067 (2018).
5. M. Hirayama, R. Okugawa, T. Miyake, and S. Murakami, "Topological Dirac nodal lines and surface charges in fcc alkaline earth metals". *Nat. Commun.*, 8, 14022 (2017).

Low-Dimensional Quantum Device Research Unit



Yuya Shimazaki (Ph.D.), Unit Leader
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Research field

Physics, Engineering, Materials Sciences

Keywords

Two-dimensional materials (2D materials), Nanodevices, Spectroscopy, Strongly correlated system, Condensed matter physics

Brief resume

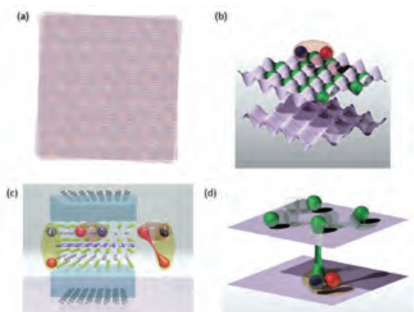
- 2016 Ph. D., The University of Tokyo
- 2016 Postdoctoral Researcher, The University of Tokyo
- 2017 Postdoctoral Researcher, Quantum Photonics Group, ETH Zurich, Switzerland
- 2021 Research Scientist, Quantum Electron Device Research Team, RIKEN Center for Emergent Matter Science
- 2024 Project Associate Professor, Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo (-present)
- 2024 Unit Leader, Low-Dimensional Quantum Device Research Unit, Cross-Divisional Materials Research Program, RIKEN CEMS (-present)

Outline

Our group focuses on the exploration of physics in novel quantum devices utilizing low-dimensional structures formed by the moiré interference effects of crystal lattices and semiconductor microfabrication, primarily based on two-dimensional materials. In particular, we aim to elucidate the quantum many-body physics and quantum device physics in semiconductor moiré superlattices through electrical control and probing and control through optical excitation. Starting from bulk single crystals of layered compounds, our research comprehensively covers the fabrication of heterostructures of two-dimensional materials, device fabrication, electrical control, optical measurements, and electrical transport measurements at extremely low temperatures, as well as the development of necessary equipment and software.

Electrical control and excitonic sensing of semiconductor moiré lattices

Two-dimensional materials, which are atomically thin materials, can acquire new functionalities by being stacked together. When two-dimensional material crystals with similar lattice constants are overlaid, moiré interference can create periodic nanostructures with a period of about 10 nanometers, longer than the original crystal's periodicity. By utilizing transition metal dichalcogenides, which are semiconductor two-dimensional materials, it is possible to electrically control and optically detect electrons in these moiré lattices. By fabricating high-quality heterostructures, we have successfully realized insulating states arising from strong electron correlations in such electrically controlled semiconductor moiré lattices. Specifically, using excitonic transitions as sensors, we have succeeded in optically detecting unique interlayer charge transfer behaviors and the formation of charge order. Additionally, we have established various control methods, such as the electrical control and optical detection of tunnel coupled states of holes in the moiré lattice, the electrical control of hybrid states of excitons, and the Feshbach resonance through electrical manipulation. Such highly controllable semiconductor moiré lattices hold great potential for use as simulators of quantum condensed matter physics.



(a) A superlattice created by moire interference of two-dimensional material crystals (moire lattice) (b) Strongly correlated electrons in a semiconductor moire superlattice and sensing by excitons (c) Electrical control of hybrid states of excitons (d) Feshbach resonance of excitons and holes induced by electrical control

Publications

1. A. Popert, Y. Shimazaki, M. Kroner, K. Watanabe, T. Taniguchi, A. Imamoğlu and T. Smoleński "Optical Sensing of Fractional Quantum Hall Effect in Graphene", *Nano Lett.*, 22, 7363 (2022).
2. I. Schwartz, Y. Shimazaki, C. Kuhlenkamp, K. Watanabe, T. Taniguchi, M. Kroner and A. Imamoğlu "Electrically tunable Feshbach resonances in twisted bilayer semiconductors", *Science*, 374, 336 (2021).
3. T. Smoleński, P. E. Dolgirev, C. Kuhlenkamp, A. Popert, Y. Shimazaki, P. Back, X. Lu, M. Kroner, K. Watanabe, T. Taniguchi, I. Esterlis, E. Demler and A. Imamoğlu "Signatures of Wigner crystal of electrons in a monolayer semiconductor", *Nature*, 595, 53 (2021).
4. Y. Shimazaki, C. Kuhlenkamp, I. Schwartz, T. Smoleński, K. Watanabe, T. Taniguchi, M. Kroner, R. Schmidt, M. Knap and A. Imamoğlu "Optical Signatures of Periodic Charge Distribution in a Mott-like Correlated Insulator State", *Phys. Rev. X*, 11, 021027 (2021).
5. Y. Shimazaki, I. Schwartz, K. Watanabe, T. Taniguchi, M. Kroner and A. Imamoglu "Strongly correlated electrons and hybrid excitons in a moiré heterostructure", *Nature*, 580, 472 (2020).
6. Y. Shimazaki, M. Yamamoto, I. V. Borzenets, K. Watanabe, T. Taniguchi and S. Tarucha "Generation and detection of pure valley current by electrically induced Berry curvature in bilayer graphene", *Nature Phys.*, 11, 1032 (2015).

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