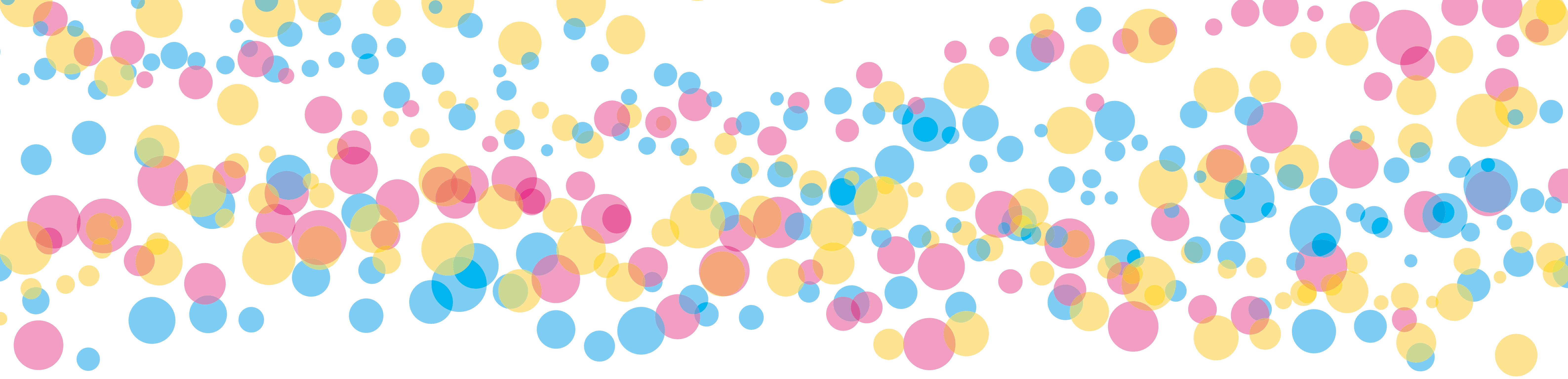

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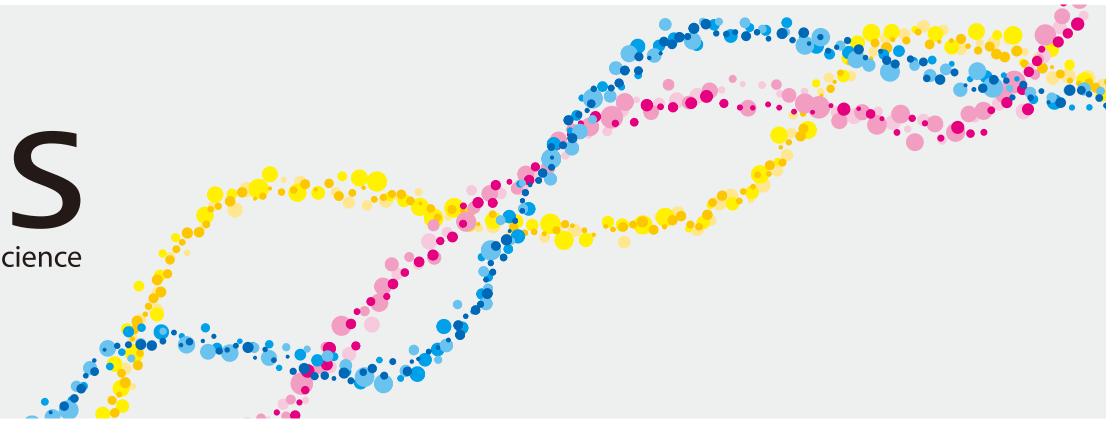

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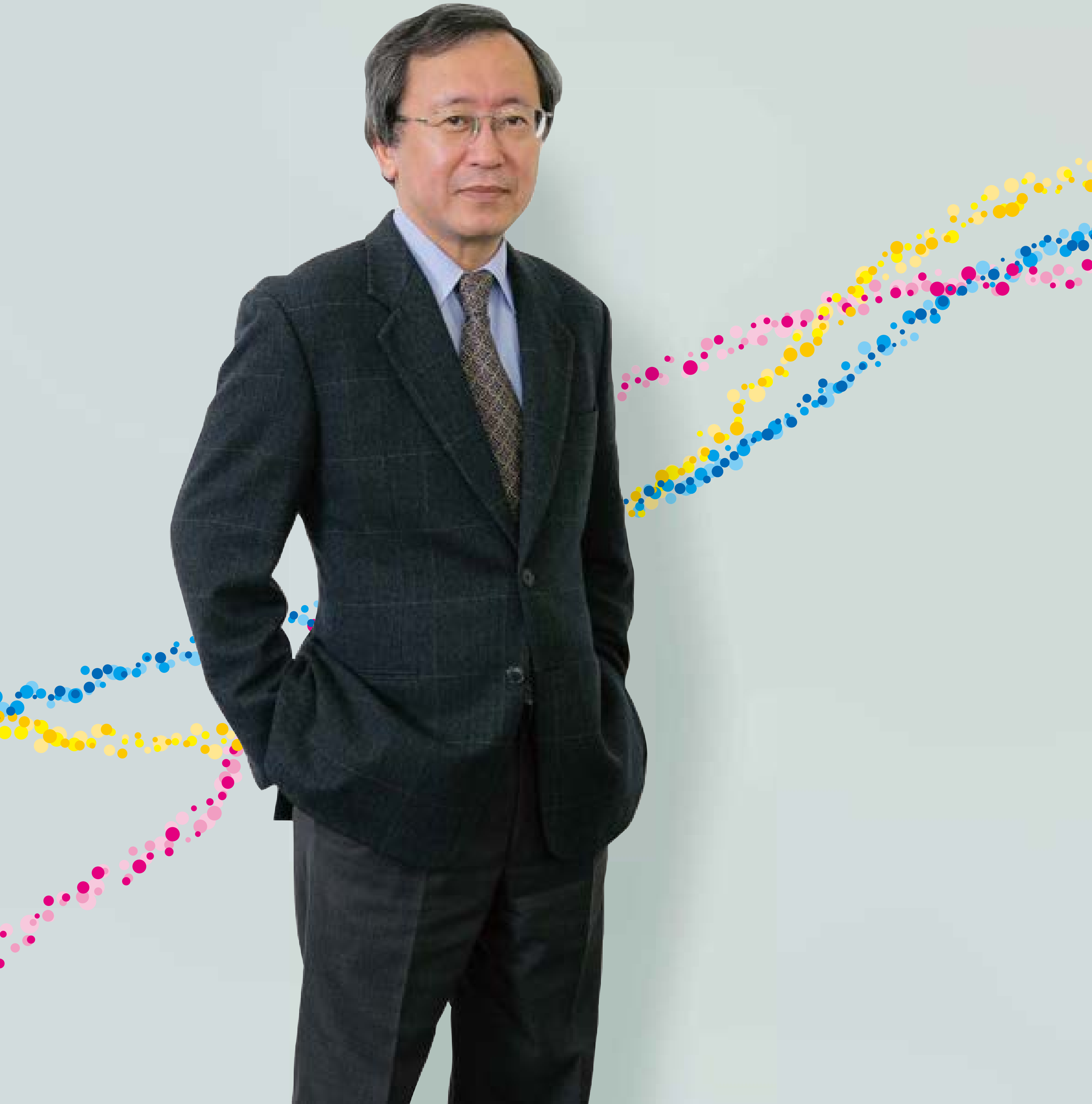
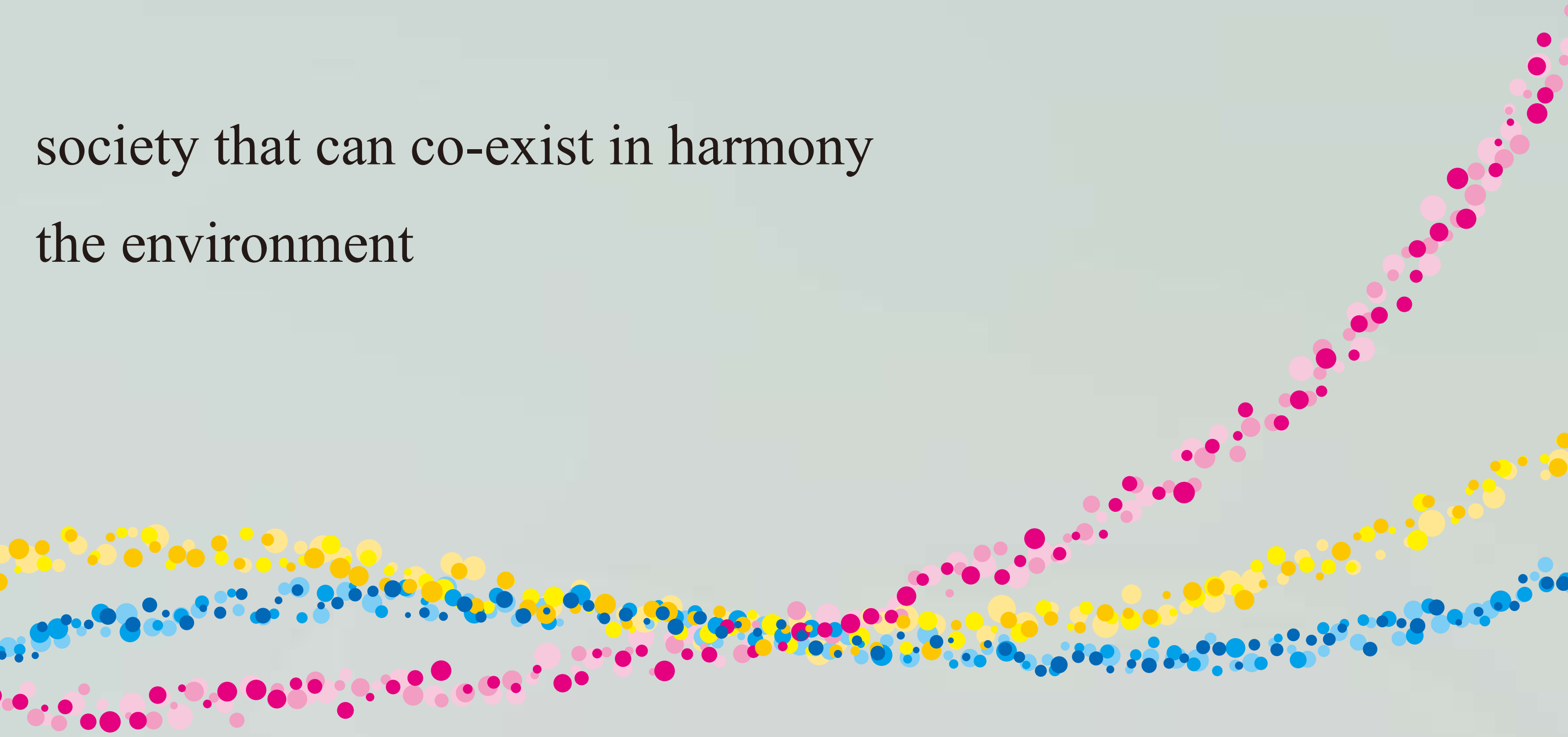
Building a sustainable
with



society that can co-exist in harmony
the environment



Message From the Director

The RIKEN Center for Emergent Matter Science (CEMS) has been launched in RIKEN unifying the fundamentals of physics, chemistry, and electronics, and rallying top-notch leaders as well as up-and-coming young researchers.

In emergent matter science, we aim at realizing emergent phenomena and functions by manipulating the dynamics of electrons, spins, and molecules in materials, and creating materials and devices for this purpose. Here the word “emergence” means that qualitatively new physical properties emerge in aggregates of many degrees of freedom, which cannot be expected in simple assemblies of individual elements. The three major-fields of CEMS are: (i) “Strong correlation physics”, exploring the astonishing functions of materials with many strongly-entangled electrons; (ii) Supramolecular/materials chemistry designing the superstructures of molecules for novel functions; and (iii) Quantum information electronics utilizing the quantum entangled states as state variables.

The mission of RIKEN centers is to solve challenging and difficult problems, which requires gathering the individual abilities of experts. The challenging goal of CEMS is to explore the energy functions of electrons in solids and molecules leading to the “third energy revolution”.

It is only about 120 years ago when humans acquired the infrastructure for accessing electric energy and its transport system. If the first and second energy revolutions are defined by the discoveries of burning energy from fuel and nuclear reactions, respectively, by transforming the mechanical energy from steam engines to electric energy, the “third energy revolution” should be the construction of emergent electro-magnetism utilizing the electron motions in solids and molecules, which is beginning now. Namely, innovative research based on electrons in solids and molecules are now going on at an accelerated pace, following the innovations of semiconductor electronics, solar cells, and high-temperature superconductivity.

CEMS aims at the discoveries of new principles/materials which bring about the discontinuous leap of the figure of merits, which can be attained only by fundamental research on materials science. The value of our research activities will be judged based on how much we transmit the new basic principles toward this goal.

Yoshinori Tokura
Director of 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.

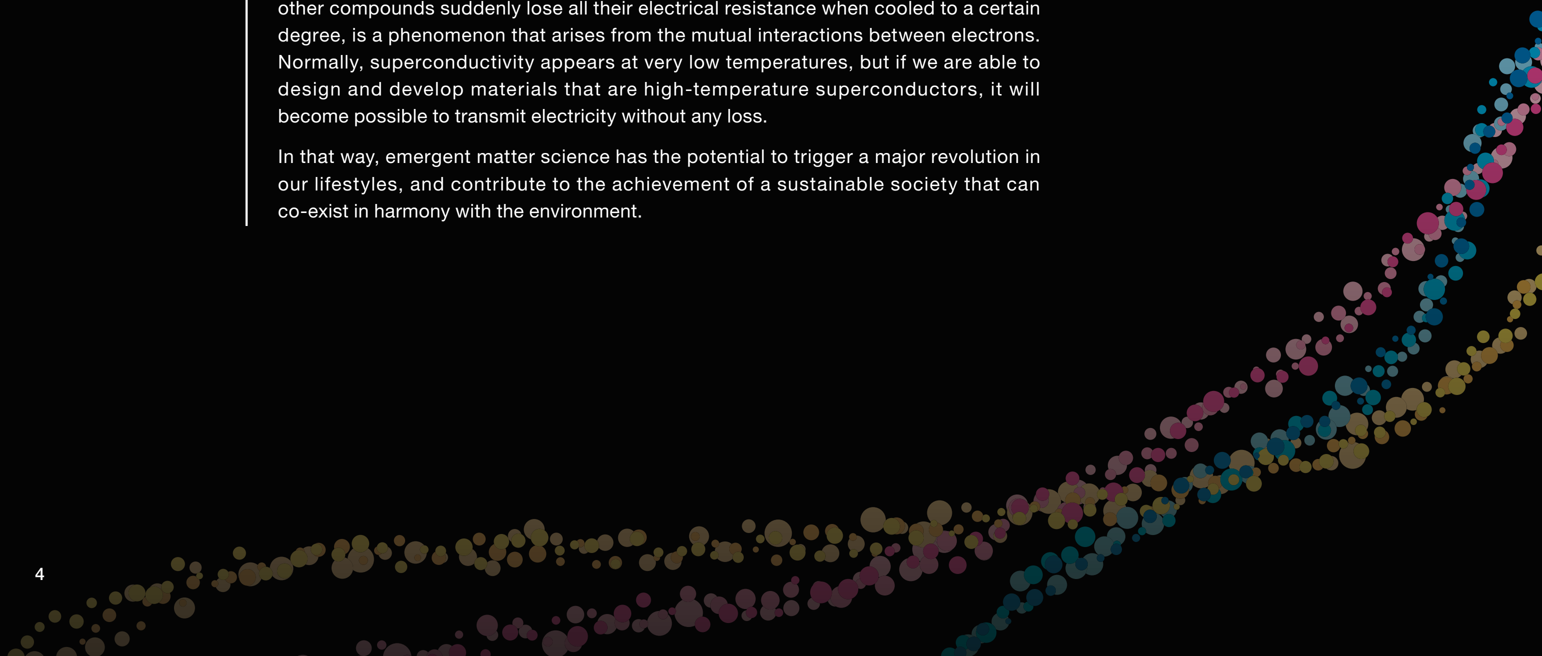
Introduction to EMS

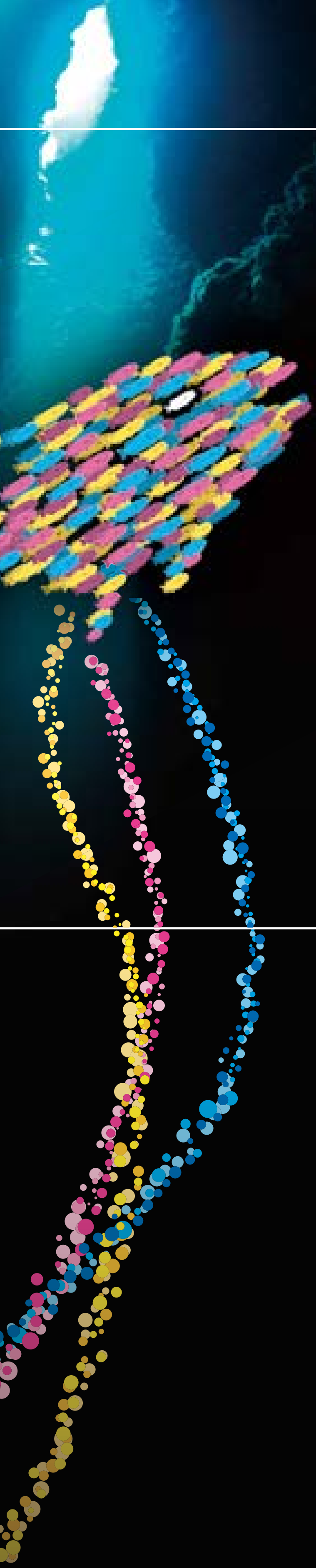
“Emergence” refers to the phenomenon in which a number of elements that are brought together gain properties that could not be predicted from the individual elements. For example, when a large number of electrons become strongly correlated, they can give rise to extremely strong electrical and magnetic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

■ Supramolecular Chemistry Division

■ Quantum Information Electronics Division

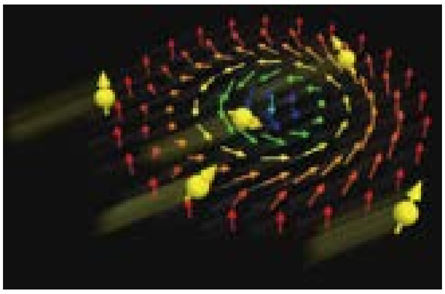
■ Cross-Divisional Materials Research Program

Office of the Center Director

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

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2. 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).
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).
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5. Y. Fujishiro, N. Kanazawa, T. Nakajima, X. Z. Yu, K. Ohishi, Y. Kawamura, K. Kakurai, T. Arima, H. Mitamura, A. Miyake, K. Akiba, M. Tokunaga, A. Matsuo, K. Kindo, T. Koretsune, R. Arita, and Y. Tokura, “Topological transitions among skyrmion- and hedgehog-lattice states in cubic chiral magnets”, *Nat. Commun.*, 10, 1059 (2019).

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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) (-present)
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

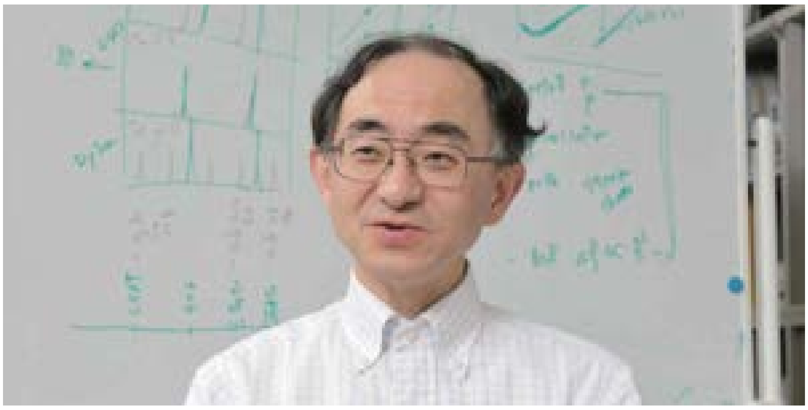
Outline

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

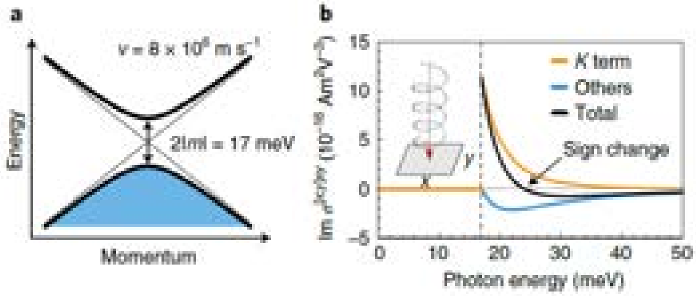
(Postdoctoral Researcher) Chenglong Zhang
(Special Postdoctoral Researcher)
Yukako Fujishiro, Hinako Murayama
(Senior Technical Scientist)
Yoshio Kaneko, Chieko Terakura

Strong Correlation Theory Research Group



Theory of quantum geometry in optical responses

The optical response is not only basic in the properties of matter, but also important from the viewpoint of application. It was beginning to be recognized that this optical response was deeply related to the geometrical properties of the wave function, but the whole picture was not clear. We find that linear response, second-order nonlinear response, and third-order nonlinear response correspond to each of metric, connection, and curvature in non-Euclidean Riemannian geometry, and succeeded to construct a general theoretical framework. Then, as a specific application thereof, we have studied the photo-induced Hall effect, which is a third-order nonlinear optical response, in the surface state of the magnetic topological insulator, and find that the term expressed by the Riemann curvature becomes dominant at the band edge.



(Left figure) Schematic band structure of the surface state of magnetic topological insulator. (Right figure) Photon energy dependence of the photocurrent for the circularly polarized light. Near the edge of the band gap, the K-term which is closely related to the Riemannian curvature, i.e., the geometric quantity of the wavefunction, is dominant over the other terms.

J. Ahn, G.Y. Guo, N.Nagaosa, A. Vishwanath, A “Riemannian geometry of resonant optical responses”, Nature Physics 18, 290 (2022).

Publications

1. J. Ahn, G.Y. Guo, N.Nagaosa, A. Vishwanath, A “Riemannian geometry of resonant optical responses”, *Nat. Phys.* 18, 290 (2022).
2. H. Ishizuka and N.Nagaosa, “Theory of bulk photovoltaic effect in Anderson insulator ”, *Proc. Nat. Acad. Sci.*, 118(10) e2023642118 (2021).
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) (-present)
2013	Group Director, Strong Correlation Theory Research Group, Division Director, Strong Correlation Physics Division, RIKEN CEMS (-present)

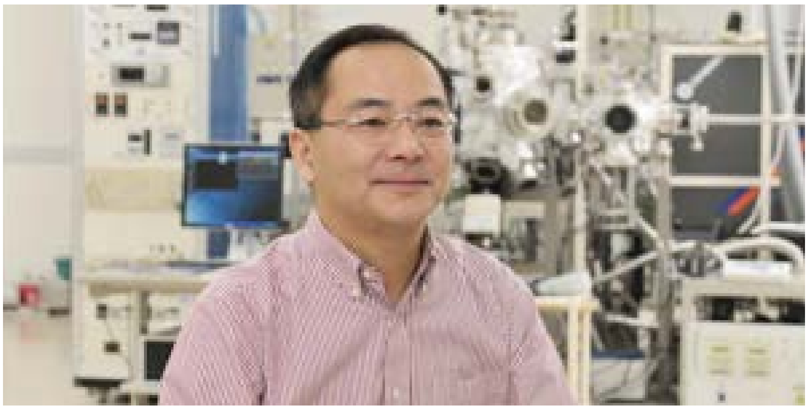
Outline

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)
Andrey Mishchenko, Wataru Koshibae
(Postdoctoral Researcher) Xiao-Xiao Zhang
(Special Postdoctoral Researcher) Yizhou Liu

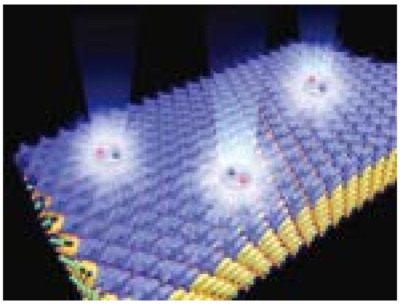
Strong Correlation Interface Research Group



Excitonic properties of high-quality iodide thin films grown by molecular beam epitaxy

Iodide semiconductors are quite promising materials for such optical devices as solar cells and light-emitting devices because of their strong optical absorption and high exciton stability. Moreover, iodides start to attract much attention as ideal platforms for exploring emergent quantum phenomena due to recently discovered topological magnetic structures and quantum transport. However, very few studies have been reported on the epitaxial films of iodides. We aim at establishing the growth method of high-quality iodide thin films employing molecular beam epitaxy (MBE), and exploring novel quantum physics and functionalities emerging at the interface of iodide heterostructures.

To begin with, we grew cuprous iodide (CuI) films on InAs substrates with excellent lattice matching, yielding in single-crystalline films having outstandingly high lattice coherence and atomically flat surfaces. The films exhibit extremely sharp free exciton emission at low temperatures that has never been observed in bulk single-crystals. This is a major step toward the development of iodide electronics.



Schematic of free exciton emission from epitaxially-grown CuI films

Publications

1. T. Yasunami, M. Nakamura, S. Inagaki, S. Toyoda, N. Ogawa, Y. Tokura, and M. Kawasaki "Molecular beam epitaxy of two-dimensional semiconductor BiI_3 films exhibiting sharp exciton absorption", *Appl. Phys. Lett.*, 119, 243101 (2021).
2. M. Uchida, S. Sato, H. Ishizuka, R. Kurihara, T. Nakajima, Y. Nakazawa, M. Ohno, M. Kriener, A. Miyake, K. Ohishi, T. Morikawa, M. S. Bahramy, T. Arima, M. Tokunaga, N. Nagaosa, and M. Kawasaki "Above-ordering-temperature large anomalous Hall effect in a triangular-lattice magnetic semiconductor", *Sci. Adv.*, 7, eabl5381 (2021).
3. D. Maryenko, M. Kawamura, A.Ernst, V.K. Dugaev. E. Ya. Sherman, M. Kriener, M. S. Barahamy, Y. Kozuka, and M. Kawasaki "Interplay of spin-orbit coupling and Coulomb interaction in ZnO-based electron system", *Nat. Commun.*, 12, 3180 (2021).
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m.kawasaki@riken.jp

Research field

Physics, Engineering, Chemistry, Materials Sciences

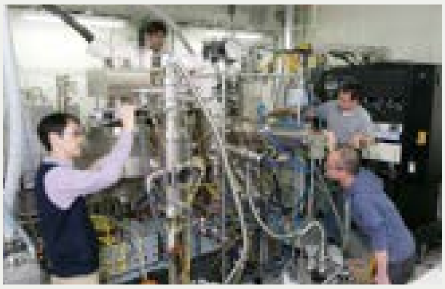
Keywords

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) (-present)
2013	Group Director, Strong Correlation Interface Research Group, Strong Correlation Physics Division, RIKEN CEMS (-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

Strong Correlation Materials Research Group

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. 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).
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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, superconductivity

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 (-present)

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 semiconductors; (4) exploration of new thermoelectric materials; and (5) exploration of new superconductors.

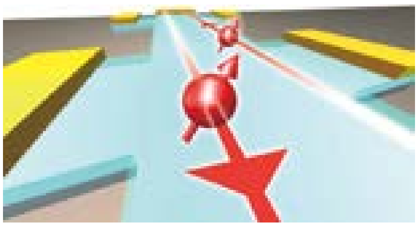
Core members

(Senior Research Scientist) Markus Kriener
(Research Scientist)
Daisuke Nakamura, Kosuke Karube, Khanh Nguyen
(Technical Scientist) Akiko Kikkawa

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. 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).
2. 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).
3. 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).
4. 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).
5. K. Yasuda, M. Mogi, R. Yoshimi, A. Tsukazaki, K. S. Takahashi, M. Kawasaki, F. Kagawa, and Y. Tokura, "Quantized chiral edge conduction on domain walls of a magnetic topological insulator", *Science*, 358, 1311 (2017).

Yoshinori Tokura (D.Eng.), Team Leader
tokura@riken.jp

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) (-present)
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

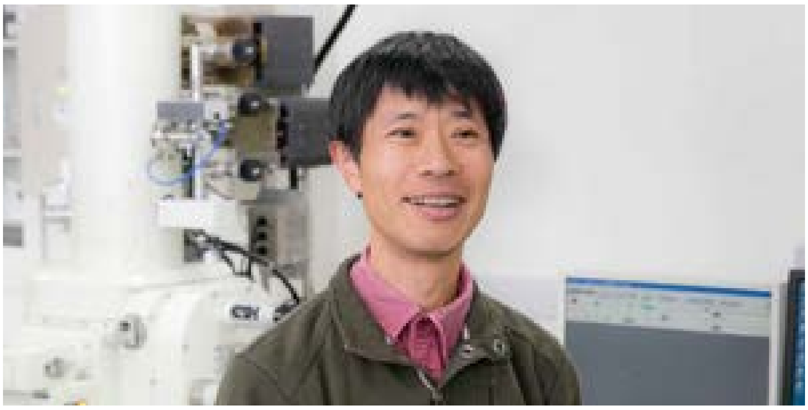
Outline

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

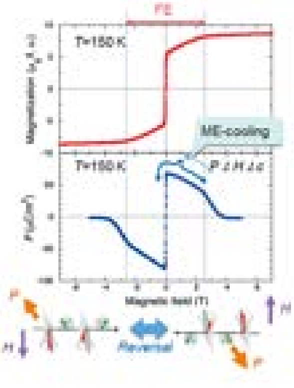
(Senior Research Scientist)
Yoshichika Onuki, Minoru Kawamura
(Research Scientist) Ryutaro Yoshimi
(Special Postdoctoral Researcher)
Ilya Boris Belopolski, Yuki Sato

Strong Correlation Quantum Structure Research Team



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. V. Ukleev, O. Utesov, L. Yu, C. Luo, K. Chen, F. Radu, Y. Yamasaki, N. Kanazawa, Y. Tokura, T. Arima, J. S. White, “Signature of anisotropic exchange interaction revealed by vector-field control of the helical order in a FeGe thin plate”, *Phys. Rev. Research* 3, 013094 (2021).
2. Y. Ishii, K. Yamamoto, Y. Yokoyama, M. Mizumaki, H. Nakao, T. Arima, Y. Yamasaki, “Soft-X-ray Vortex Beam Detected by Inline Holography”, *Phys. Rev. Appl.* 14, 064069 (2020).
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, M. Hirschberger, O. Zaharko, T. Nakajima, T. Kurumaji, A. Kikkawa, J. Shiogai, A. Tsukazaki, S. Kimura, S. Awaji, Y. Taguchi, T. Arima, Y. Tokura, “Ordering phenomena of spin trimers accompanied by a large geometrical Hall effect”, *Phys. Rev. B* 100, 241115(R) (2019).

Taka-hisa Arima (Ph.D.), Team Leader
takahisa.arima@riken.jp

Research field

Materials Science, Physics

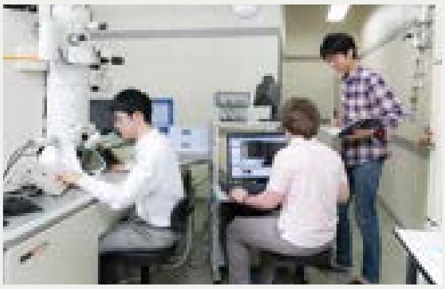
Keywords

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 (-present)

Outline

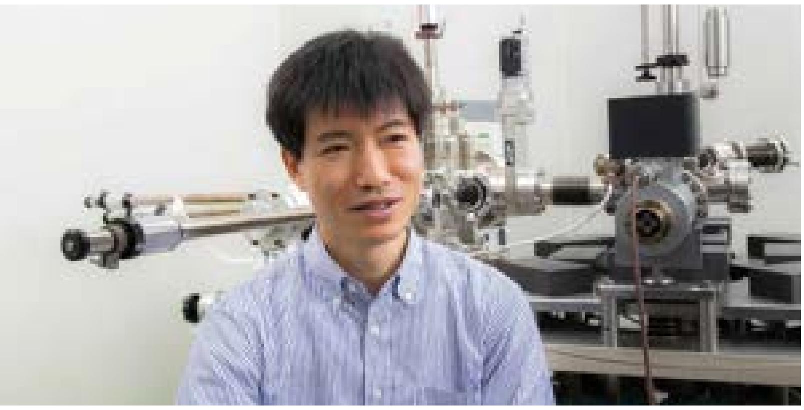


Strongly correlated electron systems may exhibit various interesting emergent phenomena such as superconductivity, colossal magneto-resistance, and giant magneto-electric effects. These emergent phenomena are directly associated with the spatial distributions as well as the spatial and temporal fluctuations 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)
Shunsuke Kito, Masaki Gen
(Postdoctoral Researcher) Kamini Gautam

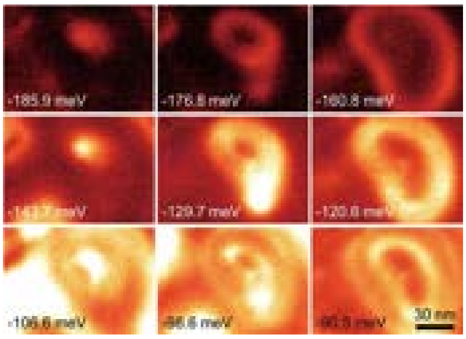
Emergent Phenomena Measurement Research Team



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. 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).
2. 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).
3. C. J. Butler, M. Yoshida, T. Hanaguri, and Y. Iwasa, “Doublonlike Excitations and Their Phononic Coupling in a Mott Charge-Density-Wave System”, *Phys. Rev. X*, 11, 011059 (2021).
4. Y. Yasui, C. J. Butler, N. D. Khanh, S. Hayami, T. Nomoto, T. Hanaguri, Y. Motome, R. Arita, T. Arima, and S. Seki, “Imaging the coupling between itinerant electrons and localised moments in the centrosymmetric skyrmion magnet $GdRu_2Si_2$”, *Nature Commun.*, 11, 5925 (2020).
5. C. J. Butler, M. Yoshida, T. Hanaguri and Y. Iwasa, “Mottness versus unit-cell doubling as the driver of the insulating state in 1*T*-TaS_2”, *Nature Commun.*, 11, 2477 (2020).

Tetsuo Hanaguri (D.Eng.), Team Leader
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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)

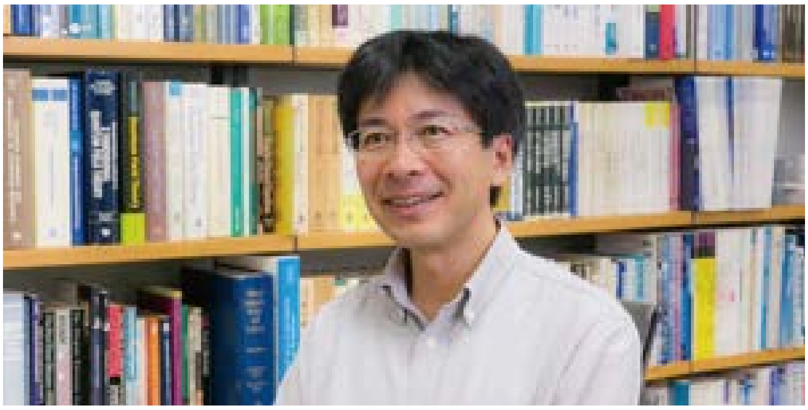
Outline

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

Quantum Matter Theory Research Team



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, the geometric (Berry) phase of 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 and A. Furusaki, “Fragile topological insulators protected by rotation symmetry without spin-orbit coupling”, *Phys. Rev. B*, 104, 195114 (2021).
2. S. Furukawa and T. Momoi, “Effects of Dzyaloshinskii-Moriya interactions in Volborthite: Magnetic orders and thermal Hall effect”, *J. Phys. Soc.*, 89, 034711 (2020).
3. M. Naka, S. Hayami, H. Kusunose, Y. Yanagi, Y. Motome, and H. Seo, “Spin current generation in organic antiferromagnets”, *Nat. Commun.*, 10, 4305 (2019).
4. S. Onoda and F. Ishii, “First-principles design of the spinel iridate Ir_2O_4 for high-temperature quantum spin ice”, *Phys. Rev. Lett.*, 122, 067201 (2019).
5. Y. Fuji and A. Furusaki, “Quantum Hall hierarchy from coupled wires”, *Phys. Rev. B*, 99, 035130 (2019).

Akira Furusaki (D.Sci.), Team Leader

furusaki@riken.jp

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 (-present)

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

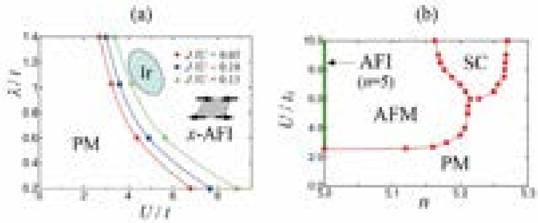
(Senior Research Scientist)
Tsutomu Momoi, Shigeki Onoda, Hitoshi Seo
(Research Scientist) Shingo Kobayashi
(Postdoctoral Researcher) Ikuma Tateishi

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_{x2-y2}-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. 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).
2. K. Seki and S. Yunoki, “Emergence of a thermal equilibrium in a subsystem of a pure ground state by quantum entanglement”, *Phys. Rev. Research* 2, 043087 (2020).
3. T. Shirakawa, S. Miyakoshi, and S. Yunoki, “Photoinduced eta pairing in the Kondo lattice model”, *Phys. Rev. B* 101, 174307 (2020).
4. T. Kaneko, T. Shirakawa, S. Sorella, and S. Yunoki, “Photoinduced eta pairing in the Hubbard model”, *Phys. Rev. Lett.* 122, 077002 (2019).
5. S. Sorella, K. Seki, O. O. Brovko, T. Shirakawa, S. Miyakoshi, S. Yunoki, and E. Tosatti, “Correlation-driven dimerization and topological gap opening in isotropically strained graphene”, *Phys. Rev. Lett.,* 121, 066402 (2018).

Seiji Yunoki (D.Eng.), Team Leader
yunoki@riken.jp

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

(Senior Reseach Scientist) Sadamichi Maekawa
(Reseach Scientist) Kazuya Shinjo

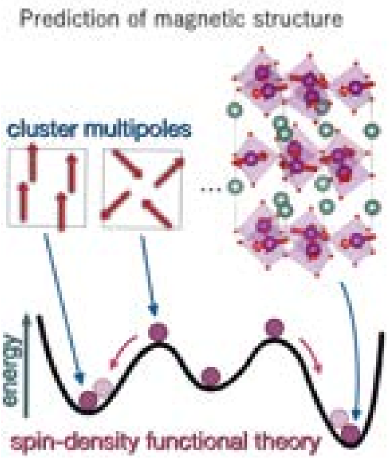
First-Principles Materials Science Research Team

Ab initio prediction of magnetic structures

In a magnetic material, some of the atoms in a crystal carry magnetic moments, which align themselves with their neighbors in very specific formations. The smallest building block of a magnetic material -the magnetic structure- fundamentally determines the properties of a magnet. Yet the prediction is highly nontrivial due to the many degrees of freedom in the system. We formulated a scheme to predict the magnetic structure from first principles by combining the cluster multipole method and spin density functional theory, in which we start with a sophisticated list of possible spin configurations.

The list of configurations is found in a spherical expansion analogous to how atomic orbitals are constructed, but highly adapted to the crystal symmetry. We then performed a high-throughput calculation with close to 3,000 possible magnetic structures for 131 materials and found many stable and meta-stable magnetic structures. We compared our prediction to the reference standard, which we aim to reproduce, that is, the experiment. This kind of high-throughput benchmark calculation showed that our approach can significantly narrow down the possible properties of a material.

With this scheme, the exploration of magnetic materials is pushed to enter a new paradigm of material design that lives up to the era of big data.



Scheme for magnetic structure prediction.

Publications

1. Y. Nomura, R. Arita, “Superconductivity in infinite-layer nickelates”, *Rep. Prog. Phys.*, 85 052501 (2022).
2. 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).
3. T. Nomoto, T. Koretsune, R. Arita, “Formation Mechanism of the Helical Q Structure in Gd-Based Skyrmion Materials”, *Phys. Rev. Lett.* 125, 117204 (2020).
4. 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).
5. A. Sakai, S. Minami, T. Koretsune, T. Chen, T. Higo, Y. Wang, T. Nomoto, M. Hirayama, S. Miwa, D. Nishio-Yamane, F. Ishii, R. Arita and S. Nakatsuji, “Iron-based binary ferromagnets for transverse thermoelectric conversion”, *Nature* 581, 53 (2020).

Ryotaro Arita (D.Sci.), Team Leader
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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)

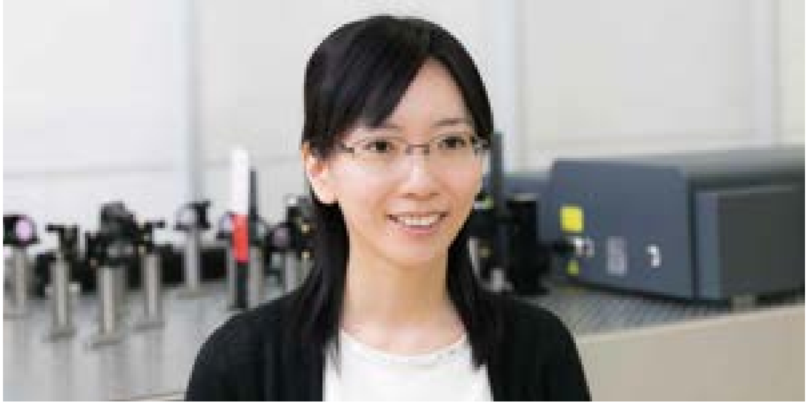
Outline

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

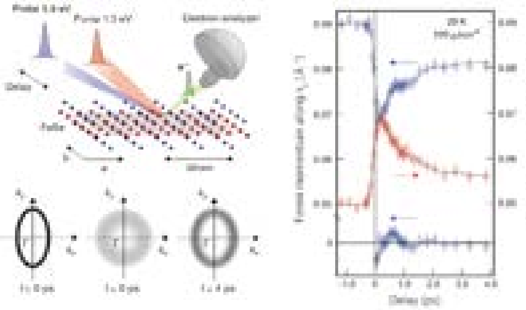
(Senior Research Scientist) Shiro Sakai
(Research Scientist) Yusuke Nomura
(Special Postdoctoral Researcher) Hsiao-Yi Chen
(Postdoctoral Researcher) Hitoshi Mori

Electronic State Spectroscopy Research Team



Ultrafast nematic electron excitation in superconductor FeSe

The electronic nematic phase is an unconventional state of matter that spontaneously breaks the rotational symmetry of electrons. In iron-pnictides/chalcogenides and cuprates, the nematic ordering and fluctuations have been suggested to have as-yet-unconfirmed roles in superconductivity. In this study, we used femtosecond optical pulse to perturb the electronic nematic order in FeSe. Through time-, energy-, momentum- and orbital-resolved photoelectron spectroscopy, we detected the ultrafast dynamics of electronic nematicity. In the strong-excitation regime, through the observation of Fermi surface anisotropy, we found a quick disappearance of the nematicity followed by a heavily-damped oscillation. This short-life nematicity oscillation is seemingly related to the imbalance of Fe 3dxz and dyz orbitals, and shows a critical behavior as a function of pump fluence. Our real-time observations reveal the nature of the electronic nematic excitation instantly decoupled from the underlying lattice.



Time- angle-resolved photoelectron spectroscopy (upper left),
schematic transient Fermi surface (lower left), and
transient Fermi momentum obtained by real-time measurement (right).

Publications

1. 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).
2. 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).
3. 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).
4. 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).
5. A. Nakamura, T. Shimojima, M. Matsuura, Y. Chiashi, M. Kamitani, H. Sakai, S. Ishiwata, H. Li, A. Oshiyama and K. Ishizaka, “Evaluation of photo-induced shear strain in monoclinic VTe_2 by ultrafast electron diffraction”, *Appl. Phys. Express* 11, 092601 (2018).

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.

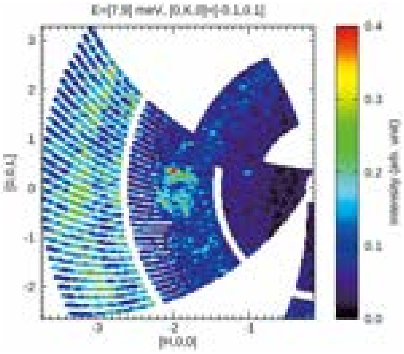
Core members

(Senior Research Scientist) Takahiro Shimojima
(Postdoctoral Researcher)
Asuka Nakamura, Natsuki Mitsuishi

Strongly Correlated Spin Research Team

Contribution of phonon excitations to the superconducting mechanism of non-centrosymmetric $LaNiC_2$

$LaNiC_2$ is a superconductor (T_c = 2.7K) without spatial inversion symmetry. Theoretical group predicted that the phonon dispersion of this material may show kohn anomalies. In rare earth-nickel-boron-carbide superconductors (eg $RENi_2B_2C$), not only a kohn-anomaly but also resonance like peaks are observed at a specific q position, where nesting of the Fermi surface is expected to occur. To verify the possibility of both kohn-anomaly and resonance behaviors and to study their contribution to the mechanism of its superconductivity, we performed neutron scattering experiments. It was impossible to carry out a new experiment in FY 2020, we proceeded to analyze previous data measured by the high-resolution chopper spectroscope HRC in the J-PARC MLF of the Japan Atomic Energy Agency (JAEA). The results revealed longitudinal and transverse acoustic phonon branches. It was also clarified that a certain amount of phonon spectral was observed on the higher energy side but the intensity was too weak to identify the dispersion relation. We plan to conduct a new inelastic neutron scattering experiment in the experimental reactor JRR-3 at JAEA to draw the whole picture of the dispersion relation of the lattice fluctuation of this system.



Phonon excitation spectrum in a range of 7<E<9 meV at 300K and in the (H0L) scattering plane.

Publications

1. M. Soda, S. Itoh, T. Yokoo, G. Ehlers, H. Kawano-Furukawa, T. Masuda, "Magnetic correlations in on kagome and triangular lattices", *Phys. Rev. B*, 101, 214444 (2020).
2. A. Yokoyama, M. Soda, H. Yoshizawa, H. Kawano-Furukawa, "Memory Effect in Spin Glass $Ni_{0.45}Mn_{0.55}TiO_3$", *JPS Conf. Proc.,* 30, 011185 (2020).
3. M. Soda, T. Hong, M. Avdeev, H. Yoshizawa, T. Masuda, and H. Kawano-Furukawa, "Neutron scattering study of the quasi-one-dimensional antiferromagnet $Ba_2CoSi_2O_7$", *Phys. Rev. B,* 100, 144410 (2019).
4. M. Takahashi, H. Takeya, A.A. Aczel, T. Hong, M. Matsuda, H. Kawano-Furukawa, "Neutron scattering study of spin density wave and weak ferromagnetic orders in $Tb_{0.47}Y_{0.53}Ni_2{}^{11}B_2C$", *Physica B: Condensed Matter* 551, 108-110 (2018).
5. M. Soda, L.-J. Chang, M. Matsumoto, V. O. Garlea, B. Roessli, J. S. White, H. Kawano-Furukawa, T. Masuda, "Polarization analysis of magnetic excitation in multiferroic $Ba_2CoGe_2O_7$", *Phys. Rev. B,* 97, 214437 (2018).

Hazuki Furukawa (Ph.D.), Team Leader
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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

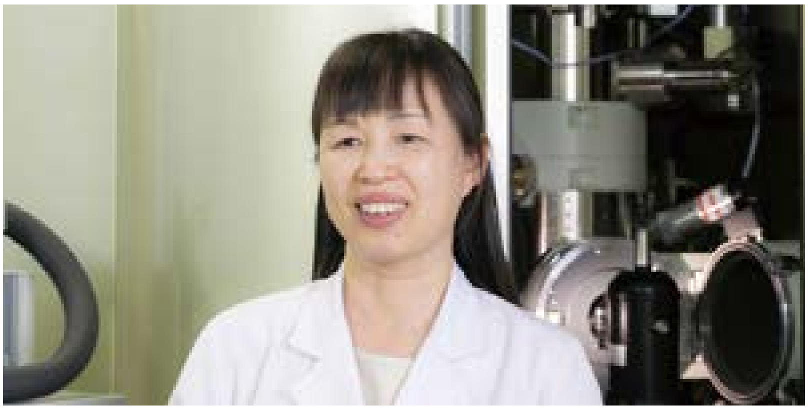
Our team studies the static and dynamic magnetic and atomic structure of strongly correlated electron systems using various neutron scattering techniques. We are working to verify the relevance of physical characteristics in controlling and enhancing the behavior of these systems.

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

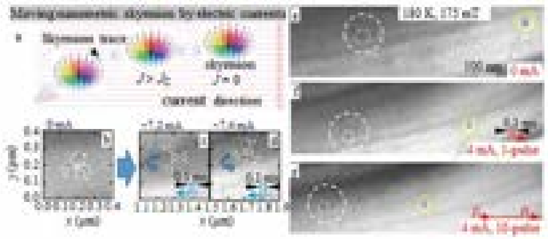
(Technical Scientist) Edward Foley

Electronic States Microscopy Research Team



Direct observation of a single skyrmion and skyrmion cluster dynamics under pulse-current excitations

The magnetic skyrmion carrying a topological number –1, as a particle-like topological texture, attracts much attention in fundamental physics as well as in spintronics. The skyrmion Hall motion (a) occurs when the conduction electron passes through skyrmion due to the interaction of the electron and the Berry phase arising from skyrmion. Accordingly, the spin polarized electric current can drive skyrmion motion when its strength is above a critical value J_C to overcome the pinning potential for the skyrmion in real materials. To manipulate small magnetic skyrmions, we set out working with a thin helimagnet FeGe with a notch hole, which allowed the spin current to be localized in a specific area near the corner of the notch and hence to generate isolated skyrmions and their cluster. The Hall motion companying a unique rotating motion (counter-clockwise in the present experimental setup; Figs. c-d) of the three-skyrmions cluster (Fig. b) has been demonstrated for the first time. Lorentz TEM observations (Figs. e-f) of pulse-current tracking a single skyrmion with 80-nm in diameter and their cluster demonstrated that the J_C for drives of skyrmions in the thin FeGe is an order of 10^9 A/m^2, three orders smaller than that for drives of magnetic domain walls in ferromagnetic materials.



(a) Skyrmion (colored vortices) Hall motion driven by electric currents. Longer arrows show current flow directions. (b-d) Lorentz TEM images of skyrmion Hall motion companying a rotation of skyrmion cluster with current-pulse excitations. (e-g) Lorentz TEM images of tracking a single skyrmion and a skyrmion cluster after several pulse-current excitations.

Publications

1. 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).
2. L. C. Peng, K. Karube, Y. Taguchi, N. Nagaosa, Y. Tokura and X. Z. Yu, “Dynamic transition of current-driven single-skyrmion motion in a room-temperature chiral-lattice magnet”, *Nat. Commun.* 12, 6797 (2021).
3. L. C. Peng, R. Takagi, W. Koshibae1, K. Shibata, K. Nakajima,T-h. Arima, N. Nagaosa, S. Seki, X.Z.Yu and Y. Tokura, “Controlled transformation of skyrmions and antiskyrmions in a non-centrosymmetric magnet”, *Nat. Nanotech.*, 15, 181 (2020).
4. 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).
5. X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa and Y. Tokura, “Real-space observation of two-dimensional skyrmion crystal”, *Nature*, 465, 901 (2010).

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

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)

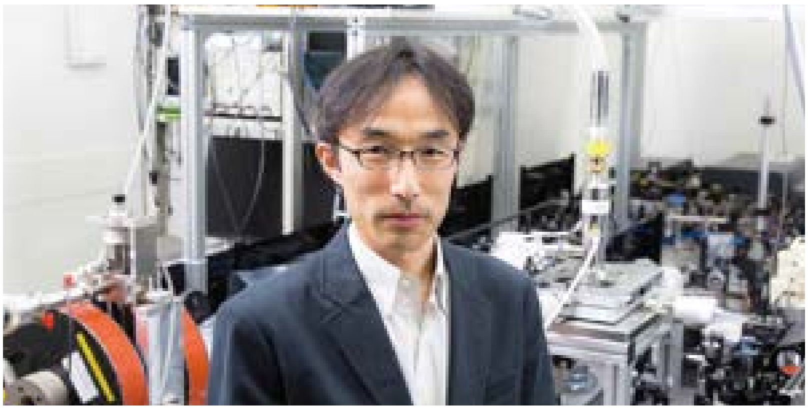
Outline

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, 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

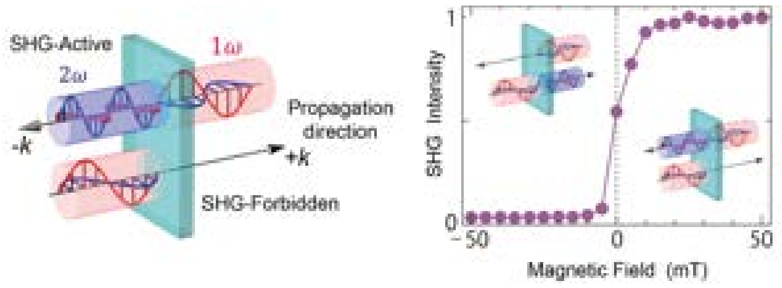
(Special Postdoctoral Researcher)
Licong Peng, Fehmi Sami Yasin
(Postdoctoral Researcher) Yao Guang, Shunsuke Mori
(Technical Staff I) Kiyomi Nakajima

Emergent Photodynamics Research Team



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 non-resonant condition. As a result, the two transitions interfere with each other in the same amplitude with controllable phase, resulting in an almost perfect nonlinear nonreciprocal effect with 97% change in the SHG intensity. We also demonstrated that the 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. 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).
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3. N. Ogawa, L. Köhler, M. Garst, S. Toyoda, S. Seki, and Y. Tokura, "Nonreciprocity of spin-waves in the conical helix state", *Proc. Natl. Acad. Sci.* 118, e2022927118 (2021).
4. 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).
5. N. Ogawa, R. Yoshimi, K. Yasuda, A. Tsukazaki, M. Kawasaki, and Y. Tokura, "Zero-bias photocurrent in ferromagnetic topological insulator", *Nat. Commun.* 7, 12246 (2016).

Naoki Ogawa (D.Eng.), Team Leader
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Research field

Physics, Materials Science, Engineering

Keywords

Strongly correlated electron systems,
Ultrafast/broadband spectroscopy,
Shift current/photocurrent spectroscopy, 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 (-present)
2020	Guest Professor, University of Tokyo (-present)

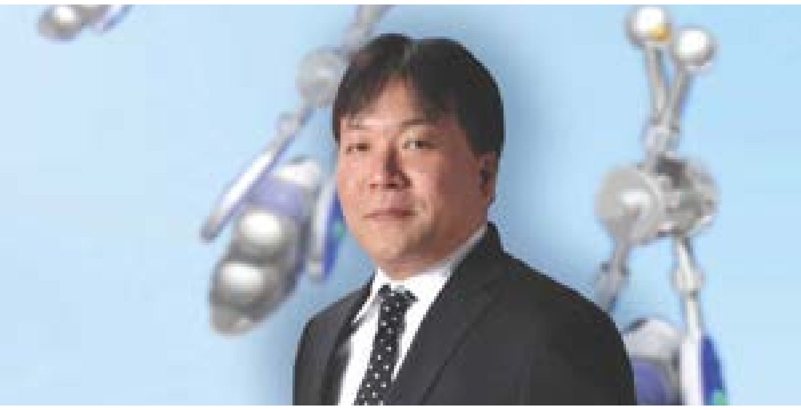
Outline

Our team 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 current, generation of spin current mediated by photoexcited Dirac/Weyl electrons, and manipulation of topological magnetic orders. With a strong command of photons, we try to realize new photo-electric/magnetic effects in solids, and visualize spatiotemporal propagation of various elementally excitations at the sub-diffraction limit.

Core members

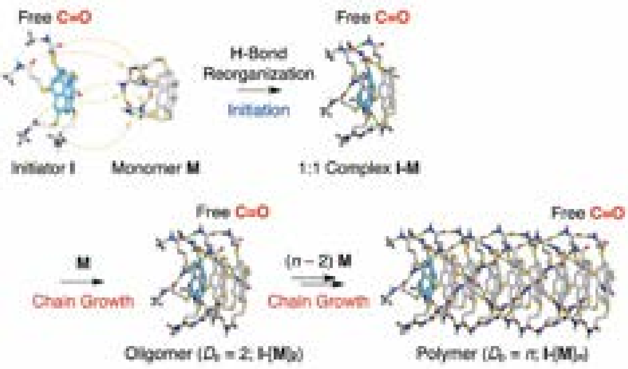
(Postdoctoral Researcher) Ziqian Wang

Emergent Soft Matter Function Research Group



Chain-growth supramolecular polymerization

Over the last decade, significant progress in supramolecular polymerization has had a substantial impact on the design of functional soft materials. However, despite recent advances, most studies are still based on a preconceived notion that supramolecular polymerization follows a step-growth mechanism. We recently realized the first chain-growth supramolecular polymerization by designing metastable monomers with a shape-promoted intramolecular hydrogen-bonding network. The monomers are conformationally restricted from spontaneous polymerization at ambient temperatures but begin to polymerize with characteristics typical of a living mechanism upon mixing with tailored initiators. The chain growth occurs stereoselectively and therefore enables optical resolution of a racemic monomer. We believe that it may give rise to a paradigm shift in precision macromolecular engineering.



Schematic illustration of chain-growth supramolecular polymerization

Publications

1. 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).
2. 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).
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4. Y. Yanagisawa, Y. Nan, K. Okuro, and T. Aida, “Mechanically robust, readily repairable polymers via tailored noncovalent cross-linking”, *Science*, 359, 72 (2018).
5. J. Kang, D. Miyajima, T. Mori, Y. Inoue, Y. Itoh, and T. Aida, “A rational strategy for the realization of chain-growth supramolecular polymerization”, *Science*, 347, 646 (2015).

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) (-present)
2013	Group Director, Emergent Soft Matter Function Research Group, Division Director, Supramolecular Chemistry Division, RIKEN CEMS (-present)

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.

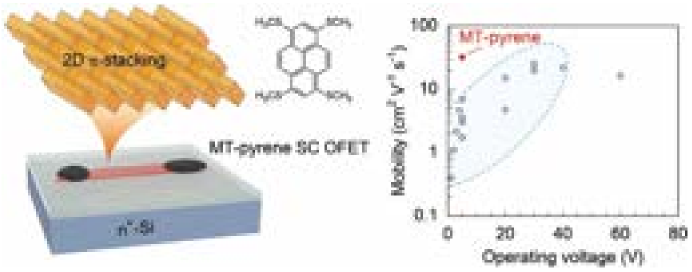
Core members

(Research Scientist) Nobuhiko Mitoma, Hubiao Huang
(Visiting Researcher) Abir Goswami, Zebin Su
(Technical Staff) Motonobu Kuwayama
(Student Trainee) Gangfeng Chen, Yiren Cheng,
Yang Hong, Niannian Wu

Emergent Molecular Function Research Team

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. Sumitomo, Y. Sudo, K. Kanazawa, K. Kawabata, K. Takimiya, "Enantiopure 2-(2-ethylhexyl)dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes: synthesis, single crystal structure and surprising lack of influence of stereoisomerism on thin-film structure and electronic properties", *Mater. Horiz.*, 9, 444 (2022).
2. 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).
3. K. Kawabata, K. Takimiya, "Quinoid-aromatic Resonance for Very Small Optical Energy Gaps in Small-molecule Organic Semiconductors: a Naphthodithiophenedione-oligothiophene triad system", *Chem. Eur. J.*, 27, 15660 (2021).
4. 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).
5. C. Wang, D. Hashizume, M. Nakano, T. Ogaki, H. Takenaka, K. Kawabata, K. Takimiya, ""Disrupt and Induce" Intermolecular Interactions to Rationally Design Organic Semiconductor Crystals: from Herringbone to Rubrene-like Pitched π-Stack", *Chem. Sci.* 11, 1573 (2020).

Kazuo Takimiya (D.Eng.), Team Leader
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 (-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

(Postdoctoral Researcher)
Masanori Sawamoto, Kirill Bulgarevich
(Visiting Scientist) Jisoo Shin, Kohsuke Kawabata
(Technical Staff) Daichi Watanabe
(Student trainee) Shingo Horiuchi

Emergent Bioinspired Soft Matter Research Team

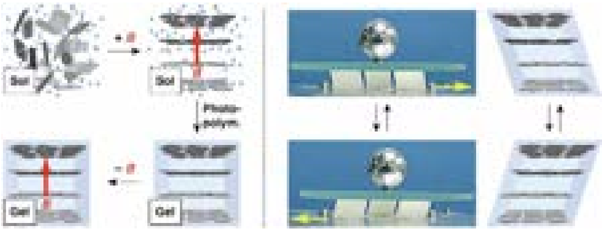
Synthetic hydrogel like cartilage, but with a simpler structure

- Potential as artificial cartilage and anti-vibration materials -

Electrostatic and magnetic repulsive forces are used in various places, as in maglev trains, vehicle suspensions or non-contact bearings etc. However, design of polymer materials, such as rubbers and plastics, has focused overwhelmingly on attractive interactions for their reinforcement, while little attention has been given to the utility of internal repulsive forces. Nevertheless, in nature, articular cartilage in animal joints utilizes an electrostatically repulsive force for insulating interfacial mechanical friction even under high compression.

We discovered that when nanosheets of unilamellar titanate, colloidally dispersed in an aqueous medium, are subjected to a strong magnetic field, they align cofacial to one another, where large and anisotropic electrostatic repulsion emerges between the nanosheets. This magneto-induced temporal structural ordering can be fixed by transforming the dispersion into a hydrogel. The anisotropic electrostatics thus embedded allows the hydrogel to show unprecedented mechanical properties, where the hydrogel easy deforms along a shear force applied parallel to the nanosheet plane but is highly resistive against a compressive force applied orthogonally.

The concept of embedding repulsive electrostatics in a composite material, inspired from articular cartilage, will open new possibilities for developing soft materials with unusual functions.



Hydrogel embedded with an anisotropic electrostatic repulsive force

Publications

1. K. Sano, X. Wang, Z. Sun, S. Aya, F. Araoka, Y. Ebina, T. Sasaki, Y. Ishida, and T. Aida, “Propagating wave in a fluid by coherent motion of 2D colloids”, *Nat. Commun.*, 12, 6771 (2021).
2. 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).
3. 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).
4. 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

Self-assembly, Biomimetics, Soft material, Stimuli-responsive material, Environmentally friendly material

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

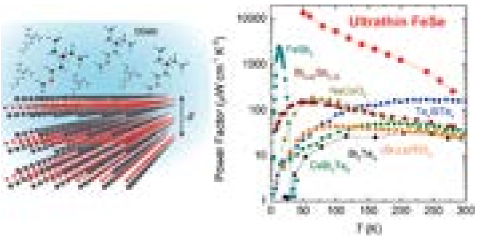
(Expert Technician) Kuniyo Yamada
(Research Scientist)
Krishnachary Salikolimi, Xiang Wang
(Postdoctoral Researcher) Zhifang Sun
(Technical Staff) Noriko Horimoto, Hayato Kanai
(Student Trainee) Shuxu Wang

Emergent Device Research Team

Quantum materials and their nanodevices toward revolutionary physical properties and energy functions

FeSe is a unique 2D superconductor, where the critical temperature exhibits a dramatic jump from 8 K to 40 K by reducing the thickness from bulk to monolayer. However, due to the difficulty in fabrications, the transport properties has remained elusive. We fabricated FeSe monolayer films by means of an iontronic technique, and succeeded in the first measurement of thermoelectric properties.

Left figure shows an electric double layer transistor (EDLT) device of a FeSe monolayer. FeSe monolayer was obtained through the detailed control of electrochemical etching processes with temperature and gate voltages. Right figure summarizes the temperature dependence of thermoelectric power factor P for various materials including monolayer FeSe. We found that monolayer FeSe exhibits gigantic value of 250 μW/cm/K^2 beyond that of well-known thermoelectric material Bi_2Te_3. Furthermore at low temperatures, record-high P values are observed exceeding all reported materials. This example unambiguously demonstrates that 2D and related materials are highly promising for our purposes.



Left: Monolayer FeSe device fabricated by an iontronic technique
Adapted from “Nature Communications 10, 825 (2019).”
Right: Temperature dependence of thermoelectric power factor of monolayer FeSe and other materials

Publications

1. 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).
2. R. Miranti, D. Shin, R. D. Septianto, M. Ibáñez, M. V. Kovalenko, N. Matsushita, Y. Iwasa, S. Z. Bisri, “Exclusive Electron Transport in Core@Shell PbTe@PbS Colloidal Semiconductor Nanocrystal Assemblies”, *ACS Nano*, 14, 3242-3250 (2020).
3. Y. J. Zhang, T. Ideue, M. Onga, F. Qin, R. Suzuki, A. Zak, R. Tenne, J. H. Smet, and Y. Iwasa, “Enhanced intrinsic photovoltaic effect in tungsten disulfide nanotubes”, *Nature,* 570, 349-353 (2019) .
4. S. Shimizu, J. Shiogai, N. Takemori, S. Sakai, H. Ikeda, R. Arita, T Nojima, A. Tsukazaki, and Y. Iwasa, “Giant thermoelectric power factor in ultrathin FeSe superconductor”, *Nat. Comm.,* 10, 825 (2019).
5. L. Liu, S. Z. Bisri, Y. Ishida, D. Hashizume, T. Aida, and Y. Iwasa, “Ligand and Solvent Effects on Hole Transport in Colloidal Quantum Dot Assemblies for Electronic Devices”, *ACS Appl. Nano Mater.,* 9, 5217-5225 (2018).

Yoshihiro Iwasa (D.Eng.), Team Leader
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 (-present)
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 (-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

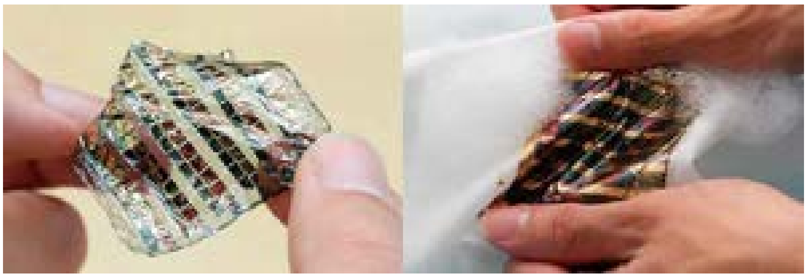
(Senior Research Scientist) Satria Bisri Zulkarnaen
(Special Postdoctoral Researcher) Hideki Matsuoka
(Postdoctoral Researcher) Ricky Dwi Septianto
(International Program Associate)
Muhammad Alief Irham, Retno Dwi Wulandari

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. 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).
2. J. Zhong, Z. Li, M. Takakuwa, D. Inoue, D. Hashizume, Z. Jiang, Y. Shi, L. Ou, M. O. G. Nayeem, S. Umezu, K. Fukuda, T. Someya, “Smart Face Mask Based on an Ultrathin Pressure Sensor for Wireless Monitoring of Breath Conditions”, *Adv. Mater.,* 34, 2107758 (2021).
3. Z. Jiang, F. Wang, K. Fukuda, A. Karki, W. Huang, K. Yu, T. Yokota, K. Tajima, T.-Q. Nguyen, and T. Someya, “Highly efficient organic photovoltaics with enhanced stability through the formation of doping-induced stable interfaces”, *PNAS*, 117, 6391-6397 (2020).
4. 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).
5. H. Jinno, K. Fukuda, X. Xu, S. Park, Y. Suzuki, M. Koizumi, T. Yokota, I. Osaka, K. Takimiya, and T. Someya, “Stretchable and waterproof elastomer-coated organic photovoltaics for washable electronic textile applications”, *Nat. Energy*, 2, 780-785 (2017). (Selected as cover picture)

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)

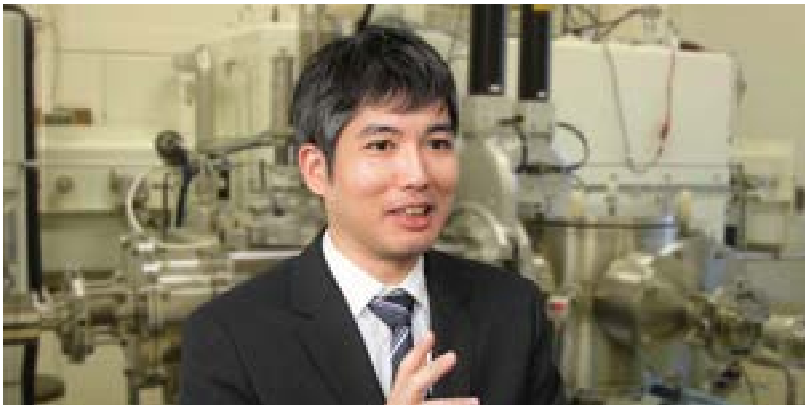
Outline

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

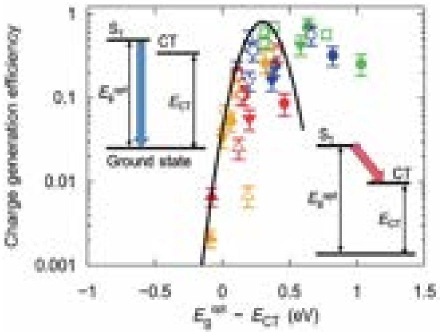
(Senior Research Scientist) Kenjiro Fukuda
(Postdoctoral Researcher) Sixing Xiong
(Student Trainee) Masahito Takakuwa, Jiachen Wang, Baocai Du, Tatsuma Miyake, Shumpei Katayama

Emergent Functional Polymers Research Team



Energetic driving force for charge generation in organic solar cells

For further improvement of the device performance of organic solar cells, optimization of electron-donating material and electron-accepting material is necessary. However, we first need to know the most suitable electronic structures for these materials. The problem was the lack of knowledge on the relation between the energetic driving force at the donor and acceptor interface and resulting device performance. To investigate the relationship between the interfacial energetic driving force and resulting device performance, the planar-heterojunction structures with simple and well-defined interfaces of electron-donating material (D) and electron-accepting material (A) are investigated. 16 planar-heterojunctions with four donor materials and four acceptor material were systematically investigated. We found that for efficient charge generation, molecularly excited state (S1) and interfacial charge-transfer (CT) state must have an energetic difference of 0.2~0.3 eV. This result provides a valuable guideline for the molecular design for efficient organic solar cells.



The charge generation efficiency is plotted against the energetic difference between the singlet excited state and charge-transfer state.

Publications

1. K. Nakano, K. Terado, Y. Kaji, H. Yoshida H., K. Tajima, “Reduction of Electric Current Loss by Aggregation-Induced Molecular Alignment of a Non-Fullerene Acceptor in Organic Photovoltaics”, ACS *Appl. Mater. Interfaces*, 13, 60299 (2021).
2. F. Wang, K. Nakano, H. Segawa, K. Tajima, “Inversion of Circular Dichroism Signals in Chiral Polythiophene Films Induced by End-On-Oriented Surface-Segregated Monolayers”, *ACS Appl. Mater. Interfaces*, 13, 7510 (2021).
3. C. Wang, H. Hao, D. Hashizume, K. Tajima, “Surface-induced Enantiomorphic Crystallization of Achiral Fullerene Derivatives in Thin Films”, *Chem. Sci.*, 11, 4702 (2020).
4. W.-C. Wang, S.-Y. Chen, Y.-W. Yang, C.-S. Hsu, and K. Tajima, “Face-on Reorientation of π-Conjugated Polymers in Thin Films by Surface-Segregated Monolayers”, *J. Mater. Chem. A*, 4, 2070013 (2020).
5. K. Nakano, Y. Chen, B. Xiao, W. Han, J. Huang, H. Yoshida, E.J. Zhou, and K. Tajima, “Anatomy of the Energetic Driving Force for Charge Generation in Organic Solar Cells”, *Nature Commun.*, 10, 2520 (2019).

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)

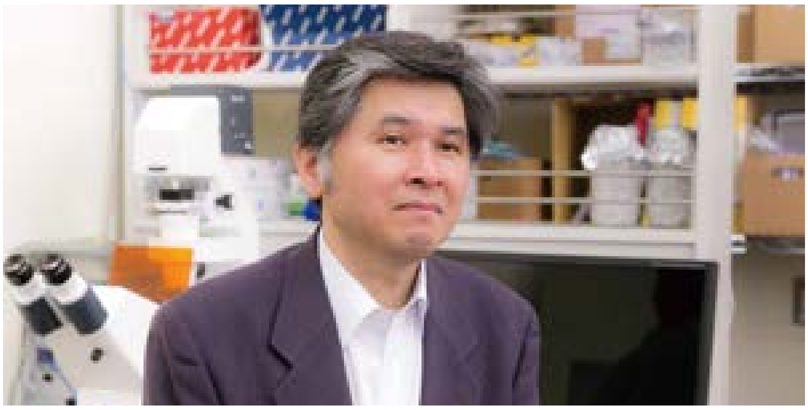
Outline

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

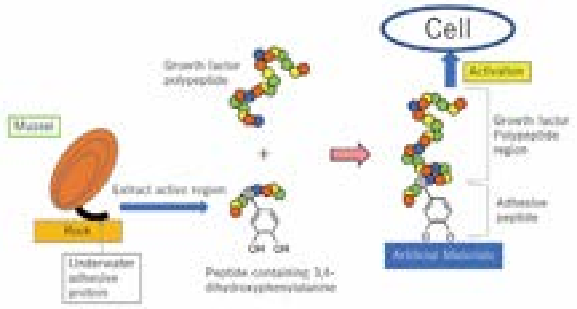
(Research Scientist) Kyohei Nakano
(Special Postdoctoral Researcher)
Chao Wang, Hitoshi Saito
(Postdoctoral Researcher)
Yuto Ochiai, Takaho Yokoyama
(Technical Staff) Yumiko Kaji
(International Program Associate) Wei-Chih Wang
(Student Trainee) Ryo Suzuki

Emergent Bioengineering Materials Research Team



Bioinspired underwater adhesive biopolymers for biologically active materials

Artificial materials have no biological functions, although they are important for medical devices such as artificial organs and matrices for regenerative medicine. Therefore, for more reliable biomaterials, biocompatibility is required to enhance the connection between materials and biological components. Our team has developed new bioactive materials by immobilization of biologically macromolecules (polypeptides) on the surfaces. For example, we designed cell activative materials by simple coating of polypeptides containing sequence of growth factor proteins with a key amino acid, 3,4-dihydroxyphenylalanine, of underwater adhesive proteins, which is secreted from mussel for adhering to rocks. The adhesive polypeptides were prepared by the bioorthogonal approaches including genetic recombination, enzymatic method, and solid phase synthesis. They formed nanolayers on various substrates involving organic and inorganic materials to conveniently provide biological surfaces. Through the direct activation of cognate receptors on interactive surfaces, the materials enhanced the cell activities more than soluble growth polypeptides.



Creation of bioactive surface by underwater-adhesive biological macromolecues prepared according to bioorthogonal approaches

Publications

1. H. Kashiwagi, N. Morishima, S. Obuse, T. Isoshima, J. Akimoto, and Y. Ito, “SARS-CoV-2 proteins microarray by photoimmobilization for serodiagnosis of the antibodies”, *Bull. Chem. Soc. Jpn.*, 94, 2435 (2021).
2. S. Tada, X. Ren, H. Mao, Y. Heo, S.-H. Park, T. Isoshima, L. Zhu, X. Zhou, R. Ito, S. Kurata, M. Osaki, E. Kobatake, and Y. Ito, “Versatile mitogenic and differentiation-inducible layer formation by underwater adhesive polypeptides”, *Adv. Sci.*, 2100961 (2021).
3. R. Wang, Y. Tian, J. Wang, W. Song, Y. Cong, X. Wei, Y. Mei, H. Miyatake, Y. Ito, and Y. Chen, “Biomimetic Glucose Trigger-Insulin Release System Based on Hydrogel Loading Bidentate β-Cyclodextrin”, *Adv. Funct. Mater.,* 20, 2104488 (2021).
4. A. Nandakumar, Y. Ito, and M. Ueda, “Solvent Effects on the Self-Assembly of an Amphiphilic Polypeptide Incorporating α-Helical Hydrophobic Blocks”, *J. Am. Chem. Soc.*, 142, 20994 (2020).
5. S. J. Park, J. Akimoto, N. Sakakibara, E. Kobatake, and Y. Ito, “Thermally induced switch of coupling reaction using morphological change of thermoresponsive polymer on reactive hetero-armed nanoparticle”, *ACS Appl. Mater. Interfaces.*, 12, 49165 (2020).

Yoshihiro Ito (D.Eng.), Team Leader
y-ito@riken.jp

Research field

Organic Chemistry, Materials Science, Bioengineering

Keywords

Energy conversion, Sensors, Precise polymer synthesis, Molecular evolutionary engineering, Nanobiotechnology

Brief resume

1987	D.Eng., Kyoto University
1988	Assistant Professor, Kyoto University
1996	Associate Professor, Kyoto University
1997	Associate Professor, Nara Institute of Science and Technology
1999	Professor, University of Tokushima
2001	Project Leader, Kanagawa Academy of Science and Technology
2004	Chief Scientist, Nano Medical Engineering Laboratory, RIKEN (-present)
2013	Team Leader, Emergent Bioengineering Materials Research Team, RIKEN Center for Emergent Matter Science (-present)

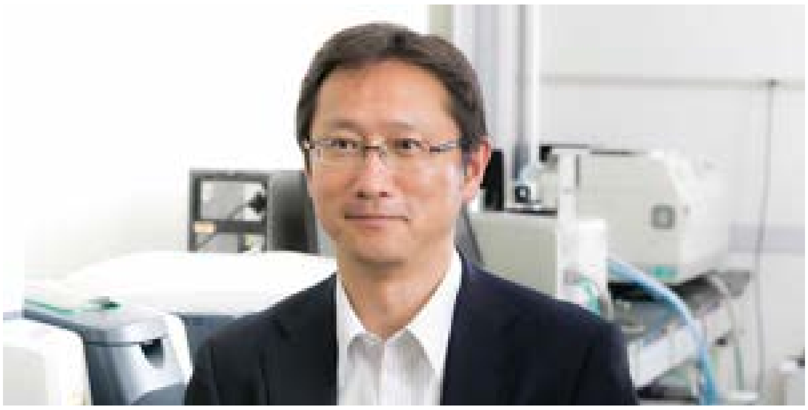
Outline

Advanced materials composed of biological and artificial components are synthesized for development of environmentally friendly energy collection and conversion systems. By combination of organic synthetic chemistry, polymer chemistry, and biotechnology, novel synthesis method will be established and materials using biological and artificial elements will be achieved by their chemical fabrication, and the characterization of the interfaces between biological and artificial elements for highly efficient energy collection and conversion. Especially our team will establish a new methodology, a chemically extended molecular evolutionary engineering as an “Emergent Chemistry” to create a specific ally functionalized polymer by screening of random sequence of polymer library containing functional monomers.

Core members

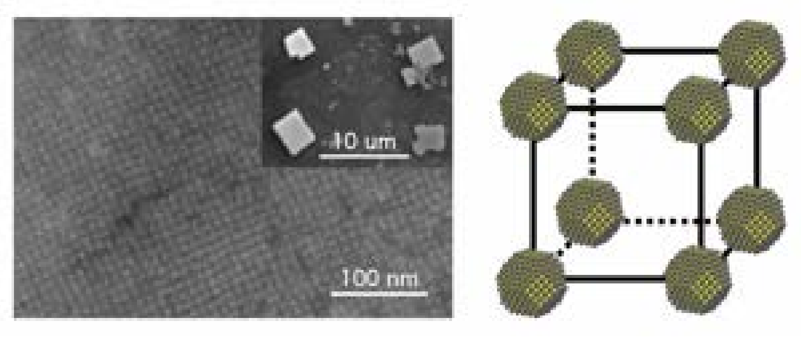
(Senior Research Scientist)
Masuki Kawamoto, Takanori Uzawa, Motoki Ueda
(Senior Visiting Scientist) Hiroshi Abe
(Visiting Scientist) Kyoji Hagiwara, Jun Akimoto
(International Program Associate)
Ahmed Emad Abdelmoneam Ali Elrefaey,
Ramadan Mohamed Mohamed Osama Metawea
(Junior Research Associate)
Mahmoud Hassan Mahmoud Othman, Minxing Hu
(Technical Staff) Noriko Minagawa, Hideaki Takaku
(Trainee) Kon Son

Emergent Supramolecular Materials Research Team



Simple cubic self—assembly of colloidal quantum dots

Colloidal quantum dots (QDs) have attracted substantial attention due to their characteristic optoelectronic properties based on their size confinement effects. They are also known to form highly ordered superlattices in the self-assembled solid state. The geometry of such self-assembled QDs has been explored theoretically and experimentally in order to better understand the ensemble effects on their optical and electrical properties, especially with regard to solid-state device applications. We achieved the selective control of the geometry of colloidal quasi-spherical PbS QDs in highly-ordered two and three dimensional superlattices: Disordered, simple cubic (sc), and face-centered cubic (fcc). Gel permeation chromatography (GPC), not based on size-exclusion effects, was developed to quantitatively and continuously control the ligand coverage of PbS QDs. This selective formation of different geometric superlattices based on GPC promises applications of such colloidal quasi-spherical QDs in high-performance optoelectronic devices.



3D self-assembly supercrystals of PbS colloidal quantum dots with simple cubic (sc) structure

Publications

1. 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).
2. 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).
3. N. Aizawa, Y. Harabuchi, S. Maeda, Y.-J. Pu, "Kinetic Prediction of Reverse Intersystem Crossing in Organic Donor–Acceptor Molecules", *Nat. Commun.*, 11, 3909 (2020).
4. 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).
5. Y.-J. Pu, Y. Koyama, D. Otsuki, M. Kim, H. Chubachi, Y. Seino, K. Enomoto, N. Aizawa, "Exciplex Emissions Derived from Exceptionally Long-Distanced Donor and Acceptor Molecules", *Chem. Sci.*, 10, 9203 (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)

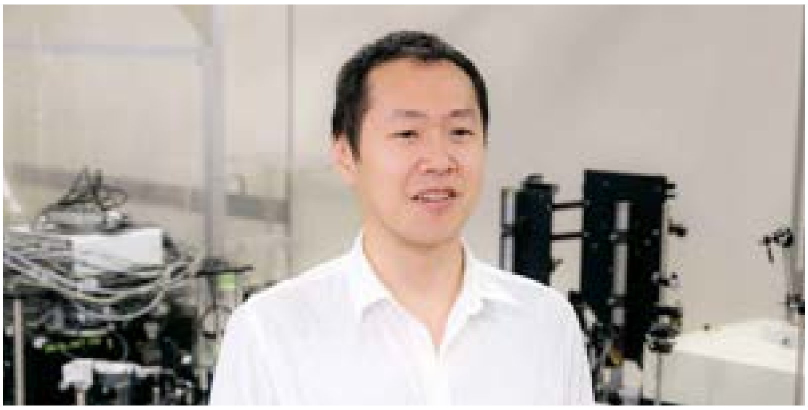
Outline

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

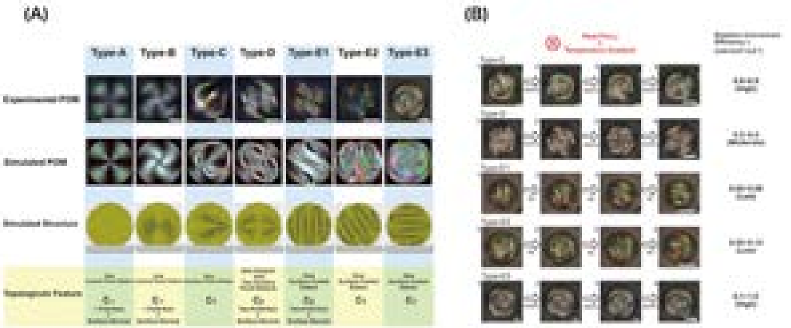
(Postdoctoral Researcher)
Minjun Kim, Jianjun Liu, Rento Miranti

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)

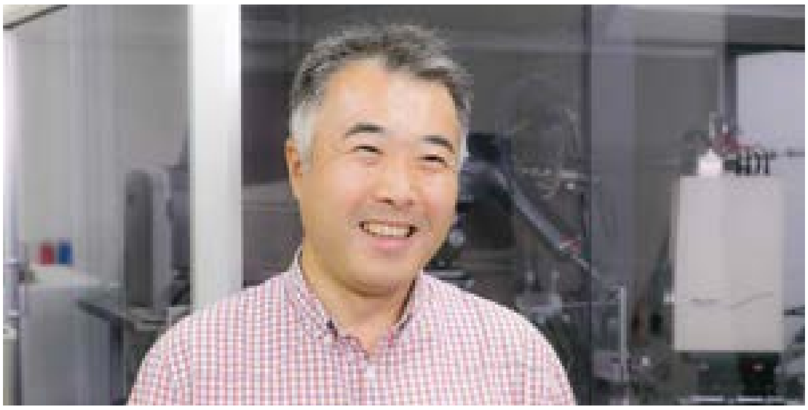
Outline

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
(Postdoctoral Researcher)
Taishi Noma, Daichi Okada, Muhammad Ali

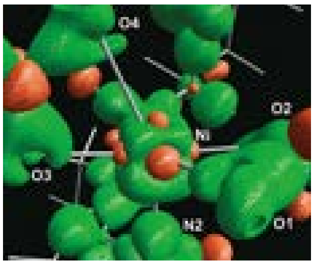
Materials Characterization Support Team



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 resulted 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 resulted models. For deeply 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. A. Li, S. Kong, C. Guo, H. Ooka, K. Adachi, D. Hashizume, Q. Jiang, H. Han, J. Xiao, and R. Nakamura, "Enhancing the stability of cobalt spinel oxide towards sustainable oxygen evolution in acid", *Nat. Catal.*, 5, 109 (2022).
2. T. Kubo, Y. Suga, D. Hashizume, H. Suzuki, T. Miyamoto, H. Okamoto, R. Kishi, and M. Nakano, "Long carbon-carbon bonding beyond 2 Å in tris(9-fluorenylidene)methane", *J. Am. Chem. Soc.*, 143, 14360 (2021).
3. T. Kajitani, K. Motokawa, A. Kosaka, Y. Shoji, R. Haruki, D. Hashizume, T. Hikima, M. Takata, K. Yazawa, K. Morishima, M. Shibayama, and T. Fukushima, "Chiral crystal-like droplets displaying unidirectional rotating sliding", *Nat. Mater.*, 18, 266 (2019).
4. 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*, 561, 516 (2018).
5. Y. Sohtome, G. Nakamura, A. Muranaka, D. Hashizume, S. Lectard, T. Tsuchimoto, M. Uchiyama, and M. Sodeoka, "Naked d-orbital in a centrochiral Ni(II) complex as a catalyst for asymmetric [3+2] cycloaddition", *Nat. Commun.*, 8, 14875 (2017).

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 by means of 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 make training in our skills. We make tight and deep collaboration 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. Furthermore, 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) Tomoka Kikitsu, Kiyohiro Adachi

Quantum Functional System Research Group

Quantum non-demolition measurement of semiconductor quantum bits

Quantum computing with single electron spins in silicon has been intensively studied,motivated by prospect for the qubit scale-up using semiconductor device processing technology. However, implementing useful measurement-based protocols, including error correction remains a challenge because the qubit measurement usually demolishes the spin state. Here we probe a neighboring electron spin Ising-coupled to the qubit spin and first succeed in the quantum non-demolition measurement of the electron spin in silicon.

In this experiment an electron spin is first initialized to an arbitral qubit state (main qubit) using a spin resonance technique. Next, an Ising-type coupling is applied to the main qubit and the partner qubit (ancilla qubit) to form entanglement between them. When the ancilla qubit is measured being spin-up or spin-down, the main qubit is readout without measuring it. This is a nondemolition projective measurement that causes no substantial error in the main qubit, and allows to raise the readout fidelity of the main qubit by repeating the ancilla measurement.

Our work offers a promising route to construct an error correction circuit in silicon.

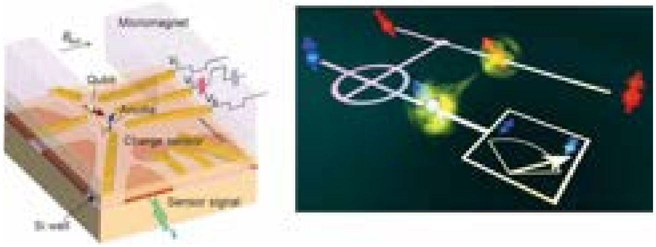


Figure (Left) Schematic view of the quantum double dot device used for the experiment.
(Right) Concept of quantum nondemolition measurement.

Publications

1. 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).
2. 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).
3. J. Yoneda, K. Takeda, A. Noiri, T. Nakajima, S. Li, J. Kamioka, T. Kodera, and S. Tarucha, “Quantum non-demolition readout of an electron spin in silicon”, *Nature Commun.* 11, 1144 (2020).
4. T. Fujita, K. Morimoto, H. Kiyama, G. Allison, M. Larsson, A. Ludwig, S.R. Valentin, A.D. Wieck, A. Oiwa, and S. Tarucha, “Angular momentum transfer from photon polarization to an electron spin in a gate-defined quantum dot”, *Nature Commun.* 10, 2991 (2019).
5. K. Ueda, S. Matsuo, H. Kamata, S. Baba, Y. Sato, Y. Takeshige, K. Li, S. Jeppesen, L. Samuelson, HQ Xu, and S. Tarucha, “Dominant nonlocal superconducting proximity effect due to electron-electron interaction in a ballistic double nanowire”, *Science Adv.* 5, eaaw2194 (2019).

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

Research field

Physics, Engineering

Keywords

Quantum computing, Qubit, Spin control, Quantum dots, Topological particles

Brief resume

1978	Staff member at the Basic Research Laboratories of Nippon Tel. & Tel. Corp.
1986	Visiting Scientist , MPI (Stuttgart, Germany)(-1987)
1995	Visiting Professor , Delft University of Technology (Delft, The Netherlands)
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 (-present)
2019	Guest Professor, Department of Physics, Tokyo University of Science (-present)
2020	Team Leader, Semiconductor Quantum Information Device 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.

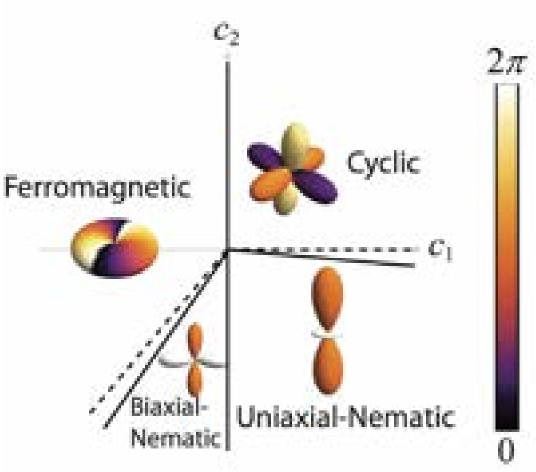
Core members

(Research Scientist) Takashi Nakajima, Kenta Takeda
(Postdoctoral Researcher) Leon Camenzind,
Yago Del Valle Inclan Redondo
(Special Postdoctoral Researcher)
Akito Noiri, Sadashige Matsuo
(Visiting Scientist) Tomohiro Otsuka,
Michael Desmond Fraser, Raisei Mizokuchi
(Technical Staff I) Xin Liu
(Research Associate) Yosuke Sato
(Student Trainee) Yusuke Takeshige, Takaya Imoto,
Toshiya Yamada, Masahiro Tadokoro,
Ryutaro Matsuoka, Takaya Imoto

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. E. Yukawa and M. Ueda, “Mophological Superfluid in a Nonmagnetic Spin-2 Bose-Einstein Condensate”, *Phys. Rev. Lett.*, 124, 105301 (2020).
2. N. Kura and M. Ueda, “Standard Quantum Limit and Heisenberg Limit in Function Estimation”, *Phys. Rev. Lett.*, 124, 010507 (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, Optical lattice, Quantum simulation, Quantum correlations, Explainable AI

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 borderlines between quantum physics, measurement, information and thermodynamics. In particular, we explore novel phenomena in ultracold atoms which offer a versatile tool to investigate universal quantum phenomena that are independent of material-specific parameters. We also aim to construct an explainable AI based on physics principles.

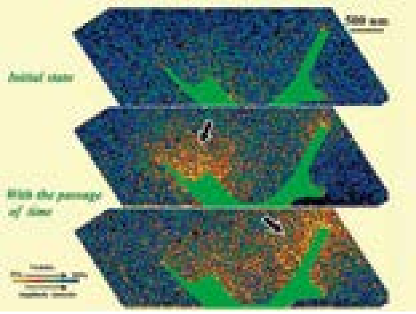
Core members

(Research Scientist) Takashi Mori
(Postdoctoral Researcher) Lennart Justin Dabelow

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 change 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 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 & 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).

Daisuke Shindo (D.Eng), Team Leader
daisuke.shindo@riken.jp

Research field

Physics, Engineering, Materials Science

Keywords

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

Brief resume

1982	D. Eng., Tohoku University
1982	Research Associate, Institute for Materials Research at Tohoku University
1992	Associate Professor, Institute for Advanced Materials Processing at Tohoku University
1994	Professor, Institute of Multidisciplinary Research for Advanced Materials at Tohoku University
2010	Visiting Scientist, Quantum Phenomena Observation Technology Team, RIKEN
2012	Team Leader, Emergent Phenomena Observation Technology Research Team, RIKEN
2013	Team Leader, Emergent Phenomena Observation Technology Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
2019	Professor Emeritus, Tohoku University (-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.

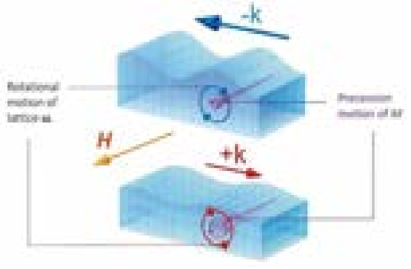
Core members

(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. K. Kondou, H. Chen, T. Tomita, M. Ikhlas, T. Higo, A. H. MacDonald, S. Nakatsuji, and Y. Otani,"Giant field-like torque by the out-of-plane magnetic spin Hall effect in a topological antiferromagnet", *Nature Commun.* 12, 6491 (2021).
2. J. Kim, D Go, H. Tsai, D. Jo, K. Kondou, H-W Lee, and Y. Otani, "Nontrivial torque generation by orbital angular momentum injection in ferromagnetic-metal/Cu/Al_2O_3 trilayers", *Phys. Rev. B* 103, L020407 (2021).
3. Y. Hwang, J. Puebla, M. Xu, A. Lagarrigue, K. Kondou, and Y. Otani, "Enhancement of acoustic spin pumping by acoustic distributed Bragg reflector cavity", *Appl. Phys. Lett.* 116, 252404 (2020).
4. M. Xu, K. Yamamoto, J. Puebla, K. Baumgaertl, B. Rana, K. Miura, H. Takahashi, D. Grundler, S. Maekawa and Y. Otani, "Nonreciprocal surface acoustic wave propagation via magneto-rotation coupling", *Sci. Adv.* 6, 1724 (2020).
5. M. Xu, J. Puebla, F. Auvray, B. Rana, K. Kondou and Y. Otani, "Inverse Edelstein effect induced by magnon-phonon coupling", *Phys. Rev. B* 97, 180301(R) (2018).

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

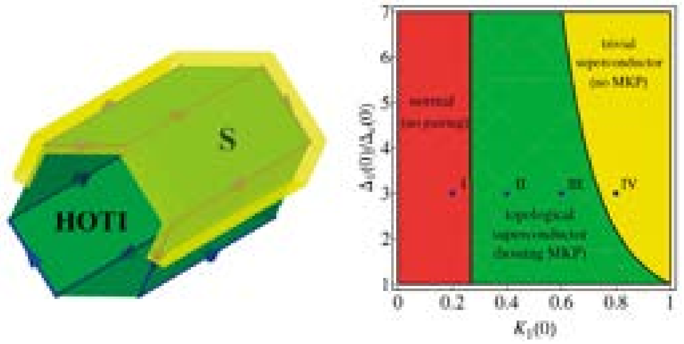
(Senior Research Scientist) Kouta Kondou
(Research Scientist)
Junyeon Kim, Jorge Luis Puebla Nunez
(Visiting Researcher) Thomas Lyons
(Student Trainee)
Mingxing Wu, Handa Wang, Liyang Liao
(Junior Research Associate / Student Trainee)
Yunyoung Hwang

Quantum System Theory Research Team

Majorana Kramers pairs in higher-order topological insulators

Higher order topological insulators are systems which realize the most recent flavor of topological matter. While being insulating in the bulk and on the surface, they host propagating states at the edges (hinges), where two facets meet. We designed a tune-free scheme to realize Kramers pairs of Majorana bound states in higher-order topological insulators with proximity-induced superconductivity.

Our scheme is an experimentally accessible setup, which proposes to use a bismuth wire half-covered by a superconductor. Namely, we find that when two hinges with the same helicity of the wire are in contact to an s-wave superconductor, moderate electron-electron interactions favor the inter-hinge pairing over the intra-hinge pairing, leading to formation of Majorana Kramers pairs. As a result, the proposed scheme does not require a magnetic field or local voltage gates, which is a highly desired property in the quest for topological states.



Left panel: Higher order topological insulator realized using a superconductor (yellow) and a wire (green). Right panel: The phase diagram of the model shown in the Left panel.
Chen-Hsuan Hsu, Peter Stano, Jelena Klinovaja, and Daniel Loss, "Majorana Kramers Pairs in Higher-Order Topological Insulators," Phys. Rev. Lett. 121, 196801 (2018) © APS

Publications

1. Ch.-H. Hsu, P. Stano, J. Klinovaja, D. Loss, "Helical Liquids in Semiconductors", *Semicond. Sci. Technol.* 36, 123003 (2021).
2. 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).
3. 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)
4. Ch.-H. Hsu, P. Stano, J. Klinovaja, D. Loss, "Majorana Kramers pairs in higher-order topological insulators", *Phys. Rev. Lett.,* 121, 196801 (2018).
5. J. Klinovaja, P. Stano, D. Loss, "Topological Floquet Phases in Driven Coupled Rashba Nanowires", *Phys. Rev. Lett.,* 116, 176401 (2016).

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

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)

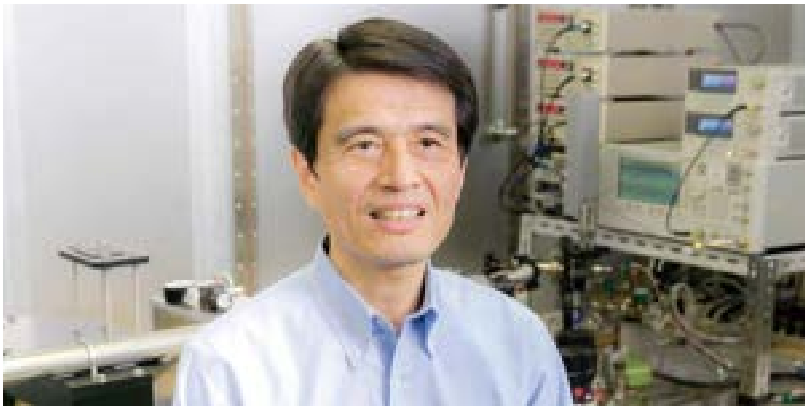
Outline

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

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

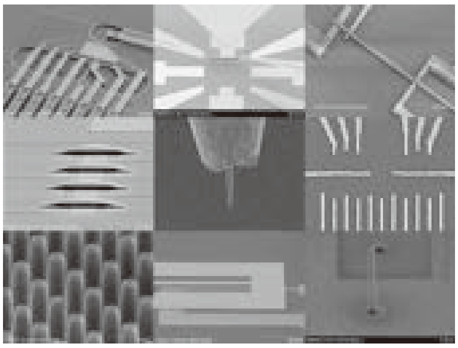
Emergent Matter Science Research Support Team



Supporting researchers for nanometer-scale fabrication

To build a sustainable society with environment friendly device, it is essential to realize energy effective devices and faster information process. To realize such devices, the researchers in the Center for Emergent Matter Science are enthusiastically pursuing to develop quantum devices, spin devices and quantum computers. In building such devices, highly sophisticated equipment and support for keeping best condition of the equipment are required.

Our team is established to support the researcher's activity by providing skillful expertise. We are responsible for operation of the equipment like lithography systems including an electron beam lithography, an maskless UV photo lithography system, deposition systems like evaporators and sputters, dry and wet etching systems and observation system as scanning electron microscopy and for keeping them in the best condition. 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 tirelessly.



Examples of the specimen fabricated in the clean room.

Publications

1. M. Hirao, D. Yamanaka, T. Yazaki, J. Osano, H. Iijima, T. Shiokawa, H. Akimoto, T. Meguro, "STM Study on Adsorption Structures of Cs on the As-Terminated GaAs(001)(2x4) Surface by Alternating Supply of Cs and O_2", *IEICE Transactions on Electronics*, E99C, 376 (2016).
2. H. Ikegami, H. Akimoto, D. G. Rees, and K. Kono, "Evidence for Reentrant Melting in a Quasi-One-Dimensional Wigner Crystal", *Phys. Rev. Lett.*, 109, 236802 (2012).
3. M. Shimizu, H. Akimoto, K. Ishibashi, "Electronic Transport of Single-Wall Carbon Nanotubes with Superconducting Contacts", *Jpn. J. Appl. Phys.*, 50, 035102 (2011).
4. S. M. Huang, Y. Tokura, H. Akimoto, K. Kono, J. J. Lin, S. Tarucha, K. Ono., "Spin Bottleneck in Resonant Tunneling through Double Quantum Dots with Different Zeeman Splittings", *Phys. Rev. Lett.*, 104, 136801 (2010).
5. H. Akimoto, J. S. Xia, D. Candela, W. J. Mullin, E. D. Adams, N. S. Sullivan, "Giant viscosity enhancement in a spin-polarized fermi liquid", *Phys. Rev. Lett.*, 99, 095301 (2007).

Hikota Akimoto (Ph.D.), Team Leader
hikota@riken.jp

Research field

Materials Sciences, Physics

Keywords

Nanometer scale fabrication, Sample characterization, Education of users

Brief resume

1988	Research Associate, University of Tokyo
1990	Ph.D., Osaka City University
1996	Visiting Scientist, Leiden University, Netherlands
1998	Post Doctoral Associate, University of Florida, USA
2001	Senior Post Doctoral Associate, University of Massachusetts, USA
2003	Development Researcher, Nanoscience Development and Support Team, RIKEN
2008	Team Head, Nanoscience Development and Support Team, RIKEN
2013	Team Leader, Emergent Matter Science Research Support Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)

Outline

Our mission is to develop novel technologies with a wide range of applications in nanoscience and nanotechnology and to support the users in RIKEN for nanometer-scale fabrication and the characterization of specimens. We are responsible for the operation of the facilities including the clean room and the chemical rooms with suitable safety measure. The clean room is for fabrication and characterization of nanometer-scale devices and the chemical rooms are for those of wet samples for chemistry and biology. In the clean room and the chemical rooms, more than 30 apparatus have been installed and are open to the users. We are also responsible for the education of the users.

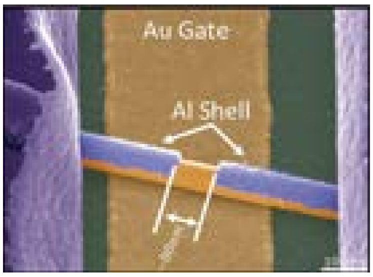
Core members

(Technical Staff) Reiko Nakatomi, Yoshio Taguchi

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. P. Zellekens, R. Deacon, P. Perla, H. A. Fonseka, T. Mörstedt, S. A. Hindmarsh, B. Bennemann, F. Lentz, M. I. Lepsa, A. M. Sanchez, D. Grützmacher, K. Ishibashi, and T. Schäpers, "Hard-Gap Spectroscopy in a Self-Defined Mesoscopic InAs/Al Nanowire Josephson Junction", *Phys. Rev. Applied* 14, 054019 (2020).
2. 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, 1052–1060 (2019).
3. J. Sun, R. Deacon, R. Wang, J. Yao, C. Lieber, K. Ishibashi, "Helical Hole State in Multiple Conduction Modes in Ge/Si Core/Shell Nanowire", *Nano Lett.* 18, 6144-6149 (2018).
4. 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).
5. A. Hida, and K. Ishibashi, "Molecule-induced quantum confinement in single-walled carbon nanotube", *Appl. Phys. Ex.*, 8, 045101 (2015).

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

Engineering, Physics

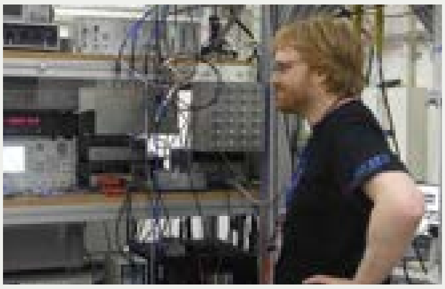
Keywords

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)
2017	Visiting Professor, Osaka University (-present)

Outline

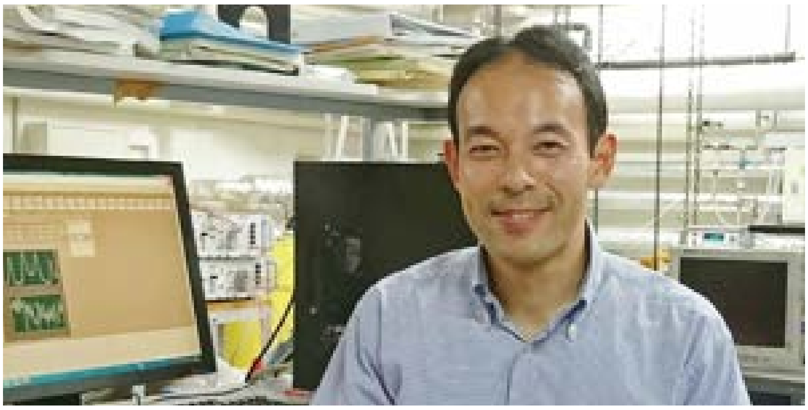


We study quantum effects that appear in nanoscale structures and apply them to functional nanodevise. We focus on hybrid nanostructures, such as carbon nanotube/molecule heterostructures and topological insulator or nanostructures/superconductor hybrid nanostructures as well as nanoscale Si transistors, 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
(Research Associate) Patrick Zellekens

Quantum Electron Device Research Team

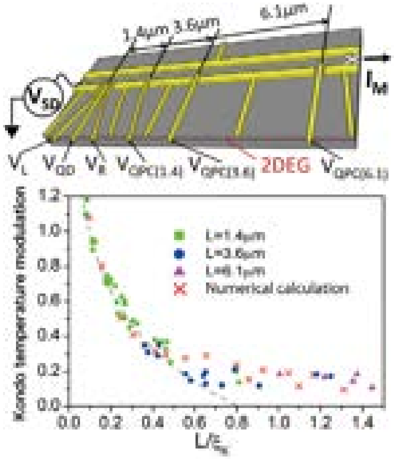


Observation of the Kondo screening cloud

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 cloud. While the size of the Kondo cloud is one of the most important parameters that determine properties of many-body states containing multiple localized spins, its detection has remained elusive for the past 50 years.

We confined a localized spin in a semiconductor artificial atom coupled to conducting electrons, embedded it into an electronic interferometer, and observed real shape of the Kondo cloud. We found that its size is inverse proportional to the Kondo temperature and that the cloud has the universal shape.

Our work is an important step towards understanding of many-body correlated states containing multiple magnetic impurities and development of novel quantum information devices based on the long-range spin coupling. We are now investigating systems, where multiple Kondo clouds overlap with one another.



Schematic illustration of the device used for detection 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)

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.

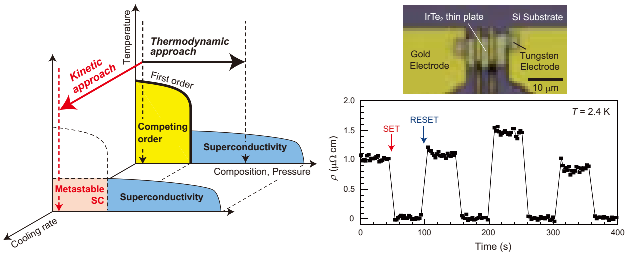
Core members

(Research Scientist) Yuya Shimazaki
(Postdoctoral Researcher)
Ngoc Han Tu, David Pomaranski, Ryo Ito

Dynamic Emergent Phenomena Research Unit

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)

Publications

1. H. Oike, K. Takeda, M. Kamitani, Y. Tokura, and F. Kagawa, “Real-space observation of emergent complexity of phase evolution in micrometer-sized $IrTe_2$ crystals” *Phys. Rev. Lett.* 127, 145701 (2021).
2. K. Matsuura, H. Oike, V. Kocsis, T. Sato, Y. Tomioka, Y. Kaneko, M. Nakamura, Y. Taguchi, M. Kawasaki, Y. Tokura, and F. Kagawa, “Kinetic pathway facilitated by a phase competition to achieve a metastable electronic phase”, *Phys. Rev. B* 103, L041106 (2021).
3. T. Sato, W. Koshibae, A. Kikkawa, T. Yokouchi, H. Oike, Y. Taguchi, N. Nagaosa, Y. Tokura, and F. Kagawa, "Slow steady flow of a skyrmion lattice in a confined geometry probed by resistance narrow-band noise", *Phys. Rev. B* 100, 094410 (2019).
4. H. Oike, M. Kamitani, Y. Tokura, and F. Kagawa, “Kinetic approach to superconductivity hidden behind a competing order”, *Sci. Adv.*, 4, eaau3489 (2018).
5. H. Oike, A. Kikkawa, N. Kanazawa, Y. Taguchi, M. Kawasaki, Y. Tokura, and F. Kagawa, “Interplay between topological and thermodynamic stability in a metastable magnetic skyrmion lattice”, *Nat. Phys.*, 12, 62 (2016).

Fumitaka Kagawa (D.Eng.), Unit 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 (-present)
2017	Associate Professor, Department of Applied Physics, University of Tokyo
2022	Professor, Department of Physics, Tokyo Institute of Technology (-present)

Outline

Our unit explores dynamic 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.

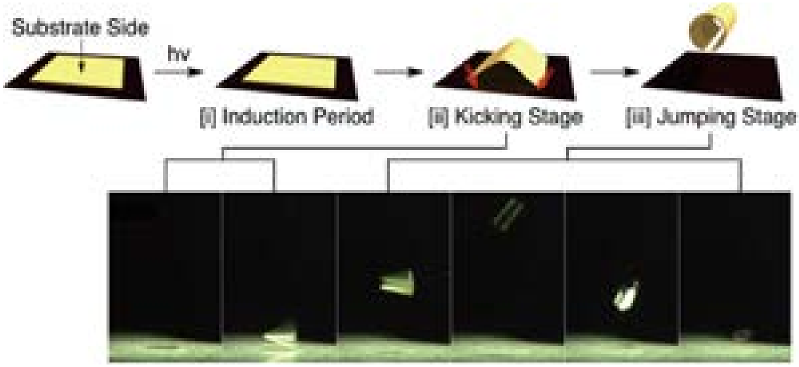
Core members

(Postdoctoral Researcher)
Meng Wang, Keisuke Matsuura
(Visiting Scientist) Hiroshi Oike, Takuro Sato

Information Transforming Soft Matter Research Unit

Actuator driven by fluctuations in environmental humidity

We have developed a film that curls up and straightens out autonomously when exposed to tiny, barely measurable changes in ambient humidity. When irradiated with ultraviolet light, which causes changes in the film’ s ability to absorb and desorb water, it can even “jump” into the air. In the same way that a mechanical watch takes advantage of the natural movements of the wrist to gain energy, this film takes tiny fluctuations in the ambient humidity and transforms them into mechanical energy. This type of device will be useful for creating a sustainable society.



Photos and schematic illustration of jumping of the film with photo-irradiation

Publications

1. K. V. Rao, D. Miyajima, A. Nihonyanagi and T. Aida “Thermally bisignate supramolecular polymerization”, *Nat. Chem.* 9, 1133 (2017).
2. H. Arazoe, D. Miyajima, K. Akaike, F. Araoka, E. Sato, T. Hikima, M. Kawamoto and T. Aida, “An autonomous actuator driven by fluctuations in ambient humidity”, *Nat. Mater.* 15, 1084 (2016).
3. J. Kang, D. Miyajima, T. Mori, Y. Inoue, Y. Itoh and T. Aida, “A rational strategy for the realization of chain-growth supramolecular polymerization”, *Science*, 347, 646 (2015).
4. J. Kang, D. Miyajima, Y. Itoh, T. Mori, H. Tanaka, M. Yamauchi, Y. Inoue, S. Harada and T. Aida, “C5-Symmetric Chiral Corannulenes: Desymmetrization of Bowl Inversion Equilibrium via “Intramolecular” Hydrogen-Bonding Network”, *J. Am. Chem. Soc.*, 136, 10640 (2014).
5. D. Miyajima, F. Araoka, H. Takezoe, J. Kim, K. Kato, M. Takata and T. Aida, “Ferroelectric columnar liquid crystal featuring confined polar groups within core–shell architecture”, *Science*, 336, 209 (2012).

Daigo Miyajima Ph. D (Eng.), Unit Leader
daigo.miyajima@riken.jp

Research field

Chemistry, Materials Science

Keywords

Self-assembly, Molecular design, Two-dimensional Materials, Polymer Synthesis, Nanobiotechnology

Brief resume

2013	Ph. D., University of Tokyo
2013	Postdoctoral Researcher, RIKEN Center for Emergent Matter Science
2014	Special Postdoctoral Researcher, RIKEN Center for Emergent Matter Science
2017	Senior Research Scientist, RIKEN Center for Emergent Matter Science
2018	Unit Leader, Information Transforming Soft Matter Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

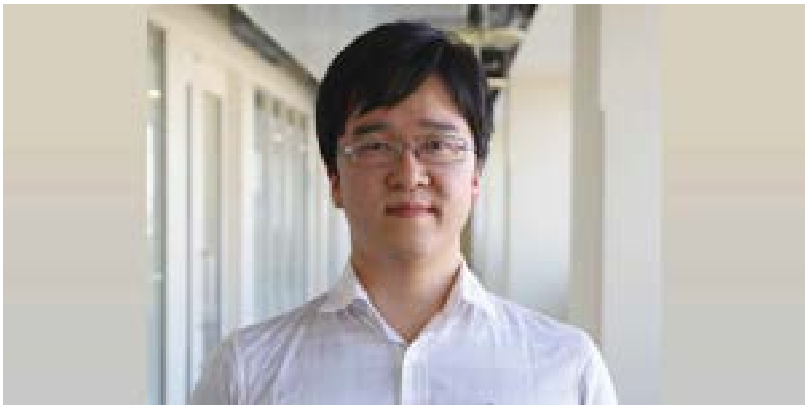
Outline

Our unit challenges to develop novel organic materials based on basic concepts of synthetic organic and supramolecular chemistries. In particular, we are mainly trying to selectively synthesize kinetic products by controlling self-assemblies of molecules.

Core members

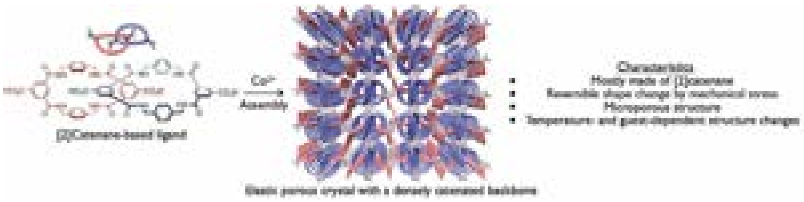
(Researcher) Ryotaro Ibuka
(Postdoctoral Researcher) Barun Dhara
(Technical Staff I) Hiroyuki Inuzuka
(Research Part-time Worker I)
Toshie Wakamatsu, Yuko Hamada

Emergent Molecular Assembly Research Unit



Topological bonds assemble to form porous crystals

Our group 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

Publications

1. 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).
2. 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).
3. 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).
4. J.-M. Lee and H. Sato “Photoswitching to the Core”, *Nat. Chem.*, 12, 584 (2020).
5. S. Suginome, H. Sato, A. Hori, A. Mishima, Y. Harada, S. Kusaka, R. Matsuda, J. Pirillo, Y. Hijikata, and T. Aida “One-Step Synthesis of an Adaptive Nanographene MOF: Adsorbed Gas-Dependent Geometrical Diversity”, *J. Am. Chem. Soc.*, 141, 15649 (2019).

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 (-present)
2021	Unit Leader, Emergent Molecular Assembly 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.

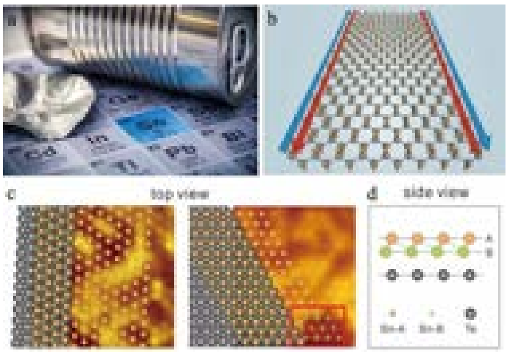
Core members

(Postdoctoral Researcher)
Jet Sing Lee, Bohan Cheng, Saiya Fujiwara
(Student Trainee)
Kunyi Leng, Wei Yuan, Mika Kawagoe

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. Y. Li, J. Li, Y. Li, M. Ye, F. Zheng, Z. Zhang, J. Fu, W. Duan, and Y. Xu "High-Temperature Quantum Anomalous Hall Insulators in Lithium-Decorated Iron-Based Superconductor Materials", *Phys. Rev. Lett.* 125, 086401 (2020).
2. C. Liu, Y. Wang, H. Li, Y. Wu, Y. Li, J. Li, K. He, Y. Xu, J. Zhang, and Y. Wang "Robust axion insulator and Chern insulator phases in a two-dimensional antiferromagnetic topological insulator", *Nature Mater.* 19, 522 (2020).
3. J. Falson, Y. Xu, M. Liao, Y. Zang, K. Zhu, C. Wang, Z. Zhang, H. Liu, W. Duan, K. He, H. Liu, J. H. Smet, D. Zhang, Q.-K. Xue "Type-II Ising Pairing in Few-Layer Stanene", *Science* 367, 1454 (2020).
4. 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).
5. 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).
6. J. Deng, B. Xia, X. Ma, H. Chen, H. Shan, X. Zhai, B. Li, A. Zhao, Y. Xu, W. Duan, S. Zhang, B. Wang, and J. Hou, "Epitaxial growth of ultraflat stanene with topological band inversion", *Nat. Mater.*, 17, 1081 (2018).
7. M. Liao, Y. Zang, Z. Guan, Y. Gong, K. Zhu, D. Zhang, Y. Xu, K. He, X.-C. Ma, S.-C. Zhang, and Q.-K. Xue, "Superconductivity in Few-Layer Stanene", *Nat. Phys.*, 14, 344 (2018).

Yong Xu (Ph.D.), Unit Leader
yong.xu@riken.jp

Research field

Condensed Matter Physics, Materials Science

Keywords

First-principles calculations, Topological quantum matters, Thermoelectric effect, Thin films and interfaces, Theoretical materials design

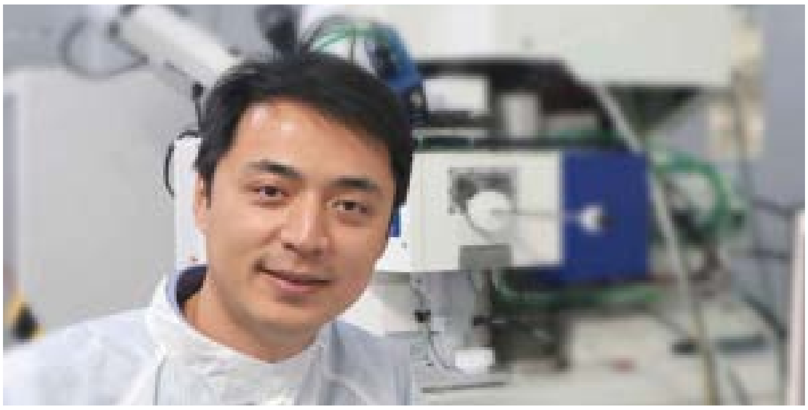
Brief resume

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



Type-II Ising pairing in few-layer stanene

In recent years, two-dimensional non-centrosymmetric superconductors show large in-plane upper critical fields, far exceeding the conventionally expected value. To explain this phenomenon, a so-called Ising pairing mechanism was proposed, in which the paired electrons stem from spin-split bands with the spin orientations locked out-of-plane. Recently, we observed enhanced in-plane upper critical field in a highly symmetric material—few-layer stanene. This is based on our previous discovery of superconductivity in the same material. In the more recent work, we clearly observed an up-turn behavior of the critical magnetic field as the temperature approaches absolute zero. However, since stanene is centrosymmetric, the observed behaviors cannot be explained by the established theory of Ising superconductivity. We therefore proposed a new type of Ising pairing—type-II Ising paring—which results from the combination of spin-orbit coupling and high lattice symmetry of the materials. Our work provides strong evidence for the existence of Ising superconductivity and substantially broadens the scope for the realization of Ising superconductors.

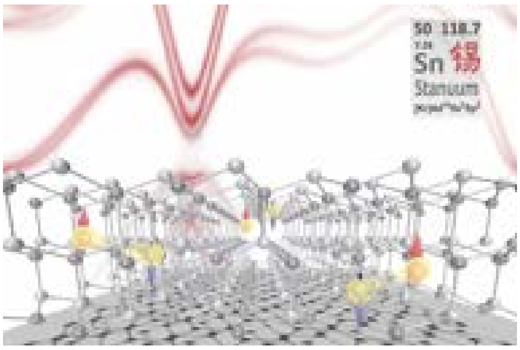


Illustration of the stanene lattice with Ising-like Cooper pairs. The background shows the corresponding band structure. Upper right shows the element information of Sn.

Publications

1. 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).
2. M. Liao, Y. Zang, Z. Guan, H. Li, Y. Gong, K. Zhu, X.-P. Hu, D. Zhang, Y. Xu, Y.-Y. Wang, K. He, X.-C. Ma, S.-C. Zhang, and Q.-K. Xue, “Superconductivity in few-layer stanene”, *Nat. Phys.* 14, 344 (2018).
3. D. Zhang, J. Falson, S. Schmult, W. Dietsche, and J. H. Smet, “Quasi-particle tunneling across an exciton condensate”, *Phys. Rev. Lett.* 124, 246801 (2020).
4. M. Rafique, Z. Feng, Z. Lin, X. Wei, M. Liao, D. Zhang, K. Jin, and Q.-K. Xue, “Ionic liquid gating induced protonation of electron-doped cuprate superconductors”, *Nano Lett.* 19, 7775 (2019).
5. M. Liao, Y. Zhu, J. Zhang, R. Zhong, J. Schneeloch, G. Gu, K. Jiang, D. Zhang, X. Ma, and Q.-K. Xue, “Superconductor-insulator transitions in exfoliated $B_2Sr_2CaCu_2O_{8+\delta}$ flakes”, *Nano Lett.* 18, 5660 (2018).

Ding Zhang (Ph.D.), Unit Leader

ding.zhang@riken.jp

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)

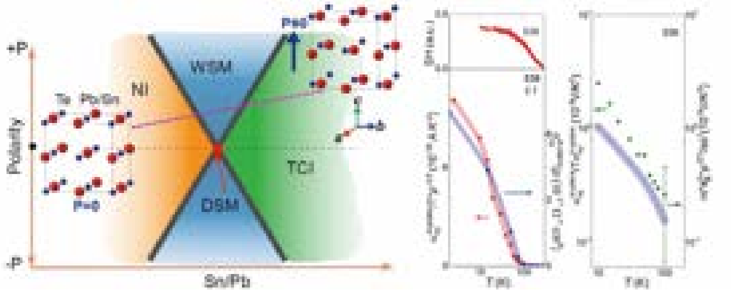
Outline

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 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. 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 (44) e2111855118 (2021).
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3. J.J. He, T. Liang, Y. Tanaka, and N. Nagaosa "Platform of chiral Majorana edge modes and its quantum transport phenomena", *Commun. Phys.,* 2(1):149, (2019).
4. 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).

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Research field

Physics

Keywords

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

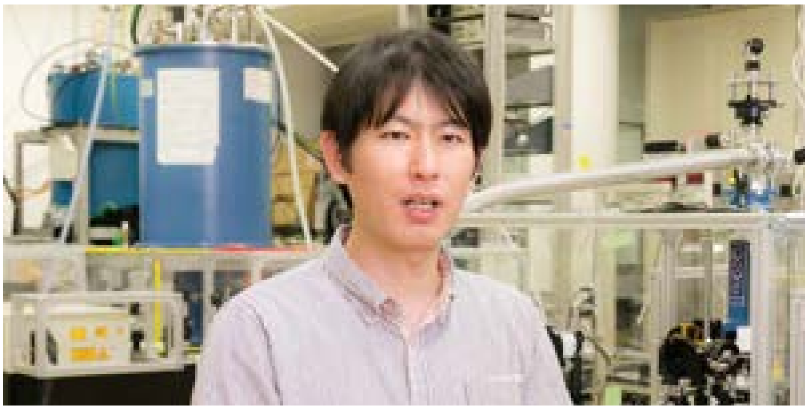
Brief resume

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 (-present)
2021	Unit Leader, Topological Quantum Phenomenon Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

Outline

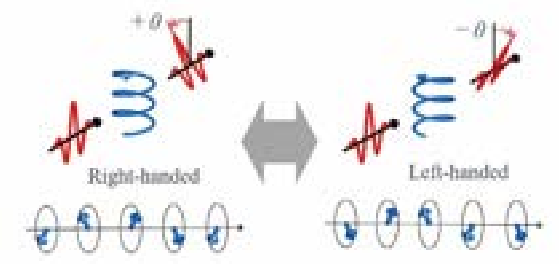
In our unit, we aim to investigate the intriguing physical properties in topological phases of matter and strongly correlated electron system, through the research based on the condensed matter experiment. First, from fundamental physics point of view, we pay attention to the nontrivial geometrical properties 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. 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).
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4. Y. Hayashi, Y. Okamura, N. Kanazawa, T. Yu, T. Koretsune, R. Arita, A. Tsukazaki, M. Ichikawa, M Kawasaki, Y. Tokura and Y. Takahashi, “Magneto-optical spectroscopy on Weyl nodes for anomalous and topological Hall effects in chiral MnGe”, *Nat. Commun.* 12, 5974 (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)

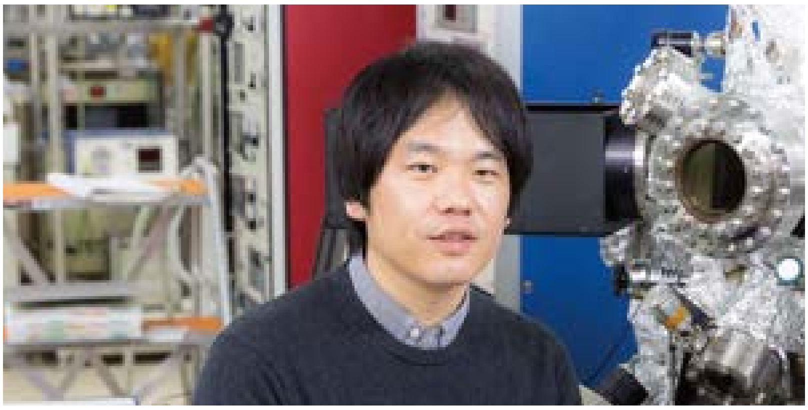
Outline

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

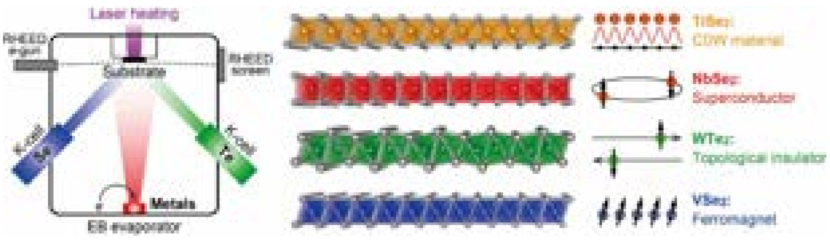
(Visiting Researcher) Yoshihiro Okamura

Emergent Functional Interface Research Unit



Emerging properties of van der Waals superstructures

When conducting electrons in a solid are confined within a two-dimensional plane, they behave differently from those moving freely in a three-dimensional space. This is called two-dimensional electron system, providing a unique platform in condensed matter physics research, although available only in semiconductor heterostructures or in electric-field devices in the 1980s and the 1990s. After entering the 21st century, however, the situation has been dramatically changed owing to the development of epitaxial growth technique as well as the discoveries of different types of materials as typified by graphene and topological insulators, and nowadays we can play with a variety of 2D phenomena more easily than in the past. We are in particular interested in emerging properties of 2D materials, and trying to build up functional interfaces from bottom-up approach by van der Waals epitaxy. We have already established a route to layer-by-layer epitaxial growth of various 2D materials, and now several research topics aiming for discovery of intriguing interface phenomena are in progress.



Van der Waals superstructures

Publications

1. N. Yoshikawa, H. Suganuma, H. Matsuoka, Y. Tanaka, P. Hemme, M. Cazayous, Y. Gallais, M. Nakano, Y. Iwasa, and R. Shimano "Ultrafast switching to an insulating-like metastable state by amplitudon excitation of a charge density wave", *Nature Phys.*, 17, 909 (2021).
2. H. Matsuoka, S. E. Barnes, J. Ieda, S. Maekawa, M. S. Bahramy, B. K. Saika, Y. Takeda, H. Wadati, Y. Wang, S. Yoshida, K. Ishizaka, Y. Iwasa, and M. Nakano "Spin-orbit-induced Ising ferromagnetism at a van der Waals Interface", *Nano Lett.*, 21, 1807 (2021).
3. M. Nakano, Y. Wang, S. Yoshida, H. Matsuoka, Y. Majima, K. Ikeda, Y. Hirata, Y. Takeda, H. Wadati, Y. Kohama, Y. Ohigashi, M. Sakano, K. Ishizaka, and Y. Iwasa "Intrinsic 2D ferromagnetism in V_5Se_8 epitaxial thin films", *Nano Lett.*, 19, 8806 (2019).
4. M. Nakano, Y. Wang, Y. Kashiwabara, H. Matsuoka, and Y. Iwasa "Layer-by-layer epitaxial growth of scalable WSe_2 on sapphire by molecular-beam epitaxy", *Nano Lett.*, 17, 5595 (2017).
5. M. Nakano, K. Shibuya, D. Okuyama, T. Hatano, S. Ono, M. Kawasaki, Y. Iwasa, and Y. Tokura "Collective bulk carrier delocalization driven by electrostatic surface charge accumulation", *Nature*, 487, 459 (2012).

Masaki Nakano (Ph.D.), Unit Leader
mnakano@riken.jp

Research field

Physics, Engineering, Chemistry, Materials Science

Keywords

Thin films and interfaces, Electric-field device, Strongly-correlated oxide, 2D materials, Van der Waals epitaxy

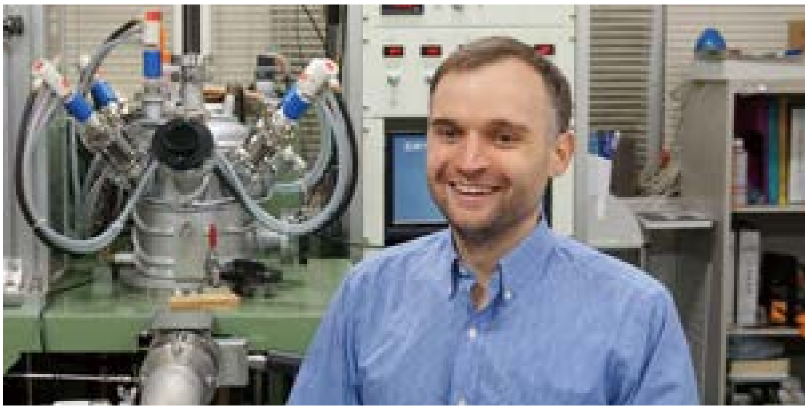
Brief resume

2009	Ph. D., Tohoku University
2009	Postdoctoral Researcher, Institute for Materials Research, Tohoku University
2009	Postdoctoral Researcher, Department of Condensed Matter Physics, University of Geneva
2010	Postdoctoral Researcher, Correlated Electron Research Group, RIKEN
2012	Research Associate, Department of Advanced Materials Science, The University of Tokyo
2013	Research Associate, Institute for Materials Research, Tohoku University
2014	Project Lecturer, Quantum-Phase Electronics Center, The University of Tokyo
2019	Project Associate Professor, Quantum-Phase Electronics Center, The University of Tokyo (-present)
2019	Unit Leader, Emergent Functional Interface Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)

Outline

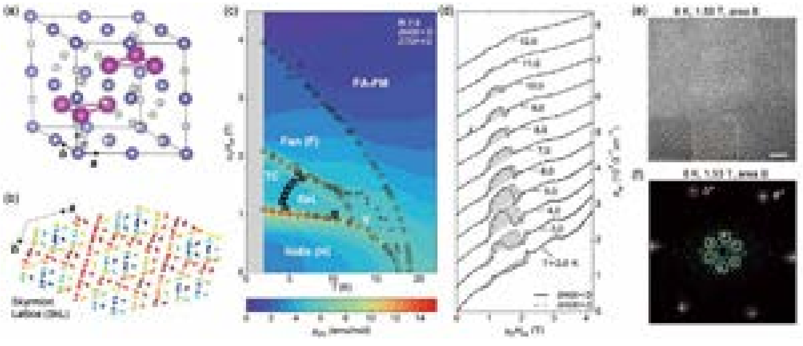
We explore physical properties and functionalities emerging when materials are thinned down to monolayer limit. We in particular focus on monolayer properties of various 2D materials including hardly-cleavable and even metastable compounds that could be realized by employing non-equilibrium epitaxial growth technique, and develop novel device functionalities in combination with electric-field doping technique. In addition, we construct van der Waals superstructures by stacking different 2D materials aiming for discovery of novel quantum phases emerging at the interfaces.

Topological Quantum Matter Research Unit



Skyrmions in a centrosymmetric breathing Kagome magnet

In hexagonal intermetallics Gd_2PdSi_3 and $Gd_3Ru_4Al_{12}$, RKKY magnetic interactions are frustrated due to the highly symmetric crystal lattice. As a result, we observed a non-coplanar skyrmion vortex lattice (SkL) on very small dimensions (λ~2-3 nanometers). We studied the resulting giant emergent magnetic field in transport experiments. Recently, we are also searching for new families of topological spin-vortices in frustrated magnets.



Skyrmions in hexagonal intermetallic $Gd_3Ru_4Al_{12}$. (a) Pink spheres indicate Gd^{3+} moments on the breathing Kagome sublattice. (b) Illustration of skyrmion spin structure. (c) Phase diagram with many magnetic phases observed due to competing interactions. (d) Large topological Hall signal (grey shaded). (e) Real space image of skyrmions and (f) its Fourier transform.

Publications

1. K. Kolincio, M. Hirschberger, J. Masell, S. Gao, A. Kikkawa, Y. Taguchi, T.-h. Arima, N. Nagaosa, and Y. Tokura, "Large Hall and Nernst responses from thermally induced spin chirality in a spin-trimer ferromagnet", *Proc. Natl. Acad. Sci. U.S.A.* 118, e2023588118 (2021).
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

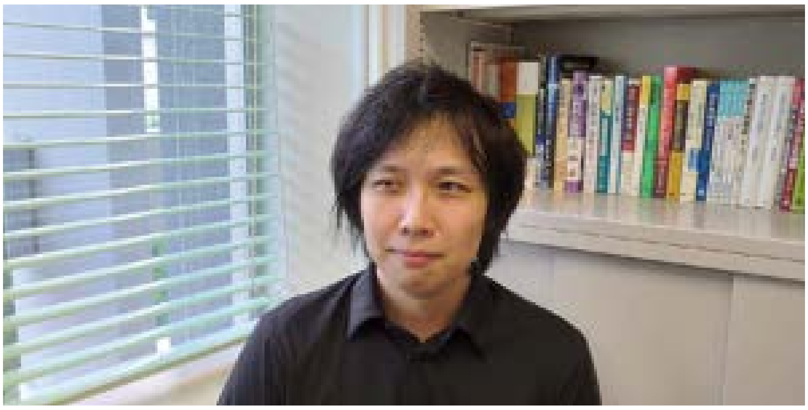
Brief resume

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

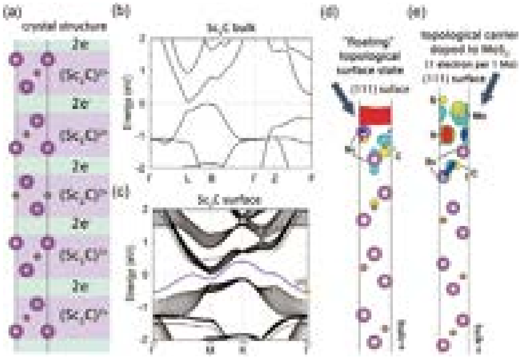
We study the interplay between magnetic order, in particular non-coplanar spin arrangements such as magnetic skyrmions, and the electronic band structure in solids. Particular emphasis is put on compounds with the potential to be grown in thin-film form and on realizing new types of protected surface 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



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. M. Hirayama, T. Tadano, Y. Nomura, and R. Arita "Materials design of dynamically stable d^9 layered nickelates", *Phys. Rev. B* 101, 075107 (2020).
2. M. Hirayama, S. Matsuishi, H. Hosono, and S. Murakami, "Electrides as a New Platform of Topological Materials", *Phys. Rev. X,* 8, 031067 (2018).
3. 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).
4. M. Hirayama, R. Okugawa, S. Ishibashi, S. Murakami, and T. Miyake "Weyl Node and Spin Texture in Trigonal Tellurium and Selenium" *Phys. Rev. Lett.,* 114, 206401 (2015).

Motoaki Hirayama (Ph.D.), Unit Leader
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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 materials in the chemical and materials fields, such as electrides.

Memo

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