www.cems.riken.jp

Center for Emergent Matter Science
2-1 Hirosawa, Wako, Saitama 351-0198 Japan
TEL: +81 (0)48-462-1111 (Switchboard Number)
FAX: +81 (0)48-462-1554
Email: cems@riken.jp

RIKEN
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.

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

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.
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the environment

Message From the Director

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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.
The Center for Emergent Matter Science (CEMS) brings together leading scientists from around the world to work as a team on truly challenging research. This is a place within the center’s research, making possible breakthroughs in co-exist with the natural environment.

CEMS carries out research in three areas: strongly-correlated materials, applications, and strongly-correlated spin research.

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To do this, it focuses on pursuing 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 pursuing radical new technological principles that will contribute to human society in five decades or even a century in the future.
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.
The emergent electric and magnetic fields originate from the Berry phase associated with the spin direction n. While the emergent magnetic field is detected as the topological Hall effect, the emergent electric field is given by the dynamics of the spin structures and can be detected as the voltage drop. For the current-driven motion of the spiral spin structure, we find that the emergent electric field and the consequent voltage drop are proportional to the time-derivative of the current density, corresponding to the inductance given by

\[ L \equiv \frac{\pi y \hbar}{2e \lambda_0 \lambda f} \]

where A and f are the cross-section and length of the sample, λ the period of the spiral, χ_int is related to the magnetic anisotropy energy, and γ is a constant of the order of unity. This emergent inductor does not require any complex structures such as coil and core, and the inductance is inversely proportional to the cross section of the sample. Therefore, it is advantageous for the miniaturization of the devices.

Theory of emergent inductor

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Publications

Generation and nonlocal spreading of shift current under local photoexcitation

Noncentrosymmetric materials exhibit a generation of photocurrent without an external electric field, called the bulk photovoltaic effect. In this study, we have revealed the mechanism of the photocurrent generation and spreading under local photoexcitation by potentiometric measurements for a prototypical ferroelectric semiconductor SbSI.

We shined a focused laser light on a SbSI single crystal, and measured the voltage inside and outside of photoirradiated region simultaneously. The results indicate that the photocurrent emerging in photoirradiated region is a less dissipative current driven by the Berry phase of electron’s wavefunction, termed shift current, whereas current spread outside as a dissipative current driven by the internal field. On the basis of result, we determined the equivalent circuit model to simulate the bulk photovoltaic effect in various devise structures. We have also succeeded in fabricating thin films of SbSI with aligned polarization axis by molecular beam epitaxy.

Publications


Room-temperature skyrmion and transformation of skyrmion-lattice in metastable state

Skyrmion is a magnetic vortex with a nano-meter size which behaves as a topologically protected stable particle, and anticipated to be applied to high-performance magnetic memory devices. However, chiral-skyrmion formation has been observed only below 280 K thus far, and new materials that exhibit skyrmions at higher temperatures have been desired from the viewpoint of applications. Recently, our team discovered a Co-Zn-Mn alloy system with a cubic and chiral, $\beta$-Mn type structure that exhibits skyrmion-lattice at and above room temperature. Furthermore, it was found that the skyrmion lattice persists as a metastable state in a very wide range of temperature and magnetic field when cooled down from the thermally equilibrium phase in the applied magnetic field. It was also discovered that the skyrmion lattice undergoes a transformation from a conventional triangular lattice to a novel square lattice during the field-cooling process.

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<tr>
<th>Core members</th>
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<tr>
<td><strong>Yasujiro Taguchi</strong> (D.Eng.), Group Director</td>
</tr>
<tr>
<td><a href="mailto:y-taguchi@riken.jp">y-taguchi@riken.jp</a></td>
</tr>
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<td><strong>Keywords</strong></td>
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<td>Strongly correlated electron system, Skyrmion, Multiferroics, Thermoelectric effect, Magnetocaloric effect</td>
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<tr>
<td><strong>Brief resume</strong></td>
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<tr>
<td>1993 Researcher, SONY Corporation</td>
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<td>1997 Research Associate, University of Tokyo</td>
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<td>2002 D.Eng., University of Tokyo</td>
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<td>2002 Associate Professor, Institute for Materials Research, Tohoku University</td>
</tr>
<tr>
<td>2007 Team Leader, Exploratory Materials Team, RIKEN</td>
</tr>
<tr>
<td>2010 Team Leader, Strong-Correlation Materials Research Team, RIKEN</td>
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<tr>
<td>2013 Team Leader, Strong Correlation Materials Research Group, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science</td>
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<tr>
<td>2018 Group Director, Strong Correlation Materials Research Group, Strong Correlation Physics Division, RIKEN Center for Emergent Matter Science (present)</td>
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<td><strong>Outline</strong></td>
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<td>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 multiferroic materials at high temperatures; (3) exploration of new magnetic semiconductors; (4) exploration of new thermoelectric materials; and (5) exploration of new superconductors.</td>
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**Publications**
Strong Correlation Quantum Transport Research Team

Quantum transport phenomena in surface Dirac states

The topological insulator is a new class of materials, whose bulk is a three-dimensional charge-gapped insulator but whose surface hosts a two-dimensional Dirac electron state. Dirac states are characterized by massless electrons and holes—known as Dirac fermions whose spins are polarized perpendicular to their crystal momentum. As a result, the quantum transport phenomena stemming from their charge or spin degrees of freedom are promising for the applications to low-power consumption electronic devices. The well-known example for this is the quantum Hall effect (QHE) in which one-dimensional conducting channel without any dissipation emerges at sample edges. We established the growth of high-quality thin film of \((Bi_{x}Sb_{1-x})_{2}Te_3\), one of topological insulators, by means of molecular beam epitaxy (MBE) method. We fabricated “field effect transistor” structures for electric gating and successfully observed QHE, while changing the number of electrons in the sample. Furthermore, we synthesized a chromium-doped compound \(Cr_{x}(Bi_{1-y}Sb_{y})_{2-x}Te_3\), which shows a spontaneous gap opening in a Dirac state due to the ferromagnetic ordering. As a result, we observed the quantum anomalous Hall effect (QAHE), which is a quantum Hall state realized at zero magnetic field. We now embark on the observation or control of the quantum transport at a ferromagnetic domain wall as the edge state in the magnetic topological insulators.

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

Publications

Strong Correlation Quantum Structure Research Team

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

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

Materials field
Materials Science, Physics

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
2003 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 SPnrg II 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.

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 Dzyaloshinsky-Moriya interaction. We performed measurements of magnetization, electric polarization, and spin-polarized neutron scattering in BaSrCo$_2$Fe$_{11}$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).

Publications

Core members

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

Research field
Physics, Engineering, Materials Sciences

Keywords
Scanning tunneling microscopy, Superconductivity, Topological insulators

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

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

Publications

Emergent Phenomena Measurement Research Team

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

Research field
Physics, Engineering, Materials Sciences

Keywords
Scanning tunneling microscopy, Superconductivity, Topological insulators

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$_2$Se$_3$. 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.
**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.

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.

**Publications**

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$_2$IrO$_4$, 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$_2$IrO$_4$ 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$_2$IrO$_4$ with several computational methods. Our calculations have clearly shown that the ground state of this material is an effective total angular momentum $J_{\text{eff}}=1/2$ antiferromagnetic insulator, where $J_{\text{eff}}$ 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 $\Delta_{x^2-y^2}$-wave “pseudospin singlet” superconductivity (SC in Fig. (b)) is induced by electron doping into the $J_{\text{eff}}=1/2$ antiferromagnetic insulator Sr$_2$IrO$_4$.

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

**Publications**

Condensed-matter physicists have devoted enormous efforts to finding a room-temperature superconductor. Recently, it has been reported that LaH$_{10}$ with a hydrogen cage enclosing the lanthanum atoms is formed at pressures higher than 130 GPa, and becomes a superconductor at a temperature between 250 and 260 K—about 40 K below room temperature. According to conventional (classical) calculation based on the Born-Oppenheimer approximation, the highly symmetric cage structure which favors superconductivity is stable only for pressures higher than 230 GPa, and it would distort at lower pressures.

We performed a calculation where atoms are treated like quantum objects, which are described with a delocalized wave function. While the energy landscape in the classical calculation is very complex with many minima, it is entirely reshaped by considering the quantum effect: There is only one minimum, which corresponds to the symmetric structure. We also performed a first-principles Eliashberg calculation and succeeded in reproducing the pressure dependence of the superconducting transition temperature.

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.

**Publications**


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.

**Outline**

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**Core members**

<table>
<thead>
<tr>
<th>Research Scientist</th>
<th>Takahiro Shimojima</th>
</tr>
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<tbody>
<tr>
<td>Special Postdoctoral Researcher</td>
<td>Asuka Nakamura</td>
</tr>
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**Keywords**

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

**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.

**Publications**

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.

Publications
Electronic States Microscopy Research Team

Directly imaging square lattices of atomic-scale skyrmions and nanometric antiskyrmions

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. Skyrmions arising from Dzyaloshinskii-Moriya interaction have been observed in several magnets with non-centrosymmetric crystal structures. Here we discovered atomic scale skyrmions causing by Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction through itinerant electrons in a magnet GdRu$_2$Si$_2$ with the centrosymmetric crystal structure. Figure 1a shows a square lattice of skyrmions (surrounded by dashed lines) observed at 8K under a 1.95T-field in a (001) thin plate of GdRu$_2$Si$_2$.

On the other hand, a square lattice of square-shape antiskyrmions with topological number $+1$, has been observed in a (001) thin Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn (Fig. 1b). By tuning the external magnetic field and the temperature, the controlled transformations between antiskyrmions and elliptic skyrmions as well as their lattice forms have been demonstrated (Figs. 1b-1f). The in-plane field-controlled skyrmion helicity has also been revealed (Fig.1c, 1g).

(a) An underfocused TEM image observed at 8K under a 1.95 T-field in a (001) GdRu$_2$Si$_2$ thin plate. Circular domains surrounded by dashed lines show skyrmions, whereas small dotted contrasts indicate crystalline elements. (b,c) Underfocused Lorentz TEM images for a square lattice of antiskyrmions (b) and for a triangular lattice of elliptic skyrmions (c) observed in a thin Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn. (d,e-f) Magnetization textures for a antiskyrmion (d), a skyrmion with counterclockwise helicity (e) and a skyrmion with clockwise helicity (f). (g) A triangular lattice of nanometric skyrmions with unique helicity (counterclockwise).

Publications
Ultrafast spectral dynamics of shift current

Shift current refers to the photocurrent in materials with broken inversion symmetry, originating from the spontaneous shift of electron clouds in real-space via the topological nature of the electronic bands. It is distinct from conventional photovoltaic effect where the interfaces of semiconductors are employed; shift current emerges in bulk crystals at ultrafast time-scale without much dissipation, in many cases accompanied by large open-circuit voltage exceeding the band gap energy. We have unveiled the ultrafast spectral dynamics of the shift current by detecting THz electromagnetic waves generated through its carrier motion. The shift current is found to appear faster than the experimental time-resolution (~100 fs) with a tensor response to the incoming photon polarization, and shows distinct time profile from that of the optical rectification. Importantly, the experimental shift current nicely compares with the spectra deduced from first-principles calculations based only on the crystal structures.

Schematic illustration of the THz emission via photoexcited shift current.

Publications

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
Control of packing structures of thienoacene-based organic semiconductors

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. The packing structures of representative organic semiconductors, e.g., acenes and thienoacenes, are classified into a herringbone packing, which is characterized with a “T-shaped” edge-to-face structural motif. On the other hand, one of the most promising materials in the organic field-effect transistor realizing the highest mobility is rubrene, which affords another characteristic packing motif, so-called “pitched n-stack”, where the long-molecular axis are inclined so as to form partial n-stacking with end-to-face intermolecular interaction. Although control and prediction of the solid state structures from the molecular level are regarded as formidable task, we recently found that simple methylthionation on a series of thienoacenes selectively induces the rubrene-like “pitched n-stack” in the solid state. These results suggest that a proper molecular modification can pave the way to “artificial rubrene”, i.e., packing structure control of thienoacenes for high-performance organic semiconductors.

Publications


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.

**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.

**Publications**

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 $250 \mu W/cm/K^2$ beyond that of well-known thermoelectric material Bi$_2$Te$_3$. 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.

Publications

Emergent Soft System Research Team

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)
2017 Hans Fischer Senior Fellow, TUM (-present)
2017 Research Director, JST/ACCEL Project (-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) Kilho Yu, Ruiyuan Liu
(Special Postdoctoral Researcher) Junwen Zhong
(Mating Scientist) Sixing Xiong
(Student Trainee) Masahito Takakuwa, Akhiro Maeda, Shuhei Shimanoe, Yusuke Otsuki

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.

Publications
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.

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.

Publications

Emergent Bioengineering Materials Research Team

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 specifically functionalized polymer by screening of random sequence of polymer library containing functional monomers.

Core members
(Senior Research Scientist) Masaki Kawamoto, Takanori Uzawa, Motoki Ueda
(Research Scientist) Seichi Tada, Jun Aki moto
(Senior Visiting Scientist) Hiroshi Abe, Hirose Taküji
(Mating Scientist) Kyöji Hagiwara
(Special Postdoctoral Researcher) Nandakumar Avanashiappan
(International Program Associate) Iljae Min, Muralidhar Jyothana Rajappa, Ahmed Emad Abdelmoneam Ali Elrefaey
(Junior Research Associate) Stefan Mueller, Shams Soliman Ahmed Raef
(Technical Staff) Noriko Minagawa, Izumi Kono

Solution-processed substrate-free thermoelectric films

Single-walled carbon nanotubes (SWCNTs) are advantageous for energy-conversion materials because of their large electrical conductivity, mechanical strength, and light weight. Unfortunately, SWCNTs exhibit poor processability owing to inevitable aggregation. We demonstrated substrate-free thermoelectric (TE) films using solution-processed methodology. Thermally cleavable polythiophene derivatives containing carbonate groups and solubilizing groups in side chains were synthesized. The polymer showed noncovalent modification of SWCNTs that led to a dispersed polymer/SWCNTs solution. This dispersed solution allowed a solution-processable polymer/SWCNTs composite film. The insoluble composite film was obtained by the thermal cleavage of the solubilizing group in a solid state. The substrate-free polymer/SWCNTs composite film prepared by solvent evaporation exhibited the TE property. These results are expected to be useful for preparation of flexible TE devices.

Schematic illustration of thermally cleavable polythiophene for dispersed SWCNTs composite and an insoluble SWCNTs film.

Publications
Emergent Supramolecular Materials Research Team

Molecules creating two electron-hole pairs from one photon

Singlet fission is one of multie exciton generation processes that one singlet exciton converts into two triplet excitons through an intermediate of two neighboring molecules. If the generated triplet excitons can dissociate into free charges at the donor/acceptor interface, it may provide a way to dramatically improve photon-electron conversion efficiency of photo voltaics. Singlet fission requires molecules to satisfy the energy condition of $E(S_1) \geq 2 E(T_1)$ and dense molecular packing, and those molecules have been limited to polycyclic $\pi$-conjugated compounds such as pentacene and tetracene.

We developed the thienoquinoid-based non-polycyclic singlet fission molecules by the modulation of the biradicaloid character of the molecules and the consequent controlling $E(T_1)$ of the molecules. The photocurrent response of thienoquinoid-based devices is largely dependent on LUMO level of an acceptor, and it was demonstrated that the triplet excitons dissociated into charges. We believe that these singlet fission molecules represent a new expansion for the molecular design of multiexciton generation materials and will lead to development of novel photon-electron conversion devices based on management of excited state and spin multiplicity.

Papers


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

Research field
Chemistry, Materials Science

Keywords
Organic/inorganic molecular hybrid, Molecular network, Semiconductor nanoparticle, 2D materials, Dynamic control

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 have developed the multi-layered photon-electron conversion devices in which an organic semiconductor layer was deposited on an inorganic semiconductor layer, or vice versa. Chemical or electrical junction at the interface between organic and inorganic layers largely affects performance of the devices. Such a junction is originally based on intermolecular interaction or chemical reaction, and the active control of the interaction at the molecular level is necessary. Our challenge is to synthesize the molecular hybrids of organic and inorganic semiconductors and develop their new functions. Especially, we develop novel photocatalysts or molecular sensors by the 2D- or 3D-controlled molecular hybridized network. We also challenge to create the macroscopic function switching device, triggered by the dynamic change of the network in non-equilibrium state.

Core members
(Research Scientist) Naoya Aizawa
(Postdoctoral Researcher) Kazushi Enomoto, Mirjun Kim, Jianjun Liu

Publications

A thienoquinoid-based singlet fission molecule and photocurrent spectra (left) and energy diagram of singlet fission and charge separation of triplet excitons.
Topological 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

Materials Characterization Support Team

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 on the individual method, we propose multifaceted research support by combining these methods. To keep our supports 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 analytical point of view, in addition to providing routinely analysis. Furthermore, we explore and develop new measurement methods directed to more advanced and sophisticated analyses.

Core members
(Senior Technical Scientist) Keiko Suzuki
(Research Scientist) Manabu Hoshino
(Expert Technician) Daishi Inoue
(Technical Staff) Tomoka Kikitsu, Toshimitsu Sato, Kiyohiro Adachi

Visualizations of chemical bonds by accurate X-ray analysis

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

Conventional X-ray diffraction method clarifies 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 critical roles in chemistry of molecule, is not included in the resulted models. For deeply understanding 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
Quantum Functional System Research Group

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)
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)

Core members
(Research Scientist)
Takashi Nakajima, Takashi Kobayashi, Kenta Takeda
(Postdoctoral Researcher)
Chien-Yuan Chang, Xuebin Wang
(Special Postdoctoral Researcher)
Akito Noiri, Sadashige Matsu
(Visting Scientist)Tomohiro Otsuka,
Michael Desmond Fraser, Raisel Mizoku
(Visting Researcher)Yago Del Valle Inclan Redondo
(Technical Staff)Hina Annapoorna Kasuti, Xin Liu
(Research Associate)Juan Rojas Arias, Yosuke Sato
(Student Trainer)Yohji Kajima, Takakoto Yokoizawa,
Yusuke Takeda, Mikio Tanaka, Kento Ueda,
Yoshishiro Uehara, Masahiro Tadokoro

Outline
Quantum information processing is an ideal information technology whose operation accompanies low-energy dissipation and high information security. We use electron spins in quantum dots to demonstrate the ability of the solid-state information processing, and finally outline a path for the realization. The specific research targets are “quantum computing” constructed by gate-based quantum logic operations, “quantum interface” useful for quantum repeaters, and “topological control” providing new concepts of quantum information. We investigate best suited quantum circuits and devices, and fundamental physics of quantum entanglement, quantum dynamics, and topological particles.

An ultra-high fidelity quantum dot qubit in a silicon quantum dot

The building block of quantum computers, or the smallest unit of quantum information, is called a qubit. A very large number of high-quality qubits will be needed to build a quantum computer. Single electron spins in quantum dots are a strong candidate as qubits, as they likely benefit from modern electronics integration technology, once sufficient quality is reached.

Enhancing the qubit quality means improving both coherence time and control time, challenging the trade-off commonly observed between these. In this work, we fabricated a quantum dot on an isotopically-clean silicon wafer to increase the coherence time, and deposited a micromagnet nearby to decrease the control time by its slanting magnetic field. With the coherence time ten times longer and the control time two orders of magnitude shorter than conventional within a single device, we implement highly coherent qubit operations (Fig. B). We further demonstrate >99.9% control fidelity (precision), above the fault-tolerance threshold.

Our work offers a promising route to large-scale, ultra-high-fidelity spin-qubit systems in silicon.

Publications
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.


Publications

Superconducting Quantum Electronics Research Team

Integrated superconducting quantum circuits

We are developing integrated superconducting quantum circuits and surrounding control hardware toward realization of a medium-scale quantum computing unit. It requires precise control and readout of a large number of qubits integrated on a chip. More concretely, we need qubits with a long coherence time, accurate and well-synchronized quantum gates, nearly quantum-limited low-noise fast qubit readouts, etc. Packaging, wiring, and electronics for microwave control and measurement also constitute important parts of our development target.

Schematic image of integrated superconducting qubits and their packaging

Main members

Yasunobu Nakamura (D.Eng.), Team Leader
yasunobu.nakamura@riken.jp

Research field
Physics, Engineering, Quantum Information Science

Keywords
Superconductivity, Quantum information, Microwave quantum optics, Quantum bit, Quantum computer

Brief resume
1992 Researcher, Fundamental Research Laboratories, NEC Corporation
1997 Senior Researcher, Fundamental Research Laboratories, NEC Corporation
2001 Principal Researcher, Fundamental Research Laboratories, NEC Corporation
2001 Visiting Scientist, Delft University of Technology, The Netherlands (-2002)
2002 Frontier Researcher, Frontier Research Systems, RIKEN
2005 Research Fellow, Fundamental and Environmental Research Laboratories, NEC Corporation
2008 Visiting Researcher, Advanced Science Institute, RIKEN
2012 Professor, Department of Applied Physics, The University of Tokyo
2012 Professor, Research Center for Advanced Science and Technology, The University of Tokyo (-present)
2014 Team Leader, Superconducting Quantum Electronics Research Team, RIKEN Center for Emergent Matter Science (-present)

Outline
Our research focus is on physics and engineering regarding superconducting quantum information electronics. Superconducting circuits allow us to manipulate quantum information on qubits, resonators, and waveguides, carried by the excitations at the energy scale of microwaves. We are developing new technologies for precisely controlling and measuring quantum states in such artificially-designed quantum systems on electric circuits. Applications in quantum information science, such as quantum computing, quantum simulation, quantum communication, and quantum sensing, are expected.

Core members

(Senior Research Scientist) Hiroki Ikegami
(Research Scientist) Alexander Badrtdinov
(Postdoctoral Researcher) Kun Zuo, Zhiguang Yan
(Special Postdoctoral Researcher) Shingo Kono
(Technical Staff) Koichi Kusuyama, Koh-ichi Nittoh, Laszlo Szikszai
(Visting Researcher) Yoshiro Urade, Arjan van Loo, Ryo Sasaki

主要論文

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

Spin conversion, the key concept of Spintronics, has been investigated to gain a deeper understanding of spin dynamics and to enrich the functionalities of electronic devices. It describes various intriguing spin-mediated interconversion phenomena taking place on the nanoscale between electricity, light, sound, vibration, heat etc. However, among the above, the interaction between spin and mechanical oscillation remains largely unexplored. The Barnett effect is the spin transfer phenomenon between mechanical angular momentum and spin. In magnetic materials, mechanical oscillation can induce spin dynamics via magnon-phonon coupling. Our group has demonstrated the spin-mediated conversion of mechanical oscillation to electrical charge current in a novel hybrid device. By passing surface acoustic waves (SAWs) across the ferromagnetic layer, periodic deformation induced by SAWs excites ferromagnetic resonance (FMR), generating spin current diffusing into adjacent nonmagnetic layer (see attached schematics). The generated diffusive spin current is then converted into electric charge current via inverse Edelstein effect at the Rashba interface.

Schematic illustration of surface acoustic wave induced spin current generation. The surface acoustic waves are generated by applying rf voltage on interdigital transducers, and spin current is caused by ferromagnetic resonance due to the lattice vibration. The generated spin current ($j_s$) converts to charge current ($j_c$) via Inverse Edelstein effect at Cu/CoO$_2$ interface.

Publications

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.


Publications

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

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

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 zero modes (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 an 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 Schaepers in Julich Research Center in Germany.

Publications

Dynamics of the Vortex-Particle Complexes Bound to the Free Surface of Superfluid Helium

Two types of quantized vortices, linear and ring shape, have been observed in superfluid helium. We observe a half-ring vortex with both ends terminated at the free surface. It exists only in the vicinity of a free surface and is visualized with charged metallic nanoparticles as tracers. The particles are guided to the free surface by an external electric field and are illuminated by a laser light. The half-ring vortices travel along the free surface at a constant speed, bouncing off obstacles.

Quantized vortices, unlike their well-known classical counterparts, exist only in quantum fluids, such as superfluid helium, atomic Bose-Einstein condensates. Our study opens a new direction of research in the field of quantum turbulence that until now was mostly concerned with the phenomena in the bulk, as opposed to the surface.

Schematic diagram of trapping charged nano-particles at a free surface of superfluid helium. Nano-particles are produced by laser ablations and trapped at the free surface by an electric field. From the analysis of the particle motion, the existence of half-ring quantum vortices terminating at the surface is concluded.


Publications

Superconducting Quantum Simulation Research Team

Integrated Superconducting chip enabling 2D packaging

A 16-bit superconducting quantum chip was designed and fabricated. It was based on new architecture compatible with surface-code universal quantum computer. The new architecture solves the wiring problem of superconducting quantum computer where qubits internal to a chip-set become inaccessible for external control/readout lines. It is a modified superconducting scalable micro-architecture that only requires a completely planar design.

The inter-qubit connections are realized by a novel pseudo-2D resonator network containing airbridges. A new Omon type superconducting qubit was developed.

A novel architecture for one-way superconducting quantum computer was also developed.

Photograph of 16-qubit superconducting quantum chip.

Publications

Quantum Electron Device Research Team

Obervation 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 mostly lies close to the localized spin accompanied with a long tail.

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.

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 applied to the quantum point contacts.

Figure taken from Nature 579, 210 (2020).

Publications

Michihisa Yamamoto (D.Sci.), Team Leader
michihisa.yamamoto@riken.jp

Research field
Physics, Engineering

Keywords
Two-dimensional electron system, 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
(Postdoctoral Researcher) Ngoc Han Tu, David Pomaranski, Genki Okano
(Research Associate) Ryo Ito
(Student Trainee) Miuko Tanaka, Takamoto Yokosawa

Publications
Quantum technologies based on microwave engineering

Quantum technologies are expected to have broad applications in the emerging fields such as “quantum computing”, “quantum network”, and “quantum sensing”. Different physical systems—superconducting circuits, electron spins in silicon, spins of nitrogen-vacancy centers in diamond—are being pursued as qubit (quantum bit) candidates for respective applications. Even so, qubit operation frequencies often fall on the gigahertz range or microwave domain, and therefore microwave engineering plays a pivotal role in qubit design, control circuitry design, pulse-shape optimization, and so on, irrespective of the physical systems being considered. We develop superconducting qubits by leveraging the knowledge and experience accumulated in other platforms such as silicon and diamond.

Eisuke Abe
(D.Sci.), Unit Leader
eisuke.abe@riken.jp

Research field
Physics, Engineering

Keywords
Superconducting circuit, Quantum computing, Quantum technology, Microwave engineering, Quantum entanglement

Brief resume
2006 D.Sci., School of Fundamental Science and Technology, Keio University
2006 Research Associate, Institute for Solid State Physics, The University of Tokyo
2010 Postdoctoral Researcher, Department of Materials, University of Oxford
2011 Specially-Appointed Researcher, Institute for Nano Quantum Information Electronics, The University of Tokyo
2011 Visiting Scholar, Ginzton Laboratory, Stanford University (2014)
2012 Specially-Appointed Researcher, Principles of Informatics Research Division, National Institute of Informatics
2013 Research Scientist, Quantum Optics Research Group, RIKEN Center for Emergent Matter Science
2014 Research Scientist, Quantum Condensate Research Team, RIKEN Center for Emergent Matter Science
2015 Project Senior Assistant Professor, Faculty of Science and Technology, Keio University
2016 Project Associate Professor, Advanced Research Centers, Keio University
2019 Unit Leader, Superconducting Quantum Electronics Joint Research Unit, RIKEN Center for Emergent Matter Science (Present)

Outline
We develop quantum technologies based on superconducting devices, with particular emphasis on the development of multi-qubit quantum computers. We aim to implement superconducting qubits (quantum bits) and functionalities for coherent control and non-demolition measurement of quantum states via microwaves on a superconducting quantum circuit consisting of Josephson junctions, microwave transmission lines, microwave cavities, Josephson parametric amplifiers, and so on, and to bring a quantum computer that executes computations intractable with classical computers closer to reality.

Publications
Dynamic Emergent Phenomena Research Unit

Core members

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 (-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.

Publications

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.
Automatic optimization of cold-atom experiments with machine learning

Cold atoms offer a promising platform for quantum simulation, quantum sensing and metrology. For such experiments, it is necessary to adjust various experimental parameters. If the parameter optimization can be conducted automatically, it will be possible to optimize a large number of parameters, which a human can hardly handle, and to discover an unknown new method. To this end, we employ machine-learning-based optimization, which will become a key technology for quantum information processing.

We have optimized evaporative cooling using Bayesian optimization. After 300 trials within 3 hours, Bayesian optimization discovered trajectories that exhibited performance comparable with those of manual tuning by a human expert. Interestingly, the obtained evaporation trajectories were significantly different from the manual one. Furthermore, by analyzing the machine-learned trajectories, we succeeded in extracting minimum requirements for successful evaporative cooling.

Publications

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.

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.

**Publications**


Discovery of robust in-plane ferroelectricity in atomic-thick SnTe

Stable ferroelectricity with high transition temperature in nanostructures is needed for miniaturizing ferroelectric devices. Here we show the robust in-plane ferroelectricity in atomic-thick SnTe with much enhanced $T_c$ comparing with bulk counterpart. We use the molecular beam epitaxial technique to prepare ultra-thin ferroelectric SnTe films of few unit-cell (UC) thickness on graphene/SiC(0001) surface. We discover stable in-plane spontaneous polarization in SnTe films of only a few UC thickness. The ferroelectric domain structures, lattice distortion, band bending induced by bound charge at edge of films, and the domain wall movement under electric field are clearly observed in SnTe films by using scanning tunneling microscope. The ferroelectric transition temperature $T_c$ of 1-UC SnTe film is greatly enhanced from the bulk value of 98 kelvin and reaches as high as 270 kelvin. Moreover, 2- to 4-UC SnTe films show robust ferroelectricity at room temperature. The significant enhancement of $T_c$ is mainly related to the strongly reduced free carrier density, which can screen ion-ion interaction, in high quality ultra-thin films. The in-plane lattice expansion in thin film may also facilitate the $T_c$ enhancement.

Publications

Cross-Correlated Interface Research Unit

Pu Yu (Ph.D.), Unit Leader
yupu@riken.jp

Research field
Condensed Matter Physics, Materials Science

Keywords
Multiferroics, Interface electronic structure, Magnetoelectric effect, Thin films and interfaces

Outline

Our unit is dedicated to exploring the emergent phenomena at complex oxide and other cross-correlated heterostructures and interfaces. In particular, we are interested about quantum manipulation of ferroelectric and ferromagnetic properties by means of heteroepitaxy, artificial design of novel multiferroic materials with strong magnetoelectric coupling and emergent phenomena (with a strong focus on the spin and charge degrees of freedom) at complex oxide interfaces and their cross correlations to other correlated material systems. Our goal is to reveal the underlying mechanisms of these heretofore-unexplored functionalities, and transfer them into novel device concepts for applications.

Publications


Electric field control of ionic evolution: a novel strategy to redesign materials

The correlation between charge, spin, orbital and lattice degrees of freedom at complex oxides generates a wealth of exotic electronic states with promising applications. Conventionally, chemical substitution during the growth forms an essential pathway to manipulate the carrier density, leading to a rich spectrum of properties. To obtain a further control of the carrier density after growth, electrostatic charge modulation has been widely employed. However, an intrinsic limitation of this approach is that it is only effective for materials with thicknesses of a few nanometers, due to the short electrostatic screening length. Recently the electric-field induced ionic evolution demonstrates a great tunability in a series of bulk compounds. Among the studies, the hydrogen ion (proton) attracts particular attention due to its comparatively small radius as well as easy accessibility. The insertion of protons electron-dopes the materials, leading to an exotic electronic and magnetic phase transition along with the increase of proton concentration. We envision that electric-field controlled protonation opens a new avenue to systematically control the electronic and magnetic phase diagram in strongly correlated complex oxide systems.

Manipulation the coupling and correlation between degrees of freedom through ionic evolution.

Pu Yu (Ph.D.), Unit Leader
yupu@riken.jp

Research field
Condensed Matter Physics, Materials Science

Keywords
Multiferroics, Interface electronic structure, Magnetoelectric effect, Thin films and interfaces

Brief resume

2011 Ph.D. in Physics, University of California, Berkeley, USA
2012 Postdoctoral Researcher, Correlated Electron Research Group, RIKEN, Japan
2012 Assistant Professor, Tsinghua University, Beijing, China
2014 Unit Leader, Cross-Correlated Interface Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science (-present)
2017 Associate Professor, Tsinghua University, Beijing, China
2018 Professor, Tsinghua University, Beijing, China (-present)
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.

Publications

Emergent Spectroscopy Research Unit

Youtarou Takahashi (Ph.D.), Unit Leader
youtarou.takahashi@riken.jp

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, 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) Magnetolectric optical effect driven by the cross-coupling between the magnetism and dielectric properties in matter. (2) Optical control of the magnetism and dielectric properties in matter. (3) Novel optical responses derived from the topology in condensed matter. We are pushing forward scientific and technological developments with these researches.

Magnetolectric optical effect with electromagnons in helimagnet

Helical spin orders exhibit the magnetically induced ferroelectricity, resulting in the concept of multiferroics with strong magnetolectric 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 magnetolectric 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 magnetolectric 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.

Publications

Core members
(Visiting Researcher) Yoshihiro Okamura
Emergent 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.

Publications

Skyrmions in a centrosymmetric breathing Kagome magnet

In hexagonal intermetallics Gd$_2$PdSi$_3$ and Gd$_3$Ru$_4$Al$_{12}$, 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$_3$Ru$_4$Al$_{12}$. (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.

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