RIKEN Center for Emergent Matter Science

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RIKEN CENTER FOR EMERGENT MATTER SCIENCE

RIKEN is the largest and most comprehensive research institute in Japan, founded in 1917, where diverse areas of fundamental and applied sciences are studied. The Center for Emergent Matter Science, hereafter abbreviated as CEMS, was launched in 2013 as the first strategic research center focusing on material sciences in the long history of RIKEN. The director of CEMS is Prof. Yoshinori Tokura, and the deputy directors are Prof. Naoto Nagaosa, Prof. Masashi Kawasaki, and Prof. Takuzo Aida. The key concept that constitutes the basis of CEMS is "emergence." "Emergence" indicates that a wide variety of astonishing phenomena, which cannot be readily anticipated from the properties of individuals, can occur from an assembly of a large number of constituents, as was emphasized by P. W. Anderson most appropriately as "More is different." Researchers at CEMS focus on such emergent collective phenomena in a broad range of condensed matter systems, and try to construct new basic sciences which are both fundamentally important and technologically useful for various future applications.

OVERVIEW OF CEMS

The energy problem is one of the most serious worldwide issues that humankind currently confronts. Given this situation, the principal mission of CEMS is to establish fundamental principles that can help resolve energy-related problems and eventually contribute to the construction of an environmentally-benign and sustainable society. For the past several decades, humankind has obtained novel ways to convert energies in various forms directly to electrical energy by using electrons in solids. For instance, solar energy and waste thermal energy can be directly converted into electrical energy by solid-state photovoltaic cells and thermoelectric devices, respectively. This progress can be regarded as the third energy revolution in the history of civilization. The first energy revolution originated from the conversion of steam energy (mechanical energy) into electrical energy, which exploits the Faraday's law of electromagnetic induction. The second revolution was based on the Einstein's equation identifying the equivalence of rest mass and energy, and nuclear energy was converted to electrical energy via the steam energy (mechanical energy) at the intermediate stage. The third energy revolution, where energy conversion is achieved without relying on any mechanical systems, should be further accelerated towards the construction of a sustainable society, and fundamental material science can play a vital role here.

In order to achieve this ultimate goal, three research divisions (the Strong Correlation Physics Division, the Supramolecular Chemistry Division, and the Quantum Information Electronics Division) were established at CEMS so that emergent phenomena and functions could be designed and realized in electronic and molecular systems. In addition, the Cross-Divisional Materials Research Program was also established. By promoting synergetic cooperation of these divisions and the program, CEMS aims at achieving novel electronics with ultra-low energy consumption and environmentally-benign, highly-efficient energy collection, transformation, and storage.

CEMS was founded on the basis of several existing center-building efforts. A major source of input in terms of both human resources and experimental equipment came from the research departments of a former organization (i.e. the Advanced Science Institute), namely, the Emergent Materials Department led by Prof. Yoshinori

Fig. 1: The newly constructed Emergent Matter Research Facility, where low-temperature and optical experiments can be performed.

Tokura, and the Green-Forefront Materials Department led by Prof. Takuzo Aida. Another important source of input came from Japan's national project, FIRST Programs, namely, "Quantum Science on Strong Correlation" by Prof. Yoshinori Tokura, "Quantum Information Processing Project" by Prof. Yoshihisa Yamamoto, and "Atomic-Resolution Holography Electron Microscope" by the late Dr. Akira Tonomura. In addition to these resources, CEMS has close connections with large-scale facilities in Japan, such as SPring-8/SACLA, J-PARC, and the K-computer.

Besides the principal investigators (PIs) who transferred from the Advanced Science Institute, new PIs have also been recruited for the past several years (from FY2012), both outside and inside of RIKEN, and as of October 2015, there are 41 laboratories in total. The number of researchers, including technical staff, is around 180, in addition to the administrative assistants. Within the 180 researchers, there are approximately 20 female researchers and nearly 50 non-Japanese researchers.

STRONG CORRELATION PHYSICS DIVISION

The Strong Correlation Physics Division is led by Prof. Naoto Nagaosa. There are now 10 laboratories in this division; six experimental and four theoretical. Research topics of this division include topological spin textures, topological insulators, Mott-insulator-metal transition, superconductivity, and a variety of cross-correlated phenomena/materials, such as colossal magnetoresisitance,

Fig. 2: Transmission electron microscope, which allows the real-space observation of skyrmions.

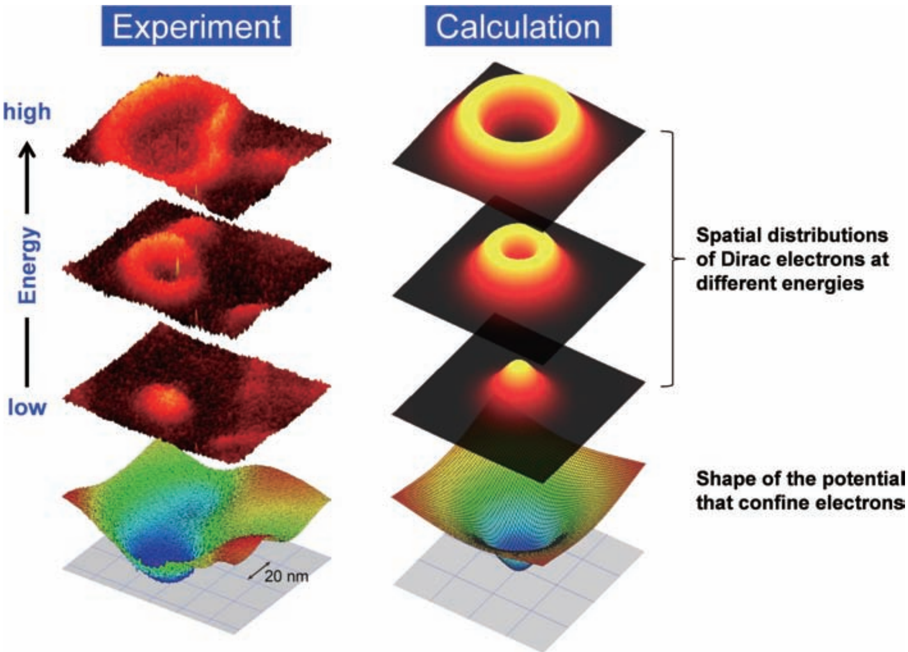

Fig. 3: Landau orbits of Dirac electrons at the surface of a topological insulator. Images taken by scanning tunneling microscopy are well captured by the theoretical calculation.

multiferroics, photovoltaics, and thermoelectrics. What is unique to this division is the very close collaboration among the laboratories, and the weekly discussion meetings that play a vital role in promoting the internal collaborations. Every Wednesday, a research meeting is held to discuss theoretical and experimental results and possible future research plans. Usually 40 to 50 researchers, including 10 PIs inside/outside of the Physics Division participate in the meeting. Also, experimental apparatuses, except for highly specialized ones, are commonly used by the members of many laboratories, mainly within the division and also within CEMS, in order to minimize waiting for machine time.

One of the recent major achievements in the Physics Division is magnetic skyrmions, which are known as topologically non-trivial spin-swirling objects of nanometer scale. These are expected to act as information carriers which are electrically controllable with low-power consumption. Following the first real-space observation of skyrmions by means of a Lorentz transmission electron microscope (Fig. 2) by a research group in this division, various important results have been continuously achieved, such as ultra-low-current driven skyrmion motion, the theoretical design of creation/annihilation methods of skyrmions, the discoveries of the ratchet motion of skyrmions induced by magnon currents, the bound states of skyrmions termed "biskyrmion", and a new class of chiral magnets which host skyrmions above room temperature.

Another recent outstanding achievement is related to topological insulators, which are known to host the dissipationless current carried by surface Dirac electrons, and therefore expected as promising materials toward future electronics with ultra-low power consumption. Important achievements have been put forward following the pioneering theoretical works of researchers at CEMS. Examples of the latest results include the identification of a Dirac electron state at a hetero-interface, the real-space observation of a Dirac electron state by scanning tunneling microscopy (Fig. 3), elucidation of the trajectory of the anomalous Hall effect toward a quantized state in a ferromagnetic topological insulator, and the observation of the quantum Hall effect on the top and bottom surfaces of a topological insulator.

SUPRAMOLECULAR CHEMISTRY DIVISION

The Supramolecular Chemistry Division, directed by Prof. Takuzo Aida, consists of eight laboratories. As a part of CEMS, the division explores new emergent phenomena in molecular- and polymer-based materials and their applications to energy conversion systems, energy-

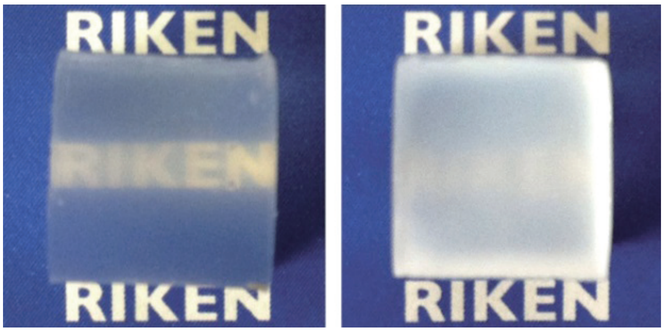

Fig. 4: The picture shows that the hybrid material has an anisotropic optical property. A RIKEN logo can be viewed clearly through the material from two directions (left), whereas the material is opaque when viewed orthogonally to the aligned titanate nanosheets (right). Reprinted from Nature **517**, 68 (2015).

saving materials and optoelectronic devices with unique functions. The research themes are wide-ranging and include: solution chemistry, polymer synthesis, soft-matter physics, organic electronic devices, device engineering and biomolecules. The diversity in the division promotes fruitful collaborations to conduct "cutting-edge" research on emergent phenomena.

A recent achievement in fundamental science is the realization of "supramolecular living polymerization". This is a combined concept of the well-established "supramolecular polymerization" and "living polymerization". Despite this simplicity and beauty, it has never been realized in experiments until recently. This study would not only add a new entry in chemistry textbooks, but also create a new frontier in materials chemistry, to construct supramolecular objects with well-defined nanostructures.

Another new phenomenon comes from an organic-inorganic hybrid soft material. A hydrogel containing titanate nanosheets synthesized in a magnetic field shows highly-anisotropic physical properties (Fig. 4). The material is easily deformed by shear forces in one direction yet resists compressive forces applied in other directions. The origin of this unique mechanical property is the electrostatic repulsive force between the titanate nanosheets, which has rarely been used for material design. This material has some potentially useful applications, such as artificial cartilages.

Organic electronics has the potential to have a great impact on society, owning to many characteristics that cannot be achieved by silicon-based electronic devices. Supramolecular chemistry can take the development of organic electronics to a whole new level. The control of molecular order and orientation enables us to manipulate structures in organic thin films, which can be directly connected to high device performance. For example, the division recently achieved high efficiency (of more than 10%) of organic solar cells (Fig. 5). Combined with strong device engineering in the division, our fundamental research will contribute to the various needs of the society.

QUANTUM INFORMATION ELECTRONICS DIVISION

The Quantum Information Electronics Division, directed by Prof. Seigo Tarucha, studies how to use quantum physics for future quantum information processing and novel forms of quantum nano-electronics. Quanta

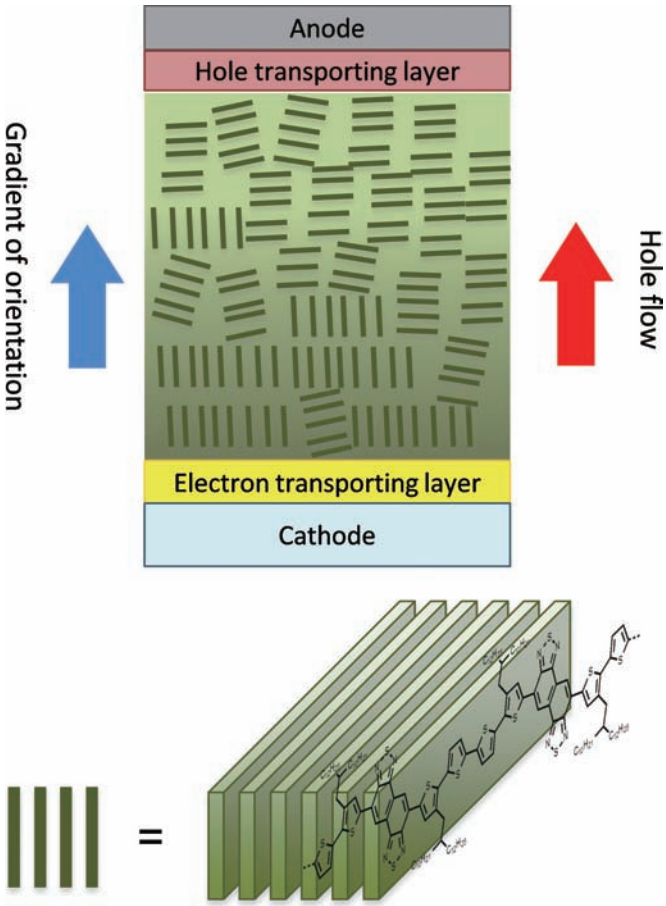

Fig. 5: Schematic representation of the organic solar cells with power conversion efficiency of over 10% achieved by the control of polymer orientation in thin films. The gradual change of the polymer chain orientation from the bottom (edge-on) to the top (face-on) enhances the hole transport in relatively thick organic films.

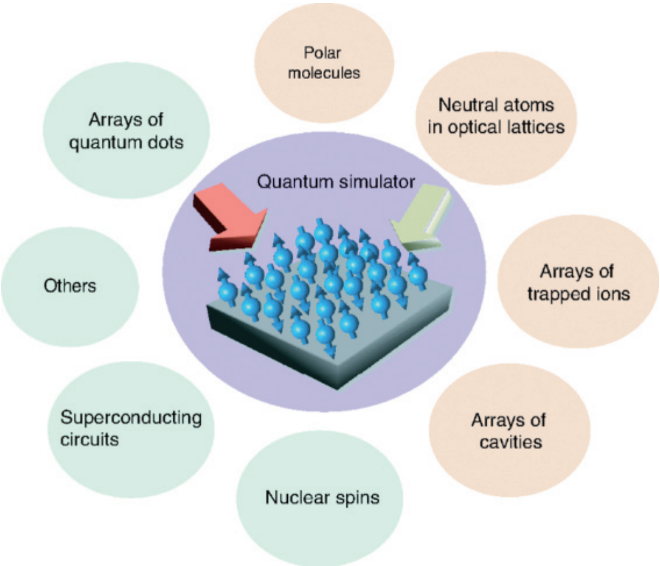

Fig. 6: Different systems that can implement a quantum simulator.

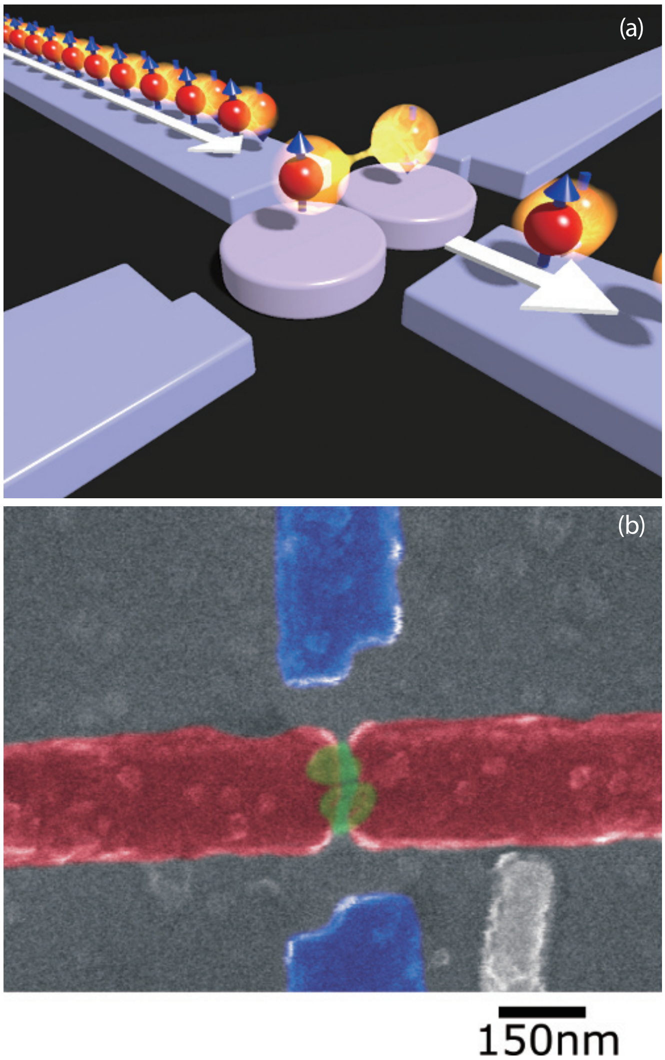

Fig. 7: (a) Schematic figure of the device for splitting Cooper pairs into quantum dots. (b) False color scanning electron microscope image of the device. It was demonstrated that electrons remain spin-entangled even when they are separated from one another on a chip. Reprinted from Nature Communications **6**, 7446 (2015).

are the smallest unit of matter, and can behave both like waves and particles. By developing technologies to control the quantum state, it is possible to create quantum devices that process information in novel ways, at higher-speeds, and with extremely low-energy consumption. This division is composed of 12 teams, eight experimental and four theoretical. These teams have obtained important results in several areas of research in quantum nano-electronics and quantum information processing, including: spintronics, magnetism, ultra-microscopy, cold atoms, quantum phases, quantum simulations, optics, quantum optics, atomic physics, as well as advanced magnetic, semiconductor, and superconducting quantum devices.

Strengths of the division include its synergism and the diversity of its research coverage. An underlying common theme in this division is to better understand nano-scale quantum systems and to devise methods to control them, as well as to develop high-speed next-generation quantum devices with low-power consumption. Several PIs in this division use physical models to make predictions that can be tested experimentally and that can be used to better understand the observed phenomena.

Figure 6 shows different systems that can implement a specialized quantum simulator. Examples of such analog quantum simulators include atoms, ions, photons, nuclear and electronic spins, as well as superconducting circuits. These systems can be manipulated in different manners. They can be thought of as toy models of the magnified lattice structure of a “solid,” with a magnification factor of about three orders of magnitude. PIs in this division have done pioneering work in several of these areas.

This division also studies artificial atoms, including semiconductor quantum dots and superconducting junctions (Fig. 7). Owing to their confinement, the electrons in atoms and quantum dots have discrete energy levels. The

Fig. 8: Group photo at the workshop on "Topological Magnets" held by the Strong Correlation Physics Division in May, 2015.

Cooper pairs confined in the potential well of the Josephson coupling energy also have discrete energy levels, and the junction can be regarded as a superconducting artificial atom.

CROSS-DIVISIONAL MATERIALS RESEARCH PROGRAM

The Cross-Divisional Materials Research Program is directed by Prof. Yoshinori Tokura, and this program includes 11 young unit leaders whose expertise range from physics and chemistry, to quantum information. This program is a very unique system, and serves as an incubation program for young research leaders who have been making outstanding achievements and who are expected to be internationally significant researchers in the future, capable of having perspective views for various research fields. Unit leaders can operate their own laboratories independently, but also can seek opinions and advice, as necessary, on scientific as well as administrative problems for senior PIs. For each unit leader, two senior PIs are assigned as mentors. In this program, unit leaders are encouraged to perform challenging interdisciplinary research, and to make cross-links between different divisions. Among 11 units, three units are operated as joint laboratories with the Department of Applied Physics, University of Tokyo and three other units with the Department of Physics, Tsinghua University, China, respectively. Unit leaders of these joint laboratories usually conduct their research at their universities, but can perform experiments or discussions at CEMS at any time they want, and also participate in the weekly discussion meeting at the Physics Division.

COLLABORATIONS WITH ACADEMIC AND INDUSTRIAL COMMUNITIES

CEMS researchers are in collaboration with almost 40 research institutions all over the world, including institutes in Asia, Europe, and North-America. CEMS attempts especially to make close collaborations with Tsinghua University and the Indian Institute of Sciences (IISc). Several PhD students work at CEMS within the International Program Associates (IPA) system, which is operated under the alliance established between RIKEN and many institutes in the world.

PIs at CEMS are also encouraged to perform collaborative research with industry for precompetitive research topics. Several researchers from private companies indeed actively participate in the daily research activities at CEMS. Through collaborative research, CEMS researchers become aware of the needs for innovation, and researchers from companies can have opportunities to find seeds for innovation, and to become acquainted with state-of-the-art scientific research activities. The experience at CEMS is also expected to serve as training toward being leaders in future research and development activities in their companies.

INTERNAL AND INTERNATIONAL WORKSHOPS

CEMS tries to promote information exchange on the latest research achievements, as well as future research collaborations at various levels. One example of such opportunities is an internal workshop within CEMS called the "Topical Research Camp," which focuses on a particular research theme, such as energy conversion or spin. The Topical Research Camp is conducted as a two-day workshop, and researchers from the three divisions and the Cross-Divisional Program participate to make active discussions, aiming at finding seeds for interdisciplinary collaborations.

Another example is the international workshop which is held by each division almost once a year. Top researchers in the respective research fields from all over the world as well as from other institutes in Japan are invited to the workshop, and discuss the latest results with researchers at CEMS. These workshops also serve as good opportunities, especially for young researchers, to establish connections with the international research community, in addition to presenting their latest achievements.

Yasujiro Taguchi received his PhD in engineering from the University of Tokyo. He worked as a research associate at the University of Tokyo in 1997-2002, and moved to the Institute for Materials Research, Tohoku University, as an associate professor in 2002. In 2007, he moved to RIKEN as a team leader. Since 2013, he has been a team leader at CEMS. His research interest is to explore and synthesize novel strongly-correlated electron materials that show gigantic cross-correlation responses, such as multiferroics, thermoelectrics, and skyrmion materials.

Keisuke Tajima received his PhD in engineering from the University of Tokyo and conducted postdoctoral research at Northwestern University for two years. He worked at the University of Tokyo in 2004-2012 and moved to RIKEN CEMS as a team leader from 2013. His research interests include the synthesis of new organic and polymeric materials for application in organic electronic devices such as polymer solar cells and the precise control of the nanostructures and the molecular interfaces in organic solar cells using molecular self-assembly.

Franco Nori received his PhD in physics from the University of Illinois, and did postdoctoral research at the Institute for Theoretical Physics of the University of California, Santa Barbara. In 1990 he became a faculty member of the Physics Department of the University of Michigan, Ann Arbor. In 2002, he joined RIKEN as a team leader. Since 2013, he has been a group director at CEMS and a RIKEN Chief Scientist. He is interested in theoretical condensed matter physics, quantum information processing, computational physics, transport phenomena, and energy conversion. His research work is interdisciplinary and also explores the interface between atomic physics, quantum optics, nano-science, and computing.