Evaluation and advice to RIKEN Center for Emergent Matter Science (CEMS) by CEMS Advisory Council (CEMSAC2014)

Members of Advisory Council

Name	Profession	Affiliation
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Introduction

RIKEN has traditionally been characterized by an organization having a number of Chief Scientists, who were allowed to perform independent, long-term basic research. Since a year ago most of the research is organized in time limited Centers of Research. This, together with a substantial decrease of the budget given directly to RIKEN as an organization but partly compensated by increased external funding, means that the central control of research has tightened and the research orientation has been more towards short time goals. We do not support this attempt to control basic, innovative research but it is not our job to comment further upon this change.

Our task is to evaluate the newly formed the RIKEN Center for Emergent Matter Science (CEMS) and comment upon the initial organization and achievements from April 1, 2013, to December 31, 2013, a period of nine months. The strategic objective of the center is: "Building a sustainable society that can coexist in harmony with the environment – Design and realization of emergent phenomena/functions in electronic and molecular systems". The cooperation may result in ultra-low energy cost electronics and environment-conscious high-efficiency energy collection/transformation/storage. The CEMS is taking a long-term view in his goals. The ambition is extremely high with a vision that these fields of research, working together, could lead to revolutionary developments in the areas of energy, environment and electronics. Behind this vision is the notion of emergence, emergence of novel phenomena when combining elements or complex materials – phenomena that one does not find in the parent compounds or elements used to make these combinations. In order to fulfill this vision, the CEMS is divided into mainly three divisions. The recommendation report by the Advisory Council is presented below on the seven terms of the reference for the CEMS.

1. Organization

Are the three divisions and research topics established by CEMS appropriate for achieving the center's strategic objectives?

Is there sufficient synergy among the three divisions?

The quality of the science in all three divisions is outstanding and what the CEMS needs is further "maturation". In order to enhance sufficient synergy among the three divisions, three divisions in the CEMS seem to engage on-going collaborations. In order to achieve the center's strategic objectives, the CEMS needs to work at the synergy by creating a formal mechanism for interaction of young people across all three divisions. A suggestion that might be effective is to select specific "technical topics" that in order to develop would need to cut across all three or at least two of the divisions. In fact a formal team of the most senior young researchers should be charged to run a discussion group to initiate completely new research projects that will eventually integrate the CEMS. The tea time weekly activity and common seminars/brainstorms are important but they are not sufficient to accomplish the synergy that the Center needs to demonstrate. Since there seems to be still a gap on the scientific communication between chemistry and physics, we hope young people try to change this situation and the interaction among three divisions including theory and experiment will give a real synergy for further progress of emergent matter science. This CEMS center is well equipped with highly sophisticated fabrication devices and characterization instruments, however, there are only few technicians or permanent staffs who can support these instruments. The CEMS or RIKEN should give continuous support personnel for the instrument maintenance. Furthermore, in order to *explore and enhance the sufficient synergetic collaboration among the three divisions* that the Center needs to demonstrate the validity and importance of emergent matter science, the AC would strongly recommend that the CEMS's activities should be under one-roof by planning a possible construction of the Emergent Matter Science Bldg. Without this geographical proximity and *possibly same coffee machine,* it has been shown in many places that it is extremely difficult to create strong links and novel collaborations. Such a building will allow many more collaborations among three divisions. We thus strongly support and recommend that a building allowing CEMS researchers to be together is built as rapidly as possible.

Meanwhile, we may expect that some unified guiding principles or new concepts should be conducted for the creation of new emergent research field. To come across new materials and new physical properties, the future effective collaborations are, we believe, developed in a smart way. Each division performed excellent and outstanding works, so it is highly possible that three divisions are bound under challenging unified concept in the near future.

2. Research output

Is the research output from CEMS of world-class quality and is it a leader in the research fields related to its strategic objectives?

General:

Since the days of the discoveries within high temperature superconductivity, Japan has had a prominent place in research regarding strongly correlated electron systems, leading research in the world. This has continued, being a leader in other aspects of strongly correlated systems such as phase separations between insulator/metal/antiferromagnetic/ferromagnetic phases with ordering in charge, spin, and orbital momenta. Multiferroic phases were pioneered, and RRAMs (resistive random access memories) were invented. Japan has also had a very prominent position within quantum information with breakthroughs in superconducting qubits, quantum dots, and optoelectronic/spin entanglement. Fundamental physics concepts have also been tackled using different artificial structures, e.g., artificial atoms and their interactions with fields and between each other, including transforming of virtual vacuum fluctuations into tangible photons. The published work has been highly recognized by the international community. The leaders of the center belong to the researchers who are most highly cited in the world, their H-indices are outstanding. The trend has continued within the first 9 months of the CEMS, the production has been remarkable with many highly recognized and cited works, a large number of invitations to international conferences, etc. Very few institutions can compete with the CEMS. Thus, the CEMS is a true leader within the research field where it has positioned itself. Each division is world-class quality and the top-notch leaders are brought together in the field of international community. One success story we would like to mention as an example of the importance of bridging fields is the amazing work of Profs. Iwasa and Kawasaki whose efforts have led to the development and application of the field-effect EDLT technique to oxides and its application to many materials demonstrating a novel way to control, switch and sometime generate new phases. This collaboration led to very many papers in the best journals and launched a new field of research.

We highly expect that in order that further emergent effect through the collaboration among three divisions takes place towards achieving its strategic objectives, RIKEN will continue to forcefully support the center.

A. Strong Correlation Physics Division

Among many excellent outputs in the recent years, the followings are particularly notable; **(1)** Dirac electron states on the surface of topological insulators are detected by using a tunnel junction formed on the surface. The states have normally been observed by photoelectron spectroscopy in a vacuum chamber. This experiment is, to the best of our knowledge, the first observation of Dirac states by electrical method, which opens the way for device application of the states. **(2)** Nano-scale skyrmion (a swirling spin texture) has recently been noticed as a novel information carrier with low energy dissipation. Most advanced experiments on skyrmion dynamics are in progress in the CEMS, being guided by theories developed in the center. **(3)**Topological superconductivity and associated Majorana fermions are attracting intense interest from the viewpoints of both the fundamental physics and the application to quantum information. According to the recent theory developed in the CEMS, p+ip pairing state (topological superconductivity) is expected to be produced in the gap of s-wave superconductor coupled to the skyrmion crystal. Intense competitions with other leading centers around the world are ongoing in the field, being mainly caused both by the very fast information spread and by accumulation of competent researchers in the field. It could, therefore, be very important for winning the competition to bring about "emergent phenomena" by synergy among the three divisions. **(4)**The Computational Study for Transition-Metal Oxide Heterostructure-Interfaces is under a progress to explore emergent quantum phenomena expecting to appear at transition metal oxide surfaces and heterostructure interfaces. The state-of-the-art numerical first-principles and many-body model simulations should be developed in the near future.

For the realization of the spintronics to go beyond Si-CMOS technology, we need that new environment friendly materials, energy saving new spintronics materials, new colossal (high-efficient) spin manipulation method by electric field, and new (low-cost) self-organization method to create nano-superstructures. It may be required to perform more materials design-oriented research and to propose the roadmap for the future real application based on spintronics. In this context, it is promising to combine quantum topology and strongly correlated matter in an emerging materials program, including, e.g., topological insulators, orbital physics phenomena, quantum simulators, and nano-structural devices. It aims at features as dissipationless functions, room-temperature superconductors, quantum information, and electronics beyond Moore.

B. **Supramolecular Chemistry Division**

All topics under investigation by the Supramolecular Chemistry Division are timely and important and executed with cutting edge approaches and great creativity. Among the great topics being pursued one can mention advancing the strategies of supramolecular polymerization which is very likely to be a source of emergent matter.**(1)** Takuzo Aida's group is recognized as a front runner of functional softmaterials in the world. His group has done not only a fundamental research but also some of his materials lead to industry-academia collaboration. His discovery on supramolecular chain growth polymerization with new monomer with C5-symmetry gave a new concept of controlled polymerization. Systematic characterization of this new polymer and application is expected. Nanostructure by paste and cutting of nano-ring is an interesting discovery. Large nanotube obtained by technique might lead various applications utilizing nanopore. Understanding of fundamental aspect of molecular interaction of his materials will bring further development of novel supramolecular systems. Also, chaperon like nanotube has been applied for cell interaction experiment with a collaboration of biomaterials group in University of Tokyo, and revealed the effectiveness of their new materials. This should be a great opportunity to engage theoretical investigators at the CEMS to model this system which in turn could be very useful in other areas covered by this division such as organic photovoltaics (OPV). **(2)** Yasuhiro Ishida utilized new self-assembled chiral LC for novel ordered 2D structures. The macroscopically oriented framework with helical nanopore gave many possibilities for functional applications. The collaboration with structure characterization group gives precise information on molecular aggregation structure. Another novel material which his group is focusing on is a novel hydrogel "aquamaterial". Well controlled structure gave a unique rheological properties which cannot be realized in another network polymers. Further understanding of physical chemistry of origin of physical properties will bring further development of novel supramolecular systems. **(3)** Kazuo Takimiya's group did the precise synthesis and characterization of organic semiconductors. His materials are very unique and collaboration with structural characterization with another group revealed the relationships among molecular structure, higher order structure and electric properties. In the case of OPV, his PNNT/PCBM almost reached a target of conversion efficiency. We hope they seek further higher value based on their molecular design and structure control. Also, his research collaboration with Bio-group expends his system to aptamer/SWCNT—P3HT hybrid which will give emergent bio-related properties. Collaboration with industry is well established in his group. Collaboration with physics group is encouraged. **(4)** Yoshi Iwasa's group utilizes organic-inorganic interface modification for resistance switching. Utilizing ionic liquid seems to provide a powerful way to control EDL and EDLT gating. Design of novel IL suitable for the interface structure and property control with a collaboration of chemistry people in the same division might open a new way to develop new devices.

Important area being pursued in this division, which could benefit enormously from supramolecular chemistry, is the field of photovoltaics (OPV). In this area the Center needs to figure out how to integrate the ongoing work in polymer based OPVs with the supramolecular small molecule approach that is under investigation in various parts of the world. At the same time the OPV research involving organic materials is an excellent area to look for integration with the other divisions and to establish important connections with industry.

C. <u>**Quantum Information Electronics Division**</u>

The groups of the division have a distinguished history with excellent work. The work during the start-up period continues the tradition but with new directions and several new and important results. One aim of the division is to develop new concepts and electronics, which will trigger breakthrough for realizing quantum computation and quantum interfaces. The division contains groups within quantum information, nano-devices and spintronics, low temperature physics, observation technology, and technology support.

Each group has strong teams directed by researchers who are world renowned pioneers and leaders. For example, **(1)** Seigo Tarucha is the pioneer who established the research area of single electron based quantum information technology with gate controlled, single quantum dots based on semiconductors. During the past year, substantial progress has been made regarding multiple quantum dots as spin qubits. **(2)** Jaw-Shen Tsai and Yasunobu Nakamura are pioneers of superconductor qubits. Lately, the group has developed parametric amplifier read-out of single pulses and a complementary version of a Josephson SQUID in the form of a phase slip nanowire. **(3)** Daniel Loss and Franco Nori are the theoretical leaders of this field with new results on spin-orbit and spin based qu-bits. They interact fruitfully with experimental groups. In addition, **(4)** Yoshihisa Yamamoto joined the CEMS and added the wider scopes in quantum information technologies including quantum optics, information science and quantum cryptography. **(5)** Other groups of the division have published excellent works on spin currents, exciton emission from nanotubes and excitations in superfluid He-3 using electron bubbles. The previously developed, novel 300 kV phase contrast electron microscope has found important uses. The nano fabrication is vital for the division; it is very effective.

The CEMS is proposing to open new aspects of future electronics based on coherent motion of electrons, arising from many body quantum correlation. Typical example is the topologically protected dissipation free current. As Daniel Loss clearly indicated, exploring this direction is an important direction of this division. This point is very important to generate synergetic activity within the CEMS.

Yoshihisa Yamamoto‘s coherent wave computing is an ambitious, novel proposal. This is a new computer architecture, which could have strong computation power to overcome the limitation of conventional computers. Although, a rigorous theoretical analysis and necessary hardware technologies have not yet been well explored, discussions with the CEMS members within the quantum information division and other divisions could be very helpful to evaluate and develop this new idea.

The field of quantum information has now reached a stage where scaling and interactions with the environment become even more important and lead to larger technological efforts. Several important directions are followed and further external financing of the program may be needed.

D. Cross-Divisional Materials Research Program

This program organized by three-full-time and five-not full time young scientists is challenging to foster the up-and-coming young researchers. This division is most typical of the CEMS, particularly expecting synergy between physics and chemistry and also fostering next-generation leaders. The selected research topics are all distinctive and creative. The AC members are most impressed by the following researches: **(1)** The magnetic and dielectric nature were explored for the single crystals of chiral-lattice helimagnets Cu_2OSeO_3 and $MnSb_2O_6$, and the helicity of spin-spiral was found to be fixed by its crystallographic chirality. This enables the directional switching of magnetically-induced electric polarization just by slight tilting of magnetic field. **(2)** The topology of the multidomain structure in a uniaxial organic ferroelectric substance can have an intrinsic impact on the degree of switchable polarization using polarization hysteresis measurements and piezo-response force microscopy. This novel research on the charge ordering in geometrical frustration may lead to deeper understanding of vitrification phenomena. **(3)** Polarization switching dependent on multidomain topology in an organic ferroelectric leads to comprehensive understandings of domain-wall dynamics, which is of essential importance for advancing ferroelectric application.

In order to encourage this type program further, an open selection system to add further members may be appreciated in future.

3. Human resources

Is CEMS contributing to the fostering of international research personnel and young research leaders?

The CEMS core consists of prominent and very experienced researchers that have taken the role of leading the center. The important mission besides the development of research activity is to foster the up-and coming young scientists. There has been an effort to let young, promising researchers, mainly from the faculties at Tokyo University and Tsinghua University, China, become leaders of smaller units (ULs) and get support from the Center not only financially but also in mentorship by the core members. The CEMS is also in Research Alliance with Max Planck Institute and with Stanford University, fostering next-generation top-caliber leaders bridging over the disciplines by Cross-Divisional Materials Research Program. Incubation policy of leading researchers are also appreciated to extend joint-Lab for the domestic organizations besides University of Tokyo and international ones besides Tsinghua University. Many post-docs are supported by the CEMS (as well as PhD and Graduate students and industrial researchers, which are not salaried by the center), often during several years. Furthermore, the open innovation with industry partners is appreciated for accepting industry researchers. This system should be further developed for encouraging to work together across fields and industrial boundary to enhance the collaboration between academia and industry.

From other context, the most pressing issue facing the CEMS and other centers is the absence of sufficient number of female investigators. The director should engage in a "pro-active" strategy to recruit female scientists. Given that the pool of investigators may be limited, this will certainly be a challenge but should be a permanent ongoing effort at the CEMS. It is also important to continue efforts to recruit international investigators. This is extremely important in exposing Japanese postdocs and graduate students to young scientists from other cultures and this way best prepares them to be integrated into a science and technology world that is increasing "global". It would be most useful to specifically target young investigators from Europe and the US, since there seems to be a healthy number of non-Japanese Asian investigators at RIKEN and possibly within the CEMS as well. We were informed that all important documentation and information at RIKEN and within CEMS are in English; we hope this will be continued to ease international participation.

The informal interview with young scientists was the good opportunity for us to notice an atmosphere in the CEMS from the bottom up view that they feel a liberty in their activity and proceed friendly collaboration and enjoy their research life. The center governance was impressed that the director, the group directors and the team leaders keep in their mind to taking care of their future promotion for post-docs, researchers and senior researchers to get some PI-like outside position as possible as they can..

4. Collaborations and public relations

How successful has CEMS been in forging collaborations with universities, research institutions, and other organizations, including companies both within and outside Japan?

There are extremely strong bonds between the CEMS and university as a very large portion of the PIs are professors of Tokyo University at the same time. Collaborations are mainly with Tokyo University but there are some common researchers also with other universities. The joint work has proven to be a very positive injection for the university and it is recommended to be continued. About 10 researchers are coming for a limited time (about 2-3 years) from Japanese industry. This is a remarkably high number, taking into account the basic nature of the research. The potential for connections to industry and other institutions world-wide is enormous as the CEMS develops further.

The CEMS is in international collaboration with more than 15 overseas research institutions and fosters a problem-solving approach that encourages researchers to work together across fields and institutional boundaries, that is, including industries both within and outside Japan. In order to foster the young researcher and to promote their carriers, we may propose to consider a program of oversea institute-internship experience, for instance, during one to three months. The collaboration of young researchers with foreign research group might give them experiences which are important for their career pass. The PIs should encourage their researchers to stay at least one or two months for collaborative research. It aims at expanding young researcher' horizons by having contact with different international top-notch researchers and other fields researchers.

Here, let us mention how this CEMS is characterized among existing domestic organizations for the science of matter. The Institute of Solid State Physics, ISSP, in the University of Tokyo may have the position of the basic research center under the diversity of matter science, we like to appreciate an instructive collaboration between both organizations through the some kind of Institute-internship program for young scientists to foster the up-and coming scientists.

5. Budget

Is budget allocation between research and human resources well balanced?

The budget allocation between research and human resources seems to be well balanced. Concerning the operating support funds or the management expenses grants, we would like to expect that the strategic and priority allocation policy should be expanded for the strategic centers in RIKEN through considering the research ability evidences. The director should be prepared to alter it as new projects emerge in a more integrated Center. We are concerned by the policy that the budget is somehow reduced each year and that the members compete hard to “recuperate” this amount. Our advice would be to provide enough means to the CEMS and to avoid having researchers “loosing” a lot of time to write proposals to get back their funding. Instead of a yearly cut, one could imagine constant funding with, say after 5 years, a solid evaluation of the results that will allow a decision on the level of future funding to be made. It is important to stress that the CEMS fields of research are central to future developments and thus should be a priority area for investment.

The PIs are needed to currently make possible effort to get external competitive funds, whereas the CMs of CEMS should encourage young researchers to apply relatively big funding of JST, NEDO and JSPS for young researchers in order to carry out their own science and for their promotion.

6. New System for Independent Administrative Institutions

RIKEN will be operating under a new system for Independent Administrative Institutions, starting in April 2015. As such, RIKEN’s primary objective will be to maximize its research and development capabilities and define goals for creative, outstanding world-class results in selected areas of problem-solving research.

Under such circumstances, what research topics, if any other than the center’s mission, can CEMS contribute to by exploiting its research resources?

The 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 first mission is to achieve high efficiency in the collection and conversion of energy. Great expectations have been placed on technologies such as photovoltaic cell, with which they convert sunlight to useful energy. In fact, it would be expected to develop organic solar cells that raise the energy conversion efficiency by controlling the position of molecules based on the principles of supramolecular chemistry. The second mission of the CEMS is to create electronic devices that use very little energy. The CEMS is endeavoring to create extremely low-power memory devices and circuits. Developing quantum information electronics and quantum computers will contribute not only to saving energy, but will also make it possible to safely and rapidly process large amounts of complex information.

As any other missions, we may suggest to design and develop materials that are high-temperature superconductors, since it will become possible to transmit electricity without any loss and realize novel electronics and sensor functions. We also suggest that the strong-correlation physics plays a vital role in increasing an efficiency of the photo-catalysis reaction. In this context, we expect that the collaboration of supramolecular chemistry division and strong-correlation physics division is necessary to create a new emergent field in the CEMS. One possible area in this regard would be “organic-inorganic hybrid” materials and their corresponding emergent phenomena as a result of rationally designed interfaces between organic molecules and semiconductors, Mott insulators, metals, etc. The achievement of these missions contributes to the achievement of a sustainable society that can coexist in harmony with the environment.

The CEMS may have three hierarchies; (1) Materials (Basic Research), (2) Devices (Research & Development), and (3) System Integrations (Industrialization). In order to make a seamless connection between the three hierarchies, to develop a roadmap and design-based research may be needed for the realization of the real devices suitable for the future applications. The CEMS has an important mission and outstanding resources, researchers and results. The program is very ambitious and full of important works, maybe too large taking into account the resources it has been given. The activity can easily be enlarged. This is true for very many of the parts.

7. **Others**

We agree well with the point that the vital goal of the CEMS is not to develop technologies that can be immediately put into application but to contribute to a sustainable human society that can coexist with the natural environment in five decades or even a century in the future. Researchers who have pioneered these three fields have been brought together along with young scientists to work as a team to take on truly challenging researches. Although only one year has passed since the CEMS was organized, we would expect that the CEMS can make possible breakthroughs in research that could not be predicted from the outset. To do this, the CEMS focuses on the basic research and the development of new theories according to a long-term policy planned by the innovative governance of RIKEN strategic centers. We stress once more the importance of the CEMS and of its objectives for the future of our society, its amazing vision, the quality of its members and the fantastic and exciting challenges it faces. They deserve the highest possible level of support. In order to make future policy transparent, we may suggest a systematic comparison of PI’s research activity evidences among all the strategic centers, utilizing the appropriate evidence data of each center, and to take them as a reference to distribute RIKEN resources. Stability is important for success of innovative research, having high risks and high profits. Crucial research leaders should not spend most of their time with funding concerns. We are concerned by the cuts in budget that occurs each year. A stable budget is recommended.

As the summary of this recommendation paper, we remark that this center is well organized and managed to solve challenging and difficult problems, which requires gathering the individual abilities of experts. We are highly expecting that this CEMS develops further towards the challenging goal to explore the energy functions of electrons in solids and molecules under a strong support through the smart and emergent governance of RIKEN.

CEMSAC2014 Program

5/7(Wed)　day 0 Hotel Metropolitan “Hikari” http://www.metropolitan.jp/e/

16：30-16：40	10	Opening remarks(Dr.Tokura)/AC member introduction
16：40-17：00	20	RIKEN’s introduction (Dr.Kawai, Executive Director)
17：00-17：30	30	CEMS introduction (Dr.Tokura) (CEMS PI Introduction)
17：30-17：50	20	AC member discussion about role-sharing
18：00-19：30	90	Buffet dinner (CEMSAC member, CEMS PI)

5/8(Thu)　day 1st Large meeting room, 2nd floor, Welfare & conference bldg, RIKEN

09：30-12：30		180	A.　Strong Correlation Physics Div. (強相関物理部門)
	09：30-10：10	40	A　Div. introduction 部門紹介（Dr.Nagaosa）
	10：10-10：35	25	A-1; Div. representative (Dr.Kawasaki)
	10：35-11：00	25	A-2; Div. representative (Dr.Hanaguri)
	11：00-11：20	20	Coffee break
	11：20-11：40	20	A-3; UL①（Dr.Kagawa)
	11：40-12：05	25	A-4; Div. representative (Dr.Taguchi)
	12：05-12：30	25	A-5; Div. representative (Dr.Furusaki)
12：30-13：30		60	Closed Lunch (AC members only) @ small meeting room
13：30-15：30		120	Interview with some young researchers
15：30-18：00		150	B.　Supramolecular Chemistry Div. (超分子機能化学部門)
	15：30-16：10	40	B　Div. introduction 部門紹介（Dr.Aida）
	16：10-16：35	25	B-1; Div. representative ①（Dr.Ishida）
	16：35-17：00	25	B-2; Div. representative ②（Dr.Takimiya)
	17：00-17：15	15	Coffee break
	17：15-17：35	20	B-3; UL②（Dr.Araoka)
	17：35-18：00	25	B-4; Div. representative (Dr.Iwasa)
18：00-18：30		30	Dep. Wako、move to Hotel by Bus
18：30-20：30		120	Working Dinner (AC members only) at Hotel Metropolitan

5/9(Fri)　day 2nd　Large meeting room, 2nd floor, Welfare & conference bldg, RIKEN

09：30-12：30		180	C.　Quantum Info Electronics Div. (量子情報エレ部門)
	09：30-10：10	40	C　Div. introduction 部門紹介（Dr. Tarucha）

	10：10-10：35	25	C-1; Div. representative ① (Dr.Yamamoto)
	10：35-11：00	25	C-2; Div. representative ② (Dr.Tsai)
	11：00-11：20	20	Coffee break
	11：20-11：40	20	C-3; UL③ (Dr.Seki)
	11：40-12：05	25	C-4; Div. representative ③ (Dr.Otani)
	12：05-12：30	25	C-5; Div. representative ④ (Dr.Loss)
12：30-13：30		60	Closed Lunch (AC members only) @ small meeting room
13：30-14：30		60	Center Director's presentation
14：30-15：30		60	Closed discussion (AC member & CM Member)
15：30-16：30		60	Closed discussion (AC member)
16：30-17：00		30	General Briefing (AC member & CEMS PI)
17：00-			Closing remarks
17：30			Dep. RIKEN to Wako-shi station and the Hotel by Bus