Report of the 3rd Advisory Council
on
RIKEN Center for Emergent Matter Science (CEMS)

The third Advisory Council meeting on RIKEN Center for Emergent Matter Science (CEMS) was held from August 15 to 17, 2019 at the RIKEN Wako Campus and Hotel Metropolitan Ikebukuro. The task of CEMS Advisory Council (CEMSAC) is to evaluate the activities of CEMS during the three years since its previous meeting. We have made the assessment based on the submitted documents as well as the presentations given during three days. In this time, all the PIs presented their research activities, in addition to the comprehensive summary given by the leaders of three divisions: strong correlation physics, supramolecular chemistry, quantum information electronics. Management, current activities, and collaborations of CEMS were explained by Director Yoshinori Tokura. We also had a chance to hear some comments/requests from early-career researchers. Based on all these results, we submit the recommendation report on the five terms of reference for CEMS.

Members of the CEMSAC2019

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1. Research Activities

Evaluate (1) whether the center's research meets international standards and is regarded as world-leading, (2) whether its research results have contributed to society, (3) and whether its up-to-date activities and strategies meet the aims of RIKEN's fourth mid- to long-term plan (7-year plan).

1-(1) World-leading Research Activities

To perform the strategic objective "building a sustainable society that can coexist in harmony with the environment", CEMS is divided into three divisions, i.e. strong correlation physics, supramolecular chemistry and quantum information electronics. CEMSAC members have a consensus that CEMS has extremely high research activities in international standards and is regarded as world-leading, for all three divisions. Collaborations between different divisions and also between theory and experiments are very fruitful and successful. The center is considered as one of the leading research institutes in the field of topological/quantum materials in the world. Statistical publication data indeed prove that the center is conducting world-class research. According to the bibliometric data, the ratio of top 1% papers is 4.97% to 5.4% of the total CEMS papers, which is far higher than the overall RIKEN data of 2.39%, and comparable to the top research institutes such as Max Planck Institute, CALTEC, and UC Berkeley.

We first summarize the extremely high-quality research activities for each division.

1-(1) A: Strong Correlation Physics Division:

The Division of Strong Correlation Physics (SCP) focuses on developing emergent phenomena to realize giant and dissipationless functionalities utilizing the strong couplings among multi-degrees of freedom in strongly correlated systems. In particular, the SCP Division has discovered a number of striking phenomena triggered by an interplay of strong correlation, symmetry and topology, which have not been observed in conventional condensed matter physics. These activities are clearly world class and many of the PI's showed very innovative, new and exciting results, also promising for possible future applications. Among many extremely high visibility research activities, which are easily confirmed by remarkable bibliometric data, breakthroughs have been reported in all of the important areas of this program including superconductivity, multiferroics, topological insulators and superconductors. With these breakthroughs, the SCP Division is developing a new and promising platform for strongly correlated systems.

Below some examples of outstanding achievements are listed for SCP.

1. Superconductivity:

As for high transition temperature T_c=250K found for LaH_{10}, first principles calculations have been successfully realized, allowing this very high T_c to be understood microscopically. For topological superconductivity, it is remarkable that STM experiments with World record characteristics at low temperatures and high magnetic fields have been achieved, which enabled to observe signatures of Majorana fermions. Furthermore, disorder-enhanced T_c in $NbSe_2$ has been observed and its relation to multifractal superconductivity has been demonstrated.

2. Multiferroics:

A remarkable magnetization-reversal phenomenon using an electric field very close to room temperature has been achieved. Also, light diode behavior has been observed in multiferroic materials, which could play a key role for applications in functional devices.

3. Topological materials：

The realization of topological insulator (TI) hetero-structures has brought about a major breakthrough, i.e. the observation of an axion insulator, which shows a quantized magnetoresistive effect. Also chiral edge conduction at an artificially realized domain wall in a TI structure has been observed. In high mobility ZnO displaying fractional quantum Hall effect, a Wigner crystal state has been observed. Non-reciprocal transport, which provides a new platform for functional materials, has been realized in a system of magnetic TI/superconductor.

4. Skyrmions:

There are a number of remarkable discoveries in this context. First, skyrmions have been observed at room temperature, and new spin structures such as tetrahedral and cubic hedgehog lattices have been realized. These active researches have then led to the discovery of merons and anti-merons (half skyrmions). In the skyrmion systems, emergent electromagnetism, such as electric-field induced motion and topological Hall effect, has been realized. As for an advanced method, ultrafast TEM has been developed, which will certainly play an important role for future investigations of skyrmion dynamics. On the theory side, dynamics of skyrmions, current driven motion, dynamical phase diagram and non-linear Hall effect have been studied comprehensively.

5. New functional devices:

One of the most striking achievements is the observation of shift currents in non-centrosymmetric materials when subjected to light illumination: (a) Shift current is robust against disorder, (b) First principles studies have been performed, (c) *I-V* characteristics and shot noise have been studied and predictions have been made. Another notable advancement is an “Emergent inductor”, which could replace an inductor by a material with a spiral spin structure: the inductance in such a system is inversely proportional to the cross-section, which could lead to a breakthrough in the realization of nano-inductors.

Among many outstanding results mentioned above, research activities on skyrmions are very impressive, involving most of the researchers in this division. A number of striking phenomena of skyrmions have been predicted theoretically and realized experimentally, and vice versa. Also, the prediction of shift current and its experimental observation are signs of innovative research, which will provide a new and promising platform for nonequilibrium transport phenomena in various kinds of matter, including hard as well as soft matter.

The very productive collaboration between theory and experiment has to be highlighted, which has produced a number of remarkable results of extremely high quality and impact. These researches will certainly contribute to topological computation, spintronics with ultralow energy cost, dissipationless circuits, emergent diode/solar cell, and emergent inductor, which are the main targets of research in the SCP Division.

Another thing to be noticed is the level of know-how within CEMS. One example is the control of the MBE growth of oxides and TI materials. This was, for instance, extremely useful to test the idea of realizing an axion insulator – the complex structure containing different TI could rapidly be grown as this would be a major development/effort in many other places. This demonstrates the speed at which CEMS can react to new findings or is able to test new ideas.

1-(1) B: Supramolecular Chemistry Division

Generally the research topics being carried out by the PIs in the Supramolecular Chemistry (SMC) Division since 2016 are at the cutting edge of SMC. The Division now has increased in size to 11 PIs including Dr. Miyajima in Cross-Divisional Materials Research Program and its research activities are overall in a very healthy state with regard to publications as well as joint publications within the Division and even close to two dozen papers across Divisions in CEMS.

The field of SMC has been emerging worldwide as the frontier of soft materials science. The Division's leader Professor Takuzo Aida is presently recognized by the international community as one of the leaders of the field of SMC. Over the past three years Aida has reported a couple of impressive breakthroughs, both published in Science, one on self-healing organic glasses of significantly high modulus which is comparable to that of some engineering plastics. A second breakthrough has been the discovery that unique supramolecular polymerizations yielding columnar polymers can occur in a liquid crystalline medium that would energetically not be feasible in isotropic media. Both discoveries could generate emergent soft materials with functionalities not previously conceived.

Excellent synthetic work in the SMC Division has been carried out by several PIs such as Takimiya, Tajima, and Miyajima. Tajima has made great progress on understanding the role of HOMO-LUMO levels on OPV efficiencies and the packing modes of mixed donor molecules in the active layer as well as the precise positioning of acceptor molecules relative to donors. Takimiya effectively has achieved the synthesis of the best known NIR-absorbing semiconducting polymers that show air-stability and ambipolar transport. Miyajima has embarked in very interesting work to achieve polar supramolecular structures with an objective which is extremely important at CEMS given recent discoveries of shift currents in non-centrosymmetric solids by Prof. Iwasa and members in the SCP Division. His work may have great consequence for the development of completely new solar photovoltaic materials.

The SMC Division has also a number of projects that offer great potential to make discoveries at the interface between inorganic materials and organic materials. This type of research is being conducted by PIs Ishida, Iwasa, and Pu. Ishida's photonic water with structural color and the first 2D material that can reversibly change magnetic direction in response to UV light is a good example of systems that have both inorganic structures as well as supramolecular and polymeric systems. Great work by Iwasa on metal sulfides and quantum dots may eventually create highly promising directions at interfaces with supramolecular systems, and similarly the ongoing research on quantum dots in Pu's lab. Iwasa's work is also connecting through outstanding work to CEMS as a whole with his efforts on shift currents (Nature 2019). Connections to the physics of supramolecular systems, particularly on liquid crystals, are also being built and developed by Araoka. Based on publication records all these groups have been highly productive over the past three years since the last review.

On the engineering side the Ito's lab and Someya's lab continue to produce very important world class work toward the development of practical devices, wearables in Someya's case and biomedical diagnostic devices as well as exotic drug delivery systems based on peptidic hollow capsules. There is for example a lot of opportunity in coupling the synthetic groups on electro-active materials with the engineering efforts.

Materials characterization support team by Dr. Hashizume plays an important role in progress of research in CEMS.

Recommendations:

Two gaps have been identified in research activities within the SMC Division. One is the great need to add more theory activity on soft matter as well as computational materials science to explore the use of both atomistic and coarse-grained strategies. The second one is the need to strengthen imaging technologies within the Division and CEMS as a whole. This would require not only acquiring equipment, but also organize core facilities that are accessible to all CEMS researchers as well as hire the technical experts to run and maintain those facilities. This responsibility should not be given to postdocs as this would not be a good use of their time. Some of the obvious needs in this regard is the improvement of electron microscopy facilities, particularly cryo-TEM and possibly liquid cell TEM. There is also room to improve capabilities in other microscopies as well including Stochastic Optical Reconstruction Microscopy (STORM) and confocal microscopy.

Another suggestion is to pursue better understanding of the dynamic nature of supramolecular materials. Since unique properties of soft materials are linked to their hierarchical structure at different length and time scales, understanding dynamics together with the physics group or through external collaboration might create a new idea on novel emergent supramolecular materials. Understanding the fundamental device performance by operando measurements is also encouraged.

1-(1) C: Quantum Information Electronics Division

In the Quantum Information Electronics (QIE) Division including topological quantum electronics, spintronics, and quantum computing, the world's highest level of research is being conducted as a research institution representing Japan. However, the main subjects currently being conducted in CEMS, such as quantum computers, strong correlation physics, topological quantum materials, and spintronics, were started by CEMS senior researchers before CEMS was launched. To come up with a new concept originated from CEMS, it depends on the success of the young people adopted by CEMS. How to create a free, vibrant environment that creates new ideas and concepts is an important role of the CEMS management layer.

Very original works toward quantum computer have been achieved by the researchers in QIE Division. Prof. Tarucha has made great contributions to the development of spin qubits, and Profs. Tsai and Nakamura were the first to demonstrate coherence in superconducting qubit. Prof. Loss has established basic concepts of quantum computing with quantum dots. Alternative approaches such as Majorana Fermions are investigated both experimentally and theoretically. In this sense, the QIE Division is a very unique center and has advantages over other institutions. It considers complementing aspects of superconducting qubits, circuits, interconnects, and systems, as well as coupled spins in semiconductor quantum dots and in new topological qubits. Going from III-V based QDs to Si ones is important and financial resources should be directed to allow cooperation with commercial foundries that possess advanced technological processes. It is important that complementary work, both using alternative principles and supplementary parts, is carried out besides the concentrated Q-LEAP project. Activity in quantum computer has flourished abroad and large American companies, like Google, IBM, Microsoft, and Intel, started activity at a relatively large scale and sizeable programs were also launched in Europe and China.

The CEMS program has been important saving Japanese competence within quantum technology. However, additional resources are needed in order to keep Japanese supremacy within information technology. This does not only contain computing but also quantum sensors, communication, and simulation.

The QIE Division in CEMS should be a R&D center for quantum computer in Japan. It is highly desired to ask MEXT to organize an official quantum computer center in order to accelerate the development of this research field. This is also valuable from the view point of the RIKEN's aim being a science and technology hub.

It is not so easy for a single team or QIE Division in CEMS to compete with foreign big projects including Google, IBM, Microsoft, and Intel for quantum-computer development. Further support from the Japanese government is expected for quantum computer research. In order to compete with foreign countries in the development of quantum computing, it is important not only to develop the technology related to quantum physics that CEMS is good at, but also to develop software products based on information science and to construct computer systems as hardware. In particular, the construction of computer hardware will become increasingly important, and collaboration between physics researchers and computer hardware researchers will become more important in the future. It is impossible to execute this only by CEMS research resources because of the limited expertise which CEMS has majorly, and collaboration with universities, AIST, and industries becomes important. At the same time, CEMS is expected to play an important role to pursue the possibility of new devices, for example, the possibility of robust quantum computing by introducing new physics such as Majorana Fermion, and there is large expectation for CEMS to lead the field.

1-(2) Contribution to society

The CEMS achievements contribute and will contribute to society - CEMS is working on different subjects/areas: Emergent energy functions; Emergent functional soft materials; Quantum information; Topological spintronics. All these areas can lead to very important applications and thus have a very good probability to "contribute" to society to assist in the realization of a sustainable, environmentally-friendly society.

Innovations related to energy devices such as batteries, superconductivity, and thermoelectric conversion devices are essential elements for realizing a sustainable society. The realization of this will depend on material science as well as physics and chemistry. Some comments are here for each division:

(1) The SCP and QIE Divisions have high expertise of mainly physics and electronics. Some collaboration with researchers outside who are capable of synthesizing new materials would be desirable to materialize new ideas created in CEMS. As for the SCP Division, the results of investigations such as skyrmions and topological shift currents are most innovating, and are promising for near-future applications.

(2) Most of the research activity in the SMC Division has some vision in terms of its relevance to solve problems of benefit to society. Some of the work is very fundamental and this is scientifically healthy for the Center. Furthermore, in SMC research, there are many researchers who can synthesize materials, so there is a high possibility that interesting applications will emerge unexpectedly.

(3) The research activities of QIE Division are still on a very fundamental stage. However, the future development of a scalable quantum computer will enable secured, highly efficient information processing that is difficult by conventional computer. When quantum computers are realized, it will be possible to design new materials and drugs, and to apply AI to complex systems that are difficult to execute with the current AI. This may greatly contribute to the future society where the cyber world and the physical world merge.

CEMS today is in a phase where it explores different directions and possibilities. This “screening” or development of “building blocks” or “seeds” is essential and key for future applications (one can mention here quantum technologies, shift current or a new revolutionary inductor). One thing to stress is that one is not talking here about “simply” improving existing technologies but CEMS is aiming at developing disruptive technologies – for such developments, basic research and “screening” are essential.

Another key contribution of CEMS to society is the education of young people – forming the next generation of scientists - in novel scientific areas that will be relevant for future technologies is a strategic mission. Educated people in these novel research areas will be essential for the companies that will develop new technologies and which will need this know-how.

We finish this part by exemplifying two possible applications of the CEMS technologies that will certainly contribute to society in the near future:

(1) Topological currents are essentially dissipationless in nature, therefore, it is expected that the topological currents can be utilized for ultra-low energy cost electronics. MRAM, which is expected to be the next generation of non-volatile memory, is faced with serious technical issues when improving their performance and a new concept of spintronic devices is required. New spin control and conversion methods being pursued in CEMS are expected to bring about innovation for future spintronic devices.

(2) Quantum Technology has become in fashion during the last few years and one has great hopes that this field, which in older times was considered to be academic and far from being applicable, now will be a basis of new types of devices and methods that will be of great value to society. The microscopic quantum world can now be controlled and designed and not merely observed. CEMS has contributed to the development of concepts within all three of its divisions. Not the least, the quantum sensors, communication, and computing work may be applicable. We should also emphasize that the research has considerably broadened our view of basic science and technology.

The visibilities of science and technologies in Japan are declining in most of research areas in terms of the number of publications and citations. The research activities in three divisions of CEMS are outstanding and internationally well recognized. The demonstration of high level research activities all over the world has been contributing a lot to our society.

1-(3) On the RIKEN’s fourth mid- to long-term plan (7-year plan)

The mission of CEMS is to establish new scientific principles and develop proof-of-concept devices that allows innovative hardware based on the concept of emergent matter science. During the coming period, research will be concentrated on four areas: Emergent Energy Functions, Functional Soft Matter, Quantum Information and Electronics Technology, and Topological Spintronics (fourth mid-to long-term plan). We highly evaluate the CEMS achievements along this plan up to now. For this purpose, CEMS has successfully accelerated fusing the 3 fields, i.e. SCP, SMC and QIE.

To be more specific, the following CEMS activities and strategies meet completely the aims of RIKEN’s fourth mid- to long-term plan:

- Emergent energy functions, which are contributing to creating innovative energy and transport function,
- Emergent functional soft matter, which is contributing to soft robotics with high level of affinity

with humans,

- ●Quantum information and electronic technology, which are contributing to ultra-high speed and efficiency information processing with low power consumption,
- ●Topological spintronics, which is contributing to the realization of energy saving electronics.

As mentioned above, many building blocks necessary to achieve the long term goals of CEMS are developed within the three programs. These studies and developments will allow the most promising directions to be followed to achieve the long term goals of CEMS. This knowledge is necessary to go one step further and develop prototypes or proof-of-concept experiments that will pave the way to future technologies – these developments should happen in the coming years.

In this way, along the fourth mid- to long-term plan, it will be possible to contribute to innovative energy and transport solutions, soft robotics designed for humans, low power ultra-high speed information processing and energy-saving electronics based on new concepts. One of the aims in RIKEN's fourth mid- to long-term plan is to produce the world's top-level research results and to become a role model of for other national R&D institutes by producing overwhelming results in basic research. The extremely high-level bibliometric data in CEMS show outstanding scientific and promote the visibility of CEMS and RIKEN. It is clear that the above up-to-date activities in four areas are suitable and meet for the aim of RIKEN's fourth mid- to long-term plan.

The leadership of CEMS has been open to follow changes in RIKEN´s strategic views and plans. Based on the concept of emergent matter science, the fusion of the 3 divisions of CEMS (SCP, SMC and QIE) will be further enhanced to assist in the realization of a sustainable, environmentally-friendly society.

2. Management

Center director will present a SWOT analysis on the management of the center to their AC. The AC is asked to evaluate whether the SWOT analysis and the director's management proficiency are suitable.

CEMS started from scratch 7 years ago, but it has performed remarkably well in the past and now it has become a world-leading center. This is due to Prof. Tokura's great leadership and ability for effective management. He is an outstanding director of the Center. Not only is he an outstanding scientist who has had a highly productive and innovative career but he has been also over the last few years a visionary leader of CEMS. It is impressive how he is able to manage just enough to keep the Center running smoothly but without interfering with the scientific ambitions of his team. He is also very supportive and a great mentor for young scientists, which is an important part aspect of a RIKEN Center Director.

Prof. Tokura is conducting high level researches in 3 divisions thanks to his strong initiative. He is organizing numerous meetings, workshops and science camps that allow young scientists to exchange and know each other better. He is widely appreciated – this was clear from the exchanges with young scientists and from the survey that was performed before the CEMSAC meeting.

A SWOT analysis by Prof. Tokura was very precise pointing out both the strengths and weaknesses of CEMS and key goals that the Institute has to achieve such as the hiring of technical assistants, hiring women scientists to improve diversity, and to try to create a CEMS laboratory all under one roof in order to further promote collaborations among the three groups.

Below, we briefly summarize our assessment of the SWOT analysis.

- **Strong points and Opportunities:**

(1) CEMS is firmly directed top-down by a directorate of capable researchers, who determine the budget and the direction of research in CEMS as well as taking up new sub-fields. However, there is still a large chance of bottom-up activity as PIs and scientists in the groups are encouraged to apply for support by external sources, which comprise about one third of the budget. This will, naturally, lead to a renewal (that will have to fit into the existing structure). It will also help younger scientists to become independent research leaders. It should be encouraged and helped by the management and may be additionally helped by internal funding.

(2) CEMS provides an excellent atmosphere for nurturing young researchers, e,g, using the program in collaboration with University of Tokyo, Tsinghua University etc., and also accepting many international researchers (about 31% of total researchers).
The young PI's presentations and their achievements during last three years were impressive although some of them were appointed quite recently. They are basically independent and have freedom to decide their research directions under the CEMS mid-to long-term plan. The management to foster young researchers is going well and it is expected that some of them will be new leaders in their research fields.
In communications with young researchers held during the CEMSAC meeting, the junior scientists expressed great satisfaction with the management of experimental facilities compared to universities, and were also extremely satisfied with the safety standards at RIKEN and specifically in CEMS labs. They mentioned it was very positive to hold a safety seminar every year.

(3) Among various activities in stimulating interactions within CEMS, "CEMS Research Meetings" are very impressive, including the meeting planned by young scientists, the group research discussion, etc. Such meetings take place frequently and at different stages. This is encouraged. In particular, "Brain storming" at different stages is important. It gives young researchers a possibility to develop and to influence, and possibly change, the activities of CEMS.

(4) It is really remarkable that CEMS fosters world-class leaders by using Cross-Divisional Materials Research Program. For example, in these three years, 13 researchers have been promoted to professors (5), associate professors (5), and lecturers (3).

(5) The successful activities and the capable management will give the researchers in CEMS a good possibility of participating in the increased activities in quantum technology that most probably will be launched in Japan. The research directions of QIE and SCP Divisions in CEMS are matched to the "Quantum information strategy in Japan". It is good news that PI Prof. Nakamura will direct the "Flagship project on Quantum Information technology". It is expected that CEMS plays a crucial role in this Japanese National project.

- **Weak points and Threats:**

(1) As for the weakness of CEMS, the increase of the number of qualified technical assistants and training of them are recommended, particularly in the fields of nanofabrication. The bottleneck of the nanofabrication facility is that it is difficult to secure talented young human resources in the long term rather than the number of people. Staff is required to maintain shared equipments and to develop new fabrication technologies for CEMS activities. If the long-term employment can

be secured, it will be possible to develop new technologies and to keep stable maintenance. Furthermore, the Nanofabrication Facility is very important for many of the groups within CEMS but also for many other groups at RIKEN. Advanced micro- (nano-) fabrication becomes more and more important in research as dimensions are continually shrunk and quantum and shape effects may determine the function of a component or system. If there is a need of further support, RIKEN on the whole should consider strengthening the staff.

(2) CEMS laboratories are distributed in the campus, which will sometimes prevent researchers from efficient collaborations. "Under one roof" would help developing strong synergies, for example, easy sharing facilities. These points should be resolved in the future.

(3) It is difficult to solve the liquid He shortage or price problem, which is becoming increasingly serious, within RIKEN alone. This would affect the research activities of CEMS. The market price is already about 4 times more expensive than last year. As a whole issue in Japan, major research institutions who are using liquid He should gather and make a unified proposal to the government. RIKEN should seriously take this problem into consideration.

(4) There were some concerns among young researchers and particularly technical staff about the difficulty in acquiring new equipment and reliance on postdocs to maintain equipment. They are not sure what are the budgetary issues behind this problem. In alignment with director Tokura, young scientists would also like to have the opportunity to meet colleagues more frequently than the spread out configuration of CEMS allows. This problem would obviously be addressed if one day it were possible to have the Center under one roof, as mentioned above. There is also some concern among young investigators about the uncertainty in their future given rules about finite employment periods and the difficulty of acquiring permanent positions.

3. Center's initiatives

Evaluate whether the center's initiatives on the items given below have resulted in improvements and recommend further measures to be implemented by the centers.

- *RIKEN is conducting a program to enhance its function as the core organization for research partnerships, which we refer to as the "Science and Technology Hub." The AC is asked to evaluate the center's achievements in collaborative activities, including those belonging to the Science and Technology Hub.*
- *Initiatives on the internationalization of the center*

● Achievements in collaborative activities, including those belonging to the Science and Technology Hub.

The CEMSAC members highly evaluate the important role played by CEMS in the "Science and Technology Hub", and also the achievements in collaborative activities. There are a number of activities along this line. For example, collaborative activities with AIST, NIMS, ISSP and private companies contribute to enhancing the center's function as a Science and Technology Hub. Also, many MOU have been signed with Universities and research centers abroad.

Seven years have passed since the establishment of CEMS, and its status and high reputation have been well established. From now on, CEMS should make effective use of the established brand, and increase its ability to influence outside through collaboration with external research institutions.

We assume that the collaborative research activity with universities is regularly monitored by the university innovation centers to establish if research undertaken has potential for technological development and commercialization. It might be of value that CEMS asks one or two persons, who are known to be broad minded innovators, to contact the different groups and discuss if their results or methods may be the basis of technical development and commercialization. Such an arrangement maybe already exists within RIKEN.

● **Initiatives on the internationalization of the center**

As for the initiatives on the internationalization of the center, there are so many collaborative activities with various overseas universities, institutes, and research centers including Tsinghua Univ. and Kavli Institute for Theoretical Sciences, to name a few. For example, Tsinghua-RIKEN workshops are very successful, providing an excellent platform to accelerate the mutual collaborations. Actually, as one of notable results, three PIs from Tsinghua University joined CEMS recently and have been continuing very active and influential researches. In this way, CEMS seems to be increasing its international network by establishing collaborations and joint appointments with Asian universities outside Japan, particularly China and Taiwan. In the globalization in the world today, it is always useful to continue to reach out to labs elsewhere to establish formal programs of international collaboration and outreach.

Also very impressive is that the number of foreign researchers is considerably higher than the RIKEN average. Except the Chinese activity lately, the participation has been mostly at the junior, post-doc, level. The part time participation by foreign experts has been of great value, particularly regarding theory where Dr. Loss and, during the first part of the evaluated period, Dr. Nori have made visible and innovative contributions, which have increased the image of CEMS. Their interactions with experimental groups have been large and have led to initiatives. It may be beneficial to increase the number of PI´s recruited from abroad, particularly if there are vacancies.

4. PI performance

Evaluate (1) whether each of the PIs fulfill their duties in accordance with the mission of the center, taking into consideration the 7-year plan; (2) whether their research meets international standards; (3) and whether they has suitable capability on the laboratory management, including their efforts to support early-career researchers.

4-(1) PIs fulfill their duties in accordance with the mission of the center, taking into consideration the 7-year plan

We find that all the PIs fulfill their duties in accordance with the mission of the center, taking into consideration the 4 major targets of 7-year plan, Energy, Soft Matter, Quantum Information, and Topological Spintronics. Indeed, all the PIs including young researchers in 3 divisions have extremely high research activities and achievements, as already mentioned above.

The results by CEMS are excellent and in many cases world leading. The publication record is truly impressive, of the highest standard in the world as measured by, e.g., impact. The individual researchers contribute to these results and we thus conclude that all PIs fulfill the criteria regarding the mission of the center and, unless noted separately, perform research of high international standards. Bibliometric data can be found in the CEMS white paper. Taking into account the age of a researcher, he/she performs very well in general with high citation scores and impact scores of publications. The creativity is high in general. Interdisciplinary collaboration is mostly high and there is good international cooperation. It was not possible to make a thorough evaluation of all PIs during the time available in the CEMSAC meeting, but we certainly found extremely high activities of each PI. In order not to be too lengthy in this report, we give a short summary and comments on each PI in the separate PI evaluation sheets.

4-(2) International standards

The research results of all the PIs meet international standards, and moreover most of PIs have achieved important and seminal researches, as world leaders. As mentioned above, AC members attended the presentations for research activities given by all the PIs at the CEMSAC meeting and found that their achievements are extremely high, as judged from a number of the research results of high impact. In particular, we would like to note that many of researches are very creative in pioneering new fields and most of such successful results have been brought about by interdisciplinary collaboration among different groups/divisions, by many theory-experiments exchanges as well as international collaborations. Some examples of remarkable achievements expected in the near future include skyrmion dynamics, new inductors, and topological shift currents, etc.

4-(3) Capability on the laboratory management, including their efforts to support early-career researchers.

Most of PIs have suitable capability on the laboratory management with their effort to support early-career researchers. Each PI provides a good platform to train young researchers. Actually, according to Questionnaires on PI's management given by laboratory staff members, more than 80% of staff members highly evaluate PI's management. We had an occasion to discuss with young researchers, and heard from them that most of PIs are providing a good atmosphere so that early-career researchers can perform their high-quality research. Most of them are satisfied with the atmosphere provided by CEMS.

CEMS has many senior researchers who are working at leading positions in the academic societies. It is a great attraction for young researchers to be able to study together with them and receive advices from them. We understand that CEMS has an important mission as an institution to conduct excellent basic research to train and foster young researchers who will lead the next generation. Colloquium, research camp, topical meeting, international symposium/workshop, etc. have been already established to execute the above mission, but we would like them to be further promoted.

Here is feedback from the discussion with young researchers held during the meeting:

<u>On the very positive side:</u>

(1) Travelling is very generous. (2) All the meetings are in English–very much appreciated. (3) The administrative staff including secretaries is very helpful with foreigners.

<u>Where improvements can be made:</u>

(1) No technician: no help on the IT side (2) Maybe some meetings are too "big" (3) Research

camp is great – maybe, for the program, more talks given by young people (4) Japanese courses 1 & 2 for foreigners – excellent but too short and nothing after this – no follow up.

About future positions:

Young researchers are quite satisfied with their current situation. Most of them are aiming at academic positions, but for some researchers we could not feel their ambition to get a position in the near future.

5. CEMS original Term of Reference: Advices to CEMS

For RIKEN to promote scientific developments in physical and materials sciences from a long-term perspective, the AC is asked to advise which directions CEMS should head for and on what subjects CEMS should lay more emphasis.

CEMSAC members have a consensus that the CEMS fourth mid-to long-term plan is very reasonable and CEMS has performed remarkably well in the past accordingly. There is excellent safety management in the Center, interdisciplinary research, extramural activities, and constant production of pioneering work in the three groups. Many if not most scientists at the Center wish that their work would have impact on society.

We strongly recommend CEMS to keep the extremely high research activities along this line and further enhance the collaboration. To this end, we suggest the following things:

(1) Further accelerate the fusion of the 3 fields, SCP, SMC and QIE.
(2) Continue to provide a platform to train early-career researchers
(3) Continue to play an important key role as a "Science and Technology Hub" and a kernel for stimulating international collaborative activities

If this activity continues along the above lines, the results will continue to be remarkable. Any large changes in directions depend upon the availability in competence and there is no reason to change personnel and inclinations during the remaining period. CEMS has presented continued activity along four directions: Energy, Soft Matter, Quantum Information, and Topological Spintronics. We encourage this plan as we see it as a direct continuation of present activity.

CEMS is now the world-leading center for the research of science and technology on quantum and topology. CEMS has a high potential in the theoretical approach to them, and its reputation overseas is also increasing. This situation should be kept. In order to apply the knowledge obtained in the three divisions of physics, chemistry, and electronics as actual materials or devices, synthesis of new materials is the key.

On the other hand, there are several points to be improved:

(1) More technical assistants who can take care of facilities may be necessary, particularly in the fields of nanofabrication, sophisticated analytical measurements and materials development.
(2) CEMS laboratories are distributed in the campus, which will sometimes prevent researchers from efficient collaborations. New one-roof building would help developing strong synergies, for example, easy sharing facilities. These points should be resolved in the future.

Here are some additional remarks/suggestions for possible other directions of interest or areas where efforts could be amplified:

(1) Ultrafast manipulations of correlated states using THz radiation is also an interesting research area.

(2) SMC Division should increase its theoretical and computational materials science efforts, as well as imaging sciences and technology. More generally the Center should continue to search for opportunities to crossbreed the topics covered in the three divisions. The theme of emergent properties should be extended to hybrid systems which are not solely organic or inorganic.

Finally, some more advices are in order below in connection with global trends in quantum technology in the world:

(1) Development of quantum technology has accelerated considerably during the last few years, particularly as American companies, China and EU have increased activities. There are not enough resources within CEMS to match these initiatives but there has to be a larger national initiative, also complemented and supported by Japanese industry, if Japan wants to remain a leading player within the market. Much of the work will be technical research and development as well as software. Within CEMS, it is recommended that the present activity is continued as it is important that alternatives and complements to the concentrated thrust programs are pursued at a basic level. In CEMS, the activity regarding quantum sensors could be increased. The performance of different sensors will be enhanced, not the least related to the bio field. There seems to be an increased need of quantum limited sensors. There should be good connections to research in quantum communication and simulation.

(2) Furthermore, devices and technologies developed in quantum computer such as high-precision of single electron and quantum correlations, time resolved detection, noise suppression method, and non-equilibrium state control by feedback are excellent tools for elucidating the physics of complex systems. In parallel with the development of quantum computer, it is highly desired to contribute fundamental physics using the above technologies.

To make effective use of quantum computers, it is important to develop compatible application software. There are not much research activities in the world. Fortunately, Q-LEAP, which promotes the research and development of quantum computers in Japan under the leadership of Prof. Nakamura, who is a CEMS PI, has gathered many excellent software researchers, and good communication and collaboration should be pursued between those software researchers and QIE researchers in CEMS. Machine learning approaches may help to develop quantum information processing. If the resource is permitted, it is crucial to establish a research unit that specially develops such application software in CEMS.

Concluding remarks:

Despite starting from scratch, CEMS, which is a very unique center having high synergy effects of physics, chemistry and quantum information, has been producing world-leading achievements one after another. It also has been fostering young talented researchers. CEMS is now a research center representing Japan in strong correlation physics, supramolecular chemistry, and quantum information electronics. It is clear that CEMS is enormously contributing to the scientific developments in Japan. We recommend CEMS to keep the extremely high research activities, and further enhance the collaboration, nurture young researchers, along the line described in RIKEN's fourth mid-to long-term plan. The termination of CEMS in 2025 is a huge loss for the Japanese scientific community. We strongly urge (RIKEN president) to take measures to continue CEMS research activities after 2025.