Report on the 4th Advisory Council
on
RIKEN Center for Emergent Matter Science (CEMS)

Foreword

The fourth Advisory Council meeting on Riken Center for Emergent Matter Science (CEMSAC) was held from May 22 to 24, 2023 at the RIKEN Wako Campus and Hotel Metropolitan Ikebukuro. The mission of CEMSAC is designated by the three terms of reference: evaluation of the CEMS response to the recommendations of the previous CEMSAC held in 2019, evaluation of the activities of CEMS since the previous CEMSAC, and evaluation and recommendations for the future plans of CEMS. During the meeting, representative members of the three CEMS research divisions, Strong Correlation Physics Division, Supramolecular Chemistry Division, and Quantum Information Electronics Division, presented their research activities. The Advisory Council also had an opportunity to exchange opinions with early-career researchers on the research environment of CEMS. An overview of RIKEN was given by the executive director Kohei Miyazono. The director of CEMS, Yoshinori Tokura, explained current research activities, responses to the 2019 CEMSAC recommendations, self-analysis of the operations and R&D activities for the 4th Mid- to Long-Term Plan period (FY2018–2024), and the future plan for the 5th Mid- to Long-Term Plan period (FY2025-2031). Based on all the information, the Advisory Council submits the report, responding to each of the three terms of reference.

Members of the CEMS2023

Masashi Takigawa, *Professor Emeritus, Institute for Solid State Physics, University of Tokyo* (chair)

Norio Kawakami, *Professor Emeritus, Graduate School of Science, Kyoto University*

Jean-Marc Triscone, *Professor, Department of Quantum Matter Physics, University of Geneva*

Allan H, MacDonald, *Professor, Department of Physics, University of Texas at Austin*

Samuel I. Stupp, *Professor, Departments of Chemistry, Materials Science and Engineering, Medicine, and Biomedical Engineering, and Director, Simpson Querrey Institute for BioNanotechnology, Northwestern University*

Hatsumi Mori, *Professor, Institute for Solid State Physics, University of Tokyo, and Vice President, University of Tokyo*

Jun'ichi Sone, *Executive Vice President Emeritus, National Institute for Materials Science*

Kensuke Kobayashi, *Professor, Department of Physics, University of Tokyo*

1. Responses to the 2019 AC recommendations

Evaluate the responses to the 2019 AC recommendations.

The CEMSAC2019 made eight recommendations. Their recommendations, the responses of CEMS, and the comments from CEMSAC2023 are shown in the following.

1-1. Further accelerate the fusion of the 3 research divisions.

CEMS response: *Three research divisions have been accelerating collaboration mainly in Theme 1,* *Emergent Energy Functions, and Theme 4, Topological Spintronics. The research on shift-current photovoltaic effect in molecular systems and two-dimensional semiconductors has been carried out under a collaboration of Supramolecular Chemistry Division and Strong Correlation Division. Quantum Information Electronics Division and Strong Correlation Physics Division have been dealing with the research on topological spintronics. For example, Quantum Information Electronics Division has demonstrated an application of magnetic skyrmions to a physical reservoir computing.*

Comments from AC: As summarized in the CEMS response, there have been high-quality research achievements due to the collaborations between different divisions. We recommend that CEMS continue and even enhance such efficient inter-division collaborations. Based on our discussions with early-carrier researchers, we find that communications between the Supramolecular Chemistry Division and the other two Divisions should be further facilitated to accelerate deep collaborations between the 3 divisions.

1-2. Continue to provide a platform to train early-career researchers.

CEMS response: *The center has continued to nurture early career researchers. Since 2019, promotions have been awarded to 4 Professors, 7 Associate Professors and 2 Lecturers.*

Comments from AC: It is remarkable that quite a few early-career researchers have been promoted to higher positions. We hope that CEMS will continue to employ this mechanism to nurture early-career researchers.

1-3. Continue to play an important key role as a "Science and Technology Hub" and a kernel for stimulating international collaborative activities.

CEMS response: *As a whole, the domestic and international collaborative activities of the Center were restricted much from 2020 to 2022 by the COVID-19 pandemic. Collaborative activities with Tsinghua University and Kavli Institute for Theoretical Sciences as well as international workshops were continued online. The ratio of foreign researchers is 31%, considerably higher than the RIKEN average. Collaboration with ISSP, University of Tokyo have been enhanced, resulting in an increase in the number of coauthored papers. Regarding collaborative activities with industry, the Center continues collaboration with NEC, intel, TGI, Sumitomo Chemical, Rohm, Hitachi, Nissan Chemical, Nikon, and Nippon Kayaku. In particular, RIKEN has just established a new research team "Correlated materials-based ecological-device research team" based on the Center's joint activity with a private company Sumitomo Chemical.*

Comments from AC: Serious problems caused by COVID-19 have made it difficult for the CEMS to play a key role as a Science and Technology Hub. Nevertheless, we recognize successful efforts for conducting online international activities, and also for continuing the collaborations with a number of domestic institutes and industries. The rather high ratio 31% of foreign researchers surely exemplifies the high international activity of the CEMS. Now that the situation regarding COVID-19 has become much better, we expect CEMS to play an important role for the Science and Technology Hub again.

1-4. More technical assistants who can take care of facilities may be necessary.

CEMS response: *The Center fully recognizes the importance of the support by technical assistants. The Center continues to improve the treatment of technical assistants; promotion, longer contract period, and salary increase. Some finite-termed technical assistants have also been newly employed. Moreover, a new team "Semiconductor Science Research Support Team", led by Dr. Fumihiro Matsukura, has been newly established. This team and "Materials Characterization Support Team" (Hashizume TL) take responsibility for supporting activity of other groups/teams.*

Comments from AC: We evaluate the attempts of the CEMS to improve the treatment of the technical assistants highly. The newly established Semiconductor Science Research Support Team as well as Materials Characterization Support Team will certainly be helpful for performing the high-quality research.

1-5. New one-roof building would help developing strong synergies.

CEMS response: *Although a one-roof building of the Center was not realized, nine rooms in the main building have been newly assigned to the Center. As a result, most of the researchers now gather in the Main Building or Frontier Research Laboratory. A building dedicated to clean rooms is now planned for* *completion in March 2028, which will be useful for the Center's experimental activity.*

Comments from AC: It is not easy to realize a one-roof building in a short term. Nevertheless, we think that the condition for this issue has been improved to some extent since 2019 because most of the researchers gather in the same building now. Also, a newly planned building for clean rooms will surely activate the experimental research.

1-6. Ultrafast manipulations of correlated states using THz radiation is also an interesting research area.

CEMS response: *The Center completely agrees with the recommendation. Ultrafast manipulations of states using THz radiation are becoming of great importance from both scientific and technological points of view. The Center is now working on THz-radiation control of electric polarization and magnetization.*

Comments from AC: We understand that research on ultrafast manipulations of states is on-going and that CEMS is planning to enhance this activity in the future. We expect fruitful results using THz-radiation control of electric polarization and magnetization.

1-7. Supramolecular Chemistry Division should increase its theoretical and computational materials science efforts, as well as imaging sciences and technology.

CEMS response: *Efforts in the theoretical and computational approaches have been made by collaboration with several groups which have specialized computational/theoretical methodologies. For example,*

1) N. Uchida, A. Kohata, K. Okuro, A. Cardellini, C. Lionello, E. A. Zizzi, M. A. Deriu, G. M. Pavan, M. Tomishige, T. Hikima, T. Aida, Nat. Commun. 2022, 13, 5424.

Simple computational works have been carried out also by ourselves thanks to some useful computational packages. For example,

2) X. Wang, Z. Li, S. Wang, K. Sano, Z. Sun, Z. Shao, A. Takeish, S. Matsubara, D. Okumura, N. Sakai, T. Sasaki, T. Aida, Y. Ishida, Science 2023, 380, 192.

For imaging science and technology, Dr. Daisuke Hashizume, Team Leader of Materials Characterization Support Team, has developed sophisticated techniques for visualization by transmission electron microscopy (TEM), which enables visualization of mechanically soft organic and polymeric materials.

Comments from AC: We positively recognize the efforts made for the theoretical and computational approaches within the division as well as by collaboration with other theoretical groups. Concerning the imaging science and technology, it is good to hear that Dr. Hashizume has developed sophisticated techniques for visualization by transmission electron microscopy, which will be helpful for conducting high-level research not only in the Supramolecular Chemistry Division but also in the other divisions.

1-8. Quantum Information Electronics Division should continue the present activity as it is important that alternatives and complements to the concentrated thrust programs are pursued at a basic level.

CEMS response: *RIKEN has established the new center, RIKEN Center for Quantum Computing (RQC), from a branch of Quantum Information Electronics Division in April 2021. RQC pursues mainstream and promising approaches to the development of quantum computers. Even after its establishment, CEMS has continued research on novel quantum information electronic systems at the basic level that is complementary to the mainstream approaches of RQC.*

Comments from AC: It is good news that RIKEN has spun off the new center for quantum computing, RQC, from a branch of Quantum Information Electronics Division of the CEMS, which will enhance the RIKEN research activity for quantum computers. Fruitful collaborations between the CEMS and the RQC will be highly appreciated.

2. Evaluations of the CEMS activities for the 4th Mid- to Long-Term Plan period

Based on the results of the Center's self-analysis, evaluate operations and R&D activities *for the 4th Mid- to Long-Term Plan period (FY2018-2024).*

Summary of the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis presented by the Director Yoshinori Tokura is shown below. The Advisory Council makes comments on each point raised by CEMS.

Strengths (internal / positive)

- Conducting high level researches in 3 divisions
- Center director's strong initiative to promote synergy among the divisions
- Various activities to promote interactions within CEMS (Research Camp, Topical Meeting, weekly research discussion etc.)
- Nurturing young researchers by cooperating with universities (student trainees, QPEC ULs, Tsinghua ULs)
- High ratio of international researchers (currently about 31 % in CEMS)

Weaknesses (internal / negative)

- Difficulty in recruiting female researchers (currently about 13 % in CEMS)

Opportunities (external / positive)

- Able to play a central role in national projects of Quantum Technology Innovation

Threats (external / negative)

- Worldwide helium/neon shortage
- Activity restriction due to COVID-19 pandemic
- Weak Yen making difficult to recruit foreign researchers

2-A Strength (Internal/positive)

2-A-1 Conducting high level research in three divisions

The Advisory Council was impressed by the outstanding quality and diversity of research conducted in CEMS. The greatest strength of CEMS is the creativity and depth of its scientific staff, chosen with insight and care to perform cutting edge impactful science. Some of the research accomplishments demonstrate novel ideas of condensed matter science, while others have strong potential for a future sustainable society. In the following, research highlights in the three divisions are discussed.

I. Strong Correlation Physics Division

It is important to recognize, first of all, that CEMS is producing outstanding materials and unique thin film structures thanks to their excellent in-house facilities. On the thin film side, advanced deposition techniques such as oxide molecular beam epitaxy or pulsed laser deposition allow very complex structures to be realized. Examples include sophisticated topological insulators and oxide heterostructures. One should also note the strong ties between groups working on synthesis of bulk new materials and single crystals and those on thin film growth / nano-fabrication, which is a unique strength of CEMS. Some prominent accomplishments are reviewed below with the names of involved PIs in the parentheses.

A new nanoscale inductor concept has been implemented in helical spin system compounds. The inductance comes from the energy stored in spin canting induced by the charge current. The inductance is proportional to the current density (and thus inversely proportional to the film cross-section for a given current), making it possible to realize very small inductors. The size of such inductors could potentially be 10^6 times smaller than standard ones. A material that would display the desired properties at room temperature was identified, YMn_6Sn_6. This discovery has the potential to be a game changer for electronics. Some problems have to be solved however. One of them is the limited frequency range over which a large inductance is obtained (typically below 10^5 Hz). The Advisory Council thinks that these developments are extremely important and it clearly encourages and supports further studies that may allow this new device to find its way to the market. (Tokura, Nagaosa, Otani, Kagawa)

A "new" approach to convert light into electrical energy, light induced shift (geometrical) currents, is under study. The idea is that light, which induces a charge transfer from the valence band to the conduction band of a weakly conducting semiconductor with *broken inversion symmetry*, will induce a second order rectified dc current that can be collected. Excitations even below the band gap can lead to shift currents. Experiments on non-centrosymmetric materials and doped ferroelectrics (SbSI and CdS, CuI crystals and $BaTiO_3$ films) revealed an efficiency, at this point, of up to 1%. Although this might seem low compared to conventional solar cells (typically 20% efficiency), the Advisory Council thinks that these results are in fact very encouraging since shift currents can in principle lead to a very large efficiency of up to 80% and do not have the open circuit voltage limitations of conventional solar cells. The Advisory Council encourages the CEMS teams to continue exploring this interesting, exciting and promising research area (Nagaosa, Kawasaki, Ogawa, Tokura, Takahashi).

The "ab-initio calculations" group reported on a series of interesting and exciting results including electronic and phonon structure calculations on different nickelates (including the infinite layer one that recently revealed superconductivity) and palladates allowing design of new compounds or artificial materials. For the palladates, high T_c superconductivity is predicted. Still on superconductivity, an ab-initio search for high T_c ternary hydride has been realized. Also, a broad investigation – high throughput - of new magnetic materials was carried out with thousands of compounds investigated that led to the discovery and study of, for instance, Fe_3Al and Fe_3Ga with large anomalous Nernst effect. A database was created. Finally, one can mention the approach developed to allow finite temperature structure optimization to be obtained with ab-initio calculations. (Arita)

Some activities on skyrmions were also presented. Among them very short period skyrmion lattices were obtained in RET_2X_2 compounds (RE = rare earth, T = 3d, 4d, 5d transition metals, Y = Si or Ge) with a very small skyrmion size of 1.9nm. These tiny skyrmions could be directly observed using the unique resolution of the low temperature Scanning Transmission Electron Microscopy (STEM) equipment allowing 8K to be reached. Also the motion and dynamics of skyrmions at low temperature generated by a very small thermal gradient (50mK/mm) could be observed using STEM - demonstrating the promising mobility of such skyrmions at low temperature. The Advisory Council wants to underline the quality and uniqueness of these low temperature STEM investigations - very key for understanding the physics of skyrmions. (Yu, Taguchi, Tokura, Furukawa, Kagawa, Arima)

The Advisory Council was also impressed by the demonstration of a giant magnetic "switching" of Second Harmonic Generation (SHG). SHG being generated or not when crossing a multiferroic material ($Eu_2MnSi_2O_7$) depending on the orientation of the magnetization of the material. (Ogawa)

Giant nonreciprocal transport was reported both in magnetic topological insulators and in superconductors. Still on superconductors, a superconducting diode effect was reported in Nb/Ta/V structures and in van der Waals heterostructures. (Tokura, Nagaosa, Iwasa)

Using $SrVO_3$, a cubic undistorted d^1 t_{2g} metal, the fabrication of heterostructures made of $SrVO_3$ and $SrTiO_3$ allowed the $SrVO_3$ thickness to be reduced and quantum wells to be realized. When very thin, $SrVO_3$ becomes a 2-dimensional Mott insulator for which metallicity can be restored by doping - moving the system away from ½ filling. This model system may show a path to explore the physics of doped (t_{2g}) transition metal oxide Mott insulators – an exciting route to possibly discover new superconducting systems. (Kawasaki)

II. Supramolecular Chemistry Division

The Supramolecular Chemistry Division (SMC) under the leadership of Professor Takuzo Aida continued to excel with outstanding scientific output since the last review of CEMS in 2019. The Division has maintained its size with 11 PIs (10 team leaders and one unit leader), and research activities have resulted in high impact publications across a broad range of subjects within supramolecular science. Supramolecular systems, ubiquitous in nature and enabling life processes, have natural potential to generate emergent soft matter since their structures and functions are the result of interactions among large populations of molecules. The SMC at Riken has the great advantage that some of its members have competency in molecular design and organic synthesis and are therefore able to access novel systems that lead to discoveries. The Division's leader Professor Takuzo Aida is widely recognized by the international community as one of the leaders of the field, and his prominence will continue to benefit this program at Riken, not only because of his own scientific achievements but also by attracting young researchers to the Wako campus. Over the past four years Aida has reported two impressive breakthroughs, one of them published in *Science* reported on fluorinated supramolecular systems that contain nanochannels with the surprising capacity to break the hydrogen bonds among clustered water molecules. The consequence is the conversion of liquid water flowing through the nanochannels to a gas phase resulting in extremely fast water transport. The fluorinated channels also have the ability to exclude anions and so these systems may eventually have an impact on the important sustainability problem of water desalination. A second breakthrough by Aida published in *Nature Materials* reported on the first example of a solvent free supramolecular polymerization which is also of great consequence to a sustainable future due to the negative environmental impact of organic solvents on industrial scales. This prototype reaction to create supramolecular polymers has great environmental implications, and it is a great demonstration that simple heating of a monomer in the absence of a solvent can create soft materials.

As mentioned earlier, one of the great competencies within SMC is the presence of groups which can undertake challenging synthetic projects and during the last 4 years great examples of this possibility are exemplified in new work by Takimiya and Tajima. Takimiya in the Emergent Molecular Function Research Team has made great progress in designing self-ordering organic molecules to afford organic semiconductor with higher dimensionality and stronger molecular interaction, resulting in ultrahigh mobility. Moreover, the developed high-performance n-type semiconductor exhibits significant thermoelectric properties as a result of designed molecular orientation. The Advisory Council also heard a presentation from Tajima from the Emergent Functional Polymers Research Team reporting on zig-zag shape electron accepting molecules, which are of interest in photovoltaics to gain versatility in molecular orientation control when building solar cells. The innovative design of these molecules results in reasonable power conversion efficiencies for fully organic solar cells, which may still be important in certain niches where the now popular perovskites are not practical because of their limited chemical stability. Other systems described by Tajima are interesting as materials with residual polarization and therefore surface potential. Here again the great ability in Tajima's group to synthesize novel molecules is a major advantage in their work on emergent polymers. A third topic in Tajima's laboratory of great interest in searching emergent properties is the design of organic molecules for magnetoresistance properties, an area that may contribute to important leads in novel organic electronics or even spintronics.

A definite highlight reported to the Advisory Council by the SMC was the paper by the Ishida group working on Emergent Bio-inspired Soft Matter. This highly innovative research was published very recently in *Science* (2023) reporting on the first example of a mechanically polar material which has potential to direct directional motion of objects as one expects to see in biological systems. In this work a material attached on one surface to a substrate, which contains graphene oxide sheets aligned macroscopically along a specific inclined direction and dispersed in a polyacrylamide hydrogel, exhibits an elastic modulus which is 60 times higher when sheared in one direction vs. the opposite direction. Thus this polar behavior could give rise to mechanical nonreciprocity, meaning that it could guide the asymmetric transmission of mechanical quantities between two points. Even though it is early to judge the functional significance of the discovery, there is no question that it is an extremely interesting and significant observation that may have impact in the development of robotic materials that transduce energy. In the spirit of emergent behavior, Ishida's earlier work on orientable 2D materials has been obviously a very good precursor to this surprising discovery.

Since CEMSAC2019, Iwasa has continued to do excellent research at the interface of inorganic and organic materials but most importantly on the spontaneous photovoltaic effect (*Science* 2021), related to his earlier discoveries in 2019 of shift currents in non-centrosymmetric solids. On the engineering side the Someya and Ito teams continued to produce important work on flexible electronics and bioengineering applications, respectively. Ito's work also covers systems for electrocatalysis for hydrogen evolution. It would be beneficial to try and connect better the engineering oriented work with some of the fundamental advances being made in basic science in other groups of the SMC. The materials characterization support team by Hashizume, who became the team leader in 2018, continues to play an important role in research progress at the SMC. His work on high resolution analysis using x-ray diffraction is very important and he reported in 2021 the interesting discovery of a carbon-carbon bond greater than 2.04 angstroms between two fluorenyl rings, which is beyond the theoretical limit.

From the Physicochemical Soft Matter Research Team led by Araoka, who became the team leader in 2018 from the unit leader, the Council heard a report on their work on exotic liquid crystals such as ferroelectric nematic fluids, ferroelectric chiral nematics, and dynamic nematic solitons. Progress on ferroelectric nematic fluids has been significant with publications in *Advanced Materials* and *Nature Communications* in 2021 and 2022, respectively. The nematic fluids have interesting properties which include giant dielectric permittivity and very large polarization, exceeding 4μC/cm^2, and very low driving voltage given their fluid nature. There was also a report from the team on photo-tunable properties in these systems by incorporating light responsive molecules, which has great potential for function, for example for photo-tunable dielectric permittivity (capacitors). The supramolecular structure details in these systems are still not clear, and will require further experiments but the systems are definitely interesting and the research worth pursuing.

Two other important achievements in SMC Division were reported by Pu and Sato. Pu discussed the surprising discovery of an aromatic and fluorinated fluorescent molecule that disobeys Hund's rule and has a negative singlet-triplet energy gap (*Nature* 2022), a finding that could have implications for innovation in optoelectronic devices for lighting, displays and lasers. Pu also reported on the role of selectively removed organic ligands to control the colloidal superlattices formed by PbS quantum dots. Finally, Sato from the Emergent Molecular Assembly Research Unit reported on interesting findings related to porous crystals. The main achievement was published in an article in *Nature* 2021 describing the use of mechanically bonded systems (catenanes) to assemble metal organic frameworks (MOFs). These systems exhibit unexpected low modulus of elasticity relative to the conventional rigid networks formed by MOFs, which is reasonable given their greater dynamic capabilities and deformability enabled by mechanical bonds. This approach to reticular chemistry could provide MOFs more functionality by facilitating selective uptake and release of guest molecules, which has been highlighted as one of the main capabilities of these supramolecular systems. Other ongoing work in the unit is currently exploring the design of photothermal pumping in porous crystals using near infrared radiation by incorporating photo-responsive units that undergo cis-trans isomerization.

Overall the achievements of the SMC Division have been outstanding, producing solid science in the field of emergent systems reported in high impact publications. The findings reported by members of the Division have certainly potential to generate novel functionality in soft materials. Members of the Division should be commended for their efforts since 2019 and also for the great translational prospects of their achievements.

III. Quantum Information Electronics Division

The Quantum Information Electronics Division lead by Prof. Seigo Tarucha has produced multiple outstanding results of world-class quality. Below we highlight some representative accomplishments for the experimental and theoretical groups.

[Quantum Functional System Research Group] The study of single spin dynamics is an essential technological element for quantum computers. Tarucha showed that 2 qubits were successfully used to achieve high-precision universal operation, which was achieved by speeding up the quantum control by a factor of 10. This has led to universal quantum operation with more than 99% fidelity. Furthermore, based on the results, quantum error correction was demonstrated using three qubits. These two works are outstanding achievements that will serve as a basis for the future development of scalable silicon quantum computers based on semiconductor spins. In addition, the study in which coherence was extended by detecting spin noise and providing real-time feedback is technically exciting. Besides, shuttling of qubits is studied as a critical elemental technology for realizing quantum links.

Several studies on Josephson junctions were presented: realizing the coherent-coupled junctions and the Josephson diode effect are excellent results in a world of active competition.

[Quantum Electron Device Research Team] Yamamoto reported the first measurement of the size of many-body wave functions formed by the Kondo effect by skillfully controlling quantum dots. This achievement is an outstanding contribution to fundamental physics. A new type of quantum computer using flying qubits is being explored. This scheme is an electronic version of the optical quantum computer. This direction is compatible with electronic technology and offers new possibilities.

[Quantum Effect Device Research Team] Studies of 1D topological superconducting states and the search for Majorana zero modes, aiming at topologically protected robust quantum computing, were carried out in Ishibashi team. Gate-controlled Josephson junctions were realized with a monolayer 2D topological Insulator, WTe_2. Clear Shapiro steps were observed, but no Majorana signature has been found so far. Semiconductor InAs nanowires with superconducting contacts were also realized, and Andreev-bound states were detected. These are encouraging results for future quantum computer applications.

[Quantum Nano-Scale Magnetism Research Team] Spin conversion refers to a variety of interesting spin transfer phenomena between electrons, photons, sound vibrations, and heat at the nanoscale, and is a central concept in spintronics. Thes Riken group lead by Otani is a world leader in antiferromagnetic spintronics and in particular in the study of materials like Mn_3Sn that are antiferromagnetic but nevertheless have an anomalous Hall effect. In recent work the group has made further progress in exploring the spin conversion properties of Mn_3Sn and in other materials. Notably the group has explored chirality-induced spin selectivity, a new topic at the interface of physics and chemistry with many open questions, which is being studied within CEMS as a joint research project between the nanomagnetism (Kondou) and chemistry groups (Miyajima and Araoka). This is an excellent collaboration topic for CEMS. The demonstration of magnetoresistance induced by simply attaching a chiral molecule to a surface is remarkable, as it could be a seed for a new chapter in spintronics. The notion of orbital angular momentum transfer is a cutting edge and still controversial idea in spintronics that is also being studied. Research on magnon-phonon coupling is in the classical regime but is the foundation for future quantum hybrids. Research using not only conventional magnetic materials but also two-dimensional antiferromagnetic materials is also promising for the future. Neuromorphic computing using skyrmions is an exceptional achievement. Nonlinearities induced by interaction among skyrmions make reservoir computing possible. Experimental handwritten-digit recognition demonstrates that the skyrmion system is a promising candidate for neuromorphic computing.

[Emergent Phenomena Observation Technology Research Team] An excellent research result on the stable skyrmion lattice in FeGe nanoparticles was achieved through collaboration within CEMS by Shindo in collaboration with Tokura group, Nagaosa group, Yu team.

[Semiconductor Science Research Support Team] Very recently, CEMS welcomed a researcher, Matsukura, from Tohoku University as the team leader of the Semiconductor Science Research Support Team. Acquiring such a highly experienced researcher in semiconductor physics directly strengthens CEMS' research capabilities.

The Quantum Information Electronics Division is active in theoretical research as well as the experimental research described above.

[Quantum System Theory Research Team] In Loss team, theoretical studies are being conducted on various aspects, such as helical liquid realization in topological materials, topological protection, and possible experimental characterization. In particular, a remarkable theory was developed for topological quantum calculations using the Majorana bound states, focusing on proximity-induced topological superconductivity. The approach also supports experimental quantum computing studies conducted in the Division.

[Quantum Condensate Research Team] Ultra-cold atomic gas is an ideal artificial quantum system in which almost all parameters characterizing the system can be controlled with high precision. In Ueda team, excellent theoretical studies on topological excitations in Bose-Einstein condensates have been performed on such systems. Several studies on non-equilibrium dynamics with Floquet states have been remarkably carried out. A new learning algorithm has been devised using restricted Boltzmann machines to take advantage of faithful parameter updates throughout the learning process while keeping the computational overhead as small as possible. This is an excellent research result.

[Spin Physics Theory Research Team] Tatara actively studies the microscopic theory of spin transport, which involves fundamental issues in the statistical physics of collective degrees of freedoms in solids. Recently considerable progress has been made on the hydrodynamic theory of electron and spin transport, on the spin-vorticity theory of the spin Hall effect, and on spin-wave emission theory.

2-A-2 Center director's strong initiative to promote synergy among divisions

Aiming at fusion of fields pursued by the three research divisions, CEMS has been promoting four synergetic cooperation projects, Emergent Energy Functions, Emergent Functional Soft Matter, Quantum Information and Electronic Technology, and Topological Spintronics. These projects are expected to advance technologies for ultra-low energy cost electronics and environment-conscious high-efficiency energy harvesting/transformation/storage; both will be essential elements for the future sustainable society. There have already been notable examples of synergy effects but further developments should be certainly encouraged as described below.

I. Ultra-low energy cost electronics

I-1. Quantum Information and Electronic Technology

Some synergies originating from the activities of the Quantum Information Electronics Division have already been observed. An excellent example is the work done with the Supramolecular Chemistry Division on chirality-induced spin selectivity. The ability to induce magnetoresistance simply by attaching a chiral molecule to a surface will be a seed for spintronics in the future. Developing topologically protected robust quantum computation is vital for fault-tolerant quantum computation. Such directions need unique new materials. CEMS, which has produced various materials, has the strong potential to promote such synergy research further.

Also importantly, the Division has several theoretical groups that continue to produce significant results on various quantum science and technology topics, including topological quantum computation, nonequilibrium quantum systems, machine learning, and spin dynamics. These activities will naturally seed synergies between the divisions in CEMS.

I-2. Topological Spintronics

CEMS has continued to break new ground in different aspects of topological spintronics. A recent publication in Advanced Materials described the observation of a new type of topologically non-trivial magnetic texture in three space dimensions dubbed a Hopfion. A Hopfion has a non-trival Hopf index, which is defined in terms of the position dependence of the magnetization direction. This study demonstrated that these exotic textures have complex novel electromagnetic properties and further enriched the study of current-driven manipulation of magnetic textures. A separate study broke new ground in momentum space topological matter by explicitly demonstrating a charge pumping effect in Corbino geometry topological insulator thin film with surface magnetization. Corbino geometry refers to a disk with a hole in its center. Charge pumping was measured by applying an alternating magnetic field which drives a small alternating current in an external circuit driven by flow between inner and outer Corbino edges. Detection of the current requires a sophisticated measurement design. The charge pumping effect occurs when the magnetizations on the top and bottom surfaces of the TI thin film are parallel, so that the TI is in a quantum anomalous Hall insulator state. The successful completion of this project points to strategies to observe the topological magnetoelectric effect, a defining characteristic property of topological insulators that has heretofore escaped demonstration.

II. Environment-conscious high efficiency energy harvesting/ transformation/ storage

II-1. Emergent Energy Functions

On emergent energy functions, collaborations can be foreseen between the strong correlation physics division and the supramolecular chemistry division.

Obvious collaborations can develop on the study and development of the “shift current approach” allowing solar to electric energy conversion to be achieved. Shift currents have been observed using several materials studied by the strong correlation physics division and also on some of the compounds studied by the supramolecular chemistry division. Since this phenomenon that requires a material with a breaking of inversion symmetry – semiconducting – is still poorly understood, there is a lot of space for further studies and improvement. On the material side, the ideal material to observe large shift currents has not yet been determined and so investigations of this promising phenomenon on different classes of materials are required and strongly supported by the Advisory Council.

Another obvious collaboration could develop on the study of thermoelectric materials. The supramolecular chemistry division reported on the discovery of a new n-type polymer semiconductor with high thermoelectric performance. Since p- and n-type semiconductors are needed to realize thermoelectric devices - and n-type are very seldom - this discovery may allow interesting thermoelectric systems to be realized. There, the experience of the physics group will be important to help characterizing in detail these new thermoelectric materials and systems.

Another collaboration should allow the ferroelectric fluids developed in the supramolecular chemistry division to be studied in detail. In particular, a very large dielectric constant (around 10’000) has been reported, essentially constant over a large temperature range. This is rather unusual and potentially very interesting for some applications. The physics group expertise on ferroelectrics will certainly be important here to better understand the behavior and the physics of these interesting new materials.

Photovoltaic applications and solar cells using the newly developed materials presented by the supramolecular chemistry division should be further studied and explored in collaboration between the physics and chemistry divisions.

II-2. Emergent Functional Soft Matter

Several synergetic activities were performed between Supramolecular Chemistry Division and others. For example, molecular chirality-induced magnetoresistance due to thermally driven spin polarization was successfully discovered as a novel molecular spintronics device [J. Am. Chem. Soc. (2022) by Otani, Araoka teams, and Miyajima unit]. As another one, the gate-controlled BCS (Bardeen-Cooper-Schrieffer) -BEC (Bose-Einstein condensation) crossover in a two-dimensional superconductor was demonstrated by varying carrier density with intercalated Li ion to the insulating material zirconium nitride chloride. [Science (2021) by Iwasa and Arita teams]

2-A-3 Various activities to promote interactions within CEMS

The Advisory Council acknowledges efforts of CEMS leadership to keep interdisciplinary activities such as colloquium, research camps, topical meetings and workshops. Also, as mentioned in the previous section, outstanding achievements have emerged from interdivision collaborations. Such interactions should be further extended and shared with more researchers on a regular basis. The Advisory Council would like to emphasize that early-career researchers should play active roles in the interdivision interactions. In the conversation with the Advisory Council, early-career researchers expressed concerns on insufficient opportunities to know what is going on in different divisions. In fact, there are many fascinating issues in the boundaries between different divisions, photovoltaic and thermoelectric effects in organic materials, ferroelectric fluids, emergent inductors, to name a few, which can be solved efficiently only by a collaboration of different expertise. It would be a valuable experience for early-career researchers to find a challenging problem and organize collaboration based on their spontaneous interaction. The CEMS leadership is advised to provide appropriate schemes for sharing information and supervise their collaborations.

2-A-4 Nurturing young researches by cooperating with universities

The Advisory Council commends the Cross-Divisional Materials Research Program as an extremely efficient vehicle for promoting talented young researchers to become independent and helping them launch their own laboratories. As the stability of employment and foreseeable career path are currently matters of serious concern in academic society of Japan as a whole, it is important to keep operating this program as a successful model. The Advisory Council encourages CEMS to further extend such cooperation with universities to other institutions, especially outside Japan. This will also allow frequent and long-term exchange of junior researchers, responding to their request as mentioned below.

During the Council meeting with junior investigators it became clear that they are highly aware of the great opportunity that CEMS provides by granting them a unique opportunity to pursue scientific research without the burden of administrative and educational duties. Thus the research environment is perceived as being nearly ideal in terms of having the freedom to focus on research. There seems to be concerns about salaries not keeping up with other places in the world, including China, and also the need for CEMS to provide more support in helping them craft their future careers.

One of the concerns voiced during the meeting was the lack of efficient support to secure patent protection for intellectual property developed at Riken. There is not sufficient proactive communication with administrators in charge of securing patents, at least that seems to be the perception of young investigators. Obviously this is important since being associated with patents is important for young people to deploy their professional careers and naturally should be of interest to Riken as well.

An additional concern is the fact that young investigators at Riken do not have sufficient opportunity to meet each other and consequently have a supportive ecosystem. There must be some special effort from the administration to facilitate this process. The problem seems to be especially serious between physics and chemistry investigators as well as foreign investigators who have the additional obstacle of a language barrier.

It was suggested during this meeting that young investigators would like to see more support from Riken in facilitating opportunities for exchange programs with investigators outside Japan. This may be a specific effort that CEMS could pioneer given the great science being developed at the Center and potential interest abroad in exchanges with laboratories around the world.

2-A-5 High ratio of international researchers

The Advisory Council commends the high ratio (31%) of international researchers. Obviously, this is a direct consequence of the very high international visibility of CEMS owing to the outstanding research activities that attract talented junior researchers worldwide. As some of the foreign researchers will launch their own laboratories in various countries in future, they will be a valuable asset for CEMS in building an extensive network of international collaboration.

2-B Weakness (internal/negative)

Difficulty in recruiting female researchers

The ratio of female researchers in CEMS is low (13%) compared with the average (31%) of RIKEN. As the ratio of female students is quite low in physics-related departments in Japanese universities, this is a common issue for the condensed matter science community as a whole. Importance of gender diversity cannot be overemphasized for sustainable development in any research organization. Besides the countermeasures proposed by RIKEN, it will be important for the CEMS administration to keep closer communication on the working environment for female researchers and make improvements if necessary, including, for example, time management of various meetings. In the conversation with early-career researchers, the Advisory Council noticed that some female researchers were not informed well about working rules such as maternity leave, which are important for planning life events. The RIKEN administration is advised to make efforts to disseminate information on benefit and take requests from female researchers. Also networking e.g. by means of lunch meeting among female researchers and graduate students will be effective for information exchange. A better working environment will attract active young scientists regardless of gender, which in turn will make it easier to improve the environment. Hopefully this positive spiral will work in future.

2-C Opportunities (external/positive)

Able to play a central role in national projects of Quantum Technology Innovations

RIKEN is expected to play a significant role as a center for developing quantum computers in Japan. The decision to spin off RQC from CEMS in 2021 was strategically sound. While RQC will focus on near-term research and development, especially for superconducting qubits, CEMS will pursue various other possibilities, which makes sense. The current structure of CEMS ensures the long-term vision and diversity required for the development of quantum technology. Here, we would like to note that the road to the realization of quantum computing is not an easy one, and many difficult challenges, including quantum error correction, will need to be solved. In the process, new physics and new materials will likely be required. Quantum technology has the potential for new developments not only in computing technology, but also in other fields, such as sensors and communications. There are high expectations that CEMS will lead the way in such fundamental fields. In this sense, we would also like to point out that it is important for CEMS and RQC to maintain a very close cooperative relationship at the researcher level, and it is vital that such a structure continues in the future.

Very recently, CEMS hired a researcher from Tohoku University as a team leader of the Semiconductor Science Research Support Team. The acquisition of such a highly experienced researcher in the field of semiconductor physics directly strengthens the research capabilities of CEMS.

2-D Threats (external/negative)

I. *Worldwide helium/neon shortage*

Helium shortage is a common threat for all cryogenic laboratories. It seems clear that best response is to make every effort to reduce helium in the short term and to replace as many refrigerators as possible by cryogen-free equipment in the long term. Neon gas that is key to run some equipment like pulsed laser deposition systems is extremely difficult to obtain these days due to the Russia-Ukraine conflict – half of the World Neon supply was coming from Ukraine. Using other thin film deposition techniques such as sputtering or molecular beam epitaxy might be necessary as long as the Neon supply is perturbed.

II. *Activity restriction due to COVID-19 pandemic*

Almost every research institution has suffered from serious restrictions due to COVID-19 in the past three years. Fortunately, the pandemic situation appears to have calmed down, allowing us to revive normal activities. The good news is that remote communications have become far easier than before. Extensive use of improved online tools should help us achieve flexible time management and higher efficiency of research activities. At the same time, efforts must be made to reestablish the benefits of direct personal interactions, perhaps by reemphasizing the importance of attendance and active participation in technical seminars and making efforts to encourage informal lunch discussions.

III. *Weak Yen making difficult to recruit foreign researchers*

As currency exchange rates are unpredictable and uncontrollable, this is a difficult problem to respond. It may take care of itself as financial markets fluctuate. In the meantime, it will certainly help to have a flexible salary scale. In the long term, it should be important to build an active international collaborative network where mutual exchange of young researchers takes place regularly. This will increase the possibility of recruiting a future rising star. Beside the salary issue, support for the livelihood of the individuals and their families would be also important.

3. Evaluations and recommendations for the 5th Mid- to Long-Term Plan period

Evaluate the policies of the 5th Mid- to Long-Term Plan period (FY2025-2031) and recommend new directions for operations and R&D that should be implemented and promoted.

In the 5th mid- to long-term plan period, CEMS proposes to continue to focus on the four synergetic projects, Emergent Energy Functions, Emergent Functional Soft Matter, Quantum Information and Electronic Technology, and Topological Spintronics. As these projects have been very successful so far in promoting synergetic collaboration among three divisions and already produced promising seeds for future innovation, the Advisory Council is convinced that this direction is appropriate. This plan is also in accord with the TRIP concept of RIKEN to *pioneer predictive control of science of the future*, as the full use of theoretical and computational capability reinforced by data-scientific approaches must be incorporated with experimental efforts for any of these four projects. This aspect is in fact one of the prominent strengths of CEMS. The Advisory Council also acknowledges that CEMS expresses strong commitment to contribute to the future society through technological innovation. It should be emphasized that CEMS is expected to present new concepts or scientific principles that could lead to innovation rather than to work on technological details. Development of a proof-of-concept device would mark a great success. In the following, specific comments are given for each of the four projects.

I. Emergent Energy Functions

Regarding the 5th Mid-to Long-Term Plan period and more specifically emergent energy functions, the Advisory Council sees, among others, several research lines that should be pursued.

The shift current approach that has been reported is a very interesting alternative route to transform solar energy into electricity. This approach should be further studied using different materials and across the physics and chemistry divisions. It is a promising route that does not suffer in principle from some of the limitations that are found in conventional solar cells.

Photovoltaic applications and solar cells using the newly developed materials presented by the supramolecular chemistry division should be further studied and explored.

The discovery of a new n-type polymer semiconductor with high thermoelectric performance is a breakthrough that should be exploited to develop new thermoelectric systems.

The emergent inductor making use of a helical spin system compound is possibly a game changer for semiconductor technology. This new device should obviously be studied in detail and the open issues (among them the limited frequency range over which the large inductance is observed) addressed.

II. Emergent Functional Soft Matter

The Supramolecular Chemistry Division has the most direct social relevance among the three CEMS divisions. For example, the fluorinated nanochannel system that excludes anions, developed by Aida's group, could have an impact on the sustainability of seawater desalination, a key issue for the SDGs. Also, the development of a plastic that dissolves in salty water and turns into food for the marine wildlife can be a game changer and potentially solve the major world issue of plastic waste. Realizing social engagement should generate seeds for basic science from industry. At the same time, the Supramolecular Chemistry Division is perhaps the most vulnerable part of CEMS given its orthogonality to correlation physics and quantum information electronics. In this context the CEMS leadership should make a special effort to generate a hybrid of the three subjects through the integration of young investigators. In this regard there should be a very special seminar program where all young investigators present their work on a regular basis, thus giving them a chance to create new things and get to know each other.

III. Quantum Information Electronics

The development of quantum information electronics is also important as a national strategy. It is necessary to make a concerted effort while combining various cutting-edge technologies. The achievements of CEMS to date are at a high level, even from a global perspective, and hold great promise for the future. Several sub-themes have been raised. These are fault-tolerant digital quantum computers, quantum hybrid systems, quantum internet, and topological quantum technology, all of which are areas where CEMS has strong experimental/theoretical groups. Attempts to broaden the scope of research are what CEMS has done best in the past. The Advisory Council commends CEMS for developing an entirely feasible vision for the future.

At the same time, it is important for CEMS to continue to deliver messages to the society, including government and industry, about what CEMS is aiming for and what kind of impact on society CEMS tries to bring about in the future. The realization of a carbon-neutral society and a highly-advanced digital society centered on computing technology are extremely important national issues, and a large national budget is being invested in the development of technologies to solve these issues. However, these challenges are not easily achievable and require both short-term and long-term approaches from various aspects. It is important for CEMS to appeal that it is working on these issues from a long-term and creative perspective and to make an effort to receive continuous support from the government and industry.

IV. Topotronics

Skyrmionics is highly anticipated for nonvolatile memory applications due to its features that topologically protected binary information can be generated, transferred, stored, read-out, and erased by electrical means. There are many competitors for nonvolatile memory applications, such as STT MRAM using tunneling MR devices and ferroelectric nonvolatile memory with miniaturized semiconductor transistors, but the racetrack method using Skyrmion is attracting attention as a high-capacity nonvolatile memory with ultra-low power consumption that outperforms the competition. In addition to the development of the physical basis for generating, controlling, and reading out high-density Skyrmion at room temperature, including material exploration, collaboration with electronics engineering researchers will be important for practical application of this technology.

The nonlinear phenomena generated by Skyrmion's Dynamics have been applied to reservoir computing. It has already demonstrated that character recognition is possible by this method. While nonlinear phenomena themselves are abundant in nature, this device is unique in that it can electrically generate various forms of nonlinear phenomena. It is desirable to clarify what advantages this device has over reservoir computing that uses other nonlinear phenomena, and what characteristics it can have as a neurocomputing device. Collaboration with computer science researchers will be important again here, as well as the establishment of a physical foundation for Skyrmion's Dynamics.

The study of the interplay between phonon and magnon degrees of freedom is extremely rich and combines well with CEMS core expertise in materials. Given the broad scope of this class of phenomena, relatively little is understood at present. This proposed project strategically combines the broad materials capabilities of CEMS with its expertise in THz spectroscopy. CEMS is probably the best place in the world to mount a systematic attack on the general problem of phonon-magnon coupling.

CEMS also proposes further fundamental work on emergent inductors. Standard inductors have an *emf* proportional to the time-derivative of current due to Maxwell's equations. In contrast emergent inductors have an *emf* that is generated by collective magnetization dynamics. This effect is of great fundamental interest. Now that the effect has been demonstrated, the focus going forward can be on finding materials in which its size is sufficiently strong to be useful for applications. The Advisory Council understands that some initial contact with technology companies has already taken place.

Recently fractional Chern insulator states have been observed in WTe_2 two-dimensional semiconductors by researchers at Cornell University and the University of Washington. This discovery can be viewed as a demonstration of the quantized topological Hall effect pioneered by CEMS. This discovery is likely to launch a new direction in topotronics. CEMS has the capability to be a leader on this research topic and could consider including it in its roadmap for the coming five year period.

4. Concluding Remarks

The three areas of science in CEMS, correlation physics, supramolecular chemistry, and quantum information electronics are truly thriving in the context of international standards. Professor Tokura has been an exemplary leader of the Center, and broadly speaking the investigators who are part of CEMS are of excellent quality and their record of productivity continues to be outstanding since the reviews by the Advisory Council in 2016 and 2019. This judgement is based on the presentations given to the Advisory Council, the quality of the publications, and the bibliometric data provided. In an advisory capacity, the Council can judge the science but it is more difficult to judge the potential societal impact as this is a more complex function with many variables. However, given the large diversity and high quality of science at CEMS, it is very likely that societal impact will happen from one or more of the three areas. In this context it is imperative that all its parts are given an equal opportunity to succeed. Finally, principal recommendations from the Advisory Council, which are discussed in various places in this report, are listed below.

Recommendations:

1. Continue to focus on the four synergetic projects.

2. Further enhance the collaborations between divisions, in particular, between SMC and other divisions.

3. Maintain close communications between CEMS and RQC so that they can take complementary leadership in the national research strategy for quantum technology.

4. Promote interactions between early-career researchers in different divisions and encourage their active participation in the collaborative research.

5. Extend cooperation with universities both domestic and international to facilitate exchange and recruitment of researchers.

6. Provide support to young researchers for consultation on future career and other issues.

7. Provide support for networking among female researchers for better information exchange and consultation.