# 7-2　理論・計算分子科学研究領域の評価

## 7-2-1　Matthias Weidemüller 外国人運営顧問

Report on the visit to the Institute for Molecular Science (IMS), Okazaki

7–9 February 2024

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This report is based on a visit to the Institute for Molecular Science from 7 to 9 February 2024. On 7 February, Director General Professor Watanabe provided me with general information, in particular concerning latest developments after my first visit in spring 2023. This year's focus was on the activities of the Department of Theoretical and Computational Molecular Science at IMS. The first meeting with Professor Saito and Associate Professor Okazaki was on the same day. On 8 February, I had meetings with Professors Okumura, Ishizaki and Ehara. Each of the meetings took about one hour, starting with presentations by the researchers followed by vivid and very insightful discussions on the research topics. We also briefly touched other issues related, *e.g.*, to the research environment offered by IMS. The scientists shared the files of their presentations with me, and they provided me with their most important publications from the last five years. The visit was closed by a review meeting with the Director General on 9 February. Further information for this report was extracted from IMS's Annual Report 2023.

**General remarks**

After having mainly met experimentally oriented researchers during my visit of last year, I now had the pleasure to discuss with five leading theoretical scientists at IMS. As a general impression, their research is of highest quality on an international scale. It addresses fundamental questions with regard to the emergence of complex dynamics in large molecular aggregates or condensed-matter systems. As far as I can judge, all researchers play a leading role in their respective fields of research. The research topics do not necessarily follow general mainstream, but indicate a large degree of independent scientific judgement of these outstanding scientists. Yet, all scientists consistently envisage applications of their research for, *e.g.*, material design or quantum control using external fields. The approaches are generally based on sophisticated theoretical and computational approaches well adapted to the intricacy of the systems under investigation. Providing insightful answers to subtle questions concerning the nature of complex molecular systems and the role of their environment is a characteristic, unique feature of IMS in general, and the research within the Department of Theoretical and Computational Molecular Science not only strongly supports this mission, but also positively contributes to IMS' outstanding reputation nationwide as well as internationally.

Unanimously, the important role of IMS' Research Center for Computational Science, headed by Professor Ehara, was emphasized by all researchers. The supercomputer facility and related infrastructure provide outstanding opportunities which are unmatched worldwide. They can be considered one important key element to the success of the theoretical groups at IMS.

All groups maintain broad collaborations with groups from other academic institutions in Japan or abroad. In most cases, theory and experiment work hand in hand. As a general feature, the theory groups at IMS are rather small in size, consisting essentially of the group leader and a small number of research staff including postdoctoral fellows. The number of graduate students in the groups is

rather small, in particular compared to the composition of typical research groups at a university. This feature is particularly striking as the topics of the research would, in my view, be ideally suited for successful PhD theses.

The following assessment follows the order of the presentations as given during the visit.

*Shinji SAITO*

The focus of Professor Shinji Saito and his group lies on the dynamics of condensed matter systems, especially with biological relevance. The studies comprise the excitation transport in light-harvesting complexes for photosynthesis, as well as structural and dynamical properties of supercooled water and other liquids. By using advanced computational methods including quantum chemical and molecular dynamics calculations, the research bridges the gap between microscopic models and macroscopic response functions. In this way, general conclusions on the nature of condensed matter and biophysical processes could potentially been drawn from the specific model systems under investigation, addressing the big question on how function follows structure. I was particularly impressed by his studies on the structure and dynamical slowdown of supercooled water, shedding new light on the largely unexplored region around 200 K.

*Kei-ichi OKAZAKI*

The group of Associate Professor Kei-ichi Okazaki addresses the fundamental processes of biomolecular machines in the cell with the goal to device possible control scenarios. In order to access long time scales, the group uses advanced molecular dynamics simulations and has develops novel methods such as coarsegrained models. These are applied to, *e.g.*, elucidate condition-dependent inhibitions mechanisms in ATP synthase. Modern techniques involving artificial intelligence such as structure predictions via AlphaFold are combined with molecular dynamics simulations to gain deeper insights into conformations in transporter proteins and other processes of biophysical relevance. The results on the conformational dynamics of oxalate transporters nicely highlight the added value of merging state-of-the-art approaches, including machine learning, with molecular structure calculations. In order to validate predictions of the theoretical models, the group maintains various cooperations with experimental groups at other places.

*Hisashi OKUMURA*

Associate Professor Hisashi Okumura and his group study the structure and dynamics of disease-related biomolecules, in particular aggregated amyloid-β (Aβ) peptides. Calculations are based on advanced replica molecular dynamics methods developed by the group. As a particular highlight, predictions concerning the Aβ peptide aggregation and behavior at interfaces extracted from these simulations are tested and validated in a cooperations with Prof. Kato's group at IMS. This successful internal collaboration impressively indicates the great potential of IMS's bundled expertise in theoretical as well as in experimental molecular science. The group also theoretically investigates possible scenarios for the breaking of amyloid fibrils in water solution through external ultrasonic or laser fields.

*Akihito ISHIZAKI*

The research of Professor Akihito Ishizaki and his group applies theoretical concepts from modern quantum optics and quantum open systems to a large variety of complex systems. Recent examples of such cross-disciplinary investigations are time-resolved

spectroscopy with entangled photons, a quantum-theoretical approach to processes in photosynthesis, non-Markovian effects in organic photovoltaic systems, or control of electron transfer reactions via techniques from cavity-QED. A characteristic feature of his research is that the chemical, condensed matter or biomolecular systems under investigation are not oversimplified, but relevant degrees of freedom are carefully selected and included into the models. In this way, one can identify which of these degrees of freedom are essential for certain dynamical processes in complex systems. Thus, this research offers an intriguing approach to the fundamental question how complexity arises from microscopic principles. A nice example is the cooperative effort with Prof. Minagawa's group at the National Institute for Basic Biology (next door to IMS) showing how advanced graph methods from network science and quantum dynamics of open systems can be combined with sophisticated analyses of molecular structure to gain deeper insights into the functionality of light-harvesting complexes in photosynthesis. At the same time, the unique approach of Prof. Ishizaki combining methodologies from different fields allows one to devise novel ways to use quantum techniques to control complex many-body systems.

*Masahiro EHARA*

Professor Masahiro Ehara and his group develop theoretical approaches to accurately describe large molecular aggregates. It was fascinating to see, that the group not only applies state-of-the-art computational approaches to tackle important problems, but also plays a leading role in developing new computational methods with large impact also in other fields of research. As a prime example, they devised an innovative inverse design method which was demonstrated by developing functional 1D molecular aggregates and moleculenanoparticle systems. The activities also comprise applications of advanced computational methods to an impressive breadth of studies on electronic structure to better understand and control technologically relevant materials and photo-induced processes. These include functional materials, such as modified single-wall carbon nanotubes, metal nano clusters, and heterogeneous catalysts. The investigations are performed in a larger framework of national and international collaborations.

**Conclusion**

In conclusion, the Department of Theoretical and Computational Molecular Science at IMS performs science at the highest international level. Each of the different research groups have achieved impressive results in the past years, contributing to a better understanding how functionality of complex molecules emerges from their microscopic structure, how these aggregates interact with their environment or with external fields, and how a deeper understanding of the underlying principles can be used for applications in material design and quantum control. The research environment offered by IMS to these scientific activities is truly exceptional, one the one hand side due to the critical density of exceptional researchers in theory and experiment at IMS, but also by the available infrastructure, in particular the supercomputer facility. The research of the theory groups is embedded into larger national and international collaborative networks, and there is even a nice example of an internal theory-experiment collaboration within IMS. Overall, my visit at IMS was outermost enjoyable and offered ample positive intellectual impressions to me as a non-expert in most of the presented research areas. Like last year, my warm thanks go to Director General, the scientists and the organizational team for the hospitality and for making my stay such a pleasant one.

Heidelberg, 8 May 2024