RESEARCH ACTIVITIES

Theoretical and Computational Molecular Science

The objective of the Department is understanding and prediction of static and dynamic properties, reactions, and functions in condensed phase including nanomaterials and biomolecular systems by developing novel theories and computational methods based on quantum mechanics, statistical mechanics, and solid state physics. The Department collaborates with Research Center for Computational Science on researches.

Theoretical Studies of Reactions, Functions, and Fluctuations in Many-Body Molecular Systems

Department of Theoretical and Computational Molecular Science
Division of Theoretical Molecular Science I

SAITO, Shinji
Professor
[shinji@ims.ac.jp]

Education
1988 B.S. Keio University
1990 M.E. Kyoto University
1995 Ph.D. The Graduate University for Advanced Studies

Professional Employment
1990 Technical staff, Institute for Molecular Science
1994 Research Associate, Nagoya University
1998 Associate Professor, Nagoya University
2005 Professor, Institute for Molecular Science
2006 Professor, The Graduate University for Advanced Studies

Member
Assistant Professor
MORI, Toshifumi
KODA, Shin-ichi
JSPS Post-Doctoral Fellow
MATSUMURA, Yoshihiro
INAGAKI, Taichi
Post-Doctoral Fellow
MAURYA, Manish
Graduate Student
KALATHINGAL, Mahroof
ZHU, Zhe
Secretary
CHIBA, Fumika

Keywords Reactions, Functions, Fluctuations

Many-body molecular systems, such as liquids and biomolecular systems, take disordered conformations, and show heterogeneous dynamics, due to complicated molecular interactions. Furthermore, various reactions and biological functions occurs in these kinds of systems. Therefore, understanding of the complicated structures and dynamics is essential for the elucidation of the reactions and functions in the systems.

Multidimensional nonlinear spectroscopy can provide detailed information on dynamics that can not be obtained from conventional IR or Raman spectroscopy. We have developed computational methods of multidimensional nonlinear spectroscopy. As a result, we have revealed the molecular origin of the ultrafast energy relaxations and heterogeneous fluctuations in water based on theoretical two-dimensional (2D) IR spectra.

We have also explored the spatiotemporal heterogeneous dynamics in supercooled liquids referred to as the dynamic heterogeneity. Especially, we have examined the lifetime of dynamic heterogeneity by using the three-time correlation function of density fluctuation, and elucidated the relationship between the lifetime and fragility.

In addition, we have been examining the molecular origin of anomalous properties of water. By performing extensive molecular dynamics simulations, we find that structural and dynamical instabilities of water are hidden in the experimentally inaccessible region between 235 K and 150 K. We also find a crucial role of specific three-coordinated defects in the structural relaxation and glass transition temperature. Now, we investigate how slow but persistent structural relaxations proceed at a very low temperatures to understand the freezing of motions toward the glass transition.

The heterogenous conformational fluctuations/dynamics are also found in biomolecular systems. It is considered that such conformational dynamics are essential for biological functions. We examine the molecular mechanisms of biological functions, i.e., the efficient excitation energy transfer in photosynthetic proteins and the robust circadian rhythm in clock protein KaiC. In addition, we investigate dynamic effects of enzymatic reactions, and explore conformational change dynamics of proteins at the molecular level by using stochastic theory.

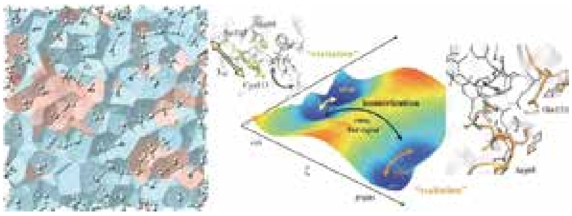

Figure 1. Snapshot of two-state model in supercooled water consisting of high- and low-density liquids (left) and schematic of 2D free energy surface for enzymatic reaction (right).

Selected Publications

- T. Yagasaki and S. Saito, *Annu. Rev. Phys. Chem.* **64**, 55–75 (2013). T. L. C. Jansen, S. Saito, J. Jeon and M. Cho, *J. Chem. Phys.* **150**, 100901 (17 pages) (2019). (Perspective)
- K. Kim and S. Saito, *J. Chem. Phys. (Special Topic on Glass Transition)* **138**, 12A506 (12 pages) (2013).
- S. Saito, B. Bagchi and I. Ohmine, *J. Chem. Phys.* **149**, 124504 (8 pages) (2018).
- J. Ono, S. Takada and S. Saito, *J. Chem. Phys. (Special Topic on Multidimensional Spectroscopy)* **142**, 212404 (13 pages) (2015).
- T. Mori and S. Saito, *J. Phys. Chem. Lett.* **10**, 474–480 (2019).

1. Thermodynamic Picture of Vitrification of Water through Complex Specific Heat and Entropy: A Journey through 'No Man's Land'1)

We investigate thermodynamic properties of supercooled water across the "no man's land" onto the formation of amorphous ice. The calculations are aided by very long computer simulations, often more than 50 µs long, with the TIP4P/2005 model potential. Density fluctuations that arise from the proximity to a putative liquid-liquid (LL) transition at 228 K, cast a long shadow on the properties of water, both above and below the LL transition. We carry out the calculations of the quantum mechanical static and frequency-dependent specific heats by combining seminal studies of Lebowitz, Percus, and Verlet and Grest and Nagel with the harmonic approximation for the density of states. The obtained values are in quantitative agreement with all available experimental and numerical results of specific heats for both supercooled water and ice. We calculate the entropy at all the state points by integrating the specific heat. We find that the quantum corrected-contributions of intermolecular vibrational entropy dominate the excess entropy of amorphous phases over the crystal over a wide range of temperatures. Interestingly, the vibrational entropy lowers the Kauzmann temperature, T_K, to 130 K, just below the experimental glass-to-liquid water transition temperature, T_g, of 136 K and the calculated T_g of 135 K in our previous study. A straightforward extrapolation of high temperature entropy from 250 K to below however would give a much higher value of T_K ~ 190 K.

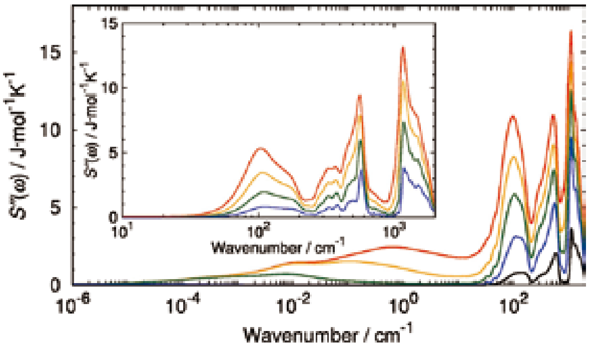

Figure 2. Imaginary part of complex entropy of (liquid, supercooled, and amorphous) water at 300 (red), 250 (orange), 220 (green), 180 (blue), and 100 (black) K. The inset shows those at 250 (red), 200 (orange), 150 (green), and 100 (blue) K of ice Ih.

2. Theory of Coherent Two-Dimensional Vibrational Spectroscopy2)

Two-dimensional (2D) vibrational spectroscopy has emerged as one of the most important experimental techniques useful to study the molecular structure and dynamics in condensed phases. Theory and computation have also played essential and integral roles in its development through the nonlinear optical response theory and computational methods such as molecular dynamics (MD) simulations and electronic structure calculations. In this article, we present the fundamental theory of coherent 2D vibrational spectroscopy and describe computational approaches to simulate the 2D vibrational spectra. The classical approximation to the quantum mechanical nonlinear response function is invoked from the outset. It is shown that the third-order response function can be evaluated in that classical limit by using equilibrium or non-equilibrium MD simulation trajectories. Another simulation method is based on the assumptions that the molecular vibrations can still be described quantum mechanically and that the relevant molecular response functions are evaluated by the numerical integration of the Schrödinger equation. A few application examples are presented to help the researchers in this and related areas to understand the fundamental principles and to use these methods for their studies with 2D vibrational spectroscopic techniques. In summary, this exposition provides an overview of current theoretical efforts to understand the 2D vibrational spectra and an outlook for future developments.

3. Site-Dependent Fluctuations Optimize Electronic Energy Transfer in the Fenna-Matthews-Olson Protein3)

Light absorbed by light-harvesting antennae is transferred to the reaction center (RC). The excitation energy transfer (EET) to the RC is known to proceed with nearly perfect quantum yield. However, understanding of EET is still limited at molecular level. Here, we examine the dynamics in the Fenna–Matthews–Olson (FMO) protein by developing an efficient molecular dynamics simulation that can properly describe the electronic properties of the bacteriochlorophylls. We find that the FMO protein consists of sites with heterogeneous fluctuations extending from fast to slow modulation. We also find that efficient EETs are facilitated by site-dependent fluctuations that enhance the resonance condition between neighboring sites with large site-energy differences and circumvent exciton trapping on the pathway to the RC. Knowledge of site-dependent fluctuations is an important component of understanding optimization of EET in photosynthetic systems.

References

1) S. Saito and B. Bagchi, *J. Chem. Phys.* **150**, 054502 (14 pages) (2019). (Featured Article)

2) T. L. C. Jansen, S. Saito, J. Jeon and M. Cho, *J. Chem. Phys.* **150**, 100901 (17 pages) (2019). (Perspective)

3) S. Saito, M. Higashi and G. R. Fleming, *J. Phys. Chem. B*, in press.

Theoretical Studies on Novel Physical Properties Arising from Many-Body Interaction

Department of Theoretical and Computational Molecular Science
Division of Theoretical Molecular Science I

MINAMITANI, Emi
Associate Professor
[eminamitani@ims.ac.jp]

Education

2005	B.S. Osaka University
2010	Ph.D. Osaka University

Professional Employment

2010	Postdoctoral Fellow, Osaka University
2011	Special Postdoctral Researcher, RIKEN
2013	Assistant Professor, The University of Tokyoy
2015	Lecturer, Cornell University
2019	Associate Professor, Institute for Molecular Science Associate Professor, The Graduate University for Advanced Studies

Awards

2008	L'Oréal–UNESCO Japan National Fellowships for Women in Science
2011	Best Poster Award in ISSS-6 Internal Symposium on Surface Science
2017	Young Scientist Award of the Physical Society of Japan
2019	The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology The Young Scientists' Prize

Member
Research Fellow
HINODE, Kenji
OKUGAWA, Shinichi
Secretary
AKABA, Atsuko

Keywords Quantum Many-Body Interaction, Density Functional Theory, Quantum Field Theory

Quantum many-body interaction is a source of novel physical properties in the condensed matters. In our group, we develop theoretical methods by combining quantum field theory and density functional theory, and carry out collaborative research with experimental groups. As specific targets, we focus on magnetism in nanostructure and energy dissipation.

For magnetism in nanostructure, we are interested in the Kondo effect and spin–orbit interaction. The Kondo effect arises from the interaction between the localized spin and conduction electrons, which forms a characteristic many-body state so called the Kondo singlet state. The spin–orbit interaction originating from relativistic effect constrains the direction of magnetic moment to specific direction. We investigate the possibility of novel physical phenomena induced by these interactions in the nanostructure and molecules on surfaces.

For energy dissipation, we focus on the effect of electron–phonon interaction. The electron–phonon interaction is one of the most fundamental interactions in the condensed matter physics, and the quantitative evaluation in realistic materials is highly demanding. We adopt the ab-initio calculation to analyze the signal of electron–phonon coupling in surface spectroscopy and thermal properties in various kind of solids.

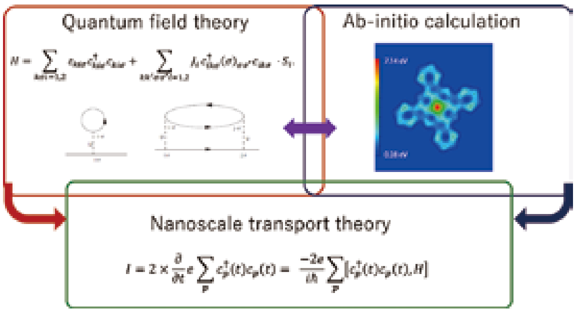

Figure 1. Schematic image of the theoretical method developed in our group.

Selected Publications

- E. Minamitani, N. Tsukahara, D. Matsunaka, Y. Kim, N. Takagi and M. Kawai, "Symmetry-Driven Novel Kondo Effect in a Molecule," *Phys. Rev. Lett.* **109**, 086602 (2012).
- E. Minamitani, R. Arafune, N. Tsukahara, Y. Ohda, S. Watanabe, M. Kawai, H. Ueba and N. Takagi, "Surface Phonon Excitation on Clean Metal Surfaces in Scanning Tunneling Microscopy," *Phys. Rev. B* **93**, 085411 (2016).
- E. Minamitani, N. Takagi and S. Watanabe, "Model Hamiltonian Approach to the Magnetic Anisotropy of Iron Phthalocyanine at Solid Surfaces," *Phys. Rev. B* **94**, 205402 (2016).
- R. Hiraoka, E. Minamitani, R. Arafune, N. Tsukahara, S. Watanabe, M. Kawai and N. Takagi, "Single-Molecule Quantum Dot as a Kondo Simulator," *Nat. Commun.* **8**, 16012 (2017).
- E. Minamitani, R. Arafune, T. Frederiksen, T. Suzuki, S. M. F. Shahed, T. Kobayashi, N. Endo, H. Fukidome, S. Watanabe and T. Komeda, "Atomic-Scale Characterization of the Interfacial Phonon in Graphene/SiC," *Phys. Rev. B* **96**, 155431 (2017).

1. Simulating Lattice Thermal Conductivity in Semiconducting Materials Using High-Dimensional Neural Network Potential

Heat generation in semiconducting materials has become a critical problem in modern nanoscale electronics. To design semiconductor materials with better thermal manageability, efficient methods for theoretical simulation of the thermal conductivity are required.

The main carrier of heat in semiconductors is the phonon, which is a quantum of lattice vibration. Current methods of simulating lattice thermal conductivity require accurate prediction of the interatomic force in the solid. Density functional theory (DFT) calculation is one of the most well-established techniques for accurate force prediction, including the effect of changes in the electronic state with atomic displacement. However, the high computational cost limits the application of DFT calculation in thermal conductivity simulations.

We focus on the application of machine learning techniques for thermal conductivity simulations.[1] Among various machine learning techniques, we chose the high-dimensional neural network potential (HDNNP) developed by Behler *et al.*[2,3] HDNNP can describe the relation between the total energy of a system and its atomic arrangement. The force acting on atoms can also be described by the HDNNP as shown in several previous studies, however, the accuracy of the prediction is limited. We showed that much higher accuracy can be obtained by training HDNNP parameters with a focus on force fitting. We chose crystalline Si and GaN as representative semiconducting materials with one and two atom types, respectively.

Figure 2 shows the compare the forces in the Si and GaN systems predicted by DFT and HDNNP. The root mean square error (RMSE) between force prediction from HDNNP and DFT calculation results was 25.5 meV/Å for Si and 37.8 meV/Å for GaN.

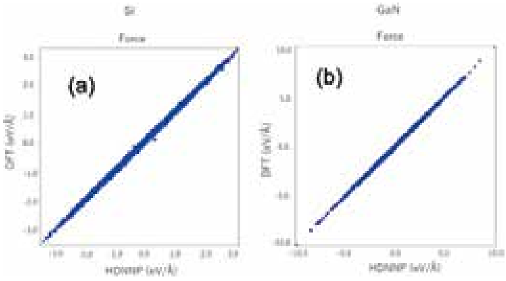

Figure 2. Comparison of interatomic forces in (a) Si and (b) GaN bulk crystals obtained by HDNNP and DFT calculations.

The phonon dispersion curves obtained using HDNNP agree well with the DFT calculation results and previous reports for both Si and GaN,[4,5] as shown in Figure 3. Then, we simulated the lattice thermal conductivity based on ALD by combining HDNNP and phono3py package.[6] Figure 4 shows a comparison of the temperature dependence of the thermal conductivity obtained from the force predictions of HDNNP and VASP calculations. The deviation from the DFT calculation results is within 1% at 200 to 500 K for Si and within 5.4% from 200 to 1000 K for GaN.

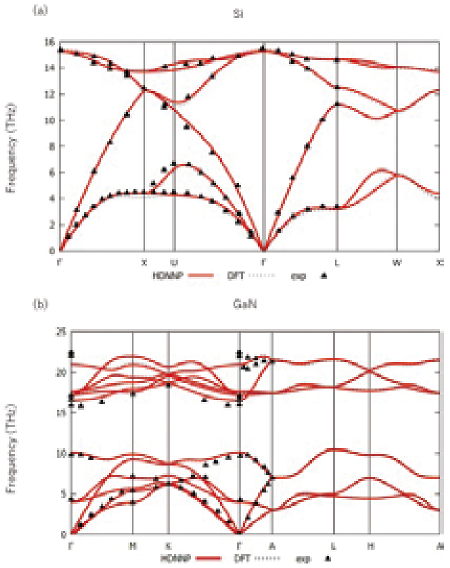

Figure 3. Comparison of phonon dispersions in (a) Si and (b) GaN obtained by HDNNP and DFT calculations. The experimental data for comparison were obtained from Ref. 4 for Si and Ref. 5 for GaN.

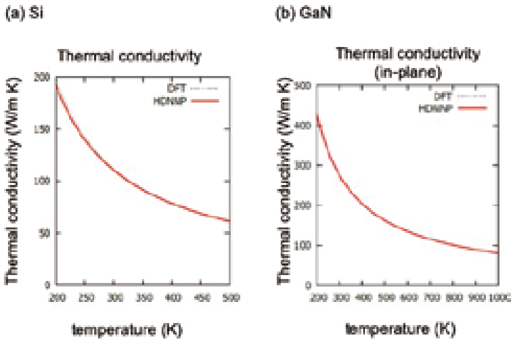

Figure 4. Comparison of thermal conductivities in (a) Si, (b) along the in-plane (100) direction in GaN obtained by HDNNP and DFT calculations.

References

1) E. Minamitani, M. Ogura and S. Watanabe, *Appl. Phys. Express*, in press.
2) J. Behler and M. Parrinello, *Phys. Rev. Lett.* **98**, 146401 (2007).
3) J. Behler, *Angew. Chem., Int. Ed.* **56**, 12828 (2017).
4) A. Ward and D. A. Broido, *Phys. Rev. B* **81**, 085205 (2010).
5) T. Ruf *et al.*, *Phys. Rev. Lett.* **86**, 906 (2001).
6) A. Togo, L. Chaput and I. Tanaka, *Phys. Rev. B* **91**, 094306 (2015).

Award

MINAMITANI, Emi; The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology The Young Scientists' Prize (2019).

Theoretical Studies of Chemical Dynamics in Condensed and Biomolecular Systems

Department of Theoretical and Computational Molecular Science
Division of Theoretical Molecular Science II

ISHIZAKI, Akihito
Professor
[ishizaki@ims.ac.jp]

Education
2008 D.S. Kyoto University

Professional Employment
2006 JPSP Research Fellow, Kyoto University
2008 JPSP Postdoctoral Fellow for Research Abroad, University of California, Berkeley
2010 Postdoctoral Fellow, Lawrence Berkeley National Laboratory
2012 Research Associate Professor, Institute for Molecular Science
2013 Fellow 2012–2013, Wissenschaftskolleg zu Berlin
2016 Professor, Institute for Molecular Science
Professor, The Graduate University for Advanced Studies
Visiting professor, Nagoya University

Awards
2015 10th Condensed-Matter Science Prize, Japan
2016 10th Young Scientist Award of the Physical Society of Japan
2016 18th Sir Martin Wood Prize
2017 The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology
The Young Scientists' Prize

Member
Assistant Professor
NGUYEN, Thanh Phuc
Post-Doctoral Fellow
KATO, Akihito
FUJIHASHI, Yuta
IKEDA, Tatsushi
Secretary
AKABA, Atsuko

Keywords Quantum Dissipative Systems in Complex Molecular Systems, Quantum Optics, Light-Matter Interaction

Quantum dynamic phenomena are ubiquitous in molecular processes, and yet remain a challenge for experimental and theoretical investigations. On the experimental side, it has become possible to explore molecules on a time scale down to a few femtoseconds. This progress in ultrafast spectroscopy has opened up real-time observation of dynamic processes in complex chemical and biological systems and has provided a strong impetus to theoretical studies of condensed phase quantum dynamics.

Essentially, any quantum systems can never be regarded as "isolated systems." Quantum systems are always in contact with "the outside world," and hence their quantum natures are sometimes sustained and sometimes destroyed. In condensed phase molecular systems, especially, quantum systems are affected by the huge amount of dynamic degrees of freedom such as solvent molecules, amino acid residues in proteins, and so forth. Balance between robustness and fragility of the quantum natures may dramatically alter behaviors of chemical dynamics and spectroscopic signals. Therefore, theoretical tools to adequately describe (1) dynamical behaviors of quantum systems affected by the huge amount of dynamic degrees of freedom and (2) the interaction with radiation fields should be developed.

For this purpose, our research group has been tackling the following subjects:

(1) Developments of condensed phase quantum dynamic theories
(2) Quantum theories to describe dynamical and transport processes in materials and biological systems
(3) Theoretical investigations on measurement and control with the use of atomic-molecular-optical (AMO) physics approaches.

In recent years, specifically, special attention is devoted to the subject (3). We have been examining whether ideas and concepts in the field of quantum science and technology would provide novel control knobs that supplement classical parameters in conventional spectroscopic tools such as frequencies and time delays.

Selected Publications

- A. Ishizaki, T. R. Calhoun, G. S. Schlau-Cohen and G. R. Fleming, "Quantum Coherence and Its Interplay with Protein Environments in Photosynthetic Energy Transfer," *Phys. Chem. Chem. Phys.* **12**, 7319 (2010). [Invited perspective article]
- A. Ishizaki and G. R. Fleming, "Quantum Coherence in Photosynthetic Light Harvesting," *Annu. Rev. Condens. Matter Phys.* **3**, 333–361 (2012). [Invited review article]
- G. D. Scholes *et al.*, "Using Coherence to Enhance Function in Chemical and Biophysical Systems," *Nature* **543**, 647–656 (2017).
- T. P. Nguyen and A. Ishizaki, "Control of Excitation Energy Transfer in Condensed Phase Molecular Systems by Floquet Engineering," *J. Phys. Chem. Lett.* **9**, 1243 (2018).
- Y. Fujihashi, M. Higashi and A. Ishizaki, "Intramolecular Vibrations Complement the Robustness of Primary Charge Separation in a Dimer Model of the Photosystem II Reaction Center," *J. Phys. Chem. Lett.* **9**, 4921 (2018).
- A. Kato and A. Ishizaki, "Non-Markovian Quantum-Classical Ratchet for Ultrafast Long-Range Electron–Hole Separation in Condensed Phases," *Phys. Rev. Lett.* **121**, 647 (2018).

1. Quantum Dynamics Investigation on Chiral-Induced Spin Selectivity in Helical Molecules

Charge transfer processes in DNA have attracted considerable attention over several decades in relation with its possible role to the long-range oxidative damage of DNA. In recent years, however, a new dimension has been brought to this research field. Naaman and coworkers revealed that electrons transmitted through a double-stranded DNA molecule exhibited a preferred spin polarization at room temperature [*Science* **331**, 894 (2011)]. Similar effects were found in various chiral molecules. This effect is currently referred to as chirality induced spin selectivity. Such organic helical molecules are non-magnetic; nevertheless, they can serve as highly efficient spin filters. In this regard, chiral molecules are expected to open a new avenue in molecular spintronics.

In this work, we developed a theoretical framework to investigate quantum dynamics of spinful electrons in a helical molecule under the influence of both the spin–orbit interaction and the surrounding environment. In the literature, the Landauer theory has offered a way to calculate spin-dependent charge current under the assumption that electrons propagated freely across a conductor. Therefore, we focused on the quantum master equation approach. Furthermore, the geometric phase associated with the spin–orbit interaction has been analyzed, and it has been revealed that impacts of the phase upon the spin dynamics depends on individual paths.1)

2. Generation of Pseudo-Sunlight via Quantum Entangled Photon Pairs and the Interaction with Molecular Systems

Light incident upon molecules trigger fundamental processes in diverse systems present in nature. However, under natural conditions such as sunlight illumination, it is impossible to assign known times for photon arrival owing to continuous pumping, and therefore, the photo-induced processes cannot be easily investigated. In time-resolved optical spectroscopy, in contrast, investigations on the processes can be conducted by synchronizing the initial excitations in the entire ensemble with pulsed laser and thereby amplifying the microscopic dynamics in a constructively interferential fashion. Hence, whether dynamics initiated by sunlight irradiation might be different from those detected with laser spectroscopy is still being debated.

In this work, we addressed quantum entangled photon pairs generated with the parametric down-conversion (PDC) in birefringent crystals. The photon number statistics obeys the geometric distribution rather than the Poisson distribution, and therefore, the entangled photons are expected to reproduce characteristics of the sunlight photons. Furthermore, it become possible to investigate photo-induced dynamical processes with quantitative underpinnings, because expressions of quantum states of the pseudo-sunlight photons can be theoretically obtained. We showed that the average photon number of the sunlight in a specific frequency spectrum, e.g., the visible light, can be reconstructed by adjusting the PDC crystal length and pump frequency, and thereby molecular dynamics induced by the pseudo-sunlight can be investigated. The entanglement time, which is the hallmark of quantum entangled photons, can serve as a control knob to resolve the photon arrival times under the pseudo-sunlight irradiation, enabling investigations on real-time dynamics triggered by the pseudo-sunlight photons.2)

3. Control of Quantum Dynamics of Electronic Excitation Transfer in Molecular Loop Structures: Spontaneous Breaking of Chiral Symmetry

Manipulation of quantum systems is the basis for many promising quantum technologies. However, how quantum mechanical principles can be used to manipulate the dynamics of quantum dissipative systems remains unanswered because of strong decoherence effects arising from interaction with the surrounding environment. In this work, we demonstrate that electron transfer dynamics in molecular loop structures can be manipulated with the use of Floquet engineering by applying a laser field. Despite strong dephasing, the system's dynamics spontaneously breaks the chiral symmetry of the loop in a controllable fashion, followed by the generation of a robust steady-state electronic current without an external voltage. An exponential scaling law that relates the magnitude of the current to the system-environment coupling strength is revealed numerically. The breaking of chiral symmetry and the consequent controllable unidirectional flow of electrons could be employed to construct functional molecular electronic circuits.3)

4. Precise Determination of Excitation Energies in Condensed-Phase Molecular Systems Based on Exciton-Polariton Measurements

The precise determination of the excitation energies in condensed-phase molecular systems is important for understanding system-environment interactions as well as for the prerequisite input data of theoretical models used to study the dynamics of the system. The excitation energies are usually determined by fitting of the measured optical spectra that contain broad and unresolved peaks as a result of the thermally random dynamics of the environment. Herein, we propose a method for precise energy determination by strongly coupling the molecular system to an optical cavity and measuring the energy of the resulting polariton. The effect of thermal fluctuations induced by the environment on the polariton is also investigated, from which a power scaling law relating the polariton's linewidth to the number of molecules is obtained. The power exponent gives important information about the environmental dynamics.4)

References

1) A. Kato, T. Ikeda and A. Ishizaki, in preparation.

2) Y. Fujihashi, R. Shimizu and A. Ishizaki, submitted.

3) T. P. Nguyen and A. Ishizaki, *Phys. Rev. B* **99**, 064301 (2019).

4) T. P. Nguyen and A. Ishizaki, *Phys. Rev. Research* **1**, 033019 (2019).

Theoretical Studies of Functional Molecular Systems and Heterogeneous Catalysts

Department of Theoretical and Computational Molecular Science
Division of Computational Molecular Science

EHARA, Masahiro
Professor
[ehara@ims.ac.jp]

Education
1988 B.E. Kyoto University
1990 M.E. Kyoto University
1993 Ph.D. Kyoto University

Professional Employment
1993 Postdoctral Fellow, Institute for Fundamental Chemistry
1994 JSPS Postdoctoral Fellow
1994 Visiting Researcher, Heidelberg University (–1995)
1995 Assistant Professor, Kyoto University
2002 Associate Professor, Kyoto University
2006 Theoretical Research Division Supervisor, Kyoto University (–2008)
2008 Professor, Institute for Molecular Science
Professor, The Graduate University for Advanced Studies
2012 Professor, Elements Strategy Initiative for Catalysts and Batteries (ESICB), Kyoto University (additional post)

Awards
2009 APATCC Pople Medal
2009 QSCP Prize CMOA

Member
Assistant Professor
ITO, Soichi
Post-Doctoral Fellow
KOIZUMI, Ken-ichi
ZHAO, Pei
VIGNESH, K. R.
Visiting Scientist
ZHAO, Xiang
PRIYAKUMAR, Deva U
BOBUATONG, Karan
Graduate Student
KANAZAWA, Yuki
SHIRAOGAWA, Takafumi
Secretary
KAWAGUCHI, Ritsuko
SUGIMOTO, Yukari

Keywords Quantum Chemistry, Photophysical Chemistry, Heterogeneous Catalysis

We develop the accurate electronic structure theories and investigate the photochemistry and catalysis theoretically. Currently, our focuses are following research subjects.

(1) Coupled cluster theory for excited states of large system

We develop the coupled cluster theories and their efficient computational algorithm aiming at large-scale calculations of molecular excited states. We also develop the basic theories and methodologies that are useful for fundamental chemistry and applied chemistry; for example, PCM SAC-CI method for effectively describing the solvent effects on excited states, CAP/SAC-CI method for locating metastable resonance states, general-R method for multiple excited states, and active-space method for efficiently describing complex electronic states.

(2) Heterogeneous catalysis

Metal nanoclusters supported by metal oxides or polymers achieve highly efficient catalytic reactions. We study the catalytic activity of these complex systems by means of quantum chemical calculations and informatics theories. We have elucidated the importance of the perimeter sites at heterojunction of Ag nanocluster supported by alumina surface in terms of H_2 activation, the mechanism of methanol oxidation on Au:PVP and the unique coupling reactions on Au/Pd:PVP. We proceed these works in the project of Elements Strategy Initiative for Catalysts and Batteries (ESICB).

(3) Photophysical chemistry

Our accurate electronic structure theories are applied to wide varieties of theoretical studies and sometimes in cooperation with experiments on the photophysical properties and excited-state dynamics of nano-bio systems like photo-electronic devices, photofunctional molecules, and biosensors. Target molecules include nanocarbons like fullerenes, near-IR absorbing phthalocyanine congeners, dye-sensitized solar cells, organometallic compounds for artificial photosynthesis, biological chemosensors, and bio-imaging probes.

(4) Theoretical spectroscopy

New quantum states, single-site and two-site double-core hole states, have been observed owing to the recent development of free electron laser and coincidence spectroscopy. We have proposed new chemical concept regarding the physical properties or relaxation processes of these quantum states in cooperation with experiments. We also perform accurate theoretical analysis for the state-of-the-art molecular spectroscopy; for example, the electronic transitions in the FUV region by ATR-FUV spectroscopy and the excited-state relaxation processes by pump–probe spectroscopy.

Selected Publications

- R. Cammi, R. Fukuda, M. Ehara and H. Nakatsuji, "SAC-CI Method in the Polarizable Continuum Model-Theory for Solvent Effect on Electronic Excitation of Molecules in Solution," *J. Chem. Phys.* **133**, 024104 (24 pages) (2010).
- N. Berrah, M. Tashiro, M. Ehara *et al.*, "Double Core-Hole Spectroscopy for Chemical Analysis with an Intense X-Ray Femtosecond Laser," *Proc. Natl. Acad. Sci. U.S.A.* **108**, 16912–16915 (2011).
- M. Ehara and T. Sommerfeld, "CAP/SAC-CI Method for Calculating Resonance States of Metastable Anions," *Chem. Phys. Lett.* **537**, 107–112 (2012).
- P. Hirunsit, K. Shimizu, R. Fukuda, S. Namuangruk, Y. Morikawa and M. Ehara, "Cooperative H_2 Activation at Ag Cluster/θ-Al_2O_3 Dual Perimeter Sites: A DFT Study," *J. Phys. Chem. C* **118**, 7996–8006 (2014).

1. Theoretical Study on the Optical Properties of Multichromophoric Systems Based on an Exciton Approach: Modification Guidelines$^{1)}$

A degree of freedom of supramolecular and polymer design has been enhanced by recent advances in experimental techniques, where the design guidelines are demanded for developing optical materials. We propose post-modification strategy of emission and circularly polarized luminescence (CPL) of multichromophoric systems based on excitonic analysis. The strong decomposed CPL components originate from the interactions of exciton electric transition dipole moments between the chromophore and its adjacent monomers. The Frenkel-exciton decomposition analysis (FEDA) provides new possibilities for utilizing the potentials of multichromophoric systems.

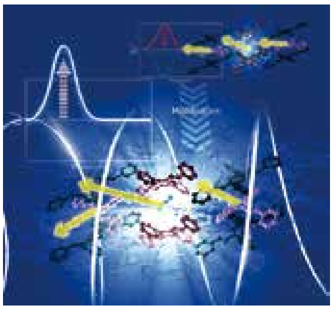

Figure 1. Post-modification strategy of emission and CPL of multichromophoric systems based on excitonic analysis.

2. Preferential Photoreaction in a Porous Crystal, Metal-Macrocycle Framework: Pd^{II} -Mediated Olefin Migration over [2+2] Cycloaddition$^{2)}$

A nano-sized confined space with well-defined functional surfaces has great potential to control the efficiency and selectivity of catalytic reactions. In this work, we report that a 1,6-diene, which normally forms an intramolecular [2+2] cycloadduct under photo-irradiation, preferentially undergoes a photo-induced olefin migration in a porous crystal, metal–macrocycle framework (MMF), and alternatively [2+2] cycloaddition is completely inhibited in the confined space. A plausible reaction mechanism for olefin migration triggered by the photo-induced dissociation of the Pd–Cl bond is suggested based on UV-vis diffuse reflectance spectroscopy, single-crystal XRD, and MS-CASPT2 calculation. The substrate scope of the photo-induced olefin migration in MMF is also demonstrated.

3. Theoretical Insight into Configurational Selectivity of Functionalized Single-Walled Carbon Nanotubes Based on Clar Sextet Theory$^{3)}$

Based on Clar's theory of the aromatic sextet, finite length models of single-walled carbon nanotubes (SWNTs) have been utilized to study the configurational selectivity of modified SWNTs via covalent functionalization with organic substitutions by density functional theory calculations. After considering near-armchair, near-zigzag, and zigzag SWNTs with distinct chiralities, it is found that the parameter R of semiconducting SWNTs plays a significant role in determining stability difference of functionalized SWNTs, *i.e.*, SWNTs with R = 2 exhibit better configurational selectivity than those with R = 1 when binding the same substituent to the sidewall of SWNTs.

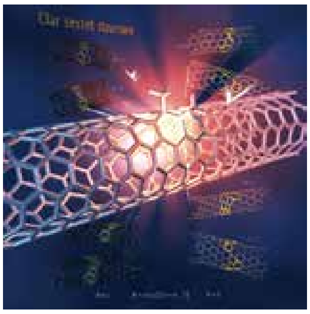

Figure 2. The configurational selectivity of modified SWNTs via covalent functionalization with organic substitutions to control the quantum dots.

4. Origin of Nb$_2$O$_5$ Lewis Acid Catalysis for Activation of Carboxylic Acids in the Presence of a Hard Base$^{4)}$

The Nb$_2$O$_5$ surface catalyzes the amidation of carboxylic acids with amines via Nb^{5+} Lewis acid activation of the C=O group. In this work, DFT calculations were applied to theoretically investigate the C=O bond activation of a model carboxylic acid (acetic acid) on θ-Al$_2$O$_3$(110), anatase TiO$_2$ (101), and T-Nb$_2$O$_5$(100) surfaces. The position of the mean DOS of the *d*-conduction band of the active metal site relative to the Fermi energy level correlates well with the efficiency in the C=O bond activation and, consequently, the catalytic activity for amidation. Unlike a classical understanding of strong acid sites of metal oxide surfaces, interaction of a carbonyl HOMO with a metal unoccupied *d*-orbital, covalent-like interaction between a carbonyl group and metal adsorption site, is relevant to the present system.

References

1) T. Shiraogawa and M. Ehara, *ChemPhotoChem* **3**, 707–718 (2019). (Special Issue, Front Cover, Cover Profile)
2) H. Yonezawa, S. Tashiro, T. Shiraogawa, M. Ehara, R. Shimada, T. Ozawa and M. Shionoya, *J. Am. Chem. Soc.* **140**, 16610–16614 (2018).
3) P. Zhao, Y. Maeda and M. Ehara, *J. Phys Chem. C* **123**, 18629–18637 (2019). (Supplementary Cover)
4) P. Hirunsit, T. Toyao, S. M. A. H. Siddiki, K. Shimizu and M. Ehara, *ChemPhysChem* **19**, 2848–2857 (2018). (Front Cover, Cover Profile)

Award

SHIRAOGAWA, Takafumi; Best Poster Award, The 22nd Annual Meeting of Japan Society of Theoretical Chemistry.

Development of New Simulation Algorithms and its Application to Protein Aggregates

Department of Theoretical and Computational Molecular Science
Division of Computational Molecular Science

OKUMURA, Hisashi
Associate Professor
[hokumura@ims.ac.jp]

Education
1998 B.S. Keio University
2002 Ph.D. Keio University

Professional Employment
2002 Postdoctoral Fellow, The University of Tokyo
2002 Research Associate, Institute for Molecular Science
2004 Research Associate, The Graduate University for Advanced Studies
2006 Research Lecturer, Nagoya University
2008 Research Assistant, Rutgers University
2009 Assistant Research Professor, Rutgers University
2009 Associate Professor, Institute for Molecular Science
Associate Professor, The Graduate University for Advanced Studies
2018 Associate Professor, Exploratory Research Center on Life and Living Systems

Award
2014 Academic Award of the Molecular Simulation Society of Japan

Member
Assistant Professor
ITOH, Satoru G.
Post-Doctoral Fellow
ISHIMURA, Kazuya
Graduate Student
YAMAUCHI, Masataka
MIYAZAWA, Kazuhisa
TACHI, Yuhei*
Secretary
KAWAGUCHI, Ritsuko

Keywords Molecular Dynamics Simulation, Protein, Amyloid

Biomolecules such as proteins and peptides have complicated free-energy landscape with many local minima. The conventional canonical-ensemble molecular dynamics (MD) simulations tend to get trapped in a few of the local-minimum states. To overcome these difficulties, we have proposed new generalized-ensemble algorithms, such as replica-permutation method. We apply these methods to proteins and peptides and try to predict the native structures of proteins as in Figure 1.

We are also interested in protein aggregates such as spherical substances called oligomers and acicular substances called amyloid fibrils (Figure 2). These protein aggregates cause more than 30 kinds of diseases. For example, Alzheimer's disease is thought to be caused by aggregated amyloid-β (Aβ) peptides. To overcome these diseases, it is essential to understand the aggregate genesis and disruption of Aβ peptides. We perform such MD simulations of oligomers and amyloid fibrils.

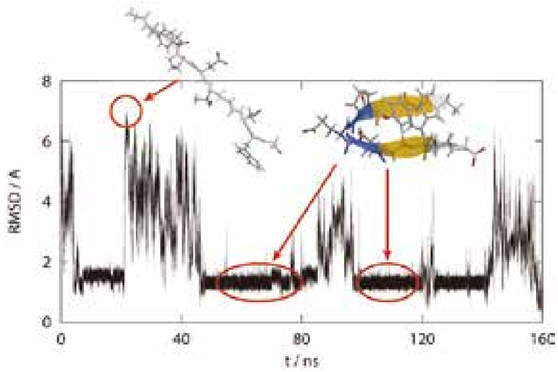

Figure 1. Time series of protein folding simulation.

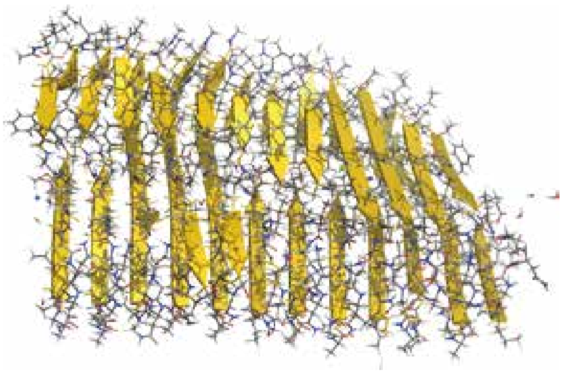

Figure 2. Snapshot of an Aβ amyloid fibril.

Selected Publications

- H. Okumura and S. G. Itoh, "Amyloid Fibril Disruption by Ultrasonic Cavitation: Nonequilibrium Molecular Dynamics Simulations," *J. Am. Chem. Soc.* **136**, 10549–10552 (2014).
- H. Okumura and S. G. Itoh, "Structural and Fluctuational Difference between Two Ends of Aβ Amyloid Fibril: MD Simulation Predicts Only One End Has Open Conformations," *Sci. Rep.* **6**, 38422 (9 pages) (2016).
- S. G. Itoh and H. Okumura, "Replica-Permutation Method with the Suwa-Todo Algorithm beyond the Replica-Exchange Method," *J. Chem. Theory Comput.* **9**, 570–581 (2013).
- S. G. Itoh and H. Okumura, "Oligomer Formation of Amyloid-β(29-42) from Its Monomers Using the Hamiltonian Replica-Permutation Molecular Dynamics Simulation," *J. Phys. Chem. B* **120**, 6555–6561 (2016).

1. Effects of a Hydrophilic/Hydrophobic Interface on Amyloid-β Peptides Studied by Molecular Dynamics Simulations and NMR Experiments

Oligomer formation of Aβ peptides is accelerated at a hydrophilic/hydrophobic interface. However, details of the acceleration mechanism have not been elucidated. To understand the effects of the interface on oligomerization at the atomic level, we performed all-atom MD simulations for an Aβ40 monomer in the presence and absence of the hydrophilic/hydrophobic interface.[1] Nuclear magnetic resonance experiments of Aβ40 peptides with gangliosidic micelles were also carried out in collaboration with Prof. Koichi Kato. We found that the Aβ peptides tend to gather at the hydrophilic/hydrophobic interface. That is, the local concentration of Aβ at the interface is higher than that in bulk water solution. In addition, β-hairpin structures are formed more at the interface than in the bulk water solution. In the β-hairpin structure, as shown in Figure 3, a part of the Aβ peptide extends straight and forms intramolecular hydrogen bonds. Therefore, another Aβ peptide that comes close to this peptide is easy to make intermolecular hydrogen bonds and tends to aggregate. In this way, we clarified that the reason for accelerating the aggregation of the Aβ peptides on the cell membrane surface is that not only the Aβ peptide tends to have high concentration on the cell membrane surface but also it takes a structure that tends to bind to each other. This discovery enables us to elucidate the mechanism by which the Aβ peptide aggregates on the membrane surface of nerve cells.

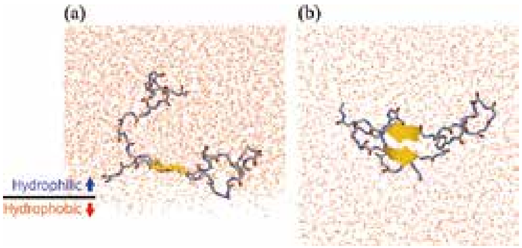

Figure 3. (a) An Aβ peptide that forms a β-hairpin structure at the hydrophilic/hydrophobic interface. (b) View from the bottom of panel (a).

2. Conformational Properties of an Artificial GM1Glycan Cluster

Recent studies showed that monosialotetrahexosyl-ganglioside (GM1) clusters induce the pathological aggregation of Aβ peptide responsible for the onset and development of Alzheimer's disease. We first performed all-atom MD simulations to characterize the conformational properties of the artificial GM1 glycan cluster. We found that more than 65% of GM1 glycans are clustered by interchain hydrogen bonds, interchain hydrogen bonds are mainly formed between Neu5Ac and Gal', and pentamers were most frequently observed in the metal-ligand complex. Our findings provide the physicochemical properties of the artificial GM1 glycan cluster under the thermal fluctuations for understanding its protein recognition.

3. Conformational Change of Amyloid-β 40 in Association with Binding to GM1-Glycan Cluster

Interaction between Aβ peptide and GM1-glycan cluster is important for the earliest stage of the toxic aggregation on GM1 cluster. We then performed all-atom MD simulations of Aβ40 on the artificial GM1-glycan cluster.[3] The GM1-glycan cluster facilitates the characterization of interactions between Aβ40 and multiple GM1-glycans. We succeeded in observing the binding of Aβ40 to the GM1-glycan cluster in all of our MD simulations. Our results indicate the importance of HHQ (13-15) segment of Aβ40 for the GM1-glycan cluster recognition. The recognition mechanism of HHQ (13-15) segment is mainly explained by non-specific stacking interactions between side-chains of histidine and rings of sugar residues, in which the HHQ regime forms coil and bend structures. Moreover, we found that Aβ40 exhibits helix structures at C-terminal side on the GM1-glycan cluster as in Figure 4. The helix formation is the initial stage of the pathological aggregation at ceramide moieties of GM1 cluster. The binding of Lys28 to Neu triggers the helix formation at C-terminus side because the formation of a salt bridge between Lys28 and Neu leads to change of intrachain interactions of Aβ40. Our findings suggest that the pathological helix formation of Aβ40 is initiated at GM1-glycan moieties rather than lipid ceramide moieties.

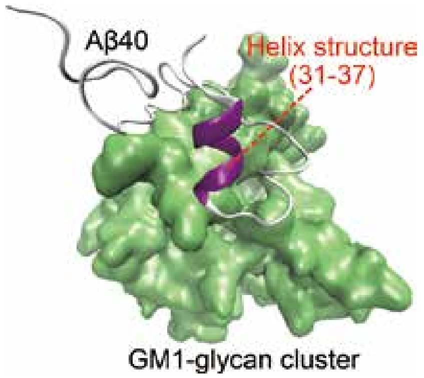

Figure 4. A typical snapshot of Aβ40 with a helix structure formed in residues 31–37. Green colored molecule is the GM1-glycan cluster.

References

1) S. G. Itoh, M. Yagi-Utsumi, K. Kato and H. Okumura, *J. Phys. Chem. B* **123**, 160–169 (2019).

2) Y. Tachi, Y. Okamoto and H. Okumura, *J. Chem. Phys.* **149**, 135101 (8 pages) (2018).

3) Y. Tachi, Y. Okamoto and H. Okumura, *Sci. Rep.* **9**, 6853 (11 pages) (2019).

---

* carrying out graduate research on Cooperative Education Program of IMS with Nagoya University

Theoretical Studies on Molecular Aggregates

Department of Theoretical and Computational Molecular Science
Division of Theoretical and Computational Molecular Science

FUJITA, Takatoshi
Research Associate Professor
[tfujita@ims.ac.jp]

Education

2006	B.H.D. Kobe University
2008	M.S. Kobe University
2011	Ph.D. Kobe University

Professional Employment

2010	JSPS Research Fellow (DC2)
2011	JSPS Postdoctoral Fellow (PD)
2012	Postdoctral Fellow, Harvard University
2015	Postdoctral Fellow, Kyoto University
2016	Research Associate Professor, Institute for Molecular Science

Member
Secretary
CHIBA, Fumika

Keywords Exciton, Energy and Charge Transfer, Organic Semiconductors

Organic molecules can assemble into an ordered structure by non-covalent interactions, forming various types of aggregates. Molecular aggregates can exhibit remarkable optical and electronic properties that are not observed in isolated molecules. We study optoelectronic properties and quantum dynamics of molecular aggregates. More specifically, we focus on energy and charge transfer dynamics, and energy conversions, and structure-property relationship. Our research also include the developments of theoretical and computational methods.

It is still challenging to simulate quantum dynamics of energy or charge transfer in condensed systems. An exciton or electron wave functions can be delocalized over many molecules by intermolecular electronic couplings. By contrast, the wave functions can be localized because of the static disorder and interactions with nuclear degree of freedom. Therefore, successful theoretical descriptions require the inclusions of electronic couplings, static disorder, and electron-phonon or electron-vibration interaction. We develop a method to simulate quantum dynamics in condensed phase by combining molecular dynamics simulations, electronic structure theories, and quantum dynamics methods, as shown in Figure 1. Electronic states of an aggregate is obtained from a large-scale electronic structure calculation, and the model Hamiltonian for an exciton or a charge carrier is derived. The model Hamiltonian is used for simulating energy or charge dynamics by a quantum dynamics method, which incorporates finite-temperature effects and electron-vibration interactions. The combine computational approach allows for bottom-up descriptions of energy or charge transfer dynamics in realistic molecular aggregates.

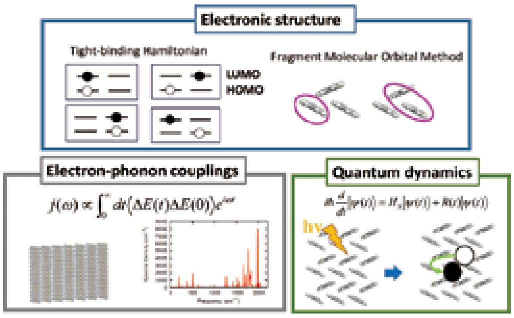

Figure 1. A combine approach to quantum dynamics in molecular aggregates.

We currently investigate electronic states and quantum dynamics at organic interfaces. We also develop the many-body perturbation theory to predict electronic levels at higher accuracy.

Selected Publications

- T. Fujita, S. Atahan-Evrenk, N. P. D. Sawaya and A. Aspuru-Guzik, “Coherent Dynamics of Mixed Frenkel and Charge Transfer Excitons in Dinaphtho[2,3-*b*:2’3’-*f*]thieno[3,2-*b*]-thiophene Thin Films: The Importance of Hole Delocalization,” *J. Phys. Chem. Lett.* **7**, 1374–1380 (2016).
- T. Fujita and Y. Mochizuki, “Development of the Fragment Molecular Orbital Method for Calculating Nonlocal Excitations in Large Molecular Systems,” *J. Phys. Chem. A* **122**, 3886–3898 (2018).

1. Development of Large-Scale GW Method for Applications to Organic Optoelectronic Materials[1)]

Organic electronics based on π-conjugated molecules or polymers have attracted considerable attention due to their attractive features. Predicting the charged-transport levels or optical excitations is essential for understanding the electronic processes governing the device operation and for rationally designing novel materials. The successful theoretical descriptions of charged and neutral excited states require an accurate quantum mechanical method: In addition, the effects of polarizable environment must be appropriately taken into account. For example, an electron addition or removal of a molecule induces the polarization of the surrounding molecules, which results in the reduction of HOMO–LUMO gap. The polarization induced by the neutral excitation (creation of electron–hole pair) increases with increasing the electron–hole separation, leading to the relative stabilization of the charge-separated states. Note that such the environmental polarization is state-specific and cannot be treated by a standard electrostatic embedding scheme.

Here, we present a method that can treat both the electron correlation and the state-specific polarization, on the basis of the fragment molecular orbital and GW methods. The GW is a many-body Green's function theory and can offer an accurate and practical scheme to calculate a quasiparticle energy corresponding to an ionization potential or an electron affinity. Electronically excited states can be also computed in combination with Bethe-Salpeter equation method. In this study, we develop the large-scale GW method based on the FMO method. The implementation is based on the fragmentation approximation of the polarization function and the combined GW and Coulomb-hole plus screened exchange approximations for self-energies. As well as the ground-state polarization treated in the FMO method, the FMO-GW method can describe the state-specific polarization effect.

The fragment-based GW was demonstrated in application to the charge-transfer states formed across the pentacene (PEN)/C_{60} bilayer heterojunction. The local interface structure approximately contains 2,000 atoms, with external molecules in the total bilayer heterojunction structure being treated by external point charges. The CT excitation energies were estimated from the quasiparticle energies and electron–hole screened Coulomb interactions and are in reasonable agreement with experimental estimates from the external quantum efficiency measurements. We highlight the impact of the induced polarization effects on the electron–hole energetics.

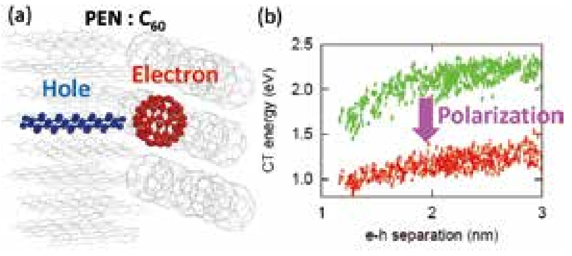

Figure 2. (a) The atomic structure of pentacene/C_{60} local interface. (b) The CT excitation energy with respect to electron–hole separation.

2. Polarization Energy of Pentacene Clusters[2)]

We investigate the electronic states of PEN clusters. The electronic states of PEN have been studied by calculations for an isolated molecule or molecular crystals. Although an isolated PEN molecule and PEN crystals have been well studied, the evolution of electronic states from the gas to the solid phase still remains unclear. In this study, we employ PEN clusters, $(\mathrm{PEN})_N$ (N = 3, 14, 33), as model systems and consider the effects of molecular packing and intermolecular interactions on the electronic states. Figure 3(b) show the HOMO–LUMO gap and S1 excitation energy of a PEN molecule in the central region in the cluster structures. The HOMO–LUMO gap and S1 excitation energy of an isolated PEN molecule are 4.83 and 2.08 eV, respectively, at the GW@B3LYP/6-31G* level. The HOMO–LUMO gap decreases with increasing the cluster size. For the intramolecular excited states, the reduction of the HOMO–LUMO gap is compensated by the weakening of the electron–hole attraction, leaving the excitation energy unchanged.

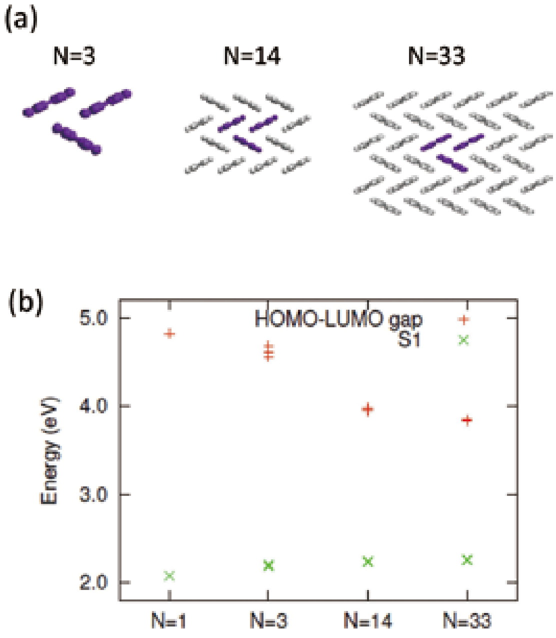

Figure 3. (a) The structures of PEN clusters. (b) The HOMO–LUMO gap and S1 excitation energy of a pentacene molecule in the central regions in cluster structurees.

References

1) T. Fujita, Y. Noguchi and T. Hoshi, *J. Chem. Phys.*, accepted.
2) T. Fujita, in preparation.

Functional Dynamics of Biomolecular Machines Revealed by Theoretical Methods

Department of Theoretical and Computational Molecular Science
Division of Theoretical and Computational Molecular Science

OKAZAKI, Kei-ichi
Research Associate Professor
[keokazaki@ims.ac.jp]

Education

2004	B.S. Kyoto University
2006	M.S. Kobe University
2009	Ph.D. Kobe University

Professional Employment

2007	JSPS Research Fellow (DC2)
2009	JSPS Postdoctoral Fellow (PD)
2009	Postdoctoral Fellow, Waseda University
2010	Part-time Lecturer, Waseda University
2011	Postdoctoral Fellow, National Institutes of Health, U.S.A.
2012	JSPS Postdoctoral Fellow for Research Abroad
2013	Postdoctoral Fellow, Max Planck Institute of Biophysics, Germany
2016	Research Associate Professor, Institute for Molecular Science

Award

2014	Early Career Award in Biophysics, Biophysical Society of Japan

Member

Post-Doctoral Fellow
  MAHMOOD, Md Iqbal
  JAUNET-LAHARY, Titouan

Secretary
  CHIBA, Fumika

Keywords Theoretical Biophysics, Molecular Motors, Transporter

Functional dynamics plays an important role when biomolecular machines fulfill their functions. For example, motor proteins walk on the rail or rotate relative to the stator by using ATP hydrolysis energy. Transporter proteins transport their substrates across the membrane by changing their conformation between the inward-open and outward-open states. We aim to clarify molecular mechanism of these precise, yet dynamic nano-machines developed by nature.

Functional dynamics of biomolecular machines involve wide spectrum of intricate motions and reactions. In order to understand such dynamics, we need a multiscale approach to cover full range of these motions and reactions. Conventional atomistic molecular dynamics (MD) simulations alone cannot cover millisecond-long (or even longer) functional dynamics, especially for a large system like typical biomolecular machines. Thus, we use techniques like importance sampling, coarse-graining, and statistical/kinetic modeling to tackle this problem.

We have been working on biomolecular motors such as ATP synthase and chitinase. ATP synthase is a rotary motor that produces most of ATP required in the cell. It is composed of two rotary motors: F_o and F_1. F_o motor is embedded in the membrane driven by proton gradient, while F_1 motor is driven by ATP hydrolysis reaction. We studied how rotation of F_1 is caused by elementary steps such as product release from the catalytic site. Chitinase is a new type of molecular motor that uses hydrolysis energy of single chitin chain, a polysaccharide from exoskeleton of crab *etc.*, for its unidirectional motion. The sliding motion of chitin chain into the catalytic site of chitinase was studied by atomistic simulations. We also developed a novel framework to estimate free energy profiles and diffusion coefficient from single-molecule trajectories.

Transporters are membrane proteins that transport their substrates across the membrane. We have studied Na^+/H^+ antiporter that exchanges sodium ions and protons inside and outside the cell. The ion-transport cycle was simulated in atomic detail with the transition path sampling technique. The simulations predicted the mutation that can speed up the ion transport, which was confirmed by experiments. Another membrane-associated protein, F-BAR protein Pacsin1 that remodels the membrane, is our interest too. The curvature induction and sensing of Pacsin1 on the membrane was studied by multiscale MD simulations using both all-atom and coarse-grained models.

Selected Publications

- K. Okazaki and G. Hummer, "Phosphate Release Coupled to Rotary Motion of F_1-ATPase," *Proc. Natl. Acad. Sci. U.S.A.* **110**, 16468–16473 (2013).
- K. Okazaki and G. Hummer, "Elasticity, Friction, and Pathway of γ-Subunit Rotation in F_oF_1-ATP Synthase," *Proc. Natl. Acad. Sci. U.S.A.* **112**, 10720–10725 (2015).
- A. Nakamura, K. Okazaki, T. Furuta, M. Sakurai and R. Iino, "Processive Chitinase is Brownian Monorail Operated by Fast Catalysis after Peeling Rail from Crystalline Chitin," *Nat. Commun.* **9**, 3814 (2018).
- K. Okazaki, D. Wöhlert, J. Warnau, H. Jung, Ö. Yildiz, W. Kühlbrandt and G. Hummer, "Mechanism of the Electroneutral Sodium/Proton Antiporter PaNhaP from Transition-Path Shooting," *Nat. Commun.* **10**, 1742 (2019).

1. Mechanism of Unidirectional Motions of Chitinase

Processive cellulase and chitinase recently have been cast new light as a different type of biomolecular motors that use hydrolysis energy of polysaccharides for their unidirectional movements. With the high-precision single-molecule experiments, it was shown that chitinase SmChiA showed fast unidirectional movement of ~50 nm s^{-1} with 1-nm forward and backward steps.[1)] The rate constants of the hydrolysis reaction and decrystallization of single chitin chain were also clarified. The sliding motion of chitin chain into the catalytic site of chitinase was simulated by atomistic simulations. These results suggested that chitinase works by the burnt-bridge Brownian ratchet mechanism. We have been developing a novel framework to estimate its diffusion model from the single-molecule trajectories behind this mechanism too.

2. Mechanism of Na^+/H^+ Antiporter and Engineering of a Faster Transporter

Na^+/H^+ antiporters control pH and Na^+ concentration in the cell by exchanging sodium ions and protons across lipid membranes. They belong to the cation/proton antiporter (CPA) superfamily, and prevail in all domains of life. The archaeal Na^+/H^+ antiporters PaNhaP from *Pyrococcus abyssi* and MjNhaP1 from *Methanocaldococcus jannaschii* as well as human NHE1, which is linked to a wide spectrum of diseases from heart failure to autism and has no structure solved yet, are electroneutral antiporters of the CPA1 family, exchanging one proton against one sodium ion. As a model system in mechanistic studies of electroneutral Na^+/H^+ exchange, we studied the transport mechanism of PaNhaP.[2)]

Na^+/H^+ antiporters use the gradient of either sodium ion or proton to drive the uphill transport of the other ion (Figure 1A). The conformational transition of the transporter makes the ion-binding site accessible from either side of the membrane in the alternating manner. For PaNhaP, the inward-open conformation was obtained by X-ray crystallography, while the outward-open conformation is not known experimentally. We modelled the outward-open conformation by MDFF flexible fitting to the low-resolution outward-open structure of the homologous MjNhaP1 from cryo-EM, followed by the long equilibrium MD simulations. It was shown that the transporter domain moves ~3.5 Å in the direction normal to the membrane to take the outward-open state (Figure 1B).

The inward-open and outward-open conformations described above only provides the end points of the ion-transport. The transition dynamics between the two states is central to the transport mechanism, revealing at once rate-limiting steps, substrate pathways, and the opening and closing of the gate preventing ion leakage. However, with ion exchange occurring on a timescale of seconds at ambient conditions, regular MD simulations are far too slow to resolve transitions. Instead, we can resort to importance sampling of transition dynamics. To sample unbiased transition paths between the inward- and outward-open states, we used techniques from the transition path sampling.

In analysis of the transition paths, we found hydrophobic gates above and below the ion-binding site, which open and close in response to the domain motions (Figure 1C). From the reaction coordinate analysis, it was shown that open-close motion of the outside gate (Ile163-Tyr255) is a rate-limiting step of the alternating-access conformational change. Based on this result, we weakened the outside gate by mutating the residues to both alanine. It was expected that this mutation lowers the barrier and makes the ion transport faster. It was confirmed by experiments that the ion-transport speed of the mutant is indeed twice faster than the wild-type transporter.

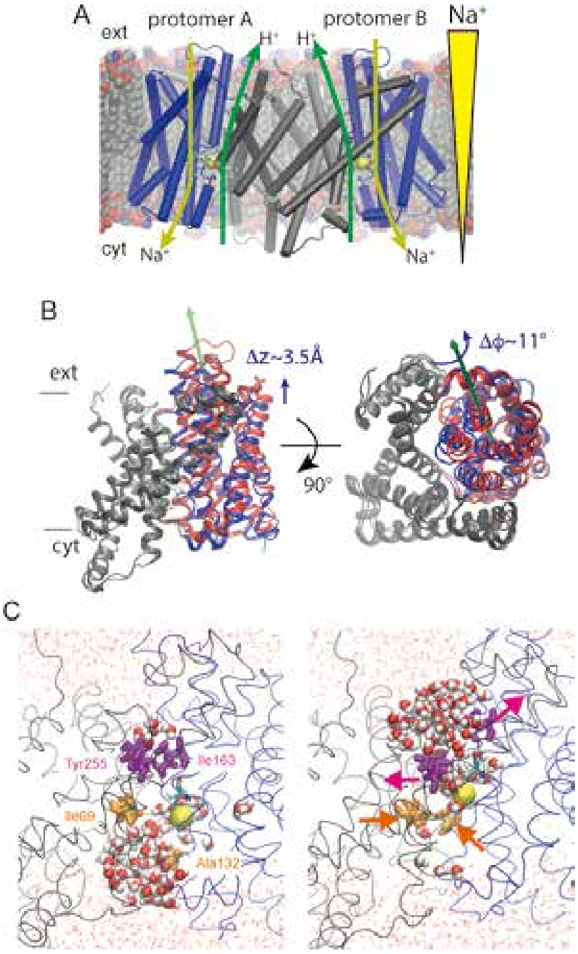

Figure 1. (A) PaNhaP dimer structure. (B) Comparison of the transporter domain between the inward-open (blue) and outward-open (red) states. (C) The outside (purple) and inside (orange) gates found in the transition paths.

References

1) A. Nakamura, K. Okazaki, T. Furuta, M. Sakurai and R. Iino, *Nat. Commun.* **9**, 3814 (2018).

2) K. Okazaki, D. Wöhlert, J. Warnau, H. Jung, Ö. Yildiz, W. Kühlbrandt and G. Hummer, *Nat. Commun.* **10**, 1742 (2019).

Theoretical Study of Heterostructures under Light and Voltage Bias

Department of Theoretical and Computational Molecular Science
Division of Theoretical Molecular Science I

IIDA, Kenji
Assistant Professor

Heterostructures consisting of different materials have various optical and electronic properties depending on their constituents and the interfacial region. We have studied the heterostructures under light and/or voltage bias using our developed first-principles computational program named SALMON.[1]

1. Photoexcited Electron Transfer in Silver/TiO_2 Heterostructure[2]

The photoexcitation of heterostructures consisting of metallic nanoclusters and a semiconductor causes electron and resonance energy transfers and is extensively investigated to develop photocatalysis and optical devices. Using SALMON, we have studied photoexcited electron dynamics in a silver nanocluster/TiO_2 heterostructure. Excited electrons are directly transferred from the silver nanocluster to the TiO_2 layer without passing through the silver conduction band because of photoinduced electrostatic interactions at the silver/TiO_2 interface.

2. Optical Near-Field Excitation of Silicon Semiconductor[3]

We have clarified that direct interband transitions between different wavenumbers can occur in an indirect band gap semiconductor of silicon by an optical near field (ONF). The energy of the absorption edge can be reduced by the ONF excitation. Furthermore, a large number of transitions are induced by the ONF excitation of the realistic silicon system with a complex band structure more than that of a simplified model system.

References

1) M. Noda *et al.*, *Comput. Phys. Commun.* **235**, 356–365 (2019).
2) K. Iida and M. Noda, submitted.
3) M. Noda and K. Iida *et al.*, *Phys. Rev. Appl.* **11**, 044053 (7 pages) (2019).

Theory and Computation of Reactions and Properties in Solutions and Liquids

Department of Theoretical and Computational Molecular Science
Division of Computational Molecular Science

ISHIDA, Tateki
Assistant Professor

We are interested in the projects on ionic liquids (ILs). ILs' projects are focused on the unique dissolution process of cellulose polysaccharides, and the investigation of statical and dynamical properties on ionic liquids including temperature effects.

1. Investigations of Dissolution and Decomposition Mechanisms of a Cellulose Fiber in Ionic Liquids[1] with Molecular Dynamics Simulation

We studied dissolution and decomposition mechanisms of cellulose (I_β) polymers in ILs. In order to investigate motion of cellulose fibers and intermolecular interactions between cellulose molecules and cationic and anionic species in ILs, we carried out molecular dynamics simulation. We employed the 1-ethyl-3-methylimidazolium acetate IL solvent for target system. It was found out that the intermolecular interaction energy between cellulose polymers in the IL are reduced, comparing with that in water. Also, it is shown that decomposition and solvation mechanisms of cellulose polymers can be interpreted not only by considering hydrogen bond strength between cellulose chains in the IL, but also by tracking both the intra- and inter-molecular (cellulose) hydrogen bond breaking processes in the IL.

2. Researches on Statical and Dynamical Properties of Ionic Liquids: Molecular Origin of Low-k Peak of ILs and Dynamical Heterogeneity

We have investigated the molecular level origin of low-k peak (< 0.5 Ang.$^{-1}$) in the structure factor in ILs. In particular, we found out that the structure factor of heterocyclic ring parts in cations largely contribute to low-k peak in ILs. Also, we are going to carry out the study of dynamical properties of ILs, dynamical heterogeneity in ILs at room temperature with molecular dynamics simulation procedure.

Reference

1) T. Ishida, to be submitted to *J. Phys. Chem. B*, in preparation.

Visiting Professors

Visiting Professor

NAKANO, Masayoshi *(from Osaka University)*

Theoretical Study on Photofunctionalities of Open-Shell Molecular Systems

Through close collaboration between theoretical and experimental research groups, we have clarified a new structure-property correlation between diradical character and singlet–triplet energy gap for indenoindenodibenzothiophene diradicals: Inclusion of thiophenes within a quinoidal polycyclic hydrocarbon imparts appreciable diradical character yet retains the large singlet–triplet energy gap, a phenomenon that has no precedent in the literature. Theoretical investigation has revealed that the low aromatic character of thiophene and its electron-rich nature are the key properties leading to these unique findings. This new structure–property relationship is not only extremely important in the field of diradical chemistry and organic electronics, but also provides new insights into the versatility of π-electron chemical bonding. We have also developed a computational method for analyzing the singlet fission dynamics for molecular aggregates beyond dimer models. Using this method, we have clarified unique size and architecture dependences of SF dynamics, which will be useful for constructing novel design guidelines for highly-efficient SF materials.

Visiting Professor

NAKAYAMA, Akira *(from The University of Tokyo)*

First-Principles Simulations of the Molecular Process at the Interface of Liquid/Metal-Oxide

A detailed understanding of the interface between liquid and metal-oxide is fundamental due to its relevance to the broad range of physicochemical phenomena and technological applications. To provide microscopic insight into the structures and dynamics at the liquid/metal-oxide interface, we perform the first-principles molecular dynamics simulations and unveil the intricate molecular process occurring at the interface. In this year, we have focused on the catalytic reactions at the water/CeO_2 and methanol/CeO_2 interfaces and investigated the role of acid-base and redox sites over CeO_2. In particular, we have worked on the following topics: (1) Substrate-specific adsorption of 2-cyanopyridine and hydration reaction over CeO_2. (2) The reaction mechanism for the direct synthesis of dimethyl carbonate from methanol and CO_2 over CeO_2 and ZrO_2. (3) Enhanced sampling employing the temperature-accelerated sliced sampling scheme for constructing multi-dimensional free energy landscape.

Visiting Associate Professor

KIM, Kang *(from Osaka University)*

Theoretical and Computational Research for Complex Fluids and Soft Matters

We are working on theoretical and simulation approaches to reveal various dynamical processes in complex fluids and soft matters. Recent topics in my research are related to slow dynamics in supercooled water. In particular, we have developed the cage jump model for the dynamics of supercooled water. The caged and jumping states of a water molecule are introduced with respect to the hydrogen-bond rearrangement process and describe the motion in supercooled states. It is then demonstrated from the molecular dynamics simulation that the characteristic length and time scales of cage jump motions provide a good description of the self-diffusion constant. Furthermore, using molecular dynamics simulations we have assessed the violations of the Stokes–Einstein and Stokes–Einstein–Debye relationships in supercooled water by the identification of timescales that appropriately characterize transport coefficients, such as translational diffusion constant, rotational relaxation time, and shear viscosity.