RESEARCH ACTIVITIES

Theoretical and Computational Molecular Science

It is our goal to develop new theoretical and computational methods based on quantum mechanics and statistical mechanics to predict and understand the structures, chemical reactions, and functions of molecules in gas and condensed phases including nano- and bio-systems.

Theoretical Studies of Reactions, Functions, and Thermodynamic Properties in Biomolecular and Liquid Systems

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Keywords Complicated Dynamics, Reactions, Functions

Nonlinear intermolecular interactions cause complicated motions in condensed phases, *e.g.* liquids and biological systems. These motions are spatially and temporally heterogeneous and produce both static and dynamic properties of the systems. The spatiotemporal non-uniform motions known as dynamic heterogeneity are considered to be a clue to understand supercooled liquids and glass transition. Furthermore, heterogeneous reaction rates have been found in biological systems. Therefore, understanding of spatiotemporal heterogeneous dynamics is essential to the elucidation of the structure, reactions, functions, and thermodynamic properties of the condensed phase systems.

We have investigated inter- and intra-molecular dynamics of water by using third-order nonlinear spectroscopy which can provide the detailed dynamics that are not available from conventional spectroscopy. We have revealed the molecular mechanism of ultrafast energy relaxation, which is one of dynamical features of water, *i.e.* the fast energy relaxation is caused by the nonlinear strong coupling between the libration motion and other intra- and inter-molecular vibrational motions.

We have also investigated the dynamics of supercooled liquids. We quantified the lifetime of dynamic heterogeneity by introducing the three-time correlation function of density fluctuation, which is sensitive to the time evolution of heterogeneity. Our systematic analysis for various systems shows that the lifetime of dynamic heterogeneity is intimately related to configurational entropy and thus the temperature dependence of lifetime of dynamic heterogeneity is more sensitive to the fragility than that of α-relaxation time determined by one-time correlation function. In addition to the analysis of dynamic heterogeneity with multi-time correlation function, we have revealed the molecular origin of anomalous temperature dependence of isobaric specific heat of water by examining the spatiotemporal fluctuations in terms of specific heat.

We examine heterogeneous conformational dynamics in proteins by exploiting the ideas used in multi-dimensional spectroscopy and glassy dynamics. Currently, we investigate how enzymatic reactions proceed at a molecular level under complicated environmental fluctuations. In addition, we elucidate the emergence of functions, *e.g.* the circadian rhythm in Kai system, as a result of dynamics over a wide range of spatiotemporal scales.

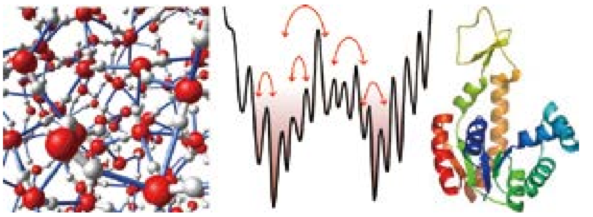

Figure 1. Schematic figure of rugged energy landscape (center) in supercooled water (left) and adenylate kinase (right).

Selected Publications

- T. Yagasaki and S. Saito, *Acc. Chem. Res.* **42**, 1250–1258 (2009), *Annu. Rev. Phys. Chem.* **64**, 55–75 (2013).
- S. Imoto, S. Xantheas and S. Saito, *J. Phys. Chem. B* **119**, 11068–11078 (2015).
- K. Kim and S. Saito, *J. Chem. Phys. (Special Topic on Glass Transition)* **138**, 12A506 (12 pages) (2013).
- S. Saito, I. Ohmine and B. Bagchi, *J. Chem. Phys.* **138**, 094503 (7 pages) (2013).
- J. Ono, S. Takada and S. Saito, *J. Chem. Phys. (Special Topic on Multidimensional Spectroscopy)* **142**, 212404 (13 pages) (2015).

1. Crucial Role of Low-Populated Conformations Facilitating Enzymatic Reactions: Example in Catalysis in Pin1 *cis-trans* Isomerase[1)]

Protein flexibility is essential for enzymes to function, yet the mechanism of catalysis has been highly controversial. Here we elucidate how protein and ligand conformational changes occur along the reaction by examining the *cis-trans* isomerization reaction catalyzed by Pin1 as an example. While free energy profiles can explain the catalytic effect, we show that the enzymatic reaction proceeds through specific conformations, which hereafter we call excited conformational state formed in the reactant. The transition trajectories therefore do not overcome the barrier in a simple stochastic manner. Furthermore, since the excited conformational state is formed by specific hydrogen bonds, the reaction occurs via bond-alternations and the excess energy is efficiently dissipated. As a result, the reaction path is direction-dependent and possesses directionality, *i.e.* different paths are used depending on the reactant character. We expect that the excited conformational states and specific bond switching mechanisms are embedded in broader enzymes.

2. A Reaction Model of Circadian Rhythm in Kai Proteins by Considering Elementary Reactions and Conformational Changes[2)]

Circadian clocks are biological timing system used in various organisms to anticipate daily changes in environment and to adjust their biological activity to the changes. Cyanobacteria are known as the simplest organisms showing a circadian rhythm, where the core oscillator is composed of only three proteins, KaiA, KaiB, and KaiC. KaiC consisting of two domains plays a central role in the circadian rhythm of Kai system, and has autokinase and autophosphatase activities. A periodic phosphorylation and dephosphorylation occur at Ser431 and Thr43 in KaiC. This periodic oscillation is generated with the help of KaiA and KaiB: KaiA promotes the phosphorylation, on the other hand KaiB inhibits KaiA to act on KaiC. Several important elementary processes have recently been unveiled, for example, the phosphorylation and dephosphorylation reactions and conformational changes that might switch between phosphorylation and dephosphorylation phases. It is, however, an open question to integrate these detailed experimental results and explain how the circadian phosphorylation occurs. In almost all previous mathematical models, only the phosphorylation/dephosphorylation reactions have been focused for the circadian rhythm of Kai system. In the present study, we propose a mathematical reaction model of the circadian rhythm in the Kai system based on conformational changes in KaiB and KaiC as well as elementary processes, such as ATP hydrolysis, ADP/ATP exchange, and phosphorylation/dephosphorylation reactions. As a result, an allosteric effect in the domains in KaiC is also considered in the current model. We find that the optimized parameters determined to reproduce the experimental data of the periodic phosphorylation can quantitatively reproduce not only the data of phosphorylation used in the optimization, but also various experimental data not used in the optimization, such as ATPase activity even when KaiA and/or KaiB are absent. In addition, the current model can successfully reproduce the synchronization of oscillation caused by environmental changes. The present study demonstrates that the circadian rhythm is regulated by conformational changes as well as elementary reactions.

3. Crucial Role of Fragmented and Isolated Defects in Persistent Relaxation of Deeply Supercooled Water[3)]

Water is the most common and the most intensively studied liquid in nature. Characteristic properties of water have been well elucidated for temperature above ~200 K. And yet a mystery still remains about the deeply supercooled region: Why and how can water stay in the liquid state even at very low temperature? Experiments show that amorphous ice when heated from very low temperature. undergoes a transition to a highly viscous liquid at 136 K and then crystallizes to ice at 150 K. This water glass transition temperature, T_{G} = 136 K, almost half of the ice melting temperature T_{M}, is much lower than what is expected from the general $T_{\mathrm{G}}/T_{\mathrm{M}} \approx 2/3$ rule of glass formers. The present study, performing extensive trajectory calculations, attempts to clarify what molecular mechanisms could be involved in promoting molecular motions in deeply supercooled water. We find that the structural and dynamical instabilities hidden behind the so-called “no man’s land” the experimentally inaccessible region for liquid water between 235 K and 150 K, strongly influence the properties of deeply supercooled water, through the fragmentation and the consequent isolation of high density (HD) clusters. The fragmentation that starts below 220 K, makes each larger HD cluster scattered into smaller clusters. When the fragmentation is completed at ~190 K, each scattered HD cluster contains only one or two defects. These isolated defects are hardly annihilated in the well-formed hydrogen bond network of low density (LD) molecules. We find that specific 3-coordinated defects play a crucial role to induce slow but persistent structural relaxations and thus lower the T_{G} of water. These defects are exactly the same ones essential in melting ice. The fragmentation of LD clusters in HD network takes place at the temperature of density maximum. The fragmentation scheme provides a unified picture on water properties in a wide temperature range.

References

1) T. Mori and S. Saito, to be submitted.
2) S. Koda and S. Saito, to be submitted.
3) S. Saito, B. Bagchi and I. Ohmine, submitted.

Theory for Optical Response in Nanostructures and Application to Unified Photonic and Electronic Devices

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Keywords Optical Response, Light-Matter Interaction, Nanodevices

Optical response of materials is undoubtedly essential for understanding their physicochemical properties. In conventional theoretical approaches to optical response of materials, two conditions are usually assumed:

(i) A scale of wavelength of an incident light is much longer than material size, *i.e.*, dipole approximation. Thus, a target material is well approximated by a point dipole and the dipole feels a spatially uniform electromagnetic field.

(ii) Electric polarization in a material induced by incident-light excitation inevitably generates a new electromagnetic field, referred to as an "optical near-filed." However, such a self-consistent light–matter (LM) interaction between electron and electromagnetic field dynamics is ignored.

Recent development of nanofabrication and nano-optical techniques requires a more general optical response theory fully taking account of *nonuniform and self-consistent* LM interactions.

We have developed a generalized theoretical description of full (nonuniform and self-consistent) LM interactions with the aim of understanding the optical near-field excitation dynamics in nanostructures. Electron dynamics in nanostructures interacting with an electromagnetic field is described by the time-dependent Kohn-Sham equation, whereas electromagnetic field dynamics is represented by the microscopic Maxwell's equations. The nonuniform LM interaction is considered in the vector potential and the self-consistent LM interaction is described by solving the electron and electromagnetic field coupled equations self-consistently. The coupled equations are solved numerically by using our developed computational program (GCEED: *Grid-based Coupled Electron and Electromagnetic field Dynamics*). Our computational approach is based on a finite-difference method in real-time and real-space. Since the approach employs very simple algorithms, it is highly suitable for massively parallelized computations. Very recently, we newly developed a computational program called SALMON (Scalable Ab-initio Light-Matter simulator for Optics and Nanoscience) including all the functions of the GCEED. By using the SALMON, we are currently computationally designing unified photonic and electronic nanodevices.

We also performed computational design of heterogeneous catalysts to develop efficient and commercially appealing ones, thus reducing the use of expensive rare catalytic metals. The simulations were carried out by using the first-principles, *i.e.*, Car-Parrinello, molecular dynamics simulations.

Selected Publications

- K. Nobusada and K. Yabana, "Photoinduced Electric Currents in Ring-Shaped Molecules by Circularly Polarized Laser Pulses," *Phys. Rev. A* **75**, 032518 (7 pages) (2007).
- K. Nobusada and T. Iwasa, "Oligomeric Gold Clusters with Vertex-Sharing Bi- and Triicosahedral Structures," *J. Phys. Chem. C* **111**, 14279–14282 (2007).
- M. Noda, K. Ishimura, K. Nobusada, K. Yabana and T. Boku, "Massively-Parallel Electron Dynamics Calculations in Real-Time and Real-Space: Toward Applications to Nanostructures of More than Ten-Nanometers in Size," *J. Comput. Phys.* **265**, 145–155 (2014).
- M. Noda, M. Yamaguchi and K. Nobusada, "Second Harmonic Excitation of Acetylene by the Optical Near Field Generated in a Porous Material," *J. Phys. Chem. C* **121**, 11687–11692 (2017).

1. Second Harmonic Excitation of Acetylene by the Optical Near Field Generated in a Porous Material[1)]

We perform first-principles calculations of the photoexcitation dynamics of an acetylene molecule in a metal organic framework, IRMOF-10. Resonant laser excitation of the IRMOF-10 generates an optical near field (ONF) around the two benzene rings that comprise the main framework of the IRMOF-10. Interestingly, along with the ONF of frequency ω, which synchronizes with the resonant frequency of the IRMOF-10, a second harmonic (= 2ω) component of the ONF is generated. The second harmonic component effectively excites the acetylene molecule at a frequency of 2ω, although the incident laser field is in tune with ω. It is noteworthy that the second harmonic excitation is caused by spatial nonuniformity of the ONF interaction. It is completely different from the conventional two-photon excitation and is much more efficient than the two-photon excitation by several orders of magnitude.

2. Development of Theoretical Approach for Describing Electronic Properties of Hetero-Interface Systems under Applied Bias Voltage[2)]

We have developed a theoretical approach for describing the electronic properties of hetero-interface systems under an applied electrode bias. The finite-temperature density functional theory is employed for controlling the chemical potential in their interfacial region, and thereby the electronic charge of the system is obtained. The electric field generated by the electronic charging is described as a sawtooth-like electrostatic potential. Because of the continuum approximation of dielectrics sandwiched between electrodes, we treat dielectrics with thicknesses in a wide range from a few nanometers to more than several meters. Furthermore, the approach is implemented in our original computational program called GCEED. Thus, the approach is capable of comprehensively revealing electronic structure changes in hetero-interface systems with an applied bias. We calculate the electronic structure of a SiO_2-graphene-boron nitride (BN) system in which an electrode bias is applied between the graphene layer and an electrode attached on the SiO_2 film. The electronic energy barrier between graphene and BN is varied with an applied bias, and the energy variation depends on the thickness of the BN film. This is because the density of states of graphene is so low that the graphene layer cannot fully screen the electric field generated by the electrodes. We have demonstrated that the electronic properties of hetero-interface systems are well controlled by the combination of the electronic charging and the generated electric field.

3. An Atomic-Level Insight into the Basic Mechanism Responsible for the Enhancement of the Catalytic Oxidation of Carbon Monoxide on a Cu/CeO_2 Surface[3)]

The reaction mechanisms of CO molecules interacting with a Cu/CeO_2 surface and related morphological modifications occurring upon removal of O atoms to generate CO_2 are investigated by first-principles dynamical simulations complemented by a free-energy sampling technique. We show that the reactivity of oxygen atoms located in the first layer in the vicinity of the Cu site is remarkably high because of a reduction of the O coordination number. Moreover, we evidence that the doped Cu atoms are responsible for an enhancement of the exposure of other surrounding O atoms, even below the first surface layer, which can then easily react with CO and are gradually removed from the system in the oxidation process. The underlying mechanism responsible for such a high catalytic reactivity of the Cu/CeO_2 surface toward CO oxidation is rationalized in terms of the characteristics of the doped Cu. In fact, this copper site is responsible for providing an increasing number of O atoms participating in the catalysis by exposing subsequently all O atoms in the vicinity which are likely to react with an approaching CO. This peculiarity of the Cu atoms extends to O atoms which initially can be deeply buried up to the fourth layer underneath the surface.

4. Large Hyperpolarizabilities of the Second Harmonic Generation Induced by Nonuniform Optical Near Fields[4)]

We studied the optical selection rules and hyperpolarizabilities of a second harmonic generation (SHG) induced by a nonuniform optical near field (ONF) on the basis of first-principles calculations. The excitations of the symmetric and asymmetric molecules para-dinitrobenzene (pDNB) and para-nitroaniline (pNA), respectively, were investigated according to the time-dependent density functional theory. By calculating the ONF excitation dynamics of symmetric pDNB, we demonstrated that the ONF causes the SHG even in symmetric materials because of nonuniformity of the field in space. To quantitatively evaluate the intensity of the SHG induced by the ONF, we estimated the first hyperpolarizability, $\beta(2\omega)$, of asymmetric pNA for both of the usual far-field light and ONF excitations. Our results showed that $\beta(2\omega)$ for the ONF excitation is 1–2 orders of magnitude larger than that for the far-field excitation when the distance between the source of the ONF and pNA is around 10 Å.

References

1) M. Noda, M. Yamaguchi and K. Nobusada, *J. Phys. Chem. C* **121**, 11687–11692 (2017).
2) K. Iida, M. Noda and K. Nobusada, *J. Chem. Phys.* **146**, 084706 (10 pages) (2017).
3) K. Koizumi, K. Nobusada and M. Boero, *Phys. Chem. Chem. Phys.* **19**, 3498–3505 (2017).
4) M. Yamaguchi and K. Nobusada, *J. Phys. Chem. C* **120**, 23748–23755 (2016).

Award

NOBUSADA, Katsuyuki; Award for excellence in research projects using the HPCI System (2017).

Advanced Electronic Structure Theory in Quantum Chemistry

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Keywords Electronic Structure Theory, Quantum Chemistry, Computational Chemistry

Computational quantum chemistry, that is, practicing quantum chemical theory using computers, is now considered to be a powerful means to provide detailed analysis of chemical phenomena. The focus of our group is to develop methods and algorithms of molecular electronic structure calculations, which are capable of supplying electronic-level interpretation and reliable prediction of chemical characters, reactivity, energetics, and spectroscopic properties of molecular systems. Also, we are interested in applying the methods to challenging chemical systems. Recently, we have developed advanced multireference methods to describe highly-correlated many-electron wavefunction, which cannot be qualitatively accounted for with mean-field or one-electron theory (*e.g.*, density functional theory). The multireference wavefunction need be represented with a quantum superposition of multiple electron configurations; however, this gives rise to a high computational expense because the degree of the superposition is in general exponentially dependent on the system size. We approach the multireference problems using the density matrix renormalization group (DMRG), which is originally a method of condensed matter physics to solve strong correlation phenomena in physical models. We developed an efficient implementation for adapting DMRG to quantum chemical calculation, in which the DMRG is exploited to describe static correlation in combination with the complete active space (CAS) model. Our DMRG-based methods have shown to be capable of handling very large correlation space, which far exceeds the limitation of conventional methods. We have further introduced a scheme to additively account for dynamic correlation on top of active-space DMRG wavefunction. Using these methods, we carried out chemical applications to multireference electronic systems, ranging from organic material molecules, such as radicals of graphene nanoribbons, to transition metal complexes, such as tetranuclear manganese cluster.

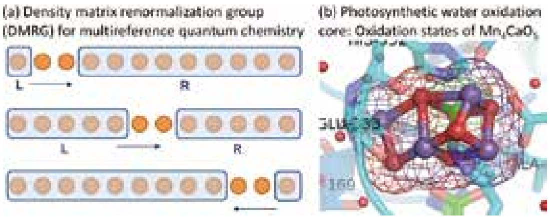

Figure 1. (a) Algorithm of density matrix renormalization group (DMRG) and (b) Its application to manganese cluster.

Selected Publications

- Y. Kurashige and T. Yanai, "High-Performance *Ab Initio* Density Matrix Renormalization Group Method: Applicability to Large-Scale Multireference Problems for Metal Compounds," *J. Chem. Phys.* **130**, 234114 (21 pages) (2009).
- W. Mizukami, Y. Kurashige and T. Yanai, "More π Electrons Make a Difference: Emergence of Many Radicals on Graphene Nanoribbons Studied by *Ab Initio* DMRG Theory," *J. Chem. Theory Comput.* **9**, 401–407 (2013).
- Y. Kurashige, G. K-L. Chan and T. Yanai, "Entangled Quantum Electronic Wavefunctions of the Mn_4CaO_5 Cluster in Photosystem II," *Nat. Chem.* **5**, 660–666 (2013).

1. Direct Observation of the Ultrafast Evolution of Open-Shell Biradical in Photochromic Radical Dimer[1)]

Delocalized biradicals have been extensively studied because of fundamental interests to singlet biradicals and several potential applications such as to two-photon absorption materials. However, many of the biradical studies only focus on the static properties of the rigid molecular structures. It is expected that the biradical properties of the delocalized biradicals are sensitive to the subtle changes of the molecular structures and their local environments. Therefore, the studies of the dynamic properties of the system will give further insight into stable radical chemistry. In this study, we directly probe the ultrafast dynamics of the delocalized biradical of a photochromic radical dimer, pentaarylbiimidazole (PABI), by time-resolved visible and infrared spectroscopies and quantum chemical calculations with the extended multistate complete active space second-order perturbation theory (XMS-CASPT2). While the photogenerated transient species was considered to be a single species of the biradical, the present ultrafast spectroscopic study revealed the existence of two transient isomers differing in the contributions of biradical character. The origin of the two metastable isomers is most probably due to the substantial van der Waals interaction between the phenyl rings substituted at the imidazole rings. Unraveling the temporal evolution of the biradical contribution will stimulate to explore novel delocalized biradicals and to develop biradical-based photofunctional materials utilizing the dynamic properties (**Figure 2**).

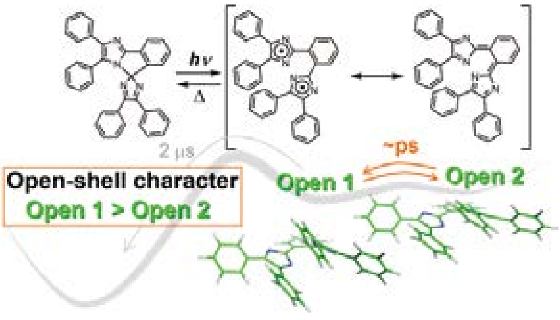

Figure 2. Quantum chemical calculations with XMS-CASPT2 method were performed on PABI in order to illuminate molecular- and electronic-level details of its photochromic ring opening and closing reaction.

2. Projector Augmented Wave Method Incorporated into Gauss-Type Atomic Orbital Based Density Functional Theory[2)]

The Projector Augmented Wave (PAW) method developed by Blöchl is well recognized as an efficient, accurate pseudopotential approach in solid-state density functional theory (DFT) calculations with the plane-wave basis. Here we present an approach to incorporate the PAW method into the Gauss-type function (GTF) based DFT implementation, which is widely used for molecular quantum chemistry calculations. The nodal and high-exponent GTF components of valence molecular orbitals (MOs) are removed or pseudized by the ultrasoft PAW treatment, while there is elaborate transparency to construct an accurate and well-controlled pseudopotential from all-electron atomic description and to reconstruct an all-electron form of valence MOs from the pseudo MOs. The smoothness of the pseudo MOs should benefit the efficiency of GTF-based DFT calculations in terms of elimination of high-exponent primitive GTFs and reduction of grid points in the numerical quadrature. The processes of the PAW method are divided into basis-independent and -dependent parts. The former is carried out using the previously developed PAW libraries libpaw and atompaw. The present scheme is implemented by incorporating libpaw into the conventional GTF-based DFT solver. The details of the formulations and implementations of GTF-related PAW procedures are presented. The test calculations are shown for illustrating the performance. With the near-complete GTF basis at the cc-pVQZ level, the total energies obtained using our PAW method with suited frozen core treatments converge to those with the conventional all-electron GTF-based method with a rather small absolute error (**Figure 3**).

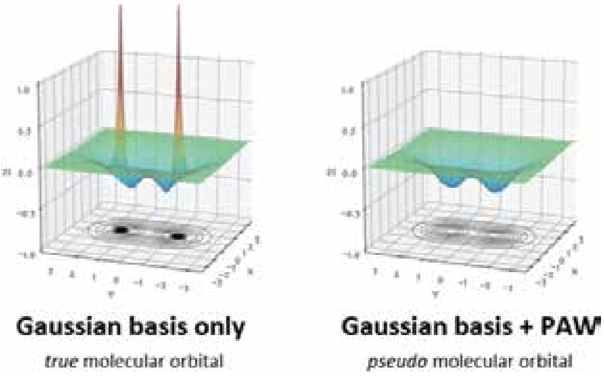

Figure 3. Plots of exact and pseudo molecular orbitals determined for the F_2 molecule with Gauss-type atomic basis functions without and with the PAW pseudopotential treatment.

References

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2) X.-G. Xiong and T. Yanai, *J. Chem. Theory Comput.* **13**, 3236–3249 (2017).

Award

YANAI, Takeshi; The 2017 Pople Medal of Asia-Pacific Conference of Theoretical and Computational Chemistry.

Theoretical Studies of Chemical Dynamics in Condensed and Biomolecular Systems

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Keywords Quantum Dynamics, Energy/Charge Transfer, Photosynthetic Light Harvesting

Photosynthesis provides the energy source for essentially all living things on Earth, and its functionality has been one of the most fascinating mysteries of life. Photosynthetic conversion of the energy of sunlight into its chemical form suitable for cellular processes involves a variety of physicochemical mechanisms. The conversion starts with the absorption of a photon of sunlight by one of the light-harvesting pigments, followed by transfer of electronic excitation energy to the reaction center, where charge separation is initiated. At low light intensities, surprisingly, the quantum efficiency of the transfer is near unity. A longstanding question in photosynthesis has been the following: How does light harvesting deliver such high efficiency in the presence of disordered and fluctuating dissipative environments? Why does not energy get lost? At high light intensities, on the other hand, the reaction center is protected by regulation mechanisms that lead to quenching of excess excitation energy in light harvesting proteins. The precise mechanisms of these initial steps of photosynthesis are not yet fully elucidated from the standpoint of molecular science. Particularly, recent observations of long-lived beating phenomena in two-dimensional electronic spectra of photosynthetic pigment-protein complexes stimulated a huge burst of activity in an interdisciplinary community of molecular science and quantum physics.

Selected Publications

- A. Ishizaki and Y. Tanimura, "Quantum Dynamics of System Strongly Coupled to Low-Temperature Colored Noise Bath: Reduced Hierarchy Equations Approach," *J. Phys. Soc. Jpn.* **74**, 3131–3134 (2005).
- A. Ishizaki and G. R. Fleming, "Unified Treatment of Quantum Coherent and Incoherent Hopping Dynamics in Electronic Energy Transfer: Reduced Hierarchy Equation Approach," *J. Chem. Phys.* **130**, 234111 (10 pages) (2009).
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- 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, G. R. Fleming, L. X. Chen, A. Aspuru-Guzik, A. Buchleitner, D. D. F. Coker, G. S. Engel, R. van Grondelle, A. Ishizaki, D. M. Jonas, J. S. Lundeen, J. K. McCusker, S. Mukamel, J. P. Ogilvie, A. Olaya-Castro, M. A. Ratner, F. C. Spano, K. B. Whaley and X. Y. Zhu, "Using Coherence to Enhance Function in Chemical and Biophysical Systems," *Nature* **543**, 647–656 (2017).

1. Using Coherence to Enhance Function in Chemical and Biophysical Systems

Coherence phenomena arise from interference, or the addition, of wave-like amplitudes with fixed phase differences. Although coherence has been shown to yield transformative ways for improving function, advances have been confined to pristine matter and coherence was considered fragile. However, recent evidence of coherence in chemical and biological systems suggests that the phenomena are robust and can survive in the face of disorder and noise. We surveyed the state of recent discoveries, present viewpoints that suggest that coherence can be used in complex chemical systems, and discuss the role of coherence as a design element in realizing function.1)

2. Modeling of High Frequency Vibrational Motion in Quantum Dynamics of Singlet Fission Process

Singlet fission is a spin-allowed energy conversion process whereby a singlet excitation splits into two spin-correlated triplet excitations residing on adjacent molecules and has a potential to dramatically increase the efficiency of organic photovoltaics. Recent time-resolved nonlinear spectra of pentacene derivatives have shown the importance of high frequency vibrational modes in efficient fission. In this work, we explored impacts of vibration-induced fluctuations on fission dynamics through quantum dynamics calculations with parameters from fitting measured linear and nonlinear spectra. We demonstrated that fission dynamics strongly depends on the frequency of the intramolecular vibrational mode. Furthermore, we examined the effect of two vibrational modes on fission dynamics. Inclusion of a second vibrational mode creates an additional fission channel even when its Huang-Rhys factor is relatively small. Addition of more vibrational modes may not enhance fission *per se*, but can dramatically affect the interplay between fission dynamics and the dominant vibrational mode.2)

3. Spin Hall Effect without Space Inversion Symmetry

A master equation approach based on an optimized polaron tranThe spin Hall effect (SHE), first proposed almost half a century ago, has been investigated and observed in a large variety of systems including electrons in semiconductors such as GaAs and In GaAs, photons passing through an interface with a refractive index gradient, and atomic Bose-Einstein condensates subject to synthetic gauge fields. In all of these studies, the SHE arises from the spin–orbit interaction which requires space inversion symmetry (SIS) breaking. In this work, we showed that the SHE can appear in a totally different but equally broad class of many-body systems with SIS. In particular, we demonstrated that the SHE can emerge from the dipole–dipole interaction (DDI), which preserves SIS. The DDI-based SHE is expected to occur in, for example, heteronuclear molecules, strongly magnetic atoms, Rydberg excitations, electron gases, etc. The SHE arising from the DDI offers a complementary tool to generate spin currents, which constitutes an essential ingredient in spintronics.3)

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Awards

ISHIZAKI, Akihito; 18th Sir Martin Wood Prize (2016).
ISHIZAKI, Akihito; Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology The Young Scientists’ Prize (2017).

Theoretical Study on Photochemistry and Catalysis

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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)

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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 hetero-junction 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. Structure and Reactivity of Nanolcluster Catalysts

In the supported nanocluster (NC) catalysts, the structure and electronic state of NC are relevant for the catalytic activity. We have investigated these factors together with bond activation of Cu-M binary NCs using DFT calculations.1) We adopted the computational model of $Cu_{38-n}M_n$ (M = Ru, Rh, Pd, Ag, Os, Ir, Pt, and Au; n = 1, 2, and 6). In the most stable structure of $Cu_{37}M_1$ (M = Ru, Ph, Os, Ir, Group 7 and 8), the M atom takes the core position, while in $Cu_{37}M_1$ (M = Pd, Ag, Pt, Au, Group 9 and 10), it takes the shell (center or corner) position. The segregation energy defined by energy difference between the most stable $Cu_{37}M_1$ (core) and the next stable structure $Cu_{37}M_1$ (shell), was found to be proportional to *d* orbital population, suggesting that the M atom with unoccupied *d* orbitals tends to take the core position. Due to the alloy effects, the adsorption energy and bond activation to CO and NO are enhanced in binary NCs, for example, on $Cu_{32}Ru_6$ NC.

We also studied the single atom catalyst, $M_1/\gamma\text{-}Al_2O_3$ (M = Pd, Fe, Co, Ni) for the low-temperature CO oxidation and found that the +II oxidation state of the M atom is crucial for its catalytic activity. We have theoretically proposed that $Ni_1/\gamma\text{-}Al_2O_3$ is an alternative efficient catalyst that has low energy barriers.2)

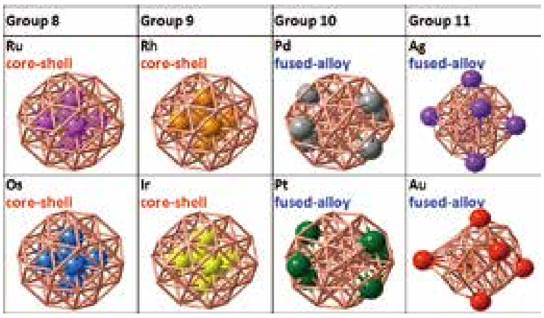

Figure 1. Stable structures of CuM (M = Ru, Rh, Pd, Ag, Os, Ir, Pt) NC.

2. Electronic Resonance States

For investigating the electronic resonance states, we have developed the complex absorbing potential (CAP)/SAC-CI method with new potential. We have systematically applied the method to the series of molecules; *i.e.* double-bond and hetero-aromatic compounds, DNA/RNA bases and their derivatives, and cyano-containing molecules.3) These successful applications showed that the CAP/SAC-CI method is a robust protocol for predicting the π* resonances of the molecules and clusters.

We also have developed another robust approach for locating the resonance states in the framework of extrapolation method; that is, analytic continuation of the coupling constant (ACCC) approach with some new stabilization potentials.4) The results for the model potential and some small molecules showed that ACCC SAC-CI is also a reliable approach for locating the electronic resonance states.

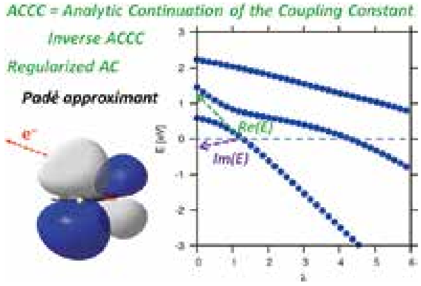

Figure 2. Analytic continuation of the coupling constant (ACCC) SAC-CI method for electronic resonance states.

3. Chemical Reaction under Extreme High Pressure

We have developed the theory for investigating the effects of high pressure on chemical reaction, XP-PCM (Polarizable Continuum Model for eXtreme Pressure). The pressure effects have been studied in the solid state physics, but, not so well in molecular systems. So far, there are accumulated experimental data of the pressure effects for molecular systems. We applied our method to the excited states of furan in condensed phase and found that level crossing and significant changes in valence-Rydberg mixing occur under the high pressure. In this work, we have investigated the pressure effects on chemical reaction, more specifically, Diels-Alder cycloaddition of cyclopentadiene and C_{60}.5) It was shown that the energy barrier drastically reduces and the reaction becomes even barrier-less under extreme high pressure.

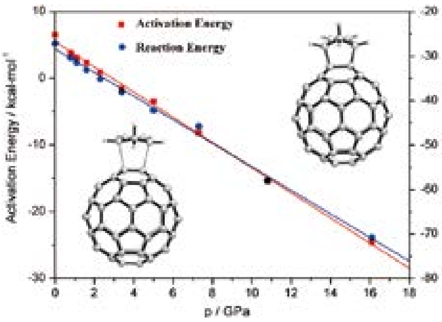

Figure 3. Extreme pressure effects on chemical reaction: Diels-Alder cycloaddition of cyclopentadiene and C_{60}.

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4) T. Sommerfeld, J. B. Melugin, P. Hamal and M. Ehara, *J. Chem. Theory Comput.* **13**, 2550–2560 (2017).
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* IMS International Internship Program

Development of New Molecular Dynamics Algorithms for Biomolecular Systems

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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.

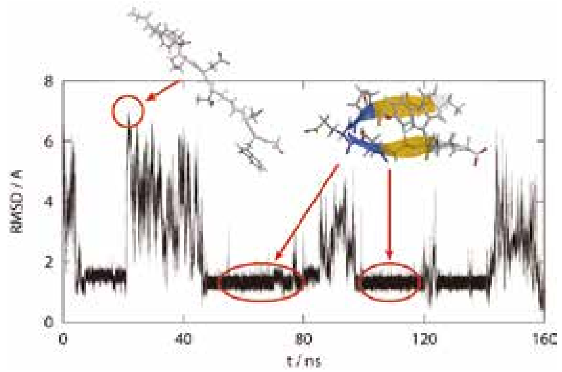

Figure 1. Time series of protein folding simulation.

We are also interested in amyloid fibrils, which are insoluble aggregates of misfolded fibrous proteins and associated with more than 20 human neurodegenerative diseases (Figure 2). For example, Alzheimer's disease is related to amyloid-β (Aβ) peptides. To overcome these diseases, it is essential to understand amyloid genesis and disruption. We perform such MD simulations of amyloid fibrils.

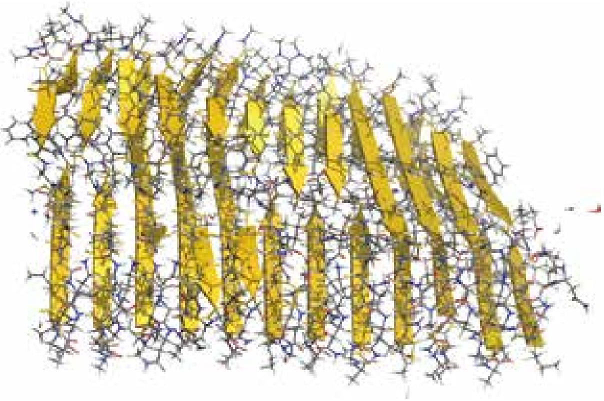

Figure 2. Snapshot of amyloid fibril.

Selected Publications

- Y. Mori and H. Okumura, "Pressure-Induced Helical Structure of a Peptide Studied by Simulated Tempering Molecular Dynamics Simulations," *J. Phys. Chem. Lett.* **4**, 2079–2083 (2013).
- 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).
- H. Okumura and S. G. Itoh, "Amyloid Fibril Disruption by Ultrasonic Cavitation: Nonequilibrium Molecular Dynamics Simulations," *J. Am. Chem. Soc.* **136**, 10549–10552 (2014).
- 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. Molecular Dynamics Simulations Predict Only One End of Aβ Amyloid Fibril Has Open Conformations

To understand the amyloid extension mechanism, we must understand the amyloid fibril structure and fluctuation at the fibril end, which has not been revealed to date. We revealed these features by all-atom MD simulations of Aβ42 and Aβ40 fibrils in explicit water.1) The structure and fluctuation were observed to differ between the two ends, as shown in Figure 3. At the even end, the Aβ peptide always took a closed form wherein β1 and β2 were closely spaced. The Aβ peptide fluctuated more at the odd end and took an open form wherein the two β-sheets were well separated. The differences were attributed to the stronger β-sheet formation by the β1 exposed at the even end than the β2 exposed at the odd end. Along with the small fluctuations at the even end, these results explain why the fibril extends from one end only, as observed in experiments. Our MD results agree well with recent observations by high-speed atomic force microscopy.

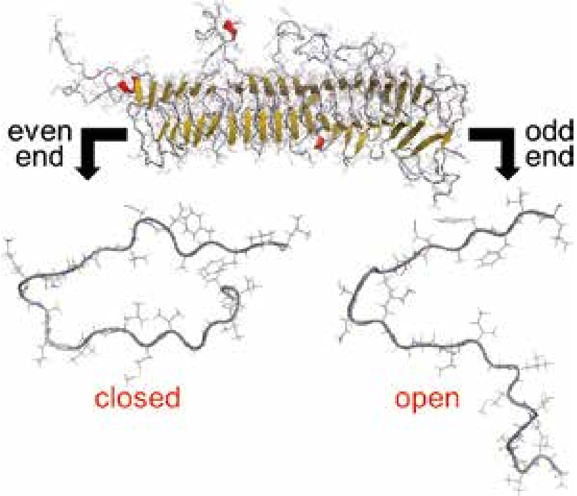

Figure 3. Typical conformation of an Aβ42 amyloid fibril and side views of the Aβ42 monomer at the even and odd ends.

2. Rapid QM/MM Approach for Biomolecular Systems under Periodic Boundary Conditions

A quantum mechanical/molecular mechanical (QM/MM) approach based on the density-functional tight-binding (DFTB) theory is a useful tool for analyzing chemical reaction systems in detail. In this study, an efficient QM/MM method was developed by the combination of the DFTB/MM and particle mesh Ewald (PME) methods.2) Because the Fock matrix, which is required in the DFTB calculation, is analytically obtained by the PME method, the Coulomb energy is accurately and rapidly computed. For assessing the performance of this method, DFTB/MM calculations and molecular dynamics simulation are conducted for a system consisting of two amyloid-β(1-16) peptides and a zinc ion in explicit water under periodic boundary conditions, as shown in Figure 4. As compared with that of the conventional Ewald summation method, the computational cost of the Coulomb energy by utilizing the present approach is drastically reduced.

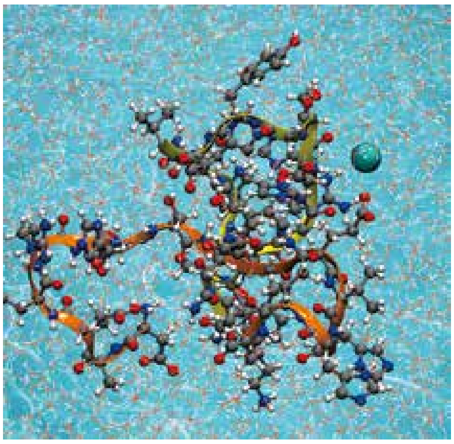

Figure 4. Test system consists of two amyloid-β(1-16) peptides, zinc ion, and water molecules.

3. Molecular Dynamics Simulation for Structural Basis of TRPA1 Inhibition by HC-030031

Pain is a harmful sensation that arises from noxious stimuli. Transient receptor potential ankyrin 1 (TRPA1) is one target for studying pain mechanisms. TRPA1 is activated by various stimuli such as noxious cold, pungent natural products and environmental irritants. Since TRPA1 is an attractive target for pain therapy, a few TRPA1 antagonists have been developed and some function as analgesic agents. Prof. Tominaga and his coworkers in National Institute for Physiological Sciences revealed that the TRPA1 antagonist HC-030031 (HC) failed to inhibit frog TRPA1 (fTRPA1) and zebrafish TRPA1 activity, but did inhibit human TRPA1 (hTRPA1). We collaborated with them and performed MD simulations of HC and hTRPA1 and found that HC stably binds to N855 in hTRPA1.3) These findings provide novel insights into the structure-function relationship of TRPA1 and could lead to the development of more effective analgesics targeted to TRPA1.

References

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3) R. Gupta, S. Saito, Y. Mori, S. G. Itoh, H. Okumura and M. Tominaga, *Sci. Rep.* **6**, 37460 (14 pages) (2016).

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Theoretical Studies on Molecular Aggregates

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Professional Employment

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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 exhibit characteristic optical and electronic properties that are not observed in isolated molecules. For example, their photophysical processes include electronic energy transfer and charge separations, which are desirable for low-cost electronic devices.

We study optoelectronic properties and quantum dynamics of molecular aggregates. More specifically, we focus on energy and charge transfer dynamics, energy conversions, and structure-property relationship.

It is still challenging to simulate quantum dynamics of energy or charge transfer in condensed systems. An exciton or electron wave function can be delocalized by electronic couplings due to molecular interactions; it is modulated by molecular vibrations. It is thus essential to consider electronic couplings and electron–phonon couplings on the same footing. 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. An electronic structure of an aggregate is described as tight-binding Hamiltonian with electronic couplings obtained from the fragment molecular orbital method. The energy or charge dynamics is described by quantum dynamics methods with incorporating finite-temperature effects and electron–phonon couplings. The combine computational approach allows for bottom-up descriptions of energy or charge transfer dynamics in realistic molecular aggregates.

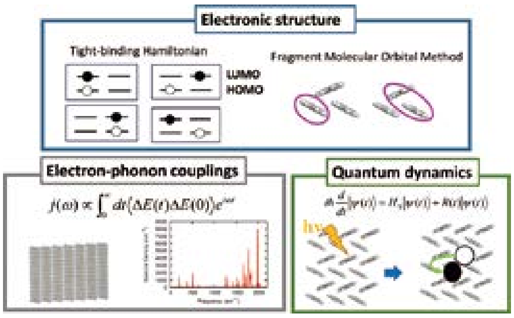

Figure 1. A combine approach to quantum dynamics in molecular aggregates.

We currently investigate electronic structures and exciton dynamics in organic optoelectronic materials, such as an organic/organic interface. We also develop an ab initio theory suitable to treat electronically excited states of large systems with reasonable accuracy, on the basis of a fragment-based approach and a many-body perturbation theory.

Selected Publications

- T. Fujita, J. C. Brookes, S. K. Saikin and A. Aspuru-Guzik, "Memory-Assisted Exciton Diffusion in the Chlorosome Light-Harvesting Antenna of Green Sulfur Bacteria," *J. Phys. Chem. Lett.* **3**, 2357–2361 (2012).
- T. Fujita, J. Huh, S. K. Saikin, J. C. Brookes and A. Aspuru-Guzik, "Theoretical Characterization of Excitation Energy Transfer in Chlorosome Light-Harvesting Antennae from Green Sulfur Bacteria," *Photosynth. Res.* **120**, 273–289 (2014).

1. Development of the Fragment Molecular Orbital Method for Calculating Non-Local Excitations in Large Molecular Systems$^{1)}$

Predicting electronically excited states of large molecular systems is still a challenging issue in quantum chemistry. In this study, we develop an excited-state theory suitable to treat large systems based on the fragment molecular orbital (FMO) method and the configuration interaction single theory with localized molecular orbitals. Although the FMO method have been well established for calculating local excited states, it is not straightforward to compute non-local excited states. We thus develop the theory which can compute non-local excitation of large molecular systems.

The method is based on the configuration interaction single (CIS) theory and was designed to reproduce low-energy excited states for a whole system with small dimensions. In order to describe non-local excited-states for the whole system, configuration state functions (CSFs) were constructed from localized MOs and the CIS amplitudes of intrafragment excitation via ground-state FMO and MLFMO-CIS calculations. The excited states of the whole system were written as the superposition of fragment CSFs for local excitations and interfragment charge transfer (CT) excitations. Exploiting fragment CSFs allows for efficient truncation of the dimension of the excited-state Hamiltonian. The excited-state Hamiltonian represented with fragment CSFs are calculated, and the resulting generalized eigenvalue problem is solved to determine the excited states of the whole system. The one-electron part of the excited-state Hamiltonian was treated by the FMO-linear combination of molecular orbital method, while the two-electron parts were efficiently treated within the two-body expansion of the FMO.

The theory was implemented based on the ABINIT-MP program package. The accuracy and efficiency of the present theory were tested for illustrative examples of molecular dimer and clusters. For example, the excitation energies of the face-to-face benzene dimer as a function of intermolecular distance is shown in Figure 2. FMO-CIS can reproduce the results of conventional CIS with quantitative accuracy for relatively large intermolecular distance of $R > 4$ Å. The mean absolute error relative to the conventional CIS is 26 meV at $R = 4$ Å. Regarding that the equilibrium distance of the face-to-face benzene dimer is $R = 3.8$ Å, the present theory can work with reasonable accuracy for practical applications. Similar benchmark calculations for π-stacked systems and realistic molecular crystals have confirmed that the absolute errors of 50 meV are achievable for molecular assemblies in their equilibrium geometries.

The present theory can compute a large number of excited states in large molecular systems; in addition, it allows for the systematic derivation of a model exciton Hamiltonian. These feature are useful for studying excited-state dynamics in condensed molecular systems based on the ab initio electronic structure theory.

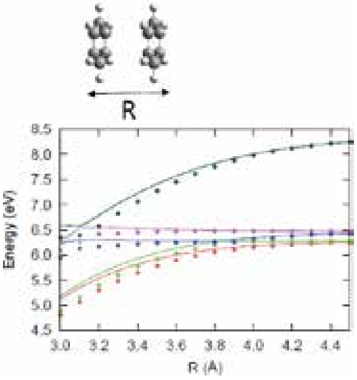

Figure 2. Excitation energies as a function of intermolecular distances from the conventional CIS (solid line) and the FMO-CIS (filled circles). The results shows energies of first six excited states.

2. Interfacial Charge Transfer States in the Pentacene/C_{60} Interface

The electronic structures at organic–organic interfaces comprising electron–donor and electron–accepter materials are of great importance in the performance of various electronic devices. In organic photovoltaic (OPV) devices, interfacial charge-transfer states play critical roles in both charge separation and charge recombination processes. Despite their critical importance, it is difficult to experimentally investigate the interfacial CT states.

In this study, we consider an organic/organic interface that in composed of pentacene molecules as electron donor and C_{60} molecules as electron acceptor. To characterize CT state manifold, we apply the FMO-based excited state theory to the pentacene/C_{60} interface containing about 50 molecules. The structure was extracted from a bilayer interface modeled by a molecular dynamics simulation. The calculated energy (1.1 eV) of the lowest CT state is in reasonable agreement with the experimental reported value. We have analyzed CT states in terms of electron–hole (e–h) separation and delocalization of electron or hole wave function. We have found that in the energy region lower than pentacene absorption, CT states are localized with their small e–h separations, while CT states are delocalized with larger e–h separation in higher-energy region. In addition, the mixing among the interfacial CT states and pentacene excited states enhance the delocalization of electron wavefunction over the pentacene and C_{60} molecules.

References

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2) T. Fujita , Md. K. Alam and T. Hoshi, in preparation.

Functional Dynamics of Biomolecular Machines Revealed by Theoretical Methods

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2012	JSPS Postdoctoral Fellow for Research Abroad
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Keywords Theoretical Biophysics, Molecular Motors, Molecular Simulations

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 inward-open and outward-open conformations. We aim to understand design principles 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 simulations alone cannot cover millisecond-long (or even longer) functional dynamics, especially for a large system like typical biomolecular machines with more than hundreds of thousand atoms including water molecules. Thus, we use both atomistic and coarse-grained molecular simulations, as well as kinetic models based on statistical mechanics, to tackle this problem.

We have been particularly focusing on ATP synthase that produces most of ATP required for living activities. The ATP synthase is composed of two rotary motors, F_o and F_1. The F_o motor is embedded in membrane and its rotation is driven by proton gradient. The F_1 motor is a catalytic part that produces ATP from ADP and P_i. However, the F_1 motor by itself (F_1-ATPase) rotates the central stalk, γ-subunit, in the opposite direction by hydrolyzing ATP. Thus, the two motors are driven by different energy sources and rotate in the opposite directions. In order to understand how ATP synthase works, we have to look into both individual motors and ATP synthase as a whole.

Selected Publications

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1. Mechanochemical Coupling Mechanism of F_1-ATPase

Many single-molecule studies as well as crystallographic studies have clarified how the γ-subunit rotation is coupled to ATP hydrolysis reactions at three catalytic sites of F_1. As summarized in Figure 1B, main points are, 1) 120° step inferred from three-fold symmetry is further divided into 80° and 40° substeps, 2) the 80° substep is driven by ATP binding and ADP release, 3) the 40° substep is driven by P_i release and ATP hydrolysis reaction, 4) typical crystal structures correspond to catalytic dwell (before 40° substep). There are still some remaining questions, though. What is the timing of P_i release: Just after the hydrolysis reaction or after ADP release? What conformation does it take in ATP-binding dwell (before 80° substep)?

We resolved the timing of P_i release by using atomistic molecular dynamics simulations.$^{1)}$ The question is, essentially, from which catalytic site, DP-site or E-site, P_i is released. Since the P_i release takes ~millisecond, a biasing method called metadynamics was employed to facilitate the functional dynamics. Different pathways were observed depending on the site P_i was released. From the E-site it went through P-loop toward outside of the ring structure, while from the DP-site it went through switch II toward inside of the ring structure (Figure 1C). We estimated mean first-passage time from free energy profile (Figure 1D) and diffusion coefficient and concluded that P_i is release from the E-site. That is, P_i is released after ADP release, which is unique among other members of ATPases.

We also identified conformational state of the ATP-binding dwell by combining single-molecule FRET measurements and systematic structural analysis.$^{2)}$ We found that an ε-inhibited *E. Coli* structure that has half-closed β_{DP} and loose $\alpha\beta_E$ interface is consistent with the conformation taken in the ATP-binding dwell.

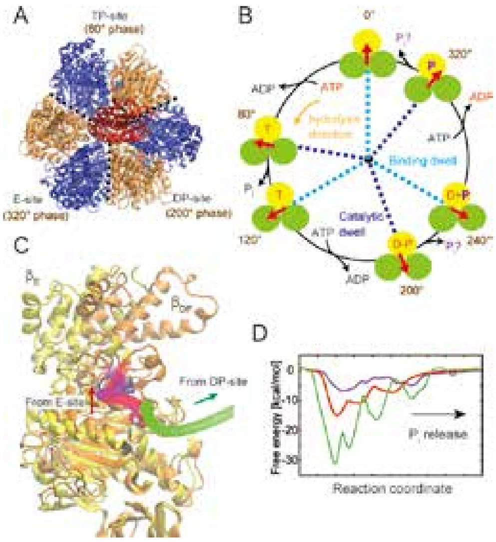

Figure 1. Mechanochemical coupling scheme and P_i release in F_1-ATPase.

2. Torsional Elasticity and Friction of Rotor in F_oF_1-ATP Synthase

It has been known that there is a symmetry mismatch between F_o c-ring and F_1 $\alpha_3\beta_3$ ring. The F_1 $\alpha_3\beta_3$ ring has (pseudo) three-fold symmetry, while the F_o c-ring in animal mitochondria has 8-fold symmetry. Thus, the common rotor, γ-subunit, has to rotate by 120° steps (or 80°+40° substeps) in F_1 part, while it has to rotate by 45° steps in F_o part. Therefore, it has to have torsional elasticity to solve the mismatch. In order to estimate torsional elasticity as well as viscosity of the γ-rotation, we built a simple viscoelastic model (Figure 2B) and fitted it against atomistic simulation trajectories in which external torque was applied on γ.$^{3)}$

The estimated torsional elasticity is consistent with values from single-molecule experiments. By using this elasticity, we identified pathways and associated free energies of the coupled F_oF_1 rotation (Figure 2C). It turned out that with the two-substep F_1 the pathway is blocked by high-energy states. To solve this situation, F_1 needs three substeps as was measured for human mitochondrial F_1 recently. From the estimated torsional friction, we predict that γ-rotation can rotate as fast as 1 MHz and this fast rotation can be observed with an attached bead as small as 20 nanometer diameter.

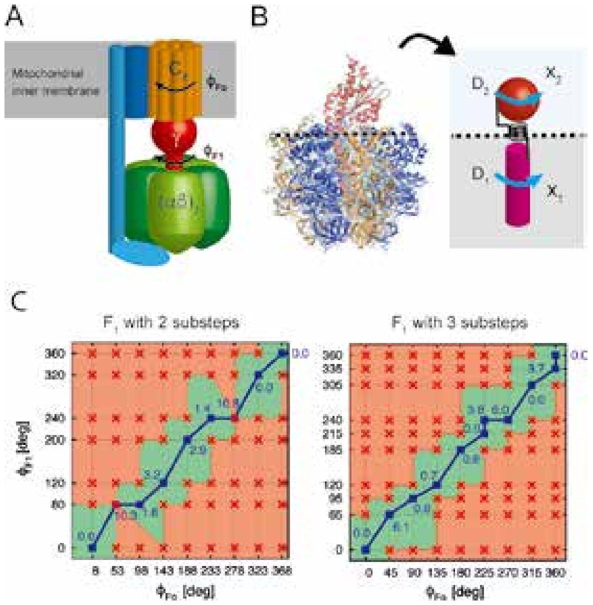

Figure 2. Viscoelastic model of F_oF_1-ATP synthase.

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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 both on ultrafast photoinduced electron energy transfer in the excited state in solution and on ionic liquids (ILs). The project on photoinduced electron energy transfer processes in the excited state in solution is aimed at the development of a theoretical method to study electron energy transfer. On the other hand, ILs' projects are focused on the investigation of dynamical properties on ionic liquids including temperature effects and the unique dissolution process of cellulose polysaccharides using molecular dynamics simulation technique.

1. The Theoretical Investigation of Photoinduced Electron Energy Transfer Processes in the Excited State in Solution[1]

We have developed a procedure for capturing the time-dependent evolution of the electronic structure of a solute molecule in solution, coupling an electronic structure theory with solvent motion. It is indicated that the coupling between solvation processes and a fast intramolecular electron energy transfer is likely to play an important role in the emergence of photoinduced unique functionalities in biochemical and metal complex systems.

2. Investigations of Ionic Liquids[1–2] with Molecular Dynamics Simulation

We focus on the dynamical properties on ionic liquids (ILs). With molecular dynamics simulation procedure, it have been found out that ILs show unique collective dynamics. We have investigated interesting dynamical heterogeneity in ILs at room temperature. Also, we have studied the solvation process of cellulose polymer in ILs.

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Visiting Professors

Visiting Professor

SHIGETA, Yasuteru *(from University of Tsukuba)*

Theoretical Analyses on Functions of Biomolecules

Several biological functions, such as molecular recognition, enzyme catalysis, signal transduction, allosteric regulation, and protein folding, are strongly related to conformational transitions of biomolecules. In order to understand these biologically relevant phenomena, we have developed new algorithms for conformational search, a fragment molecular orbital method, first-principles molecular dynamics simulations and applied them to protein folding problems, energy transfer in proteins, and enzymatic reaction analyses. In particular, we have investigated conformational changes of a GDP binding form of FtsZ from Staphylococcus aureus, which are related to shrink of Z-ring during a cell fission processes by using a newly developed conformational search method. We also suggest a few amino acid residues that are important for recognition of GDP and thus the conformational changes.

Visiting Associate Professor

NAGATA, Yuki *(from Max Planck Institute for Polymer Research)*

Combined Simulation and Experiment Reveals Physics of Ice Interface

Our group aims at obtaining molecular level understanding of the structure and dynamics of aqueous liquid interfaces, with particular emphasis on water, thought ‘theoretical sum-frequency generation (SFG) spectroscopy.’ The main highlight in our group in 2016 and 2017 is the SFG probe of the ice interface. We worked on the water conformation near the ice nucleation protein, where we found that the hydrophobic and hydrophilic patterns would be crucial for ice nucleation (*Sci. Adv.* 2016). Further focus has been made on the anomaly of the ice surface melting, where we found the presence of the excess hydrogen bond at the top most ice layer at 200 K, through the formation of non-hexagonal ice (*PRL* 2017). The details of the peak assignment of the SFG spectra were also made (*JPCL* 2017). In addition, we have contributed to several review papers for vibrational spectroscopy of water (*Chem. Rev.* 2016), modeling of interface (*JPCB* 2016) and TMAO molecule (*PCCP* 2017). Through this, it was also very fruitful to start a new collaboration, in particular, with Prof. Wataru Mizukami (Kyusyu Univ.) who used to be a graduate student in IMS.

Visiting Associate Professor

KATO, Tsuyoshi *(from The University of Tokyo)*

Development of Effective Potential Theory for Quantal Dynamics

I am studying in the area of quantal molecular dynamics focusing on the developments of new methods to calculate the electronic and nuclear dynamics in molecules. I am constructing a time-dependent effective potential theory that could be used to calculate the exact time-dependent wave function of a many-electron system. During the development of the effective potential theory, I found a solution algorithm for the time-independent/dependent inverse Kohn-Sham problem in terms of the effective potential calculated for an exact time-dependent/stationary wave function. Given the exact time-dependent wave function describing quantal many-particle dynamics, my final goal is to establish a method to derive an exact effective single- and two-particle potentials out of the many-particle wave function in order to deepen the understanding of quantal dynamics in atoms and molecules.