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Annual Report

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平成30年度 年次研究報告

東京大学 大学院　理学系研究科・理学部
物理学教室

II

Summary of group activities in 2018

1 Theoretical Nuclear Physics (Fukushima) Group

Subjects: QCD phase diagram, Lattice simulation, Neutron star, Chiral anomaly

Member: Kenji Fukushima and Arata Yamamoto

In Theoretical Hadron Physics group, many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include quark-gluon plasma in relativistic heavy-ion collisions, particle production mechanism, lattice gauge simulations, matter under extreme conditions, neutron stars, etc.

Highlights in research activities of this year are listed below:

1. Extreme matter in electromagnetic fields and rotation
2. Non-Abelian vortex in lattice gauge theory
3. Machine learning for the neutron star equation of state
4. Axial ward identity and the schwinger mechanism

2 High Energy Physics Theory Group

Research Subjects: Particle Physics and Cosmology

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo

We are working on various topics in particle physics and cosmology, such as physics beyond the Standard Model, dark matter, baryogenesis, inflation, phenomenology of supersymmetric models, grand unified theories, string theory, supersymmetric field theories, conformal field theories, holography, entanglement entropy, and so on. Specific subjects studied in 2018 are summarized below:

1. Phenomenology
   - 1.1. Swampland and Higgs [1].
   - 1.2. Supersymmetric models [2, 3].
   - 1.3. The supersymmetric flaxion model [4].
   - 1.4. Dark matter [5, 6, 7, 8].
   - 1.5. Axion and the 21 cm observation [9].
   - 1.6. Gravitational waves [10].
   - 1.7. Models with flavor symmetry [11, 12, 13].
   - 1.8. Weak-gravity conjecture and particle physics [14].
   - 1.9. Moduli problem [15].
   - 1.10. Inflation [16, 17].
   - 1.11. Neutron star cooling and axion [18].
   - 1.12. Long-lived particle searches [19, 20].
2. Superstring Theory and Formal Aspects of Quantum Field Theories
   - 2.1. Field theory on lattice [21].
   - 2.2. Algebraic structure of string theories [22, 23, 24, 25].
   - 2.3. Entanglement entropy and holography [26, 27].
   - 2.4. Defect CFT [28, 29].

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3 Sakurai Group

Research Subjects: Structure and dynamics of exotic nuclei and exotic atoms

Member: Hiroyoshi Sakurai and Megumi Niikura

Our group investigates structure and dynamics of exotic nuclei and exotic atoms. Our experimental programs utilize world-wide accelerator facilities at RIBF at RIKEN, RCNP at Osaka University, GANIL in France and NSCL at Michigan State University in US. Some of our research subjects are followings.

In-beam gamma-ray spectroscopy of ^{78}Ni

In-beam spectroscopy of a doubly-magic nucleus, ^{78}Ni, was performed at RIBF as a series of campaign experiment of the SEASTAR experiments in 2015. We clearly establish its doubly magic nature by observing a high excitation energy of the first excited state, which is also predicted by *ab-initio* calculations. However, our results also provide the first indication of the breakdown of the neutron magic number 50 and proton magic number 28 beyond this stronghold, caused by a competing deformed structure. State-of-the-art phenomenological shell-model calculations reproduce the shape coexistence, predicting further a rapid transition from spherical to deformed ground states with ^{78}Ni as turning point.

Collapse of the $N = 28$ shell closure: single-particle structure of ^{44}S

Recently the neutron shell gap at $N = 28$ has been found to be reduced especially on ^{44}S and ^{43}S and the shape coexistence/mixing has been discussed both theoretically and experimentally. Unless a lot of efforts about the macroscopic nuclear system, however, the microscopic information about the neutron configuration of these nuclei has been unknown, which keeps the mechanism of the disappearance of the $N = 28$ magic number and the emergence of the deformed states in this region unclear. In order to shed light on understanding of the neutron single-particle configuration, we have performed a in-beam γ-ray spectroscopy of ^{44}S by one-neutron knockout reaction at NSCL, Michigan State University. The full level scheme of ^{43}S was constructed for the first time. By the analysis of parallel momentum distributions, the assignment of the spin-parity of each final state was performed.The concentration of the strength of neutron knockout from $L = 1$ orbit was observed around 1.2 MeV, which is the direct observation of the quenching of the $N = 28$ shell gap.

Missing mass spectroscopy of light nuclei beyound proton-drip line

Recent experimental researches have suggested the existence of extremely neutron-rich systems such as tetra-neutron (n^4) and ^{7}H resonances. These experimental results raised a question as to whether their mirror proton-rich partners exist or not, and if so, to what extent the symmetry is preserved under the strong Coulomb field. The expriment are performed at GANIL in July 2018 to search for resonances of ^{5}Be, ^{6}B and ^{7}C, which are the mirror partners of heavy hydrogen nuclei ($^{5-7}$H) and not observed so far. The resonance states are populated via the two-neutron transfer (p, t) reaction with radioactive beams and the missing mass method was adopted by using MUST2 telescopes to reconstruct the resonance energy and the differential cross sections.

Spectroscopy of pionic atoms using a proton beam

Chiral symmetry restoration at finite density is one of the most important topics in the hadron physics. Spectroscopy of deeply-bound pionic atoms enable us to investigate the symmetry restoration. We performed a new experiment of pionic atoms using a proton beam at RCNP, Osaka University in order to improve the experimental resolution. The 1p state of the pionic atom of ^{123}Sn is identified with more than 2σ significance and there seems to be a non-negligible 1s state contribution in the spectrum. Although the statistical sensitivity is not good, the present study established the methods of the high precision spectroscopy of deeply-bound pionic atoms and shed light on the future precise measurements.

Muonic X-ray measurement on palladium isotopes

A muonic X-ray measurement is a common method to determine nuclear charge parameters. To interpret the observed muonic X rays to the nuclear charge parameters, one should solve a Dirac equation assuming a certain charge distribution. This procedure causes a model dependence on the determination of the charge parameters. A precise measurement of higher muonic X-ray series helps to reduce the model dependence. We measured the muonic X rays of isotopically enriched palladium targets (^{104,105,106,108,110}Pd) at MuSIC facility at RCNP, Osaka University. Transition energies and relative intensities of the muonic X rays up to the M series were measured and the nuclear charge parameters of the palladium isotopes were determined.

4 Wimmer Group

Research Subjects: Spectroscopy of exotic nuclei using direct reactions

Member: Kathrin Wimmer

There are several experimental as well as theoretical indications that the structure of exotic nuclei differs significantly from what is known from well-studied stable nuclei. Our group performs spectroscopic studies of neutron-rich nuclei using direct reactions. These kinds of reactions are an excellent tool to probe the single-particle properties of nuclei. Therefore information on the nuclear wave functions can be obtained. With this technique we investigate the phenomena of shape-coexistence and new magic numbers across the nuclear chart.

Spectroscopy of the $T_z = -1$ nucleus ^{70}Kr

Extremely proton-rich nuclei provide an interesting test ground for isospin symmetry in nuclei. Isospin non-conserving interactions lead to different structures of nuclei which have proton and neutron number interchanged. So far such tests are limited to lighter nuclei. In an experiment at the RIBF at RIKEN ^{70}Kr was studied by nucleon removal reactions and Coulomb excitation. Previously no excited state was known in this nucleus, our analysis reveals five new states, and comparison with theoretical calculations suggests that effects from the Coulomb interaction as well as isospin breaking components in the nuclear interaction play a major role in this $N < Z$ nucleus. A followup study of ^{62}Ge,Ga, and Zn nuclei has been approved by the RIBF program advisory committee.

Rapid shape changes at $N = 60$

The shape transition at $N = 60$ in the Sr, Zr, Mo region exhibits one of the most dramatic ground state shape transitions known today. In order to develop a better understanding of the underlying wave functions of the states, more information on the underlying single-particle structure is required. Previously we measured the transfer reactions ^{94,95,96}Sr(d,p) to track the evolution of the single-particle energies and their occupation as $N = 60$ is approached at TRIUMF. The next step is to investigate pair-transfer reactions using a radioactive tritium target. These kind of reaction will open new opportunities to investigate the nature of 0^+ states in particular and provide key information on the nature of this most rapid shape transition in the nuclear chart.

Single-particle structure of neutron-rich Ca isotopes

Within the SEASTAR collaboration we have performed an experiment to study the first spectroscopy of very exotic neutron-rich nuclei. The experiment was performed using the large acceptance SAMURAI spectrometer that allowed for the simultaneous measurement of many reaction channels. In particular, we are investigating the single-particle structure of ^{56}Ca through proton and neutron knockout, and the systematics of the production cross sections along the Ca isotopes. In order to probe the particle states, (d, p) one-neutron transfer reactions with energy degraded beams at the OEDO beam line are planned. These two experiments track the evolution of the single-particle states between $N = 32$ and 36.

Towards transfer reactions at RIBF

With the newly constructed OEDO facility at RIBF the beam energy of exotic nuclei can be effectively reduced to energies that are suitable for transfer reactions. In collaboration with RIKEN we are constructing a detector array specifically for the study of transfer reactions. The setup, called TINA, has be designed and its first implementation has been commissioned at Kyushu University Tandem accelerator and at the OEDO beam-line. Upgrades and extensions are now being designed.

Development of a new target for two-neutron transfer reactions

Two-nucleon transfer reactions are a well-suited tool to investigate specific nuclear structure properties, like shape coexistence and pairing correlations. Two-neutron transfer reactions with OEDO at RIBF require a new kind of target. A self-supporting large area tritium target based on a tritium loaded titanium foil is currently developed at the University of Tokyo. First prototypes, containing deuterons instead of tritium, were tested at Kyushu University using a ^{12}C beam. The targets have been characterized and the deuterium content has been quantified. Further tests were performed and soon the tritium target will be fabricated.

First spectroscopy of the the r-process nucleus ^{135}Sn

We plan to study the isotopes ^{135}Sn by the ^{134}Sn(d,p) one-neutron transfer reaction at HIE-ISOLDE (CERN). We aim for the identification excited states in this nucleus for the first time. Excitation energies, spin-parity assignments and spectroscopic factors extracted from the data will allow for a stringent test of predictions by state-of-the-art shell model calculations and constrain nuclear synthesis in the r-process.

High-resolution γ-ray spectroscopy at the RIBF

We will construct a high-resolution, Ge based γ-ray spectrometer composed of several detectors from the MINIBALL collaboration as well as γ-ray tracking detectors from the US and Europe. The efficiency and resolution in-beam will be 9 % and 0.2-2 %. This setup will pave the way to detailed nuclear structure and reaction studies currently not feasible at the RIBF. The project has been approved by the RIBF program advisory committee, the MINIBALL steering committee, and the RIKEN Nishina Center. The experiments will be performed in 2020.

5 Aihara-Yokoyama Group

Research Subjects: Experimental Particle Physics and Observational Cosmology.

(1) Study of CP-violation and search for physics beyond the Standard Model in the B meson and the τ lepton systems (Belle and Belle II); (2) Study of neutrino oscillations and search for proton decay (Super-Kamiokande, T2K, and Hyper-Kamiokande); (3) Dark energy survey at the Subaru telescope (Hyper Suprime-Cam); (4) R&D for an experiment to search for axion and light dark matter; (5) R&D of new generation photodetectors.

Members: Hiroaki Aihara, Masashi Yokoyama, and Yoshiuki Onuki

1. Search for new physics at KEK (super-)B-factory: Belle and Belle II experiments One of the major research activities in our group has been a study of CP-violation and searches for physics beyond the Standard Model in the B meson and the τ lepton systems using the KEK B-factory (KEKB). This year, we reported the first observation of the rare tau decay $\tau^\pm \to \pi^\pm e^+ e^- \nu_\tau$ with branching fraction of $(2.33 \pm 0.19 \pm 0, 30) \times 10^{-5}$, and the most stringent limit on the branching fraction of $\tau^\pm \to \pi^\pm \mu^+ \mu^- \nu_\tau$ to be 0.55×10^{-5} at 90% CL.

The quest for new physics will continue with the SuperKEKB accelerator, that will have 40 times higher luminosity than KEKB, and the Belle II detector upgraded with cutting-edge technologies. Since 2011, our group has been responsible for the construction of the outermost layer of the Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons, one of the key elements for the success of Belle II. This year, we completed the construction of SVD, which has been installed in the Belle II detector. The physics data taking with the full Belle II detector has been started from March 2019.

2. Study of neutrino oscillations and search for proton decay: Super-Kamiokande, T2K, and Hyper-Kamiokande experiments The discovery of neutrino oscillation by Super-Kamiokande (SK) opened a new window to physics beyond the Standard Model of elementary particles. We have been studying neutrino oscillations with the T2K long baseline neutrino experiment, in which intense neutrino and anti-neutrino beams produced with the J-PARC accelerator complex are detected with the SK detector, 295 km away. This year, with doubled data for the anti-neutrino mode beam compared to the previous year, we reported stronger hint of the CP violation in the lepton sector, which is one of major milestones in particle physics.

We lead the program to improve the sensitivity of T2K by reducing the systematics uncertainties related to the neutrino interaction. We built new neutrino detectors named WAGASCI at J-PARC and measured cross sections of neutrino interactions with water, which is the target material in the SK detector. Our group has been playing central roles in the T2K near neutrino detector upgrade project.

In order to significantly extend the reach in the neutrino physics and the proton decay search beyond T2K and SK, the next-generation water Cherenkov detector, Hyper-Kamiokande (Hyper-K) is proposed. Our group is leading this project as well.

3. Study of Dark Energy with Subaru telescope: Hyper Suprime-Cam As an observational cosmology project, we have been involved in the research with a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct an extensive wide-field deep survey to investigate the weak lensing. This data will be used to develop a 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy.

This year, we published the constraints on the mass fraction of primordial black holes to dark matter in the Milky Way and the Andromeda galaxy, using data taken with HSC.

4. R&D for an experiment to search for axion and light dark matter We continue an R&D to investigate the feasibility of an experiment to search for axion and light dark matter using silicon pixel detector with Silicon On Insulator technology.

6 Asai group

Research Subjects: (1) Particle Physics with the energy frontier accelerators (LHC) (2) Physics analysis in the ATLAS experiment at the LHC: (Higgs, SUSY and Extra-dimension) (3) Particles Physics without accelerator using high intensity of Photon (4) Positronium and QED

Member: S.Asai, A.Ishida

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry, and new diboson resonances(WW and $\gamma\gamma$).
  - Higgs: After the discovery of Higgs Boson, We are measuring the Yukawa coupling precisely.
  - SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.4 and 1.5TeV, respectively.
- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Bose Einstein Condensation of positronium.
  - Axion searches using Spring 8
  - $\gamma\gamma$ scatter Using FEL Xray.
  - Vacuum Birefringence using Strong Magnetic field or Strong light.

7 Miyashita Group

Research Subjects: Statistical Mechanics, Phase Transitions, Quantum Spin systems,

Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita, Takashi Mori, Taichi Hinokihara and Eriko Kaminishi

Quantum response and Quantum dynamics

Quantum dynamics under time dependence field is one of the most important subjects in our group. In the 2017 fiscal year, we studied the following topics.

Optical Bistability is a phenomenon of discontinuous change of output as a function of strength of input. In order to study this phenomenon. We study a system of microcavity including atoms (or spins) with discrete energy levels contacting a thermal bath. We study this system by an eigenvalue problem of time evolution operator for the master equation. We found peculiar properties due to bistability at the low photon density where the quantum hybridization of cavity-photon mode and spins is strong.[9].

We are also studying the acceleration of adiabatic motion. We study the idea to the classical systems and found the method of counter-adiabatic term works in the adiabatic motion in classical systems.[11]。The method was extended to an method to create the cat-state in Bose-Einstein condensate. [12]。

We study relations between the classical soliton solution and its counter part in quantum mechanics in the exact solvable (integrable) model of one-dimensional Bose gas model with interaction[30].

We also study quantum response in a system with strong spin-orbit interaction. Motivated by the measurement of Terahertz spectroscopy on $\alpha-$ RuCl3, d^5, we studied electronic magnetoelectric effects in d^5 Mott insulator with the octahedral crystal field. [13].

Characterization of the effective spin ($S = 1/2$) induced by impurities in the so-called gapped spin chains by making use of the matrix product state (MPS). We first studied AKLT model as a prototype and found a characteristic response to the external field, and then we studied the bond-alternating Heisenberg antiferromagnetic chain with MPS. [22, 33]。

Phase transitions and Dynamics of order parameters

Phase transitions and critical phenomena are also important subjects of our group.

As an important consequence of the change of local lattice structure, we have studied the elastic interaction which causes an effective long-range interaction. We found a specific phase diagram with a horn structure, and studied the phase diagram in detail by making use of extended cluster mean-field method, and explore possible phases with multiple phases[10, 49, 51]. We also studied the effect of elastic interaction on the dynamics of HS-LS conversion in a spin-crossover material which shows the elastic step and thermal step separately[31].

We are studying the thermal effects on the coercive force of permanent magnets, e.g. $Nd_2Fe_{14}B$, joining to the Elements Strategy Initiative Center for Magnetic Materials (ESCICMM) under the outsourcing project of MEXT. To study the process of decay from metastable state, we developed new numerical methods using atomistic model, e.g., method of free-energy landscape employing the Wang-Landau Monte Carlo method, and also an efficient method to study the dipole-dipole interaction. By these method, we studied temperature dependence of the coercive forth systematically [6, 8, 50]. . We also studied the ferromagnetic resonance (FMR) in the phase of tilted magnetization.

Prethermalization in isolated quantum and classical systems

It is one of the fundamental problems in statistical physics to understand the relaxation dynamics in isolated many-body systems. It has been well known that some isolated quantum system display prethermalization, i.e., the relaxation towards a quasi-stationary metastable state before reaching true thermal equilibrium. We studied prethermalization for quantum spin systems with long-range interactions. It was shown that prethermalization generally occurs due to the presence of long-range interactions. In addition, we studied classical isolated spin systems under periodic driving fields, and made clear that prethermalization occurs in the classical system. This prethermalization is the classical counterpart of the Floquet prethermalization observed in isolated quantum systems.

8 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Hiroyasu Matsuura

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-T_c superconductivity, Mott metal-insulator transition, topological materials, Dirac electron systems in solids, organic conductors, and magnetic systems with frustration and/or spin-orbit interactions. The followings are the current topics in our group.

- High-T_c superconductivity
  Flux states as a symmetry-breaking state in high-T_c superconductivity.
- Dirac electron systems in solids
  Quantum electrodynamics (QED) in solids: Dielectricity and diamagnetism.[1]
  Critical phenomena in Weyl semimetals due to impurities and scaling law in nuclear spin relaxation rate.
  Magnetoresistance of a three-dimensional Dirac electron system.[2]
- Thermal transport phenomena
  Range of validity of Sommerfeld-Bethe relation and phonon drag contribution.[3]
  Theory of phonon drag in Seebeck effects based on the linear response theory.[4]
- Theories on topological materials
  Z_2 index and Dirac nodal line material.[5]
  Contribution of the Berry curvature on magnetic susceptibility in a honeycomb lattice model.
- Organic conductors
  Low temperature thermal conductivity in a quantum spin liquid of κ-H_3(Cat-EDT-TTF)$_2$.
- Borophane-related materials.[6]
- Spin systems and spin-orbit interaction
  Anomalous temperature behavior of chiral spin helix in $CrNb_3S_6$.[7]
  Magnetization process and a formation of spin-liquid states in an interacting magnetic monopole system.
  Dzyaloshinskii-Moriya interactions in 5d electron systems.[8]
  New magnetic phases in the chiral magnet $CsCuCl_3$ under high pressures.[9]

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9 Tsuneyuki Group

Research Subjects: Theoretical Condensed-Matter Physics

Member: Shinji Tsuneyuki and Ryosuke Akashi

Computer simulations from first principles enable us to investigate properties and behavior of materials beyond the limitation of experiments, or rather to predict them before experiments. Our main subject is to develop and apply such techniques of computational physics to investigate fundamental problems in condensed matter physics, primarily focusing on prediction of material properties under extreme conditions like ultra-high pressure or at surfaces where experimental data are limited. Our principal tool is molecular dynamics (MD) and first-principles electronic structure calculation based on the density functional theory (DFT), while we are also developing new methods that go beyond the limitation of classical MD and DFT for the study of electronic, structural and dynamical properties of materials.

In FY2018, we developed a "data assimilation" method to find crystal structure efficiently by using incomplete powder diffraction data. We also developed a multi-scale modeling method based on the electronic entropy-driven mechanism to simulate photo-induced non-thermal processes by ultra-short-pulse laser. As for the fundamentals of the first-principles electronic state calculation, we investigated relativistic effects on the electronic structure of heavy atoms by incorporating the Breit correction. We also applied DFT to clarify the structure and properties of a permanent magnet, a ferromagnetic material, a molecular crystal, and so on.

Our research subjects in FY2018 are as follows:

- Data assimilation for crystal structure prediction
- Multi-scale simulation of non-thermal ablation of metals
- A stochastic sampling method for rare events
- Neural-network Kohn-Sham exchange-correlation potential
- Formulation of relativistic DFT and its application
- Generalized gradient approximation for nuclear matter
- Anharmonic lattice dynamics and thermal properties of materials
- Negative thermal expansion of ScF_3
- Substitution effects in $Nd_2(Fe,X)_{14}B$
- Electronic structure of Sr_3OsO_6 with the highest Curie temperature
- Spin-fluctuation effect in superconductivity of Fe at high pressure
- Electronic structure of ferromagnetic $CeRh_3B_2$
- Electronic structure of a Pt-dithiolene nanosheet

10 Todo Group

Research Subjects: Development of simulation algorithms for strongly-correlated systems; Application of machine learning technique to materials science; Fundamental theory of quantum computer; Novel state and critical phenomena in strongly correlated systems; Cooperative phenomena in non-equilibrium and non-steady states; Development of open-source software for next-generation parallel simulations

Member: Synge Todo, Tsuyoshi Okubo, and Hidemaro Suwa

We are exploring novel methods in computational physics based on stochastic method such as the Monte Carlo simulation, path-integral representation of quantum fluctuations, information compression by using the singular value decomposition and the tensor network, statistical machine learning, etc. By making full use of these powerful numerical methods, we aim to elucidate various exotic phases, phase transitions, and dynamics specific to quantum many-body systems, from strongly correlated systems such as the spin systems and the Bose-Hubbard model to real materials. We are also researching parallelization methods for leading-edge supercomputers, and developing and releasing open-source software for next-generation physics simulations.

Development of simulation algorithms for strongly-correlated systems: Design of local transition matrix in Markov chain Monte Carlo; Measurement of Rényi entanglement entropy by using quantum Monte Carlo method; Path-integral Monte Carlo in continuous space; Non-local update for quantum dimer models; Tensor network renormalization for non-uniform systems.

Application of machine learning technique to materials science: Machine learning for molecular dynamics with strongly correlated electrons; Crystal structure prediction by combined optimization of experimental data and first-principles calculation; Exploration of higher Young modulus materials by machine learning approach

Fundamental theory of quantum computer: Quantum-classical hybrid algorithm for calculation of excited energy

Novel state and critical phenomena in strongly correlated systems: Ground state of Kitaev materials; Order in magnetic field in frustrated magnets; Effective dimension of the random-field Ising model with correlated randomness,

Cooperative phenomena in non-equilibrium and non-steady states: Dynamical cooperative phenomena in in cavity system; Nonergodicity of classical harmonic oscillator system.

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11 Katsura Group

Research Subjects: Condensed Matter Theory and Statistical Physics

Member: Hosho Katsura and Yutaka Akagi

In our group, we study various aspects of condensed matter and statistical physics. In particular, our research focuses on strongly correlated many-body systems which would give rise to a variety of interesting phases. We study theoretically such systems, with the aim of predicting novel quantum phenomena that have no counterpart in weakly-interacting systems. We are currently interested in (i) topological phases of matter, (ii) low-dimensional correlated systems, (iii) magnetism in Bose and Fermi Hubbard models, and (iv) application of machine learning. In addition, we are also interested in the mathematical aspects of the above mentioned fields. Our research projects conducted in FY 2018 are the following:

- Strongly correlated systems
  - Subgap optical conductivity in honeycomb Kitaev materials [1]
  - Nambu-Goldstone fermions in interacting Majorana-fermion chains [2]
  - Topological order in interacting Kitaev/Majorana chains [3]
- Topological phases of matter
  - Machine learning phases of disordered topological superconductors [4]
  - Thermal Hall effect in chiral superconductors with gap nodes [5]
  - $\mathbf{Z}_2$ topological invariant for magnon spin Hall systems [6]
  - Zero and shift modes in a non-Hermitian Kitaev chain with parity-time symmetry [7]
- Mathematical and statistical physics
  - Rigorous results for the ground states of the spin-2 Bose-Hubbard model [8]
  - Algebraic transformations of generalized Ising models and Boltzmann machines [9]
  - Effective dimension, level statistics, and integrability of Sachdev-Ye-Kitaev-like models [10]

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12 Fujimori Group

Research Subjects: Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Goro Shibata

We study the electronic structure of superconductors and spintronics materials by high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy (ARPES) and soft x-ray magnetic circular dichroism (XMCD) using synchrotron radiation. We investigate the mechanisms of high-temperature superconductivity [1], metal-insulator transitions, giant magnetoresistance, and magnetic anisotropies in transition-metal oxides, ferromagnetic compounds [2], and their thin films and interfaces.

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13 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Ryota AKIYAMA

Surfaces/interfaces of materials and atomic-layer materials are platforms of our research where rich physics is expected due to the low-dimensionality, symmetry breakdown, a wide variety of structures, and direct access for measurements. (1) Electronic/spin/mass transports including superconductivity, (2) atomic/electronic structures, (3) phase transitions, (4) spin states and spintronics, and (5) epitaxial growths of coherent atomic/molecular layers/wires on surfaces of metals, semiconductors, topological insulators, and nano-scale phases such as surface superstructures, ultra-thin films including atomic-layer materials such as graphene and transition metal dichalcogenides. We use various kinds of ultrahigh-vacuum experimental techniques, such as electron diffraction, scanning electron microscopy(SEM), scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy(PES), *in-situ* four-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes, and surface magneto-optical effects apparatuses. Main results in this year are as follows.

(1) Surface electronic/spin transports:
- Interface superconductivity at topological crystalline insulator/trivial semimetal junction
- Anomalous Hall effect at interface between topological insulator and ferromagnetic insulator
- 2D superconductivity at monolayer alloy metallic surface superstructures and by proximity effect
- Spin injection by circularly polarized light irradiation on topological insulators
- Superconducting Graphene with intercalation
- CDW and transport at transition metal dichalcogenides

(2) Surface phases and atomic-layer materials:
- Epitaxial growth of blue Phosphor atomic layers
- Structure dynamics of Ca-intercalated bilayer graphene observed by low-energy-electron microscopy

(3) New methods:
- Fabrication of UHV-SQUID system to detect Meissner effect of atomic-layer superconductors
- Fabrication of a pure-spin-current injection/detection probe

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14 Fukuyama Group

Research Subjects: Low Temperature Physics (Experimental):
Quantum fluids and solids with strong correlations and frustration,
Novel electronic states in graphene.

Member: Hiroshi Fukuyama, Tomohiro Matsui

We are interested in (i) novel quantum phases with strong correlations and frustrations in two dimensional (2D) helium three (^{3}He), four (^{4}He) and their mixture, (ii) novel electronic properties of graphene, monatomic sheet of carbon atoms. We are investigating these phenomena at ultra-low temperatures down to 50 μK, using various experimental techniques such as NMR, calorimetry, torsional oscillator, scanning tunneling microscopy and spectroscopy (STM/S), and electronic transport measurement, *etc.*

1. **Quantum Spin Liquid state in two dimensional ^{3}He:**

   Quantum spin liquid (QSL) is a state where the spins at each lattice site are not frozen even at $T = 0$. Two dimensional ^{3}He is one of the promising candidates which shows the QSL state as magnetic ground state because of the following characters. (1) Impurity-free 2D solid can be obtained on an atomically flat substrate. (2) ^{3}He atom forms triangular lattice with strong geometrical frustrations. (3) The interaction ($J_{\rm p}$) between ^{3}He atoms can be described with the multiple spin exchange (MSE) of up to six atoms. (4) The physical properties, such as heat capacity and magnetism, can be described only by the degree of freedom of nuclear spins.

   We are recently focusing on a monatomic layer of ^{3}He solid prepared on graphite, which is preplated by bilayer of HD (^{3}He/HD/HD/gr) and studying its heat capacity (C) in wide temperature range of $0.16 < T < 90$ mK, and in wide areal density range of $0.1 \leq \rho \leq 13.63$ nm^{-2}. Since the areal density of 2D HD is smaller than that of ^{3}He and ^{4}He, one can obtain larger $|J_{\rm P}|$ for 2D ^{3}He on bilayer HD than on ^{3}He and ^{4}He. The T-dependence of C for ^{3}He/HD/HD/gr shows a single broad peak different from the double peak feature for ^{3}He/^{4}He/gr and ^{3}He/^{3}He/gr. The peak shifts to lower temperature by increasing areal density of ^{3}He. A higher ρ of $\rho > 5.05$ nm^{-2}, a C2-like phase with ~ 17 % compressibility was observed. This C2-like phase is expected to be quantum liquid crystal, or in other words "hexatic" phase, where there is no long range order while hexagonal bond order is preserved locally. We have recently succeeded to observe finite frequency shift in torsional oscillator measurements which suggests a possible superfluidity of this quantum liquid crystal. On the other hand, at $\rho = 4.74$ nm^{-2}, a novel QSL with exotic elementary excitations is observed, which is named as C3 phase. At the C3 phase, the C and χ shows peculiar T dependence, i.e., $C \propto T^{2/3}$ and $\chi \propto T^{-1/3}$. Theoretically, this unique T-dependence can be explained by considering spinons or Majorana fermions as magnetic excitations.

2. **Novel electronic properties of graphene:**

   Graphene had been attracting considerable attention owing to its remarkable electronic and structural properties, and its possible applications in many emerging fields such as graphene-based electronic devices. One of the important topics to study in graphene research is the spin polarized state expected at zigzag edges of graphene nanoribbon (z-GNR). At the edge of zigzag structure, electrons are strongly localized along the edge to form a zigzag edge state (zz-ES). It is expected that the spin degeneracy would be lifted and ferromagnetically spin polarized edge state appears under an electron-electron interaction for z-GNR through anti-ferromagnetic coupling between edges.

   To obtain such zigzag edges and z-GNR, we tried hydrogen-plasma etching of graphite surfaces. By exposing graphite to hydrogen-plasma under high temperatures, hexagonal nanopits with monatomic depth are created. The size and the density of nanopit can be controlled by tuning the excitation power to produce plasma, temperature and time duration of the process, and partial pressure of hydrogen. Moreover, and most importantly, the edges of the nanopit are aligned to the zigzag direction in atomic scale. Therefore, one can obtain z-GNR in between two hexagonal nanopits. By observing dI/dV spectra across such z-GNRs, we have succeeded to observe the spin polarized zz-ES as double peak structure in the local density of states. The double peak consists of sharp and dull peaks, and the peak separation becomes smaller for wider z-GNR.

15 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

We study low temperature electronic properties of two-dimensional systems.
The current topics are following:

1. Two dimensional electrons at cleaved semiconductor surfaces:
   At the surfaces of InAs and InSb, conduction electrons can be induced by submonolayer deposition of other materials. Recently, we have performed in-plane magnetotransport measurements on in-situ cleaved surfaces of p-type substrates and observed the quantum Hall effect which demonstrates the perfect two dimensionality of the inversion layers. Research on the hybrid system of 2D electrons and adsorbed atoms has great future potential because of the variety of the adsorbates and the application of scanning probe microscopy techniques.

   To explore exotic physical phenomena related to spin at a semiconductor surface, magnetic-adatom induced two dimensional electron systems are investigated by using low-temperature scanning tunneling microscopy and spectroscopy combined with transport measurements.

2. Superconductivity of monolayer films on cleaved GaAs surfaces:
   Recently, we studied the effect of the parallel magnetic field $H_\parallel$ on superconductivity of monolayer Pb films on GaAs(110). Superconductivity was found to occur even for $H_\parallel = 14$ T, which is much higher than the Pauli paramagnetic limiting field H_P. The observed weak $H_\parallel$ dependence of the superconducting transition temperature T_c is explained in terms of an inhomogeneous superconducting state predicted for 2D metals with a large Rashba spin splitting.

   To observe exotic superconducting states in multilayer systems, we fabricated bilayer and trilayer films on the cleaved surface of an insulating GaAs substrate, which comprise one-atomic-layer Pb films with a strong Rashba spin-orbit interaction caused by the breaking of the space inversion symmetry. A steep upturn was observed in the measurement of the temperature dependence of the parallel upper critical magnetic field. From the numerical calculations performed using the Bogoliubov-de Gennes equations, we found that this upturn corresponds to the crossover from the complex stripe phase to the helical phase in the multiple one-atomic-layer films.

In addition to the study in the multilayer systems, we have also studied nonreciprocal charge transport in one-atomic-layer Pb superconductors. The antisymmetrized second harmonic magnetoresistance is observed below the superconducting transition temperature, which suggests that the nonreciprocal effect occurs in one-atomic-layer Pb films grown on the cleaved surface of GaAs.

16 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Naotaka Yoshikawa

We study light-matter interactions and many body quantum correlations in solids, aiming at the light-control of many-body quantum phases. In order to investigate the role of electron and/or spin correlations in the excited states as well as in the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1THz∼4meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research summary in this year is as follows.

1. **Photoexcited dynamics of superconductivity in $La_{2-x}Sr_xCuO_4$** We investigated the photoexcited dynamics of archetypical single-layer cuprate superconductor, $La_{2-x}Sr_xCuO_4$, by using optical pump-THz probe spectroscopy. At below the critical temperature T_c, the photoexcitation results in continuous redshift of the Josephson plasma resonance, which indicates the suppression of superconductivity. The spectral behavior in the quasi-equilibrium state after the photoexcitation was well described by the pump-induced heating effect. We also revealed that the analysis method which has been conventionally used in optical pump and terahertz probe experiments can cause a serious artifact when there is a substantial penetration depth mismatch between the THz pump and optical probe in superconducting phase.

2. **Observation of Higgs mode in multiband superconductors:** We have investigated the Higgs mode in multiband superconductors both experimentally and theoretically. Recently, it has been theoretically demonstrated that the nonlinear terahertz response of the Higgs mode is significantly enhanced by nonmagnetic impurity scattering. However, its effect on the Leggett mode, a collective mode of the relative phase difference of order parameters in a multiband system, has been not elucidated. To clarify contributions from these collective modes, we theoretically examined nonlinear terahertz response of dirty superconductors by a density matrix method, and found that nonlinear response of the Leggett mode is not enhanced by the nonmagnetic impurity scattering. Consequently, we elucidated that the nonlinear optical responses in the gap frequency region are dominated by the Higgs mode. Experimentally, we investigated the collective mode of multiband superconductor, MgB_2 and $FeSe_{0.5}Te_{0.5}$. In MgB_2 a clear resonance was observed in the temperature deendence of THz third harmonic generation, which is most likely attributed to the Higgs mode. In $FeSe_{0.5}Te_{0.5}$, we succeeded in observing the forced oscillation of Higgs mode by THz pump-THz probe spectroscopy. Anti-phase oscillation of the two Higgs modes associated with the two bands were observed, suggesting a strong interband coupling character of $FeSe_{0.5}Te_{0.5}$ superconductor.

3. **Infrared activation of Higgs mode in superconducting NbN by supercurrent injection:** Higgs mode in superconductors is distinct from charge or spin fluctuation and thus is typically not linearly coupled to the electromagnetic field. However we experimentally demonstrated that, in the presence of dc supercurrent, the Higgs mode becomes infrared active and is directly observed in the linear optical conductivity measurement. We observed a sharp resonance peak at the superconducting gap energy in the optical conductivity spectrum of thin NbN films under the supercurrent injection over a wide temperature range below the critical temperature.

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17 Takagi-Kitagawa Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kentaro Kitagawa, Naoka Hiraoka

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2018 included, 5d complex Ir oxides with interplay of electron correlations and strong spin orbit coupling, spin liquids, anti-perovskites with Dirac electrons, and excitonic ground states.

Realization of new spin liquid and Kitaev physics:

Realization of spin liquid, where quantum spins fluctuates at abosolute zero, should be a milestone in the field of quantum spin physics. After a theoretical achievement of the exaclty solvable spin liquid state on a honeycomb lattice, by Alexei Kitaev, a materialization of this Kitaev Honeycomb Model (KHM) has been intensively pursuit. One dimensional spin liquid has been commonly accepted, while in two or three dimensions, typical known frustrated quantum spin liquid materials, like triangular compounds, is not based on an exactly solvable lattice model. We have been focussed on a two-dimensonal honeycomb iridate, $H_3LiIr_2O_6$, and discovered that $H_3LiIr_2O_6$ is indeed spin liquid, as the first material of such a liquid, down to 50 mK by specific heat, magnetic susceptibility, and nuclear magnetic resonance experiments. This key result was published this year.

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\text{eff}} = 1/2$ quantum pesudo spins of Ir on (hyper-)honeycomb lattice would be a main route. Two kinds of Majorana fermions represent KHM and they are particles on the exaclty solved ground state. Since our discovery is an only spin liquid on Kitaev system, and no report was given to proof two Majorana particles. We will pursuit identification of elementary excitations in $H_3LiIr_2O_6$ this year. We preliminary succeeded in fabricating a single crystal of this compounds, which should open a way to investigate a pristine thermally/artificially activated Majorana excitations or local excitations near an implanted defects, which can be evalulated rigorously for KHM. We expect that the latter effects can be caught by our NMR spectroscopy technique.

Three-dimensional Dirac electron systems:

We have demonstrated a realization of three-dimensional Dirac electrons in anti-perovskite oxide Sr_3PbO, which is evidenced by the quantum-limit characters in the magnetoresistance under high magnetic fields. This year, we have carried out ^{207}Pb NMR experiments on single-crystal samples with different carrier densities to establish Dirac-type dispersions. It was found that the temperature dependence of NMR relaxation rate certainly reflects three-dimensional Dirac-type density of states. Chiral anomaly is a phenomenon peculiar to this quantum-limit physics, and we have found a sign reversal of magnetoresistance with respect to direction of applied megnetic field. The anisotropic transport caused by magnetic field needs to be further considered in relation to the chiral anomaly and current jetting effect.

The semi-metallic AIrO_3 (A=Sr,Ca) perovskites are predicted to have three dimensional Dirac-node electrons and heavier holes at the fermi level. We fabricated epitaxially grown $A\mathrm{Ir}_{1-x}\mathrm{Sn}_x\mathrm{O}_3$ (A=Sr,Ca) on $SrTiO_3$(001) substrate to construct phase diagrams consisting of a magnetism phase, Dirac-node semimetal, and unknown physics in between. Substitution of Ir by Sn makes the system more insulating, and as a result, weak ferromagnetism appear. In these systems, namely, a competition between hopping and Coulomb repulsion can be well managed by a diltuion of Ir ions or a distortion of Ir-O-Ir bond. Band structures at each phase and phase boundary are yet to be identified and will be investigated.

18 Hayashi Group

Research Subjects: Quantum spintronics/optics

Member: Masamitsu Hayashi, Masashi Kawaguchi

We are working on the physics of spin orbit materials. Our studies cover tranport, magnetism, thermal and optical response of spin orbit heterostructures. Currently we put a particular focus on the strong correlations of spin, photon, magnon and phonons, which are mediated by the spin orbit interaction of the system, and look for the physics that can be applied to quantum information processing.

- Spin current generation
  - Anomalous spin Hall magnetoresistance in Pt/Co bilayers.[2]
  - Optical Detection of Spin-Orbit Torque and Current-Induced Heating[5]
  - Spin Hall effect from hybridized 3d-4p orbitals[?]
- Chiral magnetism
  - Domain-Wall Resistance in Cofeb-Based Heterostructures with Interface Dzyaloshinskii-Moriya Interaction[3]
- Light-spin interaction
  - Circular photogalvanic effect in Cu/Bi bilayers[7]

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19 Theoretical Astrophysics Group

Research Subjects: Observational Cosmology, Extrasolar Planets, Star Formation, and high-energy astrophysics

Member: Yasushi Suto, Naoki Yoshida, Kazumi Kashiyama, & Masamune Oguri

Theoretical Astrophysics Group conducts a wide range of research programmes. Observational cosmology is our primary research area, but we also pursue other forefront topics such as extrasolar planets, star formation and high-energy astrophysics.

"Observational Cosmology" attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of the recent and future data provided by Planck, Hubble Space Telescope, ALMA, and wide-field galaxy surveys such as Subaru Hyper-Suprime-Cam survey are quite important both in improving our understanding of the present universe and in determining several basic parameters of the universe which are crucial in predicting the evolutionary behavior of the universe in the past and in the future. Our current interests include nonlinear gravitational evolution of cosmological fluctuations, formation and evolution of proto-galaxies and proto-clusters, X-ray luminosity and temperature functions of clusters of galaxies, hydrodynamical simulations of galaxies and the origin of the Hubble sequence, thermal history of the universe and reionization, prediction of anisotropies in the cosmic microwave background radiation, statistical description of the evolution of mass functions of gravitationally bound objects, and statistics of gravitationally lensed quasars.

Astronomical observations utilizing large ground-based telescopes discovered distant galaxies and quasars that were in place when the Universe was less than one billion years old. We can probe directly, although not completely, the evolution of the cosmic structure all the way from the present-day to such an early epoch. Shortly after the cosmological recombination epoch when hydrogen atoms were formed, the cosmic background radiation shifted to infrared, and then the universe would have appeared completely dark to human eyes. A long time had to pass until the first generation stars were born, which illuminated the universe once again and terminate the cosmic Dark Ages. We study the formation of the first stars and blackholes in the universe. The first stars are thought to be the first sources of light, and also the first sources of heavy elements that enable the formation of ordinary stellar populations, planets, and ultimately, the emergence of life. We perform simulations of structure formation in the early universe on supercomputers. Direct and indirect observational signatures are explored considering future radio and infrared telescopes.

Can we discover a second earth somewhere in the universe? This puzzling question used to be very popular only in science fictions, but is now regarded as a decent scientific goal in the modern astronomy. Since the first discovery of a gas giant planet around a Sun-like star in 1995, more than a few thousands candidates of exoplanets have been reported as of May 2017. Though most of the confirmed planets turned out to be gas giants, the number of rocky planet candidates was steadily increasing, which therefore should give the affirmative answer to the above question. Our approaches towards that exciting new field of exoplanet researches include the spin-orbit misalignment statistics of the Rossiter-MacLaughlin effect, simulations of planet-planet scattering, simulations of tidal evolution of the angular momentum of the planetary system, photometric and spectroscopic mapping of a surface of a second earth and detection of possible biomarker of habitable planets.

Let us summarize this report by presenting recent titles of the PhD and Master's theses in our group;

2018

- Stellar Inclinations from Asteroseismology and their Implications for Spin-Orbit Angles in Exoplanetary Systems
- Numerical Investigations on Explosion Mechanisms of Core-collapse Supernovae
- Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev-Zel'dovich Effect
- Photoevaporation of Protoplanetary Disks and Molecular Cloud Cores in Star-Forming Regions
- Numerical Algorithms for Astrophysical Fluid Dynamics
- Radial velocity modulation of an outer star orbiting an unseen inner binary: analytic perturbation formulae in a three-body problem to search for wide-separation black-hole binaries
- The distribution and physical properties of emission line galaxies in the early universe
- Diversities out of the observed proto-planetary disks: migration due to planet-disk interaction and architecture of multi-planetary systems

2017

- Formation of supermassive stars and black holes via direct gravitational collapse of primordial gas clouds
- Formation and growth of massive black holes in the early universe
- Measuring Dynamical Masses of Galaxy Clusters with Stacked Phase Space
- GCM simulation of Earth-like planets for photometric lightcurve analysis
- Tidal disruption events of white dwarfs caused by black holes
- Radio, Submillimetre, and Infrared Signals from Embryonic Supernova Remnants

2016

- Evolution and Statistics of Non-sphericity of Galaxy Clusters from Cosmological Simulations
- Exploring the Architecture of Transiting Exoplanetary Systems with High-Precision Photometry
- Searching for Exoplanetary Rings via Transit Photometry: Methodology and its Application to the Kepler Data
- Superluminous supernova search with the Hyper Supreme-Cam Subaru Strategic Program
- Pulsar-driven supernova and its possible association with fast radio bursts
- Formation of massive black hole binaries in high-z universe

2015

- Chemo-thermal evolution of collapsing gas clouds and the formation of metal-poor star
- Cosmology with Weak Gravitational Lensing and Sunyaev-Zel'dovich Effect
- Far-infrared emission from SDSS galaxies in AKARI all-sky maps: Image stacking analysis and its implications for galaxy clustering
- Photo-evaporation of a proto-planetary disk

2014

- Stacking image analysis of SDSS galaxies in far-infrared and its implications for the Galactic extinction map
- Probing Cosmic Dark Matter and Dark Energy with Weak Gravitational Lensing Statistics

- Statistics of Submillimeter Line Emitters in Cosmological Simulation
- Characterization of a planetary system PTFO 8-8695 from the variability of its transit lightcurve induced by the nodal precession
- Neutrino-heating mechanism of core-collapse supernovae explosions
- Formation of Super-Massive Stars and Super-Massive Black Holes in the Early Universe

2013

- Giant primordial gas clouds and massive blackholes in the early universe
- Characterization of Multi-transiting Planetary Systems with Transit Timing Variations

20 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Akihito Soeda

Quantum mechanics allows a new type of information represented by quantum states which may be in a superposition of 0 and 1 state. Quantum information processing seeks to perform tasks which are impossible or not effective with the use of conventional classical information, by manipulating quantum states to the limits of quantum theory. Examples are quantum computation, quantum cryptography, and quantum communication.

This year, our group consisted of two faculty members, Mio Murao (Professor), Akihito Soeda (Assistant Professor), 2 postdoctoral researchers–Marco Túlio Coelho Quintino (JSPS foreign postdoctoral fellow until November and specially appointed researcher since March) and Shojun Nakayama (specially appointed researcher) —, and 5 graduate students–Ryosuke Sakai (D3), Hayata Yamasaki (D3), Qingxiuxiong Dong (D1), Oscar Bulancea Lindvall (USTEP graduate student from KTH Royal Institute of Technology), and Tian-Jiao Yin (research student). Our projects engaged in the academic year of 2018 were the following:

- Distributed quantum information processing
  - Necessary amount of quantum communication for distributed encoding and decoding of quantum information by H. Yamasaki and M. Murao
  - Quantum communication cost for quantum state merging by H. Yamasaki and M. Murao
  - Distributedly encoded quantum information through quantum state merging by H. Yamasaki and M. Murao
  - Distributed generation of multipartite entangled state under restricted quantum memories by H. Yamasaki and M. Murao with B. Kraus, W. Dür, and A. Pirker at the University of Innsbruck
  - Quantum communication cost for quantum state exchange with quantum side information by H. Yamasaki with Yonghe Lee and Soojoon Lee at Kyung Hee University, R. Takagi at Massachusetts Institute of Technology, and G. Adesso at Nottingham University.
- Higher-order quantum operations
  - Characterization of higher-order operations with indefinite causal order by W. Yokojima, M.T. Coelho Quintino, A. Soeda, and M. Murao
  - Universal quantum algorithm to invert a blackboxed unitary opertation by M.T. Coelho Quintino, Q. Dong, A. Soeda, and M. Murao
  - Controllization of higher-order operations and application to universal controllization of unitary gates by S. Nakayama, Q. Dong, and M. Murao
- Foundations on quantum mechanics

  - Quantum process with indefinite causal order and universal inversion of unitary gates by M.T. Coelho Quintino, Q. Dong, A. Soeda, and M. Murao
  - Device-independent tests of structures of measurement incompatibility by M.T. Coelho Quintino with C. Budroni at Institute for Quantum Optics and Quantum Information, A. Cabello at Universidad de Sevilla, and D. Cavalcanti at The Institute of Photonic Sciences (ICFO)
  - Semi-device-independent certification of indefinite causal order by M.T. Coelho Quintino with J. Bavaresco and Č. Brukner at Institute for Quantum Optics and Quantum Information, and M. Araújo at Institute for Theoretical Physics

- Quantum information processing with hybridized quantum systems
  - Robust control of two-qubit gates under inherent Hamiltonian dynamics by R. Sakai, A. Soeda, and M. Murao with D. Burgarth at Aberystwyth University
  - Thermal equilibration algorithm exploiting higher-order detailed balance of energy transition by S. Nakayama, O. Lindvall, and M. Murao

Please refer our webpage: http://www.eve.phys.s.u-tokyo.ac.jp/indexe.htm for more details. The publication list for the year is available at the end of the Japanese version of the group research summary.

21 Ueda Group

Research Subjects: Bose-Einstein condensation, fermionic superfluidity, topological phenomena, reservoir engineering, information thermodynamics, quantum information, measurement theory

Member: Masahito Ueda and Shunsuke Furukawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controllable systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose-Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied topological excitations and coarsening dynamics in spinor BECs, non-unitary dynamics in driven-dissipative systems, Efimov physics and impurity problems under the control of an atomic interaction strength, quantum Hall effect and vortex lattices in synthetic gauge fields, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems and the formulations of state reduction dynamics and Hamiltonian estimation in light of information flow under measurements and feedback controls. We list our main research subjects in FY2018 below.

- Quantum many-body phenomena in ultracold atoms
  - Quantum many-body dynamics under measurement backaction [1, 2]
  - Variational approach to quantum impurity problems in and out of equilibrium [3, 4]
  - Impurity-induced multibody resonances in a Bose gas [5, 6]
  - Collective modes of vortex lattices in two-component BECs under synthetic gauge fields [7]

- Quantum information, quantum measurement, and foundation of statistical mechanics
  - Classification of topological phases in non-Hermitian systems [8, 9]
  - Bulk-edge correspondence in non-Hermitian topological systems [10, 11]
  - Topological entanglement-spectrum crossing in quench dynamics [12]

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22 Yokoyama (J) Group

Research Subjects: Theoretical Cosmology and Gravitation

Members: Jun'ichi Yokoyama and Kohei Kamada

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We have also been working on gravitational wave data analysis to prepare for completion of KAGRA. Below is the list of topics studied during the academic year 2018.

Early Universe Cosmology

- Higgs- R^2 inflation
- Effects of phase transition during inflation on the primordial perturbations
- Anisotropic inflation
- Creation of the Universe from inhomogeneous fields
- Long-term dynamics of axion strings
- Electroweak symmetry breaking in the Twin Higgs models
- Gravitational reheating in the inflation models without inflaton oscillation
- Dark matter from the gravitational reheating
- Higgs vacuum instability around the compact objects
- Micro blackhole dark matter
- Reheating of the Universe triggered by the Higgs field
- Magnetogenesis and baryogenesis through the chiral anomaly

Astroparticle Physics

- Indirect detection of axions at the magnetosphere of neutron stars

Observational Cosmology

- Constraints on primordial non-Gaussianity through mini halo

Gravitational Waves

- Test of quantum gravity by the observation of the ringdown gravitational waves
- Independent component analysis with iKAGRA data

23 Takase Group

Research Subjects: High Temperature Plasma Physics Experiments, Spherical Tokamak, Wave Heating and Current Drive, Nonlinear Physics, Collective Phenomena, Fluctuations and Transport, Advanced Plasma Diagnostics Development

Member: Yuichi Takase, Akira Ejiri, Naoto Tsujii

In Takase Group, we perform experiments on the TST-2 spherical tokamak (R_0 = 0.36 m, a = 0.23 m, I_p < 120 kA) at the Kashiwa Campus to develop physics understanding and technology to realize fusion energy. Spherical tokamaks are able to achieve high β, but non-inductive plasma current start-up is a formidable challenge. We collaborate with other fusion experiments within Japan and abroad, including JT-60SA, LHD, LATE, and QUEST.

Our present focus on TST-2 is the establishment of plasma current ramp-up method using lower-hybrid waves (LHW). In FY2018, we have used the antenna installed at the top-side and the outboard-side of the plasma. To better understand the wave physics, we have installed new magnetic probes and interferometer chords. We have also made modification to the top-launch antenna to extend the plasma size.

When the LHW was launched from the top-side of the plasma, strong up-shift of the poloidal wavenumber was expected above the plasma current of 16 kA for the TST-2 parameters. In the experiment, dramatic increase of soft X-ray radiation was observed which may be consistent with the strong up-shift in the wavenumber. Hard X-ray radiation have been measured to study the dynamics of lower-hybrid wave driven fast electrons. A new detector using LYSO was installed and the time resolution was improved by a factor of 4 compared to the previous NaI based detectors. With power modulation experiment, existence of barely confined, and thus quickly lost fast electrons were suggested. An interferometer chord was added at Z = 0.3 m, above the midplane. The density measured by this chord decreased by 40 % immediately after the RF power turn on whereas density change at the midplane chord was negligible. This may be an indication of density reduction due to the ponderomotive force. Magnetic probes were used to study lower-hybrid wave propagation. The newly installed probes at the center stack showed drastically different wave propagation characteristics between the top-launch and the outboard-launch antennas, partially consistent with the ray-tracing calculations.

Ohmic discharges were also studied. Microwave imaging reflectometry (MIR) was used to observe the MHD fluctuations leading to internal reconnection events. It was found that the peak of the density fluctuation intensity measured by MIR occurred slightly (100–400 μs) before those of the magnetic probes and the radiation measurements.

AC Ohmic coil operation attempts to reduce the size of the Ohmic coil by applying AC current instead of DC current. It has been shown that AC Ohmic operation can successfully pre-ionize the plasma, which in turn, can be ramped up using LHW. Theoretical model to better describe the pre-ionization process was developed.

Several diagnostic developments were performed in FY2018. The stray-light of the Thomson scattering diagnostic was quantitatively measured and the source was identified. By installing four apertures at the critical locations along beam line, the stray-light was reduced to 4 % of the previous value.

LYSO based hard X-ray imaging diagnostic was designed to identify the source of hard X-ray radiation more accurately. Polarimeter is being developed to measure the internal current profile which is hard to estimate only with external magnetic diagnostics. Initial measurement was performed and polarimeter phase was successfully measured, but reduction of noise is necessary.

As a collaboration, Thomson scattering on QUEST is being developed. Thomson scattering measurement was performed for ECH driven discharges. For 28 GHz ECH driven discharge, the parallel refractive index was scanned. Much higher temperature was achieved at lower parallel refractive index suggesting bulk heating.

Soft X-ray imaging system is being developed as a collaboration with PPPL. In FY2018, design optimization for a DIII-D H-mode discharge and a JT-60SA neutral beam driven discharge was performed. A similar system is planned to be installed on TST-2 and the design is being finalized.

24 Sano Group

Research Subjects: Physics of out-of-equilibrium systems and living matter

Member: Masaki Sano and Tetsuya Hiraiwa

Our main goal is to discover and elucidate prototypical phenomena in systems far from equilibrium. To this end we develop our studies along the following three axes, integrating both experimental and theoretical approaches: (i) statistical mechanics in which non-equilibrium fluctuations overwhelm the thermal effects, (ii) active matters, as characteristic phenomena in far-from-equilibrium systems, (iii) biological systems, as important instances where non-equilibrium dynamics takes the essential role. Our current research topics include:

1. Statistical mechanics out of equilibrium
   (1) Establishing the method to verify the scaling law in the absorbing phase transition [2]
   (2) Non-equilibrium dynamics in large-degree of freedom system including electroconvection of liquid crystals and absorbing phase transition
2. Active matters
   (1) Self-propulsion of colloidal particle under AC fields
   (2) Collective motion of self-driven colloidal particles
   (3) Collective motion of filamentous proteins
3. Biological systems
   (1) Collective migration of neural stem cells on the restricted range of adherable substrate
   (2) Theory on mechanics of cellular dynamics and morphogenesis [1, 3, 4]

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25 Yamamoto Group

Research Subjects: Millimeter- and submillimeter-wave Astronomy, Star and Planet Formation, Chemical Evolution of Interstellar Molecular Clouds

Member: Satoshi Yamamoto and Yoko Oya

Molecular clouds are birthplaces of new stars and planetary systems, which are being studied extensively as an important target of astronomy and astrophysics. Although the main constituent of molecular clouds is a hydrogen molecule, various atoms and molecules also exist as minor components. The chemical composition of these minor species reflects formation and evolution of molecular clouds as well as star formation processes. It therefore tells us how each star has been formed. We are studying star formation processes from such an astrochemical viewpoint.

Since the temperature of a molecular cloud is 10 ? 100 K, an only way to explore its physical structure and chemical composition is to observe the radio wave emitted from atoms, molecules, and dust particles. Particularly, there exist many atomic and molecular lines in the millimeter/submillimeter wave region, and we are observing them toward formation sites of Solar-type protostars mainly with ALMA (Atacama Large Millimeter/submillimeter Array).

So far, it has well been recognized that an envelope/disk system of a Solar-type protostar shows a significant chemical diversity. One distinct case is so called Warm Carbon Chain Chemistry (WCCC), which is characterized by rich existence of various unsaturated carbon-chain molecules such as C_2H, C_4H, and HC_5N. A prototypical source is L1527 in Taurus. Another distinct case is so called hot corino chemistry, which is characterized by rich existence of various saturated organic molecules such as CH_3OH, $HCOOCH_3$, and C_2H_5CN. A prototypical source is IRAS 16293-2422 in Ophiuchus. Recently, sources having the both characteristics have also be found. Such chemical diversity would reflect the star formation history of each source, more specifically, a duration time of the starless core phase.

We are now studying how such chemical diversity is brought into protoplanetary disks by using ALMA. For the WCCC source L1527, we have found that carbon-chain molecules only exist in an infalling-rotating envelope outside its centrifugal barrier ($r = 100$ AU), while SO preferentially exists around the centrifugal barrier. For the hot corino source IRAS 16293-2422, OCS traces an infalling-rotating envelope, while saturated organic molecules such as CH_3OH and $HCOOCH_3$ trace the centrifugal barrier. Hence, chemical compositions drastically change across the centrifugal barrier of the infalling gas. Since a protostellar disk is formed inward of the centrifugal barrier, the chemical diversity at an envelope scale ($\sim$ 1000 au) is indeed inherited in the disk forming region ($\sim$ 100 au). Then, what is the initial chemical condition of the Solar System? Is it a common occurrence in our Galaxy? To answer these questions, extensive ALMA observations are in progress.

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooled HEB mixer using NbTiN and NbN in our laboratory. The receiver equipped with this HEB mixer is now used for laboratory spectroscopy of interstellar molecules at RIKEN in collaboration with Dr. Nami Sakai.

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26 Sakai (Hirofumi) Group

Research Subjects: Experimental studies of atomic, molecular, and optical physics

Members: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (3) Ultrafast phenomena in atoms and molecules in the attosecond time scale. (4) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. A part of our recent research activities is as follows:

(1) Electron-wave-packet dynamics extracted from the ellipticity dependence of high-order harmonic generation in benzene molecules [4]

We measure the ellipticity dependence of high-order harmonic intensities generated from benzene (C_6H_6) molecules with and without an yttrium aluminum garnet (YAG) laser field. We successfully extract the expansion dynamics of the electron wave packet by analyzing the ellipticity dependence based on the semiclassical electron trajectory. Without the YAG laser pulse, we find that the ellipticity dependence reflects the expansion dynamics of the electron wave packet and the difference in highest occupied molecular orbital compared to nitrogen (N_2) molecules. We also measure the ellipticity dependence under the YAG laser field and show that the difference in the ellipticity dependence with and without the YAG laser field is qualitatively explained by the harmonic-order-dependent efficiency of the sum and difference frequency generation, whose efficiency is higher as the harmonic order becomes higher.

(2) Improving molecular orientation by optimizing relative delay and intensities of two-color laser pulses [5]

We numerically explore molecular orientation dynamics with moderately intense nanosecond two-color laser pulses. It is believed that the nanosecond two-color pulse can adiabatically control the molecular orientation. However, in our simulation based on the time-dependent Schrödinger equation, which naturally includes nonadiabatic effects, the orientation dynamics shows clear deviation from the adiabatic approximation (AA) results, while the molecular alignment dynamics is in good agreement with the AA results. The nonadiabaticity is significantly influenced by three parameters, the intensities, and the relative delay of the two wavelengths. In this work, we clarify the reason behind the nonadiabaticity and provide the solution for achieving higher degrees of orientation.

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27 Gonokami, Yumoto and Ideguchi Group

Research Subjects: Experimental studies on light-matter interaction in many-body quantum systems, optical phenomena in artificial nanostructures, and development of laser based coherent light sources

Member: Makoto Gonokami, Junji Yumoto and Takuro Ideguchi

We explore new aspects of many-body quantum systems and their exotic quantum optical effects by designing light-matter interactions. Our current target topics consist of a wide variety of matters, including excitons and electron-hole ensembles in semiconductors, antiferromagnetic materials and ultra-cold atomic gases. In particular, we have been investigating the phase of Bose-Einstein condensation of excitons, which has not been experimentally proven while considered as the ground state of an electron-hole ensemble. Based on quantitative spectroscopic measurements, the temperature and density of the excitions are determined in a quasi-equilibrium condition where they are trapped in a highly pure crystal kept below 1 K. We are now investigating a stable quantum degenerate state of dark excitons at the low temperature. We also study novel optical and teraherz-wave responses of artificial nanostructures fabricated by advanced technologies. Furthermore, a project has started for developing new coherent light sources that cover broad spectral range from terahertz to soft X-rays. The Foundation for Coherent Photon Science Research was established for the project in collaboration with RIKEN. This is one of the Advanced Research Foundation initiatives from the Ministry of Education, Culture, Sports, Science and Technology. Within this initiative, we are developing intense and stable coherent light sources running at a high repetition rate (the facility is called "Photon Ring").

The group activities of this year are as follows:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   - 1.1. Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   - 1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases and their application to nuclear physics
2. The quest for non-trivial optical responses and development of applications:
   - 2.1. Development of new technology to measure laser ablation thresholds
   - 2.2. Fabrication of Moth-Eye THz Anti-Reflection Structures by Femtosecond Laser Processing
   - 2.3. Novel design and modeling technique for additive manufacturing of functional objects with arbitrarily graded internal structures
3. Development of novel coherent light sources and spectroscopic methods:
   - 3.1. VUV precision spectroscopy using higher-order harmonics
   - 3.2. Laser-based angle resolved photoemission spectroscopy
   - 3.3. Label-free microscope using coherent Raman spectroscopy
   - 3.4. "Photon ring" project
   - 3.5. Institute for Photon Science Technology

28 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Yuta Michimura

Gravitational waves has a potential to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars or binary black holes; these information can not be obtained by other means such as optics, radio-waves or X-ray. Worldwide efforts are being continued in order to construct and improve detectors.

In Japan, we are constructing a large-scale cryogenic gravitational-wave antenna, named KAGRA, at Kamioka underground site. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200 Mpc. A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

The current research topics in our group are followings:

- KAGRA gravitational wave detector
- Space laser interferometer, DECIGO
- Development of TOBA (Torsion Bar Antenna)
- High-precision experiments on relativity and opto-mechanics
  - Opto-mechanics experiments with triangular cavity
  - Optical levitation experiments
  - Experimental study of space isotropy

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29 Bamba Group

Research Subjects: High-energy astrophysics, mainly utilizing X-ray observatories in orbit. Targets are, supernova remnants, black-holes, neutron-stars, magnetars, white dwarfs, cluster of galaxies, as well as thunder-cloud gamma-rays.

Member: Associate Prof: Aya Bamba, Assistant Prof: Hirokazu Odaka

We analyze the X-ray data of, neutron star high-mass X-ray binaries, neutron star low-mass X-ray binaries, magnetors, and associated supernova remnants. Also black-hole binaries, active galactic nuclei, as well as Ultra-Luminous X-ray sources, are analyzed. White dwarf binaries are also important. Clusters of galaxies, especially in its merging phase, are also important targets for us. Supernova remnants are the origin of diversity of the universe, in the context of chemical evolution, cosmic ray acceleration, and the explosion mechanism of supernovae.

For further better observations, we developes a new generation X-ray satellites. We are members of XRISM, planned to launch on Japanese fiscal year of 2021, and charges the science magegement of galactic diffuse sources and softwares. We also study on future missions to measure the X-ray polarimetory, using CMOS sensors and coded apertures, which mission aims to launch 2020's.

We are also working on the enigmatic MeV gamma-ray emission from thunder-clouds themselves.

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30 Kusaka Group

Research Subjects: Observational Cosmology, Cosmic Microwave Background (CMB) Observation. (1) Study of Inflation in the early universe and the evolution of the universe through gravitational lensing using Polarbear and Simons Array experiment; (2) Design, Development, and Construction of Simons Observatory aiming to study Inflation, evolution of the universe, Neutrinos, Dark Energy, and Dark Radiation; (3) Research and Development of technologies for Simons Observatory and CMB-S4.

Member: A. Kusaka and K. Kiuchi

- POLARBEAR experiment and its successor, Simons Array, are optimized to measure both inflationary signature and the gravitational lensing effect in CMB polarization. POLARBEAR experiment has just concluded its observation campaign, and Simons Array experiment is about to be deployed. Our focus is on data analysis as well as the development and characterization of the continuously-rotating half-wave plate (HWP) enabling accurate measurement of CMB polarization.
- Simons Observatory experiment is planned for the first light in a few years. We plan to deploy an array of what we call "small aperture cameras," which are dedicated for the inflationary signal, and a six-meter "large aperture telescope," which enables observation for Neutrinos and the dark content of the universe. We are primarily focusing on the design and development for the small aperture camera.
- Research and Development for the next generation experiments such as Simons Observatory and CMB-S4 are crucial component of our research program. We specifically work on superconducting technologies used in the detectors and cryogenic bearing system for HWP. We also develop techniques for high-performance computation (HPC) enabling data analysis for new experiments producing order-of-magnitude larger data volume than the current instruments.

31 Takeuchi Group

Research Subjects: Physics of out-of-Equilibrium systems

Member: Kazumasa A. Takeuchi

We aim to explore laws of physics underlying out-of-equilibrium phenomena, by pushing forward research subjects encompassing soft matter such as liquid crystal and granular systems, fluids, and biological populations, mostly by experiments. In addition to understanding specific problems, we aim to extract laws of physics that are hopefully common across different systems and phenomena. As a result, there are a relatively wide range of subjects ongoing in the lab. Currently, our main subjects are "exploration of universal out-of-equilibrium scaling laws using liquid-crystal turbulence" and "search for physical principles governing populations of living cells by means of microfluidic devices", but we also continue being motivated to launch "new projects that are interesting and realistic to challenge". Below is a list of subjects we carried out in the scholar year 2018.

(1) Exploration of universal out-of-equilibrium scaling laws using liquid-crystal turbulence
(1-1) Direct test of universal statistics for the non-equilibrium steady state of interface fluctuations
(1-2) Measuring dynamic scaling laws of Ising-type relaxation and connection to critical percolation
(2) Search for physical principles governing populations of living cells by means of microfluidic devices
(2-1) Development of a microfluidic device for observing dense bacterial suspensions
(2-2) Observation of competiting two neutral bacterial populations
(2-3) Lane formation and voter-model statistics in a model of bacterial populations [3]
(3) Other experimental or experimentally motivated projects
(3-1) Development of a method to measure instability of large chaotic systems [2]
(3-2) Reversible-irreversible transition in a dense particle system under periodic shear

Published papers:
[1] K. A. Takeuchi, An appetizer to modern developments on the Kardar-Parisi-Zhang universality class. Physica A **504**, 77-105 (2018).
[2] T. P. Shimizu and K. A. Takeuchi, Measuring Lyapunov exponents of large chaotic systems with global coupling by time series analysis. Chaos **28**, 121103 (2018). (fast track article)
[3] T. Shimaya and K. A. Takeuchi, Lane formation and critical coarsening in a model of bacterial competition. Phys. Rev. E (in press).

32 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose and Hiroshi Kohsaka

The aim of our laboratory is to elucidate the mechanisms underlying the formation and function of neural networks, by using as a model, the simple nervous system of the fruity, *Drosophila*. A part of our recent research activity is summarized below.

1.Divergent Connectivity of Homologous Command-like Neurons Mediates Segment-Specific Touch Responses in Drosophila.

Animals adaptively respond to a tactile stimulus by choosing an ethologically relevant behavior depending on the location of the stimuli. Here, we investigate how somatosensory inputs on different body segments are linked to distinct motor outputs in Drosophila larvae. Larvae escape by backward locomotion when touched on the head, while they crawl forward when touched on the tail. We identify a class of segmentally repeated second-order somatosensory interneurons, that we named Wave, whose activation in anterior and posterior segments elicit backward and forward locomotion, respectively. Anterior and posterior Wave neurons extend their dendrites in opposite directions to receive somatosensory inputs from the head and tail, respectively. Downstream of anterior Wave neurons, we identify premotor circuits including the neuron A03a5, which together with Wave, is necessary for the backward locomotion touch response. Thus, Wave neurons match their receptive field to appropriate motor programs by participating in different circuits in different segments. (Collaboration with Drs. Albert Cardona, Marta Zlatic, and James Truman groups at the Janelia Research Institute in the USA and Dr Hokto Kazama at RIKEN BSI)

2.Data-driven analysis of motor activity implicated 5-HT2A neurons in backward locomotion of larval Drosophila.

Rhythmic animal behaviors are regulated in part by neural circuits called the central pattern generators (CPGs). Classifying neural activities correlated with body movements and identifying component neurons associated with the activities are critical steps in understanding the workings of CPGs and animal locomotion. Here, we present a novel method for classifying motor activities in large-scale calcium imaging data of Drosophila larvae. The method is based on pre-trained convolutional neural network model VGG-16 and unsupervised learning, and successfully classified activities correlated with forward and backward locomotion in activity data of different types of neurons and under different imaging conditions. By applying these methods to neurons targeted by 5-HT2A-Gal4, we identified two classes of interneurons, termed Seta and Leta, which are specifically active during backward but not forward fictive locomotion. Several behavior assays suggest that 5-HT modulates backward locomotion by acting on Seta and Leta neurons via the 5-HT2A receptor. This study establishes an accelerated pipeline for activity profiling and cell identification in larval Drosophila and implicates a serotonergic system in the modulation of backward locomotion. (Collaboration with Dr. Shu Kondo at NIG and Dr. Hiromu Tanimoto at Tohoku university)

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33 Higuchi Group

The function of biological system is originated by the bio-molecular function. It is difficult to measure the molecular functions in cells and animals precisely. Therefore, we understand the molecular function, especially dynamic function, of purified protein molecule first by single molecule technology. Then we investigate the function of molecules or organelle by the single and imaging method. Finally, we imaged the molecules in mouse auricle to understand the function of molecule in vivo.

Super-resolution method to detect the movement of myosin heads The direct observation of coordinated force generations in acto-myosin system has not been performed due to the technical difficulty that is the diffraction limit. Now, in order to overcome such a problem, we have applied the super-resolution imaging technique developed by Prof. Ueda's group from our department. In our single molecule assay, gold nanoparticles (GNPs) were attached to 2-3 myosin molecules embedded in each single myosin filament. The scattered images of GNPs were recorded by high-speed camera and were typically merged together because they are positioned within the diffraction limit. Therefore, the Multi-Emitters Localization algorithm (Ashida and Ueda, 2014) was used to detect the positions of individual GNPs at every 100μs interval. We found that each myosin molecules are substantially displaced during acto-myosin interactions and their displacements appear to be occasionally synchronized. However, we realized that scattered images can be influenced each other, causing a potential artifact, if their positions are too closed. Thus, we need to develop a new laser projection method and analysis technique to overcome this issue.

Reverse stroke generated by cardiac myosin In order to elucidate the molecular mechanism of how dynamics of cardiac myosins contribute to heart function, we measured forces of synthetic β-cardiac myosin filaments using optical tweezers and revealed stepwise displacements of actin filaments driven by myosins under a wide range of loads. The stepping ratio, which is the ratio of the number of forward steps relative to backward steps, under unloaded conditions decreased with increasing ATP concentrations. Compared with skeletal myosin, the stepping ratio of cardiac myosin is much lower than that of skeletal myosin, indicating cardiac myosin shows frequent backward steps. Meanwhile, the peak forces generated by cardiac myofilaments with 15 interacting molecules were 1.5-2 times higher than those observed in skeletal myofilaments with nearly the same number of interacting molecules. Based on these findings, we developed the simulation model to understand which molecular properties critically effect on stepping behaviors and force outputs in cardiac myofilaments. The simulation suggested that reverse stroke in ADP states is a key feature to cause frequent backward steps at higher ATP concentrations, resulting lower stepping ratio. Moreover, switching between two ADP states associated with the alternate execution of power and reverse strokes keeps many myosin molecules populated in force-generating states, enhancing the duty ratio and force outputs. Therefore, we further investigated whether single cardiac myosin can execute the power and reverse strokes in ADP state under a variety of loading conditions. When single cardiac myosin molecules interacting with single actin filaments were stretched by optical tweezers, beads' positions were occasionally switched between two discrete levels for high loads, implying the load-dependent execution of power and reverse strokes. To know physiological meaning of reverse stroke, we simulated dynamics of myosin molecules in sarcomere and found that the reverse stroke plays a crucial role in reducing the rate of ATP consumption during isometric contraction.

Molecular mechanism of beating of sperm flagella To investigate the collective force generation of an ensemble of dynein in sperm axoneme, we planned to measure force generation of dynein still attached on a doublet microtubule. We disintegrated axoneme by adding ATP after treating by protease to obtain doublet microtubules. We measured force generated by dynein molecules on the edge of a bundle of doublet microtubules and found two types of characteristic force. In the first type, microtubule was interacted to a bundle of doublet microtubules at right angles and then oscillatory force was measured. The peak-to-peak forces and amplitude of oscillation was about 10-15 pN and 10-15 nm, respectively. The fact that dyneins on a bundle of doublet microtubules can generate oscillatory force suggests that dynein retain characteristic oscillatory force generation in higher order of structure. In the second type, a microtubule was interacted to a bundle of doublet microtubules in parallel in which hundreds of dynein molecules can interact to a microtubule and then force of about 8 pN was generated. This suggests the possibility that very small number of dynein molecules activate at the same time.

Collective motion on cell assembly Collective motion of spindle-shaped cells has been seen during development, for example rostral migratory stream, or cancer invasion after epithelial-mesenchymal transition. As spindle-shaped cells has many functions which are significant on collective migration, their collective migration is understood only qualitatively. To establish a model on the collective migration, we have been studying on the collective motion, with nematic order, of murine neural stem cells, one of the cell types with spindle shape, under adhesive culture. To make a mechanical model on the collective motion of particles with spontaneous motility and with high aspect ratio, the system is usually coarse-grained assuming two-fold rotational symmetry. From the argument on symmetry, force generation, which is proportional to the vector calculated as the distortion of the field of particle orientation, is derived. In our study conducted until last year, this force was measured on the collective migration system of neural stem cells, utilizing the traction force microscopy. In this year, we constructed the system where we can force neural stem cells adhere on a selected area of the substrate, and this system showed the chiral migration of neural stem cells, especially on the boundary of the selected area. On the other hand, we confirmed the expression of a protein which is shown to play important roles on left-right asymmetric development. So we are trying to inhibit the function or the expression of the protein in neural stem cells, aiming to reveal the role of the protein in the collective migration.

34 Okada Group

Research Subjects: Biophysics, cell biology, super-resolution microscopy, live cell imaging and single molecule imaging.

Member: Yasushi Okada, Sawako Enoki and Keigo Ikezaki

Our primary goal is to answer the very basic question "What is life". To answer this question , we are trying to fill the gap between the world of molecules and the world of living cells. Direct measurement of molecules in living cells would serve as a basic technology to fill this gap. Thus, we have been working on the development of the technologies for the visualization and non-invasive measurement of the molecular processes in living cells. High-speed, super-resolution live-cell imaging and single-molecule measurement in living cells are the two main technologies we develop.

By using these technologies, we are trying to understand the regulatory mechanisms of motor proteins during axonal transport. Despite the many studies in the past decades by our group and others, it is still unclear how the biophysical properties of motor proteins are related to their biological functions. For example, a point mutation in kinesin-1 can cause hereditary spastic paraplegia, but it is unclear why this mutation selectively affects neurons in the longest tract in the aged patients.

Through these studies and development, we have realized the importance of the cellular states, and our microscope technologies can also be applied to the measurement of the cellular states. Thus, we have proposed a project for the visualization, prediction and control of cellular states. We are now leading this project, and the project members in our lab are working on the development of the technologies to visualize and control cellular states.

In short, our effort is now divided into the following three areas: 1) development of imaging technologies [1, 2, 3, 8], 2) study of axonal transport [5, 6], 3) measurement and control of cellular states [4].

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35 Furusawa Group

Research Subjects: Theoretical Biophysics, Evolutionary Biology, Complex Systems

Member: Chikara Furusawa and Nen Saito

Biological systems have both robustness and plasticity, a property that distinguishes them from artificial systems and is essential for their survival. Biological systems generally exhibit robustness to various perturbations, including the noise in gene/protein expressions and unexpected environmental changes. At the same time, they are plastic to the surrounding environment, changing their state through processes like adaptation, evolution and cell differentiation. Although the coexistence of robustness and plasticity can be understood as a dynamic property of complex and interacting networks consisting of a large number of components, the mechanisms responsible for the coexistence are largely unknown.

The goal of our work is to extract the universal features of cellular dynamics that are responsible for robustness and plasticity in biological systems. We aim to describe the systems using a relatively small number of degrees of freedom with the macroscopic state variables. We expect that such a description will provide novel methods for the prediction and control of complex biological systems.

The current research topics in our group are followings:

1. Construction of macroscopic state theory describing adaptation and evolution of biological systems
2. Laboratory evolution of bacterial cells to analyze dynamics of phenotype-genotype mappings
3. Theoretical analysis for symbiotic relationships in ecosystems
4. Analysis of amoeba morphogenesis using phase-field models
5. Decoding gut microbiota using artificial neural networks

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