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Annual Report

2019

令和元年度 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

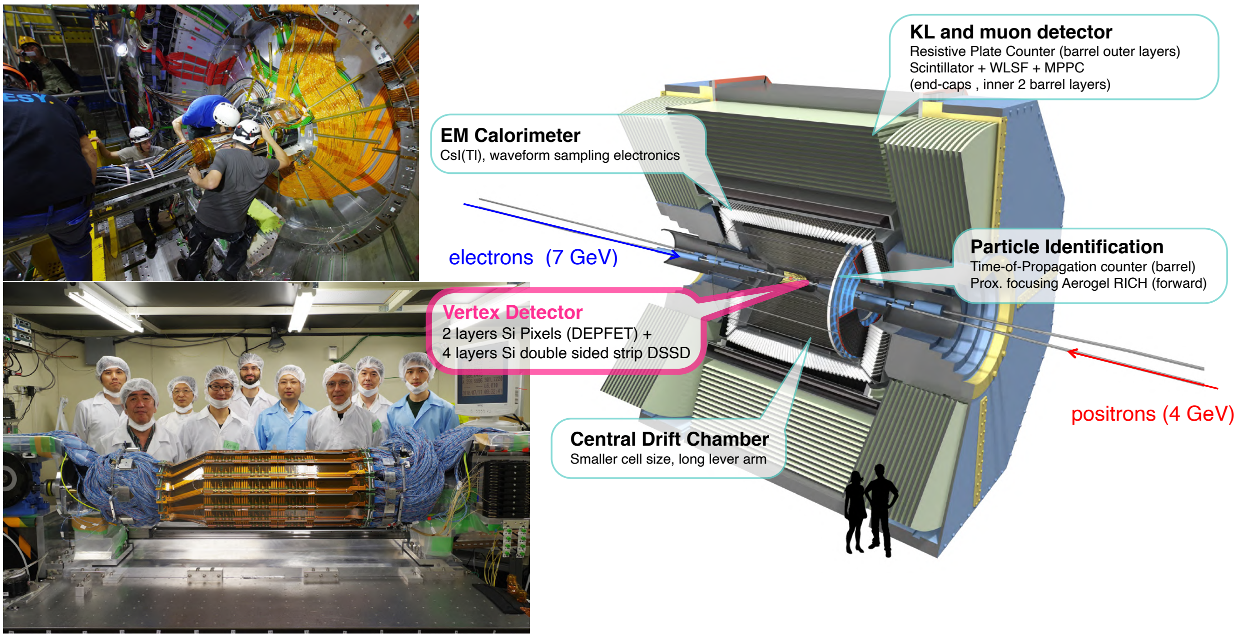

図 1: 高エネルギー加速器研究機構 (KEK) では、第 3 世代のクォークを含む B 中間子や、第 3 世代レプトンの τ 粒子などの崩壊を超精密に測定することで、素粒子の標準模型を越えた物理の発見を目指す、Belle II（ベルツー）実験が 2019 年から本格的に開始された。ナノメートルレベルまで絞られた、70 億電子ボルトの電子と 40 億電子ボルトの陽電子の衝突で生成される多様な粒子をとらえるのは、縦・横・高さがそれぞれ 8 メートル、総重量 1,400 トンの巨大な Belle II 測定器（右図）である。その心臓部であるシリコン崩壊点検出器（左下：組み上げ時の写真）は、電子と陽電子が衝突する中心部の最も近くに設置され（左上：設置時の写真）、荷電粒子の位置を 10μm 程度の精度で測定する。（相原-横山研究室 / 高エネルギー加速器研究機構, Belle II 実験グループ）

In 2019, the Belle II experiment, which aims to discover physics beyond the Standard Model by precisely measuring the decay of B mesons and τ leptons, started at the High Energy Accelerator Research Organization (KEK). The gigantic Belle II detector (right), which is 8 meters long, wide, and high and weighs 1,400 tons, captures particles produced by the collision of electrons of 7 billion electron volts and positrons of 4 billion electron volts. The Silicon Vertex Detector (bottom left: picture during assembly), is installed closest to the collison point (top left: picture during installation) and precisely measures the position of charged particles. (Aihara-Yokoyama Group / High Energy Accelerator Research Organization and Belle II Collaboration)

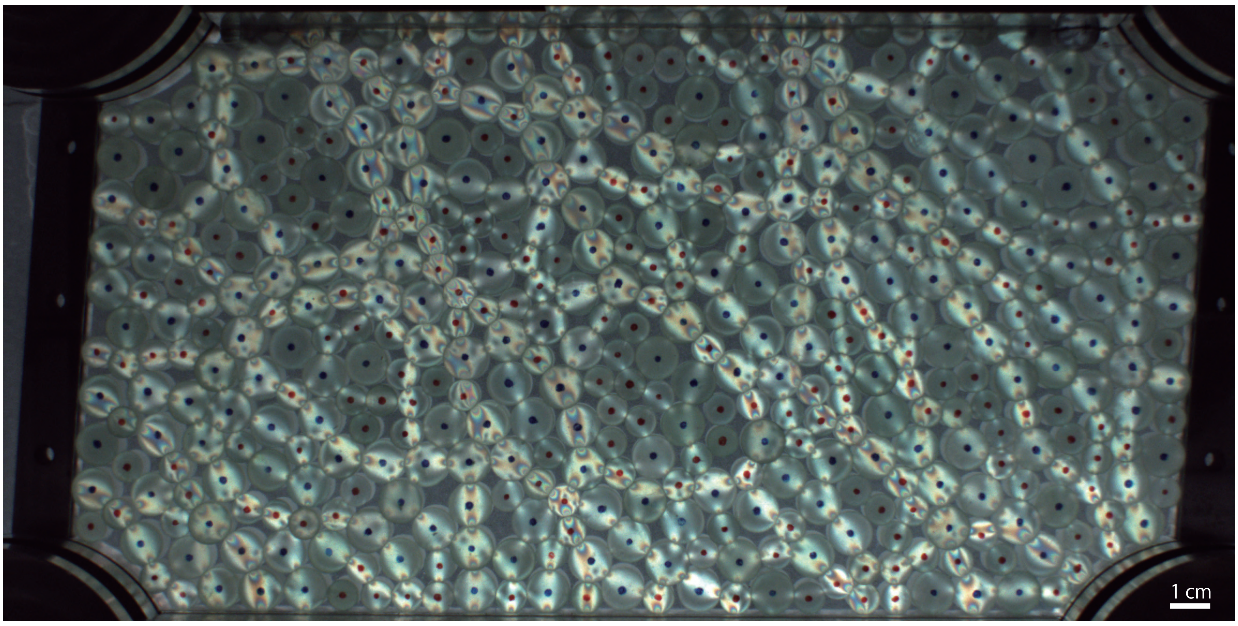

図 2: 周期的せん断下の光弾性粒子系で見られる相互作用ネットワークの様子。光弾性とは、物質が局所的な応力に応じて複屈折を示す現象のことで、偏光観察によって応力分布を可視化できる。よく知られているように、多数の粒子が充填されていても、負荷は一部の粒子に集中し、それが鎖状のネットワークを構成していることがわかる。我々は、近年研究が進んでいる、周期的なせん断を受けた多粒子系における粒子運動の可逆性相転移に対して、光弾性材料を用いることで運動と相互作用を同時に観察し、相転移の性質とレオロジーの理解を目指している。（竹内研究室）

Force chain network of a photoelastic particle system under periodic shear. Photoelasticity refers to the property of material that leads to birefringence depending on the local stress at each point. Therefore one can visualize stress distribution by polarized light observation. The photograph shows a well-known fact that, even in a densely packed system, stress concentrates on some of the particles and forms a chain-like network. We apply this method to study a phase transition in reversibility of particle motion, in a densely packed particle system under periodic shear, which has been a target of intense studies recently. (Takeuchi Group)

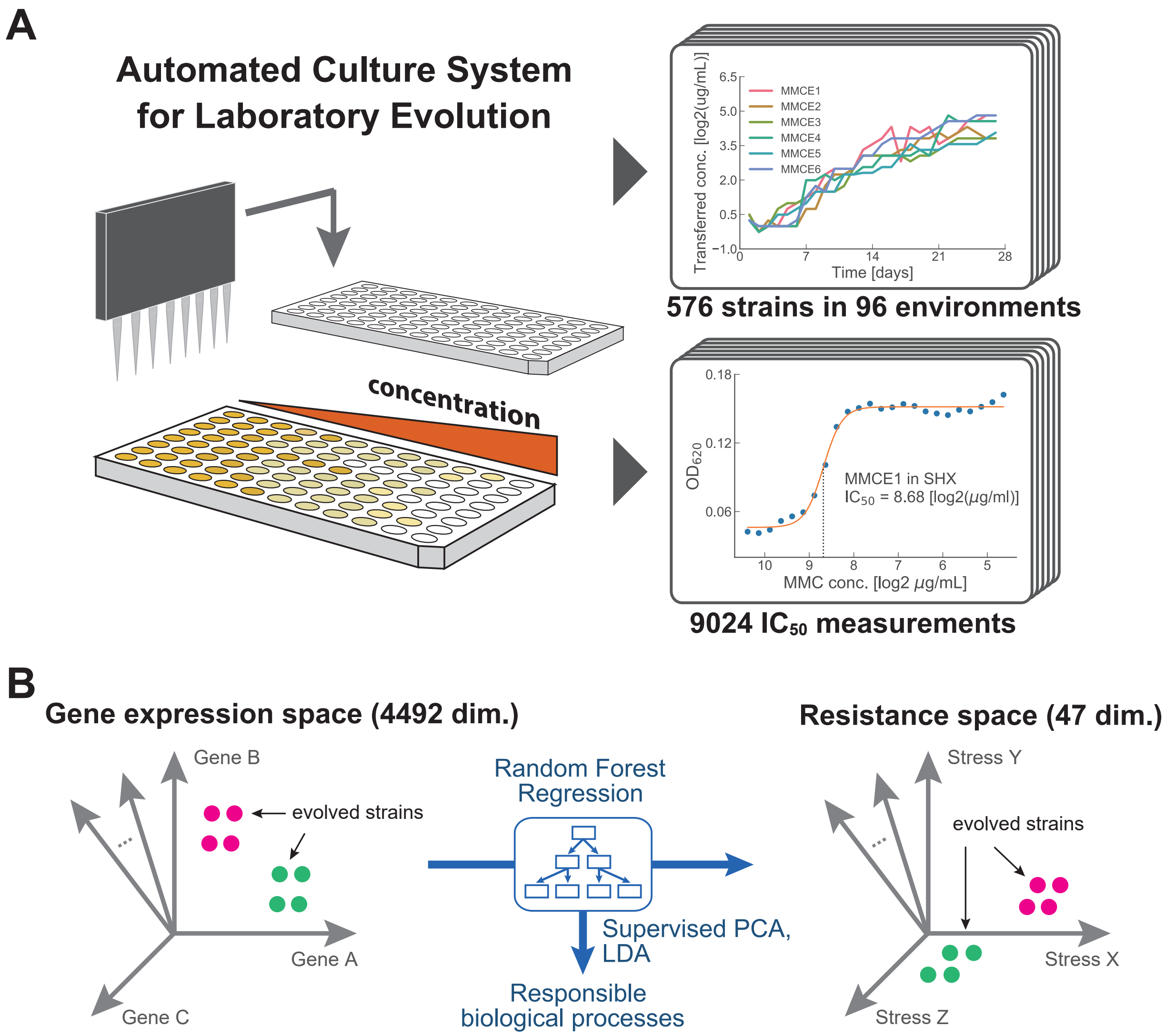

図 3: 多環境・多系統での大腸菌進化実験。ラボオートメーションを用いた全自動進化実験システムを用い、96 のストレス環境条件でそれぞれ 6 系統の大規模進化実験を実施し、それぞれのストレスに対する耐性大腸菌株を取得した。それらの耐性株について、遺伝子発現量プロファイルの定量と、様々なストレス環境に対する耐性能を定量したところ、大腸菌の表現型進化は比較的少数の特徴量によって記述可能であることが示された（古澤研究室）。

High-throughput laboratory evolution of Escherichia coli. We performed laboratory evolution of E. coli under 96 stress environments by using an automated culture system and obtained stress-resistant strains. Then, we quantified gene expression profiles and resistance to various stresses for these resistant strains. The data demonstrated that phenotypic changes in evolution can be described by a relatively small number of features, which will be a basis for prediction and control of evolutionary dynamics (Furusawa Group).

II

Summary of group activities in 2019

1 Theoretical Nuclear Physics (Fukushima) Group

Research 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 2019 are summarized below:

1. Phenomenology
   - 1.1. Neutrino physics and flavor symmetry [1, 2, 3]
   - 1.2. Phenomenology of supersymmetric Standard Models [4, 5, 6, 7, 8]
   - 1.3. Future collider experiments [9, 10]
   - 1.4. Vacuum decay [11]
   - 1.5. Neutron stars [12, 13]
   - 1.6. Supersymmetric Grand Unified Theories [14, 15, 16, 17]
   - 1.7. Gravitational particle production [18, 19]
   - 1.8. Vector dark matter [20]
   - 1.9. Black hole superradiance [21]
   - 1.10. Axion detection [22]
   - 1.11. Dark matter and structure formation [23, 24]
2. Superstring theory and formal aspects of quantum field theories
   - 2.1. Lattice gauge theories [25]
   - 2.2. Mathematical study of duality in gauge/string theory [26, 27]
   - 2.3. Algebraic structure of string theories [28, 29]
   - 2.4. Operator product expansion in conformal field theory and its holographic description [30]
   - 2.5. Complexity and holographic in conformal field theory with boundary [31]

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3 Sakurai-Wimmer Group

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

Member: Hiroyoshi Sakurai, Kathrin Wimmer 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.

Missing mass spectroscopy of resonance states in light proton-rich nuclei

In light unstable nuclei, specific correlations such as the cluster structure and halo are expected to appear. Experimental observables of light proton-rich nuclei are still limited comparing with those of neutron-rich nuclei and imporant as a basis of the study. The expriment are performed at GANIL in July 2018 to search for resonances of ^{8}C, ^{7}B and ^{6}Be. The resonance states are populated via the one-neutron transfer (p, d) reaction with radioactive beams and a liquid hydrogen target. The missing mass method was adopted by using MUST2 telescopes to reconstruct the resonance energy and the differential cross sections. The excitation energy spectra were successfully measured and new resonance states were observed.

Muonic X-ray measurement on palladium isotopes

The nuclear muon capture reaction, hereafter merely muon capture, is an analogous process to the electron capture reaction. The difference is the excination energy of the residual nucleus produced by the reaction, since the muon has larger mass by 200 times than the electron. Although the muon capture is an unique reaction with high Q-value and low angular-momentum transfer, the microscopic understanding has not been achieved yet. The experimantal data is also limited to several nuclides, and thus the experimental study is demanded. We conduct an experimental series aiming at measuring the neutrons and prompt/delayed γ rays emitted following the muon capture of palladium isotopes. The experiments were performed at RCNP, Osaka University using the continuous muon beam and at J-PARC and RAL using the pulsed muon beam.

High current beamline for transmutation accelerator

High-current beam accelerator for transmutation of waste nuclear fuels from nuclear power plant is under development. A difficulity of a high beam current transportation is a larger beam diameter than conventional system, so that the accuracy of the paraxial approximation, adopted in the conventional beam optical calculation method, deteriorates. In addition, a beam halo is generated by multipole electromagnetic field excited by the beam and the solenoid magnet. We are developing methods to estimate a beam halo considering the effects of multipole electromagnetic fields and to cancel out the multipole electromagnetic field caused by the space charge effect by an appropriate placement and excitation of the solenoid coil.

HiCARI project at RIBF

HiCARI (High-Resolution Cluster Array at RIBF) aims at measuring high level density odd nuclei and the lifetimes of the excited states on unstable nuclei. This array consists of 12 germanium detectors gathered from all over the world. A series of experiments will be held at RIBF in 2020 with world-highest beam intensity of the unstable nuclei. Our proposed experiment to investigate the neutron shell evelution of titanium isotopes was approved by RIBF program advisary commitee.

Systemtic mearuement of pion production cross section

We are planning a measurement of pion production cross section at GSI for seveal beam nuclei, such as d, t, ^{4}He and ^{6}Li, on a carbon target. The pion production production cross section has been intensively measured in the past with a proton beam, while there is few measurement of the cross section with other heavy ion beams. Our systematic measurment of the pion production reactions will shed a light for understanding the reaction mechanism.

Development of X-ray detector for non-destractive element analysis with muon beam

Low-energy muonic X-ray spectrometer for eleemnt analysis (LeXSea) is under development for a measurement of low-energy X rays of muonic atoms of C, N and O, which have energies at 75, 102 and 135 keV, respectively. The detector consists of n-type or planer type high-purity germanium detector with BGO anti-Compton suppressor. First prototype detector was designed and developed this year as shwon in Fig. 2.1.5.

4 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 data from the KEK B-factory (KEKB), our group made many key measurements including the first observation of CP violation in B meson system. The quest for new physics continues 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, the physics data taking with the full Belle II detector has been started. We will search for new physics using Flavor Changing Neutral Current (FCNC) decays of B mesons.

2. Study of neutrino oscillations and search for proton decay: Super-Kamiokande, T2K, and Hyper-Kamiokande experiments We have been studying neutrino oscillations with the T2K long baseline neutrino experiment, in which intense neutrino and anti-neutrino beams produced using the J-PARC accelerator complex are measured with the SK detector, 295 km away. T2K is now searching for a new source of CP symmetry violation in neutrino oscillations that would manifest as a difference in the measured oscillation probability for neutrinos and antineutrinos. This year, we reported a new constraint on the CP violating phase to exclude almost half of the possible values at the 3σ confidence level.

We have been leading 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 neutrino-nucleus interaction cross sections. In addition, a major upgrade of T2K near neutrino detectors is planned in 2021. Our group proposed this upgrade and has been playing central roles in the project, now approved in the framework of CERN Neutrino Platform as NP07.

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. This year, the project was approved and the construction has been started.

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 measured gravitational distortion of images of about 10 million galaxies obtained from a survey of 140 deg^2 of the sky (the area of 3000 full moons) over 90 nights. By analyzing the data, we obtained cosmological constraints on the fractional contribution of matter to the energy budget of the Universe, and the clumpiness of the matter distribution in the present Universe.

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 (SOI) technology.

5 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.

6 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, thermoelectric materials with large response, organic conductors, and magnetic systems with frustration and/or spin-orbit interactions. The followings are the current topics in our group.

- Dirac electron systems in solids
  Quantum electrodynamics (QED) in solids: Dielectricity and diamagnetic current.
  Critical phenomena in Weyl semimetals due to impurities and scaling law in NMR relaxation rate.[1]
  Thermoelectric transport theory of a three-dimensional Dirac electron system in high magnetic field.[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]
  Chiral magnonic edge states in skyrmion crystals controlled by magnetic fields.[6]
  Universal quantization of orbital-Zeeman cross term in magnetic susceptibility.
- High-T_c superconductivity
  Superconductivity in T$'$ electron-doped high-T_c cuprates.
- Organic conductors

Low temperature thermal conductivity in a quantum spin liquid of κ-H_3(Cat-EDT-TTF)$_2$.
Photo-induced phase transition using Floquet theory.[7]

- Borophane-related materials.[8]
- Spin systems and spin-orbit interaction
  Anomalous temperature behavior of chiral spin helix in $CrNb_3S_6$.[9]
  Magnetization process and spin-liquid states in an interacting magnetic monopole system.[10]
  Detection theory of multipolar quantum spin ice in pyrochlore materials.[11]

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7 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 tools are 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.

Major research topics in FY 2019 are as follows.

- Development of the data assimilation method for crystal structure exploration using incomplete diffraction data:
  In this fiscal year, in order to infer the unknown crystal structure with some atoms disorganized, we studied the efficient sampling of the average diffraction pattern of the disorganized system.

- Development of simulation methods for dealing with slow physical phenomena:
  We have developed a computational method to search for a path with a minimum energy barrier for shifting between locally stable atomic configurations without prior knowledge of the path direction and endpoints, and have released it as open source code.
- Development of new first-principles electronic state calculation methods that correctly consider electronic correlations based on the inverse Kohn-Sham method
- Development of the first-principles calculation method for superconducting transition temperatures taking account of the spin-fluctuation effect
- Definition of the ground state in an electron system driven by a periodic electric field (Floquet system)
- Origin of the strong electron-phonon interactions in the pressure-induced high-temperature superconductor H_3S
- Use of neural network potential in various structural simulations

8 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 the stochastic process 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.

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9 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 in and out of equilibrium, which would give rise to a variety of novel phases and dynamics. We study theoretically such systems, with the aim of predicting intriguing quantum phenomena that have no counterpart in weakly-interacting systems and cannot be understood within standard approaches. Our work involves a combination of analytical and numerical methods. We are currently interested in (i) topological phases of matter, (ii) low-dimensional correlated systems, (iii) dissipative quantum many-body systems, (iv) non-ergodic dynamics in non-integrable systems, and (v) 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 2019 are the following:

- Topological phases of matter
  - Three-dimensional topological magnon systems characterized by $\mathbf{Z}_2$ topological invariants [1]
- Low-dimensional correlated systems
  - Ferromagnetism in the SU(n) Hubbard model with a nearly flat band [2]
  - Haldane phase in the spin-1 Bose-Hubbard model with a flat band [3]
- dissipative quantum many-body systems
  - Constructing neural stationary states in open quantum many-body systems [4]
  - Exact analysis of dissipative spin chains using a mapping to non-Hermitian models [5, 6]
- Mathematical and statistical physics
  - Constructing an infinite sequence of non-integrable models exhibiting perfect quantum many-body scars [8]

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10 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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11 Fukuyama Group

Research Subjects: Low Temperature Physics (Experimental):
Novel quantum phases in fluids and solids of helium in two dimensions,
Novel electronic states in graphene.

Member: Hiroshi Fukuyama, Tomohiro Matsui

We are interested in (i) novel quantum phases with strong correlations of condensed phases of helium three (^{3}He) and helium four (^{4}He) in two dimensions (2D) and (ii) novel electronic properties of graphene, a monatomic sheet of carbon atoms, and their topological aspects. We are investigating those systems down to ultra-low temperatures of the order of 100 μK using various experimental techniques such as calorimetry, torsional oscillator, NMR, scanning tunneling microscopy and spectroscopy (STM/STS), and electronic transport measurement, *etc.*

1. **Search for Superfluid Liquid Crystal Phase in Monolayer of ^{4}He:**

   In 2016, based on measurements of specific heat anomalies due to melting, we proposed the possible existence of a novel quantum phase, quantum liquid crystal (QLC), in the second layer of helium adsorbed on graphite. Next, we studied nuclear magnetism of monolayers of ^{3}He where two novel quantum spin liquid phases were found to exist. Eventually, the magnetic properties of one of the phases are consistent with the large density fluctuations expected for QLC.

   We have started new experiments to seek for possible superfluidity in the possible QLC phase of ^{4}He because, if the superfluidity can be confirmed in this 2D bosonic system, it would be a strong indication of finite fluidity that may indicate QLC. To avoid unexpectedly large uncertainties in the sample densities due to substrate heterogeneities, we developed a novel technique to make simultaneous torsional oscillator (TO) and specific heat measurements.

   The simultaneous measurements are now on going. So far, we have tentatively observed novel superfluidity both in the liquid and the possible QLC phases below 200 mK.

2. **Graphene Edge State:**

   One important property of graphene for its application to future electronic devices is the spin-polarized edge state on graphene nanoribbons of widths narrower than 20 nm with zigzag edges on both sides (z-GNRs). Due to the flat band nature of the edge state, even under weak on-site interactions, electron spins are theoretically predicted to ferromagnetically align along the same edge and antiferromagnetically on different edges.

   We developed the hydrogen(H)-plasma etching technique to synthesize many hexagonal nanopits of monatomic depth and several hundred nm size, that consist of high-density zigzag edges, on the surface of graphite. The size and density of nanopits can be controlled by tuning the temperature, the pressure of hydrogen, etc., and thus narrow z-GNRs can be created in between two nanopits. STS measurements across such z-GNRs revealed a clear double peak structure (spin gap) of the edge state, indicating successful observation of the spin-polarized edge state. In addition, the spin gap energy seems to be inversely proportional to the ribbon width.

To study the possible substrate effect on the above mentioned observation, we made STS measurements for z-GNRs synthesized in graphene epitaxially grown on an SiC(000$\bar{1}$) substrate by H-plasma etching. Although doping is rather substantial ($-160 \sim +100$ mV) in this system, we were successful to observe clear local density of states (LDOS) peaks associated with the edge state. Nonetheless, even for sufficiently narrow z-GNRs, the double peak structure indicative of the spin-polarization was not observed here. This may be reasonable, as the Stoner criterion for ferromagnetism may not be fulfilled since the edge states sit usually farther away from the Fermi level.

12 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 investigate exotic superconducting states in multilayer systems, we fabricated bilayer and trilayer films on a 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 space inversion symmetry. A sharp upturn was observed in the temperature dependence of the parallel upper critical magnetic field. Using numerical calculations with the Bogoliubov-de Gennes equations, we found that it corresponds to a transition from a complex-stripe phase to a helical phase. Moreover, we have studied nonreciprocal charge transport in superconducting ultrathin films. For ultrathin Pb and Al films, the antisymmetrized second harmonic magnetoresistance was observed, which suggests that the rectification effect occurs in superconducting metallic films grown on a GaAs (110) surface.

13 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$\sim$4meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research summary in this year is as follows.

1. **Superconducting fluctuation studied by Higgs mode responses in superconducting high-T_c cuprates:** We investigated the superconducting fluctuation in high-T_c cuprates through the measurement of Higgs mode. By using THz pump-optical probe measurements, we observed the Higgs mode response in $Bi_2Sr_2CaCu_2O_{8+x}$ in a wide range of hole doping. We elucidated that there are two onset temperatures for the pump-probe signal; $T_1^{\rm ons}$ which is located about 10 K above T_c, and $T_2^{\rm ons}$ which is located substantially higher($\sim$100 K) than T_c. By comparing with the onset temperature of the superfluid density extracted from the optical conducitivy spectrum, $T_1^{\rm ons}$ is attributed to the onset of Higgs mode response, and therefore to the onset of superconducting phase coherence. On the other hand, $T_2^{\rm ons}$ conicides with that of gap opening tempreture observed in the scanning tunneling spectroscopy, potentially suggesting the Cooper pair formation temperature. Higgs mode in high-T_c cupreates were also investigated by THz-third harmonic generation(THG) measurements. In addition to the heavily damped Higgs mode, we observed a universal jump in the phase of THG signal, indicating other collective modes that couple to the Higgs mode. THG signal remains finite above T_c, suggesting a nonzero pairing amplitude above T_c.

2. **Realization of electron-hole BCS-like state in a photoexcited semiconductor:** We demonstrated that a new quantum degenerate state consisted of elctron-hole pairs, referred to as an electron-hole(e-h) BCS state, could be generated by irradiating a semiconductor with laser light. This has been predicted in theory for several decades but never demonstrated under experimental conditions. We took an unprecedented and unique approach and succeeded by utilizing the strong interaction between laser light and excitons. We tuned the wavelength of the laser beam and generated a new quantum state (i.e. an e-h BCS state) by directly aiming at excitons in GaAs cooled to 5 K. With increasing the light intensity, we show that the e-h systems truns from an emsemble of excitons to e-h BCS state. The realization of a new quantum state (i.e., an e-h BCS state) using this technique advances the understanding of the electronic state that occurs when a semiconductor is irradiated with light, and also provides deeper understanding of the new type of quantum condensation phenomena in variety of materials going forward.

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14 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 FY2019 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 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 in 2018–2019.

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\rm eff} = 1/2$ 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 realization of "true" Kitaev material. This year, we are exploring a new route to Kitaev physics, by making Lanthanoid honeycomb mateirals. For example, Na_2PrO_3 is a newly suggested candidate for a platform of an antiferromagnetic Kitaev-type interaction. We have clarified Na_2PrO_3 is indeed located closed to the true Kitaev point in the theoretical phase diagram by determination of magnetic structure though ^{23}-Na NMR experiment. We further explore $4f^{1,13}$ honeycomb systems in combination with highpressure-state survay using new highpressure magnetometry techniques.

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. In addition to this, 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. This year, we conducted very accurate angle-dependent magnetoresistance measurements to investigate chiral anomaly phenomenon which is peculiar to this quantum-limit physics. Newly developed small two-axis goniometric device was used. A current jetting effect was clearly observed as a negative resistance when an applied megnetic field directed one of elecrodes. Altough reproducibility needs to be examined further, we succeeded in separate the effects from chiral anomaly and current jetting effect.

15 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
  - Observation of a giant acoustic planar Hall effect[2]
  - Highly efficient spin orbit torque in sythetic antiferromagnets[5]
  - Giant spin orbit torque found in systems with Dirac electrons[6]
- Chiral magnetism
  - DMI and spin orbit torque at the Ir/Co interface[1]
  - DMI modulation with current[3]
  - Giant perpendicular magnetic anisotropy in Ir/Co/Pt multilayers[4]

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16 Kobayashi Group

Research Subjects: mesoscopic physics, spintronics, noise & fluctuations, nonequilibrium phenomena

Member: Kensuke Kobayashi

By virtue of nano-fabrication technique we are able to investigate fascinating behaviors of "mesoscopic systems", namely, electronic devices that work in quantum regime. Since 1980's they have been serving as ideal test-beds to demonstrate various quantum effects in a controllable and thus transparent way, as the electron transport through a single quantum site can be precisely probed and tuned. Especially, the Landauer-Büttiker formalism embodies this advantage of mesoscopic physics as has been successfully applied to many nano-fabricated conductors (e.g. Aharonov-Bohm ring, quantum dot etc.), through which mesoscopic physics has been established.

We focus on various phenomena in mesoscopic systems, especially quantum many-body effects, non-equilibrium phenomena, and spin transport. High-precision measurement of conductance and current fluctuations enables us to quantitatively understand quantum transport, which has been difficult to achieve in the past. In addition, we are developing measurement techniques to discover new phenomena in mesoscopic systems.

In FY2019, we addressed the following research topics:

- Non-equilibrium transport and many-body correlations in Kondo effect
- Rashba-type spin-orbit interaction in a double-layer quantum point contact
- Magnetization metastable state controlled by spin current
- Development of low temperature amplifier for current noise measurement
- Electric detection of spin dynamics in spinglass
- Butterfly-shaped magnetoresistance in triangular-lattice antiferromagnet Ag_2CrO_2
- Magnetic transport measurements in atomic layer ferromagnet Fe_5GeTe_2

Published papers:

[1] M. Tokuda *et al., APEX* **12,** 053005 (2019).

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17 Nakatsuji Group

Research Subjects: Condensed Matter Experiment

Member: Satoru Nakatsuji

Recent years have seen a plethora of exciting discoveries that rapidly expand the frontiers of quantum material research. The concept of topology begins to revolutionize our understanding of the emergent properties of matter such as magnetism and superconductivity – meanwhile, the novel topological materials may form the basis for conceptually new spintronics and thermoelectric applications. Moreover, emergent phenomena in quantum materials provide an excellent experimental platform to explore emergent quasiparticles that behave like the ever-elusive elementary particles, such as the magnetic monopole and the Weyl fermion, thereby boosting the development of the cosmology-driven condensed matter theory and quantum information technology. Our research activities focus on designing and synthesizing new materials with emergent quantum properties that have never been seen before, then exploring the physics behind such properties with our world-leading measurement facilities. We aim to lead the innovative quest for new quantum materials that bear a far-reaching impact not only on basic science but also on our everyday life in the future.

Major research themes:

1. Solid-state analogs of relativistic particles and new quantum phenomena
   - Weyl fermion and chiral anomaly
   - Quantum spin ice, magnetic monopole, and emergent photon
2. Room-temperature quantum transport phenomena in topological magnetic materials
   - Weyl antiferromagnets and their application to spintronic devices
   - Giant thermal and optical responses driven by the Berry curvature
3. Quantum phase transitions in strongly correlated materials
   - Anomalous metallic behavior and exotic superconductivity in multipolar Kondo materials

Summary of research subjects in 2019

1. Applications of Weyl antiferromagnets to spintronics

The Weyl antiferromagnet Mn_3Sn displays a large anomalous Hall effect (AHE) at room temperature despite the negligible net magnetization. This experimental discovery is a remarkable advance in transferring the concepts of antiferromagnetic spintronics to a variety of real-life applications. In collaboration with Prof. Otani's group at ISSP, we performed room-temperature inverse spin Hall effect experiments using Mn_3Sn nanowires, which yields an estimation of the spin Hall angle and spin diffusion length. Moreover, we observed the room-temperature THz AHE in Mn_3Sn thin films using polarization-resolved spectroscopy in collaboration with the optical measurement groups at ISSP and John Hopkins University. This finding promises ultrafast readout for antiferromagnetic spintronic devices using Mn_3Sn.

2. Anomalous metallic behavior in multipolar Kondo materials:

The heavy fermion superconductor PrV_2Al_{20} hosts a nonmagnetic crystal electric field (CEF) ground state that lacks dipolar moment but carries quadrupolar and octupolar moments, rendering an ideal ground for exploring orbital-driven anomalous metallic states. Under a [100] magnetic field, we found that, on entering the high-field phase at 12 T, the rearrangement of quadrupolar moments yields a sharp jump in the magnetoresistance, with a substantial AMR effect of about 30%. This feature signifies a Fermi surface reconstruction within the high-field quadrupolar ordered phase, owing to the strong hybridization between the local quadrupolar moment and the conduction electrons. Moreover, we observed a universal scaling behavior expected for the quadrupolar Kondo lattice via magnetoresistance, magnetization, and specific heat measurements under a [110] magnetic field, which reveals the vital role of the quadrupolar Kondo effect in shaping the non-Fermi-liquid phase of PrV_2Al_{20}.

3. Magnetic Weyl semimetal state in epitaxial $Pr_2Ir_2O_7$ thin films:
Lattice strain or magnetic field tuning of the Luttinger semimetal $Pr_2Ir_2O_7$ may engender a rich topological phase diagram. Using strained $Pr_2Ir_2O_7$ thin films, we observed a zero-field Hall effect up to 50 K without detectable spontaneous magnetization, which indicates the breaking of time-reversal symmetry induced by the magnetic order of Ir 5d electrons. Moreover, we identified a negative contribution to the magnetoresistance specific to the chiral anomaly. This study provides firm experimental evidence for a strain-induced magnetic Weyl semimetal state in pyrochlore iridates thin films, paving a new avenue to explore topological phases in strongly correlated materials.

18 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;

2019

- Observational characterization of protoplanetary disks, exo-rings, and Earth-twins in exoplanetary systems
- Non-sphericities and alignments of clusters and central galaxies from cosmological hydrodynamical simulation: theoretical predictions and observational comparison
- Probing Cosmic Star-Formation History with Blind Millimetre Searches for Galaxy Emission Lines
- Photoevaporation process of giant planets
- Dilution of heavy elements in galaxies and its implications

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

19 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 and Jun-yi Wu (JSPS foreign postdoctoral fellow since Ocotober—, and 4 graduate students–Qingxiuxiong Dong (D2), Wataru Yokojima (M2), Atsuhi Okamoto (M1), and Leonie Karr (USTEP graduate student from Ludwig Maximilian University of Munich). Our projects engaged in the academic year of 2018 were the following:

- Higher-order quantum operations
  - Universal discrimination of unitary operations with dynamic ordering of black bxoes by A. Soeda and M. Murao
  - Characterization of higher-order quantum operations without definite causal order by W. Yokojima, M. T. Quintino, A. Soeda, and M. Murao
  - Formulation of controlled quantum operations and controlled higher-order quantum operations and applications of the formulation by Q. Dong, A. Soeda and M. Murao
  - Higher-order transformations of unitary operations by probabilistic, exact, and universal quantum circuit by M. T. Coelho Quintino, Q. Dong, A. Soeda, and M. Murao
- Controls for quantum dynamics
  - Numerical optimization of robust control of one-qubit gate in Hamiltonian dynamics system by A. Okamoto, A. Soeda, and M. Murao
  - Mathematical models based on quantum field theory for artificial quantum systems by A. Soeda
- Distributed quantum information processing
  - Distributed sampling, certification of quantum communication, and incompatibility of quantum measurements by M. T. Quintino with Dr. Leonardo Guerini at International Centre for Theoretical Physics - South American Institute for Fundamental Research and Instituto de Física Teórica and Dr. Leandro Aolita at Instituto de Física, Universidade Federal do Rio de Janeiro
  - Complementarity in multiphoton linear optical network by J. Wu and M. Murao
  - Difference between LOCC quantum state discrimination and LOCC quantum information extraction by L. Karr and M. Murao

20 Ueda Group

Research Subjects: Bose-Einstein condensation, fermionic superfluidity, topological phenomena, open quantum systems, information thermodynamics, quantum information, measurement theory, machine learning

Member: Masahito Ueda and Masaya Nakagawa

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 nonunitary dynamics of atomic gases subject to dissipation and/or measurement backaction, classification of phases of matter in nonequilibrium open systems, 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. Moreover, we have recently tackled an understanding of AI and machine learning from a viewpoint of physics. We list our main research subjects in FY2019 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Quantum magnetism of the Hubbard model subject to dissipation [1]
  - Classification of topological phases in non-Hermitian systems [2, 3, 4]
  - Non-Hermitian many-body localization [5]
  - Random-matrix behavior of quantum nonintegrable systems with symmetries [6]
  - Classification of gapless topological phases in periodically driven quantum systems [7]
- Quantum information, quantum measurement, and foundation of statistical mechanics
  - Standard quantum limit and Heisenberg limit in function estimation [8]
  - Classification of nonequilibrium many-body topological phases with matrix-product unitaries [9]
  - Improvement of deep learning using portfolio theory [10]

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21 Yokoyama (J) Group

Research Subjects: Theoretical Cosmology and Gravitation

Member: 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 2019.

Early Universe Cosmology

- Cosmology with heavy right-handed neutrinos generated by gravitational particle production
- Formation of primordial black holes
- Leptogenesis through the Standard Model Higgs relaxation
- Leptogenesis from the helical primordial gravitational waves
- Phase transition mediated by black holes
- Compactification of extra dimensions with generalized Galileon
- Magnetogenesis and baryogenesis through the chiral anomaly
- Mixed Higgs-R^2 inflation
- Quantum tunneling in the curved spacetime
- Particle production associated with the phase transition of the background fields

Particle astrophysics

- Neutrino heating in supernova explosions

Supergravity and modified gravity

- Effective action for the anti D-3 brane
- Supersymmetric Horndeski theory
- Stability condition of the perturbation in the angular direction in the static spherical spacetime for the generalized Galileon

Gravitational wave analysis

- Removal of non-Gaussian noise of KAGRA data by independent component analysis

22 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 study magnetic confinement of a torus plasma to realize nuclear fusion energy. We perform basic tokamak plasma physics studies on the TST-2 device located at the university of Tokyo. We also collaborate with JT-60SA at QST, LHD at NIFS, LATE at Kyoto University, and QUEST at Kyushu University. TST-2 is a spherical tokamak with a major radius 0.36 m and a minor radius 0.23 m. The plasma current is <120 kA for inductive operation and <28 kA for RF driven operation. Spherical tokamaks are attractive since they can sustain plasmas with high β (kinetic pressure over magnetic pressure). However, plasma current startup and sustainment is a challenge due to limited space for the central solenoid normally used for current drive. Our present focus on TST-2 is current drive through generation of fast electrons by lower-hybrid waves (LHW). On FY2019, the hard X-ray measurements, scrape-off-layer measurements, and bulk electron measurements was improved, as well as the wave measurements using magnetic probes. These lead to better understanding of fast electron dynamics and wave propagation and absorption. We have also performed experiments to study electron cyclotron wave assisted Ohmic plasma startup, and shaping experiments using a compact central solenoid.

The RF current drive experiments are performed using LH waves at 200 MHz. The LH waves are excited using two capacitively coupled combline antennas located at the outboard side and the top side of the plasma. Since LH waves drive current by generating fast electrons, measurements of X-ray radiations by those fast electrons are important. On FY2019, it was found that the X-ray energy was higher when the outboard gap between the plasma and the limiter was larger. This was qualitatively consistent with RF driven radial transport of fast electrons. Parametric decay instability was observed with magnetic probes. The spatial distribution of the side band depended strongly on the current drive scenario. Langmuir probes were fabricated and installed to investigate the scrape-off-layer conditions. The measured I-V characteristic showed electron energy distribution with two distinct temperatures at 8 eV and <1 keV. Discharges with central electron temperature two to three times higher than the typical LH discharges were found. The electron temperature scaled inversely proportional to the electron density, and strongly positively to the magnetic field strength. On the other hand, dependence on RF power and plasma current was weak.

The equilibrium magnetic field in a LH driven plasma is determined by the fast electrons which are highly non-thermal and have large orbit excursions. Such an equilibrium cannot be descried by the conventional magneto-hydro dynamics (MHD). On FY2019, we have developed an extended MHD model that assumes a two component plasma with bulk MHD and kinetic collisionless fast electrons. The equilibrium reconstruction based on the extended MHD model matched better the density profile measured by the Thomson scattering diagnostic than that based on the conventional MHD.

A compact central solenoid was used for plasma shaping of electron cyclotron (EC) wave driven plasma. Shaping effect on LH driven plasma was weak due to limited coil current.

Optimum poloidal field configuration for EC assisted Ohmic startup was investigated. It was demonstrated that the so called trapped-particle configuration that has been used for pure EC startup experiments was superior to the conventional field-null startup in the presence of EC assistance.

The ion doppler spectroscopy was performed to study the time evolution of flow during internal reconnection events (IRE). From CV measurements, it was found that the flow changes by <20 km/s during IRE. The flow started to change around the peak of the magnetic fluctuations. However, the flow change did not correlate with the magnitude of the magnetic fluctuations.

Several diagnostic developments were performed in FY2019. The Thomson scattering diagnostic was rearranged to measure the edge plasma. LYSO based hard X-ray imaging diagnostic was developed and measurements were performed.

As a collaboration, Thomson scattering diagnostic on QUEST is being developed. Thomson scattering measurement was performed for ECH driven discharges.

Soft X-ray imaging system is being developed as a collaboration with PPPL. In FY2019, the system was installed on MST. The measurement agreed well with the prediction. Optimization of X-ray imaging camera parameters for JT-60SA plasmas was also performed.

23 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.

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24 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) Recipe for preparing a molecular ensemble with macroscopic threefold symmetry [1]

We propose how to prepare a molecular ensemble with macroscopic threefold symmetry. By utilizing the special laser electric field trajectory with threefold symmetry, which can be formed by superposing a counterrotating circularly polarized fundamental pulse and its second harmonic pulse, sample molecules with threefold symmetry such as BX_3 (X = F, Cl, Br, I) can be aligned with their three arms along (or in between) the laser electric fields with threefold symmetry depending on the sign of the hyperpolarizability of the sample molecule. We show that this method is feasible with practical experimental conditions as for the rotational temperature of the sample molecules and the intensities of the two wavelengths. This method will open up physics of symmetry concerning a molecular ensemble with macroscopic threefold symmetry.

(2) Orientation of linear molecules in two-color laser fields with perpendicularly crossed polarizations [2]

Molecular orientation methods based on nonresonant two-color laser pulses having parallel polarizations have been reported theoretically and experimentally. In this work, we demonstrate that perpendicularly polarized two-color laser fields can be used to achieve stronger molecular orientation when nanosecond laser pulses are used. The two-color fields align the molecules to the two-dimensional plane parallel to the field polarization; at the same time, they orient the molecules in the direction of the 2ω polarization. We show that the interplay between the interactions due to the ω- and 2ω-laser fields provides stronger molecular orientation than the parallel field configuration. This is due to temporally synchronized generations of alignment and orientation, which reduce the nonadiabatic effects.

(3) Development of a plasma shutter applicable to 100-mJ-class, 10-ns laser pulses and the characterization of its performance [3]

For the purpose of preparing a sample of aligned and oriented molecules in the laser-field-free condition, we developed a plasma shutter, which enables laser pulses with 100-mJ-class, 10-ns pulse durations to be rapidly turned off within $\sim$150 fs. In this work, the residual field intensity after the rapid turn off is carefully examined by applying the shaped laser pulse to OCS molecules in the rotational ground state. Based on the comparison between the observation of alignment revivals of the OCS molecules and the results of numerical simulations, we demonstrate that the residual field intensity is actually negligible (below 0.4% of the peak intensity) and, if any, does not influence the alignment and orientation dynamics at all.

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25 Gonokami and Yumoto 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 and Junji Yumoto

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, and electrons in topological insulators. 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, we are now developing novel coherent light sources and spectroscopic methods. We achieved precision measurements of the refractive index of materials in an EUV region using techniques of higher-order harmonics generation. We also developed laser-based angle resolved photoemission spectroscopy using time-of-flight photoelectron analyzer.

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
2. Investigation for non-trivial optical responses and development of applications:
   2.1. Circularly polarized coherent VUV generation by photonics crystal nanomembrane
   2.2. Development of new technology to measure laser ablation thresholds
   2.3. Fabrication of Moth-Eye THz Anti-Reflection Structures by Femtosecond Laser Processing
   2.4. 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. EUV precision spectroscopy using higher-order harmonics
   3.2. Laser-based angle resolved photoemission spectroscopy
   3.3. Institute for Photon Science Technology

26 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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27 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

Our target is understanding high energy phenomena in the universe, such as supernova remnants, neutron stars, and black holes. We observe them with X-ray satellites. From the supernova remnant expansion measurements, we found that the uniformity of expansion has variety among samples. We also showed that accelerated particles on the shocks of supernova remnants escape into the space as the shocks age. Black holes distort the time-space by general relativity, which makes complicated effect to their emission. This year we succeeded to include the general relativity into the Monte-Carlo simulation tool called MONACO and enable to make realistic emission models for the accreted matter onto black holes. For the next-generation observations, we develope a new generation X-ray satellite called 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, named as "cipher". The design concept got the grand prix on the 27th satellite design contest.

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28 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.

29 Takeuchi Group

Research Subjects: Experimental statistical physics for non-equilibrium systems

Members: Kazumasa A. Takeuchi and Daiki Nishiguchi

We aim to explore statistical physics of out-of-equilibrium phenomena experimentally. Using soft and living matter, such as liquid crystal, colloids, and granular materials, as well as bacteria, we carry out experiments that we design to capture underlying physical principles, in addition to the understanding of specific phenomena we observe. As a result, we deal with diverse subjects in the group, sometimes enjoying interesting connections in between. More specifically, we carried out the following projects among others in the scholar year 2019:

(1) Non-equilibrium phenomena in soft matter systems
(1-1) Growing interface fluctuations in liquid crystal turbulence [3]
(1-2) Statistical analysis of heat fluctuations in liquid crystal turbulence
(1-3) Visualization of three-dimensional dynamics of liquid crystalline topological defects
(1-4) Reversible-irreversible transition in a densely packed granular system under periodic shear
(1-5) Dynamics of self-propelled colloids under periodic driving

(2) Non-equilibrium phenomena in living systems
(2-1) Development of an extensive micro-perfusion system
(2-2) Scale invariance in cell size fluctuations
(2-3) Competition process of bacterial populations [1]
(2-4) Heterogeneous dynamics of dense suspensions of motile bacteria
(2-5) Vortex order formation in bacterial turbulence [4]
(2-6) Dynamics of type-IV pili of *Neisseria meningitidis* [2]

(3) Approaches based on nonlinear science
(3-1) Estimation of instability of large chaotic systems by time series analysis

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30 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. System level analysis of motor-related neural activities in larval Drosophila.

The way in which the central nervous system (CNS) governs animal movement is complex and difficult to solve solely by the analyses of muscle movement patterns. We tackle this problem by observing the activity of a large population of neurons in the CNS of larval Drosophila. We focused on two major behaviors of the larvae - forward and backward locomotion - and analyzed the neuronal activity related to these behaviors during the fictive locomotion that occurs spontaneously in the isolated CNS. We expressed a genetically-encoded calcium indicator, GCaMP and a nuclear marker in all neurons and then used digitally scanned light-sheet microscopy to record (at a fast frame rate) neural activities in the entire ventral nerve cord (VNC). We developed image processing tools that automatically detected the cell position based on the nuclear staining and allocate the activity signals to each detected cell. We also applied a machine learning-based method that we recently developed to assign motor status in each time frame. Our experimental procedures and computational pipeline enabled systematic identification of neurons that showed characteristic motor activities in larval Drosophila. We found cells whose activity was biased toward forward locomotion and others biased toward backward locomotion. In particular, we identified neurons near the boundary of the subesophageal zone (SEZ) and thoracic neuromeres, which were strongly active during an early phase of backward but not forward fictive locomotion.

2. Regulation of forward and backward locomotion through intersegmental feedback circuits in Drosophila larvae

Animal locomotion requires spatiotemporally coordinated contraction of muscles throughout the body. Here, we investigate how contractions of antagonistic groups of muscles are intersegmentally coordinated during bidirectional crawling of Drosophila larvae. We identify two pairs of higher-order premotor excitatory interneurons present in each abdominal neuromere that intersegmentally provide feedback to the adjacent neuromere during motor propagation. The two feedback neuron pairs are differentially active during either forward or backward locomotion but commonly target a group of premotor interneurons that together provide excitatory inputs to transverse muscles and inhibitory inputs to the antagonistic longitudinal muscles. Inhibition of either feedback neuron pair compromises contraction of transverse muscles in a direction-specific manner. Our results suggest that the intersegmental feedback neurons coordinate contraction of synergistic muscles by acting as delay circuits representing the phase lag between segments. The identified circuit architecture also shows how bidirectional motor networks could be economically embedded in the nervous system.

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31 Higuchi Group

Research Subjects: Protein dymamics in vitro, cells and mice

Member: Hideo Higuchi and Motoshi Kaya

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 by single molecule technology. Then we investigate the function of molecules or organelle in cells by the single and imaging method. Finally, we imaged the molecules in mouse auricle to understand the function of molecule in vivo. Here we showed the works on multiple molecules and, single and multiple cells.

Molecular work: Contractile mechanism of cardiac myosin filament

Muscle contractions are driven by cyclic interaction of myosins with actin filaments in heart and skeletal muscles. In heart, contractions followed by relaxation are periodically modulated, while in skeletal muscles, speeds and forces of contraction are dynamically modulated to satisfy external demands. Thus, we have focused on how molecular properties of cardiac and skeletal myosins are tuned to satisfy their functional demands. Previously, we showed that characteristics of force outputs generated by synthetic cardiac myosin filaments are distinctively different from those generated by synthetic skeletal myosin filaments. Our simulation model predicted that their different collective behaviors are attributed to the difference in the frequency of reversal action of power stroke (reverse stroke) in response to loads. To test this idea, we performed single molecule experiments to evaluate displacements of myosin heads against loads in ADP and inorganic phosphate solution. The results showed three discrete positions of cardiac myosin heads, which populations change in a load-dependent manner, suggesting that strongly-bound cardiac myosins transit between three conformational states, the pre-power stroke, post-first power stroke and post-second power stroke states by executing power/reverse stroke. In contrast, skeletal myosins primarily showed one conformational position, the post-second power stroke state. The rate of reverse stroke was found to be highly load-dependent for cardiac myosins, but not for skeletal myosins. Therefore, collective force generation by cardiac myosins is characterized by an execution of reverse stroke. Finally, our simulation model computed for force generation in sarcomere indicated that an execution of reverse stroke is a key to enhancing the force output of cardiac myosin ensembles and facilitating efficient heart contractions such as a stable systolic pressure followed by a rapid relaxation of end-systolic pressure in heart, while skeletal myosins hardly execute reverse stroke to achieve high force and high speed of shortening.

Cell work:Anisotropy of Cellular Traction Force Couples with the Cell Alignment Pattern

Spindle-shaped cells often show collective migration with the alignment of cell bodies, such as rostral migratory stream and cancer invasion after the epithelial-mesenchymal transition. In vitro cultures have mimicked the aligned collective migration and revealed that the acquisition of the cell body alignment can be understood from the steric interaction between cells and that the pattern of alignment was similar to that in a type of active matter system. Further, the dynamics of the change in the alignment pattern also matched the predictions from the active matter theorem. However, the active force generation coupled with the alignment, from which the characteristic dynamics of active matter originate, have not sufficiently been checked in experiments. To elucidate the relationship between the force and the alignment of cells under the aligned collective migration, we applied traction force microscopy to spindle-shaped cell culture systems. We observed the orientation field and measured the traction force in the adhesive culture system of neural progenitor cells or SK-LMS-1 cells. The qualitative comparison between the traction force and the orientation field, at first, showed that the force aligned with the spatial gradient of the orientation field, which indicates the coupling between the cellular force and the cell alignment. Further, we quantitatively compared the amplitude of the force and the spatial heterogeneity of alignment direction and found linear proportionality whose slope determined the strength of cellular anisotropic force generation, which is considered to control the dynamics of alignment pattern change.

Cell work: Responses of Cells to Local Heating in Cells Using a Nanoparticle

Cell function and motility depend much on temperature. Here, to understand relation between cells and high temperature localized in cells, we imaged the response of the intracellular motility under phase contrast microscope at the local temperature jump. Temperature was jumped up locally to about 57 °C by irradiating magnet nanoparticle (300 nm in diameter) in the cell with focusing infrared laser (wavelength of 1064 nm). By the temperature jump, (1) the most of vesicle transport in the cell stopped suddenly, (2) black circles at pseudopodia emerged and (3) the cell shrunk toward a heated nanoparticle. Result (1) and (2) often appeared together, so there is a deep relation between the two responses.

32 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 FY2019, we have published several papers on the development of super-resolution imaging technologies and their biological applications. For example, we have developed a super-resolution light-sheet microscope that enables high resolution 3-dimensional imaging of large samples [1]. We also developed a new fluorescent probe for the super-resolution live imaging of the inner membrane structure of mitochondria [3]. Super-resolution imaging was applied to examine the fine structure of the Par-island, a protein complex structure that determines the anterior side of the cell [2]. We have also applied a novel single-molecule measurement technology for the initial process of autophagy, and demonstrated that it is triggered by the liquid-liquid phase separation [4].

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33 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. Laboratory evolution of bacterial cells to analyze dynamics of phenotype-genotype mappings
2. Construction of macroscopic state theory describing adaptation and evolution of biological systems
3. Theoretical analysis of evolutionary process under dynamically changing environments
4. Computational analysis of amoeba morphogenesis using phase-field models
5. Effects of phenotypic fluctuation on evolutionary dynamics
6. Development of a method to characterize animal morphology using machine learning

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