ISSN 0910-0709

Department of Physics
School of Science
The University of Tokyo

Annual Report

2020

令和２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

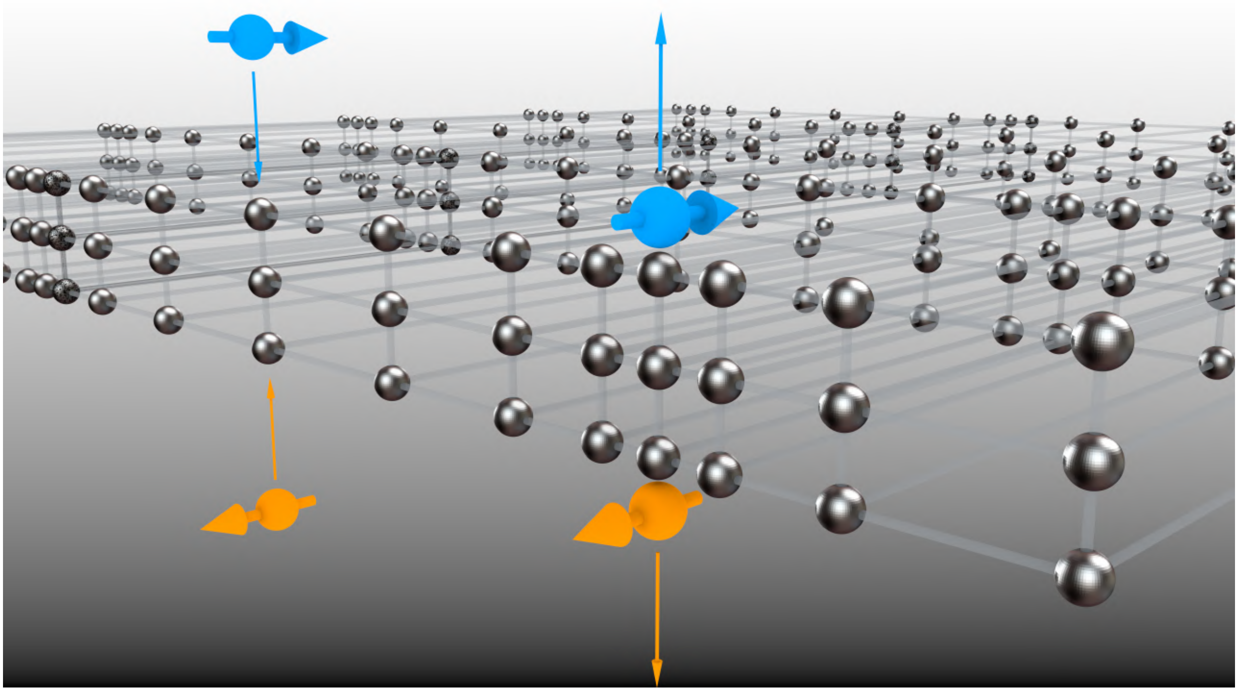


図 1: 原子振動により、スピンが流れる現象のイメージ図：電子が動くと電流が発生するが、電子がそのスピンの向きを揃えて動くと「スピン流」なる角運動量の流れが生じる。図は、「スピン軌道相互作用」が大きい物質において、原子振動によってスピン流が発生する様子を表す概念図。色付きの球とそれを貫く矢印が電子とそのスピンの向きを表す。黒球は結晶を構成する原子。原子振動により、原子の位置は平衡状態からずれている。実際には多数の電子が色付きの球と同様の動きをすることで、スピン流が生成される。（林研究室）

Illustration of lattice vibration induced spin current. In materials with large spin orbit interaction lattice vibration can cause spin current. Colored spheres represent electrons, and the arrows that penetrate them indicate their spin. (Hayashi Group)

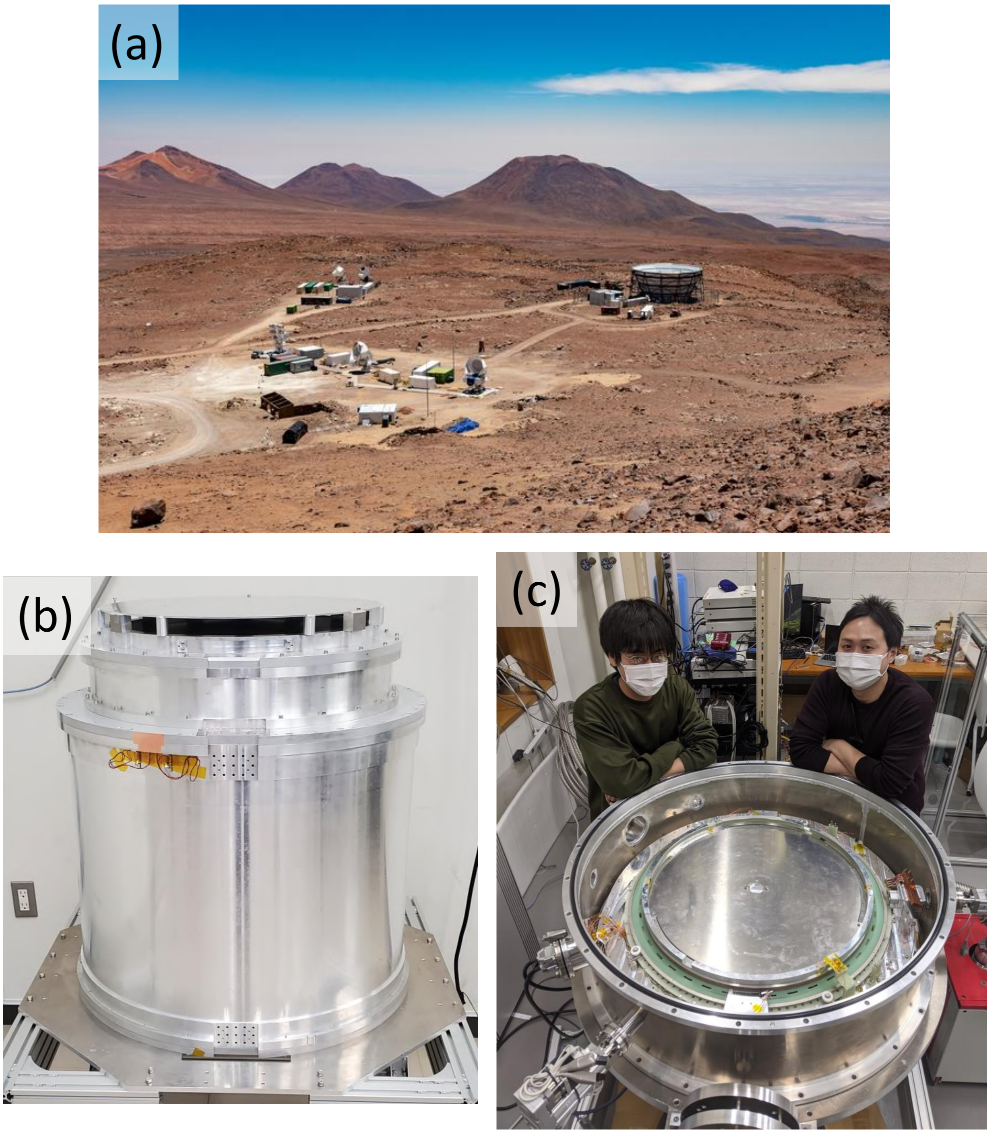
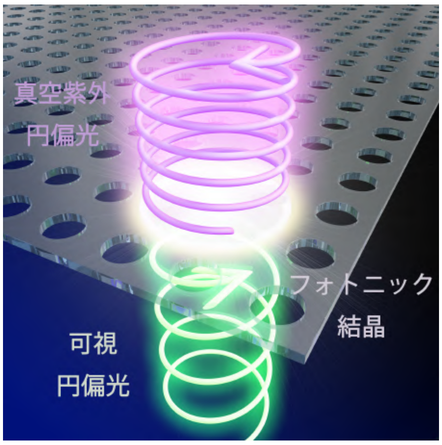


図 2: (a) 南米チリ・アタカマ砂漠、標高 5,200m に設置されている CMB 望遠鏡群（写真提供：横浜国立大学廣瀬氏)。手前の 3 台が Simons Array 望遠鏡で、うち中央の一台は POLARBEAR 望遠鏡として使用されたもの。現在は、中央部に Simons Observatory を建設中である。(b) Simons Observatory 小口径望遠鏡の光学筒。2020 年度に一台目を完成させ、米国にて望遠鏡クライオスタットとの統合試験中。(c) Simons Observatory 用低温連続回転式半波長板システム。Kavli IPMU との共同研究により開発した内径 55cm の大口径超伝導浮遊式ベアリングを採用する。（日下研究室）

(a) Array of CMB telescopes at the Atacama desert, northern Chile, at an altitude of 5,200 m (photo credit: Haruaki Hirose, Yokohama National University). Three telescopes in the front are the Simons Array telescopes. The Simons Observatory is currently under construction in the central area of the photo. (b) An optics tube for the small aperture telescope of Simons Observatory. We completed fabrication of the first tube in 2020, and it is under integration test with a receiver cryostat in the U.S. (c) The cryogenic half-wave plate rotation mechanism for Simons Observatory. It employs a large superconducting mag-lev bearing with an inner diameter of 55 cm, which we developed in collaboration with Kavli IPMU. (Kusaka Group)



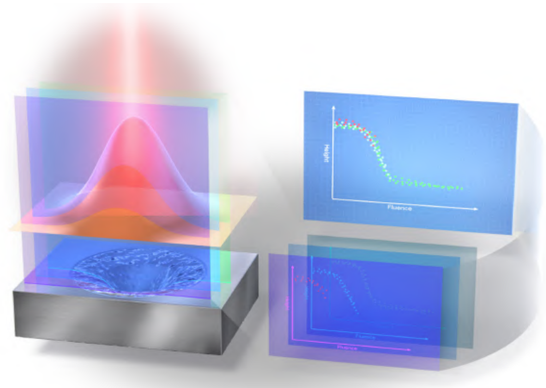


図 3: (左) 開発した真空紫外コヒーレント円偏光発生法の概念図。正方格子状に周期的な穴の開いた自立誘電体ナノ薄膜 (フォトニック結晶ナノメンブレン) に可視光の円偏光フェムト秒レーザーを照射すると、真空紫外領域の円偏光に波長変換される。これまでの真空紫外光発生の方法に比べて非常に簡便で、実験室のテーブルトップで実現可能である。本手法は今後、円偏光レーザー光電子分光や生体分子円二色性イメージング用の真空紫外コヒーレント光源として、活用される可能性がある。
(右) 今回開発した、レーザー光で破壊された物質の穴形状と入射されたレーザー光の強度の関係について、たった 1 つの加工穴から数十万点におよぶ大量のデータを取得できる手法 (フルーエンスマップ法) の概念図。本手法によって、レーザー加工技術の進歩に必要となる基礎データを、大量かつ高い精度で取得することが可能になり、レーザー加工の原理解明や光を用いたものづくり技術の発展への貢献が期待できる。(五神・湯本研究室)

(Left) Direct generation of circularly polarized vacuum ultraviolet (VUV) coherent light by third-harmonic generation in a dielectric square lattice photonic crystal nanomembrane. Our method paves the way toward the development of new tabletop coherent VUV light source for practical applications, such as laser-based angle-resolved photoemission spectroscopy and circular dichroism spectroscopy of biomolecules.
(Right) Overview of the developed method (Fluence Mapping), by which a laser ablated crater local height is directly correlated to the local fluence of laser. This method makes it possible to extract hundreds of thousands of data points from a single ablated crater. Such efficient and accurate extraction of morphology data should be important for fundamental studies regarding laser induced breakdown, which is key to furthering laser processing applications in industry. (Gonokami-Yumoto group)

II

Summary of group activities in 2020

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 Liang Group

Research Subjects: Nuclear many-body theory

Member: Haozhao Liang

In our group, we study the properties of atomic nuclei and neutron stars based on various nuclear many-body theories. In particular, one of the main research themes is nuclear density functional theory (DFT), which aims at understanding both ground-state and excited-state properties of thousands of nuclei in a consistent and predictive way. Our research interests also include the microscopic foundation of nuclear DFT, the interdisciplinary applications in nuclear astrophysics, particle physics, condensed matter physics, etc., and the relevant studies in general quantum many-body problems.

Highlights in research activities of this year include:

1. Nucleon finite-size effects on nuclear proper-ties
2. Non-relativistic expansion of the Dirac equation
3. Effects of tensor force on nuclear spin-isospin resonances
4. Relativistic DFT for superheavy elements
5. Sine-square deformation in two-dimensional Lorentzian conformal field theory
6. Lipkin model with quantum computation

3 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 this academic year are summarized below:

1. Phenomenology
   1.1. Dark matter phenomenology [1, 2, 3, 4, 5, 6, 7, 8, 9]
   1.2. Axion detection [10, 11]
   1.3. Flavor models [12, 13]
   1.4. Supersymmetric models [14]
   1.5. Supersymmetric grand unified models [15, 16, 17, 18]
   1.6. Inflation and reheating [19, 20, 21, 22, 23, 24]
   1.7. Migdal effect [25]
   1.8. Oscillon [26, 27]
   1.9. ILC beam-dump experiments [28]
   1.10. $b \to s\ell\ell$ [29]
2. Superstring theory and formal aspects of quantum field theories
   2.1. Janus interface entropy and Calabi's diastasis in superconformal field theories [30]
   2.2. Regge OPE blocks and light-ray operators [31]
   2.3. Hawking radiation and capacity of entanglement [32]
   2.4. $O(N)$ model [33]
3. Matrix model
   3.1. Dimensional oxidization on coset space [34]
4. Mathematical physics
   4.1. q-Deformation of Corner Vertex Operator Algebras by Miura Transformation [35]
   4.2. Quantum deformation of W-algebras and AGT correspondence [36]

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4 Sakurai Group

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

Member: Hiroyoshi Sakurai and Megumi Niikura

Our group investigates the structure and dynamics of exotic nuclei and exotic atoms. Our experimental programs utilize the accelerator facilities at RI Beam Factory in RIKEN, Research Center for Nuclear Physics (RCNP) in Osaka University, and Heavy Ion Medical Accelerator in Chiba (HIMAC). Some of our research subjects are the following.

Nuclear charge distribution and radius measurements using muonic X ray

The nuclear charge distribution and radius are the most basic measurable values of atomic nuclei. The muonic X-ray measurement is one of the most common methods to determine the charge radius. We developed an analysis procedure using higher transitions of the muonic atom in addition to the lowest K transitions and reduced the model dependency. Furthermore, we proposed a new method to measure the charge distribution using muonic X ray and evaluated its systematic uncertainty.

High current beamline for transmutation accelerator

A high-current beam accelerator for the transmutation of waste fuels from the nuclear power plant is under development. The difficulty of a high beam current transportation is a larger beam diameter than the 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 the 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 of unstable nuclei. This array consists of 12 germanium detectors gathered from all over the world. A series of experiments were held at RIBF in 2020 with the world's highest beam intensity of unstable nuclei. Our proposed experiment to investigate the neutron shell evolution of titanium isotopes has been conducted at RIBF in December 2021.

Study of pion production

We investigate the cluster structure in atomic nuclei by sub-threshold pion production. An experiment to measure cross-section of pion production was performed at RIBF. π^0 was produced by ^{52}Ca beam impinged on a carbon target. Two gamma rays emitted from the decay of π^0 were detected by CATANA array. A correlation between the amount of produced pions and the number of neutrons that contribute to the reaction was found. Theoretical investigation is necessary to discuss the structure of ^{52}Ca.

Development of Low-energy muonic X-ray spectrometer for element analysis

A low-energy muonic X-ray spectrometer for element analysis (μLeXSea) is under development for the 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 detectors with a BGO anti-Compton suppressor. In this year, a prototype detector was tested and demonstrate the 60% Compton background with BGO Compton suppressor as shown in Fig. 2.1.5.

Study of the equation of state of high-density neutron matter by heavy-ion collision

To study the equation of state of high-density neutron matter experimentally, measurements of the collective flow of protons and neutrons in heavy-ion collisions are promising. We have performed the heavy-ion collision experiment (400-AMeV ^{132}Xe beam + CsI) conducted at HIMAC and confirmed the collective flow of protons and neutrons at the target rapidity for the first time. We are planning a new experiment with a detector with improved resolution of the reaction plane.

5 Aihara-Yokoyama Group

Research Subjects: Experimental Particle Physics and Observational Cosmology

Members: Hiroaki Aihara, Masashi Yokoyama, Yoshiuki Onuki, and Kota Nakagiri

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 the B meson system. We played a central role in 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 of the Belle II detector. This year, using the first data set recorded with Belle II, we set upper limits for the branching fractions of $B \to K\ell^+\ell^-$ ($\ell = e\,\mathrm{or}\,\mu$) decays. These decay modes are flavor changing neutral current (FCNC) processes, which are expected to be sensitive to the effects from new physics beyond the Standard Model. In addition, we developed the proper-time resolution function for time dependent analyses, which was used for the first measurement of CP violation parameter ϕ_1 at Belle II.

2. Study of neutrino oscillations and search for proton decay: T2K, Super-Kamiokande, and Hyper-Kamiokande experiments We have been studying neutrino oscillations with the T2K long baseline neutrino experiment. In T2K, 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 probabilities for neutrinos and antineutrinos. 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. Our group proposed a major upgrade of the T2K near neutrino detector and has been playing central roles in the project. This year, we designed a test system for the quality assurance of more than 50,000 MPPC used for the new near detector. Also, we developed an algorithm to identify electrons with the new near detector and estimated the sensitivity to the electron neutrino interaction.

Proton decay is the only way to directly prove the Grand Unified Theory, which is an attractive candidate for a model of physics beyond the Standard Model. Using the data collected with the Super-Kamiokande detector, we searched for the decay $p \to e^+\eta$ and $p \to \mu^+\eta$. No signal candidate is found and we set the most stringent lower limits to the partial lifetimes of these decays.

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 under construction. This year, the delivery of photomultiplier tubes has 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.

We searched for pairs of quasars using images recorded by HSC. We examined 34,476 known quasars and identified more than 400 candidates for dual quasars. With optical spectroscopic follow-up observations, seven dual quasars are newly identified. In addition, information of those dual quasars such as the black hole mass and luminosity was obtained by detailed analysis.

6 Asai group

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

Member: S.Asai, A.Ishida

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

– $\gamma\gamma$ scatter Using FEL Xray.
– Vacuum Birefringence using Strong Magnetic field or Strong light.

7 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
  Duality of electromagnetic responses between electric conductivity and orbital magnetic susceptibility.[1]
  Anomalous conductivity of two-dimensional electron systems in organic conductors.[2]

• Thermal transport phenomena
  Theory of magnon drag in Seebeck effects: Application to thin-film Heusler alloy.[3]
  Theory of paramagnon drag in thermoelectric transport properties.
  Thermal conductivity at low temperatures in excitonic insulators.[4]

• Theories on topological materials
  Dirac nodal lines and topological crystalline insulators.[5]
  Bulk physical properties of nodal line materials.[6]
  Magnon higher order topological insulators in antyskyrmion crystals.[7]
  Universal quantization of orbital-Zeeman cross term in magnetic susceptibility.[8]

• Organic conductors
  Photo-induced phase transition using Floquet theory.[9]
  Control of magnetism by oxygen adsorption in metal-organic framework systems.[10]

• Spin systems and spin-orbit interaction
  Detection theory of multipolar quantum spin ice in pyrochlore materials.[11]

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8 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 2020 are as follows.

- Development of the data assimilation method for crystal structure exploration using incomplete diffraction data:
  In this fiscal year, we improved the method to assimilate powder diffraction data with noise.
- Electronic state of YH_6, a high-Tc superconductor at ultra-high pressure:
- Wannier-function-based analysis of the electron-phonon coupling constant
- Revisiting Floquet theory for first-principles calculations
- Density functional theory for superconductors considering spin fluctuation
- Mechanism of Li conduction in superionic conductor $LiCB_9H_{10}$
- Construction of relativistic density functional theory and electronic states of superheavy elements
- Density functional in electron systems and its application to nuclear density functional theory
- Construction of correlation density functional using functional renormalization group
- Machine learning construction of electron-temperature-dependent interatomic potential
- Development of a first-principles calculation method in the electron-lattice strong coupling limit

9 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 computational physics methods based on sampling methods such as the Monte Carlo algorithm, path integrals to represent quantum fluctuations, information compression using the singular value decomposition and the tensor networks, and statistical machine learning, etc. By making full use of these powerful numerical methods, we aim to elucidate various exotic states, phase transitions, and dynamics in various quantum many-body systems, from quantum spin systems to actual materials. Also, we are studying the basic theory of quantum computers and quantum machine learning algorithms and working on the development and release of open-source software for next-generation large-scale simulations.

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10 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) magnetism in Fermi Hubbard models, (iv) dissipative quantum many-body systems, and (v) non-ergodic dynamics in non-integrable systems. In addition, we are also interested in the mathematical aspects of the above-mentioned fields. Our research projects conducted in FY 2020 are the following:

- Topological phases of matter
  - Topological magnon systems characterized by $\mathbf{Z}_2$ topological invariants [1]
  - Topological invariants of bosonic Bogoliubov-de Gennes systems with disorder [2]
  - Skyrmions in the nonlinear sigma model with a Dzyaloshinskii-Moriya type interaction [3]
  - Symmetry-protected topological phases in spinor Bose-Hubbard models
- Strongly correlated systems
  - Ferromagnetism in the $SU(n)$ Hubbard model with a nearly flat band [4]
  - Exact analysis of nonlinear Drude weights for quantum spin chains
- Dissipative quantum many-body systems
  - Topological characterization of fractional quantum Hall states in the presence of dissipation [5]
  - Exact analysis of quantum Ising chain with boundary dephasing [6]
- Mathematical and statistical physics
  - Constructing an infinite sequence of non-integrable models exhibiting perfect quantum many-body scars [7]
  - Error bounds for constrained quantum dynamics [8, 9]
  - Classical supersymmetric ground states of the Nicolai model [10]
  - Majorana reflection positivity in the attractive $SU(n)$ Hubbard model [11]

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11 Kabashima Group

Research Subjects: Statistical mechanics of disordered systems and its application to information science

Member: Yoshiyuki Kabashima and Takashi Takahashi

We are working in a cross-disciplinary field between statistical mechanics and information science. Our research interests include error-correcting codes, cryptography, CDMA multi-user detection, data compression, compressed sensing, sparse modeling, high-dimensional statistics, probabilistic inference, neural networks, random matrix, machine learning, spin glasses, etc.

The followings are highlights in our research activities in AY 2020:

1. Performance analysis of pseudo likelihood method for Ising model selection
2. Signal recovery of compressed sensing based on SCAD regularization
3. ℓ_0-based sparse signal recovery by greedy Monte Carlo search
4. Development of approximate stability selection algorithm based on semi-analytic bootstrap method
5. Performance analysis of stability selection
6. Inference of neuronal couplings from spiking data measured by multi-electrode arrays
7. Analysis of short term memory stored in randomly connected recurrent neural networks

12 Tsuji Group

Research Subjects: Condensed matter theory, nonequilibrium quantum many-body systems

Member: Naoto Tsuji

We are interested in nonequilibrium physics of quantum many-body systems and statistical mechanics. The aim is to realize a new order or new physical property by driving quantum systems out of equilibrium. At first sight, it sounds unlikely to happen because energy injected by an external drive would turn into heat, which would destroy all the interesting properties of quantum many-body systems that might emerge at low energies. However, contrary to our intuition, recent studies have found various possibilities such that novel states of matter that can never be realized in equilibrium do emerge out of equilibrium. We are trying to understand their mechanism and explore the frontier of nonequilibrium condensed matter physics.

In the academic year of 2020, we worked on the following projects:

- Nonequilibrium superconductivity
  — Higgs mode in conventional superconductors [1, 4]
  — Higgs mode in unconventional superconductors [3]
  — Dynamical instability of η pairing states
  — Collective modes in multiband superconductors [8]
  — Superconducting fluctuations driven by electric fields [5]
- Nonequilibrium open quantum systems
  — Quantum magnetism induced by particles losses [2]
  — η pairing superfluids induced by spontaneous light emission
  — Collective modes and phase transitions in dissipative superfluids [7]
- Quantum information scrambling
  — Fluctuation theorem and quantum interference
  — SYK strange metal in multiorbital systems [6]

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13 Ashida Group

Research Subjects: Condensed matter theory, theoretical quantum optics

Member: Yuto Ashida

This group focuses on theoretical studies at the intersection of quantum many-body physics and quantum optics. We have been studying physics of open and out-of-equilibrium systems, where quantum systems interact with external world and thus feature nonunitary dynamics. We employ the ideas/methods of field theory, renormalization group, and topology as well as variational approach, Bayesian inference, and reinforcement learning. We have also been studying physical phenomena in the corresponding classical systems as well as their potential applications. More recently, we have started to study applications/understanding of machine learning from a perspective of physics. We list research projects done in the academic year of 2020 below.

- Non-Hermitian physics, open systems [1, 2, 3, 4, 5, 6, 7]
- Quantum electromagnetism and quantum many-body physics [8, 9]
- Statistical physics, machine learning [10, 11]

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14 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 breaking, a wide variety of structures, and direct access for measurements. (1) Charge/spin/mass transports including superconductivity and spin current, (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 materials, 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:

- Anomalous Hall effect and topological Hall effect due to skyrmions at interfaces/heterostructures between topological insulators and ferromagnetic materials
- 2D superconductivity at monolayer alloy metallic surface superstructures and by proximity effect
- Weak anti-localization at a two-dimensional Dirac nodal line system and non-transition-metal dichalcogenide atomic layers
- Spin injection by circularly polarized light irradiation on topological insulators
- Superconducting Graphene and ferromagnetic Graphene with metal intercalation

(2) Surface phases and atomic-layer materials:

- Epitaxial growth of Dirac nodal line material Cu_2Si atomic layers and topological crystalline insulators

(3) New methods:

- Fabrication of a four-point probe UHV system with tunneling-spectroscopy capability
- Fabrication of a UHV system with polarization-controlled mid-infrared irradiation
- Lateral-ToF system with pulsed laser for carrier mobility measurements

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15 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

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

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

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

   To 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.

16 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Naotaka Yoshikawa

We study light-matter interactions and many body quantum correlations in solids, aiming at 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) (1 THz∼4 meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research topics in FY2020 are as follows.

1. **Nonequilibrium dynamics of superconductors:** We have investigated the photoexcited nonequilibrium dynamics of high-T_c cuprate superconductors and iron-based superconductors, by using a collective mode, namely the Higgs mode and nonlinear Josephson current response as a ultrafast probe fro the superconducting order parameter.

2. **Nonequilibrium dynamics of charge density wave system:** Large amplitude driving of a specific phonon is recently developed as a new approach to access nonequilibrium matter phases in correlated electron systems. In this work, we investigated a thin film of transition metal dichalcogenide (TMD) 3R-$Ta_{1+x}Se_2$ which shows a charge density wave(CDW) order at low temperatures. Upon the irradiation of an intense THz pulse, we demonstrated the resonant excitation of CDW amplitude mode, which in turn gives rise to emergence of a gapped state, suggesting a phase transition induced by the amplitude mode excitation.

3. **Terahertz emission from Dirac electrons in Bi:** We discovered that THz radiation is efficiently emitted from thin films of the semimetal Bi, a Dirac electron system, by irradiating it with circularly polarized light pulses. It is interpreted that the THz radiation is caused by the combination of spin polarization generation at the sample's surface by circularly polarized light, spin current generation by diffusion, and its conversion into a current pulse by the inverse spin Hall effect. Our findings open a new route to simple and compact methods for generating THz wave pulses and also for the ultrafast control of spin current.

4. **Generation of azimuthal and radial polarization of THz beam from a spintronic emitter:** We succeeded in demonstrating a method for switchable generation of THz radial and azimuthal beam, where a topological vortex nature appears in its polarization state, using a spintronic emitter. By focusing radially/azimuthally polarized THz-CVB, we demonstrated a generation of longitudinal electric/magnetic field component at the focal point.

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17 Takagi-Kitagawa Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kentaro Kitagawa, Naoka Hiraoka

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2020 included, $4f$ lanthanoide honeycomb-lattice compounds with interplay of electron correlations and strong spin orbit coupling, spin liquids, anti-perovskites with Dirac electrons, bosonic Bose-Einstein condensation 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 2018–2020.

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\text{eff}} = 1/2$ quantum pesudo spins of Ir on (hyper-)honeycomb lattice would be a main route. Two kinds of Majorana fermions represent KHM and they are particles on the exaclty solved ground state. Since our discovery is an only spin liquid on Kitaev system, and no report was given to proof two Majorana particles. We will pursuit realization of "true" Kitaev material. This year, we are exploring a new route to Kitaev physics, by making Lanthanoid honeycomb materials. 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 exhibits metamagnetic behavior which has been theoretically expected for the antiferromagnetic Kitaev spin liquid and its proximate. We further explore $4f$ 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. 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.

18 Hayashi Group

Research Subjects: Quantum spintronics/optics

Member: Masamitsu Hayashi, Masashi Kawaguchi

We work in the field of quantum spintronics and optics. Currently we put a particular focus on the strong coupling of spins, photons, magnons and phonons, mediated by the spin orbit interaction of the system, and look for the physics that can be applied to quantum physics.

- Spin current generation
  - Observation of the acoustic spin Hall effect in strong spin-orbit metals[4]
  - Magnetization direction dependent spin Hall effect in ferromagnets[2]
  - First principles studies on the relation between the anomalous Hall and spin Hall effects in ferromagnets[5]
- Topological physics and superconductivity
  - Superconducting properties of W thin films on topological insulators[1]
- Non-linear optical effects
  - Terahertz wave radiation from via spin current[3]
- Machine learning for chiral magnetism
  - Machine learning and pattern recognition determine the Dzyaloshinskii Moriya interaction from a single magnetic domain image[6]

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19 Kobayashi Group

Research Subjects: mesoscopic physics, quantum sensing, diamond NV center, noise & fluctuations, nonequilibrium phenomena

Member: Kensuke Kobayashi and Kento Sasaki

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 are interested in various phenomena in mesoscopic systems, especially quantum many-body effects, non-equilibrium phenomena, and spin/thermal transport. High-precision measurement of conductance and current fluctuations enables us to quantitatively understand quantum transport, which has been difficult in the past. We now specially focus on the quantum sensing using diamond NV center (Nitrogen-Vacancy center), on which we are developing single quantum spin microscope for the application to the high-precision measurement of physical properties, especially mesoscopic systems.

In FY2020, we addressed the following research topics:

- Precise measurement of physical properties using diamond quantum sensors
- Non-equilibrium transport and many-body correlations in Kondo effect
- Nonlinear transport in magnetic tunnel junctions
- Fabrication of single electron pump
- Non-equilibrium current fluctuations in the tunneling effect using spin Esaki diodes
- Development of low temperature amplifier for current noise measurement
- Behavior of spin torque oscillator in non-linear regime
- Electric detection of spin dynamics in spinglass
- Magnetic transport measurements in atomic layer ferromagnet Fe_5GeTe_2

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20 Nakatsuji-Sakai Group

Research Subjects: Condensed Matter Experiment

Member: Satoru Nakatsuji, Akito Sakai, Tomoya Higo, Takahiro Tomita

A new era in quantum materials research arises, featuring discoveries of novel topological phases of matter and interdisciplinary approaches. Our research activities focus on designing and synthesizing new materials with emergent quantum properties that have never been seen before, then exploring the physics and functionalities of 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 in strongly correlated topological phases and frustrated magnets
2. Room-temperature topological transport in magnetic materials
3. Non-Fermi-liquid behavior and exotic superconductivity in multipolar Kondo materials

Summary of research subjects in 2020

1. Electrical Manipulation of a Topological Antiferromagnetic State
The Weyl semimetal features nodal points formed by two linearly dispersive non-degenerate bands. These touching points or Weyl nodes act monopoles or antimonopoles of underlying Berry curvature, resulting in large anomalous Hall effect (AHE). The electrical manipulation of Weyl nodes is among the key topics of technological innovation utilizing a novel topological state. Moreover, electrical manipulation of an antiferromagnetic Weyl metal is considered a significant advancement, given the prospects of antiferromagnetic (AF) spintronics for realizing high-density, ultrafast devices.

We demonstrate the electrical switching of the AF Weyl state using Mn_3Sn/nonmagnetic metals (NM = Pt, W, Cu) bilayer devices and the spin-orbit torque (SOT) switching method[5]. The AHE serves as a readout for the SOT switching. We achieved the electrical switching of the AF Weyl metal using the same protocol as the one used for ferromagnetic metals. The critical write current density in the NM layer is considerably smaller than that in the NM/FM devices. These results indicate that topological antiferromagnets offer the unmatched potential for spintronic applications that may surpass today' s ferromagnetic counterparts.

2. Omnidirectional Control of Large Electrical Output in a Topological Antiferromagnet
The magnetization of a ferromagnet determines the signal size of memory and sensor, and thus manipulating the magnetization orientation is crucial for practical applications. While a large net magnetization yields

significant responses on its reversal, it may simultaneously limit the range of its directional control owing to the demagnetizing field. Thus, alternative materials that carry negligible magnetization but a strong response are highly demanded. Using polycrystalline Mn_3Sn thin films, we report omnidirectional control of the significant transverse responses in an antiferromagnet and demonstrate that the absence of shape anisotropy is the key to the omnidirectional control[1]. This work lays the foundation for engineering simple - structured, highly efficient devices, including multi - level memory and heat flux sensors.

3. Evidence for Weyl fermions in the chiral antiferromagnet Mn_3X (X = Sn, Ge)
A significant obstacle in antiferromagnetic spintronics is the tiny response of the antiferromagnetic structure to magnetic fields. The recent discoveries of large room-temperature anomalous transport effects in antiferromagnets Mn_3X (X = Sn, Ge) signifies an experimental breakthrough in this direction. These anomalous transport properties are considered fingerprints of Weyl fermions. Therefore, understanding the role of magnetic Weyl fermions in driving the transport properties of chiral antiferromagnets is all the more important for utilizing topological states of matter in practical applications.
In this work, we establish Weyl fermions as the origin of the large anomalous Hall and Nernst effects in Mn3X systems by combining our previous reports with a new, comprehensive set of transport measurements and theoretical analysis of high-quality Mn3X single crystals[2]. Our findings of magnetotransport signatures specific to chiral anomalies in Mn3Ge and planar Hall effect in Mn3Sn provide concrete evidence for the presence of Weyl fermions in both materials.

4.Strain tuning of magnetic phase transition in Weyl antiferromagnet Mn_3Sn
Combing strain and dilatometry offers a compelling route to high-resolution thermodynamic information on magnetic phase evolution. The stoichiometric Mn_3Sn undergoes a first-order transition at about 270K from the triangular to a spin spiral structure, in which the topological transport properties vanish. Tuning this transition may help understand the underlying mechanism and access the topological properties at low temperatures.
Together with collaborators at Max Planck Institute, we developed a piezoelectric-based dilatometer for measuring thermal expansion under tunable uniaxial stress, a clean tuning method to control and probe magnetic phase transitions[3]. With this device, we show that the first-order transition in Mn_3Sn is suppressed by about 50 K under a c-axis compression of 1.5 GPa, indicating that the transition is insensitive to stress, contrast sharply with its acute sensitivity to compositional changes. This finding suggests that the lattice is not the primary driver of the transition. This uniaxial stress technique is compatible with various experimental probes and is widely applicable to other materials.

5. Large transverse thermoelectric effect in iron-based binary ferromagnets
Thermoelectricity provides vital technology for versatile energy harvesting and heat current sensors. So far, thermoelectric technologies are focused on the longitudinal Seebeck effect. Its transverse counterpart, the anomalous Nernst effect (ANE) features several potential benefits. Namely, the transverse geometry of the Nernst effect enables simplified structures of thermoelectric generators with enhanced conversion efficiency. A server obstacle here is that the anomalous Nernst effect is too small compared to the Seebeck effect for real-life thermoelectric applications. Thus, it is essential to design a new class of materials that exhibit a large ANE without an external magnetic field.

We discovered record high spontaneous transverse thermoelectric effects at room temperature in two iron-based compounds, Fe_3X (X = Ga, Al)[4]. We then succeeded in fabricating Fe_3Ga and Fe_3Al thin films suitable for designing low-cost, flexible thermoelectric generators. Our innovative iron-based thermoelectric material represents a significant step toward commercializing thermoelectric generators that can power small devices such as remote sensors or wearable devices.

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21 Theoretical Astrophysics Group

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

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

The 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, high-energy astrophysics, and artificial intelligence.

“Observational Cosmology” attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of recent and future data provided by Planck, Hubble Space Telescope, ALMA, and wide-field galaxy surveys such as Subaru Hyper-Suprime-Cam survey are very 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 evolution of the universe. Our current interests include non-linear 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, statistics of gravitationally lensed quasars, and the chemical formation history of the Milky Way.

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 the evolution of the cosmic structure 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. We study the formation and mixing of the first heavy elements in the universe. Comparing the predictions of our simulations to observations allows us to better understand the nature of the underlying physical processes.

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 4000 exoplanets have been reported as of March 2021. 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.

To maximise the information gain from astrophysical observations and numerical simulations, we also apply and develop state-of-the-art machine learning techniques. We use supervised machine learning algorithms to classify observations of metal-poor stars, quasars, and satellite galaxies of the Milky Way. We improve existing deep learning methods with a new class of activation functions that allow users to improve the extrapolation properties of their neural networks. Artificial intelligence (AI) is a rapidly evolving field with many promising applications. To better understand the social impact of AI research, we also collaborate with social scientists to better understand the impact and public attitudes towards AI research.

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

2020

- Observational signatures from tidal disruption events of white dwarfs

- Multiwavelength Signals From Pulsar-Driven Supernovae
- Measuring stellar rotation periods and stellar inclinations of kepler solar-type stars

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

22 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.

We consider that a quantum computer is not just a machine to run computational algorithms but also a machine to perform any operations allowed by quantum mechanics. We analyze what kinds of new properties and effects may appear in quantum systems by using quantum computers to improve our understanding of quantum mechanics from an operational point of view. We also investigate applications of quantum properties and effects such as entanglement for information processing, communication, quantum learning, and quantum manipulations by developing quantum algorithms and quantum protocols. Recently, we are analyzing non-locality, causal structures, parallelizability, and anonymity of quantum information processing and quantum programming by investigating higher-order quantum operations and distributed quantum computation.

This year, our group consisted of two faculty members, Mio Murao (Professor), Akihito Soeda (Assistant Professor), Jun-yi Wu, and 6 graduate students–Qingxiuxiong Dong (D3), Wataru Yokojima (D1), Atsuhi Okamoto (M2), Yutaka Hashimoto (M1), Kosuke Matsui, and Anian Altherr (USTEP graduate student from ETH Zurich). Our projects engaged in the academic year of 2020 were the following:

- Higher-order quantum operations
  - Quantum learning: Equivalence determination with quantum tester by Y. Hashimoto, A. Soeda, and M. Murao
  - Storing and retrieving of higher-order quantum operations by W. Yokojima, A. Soeda, and M. Murao
  - Success-or-Draw structure in higher-order transformations by Q. Dong, A. Soeda and M. Murao with Dr. Marco Túlio Coelho Quintino
  - The uniqueness of the extension of quantum switch on non-unitary operations by Q. Dong, A. Soeda, and M. Murao with Dr. Marco Túlio Coelho Quintino at IQOQI Vienna
  - Inclusion hierarchy of parallel, adaptive, and indefinite causally ordered startegies in discrimination of quantum channels by M. Murao with Dr.Jessica Bavaresco and Dr. Marco Túlio Coelho Quintino at IQOQI Vienna
- Controls for quantum dynamics
  - Mathematical models based on quantum field theory for artificial quantum systems by A. Soeda
- Distributed quantum information processing
  - Distributed implementation of unitary operation between two nodes by entanglement-assisted LOCC by K. Matsui, J. Wu, A. Soeda, and M. Murao
  - Entanglement detection of multi-photon states distributed between two parties in an linear optical network by M. Murao and J. Wu
  - Distributed fidelity estimation of bipartite entangled states by M. Murao and J. Wu

23 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. Furthermore, we have recently tackled an understanding of AI and machine learning from a viewpoint of physics. We list our main research subjects in FY2020 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Exact solution of a one-dimensional dissipative Hubbard model [1]
  - Effective temperature of a superfluid flowing in a random potential [2]
  - Universal error bound for constrained quantum dynamics [3, 4]
  - Non-Hermitian topological phases [5, 6, 7]
  - Continuous phase transition without gap closing in non-Hermitian quantum many-body systems [8]
  - Test of the eigenstate thermalization hypothesis based on local random matrix theory [9]
- Unification of quantum physics, statistical mechanics, information theory, and machine learning
  - Deep reinforcement learning control of quantum cartpoles [10]
  - Machine learning of periodic functions [11]
  - Thermodynamic uncertainty relation for arbitrary initial states [12]

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24 J. Yokoyama Group

Research Subjects: Theoretical Cosmology and Gravitation

Members: Jun'ichi Yokoyama and Kohei Kamada

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We have also been working on gravitational wave data analysis toward signal detection by KAGRA. Below is the list of topics studied during the academic year 2020.

Early Universe Cosmology

- Primordial magnetic fields
- Vacuum phase transition around a black hole
- Renormalization of quantum effects in the minimal gravitational leptogenesis
- Uncertainty in the improved mass spectrum of the primordial black holes
- (P)reheating in the Higgs-R^2 mixed model
- Towards the realization of the α-attractor in the M-theory
- Cosmological 21 cm circular polarization
- Particle production associated with vacuum decay
- Analytical expressions of the second order scalar perturbations
- Lorentzian path integral of the vacuum phase transition
- Comprehensive study of the gravitational production of the right-handed neutrinos
- Reheating process with the Schwinger effect

Gravitational wave analysis

- Offline noise subtraction with physical environmental monitors

25 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 of 0.36 m and a minor radius of 0.23 m. The plasma current is <120 kA for inductive operation and <27 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 FY2020, the hard X-ray 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.

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 outer midplane and the top of the plasma. Since LH waves drive current by generating fast electrons, measurements of X-ray radiations by those fast electrons are important. On FY2020, parametric decay instability was observed with magnetic probes. The spatial distribution of the sideband depended strongly on the current drive scenario. We have improved the accuracy of edge Thomson scattering measurement to study the difference between the electron density and temperature profiles. One-dimensional fast electron transport model was developed. The simulated shape of the energy spectrum of the radiated X-ray was consistent with the experimental measurements for two different outer radius locations.

The ion doppler spectroscopy was performed to study the time evolution of flow during internal reconnection events (IRE). It was found that a high temperature component (∼200 eV) appears during IRE in addition to the <100 eV component that exists before the IRE.

Several diagnostic developments were performed in FY2020. Optical design of a double-pass Thomson scattering configuration was performed to measure electron temperature anisotropy. The time resolution of the hard X-ray diagnostic was improved by one order of magnitude. New microwave interferometer optics was developed to improve the accuracy and reliability of the electron density measurement.

As a collaboration, Thomson scattering diagnostic on QUEST is being developed. As a collaboration with QST, we are investigating the optimum electron cyclotron (EC) wave assisted Ohmic start-up scenario for JT-60SA. In FY2020, we have developed models to describe the EC assisted breakdown and were able to explain the EC power and the vertical field dependences observed experimentally. We started a collaboration with ENN to develop a current drive system using LH waves. To excite LH waves in an unconventional parameter regime, we developed a novel corrugated surface antenna. A new 2.45 GHz antenna was fabricated and tested on the TST-2 device. We attempted to inject LH waves with the new antenna to a plasma generated with 200 MHz. Although we could not see a current drive effect because of the limited 2.45 GHz power (5 kW compared to 50 kW for 200 MHz), we observed a clear enhancement of hard X-ray radiation, which showed that the new antenna indeed accelerated electrons as expected.

26 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 (~ 1000 au) is indeed inherited in the disk forming region (~ 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, the ALMA large program FAUST (Fifty AU Study of the chemistry in the disk/envelope system of Solar-like protostar) is ongoing. Furthermore, we are now incorporating machine-learning techniques to explore the physical and chemical structures in an unbiased way.

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27 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) All-optical orientation of linear molecules with combined linearly and elliptically polarized two-color laser fields [1]

We show that a combination of a fundamental pulse with linear polarization along the vertical direction and an elliptically polarized second harmonic pulse with both vertical and horizontal electric field components can be used to orient linear molecules efficiently, leading to higher degrees of orientation. Due to this specific combination of polarizations, the asymmetric hyperpolarizability interaction potential, which remains the same as that in a linearly polarized two-color laser field, is created along the vertical component of the elliptically polarized second harmonic pulse. On the other hand, the horizontal component suppresses the otherwise strong symmetric polarizability potential responsible for alignment, increasing the tunneling probability from the shallower potential well to the deeper one. As a result, the degree of orientation increases and can be controlled by changing the intensity of the horizontal component of the elliptically polarized second harmonic pulse. This study is the generalization of the all-optical molecular orientation technique based on the anisotropic hyperpolarizability interaction.

(2) Comparative studies of the degrees of orientation of CO molecules pumped by intense femtosecond two-color pulses based on high-order harmonic generation and Coulomb explosion imaging [2]

With an intense femtosecond two-color pulse optimized for the generation of even-order harmonics from CO molecules, we directly measure the actual degrees of orientation by utilizing the Coulomb explosion imaging technique with appropriate probe polarization. We find that the macroscopic orientation of CO molecules is negligible even when significant even-order harmonics are observed. This finding shows that the generation of even-order harmonics cannot be ascribed to the macroscopic orientation of CO molecules. The rotational wave packet of CO molecules created with an intense femtosecond two-color pulse is thought to be in an uninvestigated quantum state, which cannot be explained by the theoretical model based on the Born-Oppenheimer approximation, without inversion symmetry at any of the three steps of high-order harmonic generation, leading to the generation of even-order harmonics.

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28 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 ultra-cold atomic gases. In particular, we have been investigating the phase of Bose-Einstein condensation of excitons, which has not been experimentally proven while considered as the ground state of an electron-hole ensemble. Based on quantitative spectroscopic measurements, the temperature and density of the excitions are determined in a quasi-equilibrium condition where they are trapped in a highly pure crystal kept below 1 K. We are now investigating a stable quantum degenerate state of dark excitons at the low temperature. We also study novel optical and teraherz-wave responses of artificial nanostructures fabricated by advanced technologies. Furthermore, 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
    - 1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases
2. Investigation for non-trivial optical responses and development of applications:

2.1. Circularly polarized coherent VUV generation by photonics crystal nanomembrane
2.2. Exploring the mechanism of laser ablation by femtosecond lasers
2.3. Development of new technology to fabricate micro three-dimensional artificial structures using laser processing and additive manufacturing

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

29 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 and precursor missions
- Development of TOBA (Torsion Bar Antenna)
- Dark Matter Seach
- 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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30 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, and active galactic nucleus.

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

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants, compact stars such as neutron stars and blackholes, and active galactic nucleus. Such high energy objects emit X-rays and gamma-rays, so we observe such high energy photons using baloons and satellites.

This year we examined carefully how and when accelerated particles on the shocks of supernova remnants escape to the space and become galactic cosmic rays. With systematic study of a few tens suprenova remnants in X-ray and gamma-ray band, it is found that accelerated particles escape from the acceleration sites (shocks of supernova remnants) within ∼10 kyrs[2]. This is the first observational measurent of particle escape from the acceleration sites. The acceleration efficiency has diversity within the order of 3, which means that only a few supernova remnants contribute the Galactic cosmic rays.

Torus of active galactic nucleus (AGNs) feed supermassive blackholes and important to understand the co-evolution of galaxy and the blackholes. This year we have made systematic analysis of AGNs hidden by their torus with the X-ray emission model we developed (”XClumpy”), and found that around half of AGNs are hidden type. It is found that the covering fluction by their torus is larger than previously expected. Our result implies that there are more undiscovered AGNs hidden by their torus.

We also study on the detector development for the near future missions. For the XRISM, to be launched on the Japanese fiscal year 2022, we fixed the performance verification targets. For Cipher mission, the first imaging polarimetory cubesat in the hard X-ray band, we tested the X-ray use of infrared CMOS sensor and found that it totally satisfies our requests wigh good efficiency. We also started GRAMS mission deverlopment in this year.

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31 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 concluded its observation campaign, and Simons Array experiment started the osbervation. 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 under constraction, with the first light expected in two years. We plan to deploy an array of what we call "small aperture telescopes," 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 telescope.
- 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, cryogenic bearing system for HWP, and anti-reflection coating for high-index optical material. 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.

32 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 academic year 2020:

(1) Non-equilibrium phenomena in soft matter systems
(1-1) Observing and characterizing 3D dynamics of topological defects in liquid crystal
(1-2) Universal scaling laws for random growth processes explored in liquid-crystal turbulence [2]
(1-3) Noise-induced phenomena in electroconvection dynamics of liquid crystal
(1-4) Positional and orientational orders in collections of self-propelled particles [3, 5]

(2) Non-equilibrium phenomena in living systems
(2-1) Scale invariance in cell size fluctuations [4]
(2-2) Crowding of motile bacterial populations
(2-3) Hydrodynamics of bacterial populations and individuals with the effect of boundaries [1]

(3) Approaches based on nonlinear science
(3-1) Machine-learning approach to spatiotemporal chaos

More detailed information can be found at the group's website, `https://lab.kaztake.org/`

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33 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 fruitfly, *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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34 Higuchi Group

Research Subjects:Protein dymamics in vitro,cells and mice

Member:Hideo Higuchi and Motoshi Kaya

Difference in molecular properties between cardiac and skeletal myosins determines types of contraction required in heart and skeletal muscles.

Changes in the molecular properties of myosin strongly affect the interactions of myosin with actin, that result in contraction and relaxation of the heart and skeletal muscles. In the 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 cardiac myosin molecules switched among three distant conformational positions, ranging from a pre- to post-power stroke positions. In contrast to cardiac myosin, fast skeletal myosin stayed primarily in the post-power stroke position, suggesting that cardiac myosin executes the reverse stroke more frequently than fast skeletal myosin. To elucidate how the reverse stroke affects the force production of myofilaments and possibly heart function, a simulation model was developed that combines the results from the single-molecule and myofilament experiments. The results of this model suggest that the reversal of the cardiac myosin power stroke may be key to characterizing the force output of cardiac myosin ensembles and possibly to facilitating 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 enhance force output along with high speed of shortening.

Molecular mechanism of kinesin denatured by temperature or pH.

Motor proteins kinesin and dynein move along microtubules converting ATP hydrolysis energy into mechanical energy and have cellular functions in organelle transport and cell division. Environmental temperature and pH are vital for survival; therefore, it is supposed that local environmental changes lead to cell death. In our previous study, we proposed that kinesin has metastable states before the complete inactivation stage, by a single molecular measurement of kinesin preincubated at high temperature for hours. In our study, we prepared kinesin or dynein preincubated at high temperature or pH for minutes to hours and investigated the transition of movement. First, we measured the behaviors of microtubules glided by multiple kinesin or dynein, called microtubule gliding assay. The velocity and microtubule-binding affinity decreased, same as the previous results. Especially, kinesin preincubated in pH 5.7 solution for 10 minutes glided microtubules in various behaviors; steady speed, stop and go, completely stop or Brownian motion. Next, we measured the stepping motion of the denatured kinesin at single molecular level using optical tweezers. The denatured kinesin generated smaller force and moved slower than wild kinesin, same as our previous results. Kinesin denatured at high temperature was previously observed to move with a slow microtubule dissociation rate in both kinesin heads and only one head. However, Kinesin denature at low pH was observed to move with a slow dissociation rate only in both heads, not observed in only one head. This suggests that the transition rate from the native state to the metastable state of slow dissociation rate was faster in pH-denatured kinesin than temperature-denatured kinesin. In summary, we propose that kinesin has metastable states in the change of temperature or pH, and this study would contribute to understanding the molecular mechanism of motor proteins upon environmental changes in axons or cells.

Analysis of intracellular diffusion constant and intensity fluctuation for quantitative evaluation of cellular damages

Decreasing mobility of organelles in cells damaged by intracellular reactive oxygen species (ROS) or local heat was found in our laboratory. Because there are some probabilities that our findings are related to "glass-like properties of cytoplasm", mobility of intracellular organelles and red fluorescent proteins (RFP) were measured with cells damaged by ROS. Cellular survival probabilities were measured at the same time for quantitative evaluation of cellular damages. As a result, both mobility of intracellular organelles and RFP decreased in damaged cells which had low survival probabilities. In addition, the decreasing ratio of intracellular organelles were higher than that of intracellular RFP. We have interested in whether the difference is meaningful or not.

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35 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.

Nearly half year from April, the laboratory works were forced to stop due to the lab closure by COVID-19 in FY2020. "Wet experiments" using protein or living cells were seriously delayed. We, therefore, rather focused on the development of the image processing algorithms using machine learning or deep learning technologies. For example, Kowashi applied deep learning based image processing algotirhms for the processing of the images of interferometric scattering microscope. Two papers were published by former international intern students from Lomonosov Moscow State University through STEPS (Students and Researchers Exchange Program in Sciences with Russian Universities) program. Yakov has developed an image henhancement algorithm for super-resolution microscopy [1], and Alex has developed a cell segmentation and tracking algorithm [2]. We also tried to develop "explainable AI" for the cell image classification. Microscope images were first classified by deep learning AI. Then, we extracted the features that AI has used for the classification by using Grad-CAM analysis. As a proof of this concept, we have classified the microscopic cell images for the cell cycle, and the Grad-CAM analysis indicated that AI has classified the cell images by focusing on nucleus and Golgi. We cell biologists expected nucleus would be most informative for the cell cycle classification, but this analysis unexpectedly identified Golgi as another marker for the cell cycle. In fact, we confirmed that Golgi changes its shape and size according to the cell cycle. This would be a primitive but first example that cell biologists learned from AI [3].

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36 Furusawa Group

Research Subjects: Theoretical Biophysics, Evolutionary Biology, Complex Systems

Member: Chikara Furusawa and Yusuke Himeoka

Biological systems have both robustness and plasticity, a property that distinguishes them from artificial systems and is essential for their survival. Biological systems exhibit robustness to various perturbations, including noise in gene/protein expressions and unexpected environmental changes. Simultaneously, they are plastic to the surrounding environment, changing their state through processes such as 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.

Our work extracts the universal features of cellular dynamics responsible for robustness and plasticity in biological systems. We 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. Metabolic simulation for understanding growth and lag-phase
5. Development of a method to characterize animal morphology using machine learning

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