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東京大学 大学院　理学系研究科・理学部
物理学教室

II

Summary of group activities in 2017

1 Theoretical Nuclear Physics (Fukushima) Group

Subjects: Curved spacetime, QCD phase diagram, Lattice simulation, Berry's phase

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. Berry phase in lattice QCD
2. Rotational effects in relativistic fermion systems
3. Vacuum structures in inhomogeneous magnetic fields
4. Non-equilibrium dynamics in kinetic theories

2 High Energy Physics Theory Group

Research Subjects: Particle Physics and Cosmology

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo

We are working on various topics in particle physics and cosmology, such as physics beyond the Standard Model, dark matter, baryogenesis, inflation, phenomenology of supersymmetric models, grand unified theories, string theory, supersymmetric field theories, conformal field theories, holography, entanglement entropy, and so on. Specific subjects studied in 2017 are summarized below:

1. Phenomenology
   - 1.1. Phenomenology of supersymmetric models [1, 2, 3, 4, 5, 6].
   - 1.2. Grand unified theories [7, 8].
   - 1.3. Vacuum decay [9, 10, 11, 12].
   - 1.4. Dark matter [13, 14, 15, 16, 17].
   - 1.5. Flavor physics [18, 19, 20].
   - 1.6. Neutrino physics and inflation [21].
   - 1.7. Axion production in supersymmetric models [22].
   - 1.8. Big-Bang Nucleosynthesis [23].
   - 1.9. Cosmic infrared background [24].
   - 1.10. Gravitino problem [25].
2. Superstring Theory and Formal Aspects of Quantum Field Theories
   - 2.1. Quantum toroidal algebra and gauge-string duality [26, 27, 28].
   - 2.2. Supersymmetric Rényi entropy and defect operators [29].
   - 2.3. Operator product expansion for conformal defects [30].
   - 2.4. Conformal field theories with boundaries [31, 32].

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3 Sakurai Group

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

Member: Hiroyoshi Sakurai and Megumi Niikura

In-beam spectroscopy of ^{78}Ni

In-beam spectroscopy of ^{78}Ni was performed at RIBF as a series of campaign experiment of the SEASTAR experiments in 2015. The de-excitation γ-rays were detected by the NaI(Tl) scintillator array DALI2 after the proton-knockout-reactions with a 10-cm-thick liquid hydrogen target surrounded by the recoil proton tracking system MINOS. The de-excitation γ-rays of ^{78}Ni has been observed successfully.

β-delayed neutron emission measurement at RIBF (BRIKEN project)

BRIKEN project is an international collaboration aiming at masurement of a β-delayed neutron emission probability (P_n) in the wide range of the nuclear chart. In this year, P_n values of neutron-rich nuclei from Nikel to Iodine region was succcessfully measured.

In-beam γ-ray spectroscopy of ^{35}Mg via knockout reactions at intermediate energies

The isotope ^{35}Mg was spectroscopically studied via nucleon-removal reactions from ^{36}Mg and ^{37}Al secondary beams at intermediate energies. The experiment's aim was to clarify the level structure of this nucleus located in between the $N = 20$ and 28 shell quenchings. De-excitation γ-ray energies, exclusive cross sections, and parallel momentum of outgoing ^{35}Mg for several final states were measured and compared to theoretical calculations. It was found that a large fraction of the one-neutron knockout reaction goes into unbound states of ^{35}Mg, which may explain missing f-wave strength.

Spectroscopy of pionic atoms using a proton beam

Chiral symmetry restoration at finite density is one of the most important topics in hadron physics. Spectroscopy of deeply bound pionic atoms enable us to investigate the symmetry restoration and they have been studied experimentally at GSI and RIBF. We are planning to perform a new experiment of pionic atoms using a proton beam at RCNP in order to improve the experimental resolution. In this fiscal year, we conducted the first experiment in RCNP using ^{124}Sn target. We succeeded in measuring the spectrum of the pionic states for about 170 hours as planned. We are now analyzing the data in order to discuss the symmetry restoration at the finite density.

Exotic cluster structure in ^{16}C

We performed an invariant mass spectroscopy in order to search for α-cluster states in ^{16}C via α-inelastic scattering at 200 MeV/u. The excitation energies of ^{16}C are reconstructed from $^{16}\mathrm{C}^* \to {}^{12}\mathrm{Be} + {}^{4}\mathrm{He}\ (+\gamma)$ decay channel by measuring their four momenta with the SAMURAI spectrometer and γ-ray energy. Candidates of α-cluster states are found in the excitation energy spectrum.

Muon capture on palladium isotopes

This year, four experiments were performed aiming at an experimental determination of neutron energies and multiplicities following the muon capture reaction on paradium isotopes. The neutron time-of-flight measurement employing the SEAMINE array was performed at RCNP (Osaka Univ.) MuSIC-M1 beamline. The muon activation measurement for the stable isotopes were performed at RAL (UK) RIKEN beamline and J-PARC MUSE facility, respectively. The activation measurement using the radio-active ^{107}Pd target was also performed at J-PARC MUSE.

4 Wimmer Group

Research Subjects: Spectroscopy of exotic nuclei using direct reactions

Member: Kathrin Wimmer

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

Triple shape coexistence at $N = 28$

One of the most interesting forms of shape coexistence is the occurrence of three different shapes within one nucleus. Such a behavior is expected for ^{44}S, where three low-lying 0^+ states of the nucleus, exhibit spherical, prolate (rugby-ball shaped) and oblate (disk shaped) deformation. Measurements of single-particle properties of these exotic nuclei give further insights in the wave function composition of states. We have performed an experiment on one-neutron knockout reaction from ^{44}S at the National Superconducting Cyclotron Laboratory (NSCL) to investigate the ground state wave function of this nuclei. From the experiment we have obtained the occupation of the $f_{7/2}$ and $p_{3/2}$ orbitals in the ground state of ^{44}S and thus we measure the shape mixing in this interesting nucleus, which is supposed to have three different shapes at the same time.

Spectroscopy of the $T_z = -1$ nucleus ^{70}Kr
Extremely proton-rich nuclei provide an interesting test ground for isospin symmetry in nuclei. Isospin non-conserving interactions lead to different structures of nuclei which have proton and neutron number interchanged. So far such tests are limited to lighter nuclei. In an experiment at the RIBF at RIKEN ^{70}Kr was studied by nucleon removal reactions and Coulomb excitation. Previously no excited state was known in this nucleus, our analysis reveals five new states, and comparison with theoretical calculations suggests that effects from the Coulomb interaction as well as isospin breaking components in the nuclear interaction play a major role in this $N < Z$ nucleus. A followup study of ^{66}Se and ^{62}Ge has been approved by the RIBF program advisory committee.

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

Single-particle structure of neutron-rich Ca isotopes Within the SEASTAR collaboration we have performed an experiment to study the first spectroscopy of very exotic neutron-rich nuclei. The experiment was performed using the large acceptance SAMURAI spectrometer that allowed for the simultaneous measurement of many reaction channels. In particular we are investigating the single-particle structure of ^{56}Ca through proton and neutron knockout, and the systematics of the production cross sections along the Ca isotopes.

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

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

Next generation γ-ray spectroscopy Most of the experiments at RIBF employ γ-ray spectroscopy as a tool. However, the present instrumentation is not sufficient to remain competitive with other laboratories in the future. A new device would open new horizons for the spectroscopy of exotic nuclei. There are two general approaches. An array based on γ-ray tracking achieves unparalleled resolution for in-beam experiments. On the other hand, highest efficiency can be obtained with scinillator detectors for γ-ray spectroscopy. Such devices are ypically easier to handle, however, the resolution is sacrificed for efficiency. We are working in both directions, developing computational approaches for γ-ray tracking and testing new scintillating crystals for their performance.

5 Komamiya group

Research Subjects: (1) Preparation for an accelerator and an experiment for the International linear e^+e^- collider ILC, including beam focus study at ATF2 of KEK using nano-meter beam size monitor (Shintake Monitor), research and development of electromagnetic calorimeter for the ILC Experiment; (2) Higgs boson studies and supersymmetric particle searches with the ATLAS detector at the LHC pp collider; (3) Experiment for studying gravitational quantum effects and searching for new short range force using ultra-cold and cold neutron beam

Member: Sachio Komamiya, Yoshio Kamiya

We, particle physicists, are entering an exciting period in which new paradigm of the field will be opened on the TeV energy scale triggered by the new discovery of a Higgs Boson at LHC. The details of the observed Higgs Boson and other new particles will be studied in a cleaner environment of e^+e^- collisions at the International Linear Collider ILC.

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to use superconducting RF system. The Technical Design Report was completed and published in 2013. Since then, ILC design and hardware development are passed to the Linear Collider Collaboration (LCC) lead by Lyn Evans. The Linear Collider Board (LCB) is an oversight body of LCC. Sachio Komamiya is a representative of Japanese particle physics community. We are working on ILC accelerator related hardware development, especially on the final focus system. We are developing the Shintake beam size monitor at the ATF2, which is a test accelerator system for ILC located in KEK. The Shintake beam size monitor measured about 40[nm] beam size which is a world record. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC. In 2017 spring to summer Japanese particle physics community studied the possibility of ILC to be a Higgs Factory machine. From precise measurements of coupling constants of the Higgs Boson to other elementary particles at the ILC and the study of deviation pattern of these couplings from the Standard Model predictions, the evolutional direction of particle physics beyond the Standard Model, i.e. towards supersymmetry or composite models, can be clarified. Therefore the scientific significance of the ILC as a Higgs Factory is enormously enhanced. The world particle physics community lead by ICFA issued "ICFA Statement on the ILC Operating at 250 GeV as a Higgs Boson Factory" in November 2017 at the Ottawa ICFA Meeting. The ILC is an international project led by Japanese initiative.

2) ATLAS experiment at LHC: The epoch of new paradigm for particle physics is going to open with the experiments at LHC. In July 2012, a Higgs Boson was discovered by the ATLAS and CMS experiments at LHC. We call this event as "2012 July Revolution". After the Higgs Boson discovery our students have been working on physics analysis beyond the Standard Model, especially on the searches for supersymmetric partners of gluon and partners of electroweak gauge bosons/ Higgs bosons. Some of the results are already published in journals.

3) Experiment for studying quantum bound states due to the earth's gravitational potential to study the equivalent theorem in the quantum level, and searching for new short-range force using ultra-cold neutron (UCN) beam: A detector to measure gravitational bound states of UCNs is developed. We decided to use CCD's for the position measurement of the UCN's. The CCD is going to be covered by a ^{10}B layer to convert neutron to charged nuclear fragments. The UCNs are going through a neutron guide of 100 [μ] height and their density is modulated in height as forming bound states within the guide due to the earth's gravity. In 2008 we tested our neutron detector at ILL Grenoble. In 2009 we started the test experiment at ILL. We significantly improved our detector system and performed the experiment in 2011, and the analysis was completed in 2012. The observed modulations in the vertical distribution of UCNs due to the quantization is in good agreement with the prediction by quantum mechanism using the Wigner function. This is the first observation of gravitationally bound states of UCNs with sub-micron spacial resolution. This result was published in PRL. In 2013 we have started a new experiment to search for a new short range force using cold neutron beams scattered with Xe atom. The experiment was performed in HANARO,

KAERI, Korea in 2014 and ILL, D22, France in 2016. The new world record of the short range force was established by this experiment and was published in PRL.

6 Aihara-Yokoyama Group

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

Members: Hiroaki Aihara, Masashi Yokoyama, and Yoshiuki Onuki

1. Search for new physics at KEK (super-)B-factory: Belle and Belle II experiments One of the major research activities in our group has been a study of CP-violation and searches for physics beyond the Standard Model in the B meson and the τ lepton systems using the KEK B-factory (KEKB). We continue a study of Michel parameters of the τ lepton, which is sensitive to physics beyond the Standard Model. In addition, we study rare decays of the τ lepton, such as $\tau^- \to \ell^- \ell'^+ \ell'^- \bar{\nu}_\ell \nu_\tau$ ($\ell, \ell' = e, \mu$) and $\tau^- \to \pi^- \ell^+ \ell^- \nu_\tau$ ($\ell = e, \mu$), to search for new physics.

The SuperKEKB accelerator will have 40 times higher luminosity than KEKB. The Belle detector is also being upgraded as the "Belle II" detector with cutting-edge technologies. Our group is responsible for the construction of the outermost layer of the Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons, one of the key elements for the success of Belle II. This year we completed the production of six ladders of the Belle II SVD.

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

We lead the program to improve the sensitivity of T2K by reducing the systematics uncertainties related to the neutrino interaction. We have been performing a test experiment named WAGASCI at J-PARC to provide more information on the interaction of neutrinos with water, which is the target material in the SK detector. Our group play central roles in the upgrade project of the T2K near neutrino detectors.

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

3. Study of Dark Energy with Subaru telescope: Hyper Suprime-Cam As an observational cosmology project, we have been involved in building 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.

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

7 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.

8 Miyashita Group

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

Quantum Dynamics, Non-equilibrium Phenomena

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

Quantum dynamics under a time-dependent field is one of the most important subjects in our group. In the 2017 fiscal year, we studied the following topics. We studied thermalization of isolated quantum systems. We examined the Eigenstate Thermalization Hypothesis (ETH) which has been believed to hold for non-integrable systems. But we constructed a counterexample for which we can prove the violation of ETH exactly [9, 10]. We also studied thermalization in the semi-classical region and made clear that the ergodicity in classical limit and ETH in quantum systems are equivalent [11]. We studied the microscopic mechanism of the optical bistability (OB) by making use of an extended parallel algorithm. In particular, we pointed out OB takes place in the so-called quantum region where the number of atoms is larger than that of photons. We study the properties of metastability including the hysteresis behavior, in particular, the size dependence of the relaxation time [37, 45, 24].This topic was studied in a collaboration with Todo group. Dynamics under external sweeping field is also studied. The size(S)- and sweeping velocity-dependences of scattered population distribution of the quantum Stoner-Wohlfarth model was studied and it was found that a sharp change of the distribution occurs after the SW point with a delay which persist in the large S [12]. If we sweep the external field very slowly, the system exhibits the adiabatic motion. In order to realize the adiabatic state in a finite time, the method of shortcuts to adiabaticity using the counter-diabatic field has been proposed. But it generally has a complicated form. We proposed the use of an approximated counter-diabatic field and demonstrated that it practically works well to create the cat state in a Bose-Einstain condensate [13, 21, 50, 14, 22, 51]. We also studied relaxation phenomena to a metastable state (the pre-thermalized state) due to the entanglement of the state. We found the prethermalization takes place in the 1D Bose gas with a large number of spins (10000) [15]. We studied how the synergetic effect of spin-orbit coupling (SOC) and Zeeman splitting (ZS) affects the optical conductivity in the one-dimensional Hubbard model using the Kubo formula[5]: the dependences of resonance (EDSR) in the metallic regime and the optical conductivity in the Mott-insulating phase on the relative angle between the SOC vector and the magnetic field direction. The effect of U was also studied. We studied a mechanism of a sub-gap optical conductivity through virtual hopping of the electron. Motivated by recent terahertz absorption measurements in α-RuCl3, we developed a theory for the electromagnetic absorption of materials described by the Kitaev model on the honeycomb lattice using the formulation in terms of Majorana fermions [35, 56]. These lase two topics were studied in collaboration with Katsura and Ogata groups. We also studied properties of induced effective spin due to inhomogeneous structures in one dimensional spin chains. e.g. the AKLT model and the alternate-bond antiferromagnetic Heisenberg model. We found the two scales of length, i.e., that of magnetization profile and that of structure of the matrix product wavefunction for the state [47]. The real time diffusion dynamics of a particle under the Berry curvature was also studied in the collaboration of Nagaosa group [16].

Phase transitions and critical phenomena are also important subjects of our group. We have studied dynamics of first order phase transition in systems with multiple order parameters [19, 36]. We also found a specific phase diagram with a horn structure in spin-crossover systems exhibiting an internal temperature phase[2]. We also studied the dynamis of transition in 3D [3]. Moreover we study dynamics of transitions after photo-irradiation and analyzed the so-called elastic expansion before the thermal one [4]. We have involved in the Elements Strategy Initiative Center for Magnetic Materials (ESCICMM) under the outsourcing project of MEXT. We have studied microscopic mechanisms of the coercive force of permanent magnets at finite temperatures [6, 7]. We have studied magnetic properties of $Nd_2Fe_{14}B$ in a realistic atomic scale at finite temperatures. For the purpose, we developed numerical methods such as Monte Carlo (MC) methods for the free energy landscape by making use of the Wang-Landau method, with which temerature dependence of the coercive force was obtained [38]. In parmanent magnets, the dipole-dipole interaction plays important roles. To perform MC simulation, we developed a new algorithm extending the idea of the stochastic cutoff method and the Fukui-Todo $O(N)$ method, and found that the anisotropy of the Fe atom which has been considered to be weak has an important role to maintain coercivity at relaviely high temperatures [8]. We also studied peculiar properties of the ferromagnetic resonance of the $Nd_2Fe_{14}B$ magnet which has a tilted magnetization from the c axis at low temperatures by making use of the LLG method [44].

9 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Hiroyasu Matsuura

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

- High-T_c superconductivity
  Flux states as a symmetry-breaking state in high-T_c superconductivity.
- Dirac electron systems in solids
  Quantum electrodynamics (QED) in solids: Dielectricity and diamagnetism.[1,3]
  Nuclear spin relaxation time of the orbital currents in Dirac electron systems.[2,3]
  Twin Dirac points realized in a antiperovskite material.[4]
- Orbital magnetism
  General theory of orbital magnetism of Bloch electrons.[5]
  Corrections to the Peierls phase in the tight-binding model.
- Theories on topological materials
  Magnon spin-momentum locking.[6]
  Z_2 index and Dirac nodal line material.[7]

Magnon spin current and spin-Seebeck effect in a topological-insulator/ferromagnet interface.[8]

- Organic conductors

  Energy landscape in charge excitations.[9]

  Electron correlation in α-$(ET)_2I_3$.

- Spin systems and spin-orbit interaction

  New spin-liquid states due to the attractive interaction between magnetic monopoles.[10]

  Dynamics of a chiral soliton lattice under a constant current.[11]

  Spin Seebeck effects in a quantum wire.[12]

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10 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 basic problems in condensed matter physics, especially focusing on prediction of material properties under extreme conditions like ultra-high pressure or at surfaces where experimental data are limited. Our principal tool is molecular dynamics (MD) and first-principles electronic structure calculation based on the density functional theory (DFT), while we are also developing new methods that go beyond the limitation of classical MD and DFT for the study of electronic, structural and dynamical properties of materials.

In FY2017, we theoretically investigated crystal structure and superconductivity in H_xs under ultra-high pressure, lattice thermal conductivity of a clathrate $Ba_8Ga_{16}Ge_{30}$ (BGG) and layered nitrides AMN_2 (A =Sr, Ba; M =Ti, Zr, Hf), photo-induced non-thermal processes by ultra-short-pulse laser, and optical trapping of excitons in graphane. We also developed various methods of materials simulations from first principles: data assimilation for crystal structure prediction, a stochastic formalism for sampling thermally distribution for rare events, neural-network Kohn-Sham potential, and so on.

Our research subjects in FY2017 are as follows:

- High-pressure phases of H_xS and their superconductivity
- Superconductivity of BiS_2
- Interference of the Bloch phase in layered materials
- Quartic anharmonic effect on the lattice thermal conductivity of clathrates
- Lattice thermal conductivity of layered nitrides
- Entropy-driven mechanism for non-thermal ablation of metals
- Stability change of Fe-Al alloys by laser irradiation
- Optical trapping of excitons in graphane
- Data assimilation for crystal structure prediction
- Stochastic sampling method for rare events
- Neural-network Kohn-Sham potential
- Generalized gradient approximation for nuclear matter

11 Todo Group

Research Subjects: Novel state and critical phenomena in strongly correlated systems, Novel non-equilibrium or non-steady states, Development of new simulation algorithms, Open-source software for next-generation parallel simulations

Member: Synge Todo, Tsuyoshi Okubo, and Hidemaro Suwa

We study novel phases and critical phenomena in strongly correlated many-body systems, such as classical/quantum magnets and Bose-Hubbard model, by using the state-of-the-art computational physics techniques like the Monte Carlo methods. We also develop new computational algorithms for quantum many-body systems, such as the tensor-network algorithms, study the parallelization technique for supercomputers, and develop open-source software for next-generation parallel simulations.

Novel state and critical phenomena in strongly correlated systems: Ground state of Kitaev materials, Ground state of Handane chain with single-ion anisotropy, Critical decay exponents of long-range interacting spin system, Effective dimension of the random-field Ising model with correlated randomness, Topological order parameter for two-dimensional SPT phase.

Novel non-equilibrium or non-steady states: Dynamical cooperative phenomena in in cavity system, Nonergodicity of classical harmonic oscillator system.

Development of new simulation algorithms: Crystal structure prediction by combined optimization of experimental data and first-principles calculation, Markov chain Monte Carlo method with transition matrix depending on physical quantity, Tensor network renormalization for non-uniform systems, Parallel processing for deep learning, Path-integral Monte Carlo method in continuous space.

Open-source software for next-generation parallel simulations

We are developing various open-source software packages: ALPS: simulation software package for quantum lattice models, ALPSCore: next-generation of ALPS core library, ALPS/looper: loop algorithm quantum Monte Carlo method, BCL: Monte Carlo algorithm without detailed balance, Cluster-MC: cluster algorithm Monte Carlo method, HΦ: parallel Exact diagonalization package, Kω: linear algebra based on shifted Krylov subspace method, MateriApps: portal of materials science simulation, MateriApps installer: collection of install scripts of MateriApps applications, MateriApps LIVE!: Live USB Linux system for materials science simulations, Rokko: parallel exact diagonalization package, standards: standard algorithm library for computational science, worms: worm algorithm quantum Monte Carlo method, etc.

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12 Katsura Group

Research Subjects: Condensed Matter Theory and Statistical Physics

Member: Hosho Katsura and Yutaka Akagi

In our group, we study various aspects of condensed matter and statistical physics. In particular, our research focuses on strongly correlated many-body systems which would give rise to a variety of quantum phases. We study theoretically such systems, with the aim of predicting novel quantum phenomena that have no counterpart in weakly-interacting systems. We are currently interested in (i) topological phases of matter, (ii) low-dimensional correlated electron systems, and (iii) entanglement in quantum spin chains. In addition, we are also interested in the mathematical aspects of the above mentioned fields. Our research projects conducted in FY 2017 are the following:

- Strongly correlated systems
  - Optical conductivity in the one-dimensional Hubbard model with spin-orbit coupling [1]
  - Subgap optical conductivity in honeycomb Kitaev materials [2]
  - Ground-state phase diagram of quantum dimer-trimer chain [3]
  - Ground-state energies of spinless free fermions and hard-core bosons [4]
- Topological phases of matter
  - Zero modes in a Kitaev chain with twisted boundary conditions [5]
  - Topological invariants for disordered topological insulators [6, 7]
- Solvable models and field theories
  - Volume-law entanglement in deformed Fredkin spin chain [8, 9]
  - Sine-square deformation of conformal field theories [10]

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13 Fujimori Group

Research Subjects: Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Goro Shibata

We study the electronic structure of superconductors and spintronics materials by high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy (ARPES) and soft x-ray magnetic circular dichroism (XMCD) using synchrotron radiation. We investigate the mechanisms of high-temperature superconductivity, metal-insulator transitions, giant magnetoresistance, and magnetic anisotropies in transition-metal oxides [1], ferromagnetic alloys [2,3], and their thin films and interfaces.

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14 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA, Akari TAKAYAMA, and Ryota AKIYAMA

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

(1) Surface electronic/spin transports:

- Interface superconductivity at topological crystalline insulator/trivial semimetal junction
- Ferromagnetism and anomalous Hall effect at interface between topological insulator and ferromagnetic insulator
- Bose metal behavior at monolayer FeSe superconductor
- 2D superconductivity at monolayer alloy metallic surface superstructures
- 2D superconductivity by proximity effect
- Spin injection by circularly polarized light irradiation on topological insulators
- Electrical transport at Graphene
- Electrical transport of organic molecule sheets measured by four-tip STM
- CDW and transport at transition metal dichalcogenides

(2) Surface phases and atomic-layer materials:

- Proximity effect at a interface between a topological crystalline insulator and a ferromagnetic metal
- Epitaxial growth of blue Phosphor atomic layers
- Structure analysis of Ca-intercalated bilayer graphene by positron diffraction

(3) New methods:

- Fabrication of UHV-SQUID system to detect Meissner effect of atomic-layer superconductors
- Fabrication of a pure-spin-current injection probe

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15 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

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

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

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

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

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

   Graphene had been attracting considerable attention owing to its remarkable electronic and structural properties, and its possible applications in many emerging fields such as graphene-based electronic devices. One of the important topics to study in graphene research is the spin polarized state expected at zigzag edges of graphene nanoribbon (GNR). It is well known that there are two types of edges in graphene, i.e. zigzag and armchair types. At the edge of zigzag structure, electrons are strongly localized along the edge to form a zigzag edge state (zz-ES). We had confirmed the state experimentally by STM/S at a monatomic step edge of graphite. In addition, it is expected that the spin degeneracy would be lifted and ferromagnetically spin polarized edge state appears under an electron-electron interaction. The ferromagnetic edge state is considered to stabilize in a GNR between two zigzag edges (z-GNR) through anti-ferromagnetic coupling between edges.

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

16 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.

   It is well known that external magnetic fields and magnetic moments of impurities both suppress superconductivity. However, their combined effect on superconductivity has not been elucidated yet. We have studied the superconducting transition in ultrathin Pb films with magnetic impurities grown on a cleaved GaAs(110) surface. It was demonstrated that the transition temperature can be enhanced by external magnetic fields applied parallel to the conducting plane. Furthermore, we found that a Pb-Ce alloy, where superconductivity is totally suppressed at zero-field, actually become superconducting in parallel magnetic fields. These phenomena were explained in terms of the suppression of the spin-exchange scattering rate, which can be controlled by the magnetic field.

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

17 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Naotaka Yoshikawa

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

1. **Photoexcited high density electron-hole system in semiconductor:** We have investigated the exciton-exciton interactions in a bulk GaAs in the high density and low temperature regime where the phase space density of excitons far exceeds unity. A large blueshift is observed after the resonant excitation of lowest 1s excitons, suggesting the realization of ultracold exciton gas. The dynamics of

the energy shift is investigated by the pump-probe spectroscopy with taking into account the spin relaxation dynamics of excitons, electrons, and holes. Ultrafast dynamics of high density coherent excitons and it's relation to the photon-dressed state of excitons is also investigated in the density range of exciton Mott transition.

2. **Observation of Higgs mode in d-wave high temperature superconductors:** We have investigated the collective amplitude mode of superconducting order parameter, namely the Higgs mode, in d-wave superconductors $Bi_2Sr_2CaCuO_{8+x}$ by terahertz(THz) pump-optical probe spectroscopy. During the irradiation of the monocycle THz pulse, an oscillatory signal that follows the squared waveform of the pump THz pulse is observed in the time-resolved reflection of the near-infrared probe pulse. The signal is prominently enhanced below the critical temperature of superconductivity. The polarization dependence of the pump and probe pulse shows that the oscillatory signal is dominated by the isotropic A_{1g} component irrespective of hole doping. A theoretical model is developed to describe the third order nonlinear susceptibility which is relevant to the terahertz(THz) pump-optical probe signal with taking into account the contributions from density fluctuation term and the Higgs term. From the comparison between the experiments and the theory, we concluded that the observed A_{1g}-dominant oscillatory signal is originated from the Higgs mode.

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18 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 FY2017 included, 5d complex Ir oxides with interplay of electron correlations and strong spin orbit coupling, spin liquids, anti-perovskites with Dirac electrons with excitonic ground states. Especially, our discovery for two-dimensional honeycomb spin liquid was pressreleased by University in this February.

Realization of new spin liquid and Kitaev physics:

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

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\mathrm{eff}} = 1/2$ quantum pseudo 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 exactly 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 pursue identification of elementary excitations in $H_3LiIr_2O_6$ this year. We preliminary succeeded in fabricating a single crystal of this compounds, which should open a way to investigate a pristine thermally/artificially activated Majorana excitations or local excitations near an implanted defects, which can be evaluated rigorously for KHM. We expect that the latter effects can be caught by our NMR spectroscopy technique.

Three-dimensional Dirac electron systems:

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

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

19 Hayashi Group

Research Subjects: Spin orbit effects in thin film heterostructures

Member: Masamitsu Hayashi, Masashi Kawaguchi

We have studied the physics of spin orbit effects that derive from the strong spin orbit interaction of materials and interfaces in thin film heterostructures. Our focuses are spin transport, magnetism and optical response of atomically engineered heterostructures. Currently we put a strong effort on studies related to generation of spin current via current-spin, heat-spin and light-spin conversion effects, and optical control of electron spins. Results of the following projects were published in FY 2017.

- Spin current generation
  - Observation of the spin Nernst effect in a heavy metal (tungsten)[1]
  - Evaluation of spin orbit torque using spin Hall magentoresistance and the harmonic Hall voltage measurements[2]
  - Simulations of spin orbit torques in magnetic multilayers[3]
- Magneto-optics
  - Enhancement of the magneto-optical Kerr effect using optical interference[4]

[1] P. Sheng, Y. Sakuraba, Y.-C. Lau, S. Takahashi, S. Mitani, M. Hayashi, The spin Nernst effect in tungsten, Science Advances 3, e1701503 (2017).

[2] Y.-C. Lau, M. Hayashi, Spin torque efficiency of Ta, W, and Pt in metallic bilayers evaluated by harmonic Hall and spin Hall magnetoresistance measurements. Jpn. J. Appl. Phys. 56, 0802B5 (2017).

[3] C. Abert, H. Sepehri-Amin, F. Bruckner, C. Vogler, M. Hayashi, D. Suess, Fieldlike and Dampinglike Spin-Transfer Torque in Magnetic Multilayers. Phys. Rev. Appl. 7, 054007 (2017).

[4] S. Sumi, H. Awano, M. Hayashi, Interference induced enhancement of magneto-optical Kerr effect in ultrathin magnetic films. Scientific Reports 8, 776 (2018).

20 Theoretical Astrophysics Group

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

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

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

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

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

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

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

2017

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

2016

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

2015

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

2014

- Stacking image analysis of SDSS galaxies in far-infrared and its implications for the Galactic extinction map
- Probing Cosmic Dark Matter and Dark Energy with Weak Gravitational Lensing Statistics
- Statistics of Submillimeter Line Emitters in Cosmological Simulation
- Characterization of a planetary system PTFO 8-8695 from the variability of its transit lightcurve induced by the nodal precession
- Neutrino-heating mechanism of core-collapse supernovae explosions
- Formation of Super-Massive Stars and Super-Massive Black Holes in the Early Universe

2013

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

2012

- Exploring the Landscape of Habitable Exoplanets via Their Disk-integrated Colors and Spectra: Indications for Future Direct Imaging Observations
- Toward a precise measurement of weak lensing signals through CMB experiments and galaxy imaging surveys: A theoretical development and its cosmological implications
- Measurements of Spin-Orbit Angles for Transiting Systems:Toward an Understanding of the Migration History of Exoplanets
- Modeling Redshift-Space Clustering of the SDSS Luminous Red Galaxies with Cosmological N-body Simulations: Implications for a Test of Gravity
- Probing the nature of dark matter by gravitational lensing observations
- The Formation and Evolution of Hot-Jupiter:Planet-Planet Scattering Followed by Tidal Dissipation
- Supernova Explosions in the Early Universe
- Validity of Hydrostatic Equilibrium in Mass Estimates of Simulated Galaxy Clusters

21 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Akihito Soeda

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

This year, our group consisted of two faculty members, Mio Murao (Professor), Akihito Soeda (Assistant Professor), one postdoctoral researcher–Marco Túlio Coelho Quintino (JSPS foreign postdoctoral fellow), and 6 graduate students–Atsushi Shimbo (D3), Ryosuke Sakai (D2), Hayata Yamasaki (D2), Qingxiuxiong Dong (M2), Paula Belzig (USTEP graduate student from University of Cologne), and Tian-Jiao Yin (research student). Our projects worked in the academic year of 2017 were the following:

- Higher-order quantum operations
  - Equivalence determination of unitary operations by A. Shimbo, A. Soeda, and M. Murao
  - Universal quantum algorithm to invert a blackboxed unitary opertation by M.T. Coelho Quintino
  - Higher-order quantum operations based on amplitude amplification by A. Soeda and M. Murao with S. Shojun at National Institute of Informatics
- Quantum information processing on hybridized quantum systems–Robust control of two-qubit quantum gates on Hamiltonian-driven systems by R. Sakai, A. Soeda, and M. Murao with D. Burgarth at Aberystwyth University
- Distributed quantum information processing and entanglement
  - Necessary amount of quantum communication for distributed encoding and decoding of quantum information by H. Yamasaki and M. Murao

  - Distributed generation of multipartite entangled state with restricted quantum memories by H. Yamasaki and M. Murao with B. Kraus and A. Pirker at the University of Innsbruck

- Foundations on quantum mechanics
  - Quantum maps implementable when multiple copies of the input state are available by Q. Dong, A. Soeda, and M. Murao
  - Quantum nonlocality with sequential measurements beyond local pre-processing by P. Belzig, M.T. Coelho Quintino, and M. Murao
  - Genuine triplewise measurement incompatibility by M.T. Quintino with D. Cavalcanti at The Institute of Photonic Sciences (ICFO) and A. Cabello at Universidad de Sevilla

- Information theoretic analysis of multipartite quantum states
  - Markovianity of stationary states in one-dimensional open quantum systems by K. Kato with B. Sahinoglu and F. Brandao at California Institute of Technology
  - Analysis based on matrix product operations for entanglement in two-dimensional systems by K. Kato
  - Entropic order parameter of topological by K. Kato with P. Naaijkens at Aachen University

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

22 Ueda Group

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

Member: Masahito Ueda and Shunsuke Furukawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controllable systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose-Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied topological excitations and coarsening dynamics in spinor BECs, non-unitary dynamics in driven-dissipative systems, Efimov physics and impurity problems under the control of an atomic interaction strength, (quantum) Hall effect in synthetic gauge fields, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems and the formulations of state reduction dynamics and Hamiltonian estimation in light of information flow under measurements and feedback controls. We list our main research subjects in FY2017 below.

- Quantum many-body phenomena in ultracold atoms
  - Zeno Hall effect [1]
  - Quantum critical phenomena in parity-time-symmetric systems [2, 3]
  - Universality of an impurity in a Bose-Einstein condensate [4]

- Many-body interferometry of magnetic polaron dynamics [5]
- Universal coarsening dynamics of a one-dimensional spinor Bose gas [6]
- Topological influence between topological excitations [7]
- Phase diagram of ferromagnetic spin-1 bosons in optical lattices [8]

- Quantum Information, quantum measurement, and foundation of statistical mechanics
  - Discrete time-crystalline order in cavity and circuit QED systems [9]
  - Atypicality of most few-body observables [10]
  - Finite-error metrological bounds on multiparameter Hamiltonian estimation [11]

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[3] K. Kawabata, Y. Ashida, and M. Ueda, Phys. Rev. Lett. **119**, 190401 (2017).
[4] S. M. Yoshida, S. Endo, J. Levinsen, and M. M. Parish, Phys. Rev. X **8**, 011024 (2018).
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[9] Z. Gong, R. Hamazaki, and M. Ueda, Phys. Rev. Lett. **120**, 040404 (2018).
[10] R. Hamazaki and M. Ueda, Phys. Rev. Lett. **120**, 080603 (2018).
[11] N. Kura and M. Ueda, Phys. Rev. A **97**, 010201 (2018).

23 Yokoyama(J) Group

Research Subjects: Theoretical Cosmology and Gravitation

Members: Jun'ichi Yokoyama and Teruaki Suyama

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We have also been working on gravitational wave data analysis to prepare for completion of KAGRA, which is now succeeded by the newly established gravitational wave data analysis section led by Professor Kipp Cannon at RESCEU in 2016. Below is the list of topics studied during the academic year 2017.

Cosmology of the early universe

- Higgs-R^2 inflation
- Anisotropic expansion in generalized G-inflation
- Spontaneous baryo and dark matter genesis after G-inflation
- Generalized second law of thermodynamics in stochastic inflation
- New physical renormalization scheme in QFT in curved space
- Negative electric conductivity in de Sitter space and its implication
- Simulation of axion electrodynamics
- Self heating of partial pair-annihilation of dark matter particles

Observational cosmology

- Observability of primordial nonGaussianity of tensor perturbation through B-mode polarization of CMB
- Modulation in CMB power spectrum
- Constraints on small-scale perturbation from dark matter minihalos
- angular correlation of 21cm line from minihalos

Gravitation

- Mass-radius relation of neutron stars in massive scalar-tensor theory
- Invertible transformation and degrees of freedom
- Stable black hole solution in shift symmetric Horndesky theory
- Mimetic gravity and cosmological perturbation
- Thermodynamic property of teleparallel gravity

Gravitational waves

- Stochastic gravitational waves from cosmic string loops
- Examining primordial black hole hypothesis of LIGO events

24 Takase Group

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

Member: Yuichi Takase, Akira Ejiri, Naoto Tsujii

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

Our present focus on TST-2 is the establishment of plasma current ramp-up method using lower-hybrid waves (LHW). Since FY2013, we have performed experiments using the capacitively-coupled combline (CCC) antenna. In FY2017, we investigated the difference of the current drive properties between the outboard-launch and top-launch antennas. The highest plasma current achieved with the present limiter configuration was 21, 26, 27 kA for the outboard-launch, top-launch, and reversed field top-launch scenarios, respectively. The reversed field top-launch scenario is equivalent to bottom-launch in forward-field.

Numerical simulation was able to explain the difference between the above three current drive scenarios qualitatively. The top-launch antenna excites waves at high phase-velocity and the generated fast electrons are more energetic compared to the outboard-launch antenna. In the bottom-launch (reversed-field top-launch) case, the phase-velocity increases initially, which results in even more energetic fast electrons.

Accurate antenna modeling is important for a quantitative prediction of lower-hybrid current drive. COMSOL (www.comsol.com) was used to model the outboard-launch and top-launch antennas in 3D. According to the simulation, it was found that the coupling was optimum in terms of the power flow and the wavenumber spectrum when the evanescent gap was 17–27 mm. Since COMSOL calculation needs to be performed on a single workstation with the present license, a 3D model based on open source libraries was developed. Problems with mesh size ten times larger than previously possible were successfully solved on a supercomputer.

Integrated lower-hybrid current drive and MHD simulation has been developed on TST-2. Converged solution could be obtained in some cases. The present current drive simulation without MHD physics substantially overpredicts the experimentally observed plasma current. By solving the lower-hybrid current drive and MHD equilibrium self-consistently, it was found that the prediction approaches the experimental value.

Measurement of plasma diamagnetism was performed. It was found that the Ohmic plasma was paramagnetic, consistently with the result of the equilibrium reconstruction.

AC Ohmic heating is a method for pre-ionization, heating and current drive of a plasma by applying ~1 kHz voltage on the Ohmic coil. A 1D model has been developed to explain the pre-ionization process. Inclusion of ExB drift and AC electric field was found to improve the agreement between the model and the experimental observation. Secondary electron emission was found to be small at the experimental condition.

Possibility of using baffle-cones for stray-light reduction was investigated for the Thomson scattering diagnostic. Cones with aperture sizes of 6, 8, 10 and 15 mm were fabricated and tested, but no improvement was observed. Microwave imaging reflectometer (MIR) is being developed in collaboration with NIFS. The diagnostic components and the data acquisition system were tested.

As a collaboration, Thomson scattering on QUEST is being developed. Thomson scattering measurement was performed for an ECH driven discharge. During the initial phase which had both 8.2 GHz and 28 GHz ECH, the electron temperature was high and the density was low. On the other hand, later in the discharge when only 28 GHz ECH was applied, the electron temperature was low and the density was high. Spectroscopy was performed on LATE plasmas. Inversion of the line-integrated measurement showed that the emission of CV, OV peaked at around the magnetic axis. Soft X-ray imaging diagnostics were developed in collaboration with PPPL. The dimension of the diagnostic was optimized by simulating the X-ray radiation with the target experimental condition of DIII-D. It was found that, with Ar injection, 0.5 cm spatial resolution and 2 ms time resolution could be achieved at the pedestal region. Similar optimization was performed for MST.

25 Sano Group

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

Member: Masaki Sano and Tetsuya Hiraiwa

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

1. Statistical mechanics out of equilibrium
   (1) Absorbing state phase transition and laminar-turbulent transition
   (2) Non-equilibrium phenomena in electroconvection of liquid crystals [3]
2. Active matters
   (1) Theory on active softmatter [5]
   (2) Collective motion of self-driven colloidal particles [7]
   (3) Collective motion of filamentous proteins
3. Biological systems
   (1) Traction force of collectively migrating neural stem cells
   (2) Theory on mechanics of cellular dynamics and morphogenesis [4]

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[5] T. Ohta: Dynamics of deformable active particles, J. Phys. Soc. Jpn, **86**, 072001 (2017).

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26 Yamamoto Group

Research Subjects: Submillimeter-wave and Terahertz Astronomy, Star and Planet Formation, Chemical Evolution of Interstellar Molecular Clouds, Development of Terahertz Detectors

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 a astrochemical viewpoint.

Since the temperature of a molecular cloud is as low as 10 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. In particular, there exist a number of atomic and molecular lines in the millimeter to terahertz region, and we are observing them with various large radio telescopes including ALMA.

We are conducting a line survey of low-mass star forming regions with Nobeyama 45 m telescope and ASTE 10 m telescope, aiming at detailed understandings of chemical evolution from protostellar disks to protoplanetary disks. In the course of this effort, we have recently established a new chemistry occurring in the vicinity of a newly born star, which is called Warm Carbon Chain Chemistry (WCCC). In WCCC, carbon-chain molecules are produced by gas phase reactions of CH_4 which is evaporated from ice mantles. The discovery of WCCC clearly indicates a chemical diversity of low-mass star forming regions, because only hot corino chemistry, which are rich in unsaturated carbon-chain molecules and deficient in carbon-chain molecules, have so far been recognized. The chemical diversity would reflect the star formation history of each source.

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 the 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. Further studies with ALMA are in progress.

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooled HEB mixer using NbTiN and NbN in our laboratory. Our NbTiN mixer shows the noise temperature of 470 K at 1.5 THz, which corresponds 7 times the quantum noise. This is the best performance at 1.5 THz in spite of the use of the wave-guide mount. The 0.8/1.5 THz dual-band HEB mixer receiver was assembled, and was installed on the ASTE 10 m telescope for astronomical observations. We successfully observed the Orion A molecular cloud in the ^{13}CO $J = 8 - 7$ line emission. This receiver is now used for laboratory spectroscopy of interstellar molecules at RIKEN.

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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)Orientation dependence in multichannel dissociative ionization of OCS molecules [1]

With 800-nm, 25-fs elliptically polarized ionization pulses, we observe molecular frame photoelectron angular distributions (MF-PADs) correlated with different dissociative ionization channels: $OCS^+ \rightarrow S^+$+CO, CO^++S, CS^++O, and O^++CS. We find that the asymmetry in the MF-PAD depends on the specific dissociation channel and the laser intensities. For the dissociation channel leading to the production of O^+, the OCS molecules are more likely to be ionized when the electric field points toward the O atom, while for other dissociation channels, they are more likely to be ionized when the electric field points toward the S atom.

(2) Ar 3*p* photoelectron sideband spectra in two-color XUV + NIR laser fields [2]

We performed photoelectron spectroscopy using femtosecond XUV pulses from a free-electron laser and femtosecond near-infrared pulses from a synchronized laser, and succeeded in measuring Ar 3*p* photoelectron sideband spectra due to the two-color above-threshold ionization. In our calculations of the first-order time-dependent perturbation theoretical model based on the strong field approximation, the photoelectron sideband spectra and their angular distributions are well reproduced by considering the timing jitter between the XUV and the NIR pulses, showing that the timing jitter in our experiments was distributed over the width of $1.0^{-0.2}_{+0.4}$ ps. The present approach can be used as a method to evaluate the timing jitter inevitable in FEL experiments.

This work was done as a collaborative study with researchers from KEK, Kyoto University, Institute of Solid State Physics (The University of Tokyo), Japan Synchrotron Radiation Research Institute, and RIKEN SPring-8 Center.

[1] Yusuke Sakemi, Shinichirou Minemoto, and Hirofumi Sakai, "Orientation dependence in multichannel dissociative ionization of OCS molecules," Phys. Rev. A **96**, 011401(R) (2017) (6 pages).

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28 Gonokami, Yumoto and Ideguchi Group

Research Subjects: Experimental studies on many-body quantum physics by light-matter interaction, Optical phenomena in artificial nanostructures, Development of laser based coherent light source

Member: Makoto Gonokami, Junji Yumoto and Takuro Ideguchi

We are trying to explore new aspects of many-body quantum systems and their exotic quantum optical effects through designed light-matter interactions. Our current target consists of a wide variety of matter, including excitons and electron-hole ensemble in semiconductors, antiferromagnetic materials and ultracold atomic gases. In particular, we have been investigating the Bose-Einstein condensation phase of excitons, which is considered as the ground state of an electron-hole ensemble but as yet not proven experimentally. Based on quantitative spectroscopic measurements, the temperature and density are determined for an exciton gas in a quasi-equilibrium condition trapped inside a high purity crystal kept below 1 K. We are now investigating a stable and quantum degenerate state of dark exciton gas at such very low temperatures. We also investigate novel optical and terahertz-wave responses for some artificial nanostructures obtained by advanced micro-fabrication technologies. A project was started to develop new coherent light sources; covering a broad frequency range from terahertz to soft X-rays. Specifically, in collaboration with RIKEN, the Foundation for Coherent Photon Science Research was established. This is one of the Advanced Research Foundation initiatives from the Ministry of Education, Culture, Sports, Science and Technology. Within this initiative, we are developing intense and stable coherent light sources at a high repetition rate (That facility is named "Photon Ring").

This year the following activities were done:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   - 1.1. Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   - 1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases and their application to nuclear physics
2. The quest for non-trivial optical responses and development of applications:
   - 2.1. Fabrication of Moth-Eye THz Anti-Reflection Structures by Femtosecond Laser Processing
   - 2.2. Generating Intense Terahertz Pulses with Longitudinal Electric fields
   - 2.3. Fabrication of quasi-metallic three-dimensional structures with 3D printing and supercritical fluid deposition
   - 2.4. Observation of optically induced multiferroicity
   - 2.5. Therotetical investigation of process of higher harmonic generation of solids
3. Development of novel coherent light sources and spectroscopic methods:
   - 3.1. VUV precision spectroscopy using higher-order harmonics
   - 3.2. Laser-based angle resolved photoemission spectroscopy
   - 3.3. Label-free microscope using coherent Raman spectroscopy
   - 3.4. "Photon ring" project
   - 3.5. Institute for Photon Science Technology

29 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Yuta Michimura

In February 2016, the LIGO gravitational-wave observatory announced detection of a gravitational-wave signal. The new field of gravitational-wave astoronomy was opend. 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 (former LCGT). The detector is now under construction in KAMIOKA. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200Mpc. 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
  - Construction and test observation run
  - Optical design of the interferometer
- Space laser interferometer, DECIGO
- Development of TOBA (Torsion Bar Antenna)
  - A new type sensor for TOBA
  - Design and development of the next generation TOBA
- Development of the ultra stable laser source using cryogenic cavity
- 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-Nakazawa Group

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

Member: Associate Prof: Aya Bamba, Lecturer: Kazuhiro Nakazawa

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

For further better observations, we also developed a new generation X-ray satellites. Hitomi, the Japanese 6th X-ray satellite, was successfully launched on 17 Feb. Its initial observation was performed before the incident on 26 March leading to the loss of the satellite. Although the life-time as an observatory was only $\sim$ 1 month, we made a lot of scientific achievement with more than 10 refereed papers. Now the recovery mission of Hitomi, XARM, is planned, and it is aimed to launch on fiscal year of $\sim$2021. We also work on more future development, the FORCE mission.

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

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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 just concluded its observation campaign, and Simons Array experiment is about to be deployed. Our focus is on data analysis as well as the development and characterization of the continuously-rotating half-wave plate (HWP) enabling accurate measurement of CMB polarization.

- Simons Observatory experiment is planned for the first light in a few years. We plan to deploy an array of what we call "small aperture cameras," which are dedicated for the inflationary signal, and a six-meter "large aperture telescope," which enables observation for Neutrinos and the dark content of the universe. We are primarily focusing on the design and development for the small aperture camera.
- Research and Development for the next generation experiments such as Simons Observatory and CMB-S4 are crucial component of our research program. We specifically work on superconducting technologies used in the detectors and cryogenic bearing system for HWP. We also develop techniques for high-performance computation (HPC) enabling data analysis for new experiments producing order-of-magnitude larger data volume than the current instruments.

32 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose and Hiroshi Kohsaka

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

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

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

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

Rhythmic animal behaviors are regulated in part by neural circuits called the central pattern generators (CPGs). Classifying neural activities correlated with body movements and identifying component neurons associated with the activities are critical steps in understanding the workings of CPGs and animal locomotion. Here, we present a novel method for classifying motor activities in large-scale calcium imaging data of Drosophila larvae. The method is based on pre-trained convolutional neural network model VGG-16 and unsupervised learning, and successfully classified activities correlated with forward and backward locomotion in activity data of different types of neurons and under different imaging conditions. By applying these methods to neurons targeted by 5-HT2A-Gal4, we identified two classes of interneurons, termed Seta and

Leta, which are specifically active during backward but not forward fictive locomotion. Several behavior assays suggest that 5-HT modulates backward locomotion by acting on Seta and Leta neurons via the 5-HT2A receptor. This study establishes an accelerated pipeline for activity profiling and cell identification in larval Drosophila and implicates a serotonergic system in the modulation of backward locomotion. (Collaboration with Dr. Shu Kondo at NIG and Dr. Hiromu Tanimoto at Tohoku university)

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33 Higuchi Group

Research Subjects: Motor proteins in in vitro, cells and mice

Member: Hideo Higuchi and Motoshi Kaya

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

ATP-dependent step size and microtubule-binding time of single-headed dynein

Cytoplasmic dynein is a molecular motor moving toward the minus end of microtubules. From the strutural studies, the swing of the linker, called as the power stroke, is supposed to be cruicial to walk processively. However, there is no direct evidence of the distance generated by the power stroke in the presence of ATP. Here, we investigated the displacement of microtubules driven by the power stroke of single-headed dynein at the varied ATP concentration using optical tweezers. The displacement dynein drived microtubules sigmoidally decreased from 8 to 0 nm as ATP concentration decreased. To verify the relationship between the displacement and the linker swing, we also measured the ATP dependent FRET efficiency of dynein, in which BFP was fused in AAA2 domain and GFP was fused at the N-terminal of the linker, in the absence of microtubule. Altogether, we proposed that the population of dynein binding to microtubules at pre/apo state decreased/increased as ATP concentration decreased and that the power stroke size was determined to be 8.3 nm. To determine the mechanochemical rates of dynein-microtubule complex, we analyzed the microtubule-binding time. The binding time increased moderately as ATP concentration decreased. The rate constants was calculated by fitting the distributions of binding time globally to the reaction model. The transition rate of dynein-microtubule complex from pre to apo state was 12 s^{-1}, which was close to the maximum ATPase rate. The dissociation rate of dynein from microtubule was relatively fast (8 s^{-1}) at apo-state, indicating that dynein dominantly dissociated from microtubule without binding to ATP at the low ATP concentration. Our new findings of step size and rate constants would be crucial for understanding the molecular mechanism of dimeric dynein.

Understanding the precise movement of vesicle on cytoskeleton in living cancer cell

A live cell maintains its intracellular homeostasis mainly through engulfing the extracellular molecules, which is called endocytosis. The molecules taken inside the cell form a vesicle, and it is known to be delivered from the cell periphery to the centrosome, which is located near the nucleus. The process of this delivery is referred to the cellular transport, and the mechanism of cellular transport is widely studied in the field of biophysics, since it is considered to include key information about the drug delivery. In fact, thanks to previous researches, now we know that the vesicles internalized into cytoplasmic area is transported by cytoskeletons, such as microtubule and actin filament, recruited by motor proteins. However, the precise movement of the vesicle in a complex network structure of cytoskeletons is not yet fully understood. In this research, we report a characteristic rotational movement of an endocytic vesicle on microtubule network in a live cancer cell. In the experiment, vesicles are labeled with quantum dot and visualized by three-dimensional fluorescence microscopy using dual focus optics, with high spatiotemporal resolution, 3 nm and 100 Hz, respectively. When the trajectory of a vesicle is analyzed via linear regression method based on principal component analysis and vector calculation, it is possible to categorize the type of vesicle movement, active transport and random diffusion. Using this method, the position and orientation of cytoskeleton can be estimated as a linear axis in the active transport section. Interestingly, linear movement section where active transport occurs showed a characteristic rotational movement along the direction of travel, and the angular velocity of the rotation is nonlinear. During the active transport, there were two different stages that the vesicle movement shows steady angular velocity and quick turn. Also, the direction of rotation is either left-handed and right-handed without preference, and the pitch of rotation is broadly distributed from hundreds of nanometers to a few micrometers. Additionally, since the velocity on the active transport is turned to be about 1 micrometer per second, which is similar to the dynein velocity, the probability is high that the rotational movement of a vesicle is based on the microtubule. Using the identical cell line with tubulin-GFP, it is proved that the rotational movement is occurred on the microtubule, via the correlative and simultaneous imaging of microtubule and endocytic vesicle.

Damage of cancer cells evaluated by intensity fluctuation of images under phase contrast microscope

Selective removal of cancer cell without side effects is necessarily for cancer therapy. Phototoxic dyes such as IR700 specifically delivered to cancer cells and the cells were photodamage by reactive oxygen species (ROS). Surviving cancer cells damaged by oxidative stress could obtain resistant to the therapy. Here to understand the effects of phototoxic dyes and detect resistant cancer cells, we developed a method to measure quantitatively cell damages induced by ROS of IR700. We evaluated cell damage by calculating the intensity fluctuation of each pixel in cell images under phase contrast microscopy. We succeeded in quantifying the change in motility of cell organelles by this method. IR700 was labeled with the antibody which binds specifically to target cells. IR700-antibody complex was endocytosed into cultured cells and then cell was photodamaged by illumination of red laser (650 nm). The degree of cell damage was controlled by adjusting the irradiation time of red laser. The motility of cell organelles detected by the intensity fluctuation method decreased gradually with a progression of cell damage. To elucidate the mechanisms of decrease in the organelles motility, we analyzed the effects of photoactivation of IR700 on activities of organelles and motor proteins. Lysosomes containing IR700 in cells were damaged quickly by the photoactivation of IR700 and the contents in lysosomes were diffused out into cytoplasm. The contents diffused from lysosomes caused the dysfunction of transporter kinesin and mitochondria. Therefore, these damages of organelles and motors may be a primary factor for causing decrease of organelles motility. These results suggested that the cell organelles motility is a primary indicator of cell viability.

34 Okada Group

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

Member: Yasushi Okada, Sawako Enoki and Keigo Ikezaki

Proteins, lipids, nucleic acids and other cellular components often form supramolecular complexes, which serve as the functional units in the cell. However, their sizes are around 100 nm and much smaller than the diffraction limited resolution of the optical microscope. Electron microscope has, therefore, been used for their observations, and it has been impossible to observe their dynamics in living cells. Although super-resolution fluorescence microscopy has broken the diffraction barrier of the spatial resolution of optical microscopy, temporal resolution is also essential to observe the dynamic structures in living cells. For example, vesicles in the cells are around 100 nm in diameter and moving at around 1-5 μm/s. Most super-resolution microscope techniques can achieve a spatial resolution better than 100 nm [1, 2], but at the same time require a long image acquisition time, thus blurring the image motion. To avoid this problem, image acquisition should be faster than the velocity of movement. For example, an image should be taken within 10 ms to achieve 100 nm resolution for vesicles moving at 5μm/s.

Among other super-resolution microscope methodologies, structured illumination microscopy (SIM) does not require strong illumination and is suitable for live cell imaging from the viewpoint of photodamage and photobleaching. Furthermore, it is based on wide-field imaging that allows larger field-of-view without sacrificing the image acquisition time. Thus, SIM is relatively faster than other super-resolution microscopies. However, SIM requires 9 to 25 raw images for the reconstruction of a single super-resolution image, so that it takes 100 ms or longer for a single frame of super-resolution image.

To improve the temporal resolution of SIM, we have re-analyzed the theoretical basis of SIM, and noticed that SIM can be implemented with confocal microscope optics, which we named as spinning disk superresolution microscope (SDSRM). Theoretically, the SDSRM is equivalent to a structured illumination microscope (SIM) and achieves a spatial resolution of 120 nm, double that of the diffraction limit of wide-field fluorescence microscopy. However, the SDSRM is 10 times faster than a conventional SIM because super-resolution signals are recovered by optical demodulation through the stripe pattern of the disk. Therefore a single super-resolution image requires only a single averaged image through the rotating disk. On the basis of this theory, we modified a commercial spinning disk confocal microscope. The improved resolution around 120 nm was confirmed with biological samples. The rapid dynamics of micro-tubules, mitochondria, lysosomes, and endosomes were observed with temporal resolutions of 30-100 frames/s. Because our method requires only small optical modifications, it will enable an easy upgrade from an existing spinning disk confocal to a super-resolution microscope for live-cell imaging [3].

These super-resolution imaging technologies were applied to various biological samples, including early mouse embryos [4], axonal transport [5], synapse of retinal photoreceptor cells [6] and genome DNA in nucleus [7].

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35 Furusawa Group

Research Subjects: Theoretical Biophysics, Evolutionary Biology, Complex Systems

Member: Chikara Furusawa and Nen Saito

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

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

The current research topics in our group are followings:

1. Construction of macroscopic state theory describing adaptation and evolution of biological systems
2. Laboratory evolution of bacterial cells to analyze dynamics of phenotype-genotype mappings
3. Dynamical systems modeling of metabolic systems
4. Analysis of amoeba morphogenesis using phase-field models
5. Theoretical analysis for collective motion of molecular motors

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