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Annual Report

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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 2016

1 Theoretical Nuclear Physics Group

Subjects: Structure and reactions of unstable nuclei, Monte Carlo Shell Model, Shell Evolution, Mean Field Calculations, Quantum Chaos, Curved spacetime, QCD phase diagram, Lattice simulation

Member: Takaharu Otsuka, Kenji Fukushima, Takashi Abe and Arata Yamamoto

In the nuclear theory group, a wide variety of subjects are studied. The subjects are divided into two major categories: Nuclear Sturcture Physics and Theoretical Hadron Physics.

Nuclear Structure Physics

In the Nuclear Structure group (T. Otsuka and T. Abe), quantum many-body problems for atomic nuclei, issues on nuclear forces and their combinations are studied theoretically from many angles. The subjects studied include
(i) structure of unstable exotic nuclei, with particular emphasis on the shell evolution,
(ii) shell model calculations including Monte Carlo Shell Model,
(iii) collective properties and Interacting Boson Model,
(iv) reactions between heavy nuclei,
(v) other topics such as dilute neutron system, quantum chaos, etc.
The structure of unstable nuclei is the major focus of our interests, with current intense interest on novel relations between the evolution of nuclear shell structure (called shell evolution for brevity) and characteristic features of nuclear forces, for example, tensor force, three-body force, etc. Phenomena due to this evolution include the disappearance of conventional magic numbers and appearance of new ones. We have published pioneering papers on the shell evolution in recent years. The new magic number 34 in an exotic nucleus ^{54}Ca was confirmed experimentally for the first time in 2013 and was reported in Nature. The structure of such unstable nuclei has been calculated by Monte Carlo Shell Model, for instance to Ni isotopes. Their applications have been made in collaborations with experimentalists internationally spread. Collaborations with many groups produce various interesting results. The Monte Carlo Shell Model has been improved with further developments, and we have carried out a number of calculations on the K computer.

We are studying on dilute neutron systems, time-dependent phenomena like fusion and multi-nucleon transfer reactions in heavy-ion collisions, double-beta-decay nuclear matrix element, and nuclear level density.

Theoretical Hadron Group

In Theoretical Hadron Physics group (K. Fukushima and A. Yamamoto), 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 [1]
2. Rotational effects in relativistic fermion systems [3, 7, 11]
3. Vacuum structures in inhomogeneous magnetic fields [5]
4. Non-equilibrium dynamics in kinetic theories

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo

The main research interests at our group are in string theory, quantum field theory and unification theories. String theory, supersymmetric field theories, and conformal field theories are analyzed relating to the fundamental problems of interactions. In the field of high energy phenomenology, supersymmetric unified theories are extensively studied and cosmological problems are also investigated.

We list the main subjects of our researches below.

1. High Energy Phenomenology
   - 1.1. Phenomenology of supersymmetric model [1, 2, 3, 4]
   - 1.2. Grand unification theory [5, 6, 7]
   - 1.3. 750 GeV diphoton excess [8, 9, 10, 11, 12]
   - 1.4. Instability of electroweak vacuum [13, 14]
   - 1.5. Particle creation and reheating [15, 16]
   - 1.6. Supergravity inflation models [17, 18]
   - 1.7. Gravitino problem [19, 20]
   - 1.8. Affleck-Dine lepton number generation [21]
   - 1.9. Flaxion models [22]
   - 1.10. High energy cosmic ray [23]
   - 1.11. Dark matter [24, 25]
2. Superstring Theory and Formal Aspects of Quantum Field Theories
   - 2.1. Aspects of supersymmetric field theories [26]
   - 2.2. Holography and entanglement entropy [28]

2.3. Entanglement entropy in quantum field theories [29]

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3 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

Laser spectroscopy of antiprotonic helium atoms

Metastable antiprotonic helium atom ($\overline{\rm p}{\rm He}^+$) is three-body Rydberg atom, which consists of a helium nuclei surrounded by a ground state electron and an antiproton with large principal ($n \sim 38$) and orbital ($\ell \sim n+1 \sim 38$) quantum numbers.

The antiproton-to-electron mass ratio ($M_{\overline{\rm p}}/m_{\rm e}$) can be derived by comparing the experimental atomic transition frequencies of antiprotonic helium atoms measured by high-precision laser spectroscopy, with three-body QED calculations. The agreement of this value and proton-to-electron mass ratio with a precision of 1.3×10^{-9} is one of the verification of the CPT symmetry. In order to reduce systematic uncertainties caused by the particle masses and various QED and finite nuclear-size effects, it is important to measure many transitions precisely.

In 2016, non-linear two-photon transition of antiproton $(n, \ell) = (36, 34) \to (34, 32)$ was measured by using two-photon laser spectroscopy with gas buffer cooling. The mass ratio will be determined with a precision of $< 3 \times 10^{-10}$. The evolutions of the population of three $\overline{\rm p}^3{\rm He}^+$ states $(n, \ell) = (34, 32), (36, 34)$ and $(39, 35)$ were measured at low target pressure ($p \sim 1$ mb) and low temperature ($T \sim 1.5 - 1.8$ K) for the first time. The lifetimes of $(n, \ell) = (34, 32)$ and $(36, 34)$ do not change between two different target densities $\rho = 5 \times 10^{18}$ cm^{-3} and 2×10^{21} cm^{-3}.

Furthermore, we deduced the antiproton-to-electron mass ratio with a relative precision of 8×10^{-10} (published in Science). Comparison of this value with the known proton-to-electron mass ratio results in one of the most stringent CPT tests.

$\bar{\rm p}$-nucleus annihilation cross section at low energies

The antiproton is absorbed by the nucleus and annihilates with a surface nucleon. The cross sections, called annihilation cross sections, has been measured in order to study the interactions between them. In 2015, we measured the cross section in a momentum region of 100 MeV/c. In that region, annihilation cross sections of antineutron on some nucleus show unexpected enhancement, and we can understand this behaviors by comparing to these data to the one of antiprotons. In this experiment, we measured the cross sections with a carbon target.

Shapes of the antiproton beams were critical for this experiment, and they were tuned especially carefully. The timing of the kicker in the accelerator was optimized to make the pulse length shorter in time, and the pulse length became ~ 60 ns (in usual it is about 200 ns). The multiple extraction was performed to reduce the intensity of the beam not to saturate our detectors. Concerning the detector, we developed a Cherenkov counter monitoring intensities of the beams. For it we used lead fluoride crystals to maximize the number of Cherenkov photons, avalanche photodiodes to reduces background events caused by the nuclear counter effect and to guarantee the linearity. The experiment was carried out for 2 weeks and obtained data successfully.

In 2016 we analyzed the data and derived the annihilation cross section of the antiproton on carbon at 100 MeV/c. The cross section was compared to the one using the antineutron instead of the antiproton. The study of the mass dependence of the antiproton-annihilation cross sections using the past data was also carried out.

Spectroscopy of pionic atoms using a proton beam

Restoration of chiral symmetry breaking at a finite density has been one of the most important problems in recent hadron physics. We are studying this problem by performing spectroscopic experiments of pionic atoms of heavy nuclei such as Pb or Sn isotopes. It is known that the binding energy of deeply bound states such as 1s or 2s is related to the order parameter of the chiral symmetry breaking at the finite density. Experiments were performed in GSI and RIKEN using missing-mass spectroscopy of (d,^{3}He) reaction and the evidence of chiral symmetry restoration in nuclear medium was found.

We are now planning a new experiment of pionic atom spectroscopy using (p,^{2}He) reaction in RCNP. In this experiment, the binding energy is determined by analyzing two protons, which are decay products of ^{2}He, by the Grand Raiden spectrometer. A strong proton beam is employed with the

GRAF beamline, which was recently installed. We will try to achieve better resolution than existing experiments, by employing the high resolution spectrometer and the dispersion matching technique that eliminates the momentum spread of the incident beam.

In 2016, we performed a test experiment for a feasibility study. We measured the background of the experiment, where the main source of background is an accidental coincidence of two inelastic scattering in a single beam bunch. The cross-section of ^{120}Sn(p,p') was measured by Grand Raiden to be about 1.5 mb/sr/MeV and the accidental rate was evaluated to be comparable to the expected signal rate. In addition to the background measurement, we checked an availability of calibration methods of beam energy using LAS spectrometer. We submitted a proposal of the main experiment to RCNP and the beam time of 12.4 days was approved.

4 Sakurai Group

Research Subjects: Nuclear structure and dynamics of exotic nuclei

Member: Hiroyoshi Sakurai and Megumi Niikura

Exotic nuclei located far from the stability are new objectives for nuclear many-body problems. Our group explores exotic structures and dynamics in the nuclei that have never been investigated before, such as those with largely imbalanced proton and neutron numbers, hence to discover new phenomena and exotic properties in unstable nuclei. Our experimental programs mainly utilize fast radioactive isotope (RI) beams available at RI Beam Factory (RIBF) at RIKEN. RIBF is the leading facility where RI beam intensities are the highest in the world. We maximize RIBF utilization to access nuclei very far from the β-stability as well as to exploit new types of experiments and new methods of spectroscopy via new ideas and detector developments. Our research subjects to be covered are followings.

SEASTAR campaign

In May 2015 and May 2016, the SEASTAR experiments to systematically measure the excitation energy of extremely exotic nuclei were conducted at RIBF. 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 obtained level structure of the neutron rich Cr and Fe isotopes revealed the enhanced deformation around that region. The analysis for the de-excitation γ-rays of ^{78}Ni has been performed and the discussion with theoretical calculations are on going.

Neutron single-particles states in ^{35}Mg populated by one-neutron knockout reaction

The in-beam γ-ray spectroscopy experiment of ^{35}Mg was performed at RIBF via an one-neutron knockout reaction to clarify the neutron single-particle configuration in ^{36}Mg. The γ-ray energy spectrum of ^{35}Mg, the exclusive one-neutron removal cross sections and the parallel momentum distribution were obtained. The level structure is discussed by comparison with several theoretical model calculations.

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 $^{16}\mathrm{C}^* \to {}^{12}\mathrm{Be} + {}^{4}\mathrm{He}\ (+\gamma)$ and $^{16}\mathrm{C}^* \to {}^{10}\mathrm{Be} + {}^{6}\mathrm{He}$ decay channels 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 experiment at RCNP MuSIC

In May and June 2016, we measured γ rays following nuclear muon capture by ^{104,105,106,108,100}Pd isotope targets. X rays from muonic atom of each isotopes have been measured as well. The experiment was conducted at RCNP (Osaka university) MuSIC muon beam line. Muon capture rates for each Pd isotopes were derived by time distribution of γ rays, and charge radii of these isotopes were discussed using measured X ray energy. The following experiment which focused on emitted neutrons after muon capture was also conducted with ^{108}Pd target at MuSIC in February 2017. SEAMINE, which is newly constructed neutron detector array, was employed for the experiment. The analysis is in progress.

Development of neutron scintillator NiGIRI

We are developing neutron detector, NiGIRI (Neutron, ion and Gamma-ray Identification for Radioactive Isotope beam), to investigate equation of states of high-density matter. The detector consists of a organic scintillator aiming at identifying detected γ rays and neutrons using a pulse shape discrimination (PSD) technique. As a result of a PSD analysis, a 3σ separation between γ rays and neutron from a ^{252}Cf source was achieved.

5 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. In this FY 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 this experiment we can obtain the occupation of the $f_{7/2}$ and $p_{3/2}$ orbitals in the ground state of ^{44}S and thus a measure of 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 shows candidates for 3 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.

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.

Isomer and β-decay spectroscopy around $N = 40$ nuclei

Although not a traditional magic number, some nuclei with 40 neutrons or protons show the typical behavior of a closed shell configuration. This harmonic oscillator shell gap disappears for neutron-rich nuclei, but towards ^{60}Ca collectivity seems to decrease again. In an experiment at RIBF using the AIDA and EURICA setups we studied the β and isomeric decay of several isotopes around ^{60}Ti. New half-lives and γ-ray spectroscopy data for a large set of nuclei was obtained.

Magicity at $N = 32$

$N = 32$ has recently been established as a new magic number, which does not show up in nuclei close to stability. We will probe the magicity of ^{52}Ca at neutron number 32 by two complementary techniques. We will quantify the collectivity for this doubly magic nucleus through Coulomb excitation. The single-particle orbital occupation in the ground state of ^{52}Ca will be obtained by measuring the one-neutron and proton removal reactions. The combination of two complementary measurements will give new insights in the magicity of ^{52}Ca. Comparison with state-of-the art shell model calculations will allow us to draw conclusions on the microscopic structure of this doubly magic nucleus.

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. A first prototype target, containing deuterons instead of tritium, was tested using a ^{20}Ne at RIKEN. The target has been characterized. Further prototypes containing a larger fraction of hydrogen have been fabricated at the University of Toyama and will be tested in beam next year.

6 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, Daniel Jeans

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), chaired by Sachio Komamiya is an oversight body of LCC. 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. Since 2012 autumn, a new staff scientist from UK who is an expert on the silicon electromagnetic calorimeter was joined our group. Since then hardware and simulation studies of silicon-tungsten sandwich electromagnetic calorimeters have been extensively performed. He is also working on precise tau-lepton reconstruction at ILC to investigate, for example, CP properties of heavy Higgs bosons.

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.

2) 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.

7 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); (2) Search for physics beyond the Standard Model at the Super B Factory (Belle II); (3) Dark energy survey at the Subaru telescope (Hyper Suprime-Cam); (4) Long baseline neutrino oscillation experiment (T2K); (5) Search for proton decays (Super-Kamiokande); (6) R&D for the next generation neutrino and nucleon decay experiment (Hyper-Kamiokande); (7) R&D for an experiment to search for axion and light dark matter; (8) R&D of new generation photodetectors.

Members: Hiroaki Aihara, Masashi Yokoyama, and Yoshiuki Onuki

1. Search for new physics at KEK B-factory: Belle experiment 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. Using $\sim$ 700 million $\tau^+\tau^-$ pairs recorded with the Belle detector, we studied the radiative leptonic decays of τ ($\tau \to \mu\nu\nu\gamma$ and $\tau \to e\nu\nu\gamma$). Using the full kinematic information of daughter particles and their correlations, we measured two Michel parameters of τ for the first time; $\bar{\eta}^\mu = -1.3 \pm 1.5 \pm 0.8$, $(\xi\kappa)^\mu = 0.8 \pm 0.5 \pm 0.3$, and $(\xi\kappa)^e = -0.4 \pm 0.8 \pm 0.9$. We are also studying an improved measurement of the CP violating parameter, ϕ_3, which is currently the least well-measured of the three CKM angles.

2. Physics at the luminosity frontier: Belle II experiment The SuperKEKB project started in 2010. The upgraded accelerator, SuperKEKB, will have a 40 times more luminosity than KEKB. The Belle detector is also being upgraded as the "Belle II" detector with cutting-edge technologies. One of the key elements for the success of Belle II will be its Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons. Our group is responsible for the construction of the outermost layer of the Belle II SVD. This year we completed production of six ladders of the Belle II SVD. The R&D for the upgrade of the Belle II electromagnetic calorimeter was also carried out.

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-filed 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. Study of neutrino oscillation with accelerator neutrino beam: T2K experiment T2K is a long baseline neutrino experiment using the J-PARC accelerator complex and the Super-Kamiokande detector, 295 km away. By combining both muon-type and electron-type neutrino interactions observed at the Super-Kamiokande detector, with both neutrino and anti-neutrino enhanced beam from J-PARC, we placed the world best constraint on the neutrino mixing angle θ_{23}, and the first-ever constraint on the CP asymmetry parameter in the lepton sector.

In order to improve the systematic uncertainty from neutrino-nucleus interaction cross sections, we have been carrying out a test experiment, named WAGASCI, at the J-PARC neutrino beam facility.

We have proposed an extension of T2K data taking (called T2K Phase II) with an upgrade of near detectors, which will allow us to observe CP violation in the lepton sector with a significance of 3 σ if the parameters are in a favorable region. Our group is leading the upgrade project of the T2K near detectors.

5. Search for proton decays: Super-Kamiokande Proton decay is the only way to directly prove the Grand Unified Theory, which is an attractive candidate for a model of physics beyond the Standard Model. We have established an analysis to enhance the sensitivity to proton decay at Super-Kamiokande with an improved event reconstruction. The lower limit of the proton lifetime, $\tau_p/\mathrm{Br}(p \to e^+\pi^0) > 1.87 \times 10^{34}$ years, has been obtained by the analysis of data recorded with the Super-Kamiokande detector.

6. Next generation large water Cherenkov detector: Hyper-Kamiokande project In order to pursue the study of neutrino properties beyond T2K, we propose the next generation water Cherenkov detector, Hyper-Kamiokande (Hyper-K). One of the main goals of Hyper-K is the search for CP violation in the leptonic sector using accelerator neutrino and anti-neutrino beams. The sensitivity to the CP violating phase is studied with full simulation by our group. It is shown that with Hyper-K and J-PARC accelerator, CP violation can be observed after five years of experiment for a large part of possible parameter space. The sensitivity to proton decay lifetime, which is expected to be an order of magnitude better than current Super-K sensitivity, is also studied in our group.

7. 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.

8 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.
  - New dibson Resonance: A small excess is found at M=750GeV for $\gamma\gamma$ resonance. We need more data to confirm the excess is new physics or just statistical fluctuation.

- (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.

9 Miyashita Group

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

Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita and Takashi Mori

Quantum response and Quantum dynamics

Quantum dynamics under time dependence field is one of the most important subjects in our group. In the 2016 fiscal year, we studied the following topics.

Quantum response to the external field has been one of projects of our group. We introduced a method to decompose the spectrum into contributions specified by the magnetizations of the resonating states, and applied the so-called moment method for each contribution. By making use of it, the size and temperature dependences of the ESR spectrum of the 1DXXZ spin model have been obtained [2].

Synergistic effects of the spin-orbit interaction and the external field on the optical conductivity of the Hubbard model were studied. In one-dimensional noninteracting case ($U = 0$: the tight-binding model), we obtained exact result of the effect as a function of the angle between the directions of the spin-orbit interaction and the external field. For the interacting case, we studied the model numerically and found the angle dependent properties.[39, 42, 47]

We have studied the relaxation of metastable state of magnetization under sweeping field in a uniaxial magnetic systems. In the fiscal year, we studied the spin size S dependence of the population dynamics over the adiabatic eigenstates after the Storner-Wohlfarh point, and found some universal aspects of the distribution which survives in the classical limit. We also studied the effect of thermal decoherence on the quantum beating which was found in the previous paper [20, 23, 26, 32].

We studied thermalization in isolated quantum systems. We formulate this problem as a general problem of the ensemble equivalence [9]. We showed that the system thermalizes when the effective dimension of the initial state is sufficiently large but may be exponentially smaller than the dimension of the Hilbert space.

We also consider the problem of the second law of thermodynamics from the viewpoint of the ensemble equivalence. We proved that the amount of increase of the entropy of the system must be extensively large, i.e. proportional to the system size, by using the large deviation property of the equilibrium state of a macroscopic quantum system [10].

We studied fundamental properties of the quantum master equation (QME). Usually QME is perturbatively derived by tracing out the degree of freedom of the thermal bath. We demonstrated this procedure in a spin system. We found that properties obtained by the QME derived by the perturbation method qualitatively agree with the numerical results, but quantitatively they differ each other [7].

The effects of noise on the apparatus to measure the current in mesoscopic quantum dot systems was quantum mechanically studied when the noise contains not only the usual gaussian noise but also a Poisson noise. [15]

We also studied relaxation phenomena to a metastable state (the pre-thermalized state) due to the entanglement of the state, which would be realized in cold atom systems, e.g., harmonic oscillators [11], and in the 1D Bose gas[12].

Cooperative Phenomena and Phase Transitions

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

The phase transitions in frustrated system show various interesting properties. We found a peculiar size dependence around the critical value of the next-nearest-neighbor (nnn) couping of the Mekata model (antiferromagnetic Ising model on the triangular lattice with nnn ferromagnetic model). If the couping is smaller than the critical value, the system exhibits an intermediate-temperature phase, i.e., the so-called partially-disordered (PD) phase, while it does not have the PD phase with large couplings. We also studied this phenomenon on the six-state clock model.[4]

We have studied the effect of the elastic interaction of the systems with bistable states which have different local lattice structure. In the fiscal year, we studied the so-called "elastic expansion" which has been observed experimentally in some spin-crossover materials after a pulse irradiation by time-resolve method. In particular, the effect of thermal diffusion was investigated.[28, 29]

We have been contributing the project of 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 [51].

We studied threshold of magnetic fields for nucleation and domain wall propagation in a sandwich structure of hard-soft-hard magnet. There, we found a novel aspect due to the narrow domain wall effect inherent to the discreteness of the lattice structure and also to the reduction of the exchange energy at finite temperatures [6].

We also studied magnetic properties of $Nd_2Fe_{14}B$ in a realistic atomic scale by making use of the real structure and exchange constants obtained from the first-principle calculations. There, we investigated thermodynamic properties such as temperature dependences of magnetization $M(T)$ and the anisotropy constant $K(T)$. Indeed, we successfully reproduced the reorientation at a low temperature [3, 5].

Temperature dependent of structure of domain walls parallel and perpendicular to the Nd plane in microscopic realistic scale. The obtained width is consistent with the experimental estimations. The domain wall along the c-axis (perpendicular to the Nd plane) is shorter than that along the a-axis. The width of the Domain wall was found to increase with the temperature [1].

Furthermore, we demonstrate LLG dynamics of nucleation process and domain wall formation from the nucleation in a lattice of 12x12x9 unit cells, in which we found the revered magnetization propagates fast in the a-axis and a domain wall is formed parallel to the Nd-plane [21].

We will also discuss on effect of the dipole-dipole interaction on the domain wall formation [41, 45].

10 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.[1]
  Microscopic theory of the electron-doped high-T_c cuprates.
- Dirac electron systems in solids
  Quantum electrodynamics in solids: Dielectricity and diamagnetism.
  Nuclear spin relaxation time of the orbital currents in Dirac electron systems.
- Orbital magnetic susceptibility
  Orbital magnetism of Bloch electrons: General theory and application to single-band models. [2]
  Corrections to the Peierls phase in the tight-binding model.[3]
  Theory of orbital susceptibility on excitonic insulator.[4]
- Theories on topological materials
  Spin current and axial current generation in a Dirac semimetal.[5]
  Magnon spin-momentum locking.
  Magnon spin current and spin-Seebeck effect in a topological-insulator/ferromagnet interface.[6]
  Relationship between fractal and quantum Hall coefficients.[7]
- Theories on heavy fermion systems and multi-band electron systems
  Quasiparticles in f^2-configuration.
- Spin systems, chiral magnets, and spin-orbit interaction
  Generic model and phase diagram for hyperkagome iridates.[8]
  Clustering of topological charges in Kagome classical spin liquid.
  Dynamics of a chiral soliton lattice under a constant current.
  Dzyaloshinskii-Moriya interaction induced from RKKY at an interface.[9]

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11 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 study of electronic, structural and dynamical properties of materials.

In FY2016, we investigated structural transformation and superconducting transition temperature of H_xs (x = 2-3) under ultra-high pressure with the density functional theory for superconductors (SC-DFT). We newly implemented a method of including the spin fluctuation effect in our SC-DFT code. We also developed various method of calculating material properties from first principles: thermal expansivity, electronic states spreading over a nano system based on the divide-and-conquer method, wave function theory to treat correlated electrons in solids (the transcorrelated method), etc.

Our research subjects in FY2016 are as follows:

- High-pressure phases of superconducting H_xS (x = 2-3)
- Effect of spin fluctuation in phonon-mediated superconductors
- Anisotropic superconducting gap in YNi_2B_2C
- Anharmonic effect of rattling atoms in clathrate
- Negative thermal expansivity of ScF_3
- Non-thermal ablation of metals by Laser pulses
- Impurity effect on the magnetic anisotropy of sintered magnets
- First-principles transcorrelated method
- A method for electronic structure calculation of large systems based on a divide and conquer method
- Data assimilation for crystal structure determination

12 Todo Group

Research Subjects: Novel state and critical phenomena in strongly correlated systems, Development of new simulation algorithms for strongly correlated many-body systems, Development of open-source software for next-generation parallel simulations

Member: Synge Todo 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

- Spinon dispersion at the deconfined quantum critical point
- Effective dimension of the random-field Ising model with correlated randomness
- Quantum critical phenomena of system with strong spatial and temporal anisotropy

- Critical decay exponents of long-range interacting spin system
- Topological order parameter for two-dimensional SPT phase
- Optical bistability in cavity system
- Molecular dynamics study of shear band in glass

Development of new simulation algorithms for strongly correlated many body systems

- Directed worm algorithm with geometric optimization
- Combined optimization method and application to determination of crystal structure
- Parameter inference based on unsteady relaxation and application to inverse Ising problem
- Quantum Monte Carlo method for calculation of velocity of excitations of quantum spin systems

Development of 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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13 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 these 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) quantum spin liquids, and (iii) entanglement in quantum spin chains. In addition, we are also interested in the mathematical aspects of the study of the above mentioned fields. Our research projects conducted in FY 2016 are the following:

- Strongly correlated systems
  - Quantum trimer model and resonating-valence-bond states [1]
  - Supersymmetry breaking and Nambu-Goldstone fermions [2, 3]
- Topological phases of matter

  - Hofstadter's butterfly and the integer quantum Hall effect [4, 5]
  - Disordered topological insulators [6, 7]
- Solvable models and statistical physics
  - Entanglement spectra of integrable spin chains [8]
  - Volume-law entanglement in deformed Fredkin spin chain [9]

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14 Fujimori Group

Research Subjects: Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Goro Shibata

We study the electronic structure of superconductors and spintronics materials by high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy (ARPES) and soft x-ray magnetic circular dichroism (XMCD) using synchrotron radiation. We investigate the mechanisms of high-temperature superconductivity [1], metal-insulator transitions [2], giant magnetoresistance, and spin/charge/orbital ordering in strongly correalted systems such as transition-metal compounds, ferromagnetic semiconductors [3], and their interfaces.

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15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA, Akari TAKAYAMA, and Ryota AKIYAMA

Surfaces of 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) electronic excitations, (5) spin states and magnetism, and (6) 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 monolayer materials such as graphene and silicene. 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 Kerr effect apparatuses. Main results in this year are as follows.

(1) Surface electronic/spin transport:

- Detection of superconductivity in double-layer Thallium and superconductor-insulator transition induced by magnetic field
- Shubnikov-de Haas oscillation at double-layer graphene with intercalation
- Transport, magnetism, and atomic structure at interface between a topological insulator and magnetic insulator
- Detection of Photogalvanic effect at surface states of topological insulators
- Measurements of conductivity of organic molecule sheets by using four-tip STM
- Measurements of superconductivity at metal-covered Ge(111) surface structures

(2) Surface phases, ultra-thin films, and phase transitions:

- STM/S measurement at ultra-low temperature under magnetic field, on a monolayer superconductor Si(111)-$\sqrt{3} \times \sqrt{3}$-(Tl+Pb), revealing unconventional superconductivity nature
- Angle-resolved photoemission spectroscopy (ARPES) of topological crystalline insulators

(3) Construction of new apparatuses:

- 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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16 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

Our interests are in (i) novel quantum phases with strong correlations and frustration in two dimensional (2D) helium three (^{3}He), four (^{4}He) and their mixture, and (ii) novel electronic properties of low dimensional materials, particularly graphene and carbon nanotube. We are investigating these phenomena in a wide temperature rage from room temperature down to microkelvins, using various experimental techniques such as NMR, calorimetry, torsional oscillator, scanning tunneling microscopy and spectroscopy (STM/S), and electronic transport measurement. Our efforts are also devoted to development of new experimental and cryogenic techniques.

1. **Quantum Spin Liquid state in 2D ^{3}He system:**

   Quantum spin liquid (QSL) is a noble magnetic ground state of $S = 0$ where the spin expectation value at each lattice site remains zero even at $T = 0$. 2D solid ^{3}He is the first candidate material for QSL which was found experimentally by our group in 1997. Since then, many other candidate materials had been found in highly frustrated electronic spin systems, but 2D ^{3}He is still one of the most promising candidates. Recently we have discovered a new QSL in 2D ^{3}He on graphite preplated with a bilayer of HD. This has anomalous power-law temperature dependencies of specific heat (C) and magnetic susceptibility (χ) with fractional powers, while the previously known QSL in the second layer of ^{3}He on graphite does a T-linear dependence for C and a T-independent χ.

2. **Possible superfluid "quantum liquid crystal" phase in 2D ^{4}He system:**

   So far, only three quantum phases, i.e., quantum gas, quantum liquid and quantum solid, have been known to exist in nature. Recently, we are proposing a new member to them, a quantum liquid crystal (QLC), which we found at densities in between the quantum liquid and solid phases below $T = 1.4$ K in the second layer of helium on graphite from heat capacity measurements. The most probable state for this is a *quantum hexatic phase* where the system possesses only the quasi-long range bond orientational ordering. In bosonic ^{4}He, superfluid order can coexist in this phase below 0.4 K, which is considered as a member of supersolids.

3. **Liquefaction of ^{3}He in two dimensions:**

   Until our recent C measurement of monolayers of ^{3}He of low densities, the ^{3}He system has long been believed not to liquefy in 2D unlike in 3D. This is because of increasing fluctuations in lower dimensions. But we found ^{3}He atoms form self-bound liquid paddles with a very low density of $0.6 - 0.9$ nm^{-2} below 1 K. Our finding stimulated theoreticians to reexamine this problem, and recent quantum Monte Carlo calculations seem to give results much closer to the experiment than the previous attempts. We are now planning to start a new C measurement using a graphite substrate with a much longer coherence length than Grafoil used previously.

4. **Zigzag edge state in graphene and its application to future nanoelectronics:**

   Graphene, a monatomic carbon sheet, has remarkable electronic and structural properties due to its unique linear dispersion relation. It is potentially applicable to a vast area of technology including graphene-based electronic devices. One of the most important topics in graphene studies is the *zigzag edge state* and its spin polarization. This localized electronic state was experimentally found for the first time by our group in 2005 using STM/S technique at naturally existing monatomic step edges on a graphite surface. It is expected that the spin degeneracy of the zigzag edge state can easily be lifted by a small perturbation like the electron-electron interaction. This will result in high spin polarization at the edge. Thus, in a nano ribbon with zigzag edges on both sides (zigzag nanoribbon), one can expect opening the band gap whose energy width is controllable by the ribbon width and applied magnetic field. Due to this, zigzag nanoribbon is considered to be highly useful in future electronics.

Fabrication of zigzag nanoribbons is highly demanding because of the difficulty of precise processing of zigzag edge in an atomic scale. We have recently succeeded in fabrication of hexagonal nanopits of monatomic depth with high-quality zigzag edges on a graphite surface by use of hydrogen plasma etching. The size and density of nanopit can be controlled by tuning the plasma excitation power, temperature, dose time, and partial pressure of hydrogen. Therefore, one can also fabricate a zigzag nanoribbon in between two adjacent hexagonal nanopits. We are now studying the local electronic state of the spin polarized zigzag edge state by STM/S with an atomic spatial resolution.

5. **Random network of carbon nanotubes:**

   Carbon nanotube (CNT) is a rolled graphene with a nanometer size diameter and a high length/diameter ratio. It is a promising quasi one-dimensional (1D) material for future technology. Depending on the rolling chirality, CNT becomes either metallic or semiconducting. The electronic properties of metallic CNTs are expected to obey the Tomonaga-Luttinger liquid (TLL) theory which describes behaviors of interacting fermions in 1D. Recently we found that the electrical resistivity of random networks of high-purity double walled metallic CNTs show surprisingly behaviors expected from the TLL theory. Magneto-transport measurements gave us hints to solve the question why such a macroscopic 3D network can follow the TLL theory. Further research is now being undertaken to obtain more information and to seek for new functions of CNTs.

6. **Development of new refrigeration systems:**

   Two projects are on going. One is to develop a compact and continuous nuclear demagnetization refrigerator (ccNDR) with which $T = 0.8$ mK can be kept continuously by use of two $PrNi_5$ nuclear spin stages connected in serious. Such ultra-low temperatures are now required in many research disciplines including material science, quantum information, and astrophysics.

   The other is to develop a refrigeration system for scanning probe microscope (SPM) based on helium circulation which enables us to take STS data at $T = 2 - 4$ K without being interrupted by liquid helium refilling which is now expensive and sometimes not available stably in industries or developing countries. We have successfully tested the high thermal shielding performance of the low-consumption and low vibration-transmission helium transfer tube we designed.

17 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 $H_{\|}$ on superconductivity of monolayer Pb films on GaAs(110). Superconductivity was found to occur even for $H_{\|} = 14$ T, which is much higher than the Pauli paramagnetic limiting field H_P. The observed weak $H_{\|}$ 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. In 2016, 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 the spatial modulation caused by the Cooper pairs with a finite momentum in two dimensional superconductivity without spatial inversion symmetry, we began to construct the scanning tunneling microscope that works under a high magnetic field in the direction parallel to the two dimensional plane.

18 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Ryusuke Matsunaga

We study light-matter interactions and many body quantum correlations in solids, aiming at the quantum phase control of many body systems by light. In order to investigate the role of electron and/or spin correlations in the excited states as well as the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1THz$\sim$4meV) frequency range where 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 Mott transition in a bulk GaAs under the condition of resonant excitation of excitons by using optical pump and THz probe spectroscopy. At high-density excitation above the Mott transition density we found that the optical conductivity spectrum remarkably deviates from that of Drude-type and shows the increase of the effective electron mass and the frequency-dependent scattering rate as typically observed in normal state of high T_c superconductors. This result indicates the transient appearance of an anomalous metallic phase with strong electron correlations, which imply a precursor of quantum condensation into the electron-hole BCS state. We also performed a rate equation analysis based on the Saha equation with a detailed balance between excitons and unbound electron-hole pairs. We found that the ionization ratio of excitons exhibits a bistability as a function of pair density in a good agreement with our experimental results.

2. **Optical control of superconductivity:** We performed the polarization-resolved nonlinear THz transmission experiment for NbN to clarify the origin of nonlinear interaction between the strong THz wave and the superconducting state. Both the collective Higgs amplitude mode and the charge-density fluctuation (or Cooper-pair breaking) can contribute the nonlinear response in superconductors and induce the strong THz third-harmonic generation (THG). We found that (i) the THG intensity is isotropic for the incident THz field polarization direction to the crystal axis, and (ii) the polarization of the THG is always parallel to that of the incident THz field for arbitrary crystal axis. From the symmetry arguments these experimental results exclusively indicates that the Higgs mode has a dominant contribution on the nonlinear response, which is opposite to the calculation based on the BCS mean-field analysis. The dynamical mean-field theory calculation has showed the BCS approximation significantly underestimates the contributions of the collective mode when the retarded electron-phonon interaction or impurity scattering is taking into consideration. Our results show

that for NbN where the electron-phonon interaction is remarkably strong, the Higgs mode appears in nonlinear susceptibility in preference to the charge-density fluctuation. We also performed the time-resolved measurement for high-T_c cuprate superconductors and for an iron-chalcogenide superconductor to study the nonlinear dynamics of the d-wave superconductivity and the strongly-coupled superconducting system.

3. **Ultrafast nonlinear optics in Landau-quantized graphene:** We studied the ultrafast nonlinear dynamics in Landau-quantized graphene by using THz pump and THz probe spectroscopy under magnetic field. From the pump-probe signals we obtained the THz pump-induced transient spectral change for right(left)-handed circular polarization. The absorption bleaching was observed for the right-handed circularly-polarized light, which can be interpreted by the Pauli blocking effect for the Landau-level transition near the Fermi energy. In addition, the induced absorption was also observed for left-handed circular polarization, indicating the drastic change of electron distribution far below the Fermi energy. These result were reproduced well by numerical calculation based on the density matrix formalism and indicates a realization of ultra-strong light-matter coupling regime in graphene.

19 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 FY2016 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.

Realization of spin liquid state in (hyper-)honeycomb iridates:

Honeycomb iridates have been believed to become Kitaev-honeycomb-model spin liquid. The key ingredient here is bond-dependent anisotropic Ising-like interactions arising from spin-orbit coupling and specifiic material engineering for $J_{\mathrm{eff}} = 1/2$ quantum pesudo spins of Ir. We have demonstrated that $H_3LiIr_2O_6$ is indeed spin liquid, as the first material of such a liquid, down to 1 K by nuclear magnetic resonance and bulk experiments. And this year we confirmed that it remains paramagnetic (spin liquid) down to 50 mK by ultralow-temperature specific heat experiment. Three-dimensional hyper-honeycomb iridate β-Li_2IrO_3 is also found to be a clean qunatum spin liquid under ultrahigh pressure of 3.3 GPa, which is demonstrated by our ultrahigh-pressure NMR measurement. We now pursuit a realization of Kitaev spin liquid by investigating fractionalized elemental excitations or exotic gapped states under magnetic fields.

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 two different carrier densities to establish Dirac-type dispersions. It was found that the temperature dependence of NMR relaxation rate certainly reflects three-dimensional Dirac-type density of states. Chiral anomaly is a phenomenon peculiar to this quantum-limit physics, and we have found a sign reversal of magnetoresistance with respect to direction of applied megnetic field. The anisotropic transport caused by magnetic field needs to be further considered in relation to the chiral anomaly and current jetting effect.

The semi-metallic $A\mathrm{IrO}_3$ (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 diltuion of Ir ions or a distortion of Ir-O-Ir bond. Details near the phase boundary are yet to be identified and will be investigated.

20 Hayashi Group

Research Subjects: Spin orbit effects in thin film heterostructures

Member: Masamitsu Hayashi, Masashi Kawaguchi

We have been working on the physics of phenomena that derive from the strong spin orbit interaction of materials and interface in thin film heterostructures. We study spin dependent transport, magnetism, thermal and optical response of metal/oxide heterostructures. Currently we put a strong effort on studies of phenomena that arise from the strong spin orbit interaction of the system: e.g. spin Hall and Nernst effects, Dzyaloshinskii-Moriya interaction, magneto-optical Kerr and Faraday effects, Rashba-Edelstein effect. The following are the research projects carried out in FY 2016.

- Spin current generation
  - Spin Hall effect of 5d transition metals[5]
  - Spin Hall magnetoresistance in metallic heterostructures[5]
- Spin orbit interaction at interfaces
  - Characterization of chiral domain walls[3]
  - Current controlled motion of chiral domain walls[1]
  - Electric field control of non-linear magnetic anisotropy[2]

[1] R. P. del Real, V. Raposo, E. Martinez, M. Hayashi, Current induced generation and synchronous motion of highly packed coupled chiral domain walls. Nano Lett. 17, 1814 (2017).

[2] Y.-C. Lau, P. Sheng, S. Mitani, D. Chiba, M. Hayashi, Electric field modulation of the non-linear areal magnetic anisotropy energy. Appl. Phys. Lett. 110, 022405 (2017).

[3] J. Torrejon, E. Martinez, M. Hayashi, Tunable inertia of chiral magnetic domain walls. Nature Comm. 7, 13533 (2016).

[4] J. Kwon, J. Yoon, P. Deorani, J. M. Lee, J. Sinha, K.-J. Lee, M. Hayashi, H. Yang, Giant nonreciprocal emission of spin waves in Ta/Py bilayers. Science Adv. 2, e1501892 (2016).

[5] J. Torrejon, J. Kim, J. Sinha, M. Hayashi, Spin-Orbit Effects in CoFeB/MgO Heterostructures with Heavy Metal Underlayers. SPIN 06, 1640002 (2016).

21 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 is 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 stars were born, which illuminate 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 supercomputer simulations of structure formation in the early universe. Direct and indirect observational signatures are explored considering future radio and infrared telescopes.

Does a second earth exist somewhere in the universe? This naive question has been 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. While most of the confirmed planets turned out to be gas giants, the number of rocky planet candidates is steadily increasing. Therefore the answer to the above question is supposed to be affirmative. Our group is approaching that exciting new field of exoplanet researches through the spin-orbit misalignment statistics of the Rossiter-MacLaughlin effect, simulations of planet-planet scattering and 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;

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

2011

- The Implication of the anomaly in the SFD Galactic extinction map on Far-infrared emission of galaxies

2010

- Precise measurement of number-count distribution function of SDSS galaxies

22 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Akihito Soeda

Quantum information processing seeks to perform tasks which are impossible or not effective with the use of conventional classical information, by using quantum information described by quantum mechanical states. Quantum computation, quantum cryptography, and quantum communication have been proposed and this new field of quantum information processing has developed rapidly especially over the last two decades.

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 7 graduate students–Kotaro Kato (D3), Jisho Miyazaki (D3), Atsushi Shimbo (D2), Ryosuke Sakai (D1), Matthias Strödtkotter (D1) and Hayata Yamasaki (D1), and Qingxiuxiong Dong. We investigate various aspects of theoretical quantum information. Our projects worked in the academic year of 2016 were the following:

- Higher-order quantum operations
  - Universal controllization of unitary operations by Q. Dong, A. Soeda, and M. Murao with S. Shojun at National Institute of Informatics
  - Complex conjugation of unitary operations by J. Miyazaki, A. Soeda, and M. Murao
  - Computation of entanglement via higher-order quantum operations by J. Miyazaki, A. Soeda, and M. Murao
  - Distinguishability of unknown unitary operations by A. Shimbo, A. Soeda, and M. Murao
  - Higher-order quantum operation by adiabatic quantum computation and Grover search by A. Soeda and M. Murao with S. Shojun at National Institute of Informatics
- Information theoretic analysis of multipartite quantum states–Topological entanglement entropy and entanglement spectrum by K. Kato with F. Brandao at California Institute of Technology
- Quantum information processing by hybrid quantum systems–Input and output algorithm of quantum information for quantum systems under low controllability by R. Sakai, A. Soeda, and M. Murao
- Entanglement theory–Resource theory for output distributed quantum information processing by H. Yamasaki, A. Soeda, and M. Murao
- Quantum nonlocality
  - Robust test of quantum steering by maximally incompatible quantum mesurements by M. Quintino with J. Bavaresco at Quantum Optics and Quantum Information
  - Device-independent test of incompatibility of quantum measurements by M. Quintino with D. Cavalcanti at Institut de Ciencies Fotoniques

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

23 Ueda Group

Research Subjects: Bose-Einstein condensation, fermionic superfluidity, cold molecules, measurement theory, quantum information, information thermodynamics

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 correlation effects in spinor BECs, BCS-BEC crossover and Efimov physics under the control of an atomic interaction strength, quantum Hall states 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 formulation of the dynamics of state reduction in light of information flow under measurements and feedback controls. We list our main research subjects in FY2016 below.

- Quantum many-body phenomena in ultracold atoms
  - Algebraic approach to continuous symmetry breaking in quantum many-body systems [1]
  - Universal properties of axisymmetry-broken p-wave Fermi gases [2]
  - Quantum dynamics and critical behavior influenced by measurement backaction [3, 4]
  - Renormalization group limit cycle in 4-body Efimov physics [5]
- Quantum Information, quantum measurement, and foundation of statistical mechanics
  - Fluctuation theorems in open quantum systems with feedback control [6]
  - Quantum Fisher information and linear-response theory [7]
  - Gibbs paradox revisited from the fluctuation theorem with absolute irreversibility [8]

[1] S. Higashikawa and M. Ueda, Phys. Rev. A **94**, 013613 (2016).

[2] S. M. Yoshida and M. Ueda, Phys. Rev. A **94**, 033611 (2016).

[3] Y. Ashida, S. Furukawa, and M. Ueda, Phys. Rev. A **94**, 053615 (2016).

[4] Y. Ashida and M. Ueda, Phys. Rev. A **95**, 022124 (2017).

[5] Y. Horinouchi and M. Ueda, Phys. Rev. A **94**, 050702(R) (2016).

[6] Z. Gong, Y. Ashida, and M. Ueda, Phys. Rev. A **94**, 012107 (2016).

[7] T. Shitara and M. Ueda, Phys. Rev. A **94**, 062316 (2016).

[8] Y. Murashita and M. Ueda, Phys. Rev. Lett. **118**, 060601 (2017).

24 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. Below is the list of topics studied during the academic year 2016.

Cosmology of the early universe

- Reheating after G-inflation
- Creation of supermassive black holes from inflation
- Entropic interpretation of the Hawking-Moss instanton
- Schwinger effects in de Sitter spacetime

Observational cosmology

- Observability of primordial nonGaussianity of tensor perturbation through B-mode polarization of CMB
- Constraints on evaporating primordial black holes by galactic gamma-ray radiation

Gravitation

- Construction of ghostless theories with higher derivative interactions
- Inflation in massive gravity
- Justification of gauge fixing at the level of the action
- Black hole perturbation in Horndeski theory with shift symmetry
- Consistent description of black hole evaporation
- Unruh effect of charged particles
- Neutron stars in scalar-tensor theories

Gravitational waves

- Primordial black holes as the origin of the LIGO events
- Constraints on primordial gravitational waves from non-detection of primordial black holes
- Accuracy of wave-form determination by pre-DECIGO
- Novel method to remove line noises in continuous gravitational wave search
- Search for stochastic gravitational wave background with phase-II TOBA
- Search for continuous gravitational waves with iKAGRA data
- Removal of nonGaussian noises by independent component methods

25 Takase Group

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

Member: Yuichi Takase, Akira Ejiri, Naoto Tsujii

In Takase Group, we 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 in order to develop physics understanding and technology to realize nuclear fusion power. Spherical tokamaks are able to achieve high β, but non-inductive plasma current start-up is a formidable challenge. We also collaborate with other fusion experiments, including JT-60SA, LHD, LATE, QUEST, and MAST (UK).

Our present focus on TST-2 is the establishment of plasma current ramp-up method using lower-hybrid waves (LHW). In FY2016, we performed more experiments using the capacitively-coupled combline (CCC) antenna installed at the top of the plasma. The antenna was developed in collaboration with General Atomics (US). Improvement of the driven current over the conventional outboard-launch scheme was expected due to up-shift of the parallel index of refraction and improved accessibility at higher density. However, there was not a significant difference in the plasma current achieved by the top-launch antenna and the outboard-launch antenna. The temperature profile of the plasma sustained with the top-launch antenna was hollow, similar to the profile obtained with the outboard-launch antenna. The poloidal flow was found to be around 0.5 km/s, and the direction was consistent with the positive plasma potential expected from fast electron loss.

Numerical simulation of LH current drive showed that there is an optimum density for current drive due to balancing of current drive saturation at low density and wave diffraction at high density. The simulated optimum density increased with the toroidal field strength, which was consistent with the experimental observation. Increase in the density limit was observed with the top-launch antenna, in agreement with the theoretical prediction. MEGA is a hybrid fluid-particle code which can be used to analyze MHD equilibria in the presence of fast particles. The code was improved for robust reconstruction of the equilibrium starting from an arbitrary initial electron distribution function. First results suggest that hollow current distribution profiles are relaxed and fast electrons migrate to the plasma center.

Internal reconnection events (IREs) of inductively formed TST-2 plasmas were studied using spectroscopy. It was found that the toroidal flow reverses its direction and poloidal flow slows down during an IRE. The phase velocity (in the lab frame) of magnetic fluctuations was in the same direction as the toroidal and the poloidal flow before an IRE, but did not change its direction during the IRE.

AC Ohmic heating is a method for pre-ionization, heating and current drive of a plasma by applying $\sim$1 kHz voltage on the Ohmic coil. Robust pre-ionization and plasma current ramp-up by applying a vertical field was demonstrated. Since the flux changes little with this method, it may be able to reduce the size of the Ohmic coil substantially. The break-down process was investigated in detail using visible camera with a dynamic range of 6 orders of magnitudes.

The magnetic pitch angle may be estimated by introducing trace impurity ions locally and measuring their spatial emission structure. Carbon was introduced using an acrylic probe and the emission was observed with a 2D visible camera. It was found that the emission at 530m$\pm$50 nm was elongated along the magnetic field line with $\pm 5^\circ$ error. The impurity ion species and the injection method needs to be reconsidered to improve the accuracy. A microwave scattering diagnostic is being developed for direct measurement of the LHWs. In FY2016, a Ka-band (26.5–40 GHz) system was installed. The sensitivity of the system was improved to be able to measure -95 dB scattering signal, but no wave signal has been detected so far. A new mount for hard X-ray (HXR) diagnostic was developed to measure fast electron Bremsstrahlung emission during the LH-driven discharge. The HXR flux as well as the effective temperature was observed to increase with the plasma current.

As a collaboration, Thomson scattering of ECH driven steady-state plasmas is being developed on QUEST. The measured electron temperature of plasmas sustained by 28 GHz ECH was lower than those sustained by 8.2 GHz ECH. Spectroscopy was performed on LATE plasmas. From CV and OV emission, the ion temperature was estimated to be around 100 eV. Current sheet during magnetic reconnection in the UTST experiment was measured with a Rogowski probe array. The size of the current sheet was $\sim$32 mm in the major radius direction and $\sim$20 mm in the vertical direction.

26 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) Directed percolation universality in absorbing state phase transition
   (2) Directed percolation with flow and active boundary
   (3) Non-equilibrium fluctuation of a growing surface

2. Active matters
   (1) Helical motion of a chiral liquid crystal droplet
   (2) Collective motion of self-driven colloidal particles [6]
   (3) Collective motion of filamentous proteins
   (4) Order and fluctuation in collective motion of bacteria [5]

3. Biological systems
   (1) Theory on mechanics of cellular dynamics and morphogenesis [1]
   (2) Application of theoretical model for cell migration to hematopoietic stem cell [2]
   (3) Traction force of collectively migrating neural stem cells

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27 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 Yoshimasa Watanabe

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 understanding 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. This has recently been confirmed by our detection of CH_3D in one of the WCCC sources, L1527. Existence of WCCC clearly indicates a chemical diversity of low-mass star forming regions, which would probably reflect a variety of star formation. We are now studying how such chemical diversity is brought into protoplanetary disks by using ALMA. In 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. Hence, chemical compositions drastically changes across the centrifugal barrier of the infalling gas. Further analyses 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. Furthermore, we successfully realized the waveguide-type NbN HEB mixer by using the NbN/AlN film deposited on the quartz wafer. 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. The commissioning runs were performed in 2011, 2012, and 2015. We successfully observed Moon and Jupiter in the 0.9 THz continuum emission, and the Orion A molecular cloud in the ^{13}CO $J = 8-7$ line emission.

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28 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) Laser-field-free three-dimensional molecular orientation [1]

Laser-field-free three-dimensional orientation, corresponding to the complete control of spatial directions of asymmetric top molecules, is achieved with combined weak electrostatic and elliptically polarized laser fields with an 8-ns turnon and a 150-fs turnoff, which is shaped by a plasma shutter. Rotationally cold 3,4-dibromothiophene molecules are used as a sample and their lower-lying rotational states are selected by a molecular deflector to increase the degrees of orientation. After the rapid turnoff of the pump pulse, higher degrees of orientation are maintained for 5-10 ps, which is long enough for various applications including electronic stereodynamics in molecules with femtosecond pulses.

(2) Structure determination of molecules in an alignment laser field by femtsosecond photoelectron diffraction using an X-ray free-electron laser [2]

We have successfully determined the internuclear distance of I_2 molecules in an alignment laser field by applying our molecular structure determination methodology to an I $2p$ X-ray photoelectron diffraction profile observed with femtosecond X-ray free electron laser pulses. Using this methodology, we have found that the internuclear distance of the sample I_2 molecules in an alignment Nd:YAG laser field of 6×10^{11} W/cm^2 is elongated by from 0.18 to 0.30 Å "in average" relatively to the equilibrium internuclear distance of 2.666 Å. Thus, the present experiment constitutes a critical step towards the goal of femtosecond imaging of chemical reactions and opens a new direction for the study of ultrafast chemical reaction in the gas phase.

This work was done as a collaborative study with researchers from KEK, Ritsumeikan University, National Institutes for Quantum and Radiological Science and Technology, Chiba University, Kyoto University, Japan Synchrotron Radiation Research Institute, and RIKEN SPring-8 Center.

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29 Bamba-Nakazawa Group

Research Subjects: High-energy astrophysics, mainly utilizing X-ray observatories in orbit. Targets are, black-holes, neutron-stars, magnetors, white dwarf, 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.

For further better observations, we are also developing 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. Now the recovery mission of Hitomi is planned, and it is aimed to launch on fiscal year of ∼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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30 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 magnons 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. Investigation of laser-breakdown process in wide band-gap dielectric materials
   - 2.2. Development of mode selective phonon exciation by waveform shaped short pulse laser
   - 2.3. Investigation of process of higher harmonic generation of solids
   - 2.4. Development of real time spectroscopic imaging by high sensitive teraherz camera
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. "Photon ring" project
   - 3.4. Institute for Photon Science Technology

31 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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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.Identification of excitatory premotor interneurons which regulate local muscle contraction during Drosophila larval locomotion..

Larval locomotion is generated by rhythmic and sequential contractions of body-wall muscles from the posterior to anterior segments, which in turn are regulated by motor neurons present in the corresponding neuromeres. Motor neurons are known to receive both excitatory and inhibitory inputs, combined action of which likely regulates patterned motor activity during locomotion. Although recent studies identified candidate inhibitory premotor interneurons, the identity of premotor interneurons that provide excitatory drive to motor neurons during locomotion remains unknown. In this study, we searched for and identified two putative excitatory premotor interneurons in this system, termed CLI1 and CLI2 (cholinergic lateral interneuron 1 and 2). These neurons were segmentally arrayed and activated sequentially from the posterior to anterior segments during peristalsis. Consistent with their being excitatory premotor interneurons, the CLIs formed GRASP- and ChAT-positive putative synapses with motoneurons and were active just prior to motoneuronal firing in each segment. Moreover, local activation of CLI1s induced contraction of muscles in the corresponding body segments. Taken together, our results suggest that the CLIs directly activate motoneurons sequentially along the segments during larval locomotion. (Collaboration with Dr. James Truman at the Janelia Research Institute in the USA)

2.Gap Junction-Mediated Signaling from Motor Neurons Regulates Motor Generation in the Central Circuits of Larval Drosophila.

In this study, we used the peristaltic crawling of Drosophila larvae as a model to study how motor patterns are regulated by central circuits. Motor neurons are generally considered passive players in motor pattern generation, simply relaying information from upstream interneuronal circuits to the target muscles. This study shows instead that MNs play active roles in the control of motor generation by conveying information via gap junctions to the central pattern-generating circuits in larval Drosophila, providing novel insights into motor circuit control. The experimental system introduced in this study also presents a new approach for studying intersegmentally coordinated locomotion. Unlike traditional electrophysiology methods, this system enables the simultaneous recording and manipulation of populations of neurons that are genetically specified and span multiple segments.

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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.

Displacement of single dynein molecules driven by the neck swing

Cytoplasmic dynein is a motor protein moving along microtubules, and plays important roles in vesicle transport and mitosis. To understand the conformational changes of dynein, we measured the efficiency of FRET from dynein ring-BFP to linker-GFP, and the distance driven by power stroke of single-headed dynein interacting with microtubules by optical tweezers. The efficiency and the (apparent) stroke distance depend on ATP concentration. The low efficiency and stroke distance at low ATP concentration indicate no structural change of dynein at no ATP binding (apo) state that is predominant at low ATP. With increasing ATP concentration, population of apo state decreased and that of pre-power stroke state such as dynein ADPPi should increase. Dynein at the pre-power stroke state will generate the stroke at binding to microtubule. Therefore, the mean power stroke distance increased with ATP concentration. High efficiency and distance (9nm) at 1mM ATP indicate that the 9-nm power stroke is generated by swing of linker. This is supported by the result that the dynein mutated at its linker did not generate the power stroke. The power stroke driven by structural change of dynein linker will be fundamental mechanism of dynein motility.

Trafficking of endocytic PAR-1 carrier vesicles in cancer cell

PAR-1 is a membrane protein in the G-protein coupled receptor family, the signal cascade of which results in enhanced cell mobility. In terms of the tumor progression, PAR-1 overexpressed cancer cell shows increased migration rate, and thus it may cause the cancer metastasis. Since the serine protease, such as thrombin, activates the PAR-1s for initializing intracellular signal cascade, we focused on the movement of the endocytic PAR-1 carrier vesicle when activated by thrombin. Using dual focus optics, the movement PAR-1 is tracked in three dimensions, from its internalization. The obtained images on the dual view are processed using the affine transformation, and the z-coordinate of a target point source is evaluated according to the calibration between the z-position and the intensity, after applying Gaussian approximation. As a result, three different movement patterns are observed: diffusion on the membrane, endocytosis, and recycling. Also, the endocytic PAR-1 particularly shows an oscillating movement along z-axis during internalization, which implies the dynamics of the cytoskeleton. When PAR-1s are activated by thrombin (50 U/ml), the ratio of the slowly diffusing endosomes decreased, indicating that the activated PAR-1s diffuse more rapidly. Furthermore, it is revealed that the activated PAR-1s are more directly internalized compared to the case that is not activated, from the successive movement analysis.

Thermotaxis mechanism of mouse macrophage

To understand the movement and shape change of macrophage induced by temperature jump, we took movies of the motility of mouse macrophage before and after the jump. The jump was initiated by local illumination, 1micrometer in diameter, of cell medium by the infrared laser (1550nm, ∼300mW). Most of mouse macrophages moved toward the heat source. They stretched filopodia and lamellipodia with time delay, 1minite, after the jump. These indicate that macrophage have an ability of thermotaxis. To understand mechanism of the thermotaxis, we observed the motility of macrophage in the presence of inhibitors for Rho family such as RhoA, Rac1, cdc42. The macrophages were able to migrate in the presence of inhibitor of RhoA but did not polarize in the direction of the temperature gradient. This suggesting thermotaxis towards heat source was regulated by RhoA family.

34 Okada Group

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

Member: Yasushi Okada and Sawako Enoki

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].

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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 cellular differentiation
4. Analysis of self/non-self discrimination ability for the immune system using computational models
5. Motif analysis for small-number effects in chemical reaction dynamics
6. Theoretical analysis for collective motion of molecular motors

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