II

Summary of group activities in 2011

1 Theoretical Nuclear Physics Group

Subjects: Structure and reactions of unstable nuclei, Monte Carlo Shell Model, Molecular Orbit Method, Mean Field Calculations, Quantum Chaos
Quark-Gluon Plasma, Lattice QCD simulations, Structure of Hadrons, Color superconductivity
Relativistic Heavy Ion Collisions, Relativistic Hydrodynamics, Color Glass Condensate

Member: Takaharu Otsuka, Tetsuo Hatsuda, Naofumi Tsunoda and Shoichi Sasaki

In the nuclear theory group, a wide variety of subjects are studied. The subjects are divided into three major categories: Nuclear Structure Physics, Quantum Hadron Physics and High Energy Hadron Physics.

Nuclear Structure Physics

In the Nuclear Structure group (T. Otsuka and N. Tsunoda), 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, (ii) shell model calculations including Monte Carlo Shell Model, (iii) collective properties and IBM, (iv) reactions between heavy nuclei, (v) other topics such as Bose-Einstein condensation, 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 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 evoltion in recent years. The tensor force effect has been clarified in [1, 2], while striking effect of three-body force has been shown in [3] for the first time. The structure of such unstable nuclei has been calculated by Monte Carlo Shell Model and conventional shell model with further developments, for example, a new extrapolation method [4]. Their applications have been made in collaborations with experimentalists in internationally spread, *e.g.*, [5, 6].

The mean-field based formulation of the Interacting Boson Model is a new original approach being developed, and a long-standing problem on strongly deformed nuclei has been solved [7]. This approach is so general and powerful that its applications are being spread very fast in big collaborations, for instance, the nature of triaxial deformation has been clarified [8].

We are studying on time-dependent phenomena like fusion and multi-nucleon transfer reactions in heavy-ion collisions. A new insight on the role of fast charge equilibration at the initial stage of the reaction has been presented [9].

Quantum Hadron Physics

In Quantum Hadron Physics group (T. Hatsuda and S. Sasaki), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). Main research interests are the quark-gluon structure of hadrons, lattice gauge theories and simulations, matter under extreme conditions, quark-gluon plasma in relativistic heavy-ion collisions, high density matter, neutron stars and quark stars, chiral symmetry in nuclei, color superconductivity, and many-body problem in cold atoms and in graphene. Highlights in research activities of this year are listed below:
1. Lattice QCD studies on H-dibaryon [10]
2. Lattice QCD studies on $Q\bar{Q}$ potential [11]
3. Chiral magnetic effect on the lattice [12]
4. U(1) gauge theory on a honeycomb lattice [13]
5. Relativistic viscous hydrodynamics [14]
6. Topolgical vorties in dense QCD [15]

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Members: Takeo Moroi, Tsutomu Yanagida, 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 LHC Phenomenology [2] [12]
    1.2 Collider Phenomenology [9] [10] [1] [26]
    1.3 Higgs boson [3] [30] [32] [27] [36]
    1.4 SUSY Phenomenology [31] [33] [34] [29]
    1.5 SUSY gauge theories [35] [37]
    1.6 Cosmological constraints on dark matter models with velocity-dependent annihilation cross section [13]
    1.7 Inflation models in supergravity [14] [18] [19] [21]
    1.8 Solution to the moduli problem [15] [20]
    1.9 Curvature perturbation from velocity modulation [16]
    1.10 Isocurvature perturbations in extra radiation [17]
    1.11 Probing the early Universe with future gravitational wave detectors [22]
    1.12 Wino LSP detection in the light of recent Higgs searches at the LHC [23]
    1.13 Boltzmann equation for non-equilibrium particles and its application to non-thermal dark matter production [11]
    1.14 Gravitino Problem
    1.15 Holographic QCD [24] [25]
    1.16 Quantum field theory on the lattice
2. Superstring Theory.
    2.1 Multiple M5 branes [6]
    2.2 Correspondence between supersymmetrig gauge theory and gravity [7] [8]
    2.3 F-Theory Compactifications [4] [5]

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3 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

1) Antimatter study at CERN's antiproton decelerator

$\bar{p}$-nucleus annihilation cross section at ultra-low energies At high energies, it is known that the $\bar{p}$-nucleus annihilation cross sections scale as $\sigma_{\rm ann} \propto A^{2/3}$ where A is the nuclear mass number. However, at very low energies, this scaling is expected to be violated, but no such measurements have been done due to the lack of ultra-low-energy antiproton beams. Using a radio-frequency quadrupole decelerator ("inverse" linac), we have started the $\sigma_{\rm ann}$ measurements at 130 keV. In 2011, we developed and tested a beam chopper and detectors which consist of MPPC, plastic scintillator, and WLS fiber. We are now developing an electrostatic quadrupole triplet and the read-out electronics of the detectors. We will carry the measurement of the $\bar{p}$-nucleus annihilation cross sections in 2012.

2) Laser spectroscopy of radioactive francium isotopes at the ISOLDE facility at CERN

Laser spectroscopy is a crucial tool for studying properties of nuclear ground states. At the ISODLE facility at CERN, the new CRIS collaboration of Manchester, Leuven, Birmingham, Orsay, Max Planck Institute of Quantum Optics, and Tokyo has proposed to measure the isotope shifts and hyperfine structures of francium isotopes by collinear resonant ionization spectroscopy (CRIS). The CRIS method may provide evidence of the anomalous structure in neutron deficient francium isotopes.

In 2011, we succeeded in measuring one francium isotope with a relatively high yield. We used a nanosecond titanium-sapphire laser developed by the ASACUSA experiment at CERN. This laser was operated with a high output power of $\sim$ kW and a narrow linewidth of 100 MHz. In 2012, we plan to measure neutron deficient isotopes with relatively low yields.

3) Precision X-ray spectroscopy of kaonic atoms

The X-ray spectroscopy of kaonic atoms is a complementary tool to study kaon-nucleon/nucleus interaction. The advent of a new type of high-resolution x-ray detector, SDD, its combination with high-intensity beamline provides clean kaon beam and various trackers/counters technique, enables us to study kaonic atoms with unprecedented precision.

X-ray spectroscopy of kaonic atoms at DAΦNE In fiscal year 2011, we analyzed the data of hydrogen target and deuterium target measurements carried out during the beam time of SIDDHARTA experiment in the fiscal year 2009. From the first time ever deuterium target measurement of kaonic atom, we did not find distinguishable kaonic deuterium X-ray events from the spectrum. However, since the two measurements share the same kaon-origin X-ray background including kaonic oxygen and kaonic nitrogen X-rays produced by the kaons stopped inside the target cell, a simultaneous analysis of the spectra reduced both the statistic and the systematic errors in the shift and width of kaonic hydrogen $1s$ state. The new result achieved the best precision up to date, providing crucial constrains to the theoretical study of $\bar{K}-p$ interaction close to the production threshold of the system. "

X-ray spectroscopy of kaonic helium The J-PARC E17, which is to be carried out at K1.8BR beamline in the J-PARC hadron experimental facility, will measure x-rays from kaonic helium 3 and kaonic helium 4 to determine the strong interaction shifts in their $2p$ level. They would impose strong constraint on $\bar{K}$-nucleus interaction. In addition, we are proposing to measure the $2p$ width in kaonic helium 3 by using a method similar to the x-ray absorption spectroscopy. In fiscal year 2011, we started with the recovery works from the earthquake. SDDs and a liquid helium 3 target system were found to be not damaged. Damaged beam line chambers were fixed or replaced with new ones. Then, in February 2012, we successfully confirmed that the -0.9 GeV/c kaon beam was just as before the earthquake.

4) Study of antikaonic nuclei

Search for $\bar{K}NN$ deeply-bound antikaonic states at J-PARC The J-PARC E15 adopts ^{3}He(K^-, N) reaction to search for $\bar{K}NN$. E15 is a kinematically complete experiment in which all reaction products are detected exclusively for $K^-pp \rightarrow \Lambda p$ decay mode, and it aims to provide decisive information on the nature of the simplest antikaonic nucleus. Within the fiscal year 2011, J-PARC Main Ring was recovered from the earthquake to provide the slow-extracted beam, and the beam was actively used to tune the K1.8BR beamline to optimize for 1.0 GeV/c K^-. The simultaneous working of the beamline and central devices as well as the ^{3}He target system were also confirmed with the extracted

K^- beam, and we are now almost ready for the physics run planned within fiscal year 2012.

5) Precision spectroscopy of pionic atoms

Pionic atoms with (d,^{3}He) reaction We are planning a precise pionic-atom spectroscopy experiment with BigRIPS at RIBF, RIKEN. The goal is to study 1s and 2s pionic states in ^{121}Sn by the ^{122}Sn(d,^{3}He) reaction. The measurement will help us better understand the strong interaction between the pion and the nucleus, which leads to quantitative evaluation of the magnitude of the quark condensate at the normal nuclear density. In 2011 we analyzed the result of a pilot experiment performed in 2010. From the analysis in 2010 we confirmed that all detectors worked correctly and ^{3}He could be identified and tracked in 1,000-times larger number of background particles at a focal plane. In 2011, we transformed these data to a position spectrum of ^{3}He at the focal plane, applying a modification from the ion transfer system of RIBF. As a result, we succeeded the first measurement of ^{121}Sn pionic atom in the world. It was also the first measurement of pionic atom in the experiment at RIBF. In addition, thanks for the large angular acceptance of RIBF we also succeeded the first measurement of the angular dependence of the (d,^{3}He) reaction cross section. Now further analysis to reconstruct Q-value spectrum and preparation for the next experiment, which aims more precise and systematic study, are on going.

Pionic atoms via inverse kinematics Previous pionic atom spectroscopy experiments with stable nuclear targets could derive chiral condensate only around 0.6 ρ_0(ρ_0 : normal nuclear density). In order to study chiral condensate at different densities, we consider the possibility of pionic atom spectroscopy with neutron rich nuclei. Then, inverse kinematics is very useful method for producing pionic atoms with neutron rich nuclei.
We plan to conduct pionic atom spectroscopy in d(HI,^{3}He) reaction by using a TPC (Time Projection Chamber) filled by D_2 gas which is also an active target, and stacked silicon detectors as a full energy detector. We finished the estimation of required detector performance and plan to perform a test experiment of stacked silicon detectors.

6) Study of η' mesic nuclei

η' meson has specially-large mass of 958 MeV/c^2. This mass is thought to be caused by $U_A(1)$ anomaly, through which η' meson interacts with quark-antiquark condensate(chiral condensate) in vacuum. In nuclear medium, where chiral condensate decreases, reduction of the η' mass is expected, and existence of η' mesic nuclei is predicted. In order to study the origin of the η' mass, we are planning an experiment to search and spectroscope the η' mesic nuclei.

This experiment will be performed at GSI laboratory in Germany. We will create η' mesons in carbon nuclei by (p, d) reaction. Then energy of η' mesic nuclei will be derived by measuring momentum of outgoing deuterons with a magnetic spectrometer. In 2011, we developed an aerogel Cherenkov detector which is neccessary for background rejection. In 2012, we will test the Cherenkov detector, and perform a pilot experiment with the whole setup at GSI.

7) Study of muonium production targets

Ultra-slow polarized muon beam with the energy of 0.5$\sim$30 keV is anticipated as a new "microscope for magnetism" for the investigation of the surface magnetism. The ultra slow muon beamline was established in the RIKEN RAL muon facility. In this site, 15$\sim$20/s ultra-slow muons can be generated while initial muon beam intensity reaches to 1.3 $\times 10^6$ /s. In order to increase the intensity of the ultra-slow muons, improvements of the escaping efficiency of the muoniums from the degrader, muonium formation target (3 %), and laser ionization ($\sim 10^{-5}$) are needed. We have searched a muonium production target by using μSR method, and found that the silica aerogel has muonium production efficiency comparable to silica powder (Cab-O-Sil EH-5) which had been known as a best muonium production target. In this year, we measured time evolution of muonium distribution on the target inside, by using MWDC as the decay positron and electron tracker. Analysis is in progress.

4 Sakurai Group

Research Subjects: Nuclear structure and dynamics of exotic nuclei, Origin of elements in universe, Equation-of-state in asymmetric nuclear matter, Nuclear reactions with exotic nuclei

Member: Hiroyoshi Sakurai, Kentaro Yako

Exotic nuclei located far from the stability line are new objectives for nuclear many-body problems. This laboratory 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 utilize fast radioactive isotope (RI) beams available at the RI Beam Factory (RIBF), RIKEN. The RIBF is a world-top leading facility where RI beam intensities are the highest in the world. This laboratory maximizes RIBF utilization to access nuclei very far from the stability line as well as to exploit new types of experiments and new methods of spectroscopy via new ideas and detector developments.

Research subjects to be covered by this laboratory are ;

- **Shell evolution and collective dynamics of exotic nuclei**

  This laboratory is aiming to discover sudden changes of nuclear properties stemming from shell evolution, and to search for exotic collective motions.

- **Explosive processes in nucleosynthesis in universe such as the r-process path**

  We measure nuclear properties of neutron-rich nuclei to discuss possible locations of the r-process path as well as the astrophysical cite.

- **Equation-of-state in asymmetric nuclear matter**

  We are willing to investigate dynamics of nucleons and their correlations in a dilute nuclear-system as well as in heavy-ion collisions.

- **Development of a new research domain of RI beam reactions**

  Toward the island-of-stability, we are aiming to develop a new field of reactions with radioactive isotope beams.

Research activities in the fiscal-year 2011 are summarized as follows;

1. discovery of deformed magic number N=64 in the Zr isotopes
2. preparation of EURICA system for decay spectroscopy in 2012-2013
3. tentative assignment of the second 2^+ state in ^{110}Mo and its possible asymmetric collective motion
4. successful identification of the second excited state in ^{42}Si and finding of collective enhancement in spite of magic number of N=28
5. development of $LaBr_3$ detectors as a new generation gamma detector
6. study of ^{12}Be(p,n) reaction via development of missing mass technique with the WINDS system

5 Komamiya group

Research Subjects: (1) Preparation for an accelerator and an experiment for the International linear e^+e^- collider ILC; (2) Higgs boson and supersymmatric particle searches with the ATLAS detector at the LHC pp collider; (3) Experiment for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (4) Data analyses for the BES-II experiment at BEPC, Beijing.

Member: Sachio Komamiya, Yoshio Kamiya

We, particle physicists, are entering an exciting period in which new paradigm of the field will be opened at the TeV energy scale by new discoveries expected in experiments at high-energy frontier colliders, LHC and 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.It was internationally agreed upon to use for the main liniac technology superconducting accelerator structures.In 2007 March, the Reference Design Report was issued by the Global Design Effort (GDE) and hence the project has been accelerated as an international big-science project. The technical design will be completed by the end of 2012. 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 for ILC located at KEK. The Shintake beam size monitor is able to measure O(10)[nm] (electron vertical) beam sizes, by using a high power laser interferometer. The electron beam is emitted to the interference fringe of the split laser beams. The total energy of photons, which are emitted from the inverse Compton scattering of beam electrons with the laser beam interference fringe, is measured by a multilayer CsI(Tl) detector in downstream section of the beamline. As the phase of the fringe is scanned step by step, the total photon energy is measured at each step, and the beam size is extracted from a fitting of modulation pattern of the total photon energy as a function of the phase. Additionally, we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC.

2) Experiment for studying quantum bound states due to the earth's gravitational potential to study the equivalent theorem at the quantum level and searching for new short-range force using an ultra-cold neutron beam: A detector to measure gravitational bound states of ultra-cold neutrons has been developed. We decided to use CCDs for the position measurement of the UCNs. The CCD is going to be covered by a ^{10}B layer to convert neutron to charged nuclear fragments. The UCNs traverse 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 improved our detector and performed the experiment in 2011, and have been analyzing the data. acquired above

3) ATLAS experiment at LHC: The epoch of new paradigm for particle physics is going to open with the experiments at LHC. The high energy collision at 7 TeV (center-of-mass energy) commenced by the end of March 2010. The ATLAS detector is continuously recording data at high energies. Our students have been working on data analysis at LHC on search for Higgs boson in the very important decay mode of $H \to \gamma\gamma$ and supersymmetric partners of third generation quarks with the missing transverse energy and with b-quark signal. These results are presented at conferences and published in journals.

4) BES-II/-III experiment at IHEP: The group has considered the BES-III experiment at the Beijing e^+e^- collider BEPC-II as the candidate for the middle term project before ILC. We have conducted research and development for TOF detector for the BES-III experiment together with IHEP, USTC. We successfully completed a test of over 500 photomultipliers in 1[T] magnetic field and they are already installed to the BES-II detector. We have studied the data analysis of Λ baryon-pair production in $J\psi$ decay to determine structure functions and to search for CP violation effects. Currently BEPC-II is operating smoothly and BES-III detector is taking large samples of ψ' and J/ψ data.

6 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

Various kinds of astro-/non-accelerator/low-energy particle physics experiments have been performed and are newly being planned in our research group.

We started a new R and D study of a compact mobile anti-electron neutrino detector with plastic scintillators to be used at a nuclear reactor station, for the purpose of monitoring the power and plutonium content of the nuclear fuel. It can be used to monitor a reactor from outside of the reactor containment with no disruption of day-to-day operations at the reactor site. This unique capability may be of interest for the reactor safeguard program of the International Atomic Energy Agency(IAEA).

We propose a segmented antineutrino detector made of plastic scintillators called PANDA, Plastic Anti-Neutrino Detector Array. A small prototype was built and deployed for two months at Ohi Power Station in Fukui, Japan. A satisfactory unmanned field operation of the detector system was demonstrated there. The prototype detector consists of a 360-kg plastic scintillator array into which gadolinium-containing sheets are introduced. It is installed on a van, transported to the site, and held in the van outside of the reactor building during the measurement. We observed a difference in neutrino-like event rate before and after the shutdown of the reactor although cosmic-ray induced background events are predominant because of aboveground operation and small detector size. This is the world's first result to detect reactor anti-neutrinos with an aboveground detector.

We are running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the TOKYO AXION HELIOSCOPE, aka Sumico. We planned to continue the measurement in which we scan the mass region from 1 eV upward.

An experiment is being performed for a search for hidden sector photons kinetically mixing with the ordinary photons. The existence of the hidden sector photons and other hidden sector particles is predicted by extensions of the Standard Model, notably the ones based on string theory. The hidden sector photon is expected to come from the direction of the sun. It would be produced in the solar core or in the space by oscillation of the ordinary photon, and can transmute into the photon again in a long vacuum chamber in the laboratory. A photon sensor in the chamber would readily detects the ordinary photon. The detector is piggybacked onto the Sumico helioscope. We let the detector track the sun to search for the hidden sector photons coming from the sun and found no significant signal for the hidden sector photon. We put upper limits to the mixing angle χ of the normal photon and the hidden sector photon in the unexplored parameter region around the hidden sector photon mass region around a few millielectron volts. This is the world's first solar hidden sector photon search experiment with a dedicated solar hidden sector photon telescope.

We developed a low-cost gamma ray spectrometer for radioactivity inspection of foods aiming at personal use at home. It consists of a 25mm$\phi\times$ 25mm CsI(Tl) scintillator and a PIN photodiode. It has cost-effective performance and can discriminate between 662keV and 796keV photoelectric peaks of ^{137}Cs and ^{134}Cs, respectively. We hope it helps the individual people suffering from radioactive fallout of Fukushima Daiichi nuclear power plant caused by the tsunami of the Great East Japan Earthquake.

7 Aihara/Yokoyama Group

Research Subjects: Study of CP-Violation and Search for Physics Beyond the Standard Model in the B Meson and the τ Lepton Systems (Belle & Belle II), Dark Energy Survey at Subaru Telescope (Hyper Suprime-cam), Long Baseline Neutrino Oscillation Experiment (T2K), R&D for the Next Generation Neutrino and Nucleon Decay Experiment (Hyper-Kamiokande), Measurement of Neutrino-nucleus Interactions (SciBooNE), and R&D for Hybrid Photodetectors.

Members: H. Aihara, M. Yokoyama, and Y. Onuki

One of the major research activities in our group has been a study of CP-violation and a search for physics beyond the Standard Model in the B meson and the τ lepton systems using the KEK B-factory (KEKB). This past year, we continued a study of Michel parameters of the τ lepton, which is sensitive to physics beyond the Standard Model. Using ~ 900 million $\tau^+\tau^-$ pairs recorded with the Belle detector, we intend to significantly improve the precision of measurement over previous measurements.

The SuperKEKB project started in 2010. The upgraded accelerator, Super KEKB, will have 40 times more luminosity than KEKB. The Belle detector is also being upgraded as Belle II detector with cuttingedge technology. One of key elements for the success of Belle II will be its Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons. This year our group started to take responsibility to construct Belle II SVD. The R&D for the upgrade of the Belle II electromagnetic calorimeter was also carried out.

As an observational cosmology project, we are involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) to be mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct extensive wide-filed deep survey to investigate weak lensing. This data will be used to develop 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy. This year, the camera was assembled and transported to Subaru telescope site at Hawaii.

The T2K long baseline neutrino oscillation experiment started in April 2009. We have searched for $\nu_\mu \to \nu_e$ oscillation using data collected from January 2010 to March 2011, and reported the first indication of ν_e appearance from ν_μ beam. The experiment recovered the damage from the earthquake in March 2011, and resumed data taking in March 2012. With more data, we expect to continue leading the study of neutrino oscillation.

In order to pursue the study of properties of neutrino beyond T2K, we have been designing the next generation water Cherenkov detector, Hyper-Kamiokande (HK). One of the main goals of HK is the search for CP violation in leptonic sector using accelerator neutrino and anti-neutrino beams. The sensitivity to CP violating phase is studied with full simulation by our group. It is shown that with HK and J-PARC accelerator, CP violation can be observed after five years of experiment for a large part of possible parameter space. We have published a document summarizing the baseline design and physics capabilities of Hyper-Kamiokande.

We have been developing hybrid photodetector (HPD) combining a large-format phototube technology and avalanche diode as photo-electron multiplier. This year, we have developed 8-inch HPD with all glass design, together with a compact high voltage supply and readout electronics. This device can be deployed for large water Cherenkov detectors, envisioned as the next generation proton-decay/neutrino detectors.

In order to reduce the uncertainty in the neutrino oscillation measurements, we have been analyzing data from SciBooNE, an experiment performed at Fermilab to study neutrino-nucleus interaction. We have also searched for neutrino oscillation together with MiniBooNE collaboration.

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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 (4) Positronium and QED

Member: S.Asai

- (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 Extra-dimension.
  - Higgs: Both the ATLAS and CMS detectors record the data more than 5 fb-1 in 2011. The tantalizing hint of Higgs boson is found at M=124-126GeV. This is not yet enough statistically, but the various analyses and both detectors point the same mass region.

- SUSY: We have excluded the light SUSY particles (gluino/squark) whose masses are lighter than 1.4TeV.
- Extra-dimension If the extra-dimension is compactified at a few TeV scale, Mini-black hole and KK excitation are interesting signals. We search for these topologies and we have set the limit of about 2-4TeV for the planck scale.

- (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:
  - Precise measurement Search HFS of the positronium.
  - Developing high power (>500W) stable sub THz RF source
  - Axion searches using Spring 8

9 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Takashi Oka

Our main interests are many-body and topological effects in electron systems, i.e., **superconductivity, magnetism and topological phenomena**, for which we envisage a **materials design for correlated electron systems** and novel **non-equilibrium** phenomena should be realised. Studies in the 2011 academic year include:

- Superconductivity
  — Superconductivity induced in non-equilibrium: Dynamical repulsion-attraction conversion in intense ac fields [1]
  — High-Tc cuprates: material- and pressure-dependence [2]
  — Superconductivity in solids of aromatic molecules [3]
  — Collective modes in multi-band superconductors
- Magnetism
  — Ferromagnetism in cold atoms and spin Hall effect
- Topological systems: Quantum Hall systems and graphene
  — Graphene QHE and generalised chiral symmetry[4]
  — Optica (THz) Hall effect in graphene[5]
  — Photovoltaic Hall effect in graphene [6]
  — Fractional quantum Hall effect in oxides [7]
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  — Non-linear transport in the dielectrically broken Mott insulators
  — Thermalisation treated with AdS/CFT [8]

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10 Miyashita Group

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

Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita and Takashi Mori

10.1 Cooperative Phenomena and Phase Transition

Study on phase transitions and critical phenomena is one of main subjects of the statistical mechanics. We have studied various types of ordering phenomena in systems with large fluctuation. In the last year, we studied the following topics of phase transitions.

Phase transitions of long-range interacting systems

Systems with bistable local electric states, such as the spin-crossover, Jahn-Teller system, and martensite systems, have been attracted interests as seminal candidates of the so-called functional material because the bistable states can be switched by the temperature, pressure, magnetic field, and photo-irradiation. We have proposed a general structure of the ordered states including metastable state, where we find various new types of phase transitions.We also pointed out that difference of local structures of the lattice of the states causes a new aspect of the ordering phenomena. In the spin-crossover systems, the size of molecules in the high spin (HS) and low spin (LS) are different and the lattice distorts in the mixture of the both spin states.This lattice distortion causes an effective long range interaction among spin states, and realizes a phase transition of the mean-field universality class.The long range interaction prefers a uniform configuration and thus the systems keeps homogeneous configuration even near the critical temperature. However, when the systems change between the two states in open boundary condition, the systems show inhomogeneous structures.In a rectangle lattice, the changes start from the corners, but the domains which appear in the process are macroscopic. That is, the configurations are the same if we scale the sizes. We also studied the switch in a circular system which has no corner. In this system, a kind of nucleation occurs from the surface. Here we again find that shapes of the critical nuclei and also the following clusters growth are geometrically similar in systems of different sizes. This feature is qualitatively different from that of short-range interaction systems, in which the critical droplet has a specific size independently of the system size.[6]

We have also studied shape and dynamics of the domain wall. In the short-range model, the width of the domain wall is proportional to the square of the system size L. However, in the long-range model, it is found to be proportional to the system size L, and thus again the shapes are geometrically similar in systems of different sizes. In Fig. 3.2.2, we show the configurations of the domain walls of different sizes.[21]

In the long-range model, configurations with large clusters are suppressed.However, if the short-range interaction is included, it cause a short range correlation. Thus the system shows a finite correlation length at the critical point. We studied a scaling relation of the shift of the critical point from the pure short range model as a function of the strength of the long-range interaction. We also studied a scaling relation of the correlation length at the critical point. We first study these properties in an Ising model of mixture of the nearest-neighbor interaction and infinite range interaction in a fixed lattice.[3] Then we found that the scaling relations work in the elastic model, too.[8]

Ordered states of long-range interacting system

We also studied in which condition systems with long range interaction are described by the mean-field theory. It is expected that in the cases where the interaction is non-additive, where the extensivity is not satisfied and the so-called Kac procedure is necessary, the thermal properties are described by the mean-field theory if the order parameter is not conserved. We investigate the condition in detail, and confirmed this property. Moreover, we found that even in this case, the properties in a fixed value of order parameter cannot be described by the mean-filed theory in some parameter region. This indicates that the uniform configuration of the mean-field theory becomes unstable in such parameter region. We are studying the properties of such states. [11, 31, 51]

Phase transitions of the mixed phases

We have pointed out that the partially-disordered phase of the antiferromagnetic Ising model in the triangular lattice is a kind of mixed phase of a generalized six-states clock model.The mixed state is an equilibrium phase in which two of the six states are chosen to appear. We have studied general structure of the mixed states as a function of energy structure of the interaction. We have demonstrated a mixed phase with more than two states, and also successive phase transitions with different types of mixing. In Fig. 3.2.3, we show a temperature dependence of populations of the states. There we find a disordered phase at high temperature where all the six states have the same population, and then a phase of a 3-phase-mixing phase and then 2-state-mixing phase and finally a ferromagnetic phase (single state) as the temperature decreases.[20]

Stochastic process

Generalization of many particle Brownian motion has been proposed by using a differential-difference operator so-called Dunkl operator. Processes given by the operator is called Dunkl processes and have been studied in the field of mathematics. We have studied explicit expression of the effect of the intertwining operator. The processes are deeply related to the Dyson's Brownian motion, and we have studied relations of them to physical processes.[36, 42, 52]

10.2 Quantum Statistical Mechanics

Cooperative phenomena in quantum systems are also important subject in our group. In quantum systems, they show interesting non-classical behavior both in static and dynamical properties. In the last year, we studied the following topics.

Qauntum phases

We studied ground and low temperature properties of antiferromagnetic Heisenberg model on the Kagome lattice. We investigated effects of types of Dzyaloshinskii-Moriya Interactions and also effects of distributions of the spin length(i.e., $S = 1/2$ and 1).[5]

We also propose an itinerant electrons model (Hubbard model) in which the total spin is controlled by the chemical potential, and proposed new types of molecular magnets[2]

Qauntum respose

We also studied the dynamical properties and also response where various interesting processes appear.[2] Coherent dynamics of quantum systems exhibits various nonclassical natures and the manipulation of such processes gives important basis of quantum information processing. We have developed formulations of the quantum master equation to describe quantum response in dissipative environments.

In the last year, we studied hybridization of a system with discrete energy structure (spins or atoms) in the cavity and the cavity photon. We studied how the nature of the system changes with the number of spins and also as a function of the strength of driving force (intensity of input field). We clarified how the system move from the weakly excited region where we observe the vacuum-field Rabi splitting to the strongly excited region where we observe the Rabi oscillation in the classical electromagnetic field.[10] We show the dependence of Rabi oscillation on the number of photons in the cavity in Fig. 3.2.4.

We provide numerical tool for super-computer to calculate the dynamics of quantum master equation (Portal site for Application Software Library: quantum-dynamics-simulator)[56].

We also developed a new master equation to study the cases with strong interaction between spins and photons, where interesting cooperativity appear. When the interaction becomes strong, the ground state of the system exhibits a phase transition and photon and polarization appear spontaneously which is called Dicke transition. Beside this transition, it is known that the system exhibits a nonequilibrium phase transition under driving force, which is called optical bistability. There, due to a change of balance between driving force and dissipation, a discontinuous changes of quantities in the stationary state take place. We studied the synergetic effects of the both phase transition, and obtained phase diagram as a function of the interaction between spin and photon and the strength of the driving force. In order to study dissipative phenomenon in strongly interacting system, we need to extend the master equation from the simple Lindblad form to ones in which effects of interaction are taken into account in dissipative mechanism. We built up such equation of motion and obtained the phase diagram for the Tavis-Cummings model and alos for Dicke mode. [37, 43]

Dissipation of the Rabi oscillation

The Rabi oscillation has been measured as a prove of quantum coherence of spins (or any discrete energy level system). We have studied mechanism of decoherence due to the randomness of the parameters for each spin such as distribution of magnetic anisotropy and strength of the magnetic field, and also due to the dipolar-dipolar interaction by using large scale computation. [7]

We also propose an experiment to check the picture of wavefunction collapse in individual events in quantum mechanics. [8]

Quantum inverse scattering method for higher spin systems

As a study on the exact solvable models, we studied the exact property of spin chain by making use of algebraic Bethe anzatz. In particular, we investigated properties of boundary states of $S = 1$ spin chain, and studied effects of boundary condition on the ground state in quantum integrable systems. We also clarified the relation between nonlinear equation and the supersymmetric sine-Gordon model. [19]

Quantum transport phenomena

Classification of fluctuations in nonequilibrium statistical mechanics has been developed extensively. The so-called fluctuation theorem is one of the typical example. We have studied to verify the fluctuation theorem in quantum transport phenomena.[12] Moreover, the so-called additivity principle is also important property and we have extend the idea.[15] We also studied exact properties of the stationary nonequilibrium states in heat conducting quantum systems.[14, 16] We also studied general properties of the thermodynamical efficiency in micro systems. [13, 17]

11 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, magnetic systems, low-dimensional electron systems, organic conductors, unconventional superconductivity, and Dirac electron systems in solids. The followings are the current topics in our group.

- High-T_c superconductivity
  Mott metal-insulator transition and superconductivity.[6]
  Theory on multi-layer cuprate superconductors.
- New superconductor: Iron-pnictide
  Effects of nonmagnetic impurities in iron-pnictide superconductors.[11]
  Quasi-particle interference patterns in d-wave superconductors.
  Orbital-selective superconductivity and the effect of lattice distortion.[9]
- Organic conductors [7]
  Modeling and magnetism in one-dimensional Fe-phthalocyanine compounds.[8]
  Antiferromagnetic interaction between LUMO electrons in $(C_6H_6)^{2-}$.
  Novel spin-liquid states in an anisotropic-triangular spin-system.
- Theories of anisotropic superconductivity
  Spatial patterns of the two-dimensional FFLO superconductivity near zero temperature.
- Dirac electron systems in solids [4]
  Spin-polarized currents in Dirac fermion systems.[5]
  Spin Hall effects in Bi.
  Electronic states in a new Dirac system: Ca_3PbO.[2,3]
  Twin Dirac points realized in a antiperovskite material.
- Theories on heavy fermion systems and Kondo effect
  Charge Kondo effect due to pair-hopping mechanism.
  Heavy fermion behavior due to orbital degrees of freedom in transition metal compounds.
  Microscopic theory on defect-induced Kondo effects in graphen.[10]

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12 Tsuneyuki Group

Research Subjects: Theoretical Condensed-matter physics

Member: Shinji Tsuneyuki and Yoshihiro Gohda

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 beoynd the limitation of classical MD and DFT for study of electronic, structural and dynamical properties of materials.

For example, the transcorrelated (TC) method is a wavefunction-based approach to correlated electrons in solids, which we are trying to establish for an alternative of the density functional theory for years. In FY2011, we have developed a new method of optimizing so-called Jastrow function in the correlated wavefunction in the TC method.

We also developed a first-principles modeling method of the anharmonic lattice vibration in solids. After first-principles MD simulations, we systematically obtain parameters of an anharmonic potential model, with which thermal properties like thermal conductivity or thermal expansion are calculated with classical molecular dynamics.

In summary, our research subjects in FY2010 were as follows:

- New methods of first-principles calculation of material properties
  - First-principles wavefunction theory for solids based on the transcorrelated method
  - Generalized anharmonic lattice model of crystals for investigating thermal conductivity
  - Density functional theory for superconductors
  - FMO-LCMO method: a new method of electronic structure calculation of huge biomolecules based on the fragment molecular orbital (FMO) method
- Applications of first-principles calculation
  - Electric double layer and its capacitance formed on solid-liquidinterfaces
  - Structural transition of graphen on GaN surface
  - Origin of ferroelectricity in $BaTiO_3$
  - Electric dipole layer at the water-electrode interface
  - Magnetic anisotropy in α''-Fe

13 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

We study the electronic structure of strongly correlated systems using high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy and soft x-ray magnetic circular dichroism using synchrotron radiation. We investigate mechanisms of high-temperature superconductivity [1], metal-insulator transitions, giant magnetoresistance, carrier-induced ferromagentism, spin/charge/orbital ordering in strongly correalted systems such as transition-metal oxides [2], magnetic semiconductors [3], and their interfaces and nano-structures.

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14 Uchida Group

Research Subjects: High-T_c superconductivity

Member:Uchida Shin-ichi (professor), Kakeshita Teruhisa. (research associate)

1. Project and Research Goal

The striking features of low-dimensional electronic systems with strong correlations are the "fractionalization" of an electron and the "self-organization" of electrons to form nanoscale orders. In one dimension (1D), an electron is fractionalized into two separate quantum-mechanical particles, one containing its charge (holon) and the other its spin (spinon). In two dimensions (2D) strongly correlated electrons tend to form spin/charge stripe order.

Our study focuses on 1D and 2D copper oxides with various configurations of the corner-sharing CuO_4 squares. The common characteristics of such configurations are the quenching of the orbital degree of freedom due to degraded crystal symmetry and the extremely large exchange interaction (J) between neighboring Cu spins due to large $d-p$ overlap (arising from 180° Cu-O-Cu bonds) as well as to the small charge-transfer energy. The quenching of orbitals tends to make the holon and spinon to be well-defined excitations in 1D with quantum-mechanical character, and the extremely large J is one of the factors that give rise to superconductivity with unprecedentedly high Tc as well as the charge/spin stripe order in 2D cuprates. The experimental researches of our laboratory are based upon successful synthesis of high quality single crystals of cuprate materials with well-controlled doping concentrations which surpasses any laboratory/institute in the world. This enables us to make systematic and quantitative study of the charge/spin dynamics by the transport and optical measurements on the strongly anisotropic systems. We also perform quite effective and highly productive collaboration with world-leading research groups in the synchrotron-radiation, μSR and neutron facilities, and STM/STS to reveal electronic structure/phenomena of cuprates in real- and momentum-space.

2. Accomplishment

(1) Ladder Cuprate

Significant progress has been made in the experimental study of a hole-doped two-leg ladder system $Sr_{14-x}Ca_xCu_{24}O_{41}$ and undoped $La_6Ca_8Cu_{24}O_{41}$:

1) From the high pressure (P) study we constructed and x-P phase diagram (in collaboration with Prof. N. Môri's group). We find that the superconductivity appears as a superconductor-insulator transition only under pressures higher than 3GPa and that the superconducting phase is restricted in the range of x larger than 10. In lower P and smaller x regions the system is insulating.

2) The pairing wave function in the superconducting phase has an s-wave like symmetry which is evidenced by a coherence peak at T_c in the nuclear relaxation rate, revealed by the first successful NMR measurement under high pressure.

3) The origin of the insulating phase dominating the whole $x - P$ phase diagram is most likely the charge order of doped holes or hole pairs as suggested by the presence of a collective charge mode in the x=0, $Sr_{14}Cu_{24}O_{41}$, compound in the inelastic light scattering (with G. Blumberg, Bell Lab.), microwave and nonlinear conductivity (with A. Maeda and H. Kitano, U. of Tokyo), and inelastic X-ray scattering (with P. Abbamonte and G. A. Sawatzky).

4) In the undoped compound $La_6Ca_8Cu_{24}O_{41}$ spin thermal conductivity is remarkably enhanced to the level of silver metal along the ladder-leg direction due to the presence of a spin gap and to a ballistic-like heat transport characteristic of 1D.

(2) Observation of Two Gaps, Pseudogap and Superconducting Gap, in Underdoped High-T$_c$ Cuprates.

The most important and mysterious feature which distinguishes cuprate from conventional superconductors is the existence of “ pseudogap ” in the normal state which has the same d-wave symmetry as the superconducting gap does. We employed c-axis optical spectrum of $Yba_2Cu_3O_{6.8}$ as a suitable probe for exploring gaps with d-wave symmetry to investigate the inter-relationship between two gaps. We find that the two gaps are distinct in energy scale and they coexist in the superconducting state, suggesting that the pseudogap is not merely a gap associated with pairs without phase coherence, but it might originate from a new state of matter which competed with d-wave superconductivity.

(3) Nanoscale Electronic Phenomena in the High-T_c Superconducting State

The STM/STS collaboration with J. C. Davis' group in Cornell Univ. is discovering numerous unexpected nanoscale phenomena, spatial modulation of the electronic state (local density of states, LDOS), in the superconducting CuO_2 planes using STM with sub-Å resolution and unprecedentedly high stability. These include (a) “+” or “×” shaped quasiparticle (QP) clouds around an individual non-magnetic Zn (magnetic Ni) impurity atom, (b) spatial variation (distribution) of the SC gap magnitude, (c) a “checkerboard” pattern of QP states with four unit cell periodicity around vortex cores, and (d) quantum interference of the QP. This year's highlights are as follows:

1) Granular structure of high-Tc superconductivity

The STM observation of “gap map” has been extended to various doping levels of $Bi_2Sr_2CaCu_2O_{8+\delta}$. The result reveals an apparent segregation of the electronic structure into SC domains of ∼3mm size with local energy gap smaller than 60meV, located in an electronically distinct background (“pseudogap” phase) with local gap larger than 60meV but without phase coherence of pairs. With decrease of doped hole density, the (coverage) fraction of the superconducting area decreases or the density of the number of superconducting islands decreases. Apparently, this is related to the doping dependence of superfluid density as well as the doping dependence of the normal-state carrier density.

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

Modulation of LDOS is observed even without vortices, at zero magnetic field. In this case, the modulation is weak and incommensurate with lattice period, showing energy (bias voltage) dependence. The dispersion is explained by quasiparticle interference due to elastic scattering between characteristic regions of momentum-space, consistent with the Fermi surface and the d-wave SC gap determined by ARPES (angle-resolved-photoemission).

These dispersive quasiparticle interference is observed at all dopings, and hence the low-energy states, dominated by the states on the “Fermi arc” formed surrounding the gap nodes, are spatially homogeneous(nodal superconductivity). By contrast, the quasiparticle states near the antinodal region degrade in coherence with decreasing doping, but have dominant contribution to superfluid density. This suggests that the volume fraction of spatial regions all of whose Fermi surface contributes to superfluid decreases with reduced doping. The result indicates the special relationship between real-space and momentum-space electronic structure.

15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Toru HIRAHARA

Surfaces of materials are platforms of our research where rich physics is expected due to the low-dimensionality and symmetry break down. (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 semiconductor surfaces, topological surfaces, and nano-scale phases such as surface superstructures and ultra-thin films. We use ultrahigh vacuum experimental techniques such as electron diffraction, scanning electron microscopy, scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy, *in-situ* four-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes, and surface mageto-optical Kerr effect measurements. Main results in this year are as follows.

(1) Surface electronic transport: Monolayer superconductivity. Current-induced spin polarization effect in strong spin-orbit-interaction materials. Control of surface electronic states and their conductivity of topological insulators. Anisotropic transport on a quasi-one-dimensional metallic surface.

(2) Surface phases, ultra-thin films, and phase transitions: 2D topological materials. Doping into topological insulators. Topological phase transition. Order-disorder phase transition, charge-density-wave transition, Mott transition on various metal-induced surface superstructures of Si. Quantum-well state in ultra-thin metal films. Rashba effect in surface state and hybridization with quantum-well states in thin films.

(3) Surface magnetism: Monolayer ferromagnetic surfaces. Diluted magnetic surface states. Kondo effect and RKKY interaction in surface states.

(4) Construction of new apparatuses: Low-temperature strong-magnetic-field scanning tunneling microscope. Micro-four-point probes apparatus at mK under strong magnetic field.

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16 Fukuyama Group

Research Subjects: Low Temperature Physics (Experimental):
Quantum fluids and solids with strong correlations and frustration,
Scanning tunneling microscopy and spectroscopy of two dimensional electron systems in graphene and superconductivity in nanometer scale.

Member: Hiroshi Fukuyama, Tomohiro Matsui

Our current interests are (i) quantum phases with strong correlations and frustration in two dimensional (2D) helium three (^{3}He), (ii) novel phenomena related to graphene, monatomic sheet of carbon atoms. We are investigating these phenomena at ultra-low temperatures down to 50 μK, using various experimental techniques such as NMR, calorimetry, scanning tunneling microscopy and spectroscopy (STM/S), low energy electron diffraction (LEED) and transport measurement, *etc.*

1. **Ground-state of two dimensional ^{3}He:**

   It is an interesting open question to ask whether the critical point, i.e., the gas-liquid transition, exists in strictly 2D ^{3}He. The previous quantum many-body calculations predict interestingly that ^{3}He does not have the critical point but ^{4}He does in pure 2D case. We have measured low-temperature heat capacities (C) of the first three atomic layers of ^{3}He adsorbed on a graphite surface to elucidate if the ground state of each layer is gas or liquid phase. The elucidation is based on the fact that the coefficient (γ) of T-linear term in $C_{(T)}$ in degenerated fermion system is determined by the surface area over which the fermions spread and the quasi-particle effective mass. It had been found until last year that there is the critical point over second layer and ^{3}He atoms form 2D paddles at low densities ($\rho < 1.5$ nm^{-2}). This year, we found that even the first layer, where the confinement potential from the substrate is stronger, does have the critical point, too. Moreover, the density of the 2D paddle is comparable with that in second and third layers. Therefore, we can conclude that the ground state of 2D ^{3}He is the liquid phase, and that the interaction between ^{3}He atoms in 2D is attractive in average.

   Though graphite is an ideal substrate for adsorbing atoms, it contains some inhomogeneous regions unavoidably, which affects the physical properties of adsorbed systems. However, the amount of the inhomogeneous regions had not been well evaluated and the areal density had not been precise enough. In our experiments, we succeeded to evaluate the amount as ~ 5 % of the total surface area, in our substrate, through the analysis of the heat capacities of the first layer ^{3}He on graphite by clearly demonstrate that the measured heat capacities can be decomposed into the one of the two dimensional ^{3}He and of the amorphous ^{3}He on graphite.

2. **The 4/7 phase of second layer ^{4}He on graphite:**

   We have prepared a new sample cell for high-precision heat capacity measurements of the possible order-disorder transition around $T = 1$ K using a ZYX exfoliated graphite substrate which has much larger micro-crystalline size than the previous one. With this set-up, the heat capacities and the vapor pressures are measured for the first and second layers of ^{4}He.
   For the first layer ^{4}He, a peak structure is observed in the temperature dependence of the heat capacity at the areal density of $\sqrt{3} \times \sqrt{3}$ commensurate phase more clearly than that observed on the other substrate.
   For the second layer ^{4}He, the gradual change of the peak in the heat capacity is observed, which suggest the growth of two dimensional phase from fluid, commensurate solid and then incommensurate solid. In addition, a clear evidence of the 4/7 phase is observed in the density dependence of the vapor pressure as a sub-step at the density. It can also be confirmed that the 4/7 phase is occured before the promotion of the third layer from the density dependence of the isosteric heat. Our experimental results clearly show the existence of the 4/7 commensurate phase around which many interesting quantum phenomena are proposed to emerge at low temperatures.
   In addition, a LEED (low energy electron diffraction) experiment below 0.5 K is also designing in order to determine the structures of the commensurate 4/7 phase unambiguously.

3. **Bandgap tuning in functionalized graphene:**

   Graphene, a single layer of graphite, has attracted considerable attention owing to its remarkable electronic and structual properties and its possible applications in many emerging fields such as graphene-based electronic devices. The charge carriers in graphene behave like massless Dirac fermions, and graphene shows ballistic charge transport, turning it into an ideal material for circuit fablication. However, graphene lackes a band gap around the Fermi level, which is essential for controlling the conductivity by electronic means. One of the routes to open a band gap is the adsorption of atoms. An energy gap is observed in Kekulé-type structure on graphene, and such structure is expected to be induced by adsorbing atoms on the hollow sites of graphene honeycomb lattice in a $\sqrt{3} \times \sqrt{3}$ commensurate strucure since the nearest-neighbor hopping amplitudes would acquire alternating values. Based on this idea, we are studying band gap formation by adsorbing Kr atoms on graphene by measuring the local density of states with STM/S and transport properties.

4. **Superconducting nano-particles on Graphite:**

   Since graphene is fabricated on top of a substrate, one can directly couple dopants with 2D electron gas in graphene, whose carrier density and type can be tuned by an applied gate voltage. Thus, graphene could provide an ideal substrate for study of superconducting proximity effect, and at the same time, superconducting nano-particles on 2D electron/hole system. This year, we have studied

Indium superconducting nano-particles self-assenbled on graphite, instead of graphene, by means of STM/S. On an In nano-particle, unexpectedly large and deep superconducting gap with small coherence peaks are observed suggesting the localization of the Cooper pairs in superconducting nano-particles. The density of states are remained suppressed at $V = 0$ mV without coherence peaks even in higher temperatures and magnetic fields than critical temperature and field. It suggests that the cooper pairs are pre-formed without macroscopic coherence above critical values which is usually defined from the macroscopic properties like conductivity and magnetisation.

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 semiconductor 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.

   In 2011, we have started to use a scanning tunneling microscope.
2. Superconductivity of ultrathin Pb films on cleaved GaAs surfaces:
   We have performed magnetotransport measurements on ultrathin Pb films down to submonolayer thicknesses. We observed superconductivity even for a film of 0.22 nm thickness, which is below one monolayer. While the critical magnetic field is 0.3 T in the perpendicular orientation, the superconductivity is not suppressed even at 9 T in the in-plane orientation. An in-plane magnetic field of $B_{\parallel} = 8.5$ T does not cause a significant change in the resistivity ρ vs T curve. Furthermore, we have studied the orbital effect of the perpendicular component $B_{\perp}$ of the magnetic field at $T = 0.5$ K and found that the ρ vs $B_{\perp}$ curve does not depend on the in-plane component at least up to $B_{\parallel} = 9$ T. These observations are surprising since a theoretical critical field is estimated to be 1.7 T from the Pauli paramagnetism. In our system, the structure inversion symmetry is broken and the spin-orbit interaction is expected to be strong. It is likely that the Rashba effect plays an essential role on the formation of the superconducting state.
3. Strongly correlated two dimensional systems:
   Cyclotron resonance of two-dimensional electrons is studied for a high-mobility Si/SiGe quantum well in the presence of an in-plane magnetic field, which induces spin polarization. The relaxation time τ_{CR} shows a negative in-plane magnetic field dependence, which is similar to that of the transport scattering time τ_t obtained from dc resistivity. The resonance magnetic field shows an unexpected negative shift with increasing in-plane magnetic field.

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. 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. **High density electron-hole system in semiconductors:** We have investigated the exciton Mott transition in Si by optical pump and terahertz probe experiments. We observed the excitonic correlation above the mean-field Mott density, as manifested by the non-vanishing 1s-2p transition of excitons at 3 THz in the high density regime. From the spectral analysis of the optical conductivity and the dielectric function, the following parameters were determined: the plasma frequency, 1s-2p transition energy of excitons, the density of free carriers and excitons, the inonization ratio of excitons, the carrier scattering rate and the damping constant of excitons associated with the 1s-2p transition. The carrier scattering rate is largely enhanced at the proximity of exciton Mott transition density, which is attributed to the non-vanishing excitonic correlation. Moreover, we found a coupled behavior of excitons and plasmons in the behovior of loss function spectrum $\mathrm{Im}(-1/\epsilon(\omega))$ in the density region across the Mott density, indicating the coupling of charge density fluctuation with the excitonic polarization.
2. **Optical control of superconductivity by intense THz pulses:** By using an intense THz light source generated by optical rectification of femtosecond laser pulses in a $LiNbO_3$ crystal, we have investigated the ultrafast dynamics of a non-equilibrium BCS state in a superconducting NbN film. After the instantaneous photo-injection of high density quasiparticles by the THz pump pulse, ultrafast suppression of BCS superconducting order is observed in the optical conductivity spectrum, associated with the spatially inhomogeneous distribution of the order parameter.
3. **Dynamical magnetoelectric effect at the resonance of electromagnon in a multiferroic helimagnet:** Dynamical magnetoelectric effect, namely the dynamical cross-coupling of spontaneous polarization(**P**) and magnetization(**M**) is discovered in a multiferroic helimagnet (Eu,Y)MnO_3 at the resonance of electromagon, i.e. the electrically driven magnetic excitation, in sub-THz frequency range. Due to the dynamical cross-coupling of **P** and **M**, the material is found to exhibit colossal directional dichroism- a difference in the absorption of light propagating in opposite directions-at the resonance frequency associated with the electromagnon.

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19 Takagi Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi

We study the properties of correlated electron systems, such as superconductivity, magnetism, spin-orbit-interaction-induced Mott transition, thermoelectric power. The summary of our research in this year is as following.

1. **Superconductivity of transition metal Pnictide:** We have studied of binary ruthenium pnictides, RuP and RuAs, with an orthorhombic MnP structure. We have found that these compounds show a metal-nonmagnetic insulator transition at T_{MI} = 270 and 200 K, respectively. These transitions

are suppressed by substituting Ru with Rh. We confirmed appearance of superconductivity with a maximum $T_c = 3.7$ and 1.8 K in a narrow composition range around the critical point for the pseudogap phase. It is characteristic that the critical point here is neither antiferromagnetic nor ferromagnetic, as is usually the case in widely discussed superconductivity at a critical point.

2. **The study of Sr_2IrO_4 with resonant inelastic X-ray scattering (RIXS):** We have performed an Ir $L3$ edge resonant inelastic x-ray scattering measurement of the low-lying electronic excitations in Sr_2IrO_4 over the complete Brillouin zone of the IrO_2 plane. A remarkably strong inelastic signal which exceeds the elastic scattering in intensity is observed. Peaks observed at 0.5, 3.2, and 6.0 eV are respectively ascribed to an interband transition across the Mott gap and charge-transfer excitations from the O 2p band to the Ir 5d bands. We have observed that the dispersion of the Mott gap excitation is weak. This indicates that the narrow 5d band of Sr_2IrO_4 is governed by the spin-orbit interaction, which induces the novel Mott insulating state.

3. **Optical study of pressure-induced metal-insulator transition in LiV_2O_4:** The metal-insulator (MI) transition in LiV_2O_4 has been studied by optical measurements in infrared regions at low temperatures and under high pressures. At 40 K, the metal phase under ambient pressure changes gradually into the insulating state under pressures above 7 GPa. At pressures higher than 8 GPa, the precursor of the structural phase transition is observed as a softening of optical phonon peak in the far-infrared region with decreasing temperatures. We have found that the pressure-induced MI transition occurs not only at low temperatures but also at room temperature. The phonon-softening behavior is only observed near the boundary to the insulator phase, where a complete homogeneous structural change seems to occur. On the contrary, an inhomogeneous structural change is realized in the intermediate phase between the metal and insulator phases.

4. **Thermoelectric performance of pseudogap system Ru_2Sn_3:** We have investigated a material with pseudo gap as a candidate for high performance thermoelectric material. Since pseudo gap system has a steep density of states around the Fermi level, high Seebeck coefficient could be expected by adjusting a position of the Fermi level through carrier doping. In this study, we have focused on Ru_2Sn_3, which is a semi-metal with pseudo gap. We observed relatively high figure of merit, ZT = 0.15, which is realized through asymmetric dispersion of electron- and hole-bands. In addition, we have improved figure of merit up to ZT = 0.30 through suppression of a thermal conductivity by introducing a Sn deficiency.

20 Theoretical Astrophysics Group

Research Subjects: Oservational Cosmology, Extrasolar Planets,

Member: Yasushi Suto, & Atsushi Taruya

The Theoretical Astrophysics Group carries out a wide range of research programmes. However, astrophysics is a very broad field of research, and it goes without saying that our group alone cannot cover all the various important astrophysical research topics on hand. Among others we place emphasis on the "Observational Cosmology".

"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.

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;

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

2009

- The Central Engine of Gamma-Ray Bursts and Core-Collapse Supernovae Probed with Neutrino and Gravitational Wave Emissions
- Numerical Studies on Galaxy Clustering for Upcoming Wide and Deep Surveys: Baryon Acoustic Oscillations and Primordial Non-Gaussianity
- Toward a precise measurement of neutrino mass through nonlinear galaxy power spectrum based on perturbation theory
- Toward Remote Sensing of Extrasolar Earth-like Planets
- Improved Modeling of the Rossiter-McLaughlin Effect for Transiting Exoplanetary Systems
- Forecasting constraints on cosmological parameters with CMB-galaxy lensing cross-correlations

2008

- Holographic non-local operators
- Neutrino Probes of Core-collapse Supernova Interiors
- Inhomogeneity in Intracluster Medium and Its Cosmological Implications
- Nuclear "pasta" structure in supernovae
- Investigation of the Sources of Ultra-high-energy Cosmic Rays with Numerical Simulations
- Formation of Pulsar Planet Systems -Comparison with the Standard Scenario of Planetary Formation-

2007

- The Rossiter effect of extrasolar transiting planetrary systems ? perturbative approach and application to the detection of planetary rings
- Stability of flux compactifications and de Sitter thermodynamics
- Study of core-collapse supernovae in special relativistic magnetohydrodynamics
- Spectroscopic Studies of Transiting Planetary Systems
- The relation of the Galactic extinction map to the surface number density of galaxies
- Brane Inflation in String Theory 2006
- Numerical studies on cosmological perturbations in braneworld
- Inflationary braneworld probed with primordial black holes
- Galaxy Biasing and Higher-Order Statistics
- Probing circular polarization of Gravitational Wave Background with Cosmic Microwave Background Anisotropy
- Gravitational Collapse of Population III Stars

2005

- Brane gravity and dynamical stability in warped flux compactification
- Neutrino Probes of Galactic and Cosmological Supernovae
- Detectability of cosmic dark baryons through high-resolution spectroscopy in soft X-ray band
- Propagation of Ultra-High Energy Cosmic Rays in Cosmic Magnetic Fields
- The study of nuclear pasta investigated by Quantum Molecular Dynamics

2004

- Strong Gravitational Lenses in a Cold Dark Matter Universe
- Effect of Rotation and Magnetic Field on the Explosion Mechanism and Gravitational Wave in Core-Collapse Supernovae
- ” Bulk Fields in Braneworld ”
- “ Gravitational collapse and gravitational wave in the brane-world ”
- Magnetohydrodynamical Simulation of Core-Collapse Supernovae
- A Search for the Atmospheric Absorption in the Transiting Extrasolar Planet HD209458b with Subaru HDS
- Baryogenesis and Inhomogeneous Big Bang Nucleosynthesis
- The large-scale structure of SDSS quasars and its cosmological implication

2003

- Non-Gravitational Heating of Galaxy Clusters in a Hierarchical Universe
- Discoveries of Gravitationally Lensed Quasars from the Sloan Digital Sky Survey
- One, Two, Three ? measuring evolved large scale structure of the Universe
- Higher-order Statistics as a probe of Non-Gaussianity in Large Scale Structure
- Primordial black holes as an imprint of the brane Universe
- Probing the Extra Dimensions with Gravitational Wave Background of Cosmological Origin

21 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao, Peter Turner

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 last two decades. Entanglement is nonlocal correlation that appears in certain types of quantum states (non-separable states) and has become considered as a fundamental resource for quantum information processing. In our group, we investigate new properties of multipartite and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- Distributed quantum information processing
  - Quantifying “Globalness” of unitary operations on quantum information [1]

  - Implementability of unitary operations over the butterfly network [2]
  - Multi-cast quantum network coding for the butterfly network

- Entanglement theory
  - Random states generation by Hamiltonian dynamics with multi-body interactions [3]
  - Analysis of phase transitions and entanglement properties of a non-uniform one-dimensional spin model [4]
  - Entanglement of phase-random states and their approximate generation [5]
  - Multipartite entanglement in graph states
  - Control of entanglement generation for two spins with anisotropic Heisenberg interactions

- Quantum algorithms
  - Universal controllization of unknown unitary operations
  - Thermalization algorithm

- Quantum measurement
  - Evaluation and improvement of estimation errors in quantum tomography [6]
  - Continuous variable 2-designs [7]

- Foundation of quantum mechanics
  - Exchange fluctuation theorem for correlated quantum systems [8]

- General probabilistic theories describing strong nonlocal correlations
  - Analysis of information causality by a generalized mutual information
  - Analysis of phases and possibility of computational speed-up in general probabilistic theories

Please refer our webpage: http://www.eve.phys.s.u-tokyo.ac.jp/indexe.htm

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22 Ueda Group

Research Subjects: Bose-Einstein condensation, Fermionic superfluidity, cold molecules, measurement theory, quantum information, quantum control

Member: Masahito Ueda and Yuki Kawaguchi

22.1 Quantum States of Ultracold Atoms

Measurement of an Efimov Trimer Binding Energy in a Three-Component Mixture of ^{6}Li

The existence of the Efimov states has been confirmed indirectly in several ultracold atomic systems via the inelastic collision enhancements and minima occurring at particular magnetic-field values. In this work, we directly measured the binding energy of an Efimov trimer state in a three-component mixture of ^{6}Li via radio-frequency association. It is found that the measurement results shift significantly with temperature, but that the shift becomes negligible at the lowest temperature in our experiment. Eliminating this shift by lowering the temperature, we precisely determined the trimer binding energy, and found that the shift-free part of the binding energy significantly deviates from the universal theory prediction and a nonuniversal theory prediction based on a three-body parameter with a monotonic binding-energy dependence. This result was published in Physical Review Letters [Nakajima, *et al.*, Phys. Rev. Lett. **106**, 143201 (2011)].

Dissipative hydrodynamic equation of a ferromagnetic Bose-Einstein condensate: Analogy to magnetization dynamics in conducting ferromagnets

The hydrodynamic equation of a spinor Bose-Einstein condensate (BEC) gives a simple description of spin dynamics in the condensate. We introduced the hydrodynamic equation of a ferromagnetic BEC with dissipation originating from the energy dissipation of the condensate. The dissipative hydrodynamic equation has the same form as an extended Landau-Lifshitz-Gilbert (LLG) equation, which describes the magnetization dynamics of conducting ferromagnets in which localized magnetization interacts with spin-polarized currents. Employing the dissipative hydrodynamic equation, we demonstrated the magnetic domain pattern dynamics of a ferromagnetic BEC in the presence and absence of a current of particles, and found that the superfluid current accerelates the patter-formation dynamics. This result was published in Phys. Rev. A [Kudo and Kawaguchi, Phys. Rev. A **84**, 043607 (2011)].

Effects of thermal and quantum fluctuations on the phase diagram of a spin-1 87Rb Bose-Einstein condensate

We investigate the effects of thermal and quantum fluctuations on the phase diagram of a spin-1 ^{87}Rb Bose-Einstein condensate (BEC) under the quadratic Zeeman effect. Due to the large ratio of spin-independent to spin-dependent interactions of ^{87}Rb atoms, the effect of noncondensed atoms on the condensate is much more significant than that in scalar BECs. We find that the condensate and spontaneous magnetization emerge at different temperatures when the ground state is in the broken-axisymmetry phase. In this phase, a magnetized condensate induces spin coherence of noncondensed atoms in different magnetic sublevels, resulting in temperature-dependent magnetization of the noncondensate. We also examine the effect of quantum fluctuations on the order parameter at absolute zero and find that the ground-state phase diagram is significantly altered by quantum depletion. This result was published in Physical Review A [Phys. Rev. A **84**, 043645 (2011)].

Symmetry classification of spinor Bose-Einstein condensates

We proposed a method for systematically finding ground states of spinor Bose-Einstein condensates by utilizing the symmetry properties of the system. By this method, we can find not only an inert state, whose symmetry is maximal in the manifold under consideration, but also a noninert state, which has lower symmetry and depends on the parameters in the Hamiltonian. We establish the symmetry-classification method for the spin-1, 2, and 3 cases at zero magnetic field, and find an additional phase in the last case. The properties of the vortices in the spin-3 system were also discussed. This result was published in Phys. Rev. A [Kawaguchi and Ueda, Phys. Rev. A **84**, 053616 (2011)].

Abe homotopy classification of topological excitations under the topological influence of vortices

A monopole with charge +1 transforms to a monopole with charge −1 by making a complete circuit around a vortex. This phenomenon is called the influence of vortices on a monopole. What is at issue is that the charge +1(−1) is not topological invariant under the influence of vortices. We have provided an Abe homotopy group to classify the topological excitations under the influence of vortices. The Abe homotopy group consists of a semi-direct product of the first homotopy group and the nth homotopy group, and we have pointed out that the semi-direct product represents the influence of vortices. By applying the Abe homotopy group to an ordered material, we have found that a monopole is classified by $\mathbb{Z}_2$ rather than $\mathbb{Z}$, and so there exists two possibilities: a monopole exists or not. These results were published in Nuclear Physics B [Kobayashi, *et al.*, Nucl. Phys. B **856**, 577 (2012)].

22.2 Quantum Information, Quantum Measurement, and Information thermodynamics

Proposal of a thermalization mechanism in isolated quantum systems

We exploited the numerical exact diagonalization of the 1-dimensional and 2-dimensional hard-core Bose-Hubbard model and calculated the expectation values of the momentum distribution over each energy eigenstate. As a result, we found the behavior that the expectation values fluctuate randomly as the energy eigenvalues increase, and named such a behavior the eigenstate randomization hypothesis(ERH). Furthermore, regarding the ERH hold, we justified the applicability of the microcanonical ensemble in isolated quantum systems under the assumption that the weights on each energy eigenstate of the initial state are smooth against the energy eigenvalue. These results were published in Physical Review E [Ikeda, Watanabe, and Ueda, Phys. Rev. E **84**, 021130 (2011)].

Uncertainty relation revisited from quantum estimation theory

In 1927, Heisenberg discussed a thought experiment of the position measurement of a particle by using a γ-ray microscope, and found a trade-off relation between the error of the measured position and the disturbance in the momentum caused by the measurement process. However, at the time Heisenberg found the complementarity, quantum measurement theory was not established yet, and the exact lower bound of the errors of two observables has yet to be clarified. We have found that the estimation process is essential to characterize the error in an arbitrary measurement, and formulated the error by using the Fisher information. We have obtained the attainable bound of the errors of two observables. The bound is stronger than the bound set by the commutation relation of the observables. These results are published in the Physical Review A [Watanabe, Sagawa, and Ueda, Phys. Rev. A **84**, 042121 (2011)].

23 Makishima Group & Nakazawa Group

Research Subjects: High Energy Astrophysics with Energetic Photons using Scientific Satellites, Development of Cosmic X-Ray/γ-Ray Instruments

Member: Kazuo Makishima, Kazuhiro Nakazawa

Using space-borne instruments such as *Suzaku* and *MAXI*, we study cosmic high-energy phenomena in the X-ray and γ-ray frequencies. We have been deeply involved in the development of the Hard X-ray Detector (HXD) onboard *Suzaku*, and are developing new instruments for future satellite missions.

Mass Accreting Black Holes: Mass accretion onto black holes provides a very efficient way of X-ray production. Utilizing wide-band *Suzaku* spectra, we are diagnosing hot "coronae" that form around stellar-mass black holes, when their mass accretion rate is below a certain threshold [5]. In active galactic nuclei (massive black holes), our new variability-assisted spectroscopy technique is revealing various emission components in a model independent manner [3]. This is expected to settle several long-lasting issues as to AGNs, including their angular momenta and the matter distribution around them.

Neutron Stars with Various Magnetic Fields: Using *Suzaku*, we are studying neutron stars (NSa) with a variety of magnetic field strengths, B. Based on new *Suzaku* data [1], we are attempting to measure the mass and radius of an NS with $B < 10^9$ G. NSs in some "fast transient" objects may have $B \sim 10^{13}$ G. We have revealed that about 10 "magnetars", supposed to have $B = 10^{14-15}$ G, emit unusual hard X-ray components. This lead us to propose a novel possibility: magnetars can be a more dominant form of new-born neutron stars, rather than ordinary binary X-ray pulsars with $B \sim 10^{12}$ G. We further speculate that the magnetism of neutron stars is a manifestation of ferromagnetism in nuclear matter.

Plasma Physic in Clusters of Galaxies: The most dominant known component of cosmic baryons exists in the form of X-ray emitting hot ($\sim 10^8$ K) plasmas associated with clusters of galaxies. We have obtained novel evidence that the member galaxies in each cluster have been falling, over the Hubble time, to its potential center [2]. This is presumably due to magneto-hydrodynamic interatcons between the galaxies and the plasma, that takes place as as the former keep moving through the latter. The interaction may also explain why these plasmas are surviving their radiative cooling.

Galactic Diffuse X-ray Emission: From the 1980', an apparently extended X-ray emission was known to distribute along our Galactic plane. Using *Suzaku*, we showed that this can be explained as an assembly of numerous X-ray emitting white dwarfs. Nevertheless, the diffuse emission is significantly enhanced around the Galactic Center region, where some truly diffuse hot plasmas may be present.

Future Instrumentation: In collaboration with many domestic and foreign groups, we are developing a successor to *Suzaku*, *ASTRO-H*. Scheduled for launch in 2014, it will conduct hard X-ray imaging observations, high-resolution X-ray spectroscopy, and low-energy gamma-ray observations. We contribute to the development of two onboard instruments, the Hard X-ray Imager and the Soft Gamma-ray Detectors. Our effort includes mechanical/thermal designs of the instruments, as well as the development of large BGO scintillators, double-strip silicon detectors, and related electronics.

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24 Takase Group

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

Member: Yuichi Takase, Akira Ejiri

Thermonuclear fusion, the process that powers the sun and stars, is a promising candidate for generating abundant, safe, and clean power. In order to produce sufficient fusion reactions, isotopes of hydrogen, in the form of a hot and dense plasma, must be confined for a long enough time. A magnetic configuration called the tokamak has reached the level where the International Thermonuclear Experimental Reactor (ITER) is being constructed to study the behavior of a burning plasma. However, improvement of the cost-effectiveness of the fusion reactor is still necessary. The spherical tokamak (ST) offers a promising approach to increasing the efficiency by raising the plasma beta (the ratio of plasma pressure to magnetic pressure). High beta plasma research using ST is a rapidly developing field worldwide, and is being carried out by our group using the TST-2 spherical tokamak. Our group is tackling the problem of creating and sustaining ST plasmas using radio frequency (RF) waves.

Noninductive plasma current (I_p) initiation and ramp-up experiments are being conducted on TST-2 with up to 100 kW of RF power in the lower hybrid (LH) frequency range (200 MHz). The plasma forms a toroidal configuration spontaneously, and subsequent I_p ramp-up to 15 kA was achieved. X-rays in various energy ranges were measured to investigate the interaction between the wave and the electrons. Soft X-ray (SX) measurements revealed that the fast electron population increases as I_p increases. Hard X-ray spectral measurements showed that the photon flux is an order of magnitude higher and the photon temperature is higher in the co-current-drive direction ($\sim$ 60 keV) than that in the counter-current-drive direction ($\sim$ 40 keV). These are clear evidences that the LH wave (LHW) produced fast electrons and induced anisotropy in the velocity distribution function. The floating potential (V_f) measured by a Langmuir probe in an LHW driven plasma was below -1 kV, more than an order of magnitude more negative than in typical inductively driven plasmas. The angular profile of V_f had a large negative peak, indicating a flow of high energy electrons. This result agrees with the expectation that electrons are accelerated in one direction by the traveling wave excited by the antenna. The combline antenna used in these experiments excites electric fields which match the polarization of the fast wave (FW), but there is evidence that the LHW is excited nonlinearly, based on the frequency spectra measured by magnetic probes in the plasma edge region. While the "pump wave" at 200 MHz has a stronger toroidal component (FW polarization), the nonlinearly excited lower sideband has a stronger poloidal component (LHW polarization). It is expected that the effectiveness of current drive would improve if the LHW can be excited directly by the antenna. A new dielectric-loaded waveguide array antenna ("grill antenna") was designed, fabricated and installed on TST-2 for this purpose. It consists of four waveguides loaded with alumina, arrayed in the toroidal direction. Initial experimental results show that the antenna-plasma coupling is strongly affected by the phase differences between adjacent waveguides. The reflection coefficient could be reduced to 15% in the optimum case. Noninductive I_p start-up to k kA has been achieved with an injected RF power of up to 50 kW. Together with up to 15 kW of ECW power at 8.2 GHz which is now available, the operating regime for I_p ramp-up experiments can be extended to higher toroidal fields ($\sim$ 0.3 T), where accessibility of the LHW to the plasma core is improved.

Plasma turbulence induces "anomalous transport" in addition to collisional transport, and is an important research topic in fusion science. The 2-dimensional structure of plasma turbulence was measured in a poloidal cross section using radially and poloidally movable Langmuir probes in inductively formed TST-2 plasmas. MHD fluctuations ($\sim$ 10 kHz) were observed inside the last closed flux surface (LCFS), and electrostatic fluctuations ($\sim$ 70 kHz) localized in the upper region of the plasma were observed. The poloidal propagation direction of floating potential fluctuation was found to reverse across the LCFS. The result of bi-spectral analysis indicated the existence of nonlinear coupling of MHD fluctuations and 70 kHz fluctuations with broad-band turbulence.

Several novel plasma diagnostic techniques are being developed, including the double-pass Thomson scattering system to measure the electron temperatures (both parallel and perpendicular to the confining magnetic field) and the electron density, a 2-D multi-chord interferometry to measure the 2-D density profile, and a compact Rogowskii coil probe to measure the local current density.

25 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Yoich ASO

The detection of gravitational waves is expected to open a new window into the universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars; 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 detectors with sufficient sensitivity to catch possible gravitational waves.

In 2010, a new science project, KAGRA (former LCGT)was approved and funded by the Leading-edge Research Infrastructure Program of the Japanese government. 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.

We summarize the subjects being studied in our group.

- Construction of the KAGRA gravitational wave detector
  - Design of KAGRA interferometer
  - Alignment control
  - Parametric instability
  - Study of cryogenic contacts
- Space laser interferometer, DECIGO
  - Development of DECIGO pathfinder, DPF
  - $\mathrm{SWIM}_{\mu\nu}$
  - Study of the effect of the residual gas
- Development of TOBA (Torsion Bar Antenna)
  - Data analysis for the background gravitational waves
  - new type of actuators for TOBA
- Development of the ultra stable laser source
  - Laser stabilization using a cryogenic cavity
  - Prestabilized laser
  - Vibration isolation for cavity
  - Properties of material at cryogenic temperature
- High sensitive laser interferometer using non-classical light
- Gravitational force at small distances
- Study of space isotropy

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26 Sano Harada Group

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

Members: Masaki Sano, Takahiro Harada, and Kazumasa Takeuchi

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) macroscopic systems, in which non-equilibrium fluctuations overwhelm the thermal effects, (ii) microscopic systems, in which non-equilibrium and thermal fluctuations take comparable effects, (iii) biological systems, as important instances where non-equilibrium dynamics takes the essential role. More specifically, our current research topics include:

1. Macroscopic systems out of equilibrium

(1) Universal fluctuations of growing interfaces evidenced in turbulent liquid crystal [1]

(2) Dynamics of topological defects in liquid crystal

(3) Thermal transport and temperature profile induced by boiling[5]

(4) Reversible-irreversible transition in low-Reynolds fluid with non-Brownian particles

(5) Collective motion of microtubules as self-propelled particles [13]

(6) Individual and collective motion of self-propelled asymmetric particles

(7) Instability of interfaces and pattern dynamics of dense suspensions [2]

2. Microscopic systems out of equilibrium

(1) Cooling due to feedback control and its relation to information [4]

(2) Maximal efficiency in conjugation chemical reactions and information thermodynamics [11]

(3) Experimental test on information heat engines in microscopic scales

(4) Motion of colloids under thermal gradient

3. Biological systems

(1) Force field of cells in motion and on division

(2) Geometrical models of cell locomotion[7, 12, 14]

(2) Microfabrication and its applications to biophysics of 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 Nami Sakai

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 the protoplanetary disks.

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 first commissioning run was performed in September to October, 2011. 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. We are expecting the scientific run from 2012.

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28 Sakai (Hirofumi) Group

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

Member: 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) Suppression of high-order-harmonic intensities observed in aligned CO_2 molecules with 1300-nm and 800-nm pulses [1]

High-order-harmonic generation from aligned N_2, O_2, and CO_2 molecules is investigated by 1300-nm and 800-nm pulses. The harmonic intensities of 1300-nm pulses from aligned molecules show harmonic photon energy dependence similar to those of 800-nm pulses. Suppression of harmonic intensity from aligned CO_2 molecules is observed for both 1300- and 800-nm pulses over the same harmonic photon energy range. As the dominant mechanism for the harmonic intensity suppression from aligned CO_2 molecules, the present results support the two-center interference picture rather than the dynamical interference picture.

(2) Measuring polarizability anisotropies of rare gas diatomic molecules by laser-induced molecular alignment technique [2]

The polarizability anisotropies of homonuclear rare gas diatomic molecules, Ar_2, Kr_2, and Xe_2, are investigated by utilizing the interaction of the induced electric dipole moment with a nonresonant, nanosecond laser pulse. The degree of alignment, which depends on the depth of the interaction potential created by the intense laser field, is measured, and is found to increase in order of Ar_2, Kr_2, and Xe_2 at the same peak intensity. Compared with a reference I_2 molecule, Ar_2, Kr_2, and Xe_2 are found to have the polarizability anisotropies of 0.45 ± 0.13, 0.72 ± 0.13, and 1.23 ± 0.21 $Å^3$, respectively, where the uncertainty (one standard deviation) in the polarizability anisotropies are carefully evaluated on the basis of the laser intensity dependence of the degree of alignment. The obtained values are compared with recent theoretical calculations and are found to agree well within the experimental uncertainties.

(3) Effect of nuclear motion observed in high-order harmonic generation from D_2/H_2 molecules with intense multi-cycle 1300 nm and 800 nm pulses [3]

We investigate high-order harmonic generation from D_2/H_2 molecules with intense multi-cycle pulses centered both at 1300 nm (60 fs) and at 800 nm (50 fs) together with that from N_2/Ar as a reference. The experimental observations with 1300 nm pulses are different from those with 800 nm pulses both in spectral shapes and in intensity ratios I_{D_2}/I_{H_2}. The effect of nuclear motion in D_2 and H_2 is more distinctive for 1300 nm pulses than for 800 nm pulses. With multi-cycle pulses of 50-60 fs, the intensity ratios I_{D_2}/I_{H_2} are found to be higher for both 800 nm and 1300 nm pulses than those with few-cycle pulses of 8 fs, which is attributed partly to the contribution of the coupling between the 1sσ_g and 2pσ_u states in D_2^+ and H_2^+ molecular ions during the higher order returns of the electron wave packets.

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29 Gonokami 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, Kosuke Yoshioka

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 the ground state of 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 also investigate novel optical and terahertz-wave responses for some artificial nanostructures obtained by advanced micro-fabrication technologies. As the Director of the Photon Science Center, within the Graduate School of Engineering, a project was started to develop new coherent light sources; covering a broad frequency range from terahertz to soft X-rays. This year, 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 included:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   (a) Systematic observation of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   (b) Low-temperature, many-body phenomena in electron-hole systems in diamond
   (c) Study strongly-correlated many-body systems using ultra-cold atomic gases
2. The quest for non-trivial optical responses and development of applications:
   (a) Photo-induced three-dimensionall chirality and acitive control of THz optical activity
   (b) Vectorial control of THz oscillation in crystals with vector-field shaped optical pulses
   (c) Terahertz vector beam generation using segmented nonlinear optical crystals
3. Development of novel coherent light sources and spectroscopic methods
   (a) Mode-locked fiber lasers
   (b) Accumulation of femtosecond laser pulses in passive cavities
   (c) Higher-order photon correlation measurements using a photon-counting streak camera
   (d) Established the Foundation for Coherent Photon Science Research

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30 Nose Group

Research Subjects: Formation and function of neural networks

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

1. Optical dissection of neural circuits that regulate larval locomotion

A major challenge in neuroscience today is to understand neural information processing in the brain. Techniques to acutely inhibit neural activity provide effective methods towards this goal. We are interested in the mechanism underlying the seamless activation of motor neurons in successive segments, particularly how it is generated by the central circuits in *Drosophila* larvae. For this investigation, we generated a transgenic line that allows halorhodopsin (NpHR) to be expressed in specific neurons and performed temporally and spatially restricted inhibition of motor neurons. NpHR is a chloride pump, which, when activated by a yellow light, suppresses the firing of neurons. Our results suggest that (1) Firing of motor neurons at the forefront of the wave is required for the motor wave to proceed to more anterior segments, and (2) The information about the phase of the wave, namely which segment is active at a given time, can be memorized in the neural circuits for several seconds.

2. Gene regulation of synaptic components

Communication between pre- and post-synaptic cells is a key process in the development and modulation of synapses. Reciprocal induction between pre- and postsynaptic cells involves regulation of gene transcription, yet the underlying genetic program remains largely unknown. To investigate how innervation-dependent gene expression in postsynaptic cells supports synaptic differentiation, we performed comparative microarray analysis of *Drosophila* muscles and identified 84 candidate genes that are potentially up- or downregulated in response to innervation. We found that one of the downregulated genes, longitudinals lacking (*lola*), which encodes a BTB-Zn-finger transcription factor, is required for proper expression of glutamate receptors. When the function of lola was knocked down in muscles by RNAi, the abundance of glutamate receptors (GluRs), GluRIIA, GluRIIB and GluRIII, as well as that of p-21 activated kinase (PAK), was greatly reduced at the neuromuscular junctions (NMJs). Lola appears to regulate the expression of GluRs and PAK at the level of transcription, and the transcriptional level of *lola*, in turn, is downregulated by increased neural activity. Lola thus may coordinate expression of multiple postsynaptic components by transcriptional regulation.

References

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[2] Fukui, A., Inaki, M., Tonoe, G., Hamatani, H., Homma, M., Morimoto, T., Aburatani, H. and Nose, A.: Lola regulates glutamate receptor expression at the Drosophila neuromuscular junction. Biol. Open, in press (2012).

31 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Synthesis of multiple quantum dots in a particle

Quantum dots (QDs) show good photostability and strong fluorescence compared to conventional organic dyes and fluorescent proteins. However, they show irregular blinking which hinder observation continuously for long time. To overcome this drawback and to manufacture brighter fluorescence conjugate in order to observe motility of the fluorophore under non-invasive conditions, we created quantum-dot aggregation by quick freezing in the liquid N2. This quantum-dot aggregation glows continuously in time and bright enough for imaging under non-invasive conditions. We were actually able to observe the aggregation on the opposite side of the mouse ear, and flowing in the blood vessel in mouse ear.

The power stroke and force generation of cytoplasmic dynein

Cytoplasmic dynein is a two-headed motor protein, which moves and generates force towards the minus end of microtubules (MT). Previous works have shown that a dynein motor domain takes the primed and unprimed conformations during the ATP hydrolysis cycle. Structural change from the primed to the unprimed conformation is widely believed to produce the power stroke of dynein, which principally drives dynein movement along MT. Here, we use optical tweezers to evaluated force produced by the power stroke. A dimer of the Dictyosterium dynein motor domain exerts the force up to 3 pN on a MT. However, this stall force of the dimer would be limited by the low unbinding force of the dynein (the external force needed to unbind dynein from a microtubule) because the motor domain immediately detached from a MT at load above the stall force. To increase the affinity, the MT binding site in the motor domain was replaced with the counterparts of human cytoplasmic dynein. The chimera motor domain resisted the force of $\tilde{5}$ pN and a dimer of the chimera motor domain exerts the stall force up to 5 pN. These results suggest that the power stroke itself could produce the force more than 5 pN but the unbinding force limit the stall force of the dynein. Next, we made a heterodimer with one head always taking the unprimed conformation. The heterodimer moved processively along a MT but exerted only a small force (1 pN). Thus, taking the primed conformation would be important to bind the forward binding site on MT against high load.

Force measurement of recombinant human cytoplasmic dynein.

Dynein is a molecular motor that moves toward the minus-end of microtubules. Cytoplasmic dynein play roles in positioning the Golgi complex and other organelles in cells, movement of chromosomes, and positioning the mitotic spindles during mitosis. Force generation by a dynein molecule, thus, is one of the important factors for understanding molecular properties of dynein. To examine the binding mode between dynein and a microtubule, we measured the unbinding force of dynein in various nucleotide conditions. We expressed truncated C-terminal motor domain of human cytoplasmic dynein using baculovirus expression system. We, thus, can eliminate possible effects of tail region and/or accessory proteins on the motor activity of dynein. Dynein with the biotin-tag was attached to avidin-coated polystyrene beads, and the bead was trapped by optical tweezers. The external load was imposed by moving the stage. The mean values of the unbinding force of strongly bound state of dynein were 8.6 - 11.3pN upon backward (plus-end of microtubule) loading. These were about 30 % smaller when force was applied to the minus end of microtubules. Furthermore, we could observe the unbinding force of weakly bound state of dynein in the presence of ADP?Vi by increasing the loading rate. The unbinding force of dynein.ADP.Vi did not show directional dependency of load. These data indicate that dynein can support greater force than 7pN and unbinds from microtubules easily toward the minus end of microtubules to which dynein moves.

Development of in vivo mouse skeletal muscle imaging

Skeletal muscles are important organs for the control of body movements and postural maintenance. However, there are a few in vivo experiments which elucidate the molecular mechanism in muscles. We developed the in vivo fluorescence imaging of mouse skeletal muscle which molecular structures are visualized by using the gene transfer of GFP-fused proteins. Not only the individual sarcomeres but also microtubule associated proteins in in vivo muscles were successfully visualized by expressing α-actinin-GFP and GFP-fused microtubule associated proteins and using the confocal microscope. In order to understand dynamics of these proteins during muscle contractions, we are currently developing the imaging feedback system to capture the same target images continuously during muscle contractions, where the images are normally disappeared within a few milli-seconds in 50×50 μm of the microscopic view.