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東京大学 大学院　理学系研究科・理学部
物理学教室

図 1: JAXA の音響試験設備に搬入される ASTRO-H 衛星。ロケットでの打ち上げ環境に耐えることを確認する試験の一こま (写真は JAXA 提供) 。ASTRO-H は 日本の 6 代目の X 線観測衛星で、重さ 2.5 t、打ち上げ時の全長 8 m で、軌道上では 14 m に伸展する、日本で最大級の科学観測衛星である。最新の X 線検出器を複数搭載し、広い帯域を高感度で観測する力、X 線を精密に分光する力が、過去の衛星より桁違いに優れている。2015 年の打ち上げをめざし、JAXA を中心に東京大学はじめ国内の研究機関に加え、NASA、ESA などの世界の研究機関が協力して開発を進めている。(牧島・中澤研)

ASTRO-H satellite in mechanical test configuration moving into the acoustic test facility on May 2013 (photo by JAXA). The cosmic X-ray satellite will be launched in 2015. (Makishima-Nakazawa group)

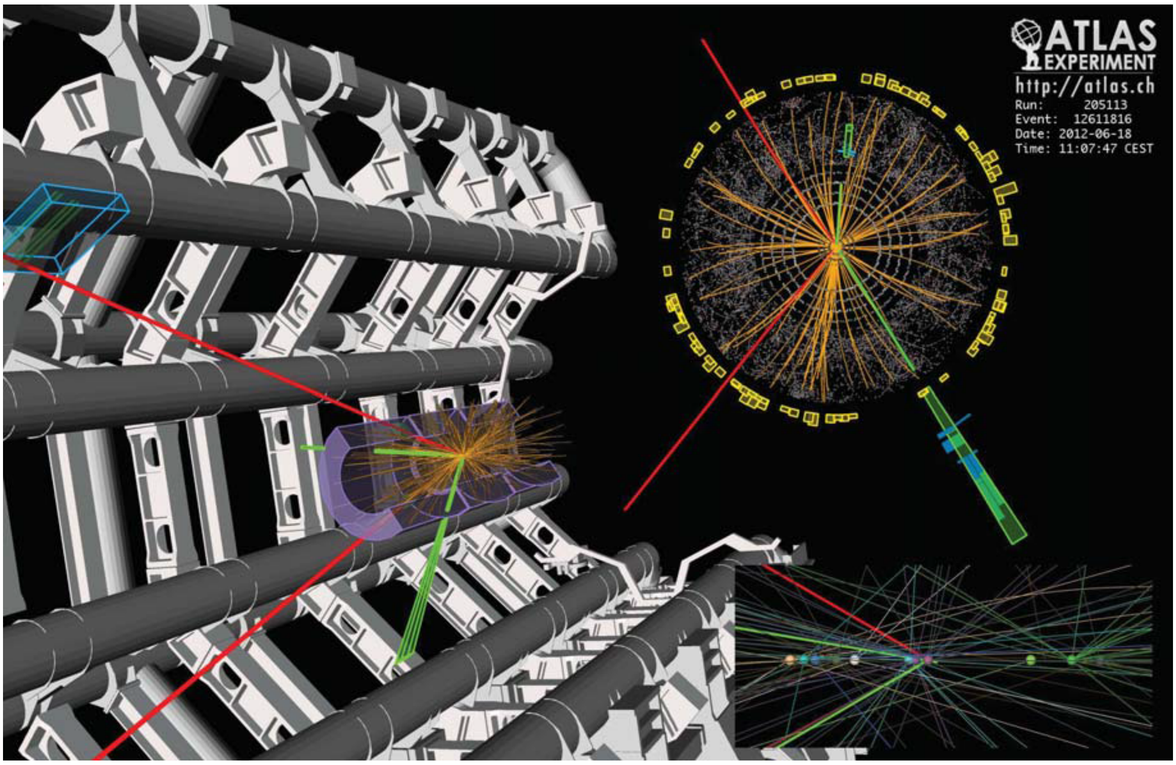

図 2: 観測されたヒッグス粒子の候補事象：ヒッグス粒子が二つの Z 粒子に崩壊し, それぞれ電子対（緑線）と μ 粒子対（赤線）にさらに崩壊した現象。再構成した不変質量は 123.9GeV。詳細は本文参照。(浅井研究室)

Event display of a H -¿ 2e2mu candidate event with m(4l) = 123.9GeV. The event was recorded by ATLAS on 18-Jun-2012, 11:07:47 CEST. Muon tracks are colored red, electron tracks and clusters in the LAr calorimeter are colored green. (Asai group)

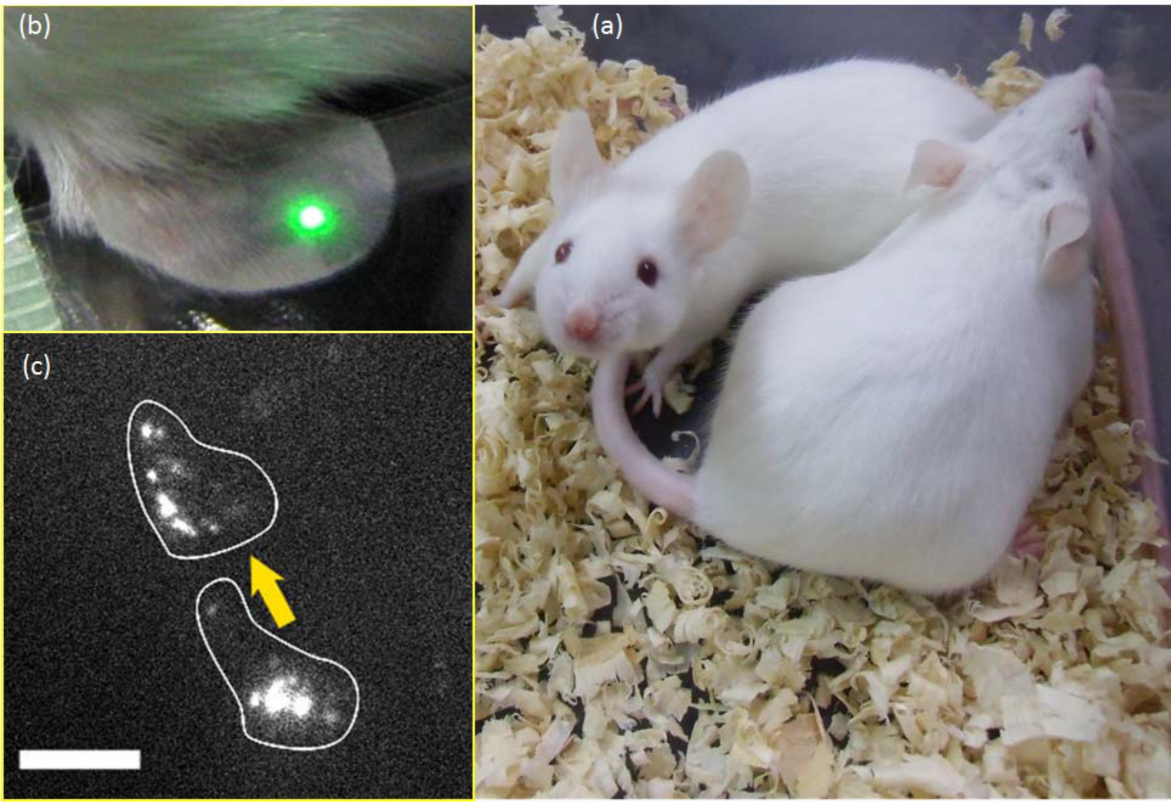

図 3: マウスに傷をつけることなく、非侵襲的に好中球（白血球の中の主要な細胞）および好中球内の小胞運動のイメージングを行った。(*a*) 実験に用いた T および B 細胞を欠失した SCID マウスは、好中球が多数イメージングできた。(*b*) マウスの耳介は、厚さ 150 μm と薄く毛も短いことから透過率が高いので、この部位を非侵襲的にイメージングした。(c) 好中球に特異的に結合する蛍光性量子ドットをマウスに注射することで、好中球の蛍光を観察した。図は 100 秒間隔で得られた像である。好中球の運動速度が 0.1 μm/s なのに対して、小胞の運動は 1 – 4 μm/s であった。特に高速度 4 μm/s は過去に報告がない大きな値であった。バーは 10 μm を示す。(樋口研)

Noninvasive imaging of neutrophil in mouse auricles. (a) The SCID mice were suitable for the neutrophil imaging. (b) Mouse was anesthetized with isoflurane on the stage of a confocal microscope. After the neutrophil-antibody labeled with fluorescent quantum dots was injected in tail vain, the mouse auricle was illuminated by a green laser at 532 nm. (c) The movements of neutrophil and vesicles in the auricle were noninvasively imaged with the spatiotemporal precision of 12-100 ms and 15-30 nm. The maximum velocity (4 μm/s) of vesicles was surprisingly high. (Higuchi group)

II

Summary of group activities in 2013

1 Theoretical Nuclear Physics Group

Subjects: Structure and reactions of unstable nuclei, Monte Carlo Shell Model, Shell Evolution, Mean Field Calculations, Quantum Chaos

Member: Takaharu Otsuka, Kenji Fukushima and Takashi Abe

In the Nuclear Structure group (T. Otsuka and T. Abe), quantum many-body problems for atomic nuclei, issues on nuclear forces and their combinations are studied theoretically from many angles. The subjects studied include
(i) structure of unstable exotic nuclei, with particular emphasis on the shell evolution
(ii) shell model calculations including Monte Carlo Shell Model,
(iii) collective properties and Interacting Boson Model,
(iv) reactions between heavy nuclei,
(v) other topics such as dilute neutron system, quantum chaos, etc.

The structure of unstable nuclei is the major focus of our interests, with current intense interest on novel relations between the evolution of nuclear shell structure (called shell evolution for brevity) and characteristic features of nuclear forces, for example, tensor force, three-body force, etc. Phenomena due to this evolution include the disappearance of conventional magic numbers and appearance of new ones. We have published pioneering papers on the shell evolution in recent years. The tensor force effect has been clarified [1] with various actual applications. The most important topic of the year 2013 was the first experimental confirmation of the new magic number 34 in an exotic nucleus ^{54}Ca [2], while striking effect of three-body force has been shown [1] for the first time.

The structure of such unstable nuclei has been calculated by Monte Carlo Shell Model, for instance to Ni isotopes [3]. Their applications have been made in collaborations with experimentalists internationally spread, *e.g.*, [4]. Collaborations with many groups produce various interesting results, for instance [5, 6, 7, 8].

We have studied the effective nucleon-nucleon interaction from a new viewpoint such as the EKK method, and have obtained a new framework for this interaction involving more than one major shell [9]. Before this work, there has been no single framework to derive effective interactions with more than two major shells, which are crucial in studying neutron-rich exotic nuclei. Thus, this is a breakthrough.

The Monte Carlo Shell Model has been improved with further developments, and we have carried out a number of calculations on the K computer.

The mean-field based formulation of the Interacting Boson Model has been developed by this group, and is now studied in somewhere else.

We are studying on dilute neutron systems, time-dependent phenomena like fusion and multi-nucleon transfer reactions in heavy-ion collisions.

Associate Professor Kenji Fukushima has arrived at the Hadron Physics group on October 1.

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Members: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo, Yuji Tachikawa

In our group, we study both phenomenological and formal aspects of theoretical high energy physics. In the field of high energy phenomenology, we investigate supersymmetric unified theories and cosmological problems extensively. On the more formal side, we study string theory, supersymmetric field theories, and conformal field theories from both physical and mathematical points of view.

We list the main subjects of our researches below.

1. High Energy Phenomenology
   - 1.1 Collider Phenomenology
   - 1.2 SUSY Phenomenology [1]
   - 1.3 Flavor Physics [2]
   - 1.4 CP Violation [3]
   - 1.5 Anomalous magnetic moment [4] [5] [6]
   - 1.6 Direct Detection of Dark Matter
   - 1.7 High Energy Cosmic Ray [9] [7] [8]
   - 1.8 Cosmological constraints on superconducting cosmic strings [10]
   - 1.9 Cosmology of axion [12]
   - 1.10 Anomaly mediation deformed by axion [13]
   - 1.11 Inflation models in supergravity [11] [14] [17] [22]
   - 1.12 Dynamics of scalar field [15] [20] [21]
   - 1.13 Moduli problem and axionic dark radiation [16] [18]
   - 1.14 Inflationary Gravitational Waves and the Evolution of the Early Universe [19]
   - 1.15 Modified supergravity [23] [24]
2. Superstring Theory
   - 2.1 Structure of the instanton partition function [25]
   - 2.2 Quantization of self-dual form fields [26]
   - 2.3 Supersymmetric theories on curved manifolds
   - 2.4 Superstring perturbation theory [27]
   - 2.5 Various quantum field theories in 4d [28] [29] [30] [31] [32]
   - 2.6 Supersymmetric theories in 2d [33] [34]

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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

Development of electrostatic beam lines for low energy antiproton beams At the Antiproton Decelerator (AD) in CERN, experimental collaborations measure antimatter's properties and test the CPT theorem. Antiprotons with kinematic energy of 5.3 MeV are ejected from AD and decelerated to from a few to hundreds kiloelectronvolts by using a series of degraders and/or a radio frequency quadrupole decelerator (RFQD) in order to produce antihydrogen or antiprotonic helium and to do precise experiments. During that deceleration processes from 70 percent to over 90 percent of antiprotons are lost by annihilation with the degraders or the walls of experimental setups, and the survived antiproton beam's six-dimensional phase-space volumes are expanded, which makes the experimental precision worse. So as to improve the efficiency and precision, a new storage ring with a diameter of 10 m, ELENA (Extra Low ENergy Antiproton storage ring), which cools antiprotons from AD by electron cooling and decelerates them to 100 keV, is designed and constructed. With accelerator technicians at CERN, we simulated electric fields and beam trajectories in electrostatic quadrupoles, which focus and defocus the beam, spherical deflectors, which bend the beam trajectory, and a five-way switchyard which are placed at a cross section of beam lines, and contributed to the designs. Beam profile monitors which measure the position of the beam trajectory with precision of 0.5–1.5 mm are also developed. These results will be published in a technical design report at early 2014 fiscal year.

$\bar{p}$-nucleus annihilation cross section at ultra-low energies The antiproton is absorbed by the nucleus and annihilates with a surface nucleon. At high energies, it is known that the $\bar{p}$-nucleus annihilation cross sections scale as $\sigma_{ann} \propto A^{\frac{2}{3}}$ where A is the nuclear mass number. On the other hand, at very low energies where the wave length of the antiproton's de Broglie wave is longer than the diameters of target nuclei, 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 σ_{ann} measurements at 130 keV. In 2012, we carried out the measurement using carbon, palladium, and platinum targets, and observed the antiproton annihilations in the targets for the first time at this low energy region. In 2013, we mainly worked for analyzing the data, carrying out simulations, and measuring the thicknesses of the target foils. We determined the number of antiprotons annihilated in the targets by analyzing the waveforms of the plastic scintillators. We also determined the number of incident antiprotons by using the number of scattered antiprotons to the lateral wall of the target chamber by means of the Rutherford scattering formula, and it was found that $10^4 \sim 10^5$ antiprotons were contained in each pulsed beam. In addition, a simulation was performed to estimate the systematic errors caused by the geometry of the experiment. The thicknesses of the targets foils were measured by the Rutherford backscattering spectroscopy, and they were consistent with the nominal values. We are going to report these results in 2014. From the results of the analyses we found some improvements in the experiment, such as reducing the dust on the surfaces of the targets and increasing the efficiencies of the detectors. We are now planning the next experiment in which these problems will be solved.

2) Precision spectroscopy of pionic atoms

Pionic atoms via (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. In 2013, we reanalyzed the result of a pilot experiment performed in 2010. More realistic optical effect and acceptance of the beam line were estimated and applied to Q-value spectrum. Now the calibration of the spectrum is being finalized. In RIKEN, we were asked to resubmit the proposal, which was already accepted as NP0802-RIBF54, according to RIBF new policy. Then we renewed our proposal based on the result of the pilot experiment, and succeeded to be accepted again. Our experiment is allocated from end of May, 2014. Now we are preparing detectors such as MWDCs and scintillators, establishing the experimental procedure, developing new method to tune the optics, and improving DAQ system.

Pionic atom spectroscopy with inverse kinematics Spectroscopy of deeply bound pionic atoms is useful to study chiral symmetry at finite density. We are planning a spectroscopy of pionic atoms with unstable nuclei to investigate the density dependence of restoration of chiral symmetry breaking. In the experiment, missing mass spectroscopy of inverse kinematics of (d,^{3}He) reaction will be performed with a setup using deuterium gas active-target TPC and silicon detectors. In this year, we studied the performance of 300 μm-thick silicon detector using an α source. In order to achieve high resolution, we tried to reduce electronic noise. As a result, the resolution was estimated to be 0.7% (FWHM) using 5.5 MeV α source. We will study the resolution using higher energy particle. We also joined an experimental group at CNS (Center for Nuclear Study, University of Tokyo) for a deuterium gas active-target TPC. We studied the properties of GEM under low pressure deuterium gas and searched suitable conditions to achieve high gain of 10^4. In addition, properties of deuterium gas detector such as electron drift velocity and diffusion were measured using an alpha source and compared with calculation based on literature data. We will carry out further measurement with higher statistics.

3) Study of η' mesic nuclei

η' meson has a large mass of 958 MeV/c^2, which is understood by the $U_A(1)$ anomaly effect. Since the magnitude of this effect on η' mass is considered to be related to the chiral condensate in nuclear medium, where chiral symmetry is partially restored, the mass of η' meson may be reduced and η' meson-nucleus bound states (η' mesic nuclei) may exist.

We will perform a spectroscopy experiment to search for η' mesic nuclei at GSI in Germany. We will inject a 2.5 GeV proton beam to a carbon target, and create η' meson by the ^{12}C(p, d) reaction. Then, the energy of the η' mesic nuclei will be obtained by measuring the momentum of the ejectile deuteron with a spectrometer.

In FY2013, we developed an ion optics of the spectrometer, prepared a data acquisition system, and tested multi-wire drift chambers and aerogel Cherenkov detectors. We desinged the ion optics for this experiment using GICOSY simulation. The data acquisition system and all detectors were tested together using a proton beam at COSY accelerator of Forschungszentrum Jülich in Germany.

The main experiment at GSI is scheduled in July 2014. We will test the spectrometer optics with an ion beam, perform the main experiment, and analyze the data in 2014.

4)Study of internal exposures of Fukushima residents

Since 2011, we have been cooperating with medical institutions in Fukushima to investigate the internal radiation exposures of Fukushima residents using whole body counters (WBCs). Our study, based on some 30,000 measurements (published in ref.[3]) showed that the internal exposure level is kept much lower than initially feared.

Since the existing WBCs are unsuitable for measuring the internal exposures of small children, we developed a special device called a BABYSCAN, which was installed in a hospital in Fukushima in December 2013. So far, no child was found to have detectable level of radiocesium (detection limit being 50 Bq/body) [31].

4 Sakurai Group

Research Subjects: Nuclear structure and dynamics of exotic nuclei, Origin of elements in universe

Member: Hiroyoshi Sakurai and Megumi Niikura

Exotic nuclei located far from the stability line are new objectives for nuclear many-body problems. Our 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) at RIKEN. The RIBF is a leading facility where RI beam intensities are the highest in the world. We maximize RIBF utilization to access nuclei very far from the β-stability line as well as to exploit new types of experiments and new methods of spectroscopy via new ideas and detector developments.

β-decay and isomeric-decay spectroscopies

Unstable nuclei is, by definition, decaying to the stable one by a β-ray emission. Since the β-decay process is well known, β-decay spectroscopy is efficient way to investigate the structures of parent and daughter nuclei. We performed decay spectroscopy studies at RIBF as a part of the EURICA project, which is aiming to exploring new isomers, half-lives, and β-γ spectroscopies in the wide region of the nuclear chart.

We measured 14 new half-lives in the region of ^{78}Ni for the first time. The new half-lives together with data from literature allowed us for a systematic study and our result indicates the existence of the doubly-magic character in neutron-rich nucleus: ^{78}Ni. We also discovered new micro seconds isomers in ^{126,128}Pd. The isomerism is understood as a seniority scheme and is an evidence for robustness of the neutron magic number at $N = 82$.

The β-decay is important for the nucleosynthesis in the rapid neutron capture process (r-process). The probability of β-delayed neutron emission (P_n) plays an crucial role in the "freeze-out era" of the r-process to understand the solar abundance. We established BRIKEN collaboration to measure the P_n values of the nuclei in the r-process path by using ^{3}He neutron detector array. We have performed a design study for the ^{3}He base neutron detector array by using simulation code (Monte-Carlo N-Paricle 5, MCNP5) to obtain the highest efficiency without initial neutron-energy dependence.

In-beam γ-ray spectroscopy with fast secondary beams

An in-beam gamma-ray experiment on ^{35}Mg was performed at the RIBF at RIKEN in 2010. ^{35}Mg was made by one-neutron knock-out reaction from ^{36}Mg which was sensitive to the neutron single-particle configuration and may reveal the microscopic mechanism of the large deformation in the $N > 22$ neutron-rich Mg isotopes. Doppler corrected gamma-ray energies were measured with DALI2 γ-ray detector. The nature of the excited states emitting these γ-rays has been discussed by comparison with the previous work. The analysis on the cascade gamma decay of ^{35}Mg will be done in the future aiming to reveal the energy level of the excited states.

We are also developing a new generation γ-ray detector array called SHOGUN (Scintillator based High-resOlution Gamma-ray spectrometer for Unstable Nuclei). To compensate the doppler broadening owing to the fast beam at the RIBF, the shape of the scintillator should be narrow and long. In this year, we introduced a semi-empirical formula to understand the relationship between the shape and the energy resolution. Energy resolutions of several $LaBr_3$(Ce) scintillators with different shapes were measured to test the universality of the new formula.

Nuclear structure study with direct reactions

We performed an experiment using the distinct Coulomb and nuclear 1n-removal reaction at RIBF. The present work addresses the spectroscopy of neutron-rich nuclei around the island of inversion, specifically, the halo, shell and deformation properties of Ne and Mg isotopes. The analysis exploits the different sensitivities of these reaction mechanisms to obtain the ground state separation energy, spin parity and the spectroscopic factors of these projectiles. The Coulomb- and nuclear-dominated 1n-removal cross sections of ^{29,31}Ne and ^{33,35,37}Mg on Pb and C targets as well as their parallel momentum distributions were measured and interpreted in terms of their shell structure and helo properties.

^{8}C nucleus is one of the most proton rich nuclei existing outside of the proton drip-line. While the mass and decay modes of ^{8}C have been studied before, the excited states have never been measured. We performed the experiment to investigate the excited states of ^{8}C nuclei by using the missing mass method of ^{10}C$(p,t)^{8}$C reaction in inverse kinematics on November in 2013. The analysis is now in progress.

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 supersymmetric particle searches with the ATLAS detector at the LHC pp collider; (3) Experiment for studying gravitational quantum effects and searching for new short range force using ultra-cold and cold neutron beam; (4) Study on possibility to investigate the EPR paradox using charmonia decays.

Member: Sachio Komamiya, Yoshio Kamiya, Daniel Jeans, Go Ichikawa

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

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed upon to use 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 was completed and published in 2013. Since then, ILC design and hardware development are passed to the Linear Collider Collaboration (LCC) lead by Lyn Evans. The oversight body of LCC is called LCB (Linear Collider Board) whose chairman is Sachio Komamiya. We

are working on ILC accelerator related hardware development, especially on the final focus system. We are developing the Shintake beam size monitor at the ATF2, which is a test accelerator system for ILC located in KEK. The Shintake beam size monitor is able to measure O(10)[nm] beam sizes, using a high power laser interferometer. Also we have been studying possible physics scenarios and the large detector concept (ILD) for an experiment at ILC. Since 2012 autumn, a new postdoctoral fellow who is an expert on the silicon electro-magnetic calorimeter joined from UK. Since then hardware and simulation studies of silicon-tungsten sandwich electromagnetic calorimeters for ILC detector have been performed.

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

3) ATLAS experiment at LHC: The epoch of new paradigm for particle physics is going to open with the experiments at LHC. In July 2012, the Higgs Boson was discovered by the ATLAS and CMS experiments at LHC. We call this the "2012 July Revolution". Our students have been working on data analysis in search for a Higgs Boson in the very important decay mode of $H \to \gamma\gamma$. Also, other students searched for supersymmetric partners of gluon and quarks with the missing transverse energy and these results have already been published in journals.

4) One of our graduate student worked on the possibility to study the EPR paradox using decays J/ψ, η_c, or $\chi_{c0} \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$. The results were published in PTEP.

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 developed a segmented reactor-antineutrino detector made of plastic scintillators for application as a tool in nuclear safeguards inspection and performed mostly unmanned field operations at a commercial power plant reactor with a 360-kg prototype called PANDA36. PANDA is an acronym for plastic anti-neutrino detector array. At a position outside the reactor building, we measured the difference in reactor antineutrino flux above the ground when the reactor was active and inactive. This was the world's first aboveground antineutrino detection of a nuclear reactor.

Unexpected gamma ray bursts were detected with the PANDA36 detector during the operation at the power plant reactor. The largest burst lasted for 180 s and the detection rate amounted to 5.5×10^2/s at its peak. The energy spectrum is continuous and extends upto 10–15 MeV. The bursts are most probably due to electromagnetic showers of relativistic electrons created in thunder clouds. Indeed, we found thunder cloud activities at the time of the bursts in the meteorological data. The detailed mechanisms of the burst generation is under the study.

An R and D study is still ongoing and a larger prototype PANDA64 of 640 kg mass is now ready. A test running has been completed in the university campus with a newly installed 24-cm thick water shield surrounding it. We are now waiting for the power plant reactor to go online. We also started a construction of an ultimate 100-module detector, PANDA100.

There is yet another motivation of PANDA. With its mobility and compactness, PANDA could be used to verify the existense of sterile neutrinos. The existing cosmological data indicate that the energy density of the Universe may contain dark radiation composed of one or two sterile neutrinos, which have been invoked for the explanation of short-baseline reactor antineutrino anomalies. We shall bring PANDA into a compact-core research reactor which fits the short oscillation length of the proposed sterile neutrinos. While almost all the compact-core reactors in Japan are in shutdown, we might consider foreign reactors as possible sites of the experiment.

One of us also contributes to a similar project called Nucifer in CEA Saclay, France. Nucifer is a small antineutrino detector made of liquid scintillator installed at the research reactor Osiris with a standoff of 7m from its core.

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 one of the candidates for the cold dark matter of the Universe. It would be converted into an ordinary photon at a surface of conductive material with a conversion probability depending on its mixing parameter with the ordinary photon. There have been an idea to use a spherical mirror to focus thus generated photons onto a photon sensor to enhance the detection efficiency of the hidden sector photon detector. We try to realize this kind of hidden photon search experiments in two wavelength bands. Hidden sector photons of ∼eV mass could be searched for using an optical concave mirror and a photon counting PMT. We are now running the search experiment with a mirror of 50cm diameter. On the other hand, dish antenna for Ku-band microwave reception could be used to search for hidden sector photons of lower mass in the range of $10^{-5} - 10^{-4}$eV. We are also preparing a hidden sector photon detector with a dish antenna of 2.2m diameter.

7 Aihara & Yokoyama Group

Research Subjects: (1) Study of CP-violation and search for physics beyond the Standard Model in the B meson and the τ lepton systems (Belle & Belle II); (2) Dark energy survey at Subaru telescope (Hyper Suprime-Cam); (3) Long baseline neutrino oscillation experiment (T2K); (4) R&D for the next generation neutrino and nucleon decay experiment (Hyper-Kamiokande); (5) R&D of new generation photodetectors.

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

1. Search for new physics at KEK B-factory: Belle experiment

One of the major research activities in our group has been a study of CP-violation and 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.

2. Physics at luminosity frontier: Belle II experiment

The SuperKEKB project started in 2010. The upgraded accelerator, SuperKEKB, will have 40 times more luminosity than KEKB. The Belle detector is also being upgraded as Belle II detector with cutting-edge 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. Our group is responsible for the construction of outer layers of Belle II SVD. This year we established the assembly and precise alignment procedures of Belle II SVD ladders. The R&D for the upgrade of the Belle II electromagnetic calorimeter was also carried out.

3. Study of Dark Energy with Subaru telescope: Hyper Suprime-Cam

As an observational cosmology project, we have been involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct 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 wide-filed survey has been started.

4. Study of neutrino oscillation with accelerator neutrino beam: T2K experiment

T2K is a long baseline neutrino experiment using J-PARC accelerator complex and Super-Kamiokande, 295 km away. Based on the data taken before the summer 2013, we reported a firm observation of the electron neutrino appearance from a muon neutrino beam, and placed the first-ever constraint on the CP asymmetry parameter in the lepton sector. We also reported the world best constraint on the mixing parameters from the measurement of muon neutrino disappearance.

5. Next generation large water Cherenkov detector: Hyper-Kamiokande project

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

As a candidate of photosensor for Hyper-K, we have been developing hybrid photodetector (HPD) combining a large-format phototube technology and avalanche diode as the photo-electron multiplier. This year, we started the evaluation of HPD in a large water Cherenkov detector using a 200-ton water tank at Kamioka. Also, we developed and tested high quantum efficiency 50 cm diameter photomultipliers.

8 Asai group

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

Member: S.Asai

- (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 and Supersymmetry.
  - Higgs: Discovery of Higgs Boson
  - SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.1 and 1.8TeV, respectively.
- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Precise measurement Search HFS of the positronium.
  - Developing high power (>500W) stable sub THz RF source

– Axion searches using Spring 8
– $\gamma\gamma$ scatter Using FEL Xray.

9 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Naoto Tsuji

Our main interests are many-body and topological effects in electron and cold-atom systems, i.e., **superconductivity, magnetism and topological phenomena**, for which we envisage a **materials design for correlated systems** and novel **non-equilibrium** phenomena should be realised. Studies in the 2013 academic year include:

- **Superconductivity**
  — High-Tc cuprates: material- and pressure-dependence [1-3]
  — Coexisting electron-electron and electron-phonon interactions
  Retardation effects, supersolid phases [4]
  — Organic and carbon-based superconductors [1]
  — Fermion and boson systems on flat-band systems [5]
  — Superconductivity induced in non-equilibrium:
- **Topological systems**
  — Topological and chiral properties of graphene [6-8]
  — Optical (THz) quantum Hall effect in graphene [9]
  — Graphene quantum dot [10]
- **Non-equilibrium phenomena**
  — Non-equilibrium dynamical mean field and dynamical cluster theories[11,12]
  — Dynamical phase transitions in correlated and topological systems
  Floquet topological insulator
  — Non-thermal fixed points
  — Nonequilibrium quantum spin systems[13]
  — Higgs modes in superconductors in intense laser [11]

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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

Cooperative Phenomena and Phase Transition

Phase transitions and critical phenomena are important main subjects of the statistical mechanics. We have studied various types of ordering phenomena of systems with large fluctuation. In the last year, we studied the following topics of phase transitions.

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. In the last year, we studied the nature of phase transitions in a system with short-range antiferromagnetic interaction and the effective long range interaction among spin states due to difference of local bistable structures of the lattice.[3] We also found that the system has two different domain walls for the spin degree of freedom and lattice degree of freedom, and they behave differently with ratio of time scales of the degree of freedoms.[5] The stress distribution of lattice during the switching was also studied. [6]

We also studied mechanisms of magnetization process of frustrated rare-earth compound.[2] And also we studied mechanisms of coercive forth of real magnets, joining to the project 'The Elements Strategy Initiative Center for Magnetic Materials'.

We also studied an itinerant ferromagnetism in a system where the electron density can be controlled, and the system exhibits both the Mott singlet and Nagaoka ferromagnetism. We studied detailed phase diagram of magnetic properties.

Stochastic process

Brownian motion of particles interacting with long range force has been formulated by the Dunkl operator. We have studied dynamics of the distribution of the particles from a view point of the intertwining operator.[13]. We studied the time scale of relaxation into an steady states of the scaled distribution. [36, 37, 29]

Quantum dynamics

Quantum dynamics under time dependence field is also important subject in our group. In these years, we have studied properties of quantum systems in periodically driven systems. We studied phase transitions in a cavity system in which strong interaction between spins and photons exists. When the interaction becomes strong, the ground state of the system exhibits a phase transition called Dicke transition. Beside this transition, a nonequilibrium phase transition called optical bistability has been known. We found cooperative phenomena in the region with strong driving force and strong coupling. In order to study such a region we developed a new master equation for the thermodynamic limit properties by making use of the property that the photon interacts with all the spin uniformly and the mean-field treatment becomes exact in the thermodynamic limit. In the Dicke model, we found a new type symmetry-broken phase. We explained mechanism of this phase by making use of the concept of coherent destruction of tunneling.[7, 20, 25, 26]

We also studied dynamics of magnetization under sweeping field in a uniaxial systems quantum mechanically, where we studied the relation to the classical Storner-Wohlfarth phenomena.

Fundamental properties of Statistical mechanism

We studied properties of statistical mechanics in long-range interacting systems. As we have mentioned above, there are many realistic systems which exhibit effective long-range interactions, We showed that the elastic models for the spin-crossover system can be expressed by an effective long-range interaction, and that the extensivity is effectively satisfied, but the additivity is violated. [8]

As we also mentioned, the atoms in a cavity have an effective long range interaction due to the common cavity photon. We gave a proof that in some condition a mean-field dynamics gives the exact results. [10]

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
  High-T_c superconductivity as a doped Mott insulator studied in the Hubbard model.[1]
  Flux states in high-T_c superconductivity.
- Organic conductors
  Thermoelectric transport coefficients for massless Dirac electrons in organic compounds.[2]
  Effect of tilting on the in-plane conductivity of Dirac electrons in organic compounds.[3]
  Spin liquid states realized in organic compounds and spin systems.
  Zero-energy localized state induced by impurity in Dirac electron system of organic conductor.[4]
- Dirac electron systems in solids [5]
  Spin-Hall effects and large diamagnetism in Dirac fermion systems.[6]
  Electronic states in a new Dirac system: Ca_3PbO and related materials.[7]
- Theories on heavy fermion systems and multi-band electron systems
  Charge Kondo effect due to pair-hopping mechanism.
  Spin triplet superconductivity in UPt_3
  Theory of Ru oxides: heavy fermion behavior and spin fluctuations.[8]
- Chiral magnets and spin-orbit interaction
  Effective model and Dzyloshinskii-Moriya interaction for chiral magnet, $CrNb_3S_6$.[9]
  Spin-orbit interaction in $4d^3$ and $5d^3$ electron systems.[10]
  Superexchange interactions from the j-j coupling.[11]

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

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 FY2013, we applied the second-order perturbation theory (MP2) to improve the accuracy of the band gap and total energy. We also used configuration interaciton single (CIS) to calculate photo-absorption spectra considering excitonic effect.

We are also developing various schemes for first-principles simulation and are applying them to the study of structural, electronic and thermal properties of materials. Our research subjects in FY2013 were as follows:

- New methods of first-principles calculation of material properties
  - First-principles wavefunction theory for solids based on the transcorrelated method and its connection to the diffusion Monte Carlo method
  - Improved tetrahedron method for the Brillouin-zone integration applicable to response functions
  - Density functional theory for superconductors
  - A new efficient method to find potential energy minima in configuration space
- Applications of first-principles calculation
  - Interfaces in $Nd_2Fe_{14}B$ sintered magnet
  - Thermal transport and the role of host-guest interaciton in type-I clathrate compounds
  - Diversity of hydrogen configuration and its roles in $SrTiO_3$
  - H^1 NMR in $BaTiO_{3-x}H_x$

13 Todo Group

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

Member: Synge Todo

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

Novel state and critical phenomena in strongly correlated systems

Analysis of quantum phases and quantum phase transitions by local Z_2 Berry phase: we have developed a new quantum Monte Carlo technique for calculating the overlap of two wave functions (including phase factor), and applied it to the local Z_2 Berry phase that is a topological order parameter for low-dimensional quantum magnets [1].

Critical phenomena of long-range interacting spin model: using the $O(N)$ cluster algorithm, we have precisely studied the critical exponents and critical amplitudes of the long-range interacting spin model on the square lattice, and revealed that the critical exponents vary smoothly as a function of the exponent of interaction σ.

Quantum phase transition of SU(N) J-Q model: by using the parallelized loop cluster algorithm for the SU(N) J-Q model, which is proposed as a candidate that exhibits the deconfined critical phenomena, we have studied its critical phenomena and found a systematic drift of the critical exponents as the system size increases. It may suggest a first-order phase transition [3].

Development of new simulation algorithms for quantum many body systems

Irreversible Markov chain Monte Carlo: we have developed a novel geometric approach that can construct an irreversible kernel with minimum rejection rate for the Markov chain Monte Carlo. It is demonstrated that the auto-correlation time of the Markov chain is greatly reduced by our proposed method.

Simulation method for systems with strong spatial anisotropy: we have developed a generic method that can automatically optimize the aspect ratio of the system by the combination of the quantum Monte Carlo method and the machine learning technique, and applied to the Néel-dimer transition of two-dimensional quantum Heisenberg model [4].

Development of open-source software for next-generation parallel simulation

Parallelization of worm algorithm quantum Monte Carlo method: we have developed a domain decomposition parallelization method of the worm algorithm for the path-integral quantum Monte Carlo for the massively parallel supercomputers [5].

We have also developed the parallel exact diagonalization package "Rokko" (https://github.com/t-sakashita/rokko), the portal site for materials science simulation "MateriApps" (http://ma.cms-initiative.jp), Live USB Linux system "MateriApps LIVE!" The performance evaluation and optimization of application software for future HPCI systems have been conducted as well.

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14 Fujimori Group

Research Subjects: Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Kozo Okazaki

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

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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 breakdown. (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 various kinds of ultra-high 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/spin transport:

- Detection of current-induced spin polarization at Bi(111) surface by using spin-polarized ion scattering spectroscopy
- Detection of spin Hall effect on Bi_2Se_3(111) surface by using *in situ* FIB-fabrication and four-tip STM
- Quasi-one-dimensional electronic transport on Si(110)-2×5-Au surface by using linear/square micro-four-point probe method
- Effect of magnetic impurities on surface electronic transport of Si(111)-$\sqrt{7} \times \sqrt{3}$-In

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

- Structure determination of multi-layer Silicene by using I-V low-energy electron diffraction
- Discrimination between the hexagonal phase and rectangular phase of Si(111)- $\sqrt{7} \times \sqrt{3}$-In by STM observation

- High-resolution angle-resolved photoemission spectroscopy of Bi(111) ultrathin films
- Proximity effect at Bi_2Se_3/MnSe interface
- Tuning of Fermi-level position of a topological insulator Bi_2Se_3 by Sb doping

(3) Construction of new apparatuses: Low-temperature strong-magnetic-field scanning tunneling microscope and scanning tunneling potentiometery.

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16 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

We are current interested in (i) quantum phases with strong correlations and frustration in two dimensional (2D) helium three (^{3}He), four (^{4}He) and their mixture, (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, tortional oscillator, scanning tunneling microscopy and spectroscopy (STM/S), and electronic transport measurement, *etc.*

1. **Self-bounded Ground-state of two dimensional ^{3}He at low areal densities:**

   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. We found that there is the critical point for every layer and ^{3}He atoms form 2D paddles at low densities ($\rho < 1.5$ nm^{-2}). It should be noted 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. 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 commensurate (C2) 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 substrate (Grafoil). 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 (C1) phase more clearly than that observed on Grafoil.

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 (C2 phase) and then incommensurate solid (IC2 phase). In addition, a clear evidence of the C2 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 C2 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 C2 commensurate phase which had been denied in Path Integral Monte Carlo simulations.

The C2 phase is a 2D solid which is stabilized by the substrate potential with a quite low areal density. Therefore, it is a strongly quantum solid where nearest atoms are always exchanging each other. In such quantum crystals, a super-solid state can be expected which shows superfluidity keeping its crystalline structure. We have started a measurement to find this novel super-solid state with a tortional oscillator.

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

Graphene, a single layer of graphite, had been attracting 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 as massless Dirac fermions, and graphene shows ballistic charge transport, turning it into an ideal material for circuit fablication.

One of a superior property of graphene is that, it can be obtained on the surface of a substrate and it is exposed to the outside. Therefore, one can shape a graphene into desired structure, and can modify its electronic property by adsorbing atoms or molecules. Recently, we studied the electronic property of graphene decorated with O_2. By measureming the time evolution of the gate voltage (V_g) dependence of the resistance, we found the time dependent change of the Dirac point (carrier doping), the maximum resistance, and the mobility. In addition, the initial electronic property can not be restored perfectly by vacuum annealing at about 100 °C. The temperature dependence of the resistance for O_2 decorated graphene suggests the variable range hopping in 2D due probably to the increase of disorder by O_2 adsorption. In addition, the conductance starts to fluctuate dependening on the carrier density at $T < 20$ K. Since the fluctuation pattern changes by O_2 adsorption and by thermal cycle above 80 K, this fluctuation is related to the disorder and the conduction path of carriers. It shoulg be noted that this fluctuation is different from the universal conductance fluctuation appears in magneto-resistance for conventional 2D electrons in some senses, i.e., the fluctuation is induced by carrier density, the fluctuation amplitude is much smaller than the quantum conductance and it is robust to much high temperature of about 20 K.

It is also characteristics of graphene that it has two edge structures with much different electronic properties, i.e. zigzag and armchair. At the edge of zigzag structure, electrons are localized along the edge to form a zigzag edge state. We had confirmed such state experimentally at the monatomic step edge of graphite. Moreover, it is expected that the spin degeneracy would be lifted and ferromagnetically spin polarized edge state appears under an electron-electron interaction. The ferromagnetic edge state is stabilized in a nano-ribbon between two zigzag edges (zigzag nanoribbon) through anti-ferromagnetic interaction between edges. This year, we have started an attempt to make such zigzag edges and the zigzag nanoribbon, and the study of their novel electronic properties.

The measurements are performed mainly with the scanning tunneling microscopy and spectroscopy (STM/S) and the electronic transport measurement. Especially, we are using an STM/S which can be operated at tempeartures down to 30 mK, in magnetic fields up to 13 T, and in ultra-high vacuum lower than 10^{-8} Pa with the energy resolutions down to 100 μeV and atomic spatial reslution.

17 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

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

   In 2013, an adsorbate-induced two-dimensional electron system at cleaved surfaces of InSb has been investigated by a low-temperature scanning tunneling microscope and spectroscopy combined with transport measurements in magnetic fields up to 14 T. The magnitude of potential disorder obtained from the spatially-averaged density of states (DOS) agrees with that deduced from damping of the Shubnikov-de Haas oscillations. A dip indicating the Coulomb gap was observed in the spatially-averaged DOS at the Fermi level.

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

   In 2013, we have extended our studies to ultrathin films of indium and aluminum. In the case of indium films, superconductivity was observed in the monolayer regime. The $H_{\parallel}$ dependence of T_c is one order of magnitude stronger than that in the Pb films. Since Δ_R is expected to be small in the indium films, we also extended the analysis to the case where Δ_R is comparable to or smaller than $\hbar\tau^{-1}$. The experimental results are well reproduced by the calculation with $\Delta_R \approx 0.04$ eV, which is much smaller than that expected for the Pb films.

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∼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 high-density excitation phenomena in an indirect gap semiconductor Ge and in a direct gap semiconductor GaAs. In Ge, aiming at the realization of quantum degenerated phases, we have succeeded in the formation of high-density magnetoexcitons by suppressing the formation of electron-hole(e-h) droplet with applying uniaxial-stress to the crystal. In GaAs, we have investigated the origin of excitonic photoluminescence(PL) observed above the Mott density by comparing the optical pump and terahertz probe spectroscopy, optical pump-optical probe spectroscopy, and time-resolved PL measurements.

2. **Higgs amplitude mode in a BCS superconductor $Nb_{1-x}Ti_xN$:** Higgs amplitude mode is a collective excitation mode accompanied with spontaneous symmetry breaking. While the Higgs mode in condensed matters has recently attracted much attention, the Higgs mode in s-wave BCS states has evaded experimental detection due to the absence of coupling with electromagnetic wave. By using terahertz pump-terahertz probe spectroscopy, we investigated the Higgs mode in s-wave BCS superconductor $Nb_{1-x}Ti_xN$ films. After the nonadiabatic excitation with strong monocycle THz pump pulse, we observed a transient oscillation in the electromagnetic response of the BCS state. The oscillation frequency coincides with the BCS gap energy, which is in excellent agreement with the theoretically-anticipated Higgs mode.

3. **Quantum Faraday effect in graphene:** Graphene is a monolayer sheet of carbon atoms tightly bound in a form of honeycomb lattice. Graphene offers a unique arena to study the fundamental physics in condensed matter because of the presence of Dirac cones in the band structure. A striking example is the half-integer quantum Hall effect(QHE), which arises from the existence of non-zero Berry phase associated with the Dirac cone. We have succeeded in observing the quantum magneto-optical Faraday and Kerr effects in the terahertz regime, namely the optical QHE in monolayer graphene epitaxially grown on SiC. With increasing the magnetic field, the rotation angle exhibits plateau structures at the quantum Hall steps. We have investigated systematically the effect of finite coverage of monolayer graphene on SiC substrate.

4. **Development of terahertz near-field spatio-temporal microscope:** We have developed a near-field terahertz spectroscopy system combined with the optical pump-terahertz probe spectroscopy. With the developed system, we have demonstrated the observation of spatio-temporal dynamics of free carriers photoexcited in Si.

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19 Takagi Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi

We are exploring novel quantum phases of correlated electrons in transition metal oxides. In FY2013, main focus was placed on the spin-orbit coupling induced phases and Dirac electrons.

1. **Novel electronic phases produced by spin-orbit coupling in complex Ir oxides:**In 5d Ir oxides, very strong spin-orbit coupling modifies the landscape of electronic structure and electrons with $J_{eff} = 1/2$ state are responsible for conduction and magnetism. $J_{eff} = 1/2$ wave function accommodate quantum phase arising from the orbital motion. We are aiming to explore exotic phase which represent the existence of such quantum phase and recently discovered hyper-honeycomb Ir oxides, with ground state critically close to quantum spin liquid state.

   (a) **Discovery of complex Ir oxide with hyper-honeycomb structure - playground for Kitaev physics:**In the $J_{eff} = 1/2$ magnet, an interference effect of wave function may emerge in the interaction of moments. In particular, when IrO_6 octahedra are connected by edges and Ir moments interact via the planer two Ir-O-Ir 90° bonds, the interference gives rise to a ferromagnetic coupling only for the specific orientation perpendicular to the plane. A honeycomb lattice with such anisotropic interactions is known as Kitaev model of which ground state is quantum spin liquid. Honeycomb α-Li_2IrO_3 attracted attention as a materialization of Kitaev model. In reality, however, there exists an antiferromagnetic interaction in addition to the anisotropic ferromagnetic interaction and α-Li_2IrO_3 turned out to be far away from Kitaev physics. During the course of the exploration, we discovered β-Li_2IrO_3. This compound has a lattice which can be viewed as a three dimensional analogue of honeycomb and the local coordination is essentially the same as that of α-Li_2IrO_3, with 90°Ir-O-Ir bonds but less distorted. The result of magnetization measurement indicated that the anisotropic ferromagnetic coupling is dominant in contrast to α-Li_2IrO_3. From those results, we concluded that the ground state should be critically close to Kitaev-type quantum spin liquid.

   (b) **1/3 hole-doped quantum spin liquid $Na_3Ir_3O_8$:**$Na_4Ir_3O_8$ hyperkagome was discovered as a quantum liquid by the present group. To further investigate the spin liquid state, we have been working on the growth of single crystal. However, the obtained single crystal was always metallic and apparently distinct from spin liquid $Na_4Ir_3O_8$. The detailed structural analysis on the single crystal was recently performed. The result indicated that it is not $Na_4Ir_3O_8$ but $Na_3Ir_3O_8$. The crystal structure is an ordered spinel. It contains the same hyper-kagome network but A-site Na occupies not octahedral site but tetrahedral site. This compound can be viewed as 1/3 hole doped hyper-kagome spin liquid. From physical property measurements and first principle calculations, we have shown that it is a spin-orbit coupling induced semimetal as a consequence of a competition of the bonding and anti-bonding splitting of molecular orbitals on Ir_3 triangles and the orbital mixture due to the strong spin-orbit coupling.

2. **Three dimensional Dirac electrons in solid:** Three dimensional Dirac electrons in antiperovskites Two-dimensional Dirac electrons in graphene are well known. We are aiming to develop a three-dimensional analogue of Dirac electrons in graphene. Due to the interplay of symmetry of lattice and wave functions, the presence of three dimensional Dirac electrons were theoretically proposed for a family of Sr_3PbO related compound with anti-perovskite structure. Single crystals of chemically unstable Sr_3PbO were successfully grown and the presence of Dirac electrons was examined by transport measurements. An extremely large and linear magneto-resistance was observed from a low temperature to room temperature, which support for the presence of Dirac electrons. Quantum oscillation measurements are now in progress.

3. **Designing novel electronic phases in this film superstructure:**

   (a) Tailoring spin-orbital Mott insulator using $SrIrO_3/SrTiO_3$ super-lattice: $SrIrO_3$ perovskite is a three-dimensional analogue of spin-orbital Mott insulator. The ground state is a semimetal due to the presence of symmetrically protected Dirac nodes in the band structure. We had successfully reduced the effective dimension of $SrIrO_3$ by slicing it with a monolayer of $SrTiO_3$. With reducing the number of $SrIrO_3$ layer m, the system undergoes a metal-insulator transition and simultaneously magnetic transition to a weak ferromagnet. The results are consistent with that the lifting the degeneracy of Dirac nodes by breaking the time reversal symmetry with magnetic moments triggers the transition to a magnetic insulator.

   (b) **Superconductivity at the interface of $BaPbO_3/BaBiO_3$ super-lattice:** $BaPbO_3/BaBiO_3$ super-lattice structure was fabricated by Pulsed Laser Deposition (PLD) technique. Superconductivity at $T_c = 4$ K was observed. The angular dependence of upper critical field H_{c2} indicated the two-dimensional superconductivity, which might support for the presence of interfacial superconductivity due to a charge transfer.

20 Theoretical Astrophysics Group

Research Subjects: Oservational Cosmology, Extrasolar Planets, First Star Formation

Member: Yasushi Suto, Naoki Yoshida, Takashi Hosokawa, Atsushi Taruya, & Masamune Oguri

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.

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

Does a second earth exist somewhere in the universe? This naive question has been very popular only in science fictions, but is now regarded as a decent scientific goal in the modern astronomy. Since the first discovery of a gas giant planet around a Sun-like star in 1995, more than a few thousands candidates of exoplanets have been reported as of May 2013. While most of the confirmed planets turned out to be gas giants, the number of rocky planet candidates is steadily increasing. Therefore the answer to the above question is supposed to be affirmative. Our group is approaching that exciting new field of exoplanet researches through the spin-orbit misalignment statistics of the Rossiter-MacLaughlin effect, simulations of planet-planet scattering and tidal evolution of the angular momentum of the planetary system, photometric and spectroscopic mapping of a surface of a second earth and detection of possible biomarker of habitable planets.

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

2013

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

2012

- Exploring the Landscape of Habitable Exoplanets via Their Disk-integrated Colors and Spectra: Indications for Future Direct Imaging Observations
- Toward a precise measurement of weak lensing signals through CMB experiments and galaxy imaging surveys: A theoretical development and its cosmological implications

- Measurements of Spin-Orbit Angles for Transiting Systems:Toward an Understanding of the Migration History of Exoplanets
- Modeling Redshift-Space Clustering of the SDSS Luminous Red Galaxies with Cosmological N-body Simulations: Implications for a Test of Gravity
- Probing the nature of dark matter by gravitational lensing observations
- The Formation and Evolution of Hot-Jupiter:Planet-Planet Scattering Followed by Tidal Dissipation
- Supernova Explosions in the Early Universe
- Validity of Hydrostatic Equilibrium in Mass Estimates of Simulated Galaxy Clusters

2011

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

2010

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

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

21 Murao Group

Research Subjects: Quantum Information Theory

Faculty Members: Mio Murao, Akihito Soeda

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

In this year, our group consisted of two faculty members, Mio Murao (Associate Professor), Akihito Soeda (Assistant Professor), two postdoctoral fellows, Michal Hajdušek (JSPS foreign postdoctoral fellow), Fabian Furrer (JSPS foreign postdoctoral fellow), and 8 graduate students, Shojun Nakayama (D3), Eyuri Wakakuwa (D2), Seiseki Akibue (D1), Kotaro Kato (M2), Kosuke Nakago (M2), Jisho Miyazaki (M2), Yuki Mori, and Atsushi Shimbo. We investigate several aspects of theoretical quantum information. Our projects worked in the academic year of 2013 were the following:

Quantum algorithm

- Random states generating algorithm [7] by Murao in collaboration with Y. Nakata (Leibniz University of Hannover) and M. Koashi (University of Tokyo)
- Possibility and impossibility of controllizing unknown quantum gates by Soeda, Nakayama, and Murao
- Implementation of projective measurement of energy and measure of implementation quality [8] by Nakayama, Soeda, and Murao

Entanglement theory

- Symmetry and typical entanglement by Murao in collaboration with Y. Nakata (Leibniz University of Hannover)
- Entanglement structure and causal order in measurement-based quantum computation [11] by Miyazaki, Hajdušek, and Murao
- Numerical analysis of geometric measures of entanglement by Mori, Soeda, and Murao

Quantum information processing in continuous variable systems

- Entropic measurement-disturbance relations [1] by Furrer in collaboration with M. Berta (ETH Zurich), V. Scholz (ETH Zurich), M. Christandl (ETH Zurich) and M. Tomamichel (CQT, National University of Singapore)
- Continuous variable uncertainty relation in the presence of a quantum memory [2] by Furrer in collaboration with M. Berta (ETH Zurich), V. Scholz (ETH Zurich), M. Christandl (ETH Zurich) and M. Tomamichel (CQT, National University of Singapore)
- Continuous variable quantum key distribution [4] by Furrer in collaboration for theory with J. Duhme (Leibniz University Hannover), T. Franz (Leibniz University Hannover), R.F. Werner (Leibniz University Hannover), and C. Pacher (Austrian Institute of Technology) and for experiments with T. Eberle (Albert Einstein Institute Hannover), V. Haendchen (Albert Einstein Institute Hannover), and R. Schnabel (Albert Einstein Institute Hannover)

Distributed quantum information processing

- Resource compression for LOCC implementations of bipartite unitary gates [9] by Wakakuwa and Murao
- Implementability of unitary operations over the butterfly, grail and cluster networks with free classical communication by Akibue and Murao
- Encoding and decoding of classical information onto quantum state by LOCC by Shimbo, Soeda, and Murao

Quantum information processing using ground states

- Entanglement theory in anyonic systems [10] by Kato, Furrer, and Murao
- Adiabatic gate teleportation [12] by Nakago, Hajdušek, Nakayama, and Murao

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

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5. J. Miyazaki, M. Hajdušek and M. Murao, *Translating measurement-based quantum computation with gflow into quantum circuit*, arXiv:1310.4043

6. K. Nakago, M. Hajdušek, S. Nakayama and M. Murao, *Parallelized adiabatic gate teleportation*, arXiv:1310.4061

7. Y. Nakata and M. Murao, *Diagonal-unitary 2-designs and their implementations by quantum circuits*, International Journal of Quantum Information **11**, 1350062 (2013)

8. S. Nakayama, A. Soeda and M. Murao, *Universal implemantation of projective measurement of energy*, arXiv:1310.3047 (2013)

9. E. Wakakuwa and M. Murao, *Resource Compression for Distributed Quantum Computation*, ar Xiv:1310.3991 (2013)

10. K. Kato, F. Furrer and M. Murao *Operational Meaning of Entanglement Entropy in Anyonic Systems*, arXiv:1310.4140 (2013)

11. J. Miyazaki, M. Hajdušek, and M. Murao, *Translating measurmeent-based quantum computation with gflow into quantu circuit*, arXiv:1310.4043 (2013)

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22 Ueda Group

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

Member: Masahito Ueda and Shunsuke Furukawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controlled systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose-Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied topological excitations and correlation effects in spinor BECs, BCS-BEC crossover and Efimov physics under the control of an atomic interaction strength, quantum Hall states in synthetic gauge fields, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems and the formulation of the dynamics of state reduction in light of information flow under measurements and feedback controls. We list our main research subjects in FY2013 below.

- Quantum many-body phenomena in ultracold atoms
  - Synthesis of spin-orbit coupling with magnetic-filed-gradient pulses [1]
  - Quantized vortices in spin-orbit-coupled BECs [2]

- Integer quantum Hall state of bosons [3]
- Fluctuation effects in quantum phase transitions in spinor BECs [5]
- Topological influence and backaction between topological excitations [8]
- Cluster expansion study of BCS-BEC crossover [9]
- Universality of three-body parameter in Efimov states [10]

- Quantum Information, Quantum Measurement, and Foundation of Statistical Mechanics
  - Simultaneous continuous measurement of photon-counting and homodyne detection [4]
  - Integral quantum fluctuation theorems under measurement and feedback control [6]
  - Thermodynamic work gain from entanglement [7]

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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 its follow-up mission, *ASTRO-H*.

Neutron Stars (NSs) and Super-Nova Remnants (SNRs): We conduct *Suzaku* studies of NSs with various magnetic field strengths, B, believing that their magnetism is a manifestation of nuclear ferromagnetism. Our research targets include X-ray bursters with $B < 10^9$ G, canonical pulsars with $B \sim 10^{12}$ G exhibiting electron cyclotron resonances, long-period pulsars possibly with $B \sim 10^{13}$ G, and "magnetars" supposed to have $B = 10^{14-15}$ G. Through an apparent age discrepancy between a magnetar and an SNR associated to it, we reinforced the view that magnetars are indeed losing its magnetic energy. From one magnetar, free precession was detected, and was interpreted as evidence for NS deformation by very high toroidal magnetic fields reaching 10^{16} G [1].

Mass Accreting Black Holes: Mass accretion onto black holes provides an efficient way of X-ray production. In active galactic nuclei (massive black holes), our new variability-assisted spectroscopy technique revealed that the primary X-ray emission in fact consists of two distinct components [2]. This is expected to settle several long-lasting issues as to AGNs, including the mechanism of their "central engines".

Unification of thermal Comptonization process: Thermal Comptonization is a process widely seen among mass-accreting objects [3]. In addition to the y-parameter, we discovered that a new parameter, $Q \equiv$ (electron emperature)/(seed photon temperature) provide good description of these processes.

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 in clusters of galaxies. We obtained novel evidence that member galaxies in each cluster have been falling, over the Hubble time, to its potential center [4]. This is presumably due to magneto-hydrodynamic interactions between the hot plasma and the galaxies moving through it. We also found an excellent example of merging cluster at its early merger phase.

GROWTH (Gamma-Ray Observation of Winter Thunder clouds) experiment: This is a semi-atuomated gamma-ray experiment placed at Kasiwazaki, Niigata, to watch for bursts of gamma-rays from winter thunderclouds. Over 7 winters, we have detected altogether more than a dozen bursts, with their energies extending to ~ 10 MeV. One of them exhibits clear 511 keV line in its spectrum.

Future Instrumentation: In collaboration with many domestic and foreign groups, we are developing a successor to *Suzaku*, *ASTRO-H*. Scheduled for launch in 2015, 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, development of large BGO scintillators [5] and their read-out electronics, double-strip silicon detectors, and onboard/ground software systems.

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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, Naoto Tsujii

We perform experiments on the TST-2 spherical tokamak at the Kashiwa Campus in order to develop physics understanding and technology to realize nuclear fusion power. The current focus of our group is the study of non-inductive plasma start-up using the lower hybrid wave (LHW) on TST-2. We have four 200 MHz transmitters with ∼100 kW source power each.

In FY2013, current drive experiments were performed using the dielectric loaded waveguide array (grill) antenna which has the capability to vary the wavenumber spectrum of the excited LHW. It was found that the optimum wavenumber is around $n_\parallel$ =1–6 ($n_\parallel = ck_\parallel/\omega$) on TST-2. Power modulation experiments were carried out and the fast electrons generated by LHW were found to be promptly lost, much faster than the collisional slowing down time. Analysis using numerical simulations show that this is due to orbit loss of fast electrons with large banana widths, which should be mitigated once the plasma current reaches ∼50 kA. A new high impedance probe was developed to measure the floating potential fluctuations of LHW. The measured wavenumber was found to be around 20 m^{-1}, consistent with the wavenumber of the LHW excited by the antenna.

Experiments using the capacitively coupled combline (CCC) antenna, newly developed in collaboration with General Atomics (US), have started. Plasma current ramp-up up to 12 kA has been achieved so far. Including the previously used inductively coupled combline (ICC) antenna, three types of antennas were compared. The dependence of the maximum current on parameters such as the magnetic field was similar for the three antennas. On the other hand, the new CCC antenna had the highest current drive efficiency among the three antennas.

Pressure anisotropy in inductively formed TST-2 plasmas was measured using a double-pass Thomson scattering diagnostic. Parallel and perpendicular pressures were measured with the plasma current in the co/counter direction. Anisotropies of up to 100% were observed. The three temperature model (co, counter, perpendicular) fits the experimental data better than the simpler shifted-Maxwellian model. The Reynolds stress and the Maxwell stress arising from turbulent fluctuations, and the plasma flow were also measured using a new probe over a wide region in the low field side edge of the torus.

For studies of plasma equilibrium created inductively or non-inductively, new diagnostics are being developed. A small Rogowski probe was developed to measure the local current density. Pick-ups from external magnetic fields were successfully eliminated by optimizing the cable winding pattern. Local current measurements with S/N of 10 are now possible in inductively formed plasmas.

A multi-pass Thomson scattering system is being developed to measure electron temperature and density in low density plasmas created non-inductively. Ten round trips of a laser pulse were observed after optimization of the optical system. With the present efficiency of the optical system, the improvement in S/N was found to be around 30%.

Our group also collaborate with other fusion experiments in Japan and abroad, including JT-60SA, LHD, LATE, QUEST, Alcator C-Mod (US), and MAST (UK).

Thomson scattering of RF driven steady-state plasmas is being developed on the QUEST spherical tokamak at Kyushu University. This fiscal year, plasmas were created with 28 GHz electron cyclotron heating. With additional injection of 8.2 GHz, mode conversion to the electron Bernstein wave (EBW) is expected. Thomson scattering measurements provided useful profile data to help with the optimization of mode conversion to EBW.

Measurements of density fluctuations associated with the ICRF (ion cyclotron range of frequencies) fast wave on LHD using a microwave reflectometer. Dependences of the RF fluctuation levels on parameters such as the minor radius, RF power, and ion species concentration, were investigated. Comparing the RF fluctuation levels for waves excited by antennas at six different toroidal locations, the decay length of the wave intensity was determined to be around 4 m.

In FY2013, a new RF magnetic probe was developed for measurements of LHW at 4.6 GHz on Alcator C-Mod at MIT. Prototypes of the probe were fabricated, and bench tests showed the wavenumber of the wave can be measured with an accuracy of 1.5%.

25 Sano Group

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

Members: Masaki Sano and Kazumasa A. 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 thermal effects, (ii) small systems, in which non-equilibrium and thermal fluctuations have comparable effects, (iii) biological phenomena, as important instances where non-equilibrium dynamics plays the essential role. More specifically, our current research topics include:

1. Macroscopic systems out of equilibrium

(1) Universal fluctuations of growing interfaces [1, 9]

(2) Laminar-turbulence transition in channel flow

(3) Rheology of non-Brownian particle suspensions

(4) Lehmann effect of cholesteric liquid crystal under temperature gradient

2. Small systems out of equilibrium

(1) Formulation of thermodynamics of subsystems in terms of information transfer [5]

(2) Scale dependence of stochastic thermodynamics and steady state thermodynamics [7]

3. Biological systems and active matter

(1) Collective motion of active matter due to short-range nematic interactions

(2) Investigations of active matter using self-propelled particles

(3) Phenomenological model of F_1-ATP-ase

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26 Yamamoto Group

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

Member: Satoshi Yamamoto, Nami Sakai, and Yoshimasa Watanabe

Molecular clouds are birthplaces of new stars and planetary systems, which are being studied extensively as an important target of astronomy and astrophysics. Although the main constituent of molecular clouds is a hydrogen molecule, various atoms and molecules also exist as minor components. The chemical composition of these minor species reflects formation and evolution of molecular clouds as well as star formation processes. It therefore tells us how each star has been formed. We are studying star formation processes from such a astrochemical viewpoint.

Since the temperature of a molecular cloud is as low as 10 K, an only way to explore its physical structure and chemical composition is to observe the radio wave emitted from atoms, molecules, and dust particles. In particular, there exist a number of atomic and molecular lines in the millimeter to terahertz region, and we are observing them with various large radio telescopes including ALMA.

We are conducting a line survey of low-mass star forming regions with Nobeyama 45 m telescope and ASTE 10 m telescope, aiming at detailed understanding of chemical evolution from protostellar disks to protoplanetary disks. In the course of this effort, we have recently established a new chemistry occurring in the vicinity of a newly born star, which is called Warm Carbon Chain Chemistry (WCCC). In WCCC, carbon-chain molecules are produced by gas phase reactions of CH_4 which is evaporated from ice mantles. This has recently been confirmed by our detection of CH_3D in one of the WCCC sources, L1527. Existence of WCCC clearly indicates a chemical diversity of low-mass star forming regions, which would probably reflect a variety of star formation. We are now studying how such chemical diversity is brought into protoplanetary disks by using ALMA. In L1527, we have found that carbon-chain molecules only exist in an infalling-rotating envelope outside the centrifugal barrier ($r = 100$ AU), while SO preferentially exists around the centrifugal barrier. Hence, chemical compositions drastically changes across the centrifugal barrier of the infalling gas. Further analyses are in progress.

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooled HEB mixer using NbTiN and NbN in our laboratory. Our NbTiN mixer shows the noise temperature of 470 K at 1.5 THz, which corresponds 7 times the quantum noise. This is the best performance at 1.5 THz in spite of the use of the wave-guide mount. Furthermore, we successfully realized the waveguide-type NbN HEB mixer by using the NbN/AlN film deposited on the quartz wafer. The 0.8/1.5 THz dual-band HEB mixer receiver was assembled, and was installed on the ASTE 10 m telescope for astronomical observations. The 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 2015.

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27 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) Laser-field-free orientation of state-selected asymmetric top molecules [1]

With combined electrostatic and shaped laser fields with a slow turn on and rapid turn off, laser-field-free orientation of asymmetric top iodobenzene molecules with higher degrees of orientation has been achieved for the first time. In order to further increase the degrees of orientation, state-selected molecules are used as a sample. It is confirmed that higher degrees of orientation is maintained in the laser-field-free condition for 5–10 ps, which is long enough to study femtosecond-attosecond dynamics in molecules, after the rapid turn off of the laser pulse. The observation of the slow dephasing time of 5–10 ps ensures future prospects in molecular orientation techniques. This accomplishment means not only that a unique molecular sample has become available in various applications but also that the present technique can be used as a new spectroscopic technique to investigate ultrafast rotational dynamics of molecules.

(2) High-order harmonics generation from aligned molecules with carrier-envelope-phase-stabilized 10-fs pulses [2]

Clear interference fringes are observed in the high-order harmonic spectra generated from aligned molecules with carrier-envelope-phase-stabilized 10-fs pulses. A detailed Fourier analysis successfully reveals that the fringes are dependent on the carrier-envelope-phase and are formed by the interference between attosecond pulses *when the harmonic chirp is significantly large.* We further examine the possibility of observing the harmonic phase change in the harmonic spectra generated from aligned CO_2, which is associated with the destructive interference in the recombination process, and in those from aligned N_2, which is associated with the contributions from multiple orbitals, HOMO and HOMO-1.

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28 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 are now investigating a stable and quantum degenerate state of dark exciton gas at such very low temperatures. We also investigate novel optical and terahertz-wave responses for some artificial nanostructures obtained by advanced micro-fabrication technologies. 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. Specifically, in collaboration with RIKEN, the Foundation for Coherent Photon Science Research was established two years ago. 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"). Institute for Photon Science and Technology was established in 2013 with the mission to create new interdisciplinary science through the developments and applications of state-of-the-art photon science and technologies. This Institute is hosting "Innovative Center for Coherent Photon Technology" that aims to paradigm-shift the concept of "manufacturing" using coherent phonon technologies and works to create new sciences needed to support the future vision of our society and the industry.

This year the following activities were done:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   (a) Systematic study 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) Polarization-controlled circular second-harmonic generation from metal hole arrays with three-fold rotational symmetry
   (b) Terahertz polarization pulse shaping with arbitrary field control
   (c) Control of THz optical activity with active spiral metamaterials
3. Development of novel coherent light sources and spectroscopic methods:
   (a) Development of vacuum ultraviolet light sources and their applications
   (b) Efficient nonlinear optical conversion using passive cavities
   (c) High-harmonic generation and its application to spectroscopic study
   (d) Established the Foundation for Coherent Photon Science Research

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29 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Yoich Aso

The detection of gravitational waves is expected to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars; 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

  - Optical design of the interferometer
  - Alignment control
  - Parametric instability

- Space laser interferometer, DECIGO
- Development of TOBA (Torsion Bar Antenna)
  - A new type sensor for TOBA
  - Design of next generation TOBA
- Development of the ultra stable laser source
  - Optical system
  - Vibration isolation of cavity
  - Cryogenics for cavity
- High sensitive laser interferometer using non-classical light
- Study of space isotropy

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30 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose, Hiroshi Kohsaka and Etsuko Takasu

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

1. Role of Sensory Experience in the Development of Motor Circuits

Neuronal circuits are formed according to a genetically predetermined program and then reconstructed in an experience dependent manner. While the existence of experience-dependent plasticity has been demonstrated for the visual and other sensory systems, it remains unknown whether this is also the case for motor systems. Here we examined the effects of eliminating sensory inputs on the development of peristaltic movements in *Drosophila* embryos and larvae. The peristalsis is initially slow and uncoordinated, but gradually develops into a mature pattern during late embryonic stages. We tested whether inhibiting the transmission of specific sensory neurons during this period would have lasting effects on the properties of the sensorimotor circuits. By using Shibire-mediated inhibition, we showed that inhibition of chordotonal organs during specific period during embryonic development led to a lasting decrease in the speed of larval locomotion. The results suggest that neural activity mediated by specific sensory neurons is involved in the maturation of sensorimotor circuits in *Drosophila* and that there is a critical period for this plastic change.

2. Neural Circuits Modulating the Larval Turning Behavior

Serotonin (5-HT) is known to modulate motor outputs in a variety of animal behaviors. However, the downstream neural pathways of 5-HT remain poorly understood. We studied the role of 5-HT in directional change, or turning, behavior of fruit fly (*Drosophila melanogaster*) larvae. We analyzed light- and touch-induced turning and found that turning is a combination of three components: bending, retreating, and rearing. Serotonin transmission suppresses rearing; when we inhibited 5-HT neurons with Shibire or Kir2.1, rearing increased without affecting the occurrence of bending or retreating. We identified a class of abdominal neurons called the abdominal LK neurons (ABLKs), which express the 5-HT1B receptor and the neuropeptide leucokinin, as downstream targets of 5-HT that are involved in the control of turning. Increased rearing was observed when neural transmission or leucokinin synthesis was inhibited in these cells. Forced activation of ABLKs also increased rearing, suggesting that an appropriate level of ABLK activity is critical for the control of turning. Calcium imaging revealed that ABLKs show periodic activation with an interval of ∼15 s. The activity level of ABLKs increased and decreased in response to a 5-HT agonist and antagonist, respectively. Our results suggest that 5-HT modulates larval turning by regulating the activity level of downstream ABLK neurons and secretion of the neuropeptide leucokinin.

References

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31 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Biophysical and Biochemical characterization of human cytoplasmic dynein

Dynein is a molecular motor that moves toward the minus-end of microtubules, and responsible for transporting various cargos, positioning the Golgi complex and mitotic spindles in cells. The motor properties of dynein are relatively well understood for yeast dynein, while those of human dynein are still obscure. Here, we performed biophysical and biochemical characterization of human cytoplasmic dynein. The maximum microtubule gliding velocity of the motor domain of dynein was 976 um/s with Km of 49uM for ATP. ADP was competitive inhibitor with Ki=135uM. When nucleotide was depleted from dynein, dynein was unable to bind to microtubules in the absence of ATP. Furthermore, dynein movement was rescued when ATP was added to nucleotide-depleted dynein, unlike kinesin.

Power Stroke Measurement of Human Cytoplasmic Dynein

Cytoplasmic dynein is a motor protein moving along microtubules toward the minus-end, and plays an important role in cellular processes. Previously we reported that dynein moves continuously along microtubule, and takes dominantly 8 nm step. The mechanism of dynein movement remains unknown. Here, we used dumbbell dual-trap optical tweezers instrument to measure the size of power stroke driven by conformational changes of single-headed dynein. We expressed the motor domain of human cytoplasmic dynein in SF9 cells and purified by Flag-tag affinity. Mutant kinesin, T93N, was used for adhesion between microtubule and bead. We finished setting up the dumbbell instrument and started to measure the power stroke distance.

A non-invasive technique for the in vivo tracking of high-speed vesicle transport in mouse neutrophils

Neutrophils play an essential role in the innate immune response. We developed a new non-invasive technique for the in vivo imaging ofneutrophils labeled with quantum dots, up to 100 um below the skin surface of mice. The quantum dots were endocytosed into vesicles in the neutrophils, allowing us to track the vesicles at 12.5 msec/frame with 15-24 nm accuracy. Most intriguingly, the vesicles containing quantum dots were transported at higher speed than the in vitro velocity of a molecular motor such as kinesin or dynein. This is the first report in which non-invasive techniques have been used to visualize the internal dynamics of neutrophils. In this symposium, I'll report recent progress in the molecular mechanism of the vesicle transport in the neutrophil.

Noninvasive in vivo imaging of tumor cells in a novel xenograft model

We developed new imaging methods to visualize molecules under noninvasive condition. We focused on the ear auricle of mouse for observation of tumor cells because very thin (about 150-200 μ m) and limited hypodermal tissue. We developed a novel xenograft model of the ear auricle with breast cancer cells in order to observe them noninvasively by spinning disk confocal (CSU) system. We injected two kinds of human breast cancer cell lines, KPL4-EB1-GFP and MDA-MB-231, into the ear auricle of SCID mice. It is known that KPL4-EB1-GFP is easily form tumor tissue at subcutaneous of mouse backs, but MDA-MB-231 is not. Tumor composed of both cells was successfully formed in mice. This indicates that the ear auricle is suitable position to form tumor. To image the molecules, specific antibodies to recognize these cells were labeled with fluorescence quantum dots and then injected to tail vein after the formation of tumor. We successfully performed real time observation of quantum dots within breast cancer cells and on its membrane under noninvasive condition.