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東京大学 大学院　理学系研究科・理学部
物理学教室

II

Summary of group activities in 2012

1 Theoretical Nuclear Physics Group

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

Member: Takaharu Otsuka 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,
(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 Bose-Einstein condensation, quantum chaos, etc.

The structure of unstable nuclei is the major focus of our interests, with current intense interest on novel relations between the evolution of nuclear shell structure and characteristic features of nuclear forces, for example, tensor force, three-body force, etc. Phenomena due to this evolution include the disappearance of conventional magic numbers and appearance of new ones. We have published pioneering papers on the shell evolution in recent years. The tensor force effect has been clarified [1] with various actual applications including nuclear shapes [2], while striking effect of three-body force has been shown [1] for the first time. This effect in Ca isotopes is discussed in [3].

The structure of such unstable nuclei has been calculated by Monte Carlo Shell Model, for instance to Be isotopes [4] and also by conventional shell model. Their applications have been made in collaborations with experimentalists internationally spread, *e.g.*, [5, 6, 7, 8].

The Monte Carlo Shell Model has been improved with further developments, for example, a new extrapolation method [9]. Thus, the advanced version of Monte Carlo Shell Model has been established [10, 11, 12], which makes our practice on the K computer possible.

The mean-field based formulation of the Interacting Boson Model is a new original approach being developed, and a long-standing problem on strongly deformed nuclei has been solved [13]. This approach is so general and powerful that its applications are being spread very fast in big collaborations, for instance, the nature of triaxial deformation has been clarified [14, 15, 16].

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

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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

The main research interests at our group are in string/M theory and high energy particle physics phenomenology. In the field of high energy phenomenology, supersymmetric unified theories are extensively studied and cosmological problems are also investigated. In the field of string/M theory, fundamental properties of branes in M-theory are intensively studied. Various supersymmetric dualities are also being pursued.

We list the main subjects of our researches below.

1. High Energy Phenomenology
   - 1.1 SUSY models [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]
   - 1.2 Resonant leptogenesis in $U(1)_{B-L}$ model [12]
   - 1.3 Observing null radiation zone at the LHC [13]
   - 1.4 Higher dimensional derivative interaction of the Higgs fields [14]
   - 1.5 CP violations [15, 16]
   - 1.6 Top forward–backward asymmetry [17]
   - 1.7 Heavy photon models [18]
   - 1.8 Cosmology in PQ models [19]
   - 1.9 A solution to the moduli problem [20, 21, 22]
   - 1.10 Primordial gravitational waves as probes of the early Universe [23, 24]
   - 1.11 Isocurvature perturbation in dark radiation [25]
   - 1.12 Inflation models in supergravity [26, 27, 28, 29]
   - 1.13 Scalar dynamics in thermal bath [30, 31]
   - 1.14 130GeV gamma-ray line from decaying dark matter [32]
   - 1.15 Gravitino problem [33]
   - 1.16 Phenomenology via gauge/gravity duality [34]

2. Superstring Theory
   2.1 Study of M-theory [35, 36]
   2.2 Relations among 4d superconformal index, 5D SYM and 2D q-YM [37, 38, 39, 40]
   2.3 Study of 4d supersymmetric gauge theory [41, 42]
   2.4 AdS/CFT corrrespondence and integrable system [43]

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3 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

1) Antimatter study at CERN's antiproton decelerator

$\bar{p}$-nucleus annihilation cross section at ultra-low energies At high energies, it is known that the $\bar{p}$-nucleus annihilation cross sections scale as $\sigma_{\text{ann}} \propto A^{2/3}$ where A is the nuclear mass number. On the other hand, at very low energies where the wave length of 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 target, and observed the antiproton annihilation in the targets for the first time at this low energy region. We are now analyzing the data we took in 2012 to determine the absolute values of the antiproton-nucleus annihilation cross sections.

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

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

In 2012, we succeeded in measuring ^{207}Fr and ^{211}Fr. We used a nanosecond titanium-sapphire laser developed by the ASACUSA experiment at CERN. A new pump laser was constructed so that the output power was ten times higher than last year. In order to measure isotopes with low yields, however, we needed to improve the detection efficiency.

3) Precision X-ray spectroscopy of kaonic atoms

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

X-ray spectroscopy of kaonic atoms at DAΦNE In fiscal year 2012, we finished the data analyses of all the measurements carried out during the beam time of SIDDHARTA experiment in the fiscal year 2009. The results include mainly the following two parts.

One comes from the simultaneous analysis of the deuterium target data and carefully selected hydrogen target data set. We determined the absolute yields of kaonic hydrogen $2p$-$1s$ transition X-rays and all K- series X-rays. Meanwhile, based on the same analysis, we estimated an upper limit for the yield of $2p$-$1s$ transition X-rays of kaonic deuterium, for reference of future measurement. Moreover, we obtained the most reliable evaluation of the kaonic hydrogen $2p$ width due to nuclear absorption from a comparison of the kaonic hydrogen X-ray yields to the Extended Standard Cascade Model calculation.

The other part of the results is about the widths of the $2p$ states of kaonic helium-3 and helium-4 atoms. In contrary to the early experiments in the 1970 's and 1980 's, the SIDDHARTA experiment concludes smaller widths of such states, which are in consistency with theoretical speculations of about 1-2 eV. Within the precision of our experiment, we did not find isotope-dependence of the strong-interaction shift and width of the $2p$ states of kaonic helium atoms.

X-ray spectroscopy of kaonic helium at J-PARC The J-PARC E17, which is to be carried out at K1.8BR beamline in the J-PARC hadron experimental facility, will measure X-rays from kaonic helium 3 and kaonic helium 4 to determine the strong interaction shifts in their $2p$ level. They would impose strong constraint on $\bar{K}$-nucleus interaction. In fiscal year 2012, as a part of E15 experiment described in the followings, we made progress on K1.8BR beam line tuning, stable liquid-helium3 target operation, and the commissioning of a cylindrical detector system, which will be used for the reaction vertex reconstruction.

4) Study of kaonic nuclei

Search for K^-pp and K^-pn deeply-bound kaonic states at J-PARC The J-PARC E15 adopts ^{3}He(K^-,N) reaction to search for $\bar{K}NN$. E15 is a kinematically complete experiment in which all reaction products are detected exclusively for $K^-pp \to \Lambda p$ decay mode, and it aims to provide decisive information on the nature of the simplest antikaonic nucleus. In the fiscal year 2012, detector systems for forward scattered neutron and protons were constructed to complete our setup. In the engineering runs performed in June and December, we have confirmed the designed performance for all the systems including the beam-line apparatus, the ^{3}He target, the cylindrical detector system and newly installed forward counters. Then, we have started 1st-stage physics data taking in March 2013, which will be completed before the summer shutdown.

5) 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. The measurement will help us better understand the strong interaction between the pion and the nucleus, which leads to quantitative evaluation of the magnitude of the quark condensate at the normal nuclear density. In 2011, we analyzed the result of a pilot experiment performed in 2010 and made the position spectrum of ^{3}He. Some clear peaks appeared in the spectrum, which indicate the first observation of ^{121}Sn pionic atom in the world. In 2012, we performed machine study at RIBF to measure acceptance and dispersion of our optics precisely. With the result of this machine study, we could apply the precise energy calibration to the position spectrum, and transform it into the binding-energy spectrum. In 2013, we will finalize the analysis and prepare for a main experiment, which will be performed in the end of the fiscal year.

Feasibility study of pionic atom spectroscopy with inverse kinematics As described above, the pionic atom can be a probe of the quark condensate at the normal nuclear density. To access density dependence of the quark condensate, we are now planning the pionic atom spectroscopy with unstable nuclei (HI) using inverse kinematics, d(HI, ^{3}He). The pionic atom spectroscopy with unstable nuclei such as neutron-rich nuclei makes it possible for us to study quark condensate at different nuclear densities from normal nuclear density due to the neutron skin effect on the pion distribution. We examined an experimental setup which consists of a pure deuterium (1 atm) active target of TPC (Time Projection Chamber) and a full energy detector. Applying magnetic field in the TPC, we can observe ^{3}He emitted near the forward 0 degree. In this method, a typical yield of $1s$ pionic states is estimated to be 1×10^3 /day assuming the incident beam intensity of 10^7 /s, and the Q value resolution is estimated to be about 500 keV (FWHM), which indicates the experiment is sufficiently feasible.

6) Study of η' mesic nuclei

We are planning the missing-mass spectroscopy of η' mesic nuclei at GSI to study in-medium properties of η' meson. We will employ 2.5 GeV proton beam and create η' meson in carbon nuclei by the ^{12}C(p,d) reaction. Then, the energy of the η' mesic nuclei will be derived by measuring the momentum of the ejectile deuterons with a spectrometer.

In 2012, we developed and tested an aerogel Cherenkov detector for the rejection of expected proton background. In the test experiment, we achieved background rejection capability larger than 99.5 %, which is sufficient for the main experimnet. We will continue preparation of other detectors and spectrometer optics in 2013.

7) Study of muonium production targets

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

We tested silica-aerogel as a muonium emitter. The silica-aerogel is aggregate of small globules of silicon dioxide and it has a large surface area as well as silica particle layer. We carried out a measurement of muonium emission from silica-aerogel in TRIUMF muon beamline in 2011. In this year, we analyzed the obtained data.

4 Sakurai Group

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

Member: Hiroyoshi Sakurai, 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), RIKEN. The RIBF is a world-top leading facility where RI beam intensities are the highest in the world. We maximize RIBF utilization to access nuclei very far from the stability line as well as to exploit new types of experiments and new methods of spectroscopy via new ideas and detector developments.

β-delayed γ-ray spectroscopy at EURICA campaign

A β-decay experiment of neutron-rich nuclei around ^{78}Ni has been performed as part of EURICA campaign at the RIBF at RIKEN in the end of 2012. The experiment aimed at exploring new isomers, half-lives, and β-decay spectroscopy of nuclei in the vicinity of the doubly-magic ^{78}Ni. Several new half-lives in this region have been measured for the first time. The new half-lives together with data from literature allowed for a systematic study and comparison between different global models and theoretical calculations. Those outputs will largely extend our knowledge about nuclear structure towards neutron drip-line.

Development of He-3 neutron detector for measurement of β-delayed neutron emission

Rapid neutron-capture process (r-process) in the universe at the extreme condition such as supernovae is known as a process of nucleosynthesis for atomic nuclei heavier than iron. However the path of the r-process is poorly known, since this process goes on the neutron-rich nuclei far from the β-stability and there are limited experimental data available. Especially, some nuclei have probability of β-delayed neutron emission, which changes the path of r-process. Hence the emission probability of β delayed neutron (P_n) must be determined experimentally.

We are now developing the neutron detector array using He-3 proportional counter. He-3 has a large absorption cross-section for the thermal neutron and is used as a converter gas by the nuclear reaction; $^3\text{He} + n \to t + p$. Therefore neutron detector based on He-3 tubes has a large detection efficiency and no cross-talk effect by the scattered neutron. This year we tested basic properties of He-3 tubes using paraffin moderator with different shapes and geometrical configurations. The obtained detection efficiency is well reproduced by the simulation using the Monte Carlo N-Particle (MCNP) code.

Development of a new γ-ray detector for in-beam spectroscopy

In-beam γ-ray spectroscopy at RIBF aims at expanding our knowledge of the structures and dynamics of exotic nuclei. In this method, a high-granular scintillator array is placed around the secondary target to detect de-excitation γ-rays emitted from nuclei after the secondary reaction.

We are now developing a new generation γ-ray detector array with very high granularity called SHOGUN (**S**cintillator based **H**igh-res**O**lution **G**amma-ray spectrometer for **U**nstable **N**uclei). SHOGUN consists of approximately 1000 $LaBr_3$(Ce) scintillators. It has not only high efficiency but also high energy and timing resolution. In this year we tested basic properties of several $LaBr_3$(Ce) scintillators with different shapes. We also start measuring the timing resolution and the detection efficiency to find the best way to measure lifetimes of exited state of exotic nuclei.

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 medium range force using ultra-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 new discovery of a Higgs Boson at LHC. The details of the observed Higgs Boson and other new particles will be studied in a cleaner environment of e^+e^- collisions at the International Linear Collider ILC.

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to use superconducting 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 in the end of 2012. 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 chair is 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 size, by using a high power laser interferometer. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC. Since 2012 autumn, a new postdoctoral fellow who is expert on the silicon electro-magnetic calorimeter joined from UK. We establish a group to work on calorimeters for ILC detector.

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

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, a Higgs Boson was discovered by the ATLAS and CMS experiments

at LHC. We call this as "2012 July Revolution". Our students have been working on data analysis on search for a Higgs Boson in the very important decay mode of $H \to \gamma\gamma$. Also other student searched for supersymmetric partners of third generation quarks with the missing transverse energy and with b-quark signal.These results are already published in journals.

4) One of our graduate student was worked out on 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 was submitted in journal.

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.

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

We built a segmented antineutrino detector made of plastic scintillators called PANDA, Plastic Anti-Neutrino Detector Array. Last year, a 360-kg prototype called PANDA36 was deployed for two months at Ohi Power Station in Fukui, Japan. It was installed on a van, transported to the site, and held in the van outside of the reactor building during the measurement. We observed a two-sigma difference in neutrino-like event rate before and after the shutdown of the reactor. This is the world's first aboveground antineutrino detection of a nuclear reactor. A larger prototype PANDA64 of 640 kg mass is now ready and under the test running in the university campus with a newly installed 24-cm thick water shield surrounding it. It should be capable of ON/OFF detection of Ohi reactor with three-sigma accuracy within two days with its larger detector mass and better background rejection power.

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

An experiment is being performed using a dedicated detector piggybacked on Sumico to search for hidden sector photons kinetically mixing with the ordinary photons. The detector consists of a cylindrical vacuum chamber with a photon sensor in it. The existence of the hidden sector photons and other hidden sector particles is predicted by extensions of the Standard Model, notably the ones based on string theory. The hidden sector photon is expected to come from the direction of the sun. It would be produced in the solar core or in the space by oscillation of the ordinary photon, and can transmute into the photon again in a long vacuum chamber in the laboratory. A photon sensor in the chamber would readily detects the ordinary photon. We published the result of the world's first solar hidden sector photon search experiment with this solar hidden sector photon telescope. We are now preparing an extended-size detector with reduced background events and less systematic effects.

7 Aihara & Yokoyama Group

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

Neutrino and Nucleon Decay Experiment (Hyper-Kamiokande), Measurement of Neutrino-nucleus Interactions (SciBooNE), and R&D for 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 procedure 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 are involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) to be mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct extensive wide-filed deep survey to investigate weak lensing. This data will be used to develop 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy. This year, the camera was mounted on the Subaru telescope at Hawaii and the commissioning was 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. The main goal of T2K is the observation of muon neutrino to electron neutrino ($\nu_\mu \to \nu_e$) flavor transition and a measurement of the third neutrino mixing angle θ_{13}, which is related to the feasibility of CP asymmetry measurement in the lepton sector. Based on the data taken before the summer 2012, we reported an evidence for the electron neutrino appearance from a muon neutrino beam.

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

In order to pursue the study of properties of neutrino 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 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 photo-electron multiplier. We are going to evaluate the performance of HPD as photosensor for a water Cherenkov detector using a 200-ton water tank at Kamioka. This year, we have calibrated ten 8-inch HPD's.

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 1.0 and 1.6TeV, 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, Takashi Oka (- May 2012), Naoto Tsuji (Oct 2012-)

Our main interests are many-body and topological effects in electron systems, i.e., **superconductivity, magnetism and topological phenomena**, for which we envisage a **materials design for correlated electron systems** and novel **non-equilibrium** phenomena should be realised. Studies in the 2012 academic year include:

- **Superconductivity**[1]
  — High-Tc cuprates: material- and pressure-dependence [2]
  — Multi-layer high-Tc cuprates [3]
  — Organic and carbon-based superconductors [4,5]
  — Superconductivity induced in non-equilibrium:
  Dynamical repulsion-attraction conversion in intense ac fields [6]

- **Topological systems**
  — Spin Hall effect in the iron-based superconductors [7]
  — Graphene quantum Hall system and the chiral symmetry[8-10]
  — Optica (THz) quantum Hall effect in the 2D electron gas and in graphene [11]
  — Graphene quantum dot [12]
  — Fractional quantum Hall effect in oxides [13]
  — Zeolite-templated carbon [14]
- **Non-equilibrium phenomena**
  — Dielectric breakdown of Mott insulators[15]
  — Dynamical phase transitions in correlated electron systems
  — Dicke transition in solids placed in an optical cavity
  — Nonequilibrium quantum spin systems[16]

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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.

Phase transitions of systems with bistable states which have different local lattice structures

The lattice distortion due to difference of local structures of the lattice causes an effective long range interaction among spin states, and realizes a phase transition of the mean-field universality class.The long range interaction prefers a uniform configuration and thus the systems keep homogeneous configuration even near the critical temperature. However, when the systems change between the two states in the open boundary condition, the systems show inhomogeneous structures.

We have pointed out that the dynamics of these systems has peculiar properties. For example the domains which appear in switching processes are proportional to the system sizes, which we call macroscopic nucleation. These new properties of ordering processes in systems with bistable states which have different local lattice strictures was summarized in the review book.[3, 6, 14]

In the last year, we studied size dependence of shape and dynamics of the domain wall in detail. In the short-range model, the width of the domain wall is proportionally to the square of the system size. However, in the present model, the dependence of the width on the size changes with the relative time scale of the dynamics of the lattice degrees of freedom and the spin degrees of freedom. If the spin dynamics is faster than the lattice dynamics, the width of the domain wall is proportional to $\sqrt{L}$ while it is proportional to L in the opposite case, where L the width of the system parallel to the domain wall.[20, 28, 34]

We also studied the effect of size difference of HS and LS in the antiferromagnetic interacting systems which have been studied for models of two-step phase transitions of the spin-crossover systems. We found that in the antiferromagnetic systems the order parameter is of the staggered structure, and thus the size difference does not affect essentially. We obtained detail phase diagram of the elastic model with the ferromagnetic and antiferromagnetic short-range interaction.[19, 39]

Phase transitions in long-range interacting systems

It has been known that the long-range interaction causes the phase transition to be the mean-filed type where the system has a uniform configuration. However, we have pointed out that in some conditions the uniform structure becomes unstable, and given the conditions in details. We showed that the same properties hold in microcanonical ensemble,[8] and also extended the studies to the quantum systems.[9] Moreover, we have shown that the long-range interacting systems can be realized in realistic systems as mentioned above, and we estimated the effective long-range interaction in those systems and peculiar properties, e.g. non-monotonic dependence of the internal energy on the temperature as shown in Fig. 3.2.3.[12]

Statistical mechanics on the coercive field

We join the project of the Elements Strategy Initiative Center for Magnetic Materials, we started studies to increase the coercive field. It has been known that the real magnets consist of assembly of small pieces of micro crystals, which has not yet been studied in statistical mechanics. We will combine the nucleation theory and also theory of domain wall pinning, and develop the theory framework on this problem. [41, 42]

Stochastic process

Generalization of many particle Brownian motion has been proposed by using a differential-difference operator so-called Dunkl operator. We have studied expression of a general form of the transformation by the intertwining operator.[26] We studied the asymptotic behavior in the strong interaction limit.[10] We have found that the particles are fixed on the freezing points which are given by the zero points of the Hermit polynomials in the case of the A-type systems and those of Lagel polynomials for the B-type.[30]

Moreover, we showed the relationship between the Dunkl system and the Calgero-Moser system by using the so-called diffusion scaling. We also studied how the distribution changes to the limiting form by numerical calculations as shown in Fig. 3.2.4.[27, 29]

Quantum Statistical Mechanics

Cooperative phenomena in quantum systems are also important subject in our group. In quantum systems, they show interesting non-classical behavior both in static and dynamical properties. In the last year, we studied an itinerant ferromagnetism in an extended Nagaoka system (Hubbard model) where the electron density is controlled by the chemical potential. We study the change of the total spin as a function of the chemical potential and also on the on-site repulsion interaction. This model shows various magnetic properties, e.g., the Mott singlet, Nagaoka ferromagnetism, and a kind of lattice-Kondo system. In Fig. 3.2.5 we depicted the chemical potential dependence of the total spin. The nature of spin correlation functions of the states was obtained. The model proposes new types of molecular magnets. [21, 23, 35, 35, 43]

Quantum dynamics

Quantum dynamics under time dependent field is also important subject in our group. In particular, in the last year, we studied properties of quantum systems in periodically driven systems. We study the survival probability and saturation energy of the stationary state of a system in driven quantum chaotic system.[2]

We also have studied hybridization of a system with discrete energy structure (spins or atoms) in the cavity and the cavity photon. We studied how the nature of the response changes as a function of the ratio between the number of spins and the number of photons in the cavity by a direct numerical study. The system moves from the low photon region where we observe the vacuum-field Rabi splitting to the high photon region where the Rabi oscillation in the classical electromagnetic field takes place.[1, 22]

We also studied phase transitions in the cases with strong interaction between spins and photons. When the interaction becomes strong, the ground state of the system exhibits a phase transition and photon and polarization appear spontaneously which is called Dicke transition. Beside this transition, it is known that the system exhibits a nonequilibrium phase transition under driving force, which is called optical bistability. We studied cooperative phenomena in the region with strong driving force and strong coupling. In order to study such a region we need take into account the effects of interaction into the dissipation mechanism. We have developed a new master equation in the thermodynamic limit 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. We depict a phase diagram of the system in the coordinate of the strength of the driving force ξ and the strength of the interaction g (Fig. 3.2.6). Moreover we found that the rotating-wave approximation causes a significant difference in this region.[13, 15, 17] In the Dicke model, we found a new type of phase where driven photon shows the symmetry breaking phenomena in the region. We propose a mechanism of this symmetry breaking by making use of the concept of coherent destruction of tunneling. [31, 38] We also investigate the effect of the memory effect of the bath system on the formulation of the master equation. [13]

We have also studied the magnetization dynamics by making use of Landau-Zener mechanism.[43] In the systems where the magnetization is not a good quantum number, e.g. the system with Dzyaloshinsky-Moriya interaction, interesting quantum responses takes place. We studied properties of the ESR spectrum of antiferromagnetic Heisenberg model with the DM interaction.[4]

Fundamental properties of Statistical mechanism

As we have mentioned, there are many realistic systems which exhibit effective long-range interactions, e.g., the spin-crossover system and the cavity system. In general the fundamental conditions of the thermodynamics, e.g., extensivity and additivity may not be satisfied. We have studied properties of those systems, and we pointed out that the extensivity is effectively satisfied, but the additivity is violated. The violation causes various peculiar properties.[12, 47, 40]

How the canonical distribution is realized in pure dynamical systems is also an interesting problem. We have studied this problem in both classical and quantum system by using large-scale numerical studies. [5, 7]

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]
  Stripe states in the t-J model.[2]
- New superconductor: Iron-pnictide
  Effects of nonmagnetic impurities in iron-pnictide superconductors as a probe of order parameter.[4,12]
- Organic conductors [8]
  Modeling and magnetism in one-dimensional Fe-phthalocyanine compounds.[9]
  Zero-energy localized state induced by impurity in Dirac electron system of organic conductor.
- Dirac electron systems in solids [5]
  Spin-polarized currents in Dirac fermion systems.[6]
  Spin Hall effects in bismuth.[7]

Microscopic theory on defect-induced Kondo effects in graphen.[10]
Electronic states in a new Dirac system: Ca_3PbO.[3]

- Theories on heavy fermion systems and Kondo effect
  Charge Kondo effect due to pair-hopping mechanism.[11]
  Theory of Ru oxides: heavy fermion behavior and spin Hall effect.[13]
- Magnetic materials and spin-orbit interaction
  Effective model for chiral magnet, $CrNb_3S_6$.
  Spin-orbit interaction in $4d^3$ and $5d^3$ electron systems.

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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 FY2012, we optimized the Jastrow function, which represents electron correlation explicitly, to get much improved band gap for large-band-gap insulators.

We are also developing a modeling method to simulate thermal transport in materials and nano-structures from first principles. With the method, we realized quantitative simulation of thermal conductivity of crystalline silicon and its mode analysis. We also clarified importance of rattling motion of encapsulated ions in a clathrate compound.

In summary, our research subjects in FY2012 were as follows:

- New methods of first-principles calculation of material properties
  - First-principles wavefunction theory for solids based on the transcorrelated method
  - Generalized anharmonic lattice model of crystals for investigating thermal conductivity
  - Density functional theory for superconductors
  - A new efficient method to find potential energy minima in configuration space
  - An efficient algorithm for Brillouin-zone integral
- Applications of first-principles calculation
  - Interfaces in $Nd_2Fe_{14}B$ sintered magnet
  - Material design of GaP solid solution for solar battery
  - Lattice thermal properties of thermoelectric materials

13 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 and soft x-ray magnetic circular dichroism using synchrotron radiation. We investigate mechanisms of high-temperature superconductivity [1], metal-insulator transitions, giant magnetoresistance, carrier-induced ferromagentism, spin/charge/orbital ordering in strongly correalted systems such as transition-metal oxides [2], magnetic semiconductors, and their interfaces and nano-structures [3].

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14 Uchida Group

Research Subjects: High-T_c superconductivity

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

1. Project and Research Goal

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

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

2. Accomplishment

(1) Ladder Cuprate

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

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

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

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

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

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

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

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

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

1) Granular structure of high-Tc superconductivity

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

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

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

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

15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Toru HIRAHARA

Surfaces of materials are platforms of our research where rich physics is expected due to the low-dimensionality and symmetry 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 transport: Control of surface electronic states and their conductivity of topological insulators by using FIB patterning techniques. Spin Hall effect, effects due to anti-weak localization and electron-electron interaction at strong spin-orbit coupling material surfaces. Anisotropic transport on a quasi-one-dimensional metallic surface.

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

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

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

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16 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

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

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

   It is an interesting open question to ask whether the critical point, i.e., the gas-liquid transition, exists in strictly 2D ^{3}He. The previous quantum many-body calculations predict interestingly that ^{3}He does not have the critical point but ^{4}He does in pure 2D case. We have measured low-temperature heat capacities (C) of the first three atomic layers of ^{3}He adsorbed on a graphite surface to elucidate if the ground state of each layer is gas or liquid phase. The elucidation is based on the fact that the coefficient (γ) of T-linear term in $C_{(T)}$ in degenerated fermion system is determined by the surface area over which the fermions spread and the quasi-particle effective mass. 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 and the areal density had not been precise enough. In our experiments, we succeeded to evaluate the amount as ~ 5 % of the total surface area, in our substrate, through the analysis of the heat capacities of the first layer ^{3}He on graphite by clearly demonstrate that the measured heat capacities can be decomposed into the one of the two dimensional ^{3}He and of the amorphous ^{3}He on graphite.

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

   We have prepared a new sample cell for high-precision heat capacity measurements of the possible order-disorder transition around $T = 1$ K using a ZYX exfoliated graphite substrate which has much larger micro-crystalline size than the previous one. With this set-up, the heat capacities and the vapor pressures are measured for the first and second layers of ^{4}He.

   For the first layer ^{4}He, a peak structure is observed in the temperature dependence of the heat capacity at the areal density of $\sqrt{3} \times \sqrt{3}$ commensurate phase more clearly than that observed on the other substrate.

   For the second layer ^{4}He, the gradual change of the peak in the heat capacity is observed, which suggest the growth of two dimensional phase from fluid, commensurate solid and then incommensurate solid. In addition, a clear evidence of the 4/7 phase is observed in the density dependence of the vapor pressure as a sub-step at the density. It can also be confirmed that the 4/7 phase is occured before the promotion of the third layer from the density dependence of the isosteric heat. Our experimental results clearly show the existence of the 4/7 commensurate phase which had been denied in Path Integral Monte Carlo simulations.

   The 4/7 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. This year, we have started a measurement to find this novel super-solid state with a tortional oscillator.

3. **Towards bandgap tuning in functionalized graphene:**

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

4. **STM/S studies of 2D Kr solid on graphite:**

   Electronic properties of submonolayer Kr solid prepared on graphite surfaces are studied with our home-built STM system. Such a cryo-crystal is prepared by controlling the temperature (around 40 K) of graphite substrate and the partial pressure of Kr (around 10^{-5} Pa) in a ultra-high vacuum chamber, and then transferred into microscope which has already been cooled down below 2 K. The STM/S measurement is then performed at $T = 40$ mK.

   The boundary of the 2D Kr solid on graphite substrate is observed in this mearuement. Detail analysis of the atomic structure, one can conclude for the first time that the Kr atom sits on the hollow site of graphite and occupy one of three honeycomb lattice to form $(\sqrt{3} \times \sqrt{3})R30^\circ$ strucure. The shape of a Kr atom is observed differently in topograph images depending on the bias voltage between the sample and the STM tip. Namely, it is rounded at high voltage above 2 eV, while it is elliptic at ± 1 eV. The direction of the ellipse is different between $+1$ eV and -1 eV. Such electronic properties are qualitatively consistent with a theoretical calculation which considers the hybridization of 2p state of carbon and 4p and 5s states of Kr atom. Only the direction of the ellipse at $+1$ eV is different from the calculation.

The differential tunnel conductance on the Kr solid suggests that there is a deep suppression of the local density of states (LDOS) of ± 150 meV around the fermi energy, which is consistent with the prediction of band gap opening by adsorbing atoms in a $(\sqrt{3} \times \sqrt{3})R30^\circ$ manner on graphene. The fact that the similar LODS is observed on graphite substrate ~ 2 nm away from the Kr solid suggests, such electronic property is oozed out into the substrate. However, because similar LDOS had also been observed on an incommensurate Kr solid, it may not be related to the modified LDOS of graphite surface but a characteristic property of 2D Kr solid regardless of the substrate.

17 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

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

   In 2012, we have performed not only magnetotransport measurements on two-dimensional electron systems formed at the cleaved surfaces of p-InAs but also observations of the surface morphology of the adsorbate atoms, which induced the 2DES at the surfaces of narrow band-gap semiconductors, with use of a scanning tunneling microscopy. The electron density of the 2DESs is compared to the atomic density of the isolated Ag adatoms on InAs surfaces.

2. Superconductivity of ultrathin films on cleaved GaAs surfaces:
Two dimensional (2D) superconductivity was studied by magnetotransport measurements on single-atomic-layer Pb films on a cleaved GaAs(110) surface. The superconducting transition temperature shows only a weak dependence on the parallel magnetic field up to 14 T, which is higher than the Pauli paramagnetic limit. Furthermore, the perpendicular magnetic field dependence of the sheet resistance is almost independent of the presence of the parallel field component. These results are explained in terms of an inhomogeneous superconducting state predicted for 2D metals with a large Rashba spin splitting.

3. Strongly correlated two dimensional systems:
Cyclotron resonance measurements were extended to the dilution refrigerator temperature range. We also measured high frequency (0.1-10 GHz) conductivity both for metallic and insulating phases of a Si/SiGe 2DES.

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 the exciton Mott transition in Si and Ge by optical pump and terahertz probe experiments. The robustness of excitons previously observed in Si was also confirmed in Ge, as manifested by the non-vanishing 1s-2p transition of excitons above the Mott density. The inonization ratio of excitons, which is defiend as the ratio of unbound e-h pairs density to the total e-h pairs density, is determined by the Drude-Lorentz fitting of the complex diectlic function of photoexcited e-h system in the terahertz frequency range. The phase diagram of e-h system in Si was determined for the first time in terms of exciton ionization ratio in a wide range of temperature and density.
2. **Development of 2-dimensional THz time-domain spectroscopy and its application to superconductors:** By using an intense THz light source generated by optical rectification of femtosecond laser pulses in a $LiNbO_3$ crystal, we have developed a 2-dimensional THz time-domain spectroscopy scheme and applied it to a BCS superconductors, NbN, in order to study the non-equilibrium dynamics of BCS state. The ultrafast dynamics of BCS states in a quasi-adiabatic excitation regime are elucidated. To observe the Higgs-amplitude mode which is expected to appear in the nonadiabatic excitation condition, we systematically evaluated the parameters such as the BCS gap energy, the pump pulse width.
3. **Observation of quantum Faraday effect in graphene:** Graphene is a monolayer sheet of carbon atoms tightly bound in a form of honeycomb lattice. Electrons in graphene behave as if they are massless. They move on the two-dimensional sheet of graphene in a velocity about c/300 with c the speed of light and do not scatter in the backward direction. Because of these exotic properties, graphene is expected as a promising material for next-generation high speed electronic devices. Graphene also offers a unique arena to study the fundamental physics in condensed matter. 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. With increasing the magnetic field, the rotation angle exhibits plateau structures at the quantum Hall steps at which the rotarion angles are determined by the fine-structure constant. This observation would open a new functionality of graphene in optoelectronic applications such as ultra-accurate and achromatic terahertz polarization rotator.

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19 Takagi Group & Taniguchi Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kouji Taniguchi

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

1. **Strong Coupling Superconductivity in an Antiperovskite Phosphide:** We have found that a family of ternary platinum phosphides APt_3P (A= Ca, Sr, La), which crystallize in an antiperovskite-based structure, show superconductivity at low temperatures and the highest critical temperature T_C = 8.4 K was observed for $SrPt_3P$. The analysis of specific heat $C(T)$ for $SrPt_3P$ shows clear evidence for very strong coupling s-wave superconductivity with a large ratio between superconducting gap Δ_0 and T_C, $2\Delta_0/k_BT_c \sim$5, and the presence of low-energy phonons. The presence of multiple Fermi surface pockets was inferred from the nonlinear magnetic field dependence of Hall resistivity, which we argue might play a role in realizing the strong coupling of charge carriers with the low-lying phonons.

2. **Visualization of the emergence of the pseudogap state and the evolution to superconductivity in a lightly hole-doped Mott insulator:** Superconductivity emerges from the cuprate antiferromagnetic Mott state with hole doping. At higher doping levels, the "pseudogap", a weakly conducting state with an anisotropic energy gap appears. However, a direct visualization of the emergence of these phenomena with increasing hole density has never been achieved. We have succeeded in obtaining atomic-scale image of electronic structure evolution from the weak insulator through the emergence of the pseudogap to the superconducting state in $Ca_{2-x}Na_xCuO_2Cl_2$. At slightly higher hole density, nanoscale regions exhibiting pseudogap spectra and 180° rotational (C_{2v}) symmetry form unidirectional clusters within the C_{4v}-symmetric matrix. Thus, hole doping proceeds by the appearance of nanoscale clusters of localized holes within which the broken-symmetry pseudogap state is stabilized.

3. **Two-Dimensional Heisenberg Behavior of $J_{eff} = 1/2$ Isospins in the Paramagnetic State of the Spin-Orbital Mott Insulator Sr_2IrO_4:** We have investigated the dynamical correlations of $J_{eff} = 1/2$ isospins in the paramagnetic state of spin-orbital Mott insulator Sr_2IrO_4 by resonant magnetic x-ray diffuse scattering. We found a two-dimensional antiferromagnetic fluctuation with a large in-plane correlation length exceeding 100 lattice spacings at even 20 K above the magnetic ordering temperature. In marked contrast to the naive expectation of the strong magnetic anisotropy associated with an enhanced spin-orbit coupling, we discovered an isotropic isospin correlation that is well described by the two-dimensional $S = 1/2$ quantum Heisenberg model.

4. **Weak antiferromagnetism of $J_{eff} = 1/2$ band in bilayer iridate $Sr_3Ir_2O_7$:** We studied the antiferromagnetic structure of $Sr_3Ir_2O_7$, which is the bilayer analog of a spin-orbital Mott insulator Sr_2IrO_4 by resonant magnetic x-ray diffraction. Contrasting intensities of the magnetic diffraction at the Ir L_{III} and L_{II} edges show a $J_{eff} = 1/2$ character of the magnetic moment as is argued in Sr_2IrO_4. The magnitude of moment, however, was found to be smaller than that of Sr_2IrO_4 by a factor of 5 to 6, implying that $Sr_3Ir_2O_7$ is no longer a Mott insulator but a weak antiferromagnet.

5. **Electric-field-induced superconductivity in MoS_2 with double-layer FET:** We have attempted electro-static carrier doping in a layered transition metal disulphide MoS_2 by constructing an electric double-layer transistor with an ionic liquid. With the application of gate voltage V_G higher than 3 V, a metallic behavior was observed in the MoS_2 channel. We found an onset of electric field-induced superconductivity in the field induced metallic phase. A maximum $T_C \sim 9.4$ K was observed, which could be higher than those in chemically doped bulk materials.

20 Theoretical Astrophysics Group

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

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

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

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

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;

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

2008

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

21 Murao Group

Research Subjects: Quantum Information Theory

Faculty Members: Mio Murao, Peter S. Turner

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

In this year, our group consisted of two faculty members, Mio Murao (Associate Professor), Peter S. Turner (Assistant Professor), two postdoctoral fellows, Michal Hajdušek (JSPS foreign postdoctoral fellow), Fabian Furrer (JSPS foreign postdoctoral fellow) and 8 graduate students, Yoshifumi Nakakata (D3), Takanori Sugiyama (D3), Shojun Nakayama (D2), Eyuri Wakakuwa (D1), Seiseki Akibue (M2), Kotaro Kato (M1), Kosuke Nakago (M1) and Jisho Miyazaki (M1). We investigate several aspects of theoretical quantum information. Our projects worked in the academic year of 2012 were the following:

Measurement-based quantum computation

- Measurement-based quantum computation on symmetry breaking thermal states [1], Nakata and Murao in collaboration with K. Fujii (Osaka University) and M. Ohzeki (Kyoto University)

- Quantification of entanglement of pure graph states using graph theory [2], Hajdušek and Murao
- Analysis of parallelism and causality in measurement-based quantum computation, Miyazaki, Hajdušek and Murao

Network coding for quantum computation

- Analysis of implementing two-qubit unitary operations in ladder networks, Akibue and Murao
- Multicast quantum network coding, Murao in collaboration with M. Owari and G. Kato (NTT)
- Block coding for distributed implementations of bipartite unitary operations, Wakakuwa, Furrer and Murao

Quantum algorithms

- Algorithm for implementing diagonal-unitary 2-designs [3,4], Nakata and Murao
- Universal algorithm for energy eigenbasis measurement, Nakayama and Murao in collaboration with A. Soeda (National University of Singapore
- Thermalization algorithm based on higher order detailed balance, Nakayama and Murao

Quantum measurement (tomography)

- Adaptive experimental design for one-qubit state estimation with finite data [5], Sugiyama, Turner and Murao
- Quantitative evaluation of estimation errors with finite data in terms of expected loss [6], Sugiyama, Turner and Murao
- Quantitative evaluation of estimation errors with finite data in terms of error probabilities, Sugiyama, Turner and Murao

Properties of different quantum computational models

- Analysis of parallelism and causality in adiabatic quantum computation, Nakago, Nakayama, Hajdušek and Murao
- Quantum information processing with non-Abelian anyons, Kato, Furrer and Murao

Quantum cryptography

- Continuous variable uncertainty relation in the presence of a quantum memory, Furrer in collaboration with M. Berta, V. Scholz M. Christandl (ETH Zurich) and M. Tomamichel (National University of Singapore)
- Resource theory for two-party cryptographic protocols, Furrer in collaboration with S. Wehner (National University of Singapore) and I. Kerenidis (University Paris Diderot)

Implementations of quantum information processing in quantum optics

- Experimental demonstration of quantum data compression, Turner in collaboration with L.A. Rozema, D. Mahler, A. Hayat and A.M. Steinberg (University of Toronto)
- Implementation of photonic quantum t-designs, Turner in collaboration with J.C.F. Matthews (University of Bristol)

Quantum control

- Control of entanglement generation for two spins with anisotropic Heisenberg interactions, Nakata, Turner and Murao in collaboration with K. Nemoto (NII)

Foundation of quantum mechanics

- Analysis of information causality using a generalized mutual information [7], Wakakuwa and Murao
- Exchange fluctuation theorem for correlated quantum systems [8], akayama and Murao in collaboration with Y. Hirono (University of Tokyo), D. Jennings and T. Rudolph (Imperial College, London)
- Analysis of phases and interference in general probabilistic theories, Nakata and Murao in collaboration with A. Garner, Oscar Dahlsten and V. Vedral (University of Oxford)

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

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22 Ueda Group

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

Member: Masahito Ueda and Shunsuke Furukawa

Quantum Many-body Phenomena in Ultracold Atoms

Criteria of off-diagonal long-range order in Bose and Fermi systems based on the Lee-Yang cluster expansion method: The superfluid state of cold fermionic gases displays a crossover from a Bardeen-Cooper-Schrieffer (BCS) state to a Bose-Einstein condensate (BEC) of molecules, as the interaction is tuned by a Feshbach resonance. Since this system is strongly correlated especially in the crossover regime, no mean field theory has been known to describe the superfluid transition of this system in the entire range of the interaction strength. In this work, we formulated a new approach to this problem on the basis of the Lee-Yang cluster expansion method. We extended this method so that it can identify the criteria of the off-diagonal long-range order of the density matrices in both Bose and Fermi systems. This formulation is applicable to both a uniform system and a trapped system without relying on a local-density approximation and provides systematic expansions of one-particle and multiparticle density matrices in terms of cluster functions. This work was published in Phys. Rev. A [N. Sakumichi, N. Kawakami, and M. Ueda, Phys. Rev.A **85**, 043601 (2012)].

Finite-temperature phase diagram of a spin-1 Bose gas: Depending on the relative strengths of the spin-dependent interaction, linear and quadratic Zeeman shifts, a BEC with spin degrees of freedom (spinor BEC) can exist in various phases. These phases have different magnetizations and symmetries in spin space. By developing a Hartree-Fock mean-field formalism for a spinor system, we investigated both numerically and analytically how the phase boundaries and the system's magnetizations are modified by finite temperatures. Due to the coherent collisions between condensed and noncondensed atoms, the noncondensate also acquires a finite magnetization provided the condensate is magnetized. We found that off-diagonal coherence within the noncondensate can shift the phase boundaries greatly, and thus, it cannot be neglected as in some previous studies. This work was published in Phys. Rev. A [Y. Kawaguchi, N. T. Phuc, and P. B. Blackie, Phys. Rev. A **85**, 053611 (2012)].

Topological classification of vortex core structures in spinor Bose-Einstein condensates: We proposed a method for topologically classifying vortex-core structures in spinor BECs. Vortices (line defects) are classified by topological charges within a conventional use of the homotopy theory. However, vortices having the same topological charge can in general have different core structures. We extended the conventional homotopy theory so that it can classify core structures. We introduced the "extended order parameter manifold (OPM)", which can treat the spatial variation of order parameters in vortex core states. By applying our method to spin-1 BECs and calculating its extended OPM, we systematically found exotic vortex-core structures in which phases with different magnetizations appear in a concentric fashion. We identified a localized topological charge defined in each phase forming an annulus region. This work was published in Phys. Rev. A [S. Kobayashi, Y. Kawaguchi, M. Nitta, and M. Ueda, Phys. Rev. A **86**, 023612 (2012)].

Quantum Hall states in rapidly rotating two-component Bose gases: Ultracold atomic gases under rapid rotation offer interesting analogues of quantum Hall systems with a variety of statistics and internal states of constituent particles. We studied strongly correlated phases of two-component (or pseudo-spin-1/2) Bose gases under rapid rotation by means of exact diagonalization. As the ratio of the inter-component contact interaction $g_{\uparrow\downarrow}$ to the intra-component one g increases, the two components are expected to be entangled to form novel ground states. For $g_{\uparrow\downarrow} = g$, we find the formation of gapped spin-singlet states at the filling factors $\nu = k/3 + k/3$ (the $k/3$ filling for each component) with integer k. In particular, we presented numerical evidences that the gapped state with $k = 2$ is well described as a non-Abelian spin-singlet (NASS) state, in which excitations feature non-Abelian statistics. Furthermore, we find the phase transition from the product of composite fermion states to the NASS state by changing the interaction ratio $g_{\uparrow\downarrow}/g$. This work was published in Phys. Rev. A [S. Furukawa and M. Ueda, Phys. Rev. A **86**, 031604 (2012)].

Symmetry classification of spin-orbit-coupled spinor Bose-Einstein condensates: We developed a symmetry classification scheme to classify ground states of strongly spin-orbit-coupled spinor BECs, including pseudo-spin-1/2, spin-1, and spin-2 cases. Associated with breaking of simultaneous $SO(2)$ spin-space rotation symmetry in favor of discrete symmetries, various types of lattice structures emerge in the absence of lattice potentials. Examples include two different kagome lattices for pseudo-spin-1/2 condensates and a nematic vortex lattice in which uniaxial and biaxial spin textures align alternately for spin-2 condensates. For the pseudo-spin-1/2 system, although mean-field states always break time-reversal symmetry, there exists a time-reversal-invariant many-body ground state, which is fragmented and expected to be observed in a microcondensate. This result was published in Phys. Rev. A [Z. F. Xu, Y. Kawaguchi, L. You, and M. Ueda, Phys. Rev. A **86**, 033628(1)-033628(8) (2012)].

Crossover trimers connecting continuous and discrete scaling regimes: In a three-body system composed of two component fermions, two types of trimers were known to exist. When the mass ratio between the two components is large, the Efimov states appear, which show a discrete scaling symmetry. For a smaller mass ratio, on the other hand, the Kartavtsev-Malykh trimers emerge, which feature a continuous scaling symmetry. We investigated how these two trimers evolve into each other and how the scaling symmetry of the trimers changes. We found a new type of trimers, the crossover trimers. This trimer neither possesses continuous nor discrete symmetries, and smoothly connect the Kartavtsev-Malykh trimers and the Efimov trimers. We varied the mass ratio and scattering length and mapped out in which region of parameter space each of the trimers can exist. This work was published in Phys. Rev. A [S. Endo, P. Naidon, and M. Ueda, Phys. Rev. A **86**, 062703 (2012)].

Hydrodynamic description of spin-1 Bose-Einstein condensates: Recently, non-destructive imaging of spin textures in spin-1 BECs has been established, which has prompted theoretical researches of the hydrodynamic description of spinor BECs. We derived a complete set of hydrodynamic equations for spin-

1 BECs that is valid regardless of the spatiotemporal dependence of the spin polarization. The obtained equations, which are expressed in terms of the density, the spin density, the nematic tensor, and the mass current, involve the continuity equations for the density, the spin density, and the nematic tensor, and the "generalized" Mermin-Ho relation for the vorticity. We also show that our hydrodynamic equations are equivalent to the multi-component Gross-Pitaevskii equations and reproduce the low-lying collective modes for phonons and magnons. This work was published in Phys. Rev. A [E. Yukawa and M. Ueda, Phys. Rev. A **86**, 063614 (2012)].

Beliaev theory of spinor Bose-Einstein condensates: For a scalar (spinless) BEC, both the mean-field results and the associated leading-order quantum corrections of the ground-state energy, the pressure, and the phonons' velocity can be derived analytically. Recent experiments and quantum Monte-Carlo simulations have shown that those leading-order corrections can accurately describe the deviations from the mean-field results for the maximum value of interaction realized in the field of ultracold atoms. We developed the spinor Beliaev theory which can give the leading-order quantum corrections of observables in a spinor Bose gas. In a spinor BEC, there exist spin waves (magnons) with quadratic dispersion relations in addition to density wave (phonons) with linear dispersion relations. We find that the effective mass of magnons increases due to density fluctuations, i.e., the motion of magnons is hindered by interaction with other particles. The enhancement factor of magnons' effective mass is the same for two different phases investigated. The effective mass of magnons, and, in turn, the quantum fluctuation effects can be experimentally probed by using a spinor wave packet. This work was published in Ann. Phys. [N. T. Phuc, Y. Kawaguchi and M. Ueda, Ann. Phys. **328**, 158 (2013)].

Quantum Information, Quantum Measurement, and Foundation of Statistical Mechanics

Bethe ansatz analysis of the thermalization mechanism of an isolated quantum system: Two thermalization mechanisms, the eigenstate thermalization hypothesis (ETH) and the typicality, have been recently proposed. However, the relative importance of these mechanisms has not yet been clarified. This is because a huge computational cost is required to perform a finite-size scaling analysis of the ETH by numerical diagonalization of interacting Hamiltonians. In this work, we used a Bethe ansatz solution of a one-dimensional Bose gas, and performed a systematic finite-size scaling analysis of the ETH. The use of an exact solution significantly reduced the computational cost. We found that the typicality gives a greater effect in the thermalization than the ETH. This work was published in Phys. Rev. E [T. N. Ikeda, Y. Watanabe, and M. Ueda, Phys. Rev. E **87**, 012125 (2013)].

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*.

Mass Accreting Black Holes: Mass accretion onto black holes provides a very efficient way of X-ray production. Utilizing wide-band *Suzaku* spectra, we are diagnosing hot "coronae" that form around stellar-mass black holes. In active galactic nuclei (massive black holes), our new variability-assisted spectroscopy technique is revealing various emission components in a model independent manner [1]. This is expected to settle several long-lasting issues as to AGNs, including the mechanism of their "central engines".

Neutron Stars with Various Magnetic Fields: We conduct *Suzaku* studies of neutron stars (NSa) with various magnetic field strengths, B, believing that their magnetism is a manifestation of nuclear ferromagnetism. The targets include X-ray burst sources with $B < 10^9$ G [2], canonical magnetized NSs 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 [3]. From one magnetar, a hint of free precession was detected, and was interpreted as evidence for NS deformation under very high toroidal magnetic fields.

Supernova Remnants and Galactic Diffuse X-ray Emission: An apparently extended X-ray emission has long been known to distribute along our Galactic plane. Using *Suzaku*, we showed that this can be explained as an assembly of numerous X-ray emitting white dwarfs [4]. However, a brighter diffuse X-ray emission around the Galactic Center region, may be contributed significantly by some truly diffuse hot plasmas. *Suzaku* data also allow us to detect thermal and non-thermal emission components from supernova remnants. One such object, CTB109, was studied in depth, and its peculiar half-moon shape was found to arise via its interaction with a giant molecular cloud.

Plasma Physic in Clusters of Galaxies: The most dominant known component of cosmic baryons exists in the form of X-ray emitting hot ($\sim 10^8$ K) plasmas associated with clusters of galaxies. We have obtained novel evidence that the member galaxies in each cluster have been falling, over the Hubble time, to its potential center [5]. This is presumably due to magneto-hydrodynamic interatctons between the galaxies and the plasma, that takes place as as the former keep moving through the latter. The interaction may explain various puzzles with clusters, including why these plasmas are surviving their radiative cooling.

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 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

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

Noninductive plasma current (I_p) initiation and ramp-up experiments are being conducted on TST-2 with up to 100 kW of RF power in the lower hybrid (LH) frequency range (200 MHz) using a newly developed dielectric-loaded waveguide array antenna. Measurements of RF wave polarization and wavevector were performed using an array of RF magnetic probes. The detected wave was identified as the LH wave with a parallel wavenumber of $|k_\parallel| \sim 10$ m^{-1}, which is substantially smaller than $|k_\parallel| \sim 50$ m^{-1} excited by the antenna, which should be absorbed efficiently by the electrons. Plasma initiation by waves at 8.2 GHz was studied since the magnetic field of 0.3 T is required for the LH wave to propagate to the plasma core. The central electron density of 8.0×10^{17} m^{-3} was a factor of four higher than the plasma initiated by waves at 2.45 GHz.

An advanced diagnostic technique to measure the plasma current density using the double-pass Thomson scattering is being developed on TST-2. The laser light makes a round trip through the plasma. Only the signal from the second pass is affected by the plasma current and is used to derive the current density, while the signal from the first pass is used to evaluate the accuracy of the density and temperature measurements. The sign and the average value of the measured plasma current density were consistent with a theoretical estimate. Since it is difficult to measure the density and temperature by Thomson scattering in low-density plasmas, a multi-pass system is being developed to increase the scattered signal. The laser light makes multiple passes through the plasma by switching the beam path quickly using a pockels cell and a polarizer.

An electrostatic RF probe capable of measuring the 200 MHz LH wave in TST-2 is being developed. At such high frequencies, the cable capacitance shorts out the RF wave signal. A high resistance (100 kΩ or greater) is inserted just after the probe electrode to prevent shorting of the probe current. The eventual goal is to measure the wavevector of the LH wave using an array of electrostatic RF probes.

A local plasma current diagnostic using a small Rogowski probe is being developed. The probe consists of two Rogowski coils, two magnetic pick-up coils and five Langmuir probes. Small 300-turn Rogowski coils with outer and inner radii of 9.5 mm and 5 mm were made successfully. The Rogowski coils had sensitivities to toroidal and poloidal magnetic fields. Magnetic pick-up coils were placed between the two Rogowski coils to subtract these components. The local plasma current density of 750 kA/m^2 measured successfully by this probe agreed with the value calculated by magnetic equilibrium analysis.

Numerical simulation of LH current drive experiments on TST-2 were performed using the TORLH full-wave code and CQL3D Fokker-Planck code in collaboration with MIT. The calculation of the X-ray energy spectrum measured along the sightlines used in the TST-2 experiment is under preparation. Simulation using the GENRAY ray-tracing code showed that it is difficult to obtain a smooth distribution function. This is likely the result of weak absorption of the LH wave under the experimental condition on TST-2.

Analysis of non-inductive plasma start-up scenarios on the JT-60SA tokamak, currently under construction at Japan Atomic Energy Agency, were performed using the TOPICS transport code in collaboration with JAEA. The aim is to find a scenario which minimizes the consumption of magnetic flux provided by the central solenoid. A scenario which reaches the fully non-inductively driven state at an early stage of the discharge, followed by ramp-up to 2.1 MA maintaining such condition was identified.

25 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Yoich ASO

The detection of gravitational waves is expected to open a new window 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
  - Study of cryogenic contacts
  - Study of the homogeneity of PD surface
- Space laser interferometer, DECIGO
  - Development of DECIGO pathfinder, DPF
  - $\mathrm{SWIM}_{\mu\nu}$
  - Study of the effect of the residual gas
- Development of TOBA (Torsion Bar Antenna)
  - 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
- Gravitational force at small distances
- Study of space isotropy

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

1. Macroscopic systems out of equilibrium

(1) Universal fluctuations of growing interfaces probed in turbulent liquid crystal [1, 2]

(2) Topological-defect turbulence of liquid crystal

(3) Reversible-irreversible transition in low-Reynolds fluid with non-Brownian particles and its rheology

(4) Local structure formed in dense suspensions under vertical vibration [4]

(5) Spontaneous segregation of granular particles in a double rotating drum

(6) Anomalous efficiency and statistical properties of thermal transport coupled to boiling

2. Microscopic systems out of equilibrium

(1) Motion of chains of self-propelled asymmetric particles

(2) Collective motion of self-propelled particles [3, 6]

(3) Lehmann effect of cholesteric liquid crystal as thermo-mechanical coupling by temperature gradient

(4) Realization of an informatic heat engine in a microscopic system

(5) Hidden entropy production due to coarse-graining

(6) Stochastic energetics in out-of-equilibrium systems

(7) Relation of information and thermodynamics in subsystems

3. Biological systems

(1) Force field of cells in motion and on division [5]

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27 Yamamoto Group

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

Member: Satoshi Yamamoto, 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 the protoplanetary disks by using ALMA. The ALMA Cycle 0 result for L1527 shows that carbon-chain molecules do exist even in the closest vicinity of the protostar ($\sim$100 AU). Further analyses are now 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 2013.

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28 Sakai (Hirofumi) Group

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

Member: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (3) Ultrafast phenomena in atoms and molecules in the attosecond time scale. (4) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. A part of our recent research activities is as follows:

(1) Characteristics of high-order harmonics generated from atoms and aligned molecules with carrier-envelope-phase-stabilized 25-fs pulses [1]

With carrier-envelope phase stabilized pulses, the self-referencing technique is applied to evaluate the relative phase of high-order harmonics generated in atoms and aligned molecules. The Fourier transform analysis from the frequency domain to the time domain shows that the *effective* duration of the driving pulse, during which the specific orders of harmonics are efficiently generated, is decreased as the harmonic order is increased. In the case of aligned molecules, the interference fringes between the two adjacent odd-order harmonics from N_2 are more distinctive than those from CO_2, which may be explained by the difference in the complexity associated with the symmetry of highest occupied molecular orbitals between N_2 and CO_2.

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

With carrier-envelope-phase-stabilized 10-fs pulses, harmonic spectra from aligned molecules are observed and analyzed. The control of the carrier-envelope phase allows us to observe spectral interferences caused by nonadiabatic change in the intensity of the driving pulse. The Fourier transform analysis reveals that there are clear contributions from the spectrally broadened short and long trajectory components in addition to the contribution from the usual odd-order harmonic components. We further examine the possibility of evaluating the phase change accompanied by the destructive interference in harmonic spectra observed in aligned CO_2 and N_2 molecules.

(3) Laser-field-free orientation of state-selected asymmetric top molecules

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 are maintained in the laser-field-free condition for about 10 ps, which is long enough to study femtosecond-attosecond dynamics in molecules, after the rapid truncation of the laser pulse. 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 approach to investigate rotational dynamics of molecules.

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29 Gonokami Group

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

Member: Makoto Gonokami, Kosuke Yoshioka

We are trying to explore new aspects of many-body quantum systems and their exotic quantum optical effects through designed light-matter interactions. Our current target consists of a wide variety of matter, including excitons and electron-hole ensemble in semiconductors, antiferromagnetic magnons and ultracold atomic gases. In particular, we have been investigating the Bose-Einstein condensation phase of excitons, which is considered the ground state of electron-hole ensemble but as yet not proven experimentally. Based on quantitative spectroscopic measurements, the temperature and density are determined for an exciton gas in a quasi-equilibrium condition trapped inside a high purity crystal kept below 1 K. We 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").

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) Understanding optical activity in quasi two-dimensional structures and second harmonic generationPhoto-induced three-dimensional chirality and acitive control of THz optical activity
   (b) Vectorial control of THz oscillation in crystals with vector-field shaped optical pulses
   (c) Terahertz vector beam generation using segmented nonlinear optical crystals

3. Development of novel coherent light sources and spectroscopic methods:
   (a) 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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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 fruitfly, *Drosophila*. A part of our recent research activity is summarized below.

1. Optical dissection of neural circuits that regulate larval locomotion

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

2. Gene regulation of synaptic components

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

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31 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Noninvasive in-vivo imaging of vesicles in mouse neutrophil

Tumor was exposed by dissecting the skin and a epicedium, so far. Many biological systems especially the immune system were activated by the dissection. To avoid the dissection, we developed the method of non-invasive imaging. The auricle was selected for non-invasive imaging because of thin and short hair. The auricle was illuminated by high power laser for short time. We investigated the motility of vesicle in neutrophil, a kind of white blood cell, in mice. Neutrophil is activated by the inflammation of TPA and goes out of blood vessel to cure the inflammation. 1 day after the inflammation, many of neutrophil go out of the blood vessel. We observed clearly the movement of vesicle containing antibody-quantum dot. The shape of neutrophil becomes long and front domain may pull the cell. The velocity of the vesicle was changed very much from 0.3 to 3.1 um/s. Surprisingly, the velocity of 3 um/s is about three times of velocity of dynein and kinesin. The MSD plots indicate that the “ stop and go ” fassion (figure).

Noninvasive in-vivo imaging of single molecules in mouse

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 were 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.

Imaging of dynein in muscle

Skeletal muscles are thought to be rigid structure, but it must be always maintained. In non-muscle cells, cytoplasmic dynein is bearing important roles for intracellular maintenance. However, the roles of dynein are not understood in skeletal muscles. In order to understand the role of cytoplasmic dynein, we developed the in vivo fluorescence imaging of mouse skeletal muscle which molecular structures are visualized by using the gene transfer of GFP-fused proteins. Microtubules and cytoplasmic dyneins in in vivo muscles were successfully visualized by expressing GFP-Tubulin and dynein IC74-GFP with confocal microscope. The distribution and dynamics of vesicles transported by cytoplasmic dyneins in living muscle differed from non-muscle cells, and these vesicles did not move along the microtubule in living muscle. Meanwhile, dynein IC74-GFP were stably expressed in the myoblast cell line C2C12 and, vesicle transports were observed in myoblast cell and myotube. The dynein binding vesicles in the myoblast stage distributed as similar as in non-muscle cells. However, in myotube, the vesicles mainly moved along longitudinal axis and the speed of the vesicles was decreased to 20