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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 2015

1 Theoretical Nuclear Physics Group

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

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

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

Nuclear Structure Physics

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

The structure of unstable nuclei is the major focus of our interests, with current intense interest on novel relations between the evolution of nuclear shell structure (called shell evolution for brevity) and characteristic features of nuclear forces, for example, tensor force, three-body force, etc[8]. Phenomena due to this evolution include the disappearance of conventional magic numbers and appearance of new ones. We have published pioneering papers on the shell evolution in recent years. The new magic number 34 in an exotic nucleus ^{54}Ca was confirmed experimentally for the first time in 2013 and was reported in Nature.

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

The Monte Carlo Shell Model has been improved with further developments, and we have carried out a number of calculations on the K computer[2, 5, 8].

We are studying on dilute neutron systems[7], time-dependent phenomena like fusion and multi-nucleon transfer reactions in heavy-ion collisions[1] , double-beta-decay nuclear matrix element[4] , and nuclear level density [6] .

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Theoretical Hadron Physics

In Theoretical Hadron Physics group (K. Fukushima and A. Yamamoto), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include quark-gluon plasma in relativistic heavy-ion collisions, perticle production mechanism, lattice gauge simulations, matter under extreme conditions, neutron stars, etc.

Highlights in research activities of this year are listed below:
1. New formulation of the complex Langevin method with Lefschetz thimble [4]
2. Nonrelativistic Banks-Casher relation [6]
3. Effects of rotation in field theories
4. Anomaly-induced phenomena in rotating electric fields [9]

[1] A. Flachi, K. Fukushima, and V. Vitagliano, "Geometrically induced magnetic catalysis and critical dimensions", Phys. Rev. Lett. **114**, 181601 (2015).

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

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

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

We list the main subjects of our researches below.

1. High Energy Phenomenology
   - 1.1. Higgs phenomenology [1]
   - 1.2. Vacuum decay [2]
   - 1.3. Phenomenology of supersymmetric model [3, 4]
   - 1.4. LHC phenomenology [5, 6, 7, 8]
   - 1.5. Physics of e^+e^- linear collider [9]
   - 1.6. Cosmic-ray anti-protons from dark matter [10]
   - 1.7. Cosmological constraint on dark matter annihilation [11, 12]
   - 1.8. Diquark Bethe-Salpeter equation [13]
   - 1.9. Heavy quarkonium [14, 15]
   - 1.10. Gravitational particle production [16, 17, 18]
   - 1.11. Cosmology of Higgs field [19, 20]
   - 1.12. Pseudo-scaling scalar dynamics [21]
   - 1.13. Inflation models [22, 23]
2. Superstring Theory and Formal Aspects of Quantum Field Theories
   - 2.1. Aspects of supersymmetric field theories [24, 25]
   - 2.2. Compactification of $6d$ SCFTs [26, 27]
   - 2.3. $5d$ $\mathcal{N} = 2$ SuperYang-Mills Theory [28]
   - 2.4. Instanton partition functions [29]
   - 2.5. Conformal field theory and integrable lattice model [30]
   - 2.6. Study of the representation theory of SH^c algebra [31]
   - 2.7. String theory in Ambitwistor space and scattering amplitudes [32]
   - 2.8. Holography and entanglement entropy [33]
   - 2.9. Entanglement entropy in quantum field theories [34, 35]

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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

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

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

In 2015, non-linear two-photon transition of antiproton $(n, \ell) = (36, 34) \to (34, 32)$ was measured by using two-photon laser spectroscopy with gas buffer cooling. We will continue to study systematic uncertainties such as the AC Stark effect, power broadening effect, and collisional shift effect in 2016. The mass ratio will be determined with a precision of $< 3 \times 10^{-10}$.

The evolutions of the population of four $\overline{\mathrm{p}}\mathrm{He}^+$ states $(n, \ell) = (35, 33), (37, 35), (38, 35)$ and $(40, 36)$ were measured at low target pressure ($p \sim 1$ mb) and low temperature ($T \sim 1.5$ K) for the first time. The most lifetimes, except $(n, \ell) = (38, 35)$, does not change between two different target densities $\rho = 5 \times 10^{18}$ cm^{-3} and 2×10^{21} cm^{-3}

$\bar{p}$-nucleus annihilation cross section at low energies The antiproton is absorbed by the nucleus and annihilates with a surface nucleon. The cross sections, called annihilation cross sections, has been measured in order to study the interactions between them. In 2012, we performed an experiment with antiproton beam of 5.3 MeV/c, and identify the signal of its annihilation for the first time in that region.

In 2015, we measured the cross section in a momentum region of 100 MeV/c. In that region, annihilation cross sections of antineutron on some nucleus show unexpected enhancement, we can understand this behaviors by comparing to these data to the one of antiprotons. In this experiment, we measured the cross sections with carbon target.

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

The experiment was carried out for 2 weeks and obtained data successfully. We are now analyzing the data, and results will be summarized as a doctoral thesis.

2) Spectroscopy of pionic atoms using a proton beam

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

We are now planning a new experiment of pionic atom spectroscopy using (p, ^{2}He) reaction in RCNP. In this experiment, the binding energy is determined by analyzing two protons, which are decay products of ^{2} He, by Grand Raiden spectrometer. A strong proton beam is employed with a GRAF beamline, which was recently installed. We will try to achieve better resolution than existing experiments, by employing the high resolution spectrometer and the teqnique of dispersion matching that eliminates the momentum spread of the incident beam.

In the fiscal year of 2015, we performed a test experiment as a feasibility study. We confirmed that beam transportation to the new beam line was good enough to performed the experiment. In addition, we measured ^{12}C(p, ^{2}He)^{11}B reaction and could observe a peak of the ^{11}B grand state. This is the first case to observe (p, ^{2}He) by the Grand Raiden spectrometer. We will analyze the properties of background of (p, ^{2}He) reactions with this data.

4 Sakurai Group

Research Subjects: Nuclear structure and dynamics of exotic nuclei

Member: Hiroyoshi Sakurai and Megumi Niikura

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

SEASTAR campaign

In May 2015 and May 2016, the SEASTAR experiments to systematically measure the excitation energy of extremely exotic nuclei were conducted at RIBF. The de-excitation γ-rays were detected by the NaI(Tl) scintillator array DALI2 after the proton-knockout-reactions with a 10-cm-thick liquid hydrogen target surrounded by the recoil proton tracking system MINOS. The obtained level structure of the neutron rich Cr and Fe isotopes revealed the enhanced deformation around that region. The analysis for the de-excitation γ-rays of ^{78}Ni has been performed and the discussion with theoretical calculations are on going.

Neutron configuration of ^{29}Ne ground state

The inclusive cross-section and parallel momentum distribution of single-neutron removal reaction have been measured at the nuclei supposed to be on the edge of an "island of inversion"; ^{29}Ne. A combined analysis of distinct nuclear- and Coulomb-dominated reaction with C and Pb targets, respectively, shows that this nuclei locates inside an "island of inversion" and exhibits a halo-like neutron spacial distribution.

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

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

Exotic cluster structure in ^{16}C

We performed an invariant mass spectroscopy in order to search for α-cluster states in ^{16}C via α-inelastic scattering at 200 MeV/u. The excitation energies of ^{16}C are reconstructed from $^{16}\mathrm{C}^* \rightarrow {}^{12}\mathrm{Be} + {}^{4}\mathrm{He}\ (+\gamma)$ and $^{16}\mathrm{C}^* \rightarrow {}^{10}\mathrm{Be} + {}^{6}\mathrm{He}$ decay channels by measuring their four momenta with the SAMURAI spectrometer and γ-ray energy. Candidates of α-cluster states are found in the excitation energy spectrum.

BRIKEN project

We are planning to systematically measure a β-delayed neutron emission probability (P_n) at RIBF, named the BRIKEN project. The P_n value will be deduced by measuring implanted ions and β rays with Advanced Implantation Detector Array (AIDA) combined with 166 ^{3}He neutron detectors (BRIKEN array). The performance test of AIDA was carried out in 2015 and the BRIKEN array is now under construction at RIKEN. The measurement will be performed in fall 2016.

Development of neutron scintillator NiGIRI

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

NINJA detector at SAMURAI spectrometer

We are developing a proton detector, NINJA, in addition to the currently using SAMURAI standard detectors at RIBF. NINJA consists of plastic scintillator array using MPPC readout in order to operate inside of a high magnetic field in the SAMURAI dipole magnet. This detector was tested in November 2015 and succeeded to identify charged particles in the dipole magnet.

5 Wimmer Group

Research Subjects: Nuclear structure and reactions, shape coexistence in exotic nuclei

Member: Kathrin Wimmer

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

Triple shape coexistence at $N = 28$

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

Spectroscopy of the $T_z = -1$ nucleus ^{70}Kr

Extremely proton-rich nuclei provide an interesting test ground for isospin symmetry in nuclei. Isospin non-conserving interactions lead to different structures of nuclei which have proton and neutron number interchanged. So far such tests are limited to lighter nuclei. In an experiment at the RIBF at RIKEN ^{70}Kr was studied by nucleon removal reactions and Coulomb excitation.

Rapid shape changes at $N = 60$

The shape transition at $N = 60$ in the Sr, Zr, Mo region exhibits one of the most dramatic ground state shape transitions known today. In order to develop a better understanding of the underlying wave functions of the states, more information on the underlying single-particle structure is required. Previously, we performed two very successful experiments at TRIUMF (Canada) using the transfer reactions ^{94,95,96}Sr(d,p) to track the evolution of the single-particle energies and their occupation as $N = 60$ is approached. The next step is to investigate pair-transfer reactions using a radioactive tritium target.

Magicity at $N = 32$

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

6 Komamiya group

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

Member: Sachio Komamiya, Yoshio Kamiya, Daniel Jeans

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

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to use superconducting RF system. The Technical Design Report was completed and published in 2013. Since then, ILC design and hardware development are passed to the Linear Collider Collaboration (LCC) lead by Lyn Evans. The Linear Collider Board (LCB), chaired by Sachio Komamiya is an oversight body of LCC. We are working on ILC accelerator related hardware development, especially on the final focus system. We are developing the Shintake beam size monitor at the ATF2, which is a test accelerator system for ILC located in KEK. The Shintake beam size monitor measured about 40[nm] beam size which is a world record. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC. Since 2012 autumn, a new staff scientist from UK who is an expert on the silicon electromagnetic calorimeter was joined our group. Since then hardware and simulation studies of silicon-tungsten sandwich electromagnetic calorimeters have been extensively performed. He is also working on precise tau-lepton reconstruction at ILC to investigate, for example, CP properties of heavy Higgs bosons.

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

2) Experiment for studying quantum bound states due to the earth's gravitational potential to study the equivalent theorem in the quantum level, and searching for new short-range force using ultra-cold neutron (UCN) beam: A detector to measure gravitational bound states of UCNs is developed. We decided to use CCD's for the position measurement of the UCN's. The CCD is going to be covered by a ^{10}B layer to convert neutron to charged nuclear fragments. The UCNs are going through a neutron guide of 100 [μ] height and their density is modulated in height as forming bound states within the guide due to the earth's gravity. In 2008 we tested our neutron detector at ILL Grenoble. In 2009 we started the test experiment at ILL. We significantly improved our detector system and performed the experiment in 2011, and the analysis was completed in 2012. The observed modulations in the vertical distribution of UCNs due to the quantization is in good agreement with the prediction by quantum mechanism using the Wigner function. This is the first observation of gravitationally bound states of UCNs with sub-micron spacial resolution. This result was published in PRL. In 2013 we have started a new experiment to search for a new short range force using cold neutron beams scattered with Xe atom. The experiment was performed in HANARO, KAERI, Korea in 2014. The new world record of the short range force was established by this experiment and was published in PRL.

7 Minowa Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

Minowa group stopped its activities after professor Minowa retired at the end of the 2015 fiscal year. This is the report of the final year.

We have been developing a segmented reactor-antineutrino detector made of plastic scintillators for application as a tool in nuclear safeguards inspection and performed mostly unmanned field operations at Ohi Power Station in Fukui, Japan with a 360-kg prototype called PANDA36. PANDA is an acronym for plastic anti-neutrino detector array. At a position outside the reactor building, we succeeded in the world's first aboveground antineutrino detection of a nuclear reactor.

Unexpected gamma ray bursts were detected with PANDA36 detector during the operation at the power plant reactor with a typical duration of 180 s and a peak detection rate of $\sim 5 \times 10^2$/s. The energy spectrum is continuous and extends upto 10–15 MeV. Similar bursts were also detected by a larger prototype PANDA64 of 640 kg mass at the Norikura Observatory, located at 2,770m above sea level, of Institute for

Cosmic Ray Research, the University of Tokyo. The bursts are most probably due to electromagnetic showers of relativistic electrons created in thunder clouds.

The construction of an ultimate 100-module detector, PANDA100 is now completed and waiting for the power plant reactor to go online.

The existence of the hidden sector photons and other hidden sector particles are predicted by extensions of the Standard Model, notably the ones based on the string theory. The hidden sector photon is one of the candidates for the cold dark matter of the Universe. It would be converted into an ordinary photon at a surface of conductive material with a conversion probability depending on its mixing parameter with the ordinary photon. There have been an idea to use a spherical mirror to focus thus generated photons onto a photon sensor to enhance the detection efficiency of the hidden sector photon detector.

We demonstrated the effectiveness of this method of hidden photon search experiments in two wavelength bands corresponding to $\sim$eV and $\sim 50\mu$eV hidden photon mass ranges.

We invented a new method for the latter mass range to use a commercially available dish antenna with a plane reflector in front of the dish. Though the dish antennas usually have parabolic shape, which cannot be approximated as spherical shape because of their short focal lengths compared to their diameters. Plane radio wave of HP CDM origin would be emitted from the plane reflector perpendicularly to the surface. Because parabolic dishes concentrate plane wave to their focal point, the amplification of HP CDM signal properly works.

8 Aihara-Yokoyama Group

Research Subjects: Experimental Particle Physics and Observational Cosmology.

(1) Study of CP-violation and search for physics beyond the Standard Model in the B meson and the τ lepton systems (Belle); (2) Search for physics beyond the Standard Model at the Super B Factory (Belle II); (3) Dark energy survey at the Subaru telescope (Hyper Suprime-Cam); (4) Long baseline neutrino oscillation experiment (T2K); (5) Search for proton decays (Super-Kamiokande); (6) R&D for the next generation neutrino and nucleon decay experiment (Hyper-Kamiokande); (7) R&D of new generation photodetectors.

Members: Hiroaki Aihara, Masashi Yokoyama, Yoshiuki Onuki, and Denis 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). We continue 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. We are also studying an improved measurement of the CP violating parameter, ϕ_3, which is currently the least well-measured of the three CKM angles.

2. Physics at luminosity frontier: Belle II experiment The SuperKEKB project started in 2010. The upgraded accelerator, SuperKEKB, will have a 40 times more luminosity than KEKB. The Belle detector is also being upgraded as the "Belle II" detector with cutting-edge technologies. One of the key elements for the success of Belle II will be its Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons. Our group is responsible for the construction of the outermost layer of the Belle II SVD. This year we completed the first full-quality ladder of the Belle II SVD and started the mass production. In addition, we have been developing the track finder software with SVD for long-lived particles, such as K_S. The R&D for the upgrade of the Belle II electromagnetic calorimeter was also carried out. We studied the counter based on a pure CsI crystal and avalanche photodiodes, and found that the wavelength shifting plates with nanostructured organosilicon luminophores (NOL-9) provide a large improvement of the light output.

3. Study of Dark Energy with Subaru telescope: Hyper Suprime-Cam As an observational cosmology project, we have been involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct an extensive wide-filed deep survey to investigate the weak lensing. This data will be used to develop a 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy. This year, we developed a novel method of measuring the cluster lensing distortion profiles, and adopted it to Suprime-Cam data. We will continue to study dark matter and dark energy with the data from wide-field survey started last year.

4. Study of neutrino oscillation with accelerator neutrino beam: T2K experiment T2K is a long baseline neutrino experiment using the J-PARC accelerator complex and Super-Kamiokande, 295 km away. By combining both muon-type and electron-type neutrino interaction events observed at the Super-Kamiokande detector, we placed the world best constraint on the neutrino mixing angle θ_{23}, and the first-ever constraint on the CP asymmetry parameter in the lepton sector. This year T2K has released the first neutrino oscillation results from anti-neutrino data. A discussion is underway towards a possible extension of T2K data taking (called T2K Phase II) with an upgrade of near detectors. Such an extension will allow us to observe CP violation in the lepton sector with a significance of 3σ, if the parameters are in a favorable region.

In order to improve the systematic uncertainty from neutrino-nucleus interaction cross sections, we have proposed a new experiment at J-PARC neutrino beam facility. The experiment, named WAGASCI, was approved as a test experiment at J-PARC. This year, we have constructed a prototype of WAGASCI detector, which will be installed in front of existing T2K near detector to measure the neutrino cross section on water.

5. Search for proton decays: Super-Kamiokande Proton decay is the only way to directly prove the Grand Unified Theory, which is an attractive candidate for a model of physics beyond the Standard Model. We aim to enhance the sensitivity to proton decay at Super-Kamiokande with an improved event reconstruction. This year, we have established the calibration of the detector that is necessary for the new algorithm, and started estimating the systematic uncertainties.

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

9 Asai group

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

Member: S.Asai, A.Ishida

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry, and new diboson resonances(WW and $\gamma\gamma$).
  - Higgs: After the discovery of Higgs Boson, We are measuring the Yukawa coupling precisely.

- SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.4 and 1.5TeV, respectively.
- New dibson Resonance: A small excess is found at M=750GeV for $\gamma\gamma$ resonance. We need more data to confirm the excess is new physics or just statistical fluctuation.

- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Bose Einstein Condensation of positronium.
  - Axion searches using Spring 8
  - $\gamma\gamma$ scatter Using FEL Xray.
  - Vacuum Birefringence using Strong Magnetic field or Strong light.

10 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Shintaro Takayoshi

Our main interests are many-body and topological effects in electron and cold-atom systems, i.e., **superconductivity, magnetism and topological phenomena**, for which we envisage a **materials design** and novel **non-equilibrium** phenomena should be realised. Studies in the 2015 academic year include:

- **Superconductivity**
  — Electron correlation and High-Tc superconductivity [1]
  — Organic and carbon-based superconductors
  — Superconductivity in non-equilibrium [2]
- **Topological systems**
  — Topological Mott insulator designed for cold atoms [3]
  — Topological and chiral properties of graphene and silicene [4-7]
  — Optically detected quantum Hall effect [8]
  — Graphene quantum dot
- **Non-equilibrium phenomena**
  — Non-equilibrium dynamical mean field and dynamical cluster theories
  — Floquet topological insulator [9]
  — Design of organic topological systems [10]
  — Relaxation in electron-phonon systems [11]
  — Higgs modes in superconductors [12,13]

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11 Miyashita Group

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

Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita and Takashi Mori

Quantum dynamics

Quantum dynamics under time dependent field is one of the most important subjects in our group.

We studied properties of quantum systems in periodically driven systems. Last year, we have obtained new insights for the distribution of the states under driving force. We have studied conditions that the stationary state of a system at a finite temperature driven by periodic external field is given by a canonical distribution of Floquet quasi-eiegenstates, and found the conditions are rather severe. In the last year we examine possibility to relax them, and found that strong coupling between the thermal bath and the system, and suppression of high frequency of the spectrum density of the thermal bath work for the purpose.[17, 19] We also studied properties of quasi-stationary state of the system driven by high frequency external force by making use of Floquet-Magnus expansion method. [12, 13, 35, 59]

Relaxation from metastable state under sweeping field in a uniaxial magnetic systems was studied. We found that the classical spinodal type dynamics is characterized by singular distribution of energy gap. Beating of the spin-amplitude after the critical point was found, and mechanism of the beating was explained from the view point of quantum interference.[8, 21, 34]

Quantum response to the external field has been one of projects of our group. We studied the line shape of ESR spectrum and examined the size and temperature dependence of the double peak structure of the 1DXXZ spin model. [5, 20, 57]

Fluctuation of current in mesoscopic semiconductor is also an interesting problem. We studied a system including electric coupling between the quantum dots and lead, and found particular I-V property by making use of a functional renormalization group method.

[16, 24, 67, 51]

Cooperative Phenomena and Phase Transitions

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

Systems with local bistable state can be modeled by the Ising model. But if the lattice structure of the bistable states are different, transition between the bistable states causes changes of the elastic energy, which introduces an effective long-range interaction.[31] Competition between the long-range interaction and short-range interaction causes new types of ordering processes. In the last year, we studied the case of fully frustrated short-range interaction of antiferromagnet on the triangular lattice with next nearest neighbor interaction (Mekata model), and found that the dual Kosterlitz-Thouless transitions is modified. [4] In systems of antiferromagnetic short range interaction without frustration, it has been known that the long-range interaction does not cause intrinsic change of the phase transition at no magnetic field. However, we found that at finite field the competition between the long-range interaction and short-range interaction introduce a gas-liquid phase transition. [9, 32, 33, 58] We also analyzed experimental data of a system which has the ANNNI model type short-range interaction and successfully explained the successive phase transitions of the system.[7]

We also studied mechanisms of permanent magnets at finite temperatures. [2, 36, 43, 61]

Stochastic process

Dunkl process is a diffusion process replacing the thermal kernel by the so-called Dunkl operator. We studied asymptotic scaling properties of stochastic process of this type. [3]

Fundamental properties of thermodynamics ensembles

We studied thermodynamic properties of systems which are extensive but not additive, and found the Gibbs-Duhem theorem is violated when the thermodynamic properties depend on the shape of the system, and, in contrast , it must hold when the shape is fixed.[14] Equivalence between two statistical ensembles, which are not necessarily thermal, is formulated, and it is shown that the specific relative entropy of two ensembles gives crucial information on the macroscopic equivalence of these ensembles. [15]

12 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Hiroyasu Matsuura

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-T_c superconductivity, Mott metal-insulator transition, topological materials, Dirac electron systems in solids, organic conductors, and magnetic systems such as chiral magnets with spin-orbit interactions. 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.
  Flux states as a symmetry-breaking state in high-T_c superconductivity.[1]
- Dirac electron systems in solids
  Unscreening effect on electron-phonon coupling and superconductivity in Dirac electron systems.[2]
  Meissner effects in the superconducting states in Dirac electron systems.[3]
- Orbital magnetic susceptibility
  Orbital magnetism of Bloch electrons: General theory and application to single-band models. [4–6]
- Organic conductors
  Effect of tilting on the magnetoconductivity of Dirac electrons in organic compounds.[7]
- Theories on topological materials
  Spin current and axial current generation in a Dirac semimetal.[8]
  Relationship between fractal and quantum Hall coefficients.[9]
- Theories on heavy fermion systems and multi-band electron systems
  Quasiparticles in f^2-configuration. Charge Kondo effect.
- Spin systems, chiral magnets, and spin-orbit interaction
  Generic model and phase diagram for hyperkagome Iridates.[10]
  Dzyaloshinskii-Moriya interaction induced from RKKY at an interface.[11]
  Dynamics of antiferromagnetic domain walls.

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[9] N. Yoshioka, H. Matsuura and M. Ogata: to appear in J. Phys. Soc. Jpn."Quantum Hall effect of massless Dirac fermions and free fermions in Hofstadter's butterfly"

[10] T. Mizoguchi, K. Hwang, K.-H. Lee and Y. B. Kim: submitted to Phys. Rev. B. "Generic Model for Hyperkagome Iridate in the Local Moment Regime"

[11] T. Shibuya, H. Matsuura and M. Ogata: submitted to J. Phys. Soc. Jpn. "Magnetic chirality induced from RKKY interaction at an interface of a ferromagnet/heavy metal heterostructure"

13 Tsuneyuki Group

Research Subjects: Theoretical Condensed-Matter Physics

Member: Shinji Tsuneyuki and Ryosuke Akashi

Computer simulations from first principles enable us to investigate properties and behavior of materials beyond the limitation of experiments, or rather to predict them before experiments. Our main subject is to develop and apply such techniques of computational physics to investigate basic problems in condensed matter physics, especially focusing on prediction of material properties under extreme conditions like ultra-high pressure or at surfaces where experimental data are limited. Our principal tool is molecular dynamics (MD) and first-principles electronic structure calculation based on the density functional theory (DFT), while we are also developing new methods that go beyond the limitation of classical MD and DFT for study of electronic, structural and dynamical properties of materials.

In FY2015, we investigated superconducting transition of sulfur hydride under ultra high pressure with DFT for superconductors (SC-DFT). We proposed a sequential structural transformation from H_2S to H_3S by compression at around 180-200GPa to explain gradual but drastic increase of the superconducting transition temperature. We also developed a method of first-principles phonon calculation of highly anharmonic lattice based on the self-consistent phonon approach, which is applicable even when the material has imaginary phonon modes with ordinary harmonic approximation. With the method, we successfully calculated the lattice thermal conductivity of $SrTiO_3$ in high-temperature cubic phase. Development of the first-principles electronic structure theory for strongly correlated electrons is also one of our important activities, for which we have studied the first-principles transcorrelated (TC) method for periodic systems. In FY2015, we implemented an interative scheme for the solution of the TC self-consistent equation and succeeded in drastic speed-up of the calculation.

Our research subjects in FY2015 are as follows:

- New methods of first-principles calculation of material properties
  - Sparse modeling of anharmonic lattice vibration
  - First-principles transcorrelated method

  - A method for electronic structure calculation of large systems based on a divide and conquer method
  - A method of calculating magneto-crystalline anisotropy

- Applications of first-principles calculation
  - Charge state of hydrogen impurity in crystalline SiO_2
  - Theoretical design of perovskite-type oxy-hydrides
  - Magnetic anisotropy in Cu-doped $Nd_2Fe_{14}B$ sintered magnet
  - Interface structure of $Nd_2Fe_{14}B$ sintered magnet
  - Non-thermal structural transformation in phase-change recording materials
  - Stability of excitonic complexes in a multi-valley/band semiconductor

14 Todo Group

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

Member: Synge Todo and Hidemaro Suwa

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

Novel state and critical phenomena in strongly correlated systems

Critical Phenomena of quantum systems with strong spatial and temporal anisotropy: we have developed a generic method that can automatically optimize the aspect ratio of the system by the combination of the quantum Monte Carlo method and the machine learning technique, and applied to the two-dimensional Bose-Hubbard model with dynamical exponent $z > 1$. We also extended our method to systems with quenched randomness and studied the dynamical property of the Superfluid-Bose-Glass transition.

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

Critical phenomena of long-range interacting spin model: using the $O(N)$ cluster algorithm, we have precisely studied the critical exponents and critical amplitudes of the long-range interacting spin model on the square lattice, and established the non-trivial dependence of the critical exponents on the exponent of interaction σ.

Development of new simulation algorithms for quantum many body systems

The energy gap of a quantum system not only characterizes the system, such as the Z_2 topological phase, but also provides an effective analysis for quantum criticality. It is, however, hard to estimate the gap precisely in the quantum Monte Carlo simulations because it is not simply expressed by an average with respect to the Boltzmann distribution. Reducing the bias of the conventional estimator to zero asymptotically, we devised an unbiased and reliable gap-estimation method in the worldline quantum Monte Carlo simulations. It was shown that the criticality of the spin-phonon model is described by the Wess-Zumino-Witten model and the quantum nature of the lattice degrees of freedom is essential to the one-dimensional quantum spin or spinless fermion systems.

Many quantum spin systems are effectively described by the $O(N)$ non-linear sigma model. The theory provides the comprehensive understanding of the magnetically ordered phase, the disordered phase, and the critical point. Three parameters, the magnetization, the stiffness, and the excitation velocity, naturally appear in the effective model. The velocity has been tough to estimate precisely, while the calculation methods have been established for the other two. We calculated precisely the velocity of the one-dimensional, the two-dimensional, and the bilayer antiferromagnets without any approximation. It was clarified that the finite $N(=3)$ critical point has a non-trivial correction from the large-N limit in the effective theory.

We have also investigated and developed several novel algorithms and methodologies, such as the tensor-network algorithm, irreversible Markov chain Monte Carlo, continuous-space worm algorithm quantum Monte Carlo method, machine-learning, application of information science to materials science, etc.

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

We have developed various open-source software packages: simulation software package for quantum lattice models “ALPS” (`http://alps.comp-phys.org`), loop algorithm quantum Monte Carlo method “ALPS/looper” (`http://wistaria.comp-phys.org/alps-looper`), balance condition library “BCL” (`https://github.com/cmsi/bcl`), cluster algorithm Monte Carlo method “Cluster-MC” (`https://github.com/wistaria/cluster-mc`), collection of install scripts of MateriApps applications “MateriApps Installer” (`https://github.com/wistaria/MateriAppsInstaller`), portal site for materials science simulation “MateriApps” (`http://ma.cms-initiative.jp`), Live USB Linux system “MateriApps LIVE!” (`http://cmsi.github.io/MateriAppsLive`), parallel exact diagonalization package “Rokko” (`https://github.com/t-sakashita/rokko`), etc.

15 Katsura Group

Research Subjects: Condensed Matter Theory and Statistical Physics

Member: Hosho Katsura and Yutaka Akagi

In our group, we study various aspects of condensed matter and statistical physics. In particular, our research focuses on strongly correlated many-body systems which would give rise to a variety of quantum phases. We study theoretically these systems, with the aim of predicting novel quantum phenomena that have no counterpart in weakly-interacting systems. We are currently interested in (i) topological phases of matter, (ii) spin-charge coupled systems, and (iii) periodically driven quantum systems. In addition, we are also interested in the mathematical aspects of the study of the above mentioned fields. Our research projects conducted in FY 2015 are the following:

- Strongly correlated systems
  - Topological order in interacting Kitaev/Majorana chains [1]
  - Kagome network and Dirac half-semimetal in ferromagnetic Kondo lattices [2]
- Topological phases of matter
  - Disordered topological insulators [3]
  - Topological defects in quantum spin nematics [4]
  - Thermal Hall effect of magnons and phonons
- Solvable models and statistical physics
  - Sine-square deformation and supersymmetric quantum mechanics [5]
  - Transient dynamics of periodically driven quantum systems [6, 7]

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16 Fujimori Group

Research Subjects: Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Goro Shibata

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

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17 Hasegawa Group

Research Subjects: Experimental Surface/Nano Physics

Member: Shuji HASEGAWA, Akari TAKAYAMA, and Ryota AKIYAMA

Surfaces of materials are platforms of our research where rich physics is expected due to the low-dimensionality, symmetry breakdown, a wide variety of structures, and direct access for measurements. (1) Electronic/spin/mass transports, (2) atomic/electronic structures, (3) phase transitions, (4) electronic excitations, (5) spin states and magnetism, and (6) epitaxial growths of coherent atomic/molecular layers/wires on surfaces of metals, semiconductors, topological insulators, and nano-scale phases such as surface superstructures, ultra-thin films including monolayer materials such as graphene and silicene. We use various kinds of ultrahigh-vacuum experimental techniques, such as electron diffraction, scanning electron microscopy, 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 magneto-optical Kerr effect apparatuses. Main results in this year are as follows.

(1) Surface electronic/spin transport:

- Detection of superconductivity in Ca-intercalated double-layer graphene grown on Silicon Carbide crystal surface
- Detection of carrier localization in double-layer graphene at low temperatures, depending on thermal-treatment history
- Detection of superconductivity of double-layer Thallium on Silicon crystal
- Detection of electrical resistance across atomic steps on topological insulator crystals, revealing suppression of backscattering in the topological surface states
- Detection of Shubnikov-de Haas oscillation in topological surface states, revealing high mobility depending on the Fermi-level position

- Transport, magnetism, and atomic structure at interface between a topological insulator and magnetic insulator
- Detection of Photogalvanic effect in Rashba-type spin-splitting surface states
- Measurements of conductivity of organic molecule sheets by using four-tip STM

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

- STM/S measurement at ultra-low temperature under magnetic field, on a monolayer superconductor Si(111)-$\sqrt{3} \times \sqrt{3}$-(Tl+Pb), revealing the superconducting energy gap and vortex structure.
- Angle-resolved photoemission spectroscopy (ARPES) of topological crystalline insulators
- ARPES of metal-covered Ge(111) surface structures, possible monolayer superconductors

(3) Construction of new apparatuses:

- Fabrication of a pure-spin-current injection probe

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18 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

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

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

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

We are currently focusing on a monatomic layer of ^{3}He solid prepared on graphite, which is preplated by bilayer of HD (^{3}He/HD/HD/gr) and studying its heat capacity (C) in wide temperature range of $0.35 < T < 90$ mK. Since the areal density of 2D HD is smaller than that of ^{3}He and ^{4}He, one can obtain larger $|J_{\rm P}|$ for 2D ^{3}He on bilayer HD than on ^{3}He and ^{4}He. The T-dependence of C for ^{3}He/HD/HD/gr shows a single broad peak different from the double peak feature for ^{3}He/^{4}He/gr and ^{3}He/^{3}He/gr. The peak shifts to lower temperature by increasing areal density of ^{3}He. Here, the C-T curves are found to cross at $T = 22.5$ mK for $4.95 \le \rho \le 5.25$ nm^{-2} and at $T = 11.6$ mK for $5.25 \le \rho \le 5.55$ nm^{-2}, which suggests that 4/7 phase and Fermi fluid (C2-like phase) coexist at lower (higher) ρ region. The C2 phase is expected to be quantum liquid crystal, or in other words "hexatic" phase, where there is no long range order while hexagonal bond order is preserved locally. On the other hand, 4/7 phase can be a novel QSL with exotic elementary excitations. The C and χ shows peculiar T dependence, i.e., $C \propto T^{2/3}$ and $\chi \propto T^{-1/3}$. Theoretically, this unique T-dependence can be explained by considering spinons or majorana fermions as magnetic excitations.

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

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

   To obtain such zigzag edges and zigzag nanoribbons, we tried hydrogen-plasma etching of graphite surfaces. By exposing graphite to hydrogen-plasma under high temperatures, hexagonal pits with monatomic depth are found to be created. The size and the density of nanopit can be controlled by tuning the excitation power to produce plasma, temperature and time duration of the process. Moreover, and most importantly, the edges of the nanopit are found to be aligned to the zigzag direction. Therefore, one can obtain zigzag nanoribbon in between two hexagonal pits, where the spin polarized zigzag edge state can be expected to observe by STM/S measurement. In addition, we also found that the shape of nanopits are changed from hexagonal to circular by etching at lower temperatures. The spin polarized nature of zigzag edges can be confirmed more clearly by comparing the electronic properties of circular and hexagonal nanopits.

19 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

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

An adsorbate-induced quantum Hall system at the cleaved InSb surfaces is investigated in magnetic fields up to 14 T using low-temperature scanning tunneling microscopy and spectroscopy combined with transport measurements. We show that an enhanced Zeeman splitting in the Shubnikov-de Haas oscillations is explained by an exchange enhancement of spin splitting and potential disorder, both of which are obtained from the spatially averaged density of states (DOS). Moreover, a strong magnetic-field suppression of a correlation gap is observed in the spatially averaged DOS near the QH transition.

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

   In 2015, we have studied the effect of an adsorbate material on superconductivity of an ultrathin Pb film grown on semiconductor surfaces. The temperature dependence of the parallel critical field for monolayer ultrathin Pb films over-deposited by Sb or Se is almost the same as that for a pristine ultrathin Pb film. In contrast, for the bilayer system of Pb/Sb/Pb, the temperature dependence of the parallel critical field is different from that for the monolayer system. Further experiments are ongoing to understand the observed results.

20 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Ryusuke Matsunaga

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

1. **Exciton Mott transtion:** We have investigated the exciton Mott transition in a bulk GaAs under the condition of resonant excitation of excitons by using optical pump and terahertz probe spectroscopy. At low excitation densities, the conductivity spectrum is dominated by the exctonic 1s-2p transition. With increasing excitation densities, the spectrum changes to Drude-like metallic one, indicating the exciton Mott transition. However, a precise analysis of the specrum shows that it largely deviates from the Drude-type conductivity and apparently shows the anomalous metallic behavior above the Mott transition density. This result indicates that charge carrier dynamics in the low temperature electron-hole(e-h) metal phase is significantly influenced by electron-hole Coulomb correlations. First order like phase transition from oversaturated exciton gas to e-h metal was also observed.

2. **Higgs amplitude mode in superconductors:** We have extended the study of Higgs amplitude mode in conventional *s*-wave superconductors to that in a multiband superdoncutor MgB_2 and unconventional superconductors. We observed the third harmonic generation(THG) from a MgB_2 thin film. The temprature dependence of THG for a fixed incident frequency shows a resonant enhancement when twice of the incident frequency coincides with the higher gap energy 2Δ, suggesting the existence of Higgs mode resonance. In cuprate superconductors, terahertz pump and optical probe experiments were performed to explore the Higgs modes with d-wave paring symmetry.

3. **Ultrafast nonlinear optics in Landau-quantized graphene:** We have studied the ultrafast nonlinear optics in Landau-quantized graphene by using terahertz pump and terahertz probe spectroscopy under the strong magnetic field. Large and ultrafast nonlinear responses were observed associated with the inter-Landau level transitions in the terahertz frequency range.

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21 Takagi-Kitagawa Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kentaro Kitagawa, Naoka Ohta

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2015 included, 5d complex Ir oxides with interplay of electron correlations and strong spin orbit coupling, spin liquids, anti-perovskites with Dirac electrons and layered $Ta_2Ni(S, Se)_5$ with excitonic ground states.

Possible realization of Kitev spin liquid state in β-Li_2IrO_3:

We discovered a new iridium oxide β-Li_2IrO_3 which comprises edge-sharing network of IrO_6 octahedra in the three dimensions. Each Ir^{4+} ion has 3 bonds to the neighboring Ir^{4+} ions which are rotated by 120 degrees. β-Li_2IrO_3 undergoes a magnetic ordering at 38 K and its positive Weiss temperature $\theta_W \sim 40$ K indicates the predominance of ferromagnetic interaction. The proximity to a ferromagnetic state and the presence of large fluctuation suggest that the ground state of β-Li_2IrO_3 is close to Kitaev spin liquid. Under a high pressure of 2 GPa, we discovered that the static magnetic moment disappear and moment remains fluctuating, suggestive of the emergence of Kitaev quantum spin liquid state.

Fabrication of strongly-correlated Dirac semimetal AIrO$_3$ (A=Sr,Ca) and carrier doping:

AIrO$_3$ (A=Sr,Ca) perovskites have been thought to be semimetal, composed of three-dimensional Dirac-nodal electron and heavier hole bands. We fabricated epitaxially grown AIrO$_3$ thin films on 3 kinds of substrates, and studied transport properties which depend on the epitaxial strains. The above two-carrier model successfully reproduced our transport results. In addition, we found that the two-carrier coexisting state can be tuned into a simple Dirac-electron metal through electron doping of La substitution. In other words, we have successfully demonstrated doping on strongly-correlated $J_{\rm eff} = 1/2$ Ir oxide with the thin-film technology.

New three-dimensional Dirac electron systems:

We have obtained evidences for 3D Dirac electrons in anti-perovskite oxide Sr_3PbO, and realized the quantum-limit state where all of carriers fall into the lowest Landau level. This year, we have investigated the quantum oscillations of the magnetoresistance in Sr_3PbO single crystals, and found anisotropic Dirac fermi surfaces, in good accordance with band calculations by Kariyado and Ogata. The experiment revealed that only a part of 6-fold degenerated Dirac fermi surfaces reaches the quantum limit under the magnetic field between 5 T and 15 T. We continue to search for chiral anomaly or various phenomena related to this quantum-limit physics.

22 Theoretical Astrophysics Group

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

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

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

"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 PhD and Master's theses in our group;

2015

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

2014

- Stacking image analysis of SDSS galaxies in far-infrared and its implications for the Galactic extinction map
- Probing Cosmic Dark Matter and Dark Energy with Weak Gravitational Lensing Statistics

- Statistics of Submillimeter Line Emitters in Cosmological Simulation
- Characterization of a planetary system PTFO 8-8695 from the variability of its transit lightcurve induced by the nodal precession
- Neutrino-heating mechanism of core-collapse supernovae explosions
- Formation of Super-Massive Stars and Super-Massive Black Holes in the Early Universe

2013

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

2012

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

2011

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

2010

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

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

23 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Akihito Soeda

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

In this year, our group consisted of two faculty members, Mio Murao (Professor), Akihito Soeda (Assistant Professor), 8 graduate students– Seiseki Akibue (D3), Kotaro Kato (D2), Jisho Miyazaki (D2), Atsushi Shimbo (D1), Ryosuke Sakai (M2), and Hayata Yamasaki (M2). We investigate several aspects of theoretical quantum information. Our projects worked in the academic year of 2015 were the following:

- Distributed quantum information processing
  - Coding theorem for bipartite unitaries in distributed quantum computation by A. Soeda and M. Murao in collaboration with E. Wakakuwa at The University of Electro-Communications
  - Implementability of unitary operations over the butterfly and cluster networks with free classical communication by S. Akibue and M. Murao
  - Operational characterization of multipartite entanglement through construction tasks by H. Yamasaki, A. Soeda, and M. Murao
- Quantum information theoretic analysis of multipartite quantum states
  - Quantum Hammersley-Clifford Theorem for 1D Gibbs states with non-commuting Hamiltonian by K. Kato in collaboration with F. Brandao at Microsoft Research Redmond (currently, at California Institute of Technology)
  - Topological entanglement entropy and non-locality of the entanglement Hamiltonian by K. Kato and M. Murao in collaboration with F. Furrer at NTT Basic Research Laboratories
  - Markovianizing cost of tripartite quantum states by A. Soeda and M. Murao in collaboration with E. Wakakuwa at The University of Electro-Communications
- Foundations of quantum mechanics
  - Non-locality and non-causality of quantum operations by S. Akibue and M. Murao in collaboration with G. Kato and M. Owari at NTT Basic Research Laboratories (MO is now affiliated with Shizuoka University)
  - Extensions and composites in topos quantum theory by J. Miyazaki, A. Soeda, and M. Murao in collaboration with C. Heunen at University of Oxford (currently, at The University of Edinburgh)
- Quantum algorithms
  - Reproduction of unitary operations via quantum learning by A. Shimbo, A. Soeda, and M. Murao
  - Quantum input-output algorithms for quantum systems with limited controllability by R. Sakai, A. Soeda, and M. Murao

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

24 Ueda Group

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

Member: Masahito Ueda and Shunsuke Furukawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controllable systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose-Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied topological excitations and correlation effects in spinor BECs, BCS-BEC crossover and Efimov physics under the control of an atomic interaction strength, quantum Hall states in synthetic gauge fields, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems and the formulation of the dynamics of state reduction in light of information flow under measurements and feedback controls. We list our main research subjects in FY2015 below.

- Quantum many-body phenomena in ultracold atoms
  - Diffraction-unlimited position measurement for quantum gases and biomolecules [1, 2]
  - Universal relations in a Fermi gas with a resonant p-wave interaction [3]
  - Excitation band topology in Bose-Einstein condensates in optical lattices [4]
  - Entanglement pre-thermalization in a one-dimensional Bose gas [5]
- Quantum Information, quantum measurement, and foundation of statistical mechanics
  - Quantum nonequilibrium equalities with absolute irreversibility [6]
  - Work fluctuation-dissipation trade-off in heat engines [7]
  - Accuracy of the microcanonical ensemble in small isolated quantum systems [8]
  - Generalized Gibbs ensemble in a nonintegrable system with local symmetries [9]
  - Trade-off relation between information and disturbance in quantum measurement [10]

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25 Yokoyama(J) Group

Research Subjects: Theoretical Cosmology and Gravitation

Members: Jun'ichi Yokoyama and Teruaki Suyama

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We are also working on gravitational wave data analysis to prepare for completion of KAGRA, which will be succeeded by the newly established KAGRA gravitational wave data analysis international cooperation section at RESCEU. Below is the list of topics studied during the academic year 2015.

Cosmology of the early universe

- Creation of the inflationary universe without initial singularity
- Consistency of the Generalized G-inflation
- Creation of the inflationary universe out of a black hole
- Resolution of the domain-wall problem in NMSSM
- Properties of spatially covariant scalar-tensor theory
- Global phase transition and thermal history of the early universe
- CMB anisotropy induced by cosmic strings in the delayed scaling scenario
- Primordial black holes and long-wave solutions of cosmological perturbation theory
- Primordial gravitational waves probed by primordial black holes

Observational cosmology

- Probing small scale density perturbations using minihalos
- Cosmology of SKA
- Inflationary universe models probed by future radio observations
- Vector perturbations probed by weak gravitational lensing

Quantum field theory in curved space

- New interpretation of the Hawking-Moss instanton
- Schwinger effect in de Sitter space
- QED correction to dipole magnetic radiation
- Probing the Unruh effect by a high-intensity laser

Gravitation

- Spontaneous scalarization
- Scalar-tensor theories and black holes
- Instability of black holes in D dimensional Lovelock-Galileon theory

Gravitational waves

- Construction of analysis pipeline for continuous gravitational waves
- Low frequency gravitational waves probed by Phase-II TOBA
- Estimation method of the mass of a neutron star using continuous gravitational waves
- Non-gaussianity in gravitational wave data analysis

26 Takase Group

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

Member: Yuichi Takase, Akira Ejiri, Naoto Tsujii

We perform experiments on the TST-2 spherical tokamak at the Kashiwa Campus in order to develop physics understanding and technology to realize nuclear fusion power. The current focus of our group is the study of non-inductive plasma start-up using the lower hybrid wave (LHW) on TST-2. We also collaborate with other fusion experiments in Japan and abroad, including JT-60SA, LHD, LATE, QUEST, Alcator C-Mod (US), and MAST (UK).

In FY2015, non-inductive plasma start-up experiments were performed using the capacitively-coupled combline (CCC) antenna on TST-2. The antenna was developed in collaboration with General Atomics (US). With a small increase in the toroidal field and installation of the top and bottom limiters, plasma current ramp-up up to 25 kA has been achieved. Since the maximum plasma current is strongly correlated with the toroidal magnetic field, increasing the toroidal field coil power supply is necessary for further current ramp-up. A new top-launch antenna was developed for better wave accessibility to the plasma core at higher density. The antenna was installed at the end of FY2015, and plasma current ramp-up up to 13 kA has been achieved so far.

The hard X-ray detector using APD to read out the NaI scintillation light was developed. Energy resolution was better than the previously used system with a photo-multiplier. Soft X-ray emission profile was measured using a photo-diode array. It was inferred that the power absorption profile shifted to the plasma edge at higher density. Copper impurity radiation from CCC antenna current straps was observed but the radiated power was found not to be substantial. The electron density profile was evaluated with the horizontal interferometer chords. It was found that significant parasitic ionization exists around $z = 200$ mm when the plasma current is above 10–15 kA.

An LHW plasma configuration at I_p=9 kA was numerically investigated using MEGA, a non-linear magneto-hydrodynamic (MHD) solver to describe the bulk plasma in combination with a full-f particle method. The distribution function f provided by a coupled GENRAY/CQL3D simulation or tailored functions based on semi-empirical analytic distribution functions was used for the initial condition. The resulting time averaged pressure and temperature distributions were compared to the outcome of a three-fluid-equilibrium code [6] and a qualitatively and quantitatively satisfying agreement was obtained. However, the time-dependent electric fields that show modal structures will require in-depth analysis.

Inductively formed TST-2 plasmas were studied using a Rogowski probe. The sheath generated inside the probe was found to increase the width of the angular current profile. It was found that, during IRE events, the local current reverses direction at the plasma edge.

A multi-pass Thomson scattering system is being developed to measure electron temperature and density in low density plasmas created by LHW. A ten-fold increase in the scattered signal was observed after optimization of the optical system.

A microwave scattering diagnostic is being developed for direct measurement of the lower-hybrid waves. The system will be installed in FY2016.

As a collaboration, Thomson scattering of RF driven steady-state plasmas is being developed on the QUEST spherical tokamak at Kyushu University. Using a laser pulse timing system, compact torus injection experiments were investigated.

Waves in the ion cyclotron range of frequencies (ICRF) in LHD plasmas were measured using a microwave reflectometer. The system was extended for two microwave frequencies. The analysis of the relative phases at the two points showed a inward propagating fluctuation. When the absorption was weak, a standing wave structure was observed.

27 Sano Group

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

Member: Masaki Sano and Tetsuya Hiraiwa

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

1. Statistical mechanics out of equilibrium
   (1) Universality in transition to turbulence [8]
   (2) Non-equilibrium fluctuation of a growing surface
   (3) Rheology of a non-Brownian suspension [9]
2. Active matters
   (1) Helical motion of a chiral liquid crystal droplet
   (2) Collective motion of self-driven colloidal particles [3]
   (3) Collective motion of filamentous proteins
   (4) Long-range order and giant number fluctuation in collective motion of bacteria
3. Biological systems
   (1) Traction force of collectively migrating neural stem cells
   (2) Theory on mechanics of cellular dynamics and morphogenesis [5, 2, 10]

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28 Yamamoto Group

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

Member: Satoshi Yamamoto, Nami Sakai, and Yoshimasa Watanabe

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

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

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

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooled HEB mixer using NbTiN and NbN in our laboratory. Our NbTiN mixer shows the noise temperature of 470 K at 1.5 THz, which corresponds 7 times the quantum noise. This is the best performance at 1.5 THz in spite of the use of the wave-guide mount. Furthermore, we successfully realized the waveguide-type NbN HEB mixer by using the NbN/AlN film deposited on the quartz wafer. The 0.8/1.5 THz dual-band HEB mixer receiver was assembled, and was installed on the ASTE 10 m telescope for astronomical observations. The first commissioning run was performed in September to October, 2011. We successfully observed Moon and Jupiter in the 0.9 THz continuum emission, and the Orion A molecular cloud in the ^{13}CO $J = 8 - 7$ line emission. We are expecting the scientific run from 2015.

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29 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) Photoelectron diffraction from laser-aligned molecules with X-ray free-electron laser pulses [1]

We report on the measurement of deep inner-shell $2p$ X-ray photoelectron diffraction (XPD) patterns from laser-aligned I_2 molecules using X-ray free-electron laser (XFEL) pulses. The XPD patterns of the I_2 molecules, aligned parallel to the polarization vector of the XFEL, were well matched with our theoretical calculations. Further, we propose a criterion for applying our molecular-structure-determination methodology to the experimental XPD data. In turn, we have demonstrated that this approach is a significant step toward the time-resolved imaging of molecular structures.

This work was done as a collaborative study with researchers from KEK, Ritsumeikan University, Japan Atomic Energy Agency, Chiba University, Kyoto University, Riken SPring-8 Center, and Japan Synchrotron Radiation Research Institute.

(2) Laser-field-free three-dimensional molecular orientation [2]

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

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30 Nakazawa Group

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

Member: Lecturer: Kazuhiro Nakazawa, Post doctorial fellow: Zhongli Zhang

We analyze the X-ray data of, neutron star high-mass X-ray binaries, neutron star low-mass X-ray binaries, magnetors, and associated supernova remnants. Also black-hole binaries, active galactic nuclei, as well as Ultra-Luminous X-ray sources, are analyzed. White dwarf binaries are also important. Clusters of galaxies, especially in its merging phase, are also important target for us.

For further better observations, we are also developing a new generation X-ray satellite. Hitomi, the Japanese 6th X-ray satellite, was successfully launched on 17 Feb. Its initial observation was performed before the incident on 26 March. Now we lose contact to it, and trying to resume it as soon as possible. We also work on more future development, the FORCE mission.

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

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31 Gonokami, Yumoto and Yoshioka Group

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

Member: Makoto Gonokami, Junji Yumoto and 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. A project was started to develop new coherent light sources; covering a broad frequency range from terahertz to soft X-rays. Specifically, in collaboration with RIKEN, the Foundation for Coherent Photon Science Research was established. This is one of the Advanced Research Foundation initiatives from the Ministry of Education, Culture, Sports, Science and Technology. Within this initiative, we are developing intense and stable coherent light sources at a high repetition rate (That facility is named "Photon Ring").

This year the following activities were done:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   1.1. Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases and their application to nuclear physics
2. The quest for non-trivial optical responses and development of applications:
   2.1. Development of active terahertz polarization control device using MEMS spiral metamaterials
   2.2. Development of high-sensitivity terahertz camera
   2.3. Control of antiferromagnetic domain distribution via optical annealing
   2.4. Investigation of laser-breakdown process in wide band-gap dielectric materials
3. Development of novel coherent light sources and spectroscopic methods:
   3.1. VUV precision spectroscopy using higher-order harmonics
   3.2. Laser-based angle resolved photoemission spectroscopy
   3.3. "Photon ring" project
   3.4. Institute for Photon Science Technology

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32 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Yuta Michimura

In February 2016, the LIGO gravitational-wave observatory announced detection of a gravitational-wave signal. The new field of gravitational-wave astoronomy was opend. Gravitational waves has a potential to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars or binary black holes; these information can not be obtained by other means such as optics, radio-waves or X-ray. Worldwide efforts are being continued in order to construct and improve detectors.

In Japan, we are constructing a large-scale cryogenic gravitational-wave antenna, named KAGRA (former LCGT). The detector is now under construction in KAMIOKA. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200Mpc. A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

The current research topics in our group are followings:

- KAGRA gravitational wave detector
  - Construction and test observation run
  - Optical design of the interferometer
- Space laser interferometer, DECIGO
- Development of TOBA (Torsion Bar Antenna)
  - A new type sensor for TOBA
  - Design and development of the next generation TOBA
- Development of the ultra stable laser source using cryogenic cavity
- High-precision experiments on relativity and opto-mechanics
  - Opto-mechanics experiments with triangular cavity
  - Optical levitation experiments
  - Experimental study of space isotropy

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33 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose and Hiroshi Kohsaka

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

1.A circuit mechanism for the propagation of waves of muscle contraction in Drosophila larvae.

Animals move by adaptively coordinating the sequential activation of muscles. The circuit mechanisms underlying coordinated locomotion are poorly understood. In this study, we revealed a novel circuit for the propagation of waves of muscle contraction, using the peristaltic locomotion of Drosophila larvae as a model system. We found an intersegmental chain of synaptically connected neurons, alternating excitatory and inhibitory, necessary for wave propagation and active in phase with the wave. The excitatory neurons (A27h) are premotor and necessary only for forward locomotion, and are modulated by stretch receptors and descending inputs. The inhibitory neurons (GDL) are necessary for both forward and backward locomotion, suggestive of different yet coupled central pattern generators, and its inhibition is necessary for wave propagation. The circuit structure and functional imaging indicated that the commands to contract one segment promote the relaxation of the next segment, revealing a mechanism for wave propagation in peristaltic locomotion. (Collaboration with Drs. Cardona A, Zwart MF, and Fetter RD at the Janelia Research Institute in the USA)

2. Identification of Inhibitory Premotor Interneurons Activated at a Late Phase in a Motor Cycle during Drosophila Larval Locomotion.

Rhythmic motor patterns underlying many types of locomotion are thought to be produced by central pattern generators (CPGs). We use the motor circuitry underlying crawling in larval Drosophila as a model to try to understand how segmentally coordinated rhythmic motor patterns are generated. We reported on the identification of a distinct class of glutamatergic premotor interneurons called Glutamatergic Ventro-Lateral Interneurons (GVLIs). We used calcium imaging to search for interneurons that show rhythmic activity and identified GVLIs as interneurons showing wave-like activity during peristalsis. Optogenetic activation of GVLIs with the red-shifted channelrhodopsin, CsChrimson ceased ongoing peristalsis in crawling larvae. Simultaneous calcium imaging of the activity of GVLIs and motoneurons showed that GVLIs' wave-like activity lagged behind that of motoneurons by several segments. Thus, GVLIs are activated when the front of a forward motor wave reaches the second or third anterior segment. We propose that GVLIs are part of the feedback inhibition system that terminates motor activity once the front of the motor wave proceeds to anterior segments. (Collaboration with Drs. Pulver SR Zlatic M, and Ohyama T at the Janelia Research Institute in the USA)

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34 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Works of Purified single molecule

1.Kinesin is a molecular motor which carries cargo such as organelles moving along microtubules unidirectionally using ATP hydrolysis energy in a cell. The mechanisms determining the moving direction remain unknown. Here we have established optical tweezers system in order to detect the displacement generated by the conformational change of the neck linkers, which is an essential for kinesin ' s unidirectional movement. Then we determined the energy gap between two conformations. The displacement of 5.1nm is consistent with that estimated by kinesin crystal structure. Unexpectedly the energy gap between two conformations of 0.9kBT was considerably smaller than the mechanical work produced by single kinesin motor.

2.Cytoplasmic dynein is a motor protein moving along microtubules toward the minus-end with the energy of ATP hydrolysis in cellular processes. Dynein ' s large conformational change, called power stroke, is assumed to generate driving forces moving along the microtubule. First, we predicted that the rate-limiting states were on both ATP+Pi and non-nucleotide states, evaluated from the difference value of the FRET efficiency. Then, we measured the distance driven by dynein ' s power stroke and the dwell time that single-headed human cytoplasmic dynein binds to a microtubule with optical tweezers. The ATP concentration dependence of dwell time can be definitely consistent with the two rate-limiting states with chemical reaction rate constants. Taken it into consideration, the distance by dynein also depends on ATP concentration. We concluded that we found new knowledge of the detailed mechanochemical cycle of human cytoplasmic dynein by quantitative evaluation experiments.

3.To understand the molecular mechanism of cooperative force generation between skeletal myosin molecules, we measured forces generated by synthetic myofilaments, in which approximately 17 myosin molecules interact with an single actin filament. Optical tweezers was used to measure forces generated by myosins, providing stepwise actin displacements, which imply that forces are generated by synchronous actions of active myosin motors. Combined with results from the computational model, three factors are important for synchronization of power strokes (i.e., conformational changes in myosin head during force generations) between myosin motors. First, strain-dependent kinetics are necessary to couple mechanochemical cycles between myosins. Second, multiple power stroke states further enhance a chance of power stroke synchronization. Finally, the physiological ATP concentration is another important factor to enhance a chance of power stroke synchronization. Our findings reveal how molecular properties of skeletal myosin are specifically tuned to cooperative force generations and its ensemble effects towards efficient muscle contractions

Cell works

1. Brain tumor stem cells (BTSCs) are recent topics in cancer science because it showed distinctive characteristics such as high resistance to radiotherapy and chemotherapy, invasion, metastasis, multiline age and self-renewal potential. For removing the brain tumor, the therapy resistance of BTSCs should be evaluated and compared with normal tumor cells. Thus, we selectively damage BTSCs and normal tumor cells by laser activation of near-infrared dyes. We observed the dynamics of membrane proteins and intracellular granules of the damaged cells with a confocal microscope. The motility of membrane proteins and granules in damaged BTSCs was more accelerated than that of normal tumor cells, suggesting that dynamics of proteins would be a key property in therapy resistance of BTSCs.

2. Sarcomere is an essential unit of cardiomyocyte. It is well known that sarcomere has three state (i.e. contraction, relaxation and spontaneous oscillation state) dependent of the solution condition. In intact cardiomyocytes, we found hyperthermal sarcomeric oscillations (HSOs) that is Ca-ion independent and high-frequency (5-10 Hz) auto-oscillations induced by a rapid increase in temperature to ¿ 38 o C. This finding suggest that the temperature shift the state from relaxation to oscillation. We found that the HSOs was occurred in skinned cardiac myofibrils. The skinned myofibrils are suitable for exchanging chemical compounds and proteins. Therefore using this system, we will understand the molecular aspect of HSOs.