ISSN 0910-0709

Department of Physics
School of Science
The University of Tokyo

Annual Report

2014

平成26年度 年次研究報告

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 2014

1 Theoretical Nuclear Physics Group

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

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

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

Nuclear Structure Physics

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

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

The structure of such unstable nuclei has been calculated by Monte Carlo Shell Model, for instance to Ni isotopes. Their applications have been made in collaborations with experimentalists internationally spread, *e.g.*, [1, 2]. Collaborations with many groups produce various interesting results, for instance [3, 4, 5, 6, 7].

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

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

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

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. Real-time stochastic quantization [9]
2. Chiral condensate in curved spacetimes [11]
3. Lattice QCD in curved spacetimes [14]
4. Topological structure of QCD vacuum [23]

References

[1] F. Flavigny et al., "Characterization of the low-lying 0^+ and 2^+ states in ^{68}Ni via beta decay of the low-spin ^{68}Co isomer", Phys. Rev. C **91**, 034301, (2015).

[2] C. J. Chiara et al., "Identification of deformed intruder states in semi-magic ^{70}Ni", Phys. Rev. C **91**, 044309 (2015).

[3] P. Doornenbal et al., "Rotational level structure of sodium isotopes inside the "island of inversion"", Prog. Theor. Exp. Phys. **2014**, 053D01 (2014).

[4] N. Kobayashi et al., "Observation of a p-Wave One-Neutron Halo Configuration in ^{37}Mg", Phys. Rev. Lett. **112**, 242501 (2014).

[5] A. Sanetullaev et al., "Neutron spectroscopic factors of ^{55}Ni hole-states from (p, d) transfer reactions", Phys. Lett. B **736**, 137 (2014).

[6] H. Watanabe et al., "Monopole-Driven Shell Evolution below the Doubly Magic Nucleus ^{132}Sn Explored with the Long-Lived Isomer in ^{126}Pd", Phys. Rev. Lett. **113**, 042502 (2014).

[7] T. Nakamura et al., "Deformation-Driven p-Wave Halos at the Drip Line: ^{31}Ne", Phys. Rev. Lett. **112**, 142501 (2014).

[8] K. Fukushima, "Spectral representation of the particle production out of equilibrium - Schwinger mechanism in pulsed electric fields", New J. Phys. **16**, 073031 (2014).

[9] K. Fukushima and T. Hayata, "Schwinger mechanism with stochastic quantization", Phys. Lett. B **735**, 371 (2014).

[10] R. Anzaki, K. Fukushima, Y. Hidaka and T. Oka, "Restricted phase-space approximation in real-time stochastic quantization", Annals of Phys. **353**, 107 (2015).

[11] A. Flachi and K. Fukushima, "Chiral Mass-Gap in Curved Space", Phys. Rev. Lett. **113**, 091102 (2014).

[12] K. Fukushima, "Hadron resonance gas and mean-field nuclear matter for baryon number fluctuations", Phys.Rev.C (in press).

[13] A. Flachi, K. Fukushima and V. Vitagliano, "Geometrically induced magnetic catalysis and critical dimensions", Phys.Rev.Lett. (in press).

[14] A. Yamamoto, "Lattice QCD in curved spacetimes", Phys. Rev. D **90**, 054510 (2014).

[15] T. Kanazawa and A. Yamamoto, "Asymptotically free lattice gauge theory in five dimensions", Phys. Rev. D **91**, 074508 (2015).

[16] T. Hayata and A. Yamamoto, "Inhomogeneous Polyakov loop induced by inhomogeneous chiral condensates", Phys. Lett. B, in press (2015).

[17] S. Benic, D. Horvatic, D. Kekez and D. Klabucar, "A $U_A(1)$ symmetry restoration scenario supported by the generalized Witten-Veneziano relation and its analytic solution", Phys. Lett. B **738**, 113 (2014).

[18] N. Yasutake, R. Lastowiecki, S. Benic, D. Blaschke, T. Maruyama and T. Tatsumi, "Finite-size effects at the hadron-quark transition and heavy hybrid stars", Phys. Rev. C **89**, 065803 (2014).

[19] S. Benic, "Heavy hybrid stars from multi-quark interactions", Eur. Phys. J. A**50** 111, (2014).

[20] B. Radovcic and S. Benic, "Electroweak breaking and Dark Matter from the common scale", Phys. Lett. B **732**, 91 (2014).

[21] S. Benic, D. Horvatic and J. Klaric, "Recovering the chiral critical end-point via delocalization of quark interactions", Phys. Rev. D **89**, 054025 (2014).

[22] S. Benic, D. Blaschke, G. A. Contrera and D. Horvatic, "Medium induced Lorentz symmetry breaking effects in nonlocal PNJL models", Phys. Rev.D **89**, 016007 (2014).

[23] K. Mameda, "QCD θ-vacua from the chiral limit to the quenched limit", Nucl. Phys B **889**, 712 (2014).

2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Members: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo, Yuji Tachikawa
Motoi Endo, Teruhiko Kawano, Kazunori Nakayama, Tatsuma Nishioka

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 SUSY Phenomenology [6, 7, 8, 2]
   - 1.2 Collider Phenomenology [1, 23, 24, 25]
   - 1.3 Anomalous magnetic moment
   - 1.4 Cosmic-ray [3, 5, 11, 12, 13]
   - 1.5 Gravitational waves [4, 22]
   - 1.6 Scalar dynamics [9, 10, 21, 26]
   - 1.7 Baryogenesis [20]
   - 1.8 Inflation models [14, 15, 18, 19, 16, 17, 27, 28, 29, 30]
2. Superstring Theory and Formal Aspects of Quantum Field Theories
   - 2.1 Formulation of M5-branes [32]
   - 2.2 Dualities and Integrable systems [31, 33]
   - 2.3 Quantum field theories and entanglement entropies [34, 35, 36, 37]
   - 2. 4d Super Yang-Mills theory [39]
   - 2.2 5d Super Yang-Mills theory [38, 40]
   - 2. 6d superconformal field theories [41, 42]
   - 2. Supersymmetric quantum field theories in general [43, 44]

References

[1] M. Endo and Y. Yamamoto, JHEP **1406**, 126 (2014) [arXiv:1403.6610 [hep-ph]].

[2] K. Hamaguchi, M. Ibe, T. T. Yanagida and N. Yokozaki, Phys. Rev. D **90** (2014) 1, 015027 [arXiv:1403.1398 [hep-ph]].

[3] Y. Ema, R. Jinno and T. Moroi, Phys. Lett. B **733**, 120 (2014) [arXiv:1312.3501 [hep-ph]].

[4] R. Jinno, T. Moroi and T. Takahashi, JCAP **1412**, no. 12, 006 (2014) [arXiv:1406.1666 [astro-ph.CO]].

[5] Y. Ema, R. Jinno and T. Moroi, JHEP **1410**, 150 (2014) [arXiv:1408.1745 [hep-ph]].

[6] M. Endo, T. Kitahara and T. Yoshinaga, JHEP **1404**, 139 (2014) [arXiv:1401.3748 [hep-ph]].

[7] K. Ishikawa, T. Kitahara and M. Takimoto, Phys. Rev. Lett. **113**, no. 13, 131801 (2014) [arXiv:1405.7371 [hep-ph]].

[8] K. Ishikawa, T. Kitahara and M. Takimoto, Phys. Rev. D **91**, no. 5, 055004 (2015) [arXiv:1410.5432 [hep-ph]].

[9] K. Mukaida, K. Nakayama and M. Takimoto, JCAP **1406**, 013 (2014) [arXiv:1401.5821 [hep-ph]].

[10] K. Mukaida, K. Nakayama and M. Takimoto, Phys. Rev. D **89**, no. 12, 123515 (2014) [arXiv:1402.1856 [astro-ph.CO]].

[11] K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **735**, 338 (2014) [arXiv:1403.1733 [hep-ph]].

[12] K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **734**, 178 (2014) [arXiv:1403.7390 [hep-ph]].

[13] K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **737**, 311 (2014) [arXiv:1405.4670 [hep-ph]].

[14] K. Nakayama and F. Takahashi, Phys. Lett. B **734**, 96 (2014) [arXiv:1403.4132 [hep-ph]].

[15] K. Mukaida and K. Nakayama, JCAP **1408**, 062 (2014) [arXiv:1404.1880 [hep-ph]].

[16] K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **734**, 358 (2014) [arXiv:1404.2472 [hep-ph]].

[17] H. Murayama, K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **738**, 196 (2014) [arXiv:1404.3857 [hep-ph]].

[18] K. Nakayama, F. Takahashi and T. T. Yanagida, JHEP **1409**, 014 (2014) [arXiv:1406.4265 [hep-ph]].

[19] K. Nakayama, F. Takahashi and T. T. Yanagida, Phys. Lett. B **737**, 151 (2014) [arXiv:1407.7082 [hep-ph]].

[20] T. Higaki, K. Nakayama, K. Saikawa, T. Takahashi and M. Yamaguchi, Phys. Rev. D **90**, no. 4, 045001 (2014) [arXiv:1404.5796 [hep-ph]].

[21] T. Moroi, K. Mukaida, K. Nakayama and M. Takimoto, JHEP **1411**, 151 (2014) [arXiv:1407.7465 [hep-ph]].

[22] S. Kuroyanagi, K. Nakayama and J. Yokoyama, PTEP **2015**, no. 1, 013E02 (2015) [arXiv:1410.6618 [astro-ph.CO]].

[23] M. Endo, K. Hamaguchi, K. Ishikawa and M. Stoll, Phys. Rev. D **90** (2014) 5, 055027 [arXiv:1405.2677 [hep-ph]].

[24] M. Stoll, JHEP04(2015)111 [arXiv:1410.4637 [hep-ph]].

[25] M. Endo and Y. Takaesu, Phys. Lett. B **743**, 228 (2015) [arXiv:1407.6882 [hep-ph]].

[26] K. Mukaida and M. Takimoto, JCAP **1408**, 051 (2014) [arXiv:1405.3233 [hep-ph]].

[27] K. Hamaguchi, T. Moroi and T. Terada, Phys. Lett. B **733** (2014) 305 [arXiv:1403.7521 [hep-ph]].

[28] S. V. Ketov and T. Terada, Phys. Lett. B **736** (2014) 272 [arXiv:1406.0252 [hep-th]].

[29] S. V. Ketov and T. Terada, JHEP **1412** (2014) 062 [arXiv:1408.6524 [hep-th]].

[30] T. Terada, Y. Watanabe, Y. Yamada and J. Yokoyama, JHEP **1502** (2015) 105 [arXiv:1411.6746 [hep-ph]].

[31] Y. Matsuo, C. Rim and H. Zhang, JHEP **1409**, 028 (2014) [arXiv:1405.3141 [hep-th]].

[32] P. M. Ho and Y. Matsuo, JHEP **1412**, 154 (2014) [arXiv:1409.4060 [hep-th]].

[33] S. Nakamura, F. Okazawa and Y. Matsuo, PTEP, no. 3, 033B01 (2015) [arXiv:1411.4222 [hep-th]].

[34] N. Hama, T. Nishioka and T. Ugajin, JHEP **1412** (2014) 048 [arXiv:1410.2206 [hep-th]].

[35] T. Kawano, Y. Nakaguchi and T. Nishioka, JHEP **1412**, 161 (2014) [arXiv:1410.5973 [hep-th]].

[36] Y. Nakaguchi and T. Nishioka, JHEP **1504**, 072 (2015) [arXiv:1501.01293 [hep-th]].

[37] K. Ohmori and Y. Tachikawa, Journal of Statistical Physics, in press. arXiv:1406.4167 [hep-th].

[38] H. Hayashi, Y. Tachikawa and K. Yonekura, JHEP **1502** (2015) 089 [arXiv:1410.6868 [hep-th]].

[39] Y. Tachikawa, JHEP **1503** (2015) 035 [arXiv:1412.2830 [hep-th]].

[40] Y. Tachikawa, PTEP **2015** 4, 043B06 [arXiv:1501.01031 [hep-th]].

[41] K. Ohmori, H. Shimizu and Y. Tachikawa, JHEP **1408**, 002 (2014) [arXiv:1404.3887[hep-th]].

[42] K. Ohmori, H. Shimizu, Y. Tachikawa and K. Yonekura, PTEP **2014**, no. 10, 103B07 (2014) [arXiv:1408.5572 [hep-th]].

[43] Y. Tachikawa, J. Phys. Conf. Ser. **597** (2015) 1, 012005.

[44] Y. Tachikawa, Lect. Notes Phys. **890** 2014 [arXiv:1312.2684 [hep-th]].

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 ($\overline{p}He^{+}$) is three-body Rydberg atom, which consists of a helium nucleus 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 ($M_{\overline{p}}/m_e$) 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 2014, systematic uncertainty studies of two transitions in $(n, \ell) = (36, 34) \rightarrow (37, 33)$ and $(34, 32) \rightarrow (33, 31)$ were carried out using single-photon laser spectroscopy. The result was carefully analyzed together with existing 13 transition frequencies. The preliminary experimental transition frequencies are decided with a precision of around 2.5×10^{-9}.

The more precise $M_{\overline{p}}/m_e$ value will be published during 2015.

$\bar{p}$-nucleus annihilation cross section at ultra-low energies Normally, an antiproton is absorbed by a 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 identified the signal of its annihilation for the first time in that energy region.
We are planning to measure the cross section in a momentum region of 100 MeV/c. In that region, annihilation cross sections of antineutron on some nucleus show unexpected enhancement, and we can understand this behaviors by comparing to these data to the one of antiprotons. In 2015, we are going to measure the cross sections with carbon and aluminum target. In 2014, we made a proposal of the experiment and submitted it to the program advisory committee. In that proposal we performed Monte-Carlo simulations in order to estimate the backgrounds, determined the experimental setup, and showed the feasibility of the experiment. The proposal was accepted and we are going to perform the experiment in the end of 2015.

2) Spectroscopy of pionic atoms in inverse kinematics

We are planning a spectroscopy of pionic atoms with unstable nuclei to investigate the density dependence of restoration of chiral symmetry breaking. In the experiment, missing mass spectroscopy of inverse kinematics of (d,^{3}He) reaction will be performed with a setup using a deuterium gas active-target MWDC (Multi Wire Drift Chamber) and silicon detectors.

In this year, we fabricated a prototype of the deuterium gas MWDC and studied its performance. Honeycomb structure of 6 mm wire geometry was adopted for the prototype and it consisted of 10 planes. As the first step, the detector was tested with H_2 gas instead of D_2 gas. An α source and a silicon strip detector were installed inside the detector and gas gain and position resolution were evaluated. In the measurement, the position resolution was estimated to be 100–300 μm for each plane, which was good enough for the experiment. However, position dependence of gas gain was observed and we could not achieved enough gas gain due to a discharge in specific cells. We will improve the situation by separating high voltage for each cell.

3) Study of η' mesic nuclei

η' meson has a large mass of 958 MeV/c^2. This is understood by the $U_{\mathrm{A}}(1)$ anomaly effect, and the strength of this effect on the η' mass may be related to spontaneous breaking of chiral symmetry. In the nuclear medium, due to partial restoration of chiral symmetry, the η' mass may be reduced. In this case, an attraction between an η' and a nucleus is induced, and η' meson-nucleus bound states (η' mesic nuclei) may exist.

In 2014, we performed a missing-mass spectroscopy experiment to search for η' mesic nuclei at GSI. A 2.5 GeV proton beam impinged onto a carbon target to potentially produce the η' mesic nuclei in the ^{12}C(p,d) reaction. The momentum of the ejectile deuteron was measured by FRS to obtain the missing-mass of the reaction. The analysis of the accumulated data is in progress.

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 line 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 utilize fast radioactive isotope (RI) beams available at RI Beam Factory (RIBF) at RIKEN. RIBF is a leading facility where RI beam intensities are the highest in the world. We maximize RIBF utilization to access nuclei very far from the β-stability line as well as to exploit new types of experiments and new methods of spectroscopy via new ideas and detector developments.

Research subjects to be covered by our group are followings.

Half-lives measurement in the vicinity of doubly-magic ^{78}Ni

The half-lives of 20 neutron-rich nuclei with $Z = 27$-– 30 have been measured at RIBF, including five new half-lives of ^{76,77}Co, ^{79,80}Ni and ^{81}Cu. In addition, the half-lives of $^{73-75}$Co, $^{74-78}$Ni, $^{78-80}$Cu, and $^{80-82}$Zn were determined with higher precision than previous works. Based on these new results, a systematic study of the β-decay half-lives has been carried out, which suggests a sizable magicity for both the proton number $Z = 28$ and the neutron number $N = 50$ in ^{78}Ni.

In-beam γ-ray spectroscopy on ^{78}Ni

In May 2015, the in-beam γ-ray spectroscopy experiment named as SEASTAR to investigate the excited states of ^{78}Ni by measuring the de-excitation γ-rays after the ^{79}Cu$(p, 2p)^{78}$Ni reaction was conducted at RIBF. The secondary beam ^{79}Cu impinged onto a 10-cm-thick liquid hydrogen target with recoil proton tracking system MINOS surrounded by NaI(Tl) γ-ray detection array DALI2. Although the analysis is still on going, we succeeded in observing an indication of de-excitation γ-rays of ^{78}Ni in the spectrum.

Deformed halo structure in ^{31}Ne and ^{37}Mg

The inclusive cross-sections and parallel momentum distribution of single-neutron removal from the very neutron-rich nuclei in an “island of inversion”, ^{31}Ne and ^{37}Mg, on Pb and C targets have been measured at RIBF. A combined analysis of these distinct nuclear- and Coulomb-dominated reaction data shows that the both ^{31}Ne and ^{37}Mg ground states have small separation energy and an appreciable p-wave neutron single-particle strength. We confirm that ^{31}Ne and ^{37}Mg are the heaviest deformed p-wave halo nuclei identified to date.

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 and the exclusive one-neutron removal cross-sections were obtained. The level structure and single-particle nature of the excited states are discussed by comparison with several theoretical model calculations.

Exotic cluster structure in ^{16}C

An invariant mass spectroscopy was performed aiming at search for α-cluster states in ^{16}C populated by α-inelastic scattering at 200 MeV/u. The excitation energies of ^{16}C are reconstructed from invariant mass of $^{16}\mathrm{C} \rightarrow {}^{12}\mathrm{Be} + {}^{4}\mathrm{He}$ decay channel by measuring their four momenta with the SAMURAI spectrometer. Candidates of α-cluster states near the decay threshold energy are found in an excitation energy spectrum.

Missing mass spectroscopy beyond proton drip-line nucleus

The neutron transfer reactions on a radioactive ^{10}C secondary beam were applied to study the nuclear structure of beyond the proton drip-line nucleus, ^{8}C. The recoiling particles of the (p, t) reaction were identified by the Dubna telescope consisting of the double-sided strip silicon detector followed by the CsI scintillators. The excitation energy of ^{8}C was deduced via missing mass method and the differential cross-sections for ground and excited states of ^{8}C were measured for the first time.

5 Wimmer Group

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

Member: K. 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.

Experimental studies are performed at world-leading laboratories, such as the RIBF, RIKEN, the NSCL in the USA or the TRIUMF facility in Canada. Employing different experimental techniques, like knockout and transfer reactions, we will obtain new information on the single-particle wave function composition of exotic nuclei. Complementary studies of Coulomb excitation will result in measures of the collective properties. A combination of different experimental approaches leads to a deeper understanding of the structure of exotic nuclei and allows us to track the evolution of nuclear shell structure towards the drip-lines.

6 Komamiya group

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

Members: Sachio Komamiya, Yoshio Kamiya, Daniel Jeans

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

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In August 2004 it was internationally agreed to use a superconducting RF system as the main linac technology. The Technical Design Report was completed and published in 2013. Since then, ILC design and hardware development have been passed to the Linear Collider Collaboration (LCC) lead by Lyn Evans. The Linear Collider Board (LCB), chaired by Sachio Komamiya, is the 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, a test accelerator system for ILC located at KEK. The Shintake beam size monitor recently measured the world record beam size of 44 nm. We are also studying possible physics scenarios and the large detector concept (ILD) for an experiment at ILC. Since autumn 2012 a staff scientist from UK who is an expert on the silicon electromagnetic calorimeter has joined our group. Since then hardware and simulation studies of silicon-tungsten sandwich electromagnetic calorimeters for ILC detector have been extensively performed.

2) ATLAS experiment at LHC: The epoch of the new paradigm for particle physics is being opened by the experiments at LHC. In July 2012, a Higgs Boson was discovered by the ATLAS and CMS experiments at LHC. We call this the "2012 July Revolution". Our students have been analysing ATLAS data to elucidate the properties of the Higgs Boson. Other students are performing searches for supersymmetric partners of the gluon and partners of electroweak gauge bosons and Higgs bosons. Some of these results have already been published in journals.

3) 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 forces using beams of ultra-cold neutrons (UCN): A detector to measure gravitational bound states of UCNs has been developed. We decided to use CCDs to measure the position of UCNs. The CCD is covered by a layer of ^{10}B to convert neutrons into charged nuclear fragments. The UCNs pass through a neutron guide of height 100 μm in which they form bound states due to their interaction with the earth's gravity, modulating their vertical distribution. In 2008 we tested our neutron detector at ILL Grenoble, where a first test experiment was subsequently performed in 2009. We significantly improved our detector system and performed a full experiment in 2011; the data analysis was completed in 2012. The observed modulations in the UCNs' vertical distribution are in good agreement with the predictions of quantum mechanics, as calculated using the Wigner function. This is the first observation of gravitationally bound states of UCNs with sub-micron spatial resolution. This result was published in PRL. In 2013 we have started a new experiment to search for new short range forces using cold neutron beams scattered off Xe atoms. The experiment was performed in HANARO, KAERI, Korea in 2014. A new world record of the limit on short range forces was established by this experiment and will soon be published in PRL.

7 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

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

Sumico, Tokyo Axion Helioscope, withdrew from the Lab. in March, 2015. Its first result was published in 1998, 7 years before CAST of CERN. We sincerely thank her for her work in state-of-the-art science over the years.

We developed a segmented reactor-antineutrino detector made of plastic scintillators for application as a tool in nuclear safeguards inspection and performed mostly unmanned field operations at 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 measured the difference in reactor antineutrino flux above the ground when the reactor was active and inactive. This was the world's first aboveground antineutrino detection of a nuclear reactor.

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

A larger prototype PANDA64 of 640 kg mass is now ready and was deployed at the Norikura Observatory, located at 2,770 m above sea level, of Institute for Cosmic Ray Research, the University of Tokyo. We observed 12 long duration gamma-ray bursts during the measurement from July through September, 2014.

The bursts observed at Norikura are similar to those observed at Ohi Power Station at sea level, but energy and rate are quite different. While energy is higher at Norikura than at Ohi, rate is lower at Norikura than at ohi to the contrary. It might probably be due to lower air density at Norikura.

We just started a construction of an ultimate 100-module detector, PANDA100 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 tried to realize this kind of hidden photon search experiments in two wavelength bands. Hidden sector photons of $\sim$eV mass have been searched for using an optical concave mirror of 50cm diameter and a photon counting PMT. On the other hand, a dish antenna of 2.2m diameter for Ku-band microwave reception has been used to search for hidden sector photons of lower mass in the range of $\sim 50\mu$eV.

No signal was found in either of the search and upper limits to the mixing parameter χ were set at $\chi < 6 \times 10^{-12}$ and $\chi < 2 \times 10^{-12}$ for the hidden photon mass $m_{\gamma'} = 3.1 \pm 1.2$eV and $m_{\gamma'} \simeq 50\mu$eV, respectively.

8 Aihara & Yokoyama Group

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

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

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

One of the major research activities in our group has been a study of CP-violation and a search for physics beyond the Standard Model in the B meson and the τ lepton systems using the KEK B-factory (KEKB). This past year, we continued a study of Michel parameters of the τ lepton, which is sensitive to physics beyond the Standard Model. Using $\sim$ 900 million $\tau^+\tau^-$ pairs recorded with the Belle detector, we intend to significantly improve the precision of measurement over previous measurements. We also established analysis for an improvement of CP violating parameter, ϕ_3, using $B^- \to D^*K^-$ decays in addition to already analyzed $B^- \to DK^-$ mode.

2. Physics at luminosity frontier: Belle II experiment

The SuperKEKB project started in 2010. The upgraded accelerator, SuperKEKB, will have 40 times more luminosity than KEKB. The Belle detector is also being upgraded as Belle II detector with cutting-edge technology. One of key elements for the success of Belle II will be its Silicon Vertex Detector (SVD) to precisely measure the decay points of B mesons. Our group is responsible for the construction of outer layers of Belle II SVD. This year we established the electrical quality assurance procedures of Belle II SVD ladders. The R&D for the upgrade of the Belle II electromagnetic calorimeter was also carried out.

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

As an observational cosmology project, we have been involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct extensive wide-filed deep survey to investigate weak lensing. This data will be used to develop 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy. This year, 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. Search for proton decays: Super-Kamiokande

Proton decay is the only way to directly probe the Grand Unified Theory, which is an attractive candidate for a model of physics beyond the Standard Model. We have started a study to enhance the sensitivity to proton decay at Super-Kamiokande with an improved event reconstruction.

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

T2K is a long baseline neutrino experiment using J-PARC accelerator complex and Super-Kamiokande, 295 km away. By combining both muon-type and electron-type neutrino interaction events observed at 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 started to take data with anti-neutrino enhanced beam, which will give a direct test of the CP symmetry in the lepton sector when comnined with neutrino-mode data.

In order to improve the systematic uncertainty from neutrino-nucleus interaction cross section, we have designed 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 finalized the design of the detector and developed new scintillator and photosensor (MPPC).

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.

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

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 and Supersymmetry.
  - Higgs: Discovery of Higgs Boson
  - SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.1 and 1.8TeV, respectively.
- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Precise measurement Search HFS of the positronium.
  - Developing high power (>500W) stable sub THz RF source
  - Axion searches using Spring 8
  - $\gamma\gamma$ scatter Using FEL Xray.

10 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Naoto Tsuji

Our main interests are many-body and topological effects in electron and cold-atom systems, i.e., **superconductivity, magnetism and topological phenomena**, for which we envisage a **materials design** and novel **non-equilibrium** phenomena should be realised. Studies in the 2014 academic year include:

- **Superconductivity**
  — High-Tc cuprates: material- and pressure-dependence [1,2]
  — Electron-phonon systems: supersolid and quantum critical point [3]
  — Organic and carbon-based superconductors [1]
  — Fermion and boson systems on flat-band systems
- **Topological systems**
  — Topological Mott insulator designed for cold atoms [4]
  — Topological and chiral properties of graphene and silicene [5-7]
  — Graphene quantum dot
- **Non-equilibrium phenomena**
  — Non-equilibrium dynamical mean field and dynamical cluster theories[8,9]
  — Floquet topological insulator
  — Relaxation in electron-phonon systems [10]
  — Nonequilibrium quantum spin systems[11]
  — Higgs modes in superconductors [12]

[1] H. Aoki and T, Kariyado: Pressure effects and orbital characters in cuprate and carbon-based superconductors, *J. Superconductivity and Novel Magnetism* **27**, 995 (2014).

[2] H. Sakakibara, K. Suzuki, H. Usui, S. Miyao, I. Maruyama, K. Kusakabe, R. Arita, H. Aoki, and K. Kuroki: Orbital mixture effect on the Fermi surface-Tc correlation in the cuprate superconductors — bilayer vs single layer, *Phys. Rev. B* **89**, 224505 (2014).

[3] Y. Murakami, P. Werner, N. Tsuji and H. Aoki: Supersolid phase accompanied by a quantum critical point in the intermediate coupling regime of the Holstein model, *Phys. Rev. Lett.* **113**, 266404 (2014).

[4] S. Kitamura, N. Tsuji and H. Aoki: An interaction-driven topological insulator in fermionic cold atoms on an optical lattice: A design with a density functional formalism, arXiv:1411.3345.

[5] Hideo Aoki and Mildred S. Dresselhaus (eds.): *Physics of Graphene* (Springer-Verlag, 2014).

[6] H. Aoki and Y. Hatsugai: Polarization as a topological quantum number in graphene, *Phys. Rev. B* **90**, 045206 (2014).

[7] Y. Hatsugai, K. Shiraishi and H. Aoki: Flat bands in Weaire-Thorpe model and silicene, *New J. Phys.* **17**, 025009 (2015).

[8] H. Aoki, N. Tsuji, M. Eckstein, M. Kollar, T. Oka and P. Werner: Nonequilibrium dynamical mean-field theory and its applications, *Rev. Mod. Phys.* **86**, 779 (2014).

[9] N. Tsuji, P. Barmettler, H. Aoki and P. Werner: Nonequilibrium dynamical cluster theory, *Phys. Rev. B* **90**, 075117 (2014).

[10] Y. Murakami, P. Werner, N. Tsuji and H. Aoki: Interaction quench in the Holstein model — Thermalization crossover from electron- to phonon-dominated relaxation, *Phys. Rev. B* **91**, 045128 (2015).

[11] S. Takayoshi, H. Aoki and T. Oka: Many-body Floquet theory of laser-induced phase transition in quantum magnets, *Phys. Rev. B* **90**, 085150 (2014).

[12] R. Matsunaga, N. Tsuji, H. Fujita, A. Sugioka, K. Makise, Y. Uzawa, H. Terai, Z. Wang, H. Aoki, and R. Shimano: Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor, *Science* **345**, 1145 (2014); N. Tsuji and H. Aoki: Theory of Anderson pseudospin resonance with Higgs mode in a superconductor, arXiv:1404.2711.

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 of many-body systems

Quantum dynamics under time dependence field is one of the most important subjects in our group. In these years, we have 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 found that under some condition stationary state of a system driven by periodic external field is given by a canonical distribution of Floquet quasi-eiegenstates.[1] We also found that there exists a metastable long-lived state in the relaxation process of a system with driving force.[2]

We also studied quantum dynamics of magnetization under sweeping field in a uniaxial magnetic systems, where we found that the classical spinodal type dynamics is characterized by singular change of gaps at avoided-level crossings. The adiabatic motion in the classical system corresponds to the perfect non-adiabatic transition in quantum system. Moreover, we found a characteristic beating of the spin-amplitude after the critical point. Dependence of the period of the oscillation on the parameters is clarified. [24, 44]

Quantum response to the external field is also interesting problem. We studied topics of the electron spin resonance (ESR). We analyzed very detailed experimental observations on the single molecular magnet V_{15} and clarified the nature of anisotropy of the system.[3] We also study the ESR of the antiferromagnet on the kagome lattice.[4] Moreover, we have proposed a new scheme of the numerical method for ESR by making use of the Wiener-Khinchin relation.[40]

Cooperative Phenomena and Phase Transitions

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

We studied nature of phase transition of an Ising model on the so-called small-world network. It is known that the system exhibits a phase transition of the mean-field universality class. We confirmed this property. We found that the system does not show metastability below the critical temperature. The infinite-range (Husimi-Temperley) model has the mean-field type phase transition and the model also shows the thermodynamically metastable state and exhibits the spinodal transition as a dynamical phase transition. We characterized its deterministic relaxation curve.[14] We also have studied phase transitions in systems with bistable local electric states, such as the spin-crossover, Jahn-Teller system, and martensite systems.They attract interests as seminal candidates of the so-called functional material because the bistable states can be switched by the temperature, pressure, magnetic field, and photo-irradiation. We studied phase transitions in a system with various types of short-range interactions. In particular, we studied the ANNNI model which seems realized in a material: $[FeH_2L^{2-Me}](ClO_4)_2$.[26] We also studied the effective long range interaction due to difference of local bistable structures of unit cell of the lattice. We clarified dependence of nucleation on shape of the system.[8] We also found that critical property of antiferromagnet on the triangular lattice with next nearest neighbor interaction (Mekata model) is changed by the elastic interaction.[25, 45] We studied fundamental properties of statistical mechanism for the long-range interacting model.[12] We also studied mechanisms of coercive forth of real magnets, joining to the project 'The Elements Strategy Initiative Center for Magnetic Materials'. We have formulated the temperature effect in the LLG (Landau-Lifshitz-Gilbert) equation, and we studied the stability of the metastable magnetic structure at finite tempertures.[9, 30, 31, 32] Quantum phase transition of an itinerant ferromagnetism is studied, too. In the model, the system exhibits both the Mott singlet and Nagaoka ferromagnetic state under a continuous control of the electron density profile.[10]

Stochastic process

Duncl process is a diffusion process replacing the thermal kernel by the so-called Duncl operator. One of the Duncl process is Brownian motion of particles interacting with long range force. We have studied dynamics of the distribution of the particles from a view point of the intertwining operator. We found characteristics of the relation from a given initial state to the stationary state.[11]

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, organic conductors, Dirac electron systems in solids, topological materials, 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 in high-T_c superconductivity.
- Dirac electron systems in solids
  Spin-Hall effects and large diamagnetism in Dirac fermion systems.[1,2]
  Meissner effects in the superconducting states in Dirac electron systems.[3]
  Anomalous Hall effects in Dirac systems.
- Organic conductors
  Effect of tilting on the magnetoconductivity of Dirac electrons in organic compounds.[4]
  Zero-energy localized state induced by impurity in Dirac electron system of organic conductor.[5]
- Theories on topological materials
  Effects of long-range Coulomb interaction in the surface states of topological insulators.[6]
  Definitions of spin current in quantum transport equations.
  Relationship between fractal and quantum Hall coefficients.
- Theories on heavy fermion systems and multi-band electron systems
  Quasiparticles in f^2-configuration.
  Charge Kondo effect.
  Spin Hall effects in the multi-orbital systems with parity violation.[7]

- Chiral magnets and spin-orbit interaction
  Effective model and Dzyloshinskii-Moriya interaction for chiral magnet.[8]
  Superexchange interactions from the j-j coupling.[9]
  Dynamics of chiral solitons and antiferromagnetic domain walls.

[1] Y. Fuseya, M. Ogata, and H. Fukuyama: (invited review article) J. Phys. Soc. Jpn. **84**, 012001-1-22 (2015). "Transport Phenomena and Diamagnetism of Dirac Electrons in Bismuth"

[2] Y. Fuseya, M. Ogata, and H. Fukuyama: J. Phys. Soc. Jpn. **83**, 074702-1-11 (2014). "Spin-Hall Effect and Diamagnetism of Anisotropic Dirac Electrons in Solids"

[3] T. Mizoguchi and M. Ogata: submitted to J. Phys. Soc. Jpn. "Meissner effect of Dirac electron in superconducting state"

[4] I. Proskurin, M. Ogata, and Y. Suzumura: to appear in Phys. Rev. B. "Longitudinal conductivity of massless fermions with tilted Dirac cone in magnetic field"

[5] T. Kanao, H. Matsuura, and M. Ogata: in preparation. "Localized State of Massless Dirac Fermions in Quasi-Two-Dimensional Organic Conductor α-(BEDT-TTF)$_2$I$_3$ Induced by Singlet Defect"

[6] N. Okuma and M. Ogata: J. Phys. Soc. Jpn. **84**, 034710-1-4 (2015). "Long-Range Coulomb Interaction Effects on the Surface Dirac Electron System of a Three-Dimensional Topological Insulator"

[7] T. Mizoguchi and N. Arakawa: submitted to Phys. Rev. B. "Controlling spin Hall effect by using a band anticrossing and nonmagnetic impurity scattering"

[8] H. Matsuura, T. Shishidou, and M. Kishine: in preparation. "Derivation of Dzyloshinskii-Moriya Interaction on Metallic Chiral Magnet $CrNb_3S_6$"

[9] H. Matsuura and M. Ogata: J. Phys. Soc. Jpn. **83**, 063701-1-4 (2014). "A Poorman's Derivation of of Quantum Compass-Heisenberg Interaction: Superexchange Interaction in J-J Coupling Scheme"

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.

One of the important achievements in FY2014 is the development of a scheme for calculating lattice themal conductivity of materials from first principles. In the simulation of thermal physics, where spaciotemporal fluctuation of the atomic structure is so large, we need careful modeling and long-time/large-scale simulation of the atomic motion to get statistically meaningful results. This is a hard requirement for first-principles simulations, firstly because the computational cost of the electronic structure calculation usually scales as N^3 with N being the number of electrons, and secondly because it is essentially impossible to parallelize the dynamical simulation due to causality. In order to overcome the difficulty, we have developed an efficient scheme of modeling anharmonic interaction between atoms from first principles, with which we succeeded in accurate calulation of thermal conductivity in cluding cubic $SrTiO_3$ dynamically stabilized at high temperature.

We are also developing various schemes for first-principles simulation and are applying them to the study of structural, electronic and thermal properties of materials. Our research subjects in FY2014 were as follows:

- New methods of first-principles calculation of material properties

  - A scheme for calculating lattice themal conductivity of materials from first principles
  - First-principles wavefunction theory for solids based on the transcorrelated method and its connection to the diffusion Monte Carlo method
  - A new method for electronis structure calculation of large systems based on a divide and conquer method
  - A new efficient method to find potential energy minima in configuration space
- Applications of first-principles calculation
  - Superconductivity in compressed H_2S
  - Superconductivity in YNi_2B_2C
  - Interfaces in $Nd_2Fe_{14}B$ sintered magnet
  - Magnetic properties of ε-Fe_2O_3
  - Theoretical design of perovskite-type oxy-hydrides

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 simulation

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

Quantum Monte Carlo level spectroscopy: we have formulated a convergent sequence for the energy gap estimation in the worldline quantum Monte Carlo method. Our estimation will be unbiased in the low-temperature limit and also the error bar is correctly estimated in general. The level spectroscopy from quantum Monte Carlo data is developed as an application of the unbiased gap estimation. From the spectral analysis, we precisely determine the Kosterlitz-Thouless quantum phase-transition point of the spin-Peierls model.

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.

Quantum phase transition of SU(N) J-Q model: by using the parallelized loop cluster algorithm for the SU(N) J-Q model, which is proposed as a candidate that exhibits the deconfined critical phenomena, we have studied its critical phenomena and found a systematic drift of the critical exponents as the system size increases. We have investigated the finite-temperature phase transition of the J-Q models on square and honeycomb lattices precisely.

Development of new simulation algorithms for quantum many body systems

Tensor-network algorithms: we have applied the PEPS and corner transfer matrix renormalization group technique to the J_1-J_2 Heisenberg antiferromagnet. We have developed the analysis method based on the convergence of imaginary time evolution of tensors.

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

Simulation method for systems with strong spatial anisotropy: we have developed a generic method that can automatically optimize the aspect ratio of the system by the combination of the quantum Monte Carlo method and the machine learning technique, and applied to the two-dimensional Bose-Hubbard model with dynamical exponent $z > 1$.

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

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

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) magnetism in the Bose/Fermi Hubbard model, and (iii) quantum entanglement in exactly solvable 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 2014 are the following:

- Strongly correlated systems
  - Topological order in interacting Kitaev/Majorana chains [1]
  - RVB ground states of the Hubbard model on Δ chains
  - Magnetism in the spin-1 & spin-2 Bose-Hubbard models
  - Thermal Hall effect of magnons in insulating magnets
- Solvable/Integrable systems
  - Composite kink solutions of coupled nonlinear Klein-Gordon equations [2]
  - Integrable matrix product operators related to the spin-1/2 Heisenberg chain [3]
  - Sine-square deformation and supersymmetric quantum mechanics

[1] Hosho Katsura, Masahiro Takahashi, and Dirk Schuricht, in preparation.

[2] Hosho Katsura, Phys. Rev. D, **89**, 085019 (2014).

[3] Hosho Katsura, J. Stat. Mech., P01006 (2015).

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 using high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy (ARPES) and soft x-ray magnetic circular dichroism (XMCD) using synchrotron radiation. We investigate the mechanisms of high-temperature superconductivity [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.

[1] T. Yoshida, S. Ideta, T. Shimojima, W. Malaeb, H. Suzuki, I. Nishi, A. Fujimori, S. Shin, Y. Nakashima, H. Anzai, M. Arita, A. Ino, H. Namatame, M. Taniguchi, K. Ono, S. Kasahara, T. Shibauchi, T. Terashima, Y. Matsuda, M. Nakajima, S. Uchida, Y. Tomioka, T. Ito, K. Kihou, C.H. Lee, A. Iyo, H. Eisaki, H. Ikeda, and R. Arita: Anisotropy of the superconducting gap in the iron-based superconductor $BaFe_2(As_{1-x}P_x)_2$, Sci. Rep. **4**, 7292–1-6 (2014).

[2] G. Shibata, K. Yoshimatsu, E. Sakai, V. R. Singh, V. K. Verma, K. Ishigami, T. Harano, T. Kadono, Y. Takeda, T. Okane, Y. Saitoh, H. Yamagami, A. Sawa, H. Kumigashira, M. Oshima, T. Koide, and A. Fujimori: Thickness-dependent ferromagnetic metal to paramagnetic insulator transition in $La_{0.6}Sr_{0.4}MnO_3$ thin film studied by x-ray magnetic circular dichroism, Phys. Rev. B **89**, 235123–1-5 (2014).

[3] H. Suzuki, K. Zhao, G. Shibata, Y. Takahashi, S. Sakamoto, K. Yoshimatsu, B. J. Chen, H. Kumigashira, F.-H. Chang, H.-J. Lin, D. J. Huang, C. T. Chen, Bo Gu, S. Maekawa, Y. J. Uemura, C. Q. Jin, and A. Fujimori1: Photoemission and x-ray absorption studies of the isostructural to Fe-based superconductors diluted magnetic semiconductor $Ba_{1-x}Kx(Zn_{1-y}Mn_y)_2As_2$, Phys. Rev. B **91**, 140401(R)–1-5 (2015).

17 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA, Akari TAKAYAMA, and Ryota AKIYAMA

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

(1) Surface electronic/spin transport:

- Detection of superconductivity in giant Rashba spin-split surface states
- Detection of spin Hall effect on $Bi_2Se_3(111)$ surface by using *in situ* FIB-fabrication and four-tip STM
- Detection of circular dichroism in photocurrent due to spin-split surface states
- Detection of Quasi-one-dimensional electronic transport on Si(110)-2×5-Au surface
- Detection of Surface-bulk coherent transport in Bi ultrathin films

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

- Detection of semimetal-to-semiconductor transition in Bi ultrathin film
- Detection of magnetic proximity effect at topological insulator/magnetic material interface

(3) Construction of new apparatuses:
- Low-temperature strong-magnetic-field scanning tunneling potentiometery
- Spin-dependent scattering of He ion beam by Bi ultrathin films
- Improvements in a combined UHV system of focused ion beam, four-tip STM, SEM and RHEED-MBE

[1] M. Aitani, T. Hirahara, S. Ichinokura, M. Hanaduka, D. Y. Shin, S. Hasegawa:*In situ Magnetotransport Measurements of Ultrathin Bi films: Evidence for a Surface-Bulk Coherent Transport*, Phys. Rev. Lett. **113**, 206802 (Nov, 2014).

[2] T. Shirasawa, M. Sugiki, T. Hirahara, M. Aitani, T. Shirai, S. Hasegawa, and T. Takahashi: *Structure and transport properties of Cu doped Bi_2Se_3 films*, Phys. Rev. B **89**, 195311 (May, 2014).

[3] T. Shirai, T. Shirasawa, T. Hirahara, N. Fukui, T. Takahashi, and S. Hasegawa: *Structure Determination of Multilayer Silicene Grown on Ag(111) films by Electron Diffraction: Evidence for Ag Segregation at the Surface*, Phys. Rev. B **89**, 241403(R) (Jun, 2014).

[4] N. Fukui, R. Hobara, T. Hirahara, Y. Miyatake, H. Mizuno, T. Sasaki, T. Nagamura, and S. Hasegawa: *In-situ Micro-fabrication and Measurements of Bi_2Se_3 Ultrathin Films in a Multi-chamber System having Focus Ion Beam, Molecular Beam Epitaxy, and Four-Tip Scanning Tunneling Microscope*, e-J. Surf. Sci. Nanotech. **12**, 423 (Oct, 2014).

[5] R. Sakamoto, T. Kambe, T. Kusamoto, T. Pal, N. Fukui, T. Shimojima, Z. Wang, T. Hirahara, K. Ishizaka, S. Hasegawa, F. Liu, and H. Nishihara: *Redox control and high conductivity of nickel bis(dithiolene) complex π-nanosheet, a candidate of the first organic topological insulator*, J. Am. Chem. Soc. **136** (41), 14357 (Sep, 2014).

[6] S. Ichinokura , T. Hirahara, S. Hasegawa, O. Sakai and T.T. Suzuki: *Electron-spin dependent $^4He^+$ ion scattering on Bi surfaces*, Radiation Effects and Defects in Solids **169** (12), 1003 (Nov, 2014) .

[7] T.T. Suzuki, O. Sakai, S. Ichinokura , T. Hirahara, and S. Hasegawa: *Target element dependent spin-orbit coupling in polarized $^4He^+$ ion scattering*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms (Dec, 2014) DOI:10.1016/j.nimb.2014.11.055.

[8] A. Takayama, T. Sato, S. Souma, and T. Takahashi: *Rashba effect of bismuth thin film on silicon studied by spin-resolved ARPES*, Journal of Electron Spectroscopy and Related Phenomena (Nov, 2014 online).

[9] A. Takayama, T. Sato, S. Souma, T. Oguchi, and T. Takahashi, *One-Dimensional Edge States with Giant Spin Splitting in a Bismuth Thin Film*, Phys. Rev. Lett. **114**, 066402 (Feb, 2015).

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

1. **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 freezed even at $T = 0$. Two dimensional ^{3}He is one of a promising candidate which shows the QSL state as magnetic ground state because of 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 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 $|J_\mathrm{P}|$ for 2D ^{3}He on bilayer HD than on ^{3}He and ^{4}He. The T-dependence of the heat capacity for ^{3}He/HD/HD/gr shows a single broad peak at $T \approx 20$ mK different from the double peak feature for ^{3}He/^{4}He/gr and ^{3}He/^{3}He/gr. In addition, the heat capacity is found to change depending on $T^{2/3}$ in wide temperature range of $0.35 < T < 7$ mK. This T-dependence is surprising because it is different from other candidates for QSL such as 2D ^{3}He on either ^{3}He or ^{4}He and materials with frustrated electron spin system, which show $C \propto T$. 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 structual properties, and its possible applications in many emerging fields such as graphene-based electronic devices. However, graphene itself is not proper enough to apply to electronic devices because of its linear energy dispersion crossing at the Dirac point, i.e. the charge neutrality point. It is one of the important subjects to study, how to induce a band gap in graphene. So far, many possibilities are proposed and, among them, we are focuing on a mechanism to break the chiral symmetry of graphene by decorating with atoms/molecules. For example, it is theoretically expected that the band gap can be induced when atoms are adsorbed on graphene to form $(\sqrt{3} \times \sqrt{3})$R30° structure. To verify this possibility, we use Kr atom as an adsorbate, because Kr atom is confirmed to form $(\sqrt{3} \times \sqrt{3})$R30° structure on the surface of graphite by our STM measurement.

The gate-voltage (V_g) dependence of the resistance of graphene, which is prepared on the surface of SiO_2/Si by exfoliating graphite, was studied with various areal densities of Kr and at various temperatures down to 1.6 K. However, no change had been observed. This is possibly because the modification by adsorbates is hindered due to the substrate. One can easily expect that the charges are transferred from the substrate, and the roughness of the substrate can also change the electronic transport property of graphene. It is also observed in our STM measurements that Kr atoms slip in between graphene and the substrate in the case of graphene synthesised on SiC.

Therefore, we prepared graphene which is free from the substrate. The V_g-dependence of graphene resistance show two peaks, which can be clearly asigned to the peak for free-standing graphene and for graphene supported by substrate. The effect of adsorbate is expected to be observed by using such free-standing graphene.

The other important topic 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 such state experimentally by STM/S at a monatomic step edge of graphite. Moreover, it is expected that the spin degeneracy would be lifted and ferromagnetically spin polarized edge state appears under an electron-electron interaction. The ferromagnetic edge state is considered to stabilize in a nano-ribbon between two zigzag edges (zigzag nanoribbon) through anti-ferromagnetic interaction between edges.

To obtain such zigzag edges, we tried hydrogen-plasma etching of graphite surfaces. By exposing graphite to hydrogen-plasma under high temperatures, hyxagonal pits with monatomic depth are found to be created. The size and the density of the pit 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 pit are found to be aligned to the zigzag direction. Therefore, one can obtain zigzag nanoribbon in betweeen two hexagonal pits, where the spin poralized zigzag edge state can be expected to observe by STM/S measurment.

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.

   In 2014, 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, the Altshuler–Aronov correlation gap is observed in the spatially averaged DOS at 0 T.

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 2014, in order to perform tunneling spectroscopy measurements, several layers of Sb were used for superconducting one-atomic-layer Pb films as a capping layer. The superconducting transition was observed after the thermal annealing in the air at 300 K. In the next step, the formation of a tunneling barrier is necessary for the tunneling spectroscopy measurement.

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. In order to investigate the role of electron and/or spin correlations in the excited states as well as the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1THz$\sim$4meV) frequency range where quasi-particle excitations and various collective excitations exist. The research summary in this year is as follows.

1. **High density electron-hole system in semiconductors:** We have investigated high density excitation pheomena in an indirect gap semiconductor Ge, and in a direct gap semiconductor GaAs. In Ge, we have observed that the exciton 1s-2p energy hardly changes upon the exciton Mott transition. Combined with the previuos results in Si, we concluded that the robust exciton correlation against the screening is a generic character in photoexcited electron-hole(e-h) systems in semiconductors. In GaAs, we have investigated the exciton Mott transiton caused by the resonant excitation of excitons.

We found that, even in th ehigh density regime where the mean distance between e-h pairs approaches the exciton Bohr radius, the optical conductivity spectrum of the photoexcited e-h system significantly deviates from that of Drude model, indicating a strong excitonic correlation in the e-h metallic phase.

2. **Higgs amplitude mode in a BCS superconductor $Nb_{1-x}Ti_xN$:** We investigated the Higgs amplitude modein s-wave BCS superconductor $Nb_{1-x}Ti_xN$ under the intense irradiation of terahertz pulse. We found that when the pump frequency is tuned below the superconducting gap 2Δ, the order parameter oscillates at the twice of the incident frequency. When the pump freqeuncyω matches with Δ, the amplitude of the order paramter oscillation significantly enhances, resulting in an efficient third harmonic generation from the superconducting film samples. The observed phenomena are well described by the Anderson's pseudospin model, and the results are interpreted as the indication of nonlienar resonant coupling betwee the Higgs mode and the radiation field.

3. **Nonlinear Faraday effect in graphene:** We extended our recent observation of quantum Faraday effect in graphene into the nonlinear optics regime. Faraday rotation angle is largely supresses, when the incident electric field exceeds a critical value. the results are accounted for by the dynamical reduction of effective magnetic field which phenomenon is expected to occur in the 2-dimensional electron system with Lorenz-invariance.

References

[1] Ryusuke Matsunaga, Naoto Tsuji, Hiroyuki Fujita, Arata Sugioka, Kazumasa Makise, Yoshinori Uzawa, Hirotaka Terai, Zhen Wang, Hideo Aoki, and Ryo Shimano: Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor, Science. **345**, 1145 (2014).

[2] Fumiya Sekiguchi and Ryo Shimano: Excitonic correlation in the Mott crossover regime in Ge, Phys. Rev. B **91**, 155202 (2015).

21 Takagi-Kitagawa Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kentaro Kitagawa, Daigoro Hirai

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2014 included, 5d complex Ir oxides with interplay of electron correlations and strong spin orbit coupling, anti-perovskites with Dirac electrons and layered Ta_2NiSe_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 ferromagnetic moment suddenly disappear, suggestive of the emergence of some kind of liquid state.

Fabrication of (111)-oriented $Ca_{0.5}Sr_{0.5}IrO_3/SrTiO_3$ superlattice; a designed playground for honeycomb physics:

We fabricated (111)-oriented superlattice structures with alternating $2m$-layers ($m = 1$, 2, and 3) of $Ca_{0.5}Sr_{0.5}IrO_3$ perovskite and two layers of $SrTiO_3$ perovskite on $SrTiO_3(111)$

substrate. In the case of $m = 1$ bilayer film, Ir sub-lattice is a buckled honeycomb, where a topological state may be anticipated. The successful growth of superlattice structure on atomic level along [111] direction was clearly demonstrated by the superlattice reflections in x-ray diffraction patterns and by the atomically-resolved transmission electron microscope image. The ground states of the superlattice films were found to be a magnetic insulator, which may suggest the importance of electron correlations in Ir perovskite in addition to much discussed topological effect.

Excitonic Insulator Transition in a Zero-Gap Semiconductor Ta_2NiSe_5:

Excitonic insulator is a long conjectured correlated electron phase of narrow gap semiconductors and semimetals, driven by weakly screened Coulomb interaction between electrons and holes. While having been proposed more than 50 years ago, conclusive experimental evidence for its existence remains yet elusive. A key candidate compound is a layered transition metal selenide Ta_2NiSe_5, which has an almost zero one-electron band gap E_G and hosts a putative excitonic insulator phase below T_c = 326 K. Optical, transport and thermodynamic data on Ta_2NiSe_5 demonstrated the opening of an excitation gap $2\Delta E \sim 0.3$ eV below T_c which yields $2\Delta E/k_B T_c \sim 12$ and is comparable to an estimate of exciton binding energy E_B of a few tenth eV. E_G was controlled by chemical and physical pressures. Suppression of T_c was observed both by decreasing or increasing E_G, indicative of a dome-like behaviour of T_c - E_G relation. These results are fully consistent with that an excitonic insulator is realized below T_c =326 K in a zero-gap semiconductor Ta_2NiSe_5.

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;

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 (Associate Professor [full professor since Jan. 2015]), Akihito Soeda (Assistant Professor), two postdoctoral fellows – Fabian Furrer (JSPS foreign postdoctoral fellow) and Shojun Nakayama –, a visiting Ph.D student Adel Sohbi, and 8 graduate students, Eyuri Wakakuwa (D3), Seiseki Akibue (D2), Kotaro Kato (D1), Jisho Miyazaki (D1), Yuki Mori (M2), Atsushi Shimbo (M2), Ryosuke Sakai (M1), and Hayata Yamasaki (M1). We investigate several aspects of theoretical quantum information. Our projects worked in the academic year of 2014 were the following:

- Causality, parallelizability, and nonlocality in quantum computation
  - Parallelizability of the adiabatic gate teleportation and implementability of the dynamics of the time-reversed Hamiltonian by K. Nakago, S. Nakayama, and M. Murao in collaboration with M. Hajdušek at Singapore University of Technology and Design
  - Causal order and parallelizability of measurement-based quantum computation by J. Miyazaki and M. Murao in collaboration with M. Hajdušek at Singapore University of Technology and Design
  - Globalness of separable maps characterized by classical correlations without globally causal structure by S. Akibue and M. Murao in collaboration with M. Owari and G. Kato at NTT Communication Science Laboratories
- Distributed quantum computation
  - Resource compression for LOCC implementations of bipartite unitary gates by E. Wakakuwa, A. Soeda, and M. Murao

  - Entanglement convertibility of multipartite quantum states and an operational interpretation of the Kraus-Cirac number of two-qubit unitaries by A. Soeda, S. Akibue, and M. Murao
  - Implementability of unitary operations over the butterfly, grail and cluster networks with free classical communication by S. Akibue and M. Murao
  - Encoding classical information onto quantum state by local operations by A. Shimbo, A. Soeda, and M. Murao
  - An efficient preparation of a multipartite entangled state on a quantum network by H. Yamasaki, A. Soeda, and M. Murao
  - Description of composite quantum systems in a topos theoretic approach by J. Miyazaki, A. Soeda, and M. Murao

- Entanglement theory
  - Markovianizing cost of tripartite quantum states by E. Wakakuwa, A. Soeda, and M. Murao
  - Entanglement theory for anyonic systems by K. Kato and M. Murao in collaboration with F. Furrer at NTT Basic Research Laboratories
  - Numerical analysis of the geometric measure of entanglement by Y. Mori, A. Soeda, and M. Murao

- Quantum algorithms
  - Implementation of projective measurement of energy by S. Nakayama, A. Soeda, and M. Murao
  - Quantum algorithms for simulation of imaginary-time dynamics by R. Sakai, A. Soeda, and M. Murao

- Continuous variable quantum cryptography by F. Furrer in collaboration with: J. Duhme, T. Franz and R.F. Werner at Leibniz University Hannover; C. Pacher at Austrian Institute of Technology; and T. Eberle, V. Haendchen and R. Schnabel at Albert Einstein Institute Hannover

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 FY2014 below.

- Quantum many-body phenomena in ultracold atoms
  - Phase diagram of two-component Bose gases in antiparallel magnetic fields [1]
  - Quantum mass acquisition in spinor Bose-Einstein condensates [4]
  - Onset of a limit cycle and universal three-body parameter in Efimov physics [5]
- Quantum Information, Quantum Measurement, and Foundation of Statistical Mechanics
  - Nonequilibrium equalities in absolutely irreversible processes [2]
  - General achievable bound of extractable work under feedback control [3]
  - The second law of thermodynamics under unitary evolution and external operations [6]
  - Relative-entropy conservation law in quantum measurement [7]

[1] S. Furukawa and M. Ueda, Phys. Rev. A **90**, 033602 (2014).

[2] Y. Murashita, K. Funo, and M. Ueda, Phys. Rev. E **90**, 042110 (2014).

[3] Y. Ashida, K. Funo, Y. Murashita, and M. Ueda, Phys. Rev. E **90**, 052125 (2014).

[4] N. T. Phuc, Y. Kawaguchi, and M. Ueda, Phys. Rev. Lett. **113**, 230401 (2014).

[5] Y. Horinouchi and M. Ueda, Phys. Rev. Lett. **114**, 025301 (2015). Editors' Suggestion.

[6] T. N. Ikeda, N. Sakumichi, A. Polkovnikov, and M. Ueda, Annals of Physics **354**, 338 (2015).

[7] Y. Kuramochi and M. Ueda, Phys. Rev. A **91**, 032110 (2015).

25 Makishima Group & Nakazawa Group

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

Member: Kazuo Makishima, Kazuhiro Nakazawa

Using space-borne instruments such as *Suzaku* and *MAXI*, we study cosmic high-energy phenomena in the X-ray and γ-ray frequencies. We have been deeply involved in the development of the Hard X-ray Detector (HXD) onboard *Suzaku* (now in orbit), and are developing new instruments for its follow-up mission, *ASTRO-H*, to be launched in late JFY 2015.

Neutron Stars (NSs) and Super-Nova Remnants (SNRs): We conduct *Suzaku* studies of NSs with various magnetic field strengths, B. Our research targets include X-ray bursters with $B < 10^9$ G, canonical pulsars with $B \sim 10^{12}$ G exhibiting electron cyclotron resonances, long-period pulsars possibly with $B \sim 10^{13}$ G [3], and "magnetars" supposed to have $B = 10^{14-15}$ G. Through an apparent age discrepancy between a magnetar and an SNR associated to it, we reinforced the view that magnetars are indeed losing its magnetic energy [4]. From one magnetar, free precession was detected, and was interpreted as evidence for NS deformation by very high toroidal magnetic fields reaching 10^{16} G [1]. Mass accretion geometry to weakly magnetized ($B < 10^9$ G) neutron star is also studied in detail (e.g. [2]).

Mass Accreting Black Holes: Mass accretion onto black holes provides an efficient way of X-ray production. In active galactic nuclei (massive black holes), our new variability-assisted spectroscopy technique revealed that the primary X-ray emission in fact consists of two distinct components, digging into the geometry of their "central engines". We are also studying sources with luminosity too large as a well known "stellar mass" black hole ($\sim 10\ M_\odot$), trying to look for ones with intermediate mass (100-1000 $M_\odot$).

Clusters of Galaxies: Cosmic large scale structure is evolving via gravity. Cluster of galaxies is located at their hub, forming the largest self-gravitating objects in the universe. We found an excellent example of merging cluster at its early merger phase, very near to our galaxy. It shows clear shock signature, expanding out to Virial radius in almost linear geometry [5]. It provides us the clue to understand poorly known mechanisms of energy dissipation within the vast hot plasma, and is a good target for *ASTRO-H*.

GROWTH (Gamma-Ray Observation of Winter Thunder clouds) experiment: This is a semi-automated gamma-ray experiment placed at Kasiwazaki, Niigata, to watch for bursts of gamma-rays from winter thunderclouds. In the 2014 winter season, we commissioned a new detector with moderate angular resolution. Thanks to its large stopping power and "bad" weather in this season, we obtained 8 new events. Compared to 12 events detected in past 8 years, the event rate was very high. Detailed analysis is on-going.

Future Instrumentation: In collaboration with many domestic and foreign groups, we are developing a successor to *Suzaku*, *ASTRO-H*. The satellite will conduct hard X-ray imaging observations, high-resolution X-ray spectroscopy, and low-energy gamma-ray observations. We contribute to the development of two on-board instruments, the Hard X-ray Imager and the Soft Gamma-ray Detectors, both made of Si/CdTe semiconductor detector and BGO scintillators. This year we achieved inportant milestone: finished developing the flight-detectors and handed them over to the satellite. Pre-launch satellite system level verification will continue through out the year 2015, followed by the lunch using H-IIA rocket.

1. Makishima, K., Enoto, T., Hiraga, J.S., Nakano, T., Nakazawa, K., Sakurai, A., Sasano, M. & Murakami, H.: "Possible Evidence for Free Precession of a Strongly Magnetized Neutron Star in the Magnetar 4U 0142+61", *Phys. Rev. Lett.* **112**. id.171102 (2014)
2. Zhang, Z., Makishima, K., Sakurai, S., Sasano, M., & Ono, K.: "Probing the Accretion Scheme of the Dipping X-ray Binary 4U 1915-05 with Suzaku" , *Publ. Astron. Soc. Japan* **66**, id.120 (2014)
3. Sasano, M., Makishima, K., Sakurai, S., Zhang, Z. & Enoto, T.: "Suzaku View of the Neutron Star in the Dipping Source 4U 1822−37", *Publ. Astron. Soc. Japan* **66**, id.35 (2014)
4. Nakano, T., Murakami, H., Makishima, K., Hiraga, J.S., Uchiyama, H., Kaneda, H., Enoto, T., : "Suzaku studies of the supernova remnant CTB 109 hosting the magnetar 1E 2259+586", *Publ. Astron. Soc. Japan* **67**, id.912 pp.
5. Kato, Y., Nakazawa, K., Gu, L., Akahori,T., Takizawa, M., Fujita, Y., & Makishima, K., : "Discovery of a nearby early-phase major cluster merger CIZA J1358.9-4750", *Publ. Astron. Soc. Japan* **67**,in press (2015)

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 FY2014, 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). Plasma current ramp-up up to 18 kA has been achieved so far. It was also found that the achieved maximum plasma current was strongly correlated with the toroidal magnetic field. It is probably necessary to increase the toroidal field coil power supply for further current ramp-up. COMSOL was used to perform full-wave modeling of the LHW antenna and to optimise the limiter location. The launched spectrum of the parallel index of refraction ($n_\parallel$) was shown to improve if the limiter was extended radially by 30 mm.

The radial profile of the hard X-ray emitted by lower hybrid driven fast electrons was observed using a 5-channel NaI scintillator array. Copper impurity was observed in correlation with the LHW power injection which was likely from the CCC antenna current straps made out of copper. Substantial plasma flow was expected in plasmas started up non-inductively when fast electrons are present. CIII radiation was observed on TST-2 and LATE. The observed toroidal flow was 1 km/s and 5 km/s, respectively, which was much smaller than the expected value of several tens of km/s. It was found in these experiments that the ion orbit loss may also be significant, which may have canceled the radial electric field generated by fast electron loss.

A ray-tracing code GENRAY was used to investigate the optimum poloidal launch angle of the LHW. The top-launch was found to be favorable for the TST-2 geometry due to strong upshift of $n_{\parallel}$. We are now developing a top-launch antenna in collaboration with General Atomics.

Inductively formed TST-2 plasmas were studied using a probe capable of measuring the fluctuations of flow, electric and magnetic fields simultaneously. It was confirmed that the background electric field and the flow measured by the probe satisfy the equilibrium condition.

Pressure anisotropy during internal reconnection events (IREs) were measured using a double-pass Thomson scattering system. Anisotropic temperature was observed after the IRE crash.

A Rogowski probe was used to measure the local current density in the edge plasma. The effect of the sheath inside the probe is being investigated numerically and experimentally. The probe was also installed in UTST to measure current sheet during magnetic reconnection.

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

As a collaboration, Thomson scattering of RF driven steady-state plasmas is being developed on the QUEST spherical tokamak at Kyushu University. This fiscal year, a laser pulse timing system was developed to improve the time resolution of the system.

ICRF (ion cyclotron range of frequencies) waves in LHD plasmas were measured using a microwave reflectometer. The system was extended for two microwave frequencies. Full-wave simulation of ICRF waves was also performed using AORSA developed at Oak Ridge National Laboratory (US). Quantitative analysis of reflectometer measurements will be performed.

A new RF magnetic probe was continued to be developed for measurements of LHW at 4.6 GHz on Alcator C-Mod at MIT. Full-wave modeling of the probe was performed using COMSOL, and the probe geometry was determined so that there is no resonance close to 4.6 GHz. The fabricated probe was tested by measuring the wave magnetic field in a waveguide. It was confirmed that the frequency response was flat around 4.6 GHz. The LHW measurement will be performed using this probe in the next fiscal year.

27 Sano Group

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

Member: Masaki Sano, Kazumasa Takeuchi

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

1. Macroscopic systems out of equilibrium
   (1) Universality in turbulent transition
   (2) Universal fluctuations of growing interfaces probed in turbulent liquid crystal [2]
   (3) Initial condition dependency of the universality in growing interfaces of turbulent liquid crystal
   (4) Lehmann effect of cholesteric liquid crystal as thermo-mechanical coupling by temperature gradient [9]
   (5) Reversible-irreversible transition in low-Reynolds fluid with non-Brownian particles and its rheology

2. Microscopic systems out of equilibrium
   (1) Stochastic thermodynamics in out-of-equilibrium systems [1, 8]
   (2) Information thermodynamics of small systems [7]

3. Active matters
   (1) Self-propelled liquid droplets [11]
   (2) Collective motion and nematic ordering of self-propelled particles
   (3) Collective motion and pattern formation of microtubules as self-propropelled filaments

4. Biological systems
   (1) Collective motion of neural stem cells
   (2) Information thermodynamics on causal networks and its application to biochemical signal transduction [12].

References

[1] K. Kawaguchi, S. -i. Sasa and T. Sagawa: Nonequilibrium dissipation-free transport in F1-ATPase and the thermodynamic role of asymmetric allosterism, Biophysical Journal, **106**, 2450-2457, (2014).

[2] I. S. S. Carrasco, K. A. Takeuchi, S. C. Ferreira and T. J. Oliveira: Interface fluctuations for deposition on enlarging flat substrates, New J. Phys., **16**, 123057 (2014).

[3] T. Ohta and S. Yamanaka: Traveling bands in self-propelled soft particles, Euro. Phys. J. Special Topic (D&D), **223**, 1279-1291 (2014).

[4] T. Ohta and S. Yamanaka: Discussion notes: Soliton-like behavior of traveling bands, Euro. Phys. J. Special Topic (D&D), **223**, 1417-1418 (2014).

[5] T. Sakaue, K. Shitara and T. Ohta: Dynamics and electrorheology of sheared immiscible fluid mixtures, Phys. Rev. E, **89**, 052301(1-7) (2014).

[6] S. Yamanaka and T. Ohta: Collision dynamics of traveling bands in systems of deformable self-propelled particles, Phys. Rev. E, **90**, 042927(1-10) (2014).

[7] N. Shiraishi, S. Ito, K. Kawaguchi and T. Sagawa: Role of measurement-feedback separation in autonomous Maxwell's demons, New J. Phys., **17**, 045012 (2015).

[8] Y. Nakayama and K. Kawaguchi: Invariance of steady-state thermodynamics between different scales of description, Phys. Rev. E, **91**, 012115 (2015).

[9] T. Yamamoto, M. Kuroda and M. Sano: Three-dimensional analysis of thermo-mechanically rotating cholesteric liquid crystal droplets under a temperature gradient, Europhys. Lett., **109**, 46001 (2015).

[10] H. Shoji and T. Ohta: Computer simulations of three-dimensional Turing patterns in the Lengyel-Epstein model, Phys. Rev. E, **91**, 032913(1-11) (2015).

[11] H. Ebata and M. Sano: Swimming droplets driven by a surface wave, Sci. Rep., **5**, 8546 (2015).

[12] S. Ito and T. Sagawa: Maxwell's demon in biochemical signal transduction, Nature Communications, accepted.

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.

[1] Shiino, T., Shiba, S., Sakai, N., Yamakura, T., Jiang, L., Uzawa, Y., Maezawa, H., and Yamamoto, S., Improvement of the Critical Temperature of Superconducting NbTiN and NbN Thin Films Using the AlN Buffer Layer, Supercond. Sci. Technol. **23**, 045004 (2010).

[2] Watanabe, Y., Sakai, N., Lindberg, J.E., Jorgensen, J.K., Bisschop, S.E., and Yamamoto, S., "An Unbiased Spectral Line Survey toward R CrA IRS7B in the 345 GHz Window with ASTE", ApJ, **745**, 126 (2012).

[3] Sakai, N. and Yamamoto, S., "Warm Carbon-Chain Chemistry", Chemical Reviews, **113**, 8981 (2014).

[4] Sakai, N. et al., "Change in the Chemical Composition of Infalling Gas Forming a Disk around a Protostar", Nature, **507**, 78, 2014.

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

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

(2) Phase differences of near-threshold high-order harmonics generated in atoms and molecules [2]

We present the observations of the phase differences $\Delta\phi_{\mathrm{HH}}^{(2n)}$ between adjacent high-order harmonics generated from Ar and N_2 at the near-threshold region. The $\Delta\phi_{\mathrm{HH}}^{(2n)}$'s are extracted from the photoelectron signals resulting from two-color two-photon ionization of rare-gas atoms, which are produced by high-order harmonics to be measured and a part of the fundamental pulse for probing. An analysis method is employed to remove the inevitable modulations in high-order harmonic intensities based on the underlying mechanism of the production of photoelectrons. We find a significant difference in the $\Delta\phi_{\mathrm{HH}}^{(2n)}$ at the nearest-threshold order between Ar and N_2. This difference cannot be reproduced by the model calculation by using the saddle-point method within the strong-field approximation. To elucidate the origin of the difference between the $\Delta\phi_{\mathrm{HH}}^{(2n)}$ for Ar and that for N_2, we note the fact that the phase difference $\Delta\phi_{\mathrm{HH}}^{(2n)}$ contains information both on the recombination time t_r of the freed electron and on the phase of the recombination dipole moment d^*. With the help of some numerical calculations, we discuss the effect of the potential created by the parent ion on t_r and d^* which are neglected in the strong-field approximation.

[1] Je Hoi Mun, Daisuke Takei, Shinichirou Minemoto, and Hirofumi Sakai, "Laser-field-free orientation of state-selected asymmetric top molecules," Physical Review A **89**, 051402(R) (5 pages) (2014).

[2] Kosaku Kato, Shinichirou Minemoto, Yusuke Sakemi, and Hirofumi Sakai, "Phase differences of near-threshold high-order harmonics generated in atoms and molecules," Physical Review A **90**, 063403 (10 pages) (2014).

30 Gonokami Group

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

Member: Makoto Gonokami, Kosuke Yoshioka

We are trying to explore new aspects of many-body quantum systems and their exotic quantum optical effects through designed light-matter interactions. Our current target consists of a wide variety of matter, including excitons and electron-hole ensemble in semiconductors, antiferromagnetic magnons and ultracold atomic gases. In particular, we have been investigating the Bose-Einstein condensation phase of excitons, which is considered the ground state of electron-hole ensemble but as yet not proven experimentally. Based on quantitative spectroscopic measurements, the temperature and density are determined for an exciton gas in a quasi-equilibrium condition trapped inside a high purity crystal kept below 1 K. We are now investigating a stable and quantum degenerate state of dark exciton gas at such very low temperatures. We also investigate novel optical and terahertz-wave responses for some artificial nanostructures obtained by advanced micro-fabrication technologies. As the Director of the Photon Science Center, within the Graduate School of Engineering, a project was started to develop new coherent light sources; covering a broad frequency range from terahertz to soft X-rays. Specifically, in collaboration with RIKEN, the Foundation for Coherent Photon Science Research was established two years ago. This is one of the Advanced Research Foundation initiatives from the Ministry of Education, Culture, Sports, Science and Technology. Within this initiative, we are developing intense and stable coherent light sources at a high repetition rate (That facility is named "Photon Ring").

This year the following activities were done:

1. The quest for macroscopic quantum phenomena in photo-excited systems:

   (a) Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   (b) 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:
   (a) Development of highly precise and accurate terahertz polarization measurement method
   (b) Generation of broadband terahertz vortex beams

3. Development of novel coherent light sources and spectroscopic methods:
   (a) Laser-based angle resolved photoemission spectroscopy
   (b) "Photon ring" project
   (c) Institute for Photon Science Technology

References

[1] Z. Zheng, N. Kanda, K. Konishi, and M. Kuwata-Gonokami: Efficient coupling of propagating broadband terahertz radial beams to metal wires, Optics Express, **21**, 10642 (2013).

[2] T. Kan, A. Isozaki, N. Kanda, N. Nemoto, K. Konishi, M. Kuwata-Gonokami, K. Matsumoto, and I. Shimoyama: Spiral metamaterial for active tuning of optical activity, Appl. Phys. Lett., **102**, 221906 (2013).

[3] T. Higuchi, M. Kuwata-Gonokami: Microscopic origin of magnetic linear dichroism in the antiferromagnetic insulator MnF_2, Phys. Rev. B, **87**, 224405 (2013).

[4] J. Omachi, T. Suzuki, K. Kato, N. Naka, K. Yoshioka, and M. Kuwata-Gonokami: Observation of excitonic N-body bound states: Polyexcitons in diamond, Phys. Rev. Lett., **111**, 026402 (2013).

[5] K. Yoshioka, Y. Morita, K. Fukuoka, and M. Kuwata-Gonokami: Generation of ultracold paraexcitons in cuprous oxide: A path toward a stable Bose-Einstein condensate, Phys. Rev. B, **88**, 041201(R) (2013). Editors' Suggestion

[6] M. Sato, T. Higuchi, N. Kanda, K. Konishi, K. Yoshioka, T. Suzuki, K. Misawa, and M. Kuwata-Gonokami: Terahertz polarization pulse shaping with arbitrary field control, Nature Photonics, **7**, 724 (2013). Selected for the issue cover

[7] Y. Hazama, N. Naka, M. Kuwata-Gonokami, K. Tanaka: Resonant creation of indirect excitons in diamond at the phonon-assisted absorption edge, Web of Science, **104**, 47012 (2013).

[8] K. Kitano, N. Ishii, N. Kanda, Y. Matsumoto, T. Kanai, M. Kuwata-Gonokami, J. Itatani: Orientation of jet-cooled polar molecules with an intense single-cycle THz pulse, Phys. Rev. A, **88**, 061405 (2013).

[9] P. A. Obraztsov, T. Kaplas, S. V. Garnov, M. Kuwata-Gonokami, A. N. Obraztsov, Y. P. Svirko: All-optical control of ultrafast photocurrents in unbiased grapheme, SCIENTIFIC REPORTS, **4**, 4007 (2013)

[10] K. Yoshioka, K. Miyashita, and M. Kuwata-Gonokami: Selective generation of ultracold high-density 1s orthoexcitons in Cu_2O with phase-modulated pulse using acousto-optic programmable filter, Optics Express **22**, 3261 (2014)

[11] P. A. Obraztsov, T. Kaplas, S. V. Garnov, M. Kuwata-Gonokami, A. N. Obraztsov, Y. P. Svirko: All-optical control of ultrafast photocurrents in unbiased grapheme, SCIENTIFIC REPORTS **4**, 4007 (2014)

[12] K. Konishi, T. Higuchi, J. Li, J. Larsson, S. Ishii, and M. Kuwata-Gonokami: Polarization-controlled circular second-harmonic generation from metal hole arrays with threefold rotational symmetry, Phys. Rev. Lett., **112**, 135502 (2014)

31 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Yuta Michimura

The detection of gravitational waves is expected to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars; these information can not be obtained by other means such as optics, radio-waves or X-ray. Worldwide efforts are being continued in order to construct detectors with sufficient sensitivity to catch possible gravitational waves.

In 2010, a new science project, KAGRA (former LCGT) was approved and funded by the Leading-edge Research Infrastructure Program of the Japanese government. The detector is now under construction in KAMIOKA. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200Mpc.

A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

We summarize the subjects being studied in our group.

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

Reference

[1] K. Eda, A. Shoda, Y. Itoh, M. Ando: Improving parameter estimation accuracy with torsion-bar antennas, Phys. Rev. D, 90, 064039 (2014).

[2] M. Adier, F. Aguilar, T. Akutsu, M.A. Arain, M. Ando *et al.*: Progress and challenges in advanced ground-based gravitational-wave detectors General Relativity and Gravitation, 46, 1749 (2014).

[3] K. Nakamura, M. Ando: Torsion-bar antenna in the proper reference frame with rotation, Phys. Rev. D, 89, 064008 (2014).

[4] A. Shoda, M.Ando, K. Ishidoshiro, K. Okada, W. Kokuyama, Y. Aso, K. Tsubono: Search for a stochastic gravitational-wave background using a pair of torsion-bar antennas, Phys. Rev. D, 89, 027101 (2014).

32 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose and Hiroshi Kohsaka

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

1. Premotor Interneurons controling Locomotion Speed

Animals control the speed of motion to meet behavioral demands. Yet, the underlying neuronal mechanisms remain poorly understood. In this study, we showed that a class of segmentally arrayed local interneurons (period-positive median segmental interneurons, or PMSIs) regulates the speed of peristaltic locomotion in *Drosophila* larvae. PMSIs form glutamatergic synapses on motor neurons and, when optogenetically activated, inhibited motor activity, indicating that they are inhibitory premotor interneurons. Calcium imaging showed that PMSIs are rhythmically active during peristalsis with a short time delay in relation to motor neurons. Optogenetic silencing of these neurons elongated the duration of motor bursting and greatly reduced the speed of larval locomotion. These results suggest that PMSIs control the speed of axial locomotion by limiting, via inhibition, the duration of motor outputs in each segment. Similar mechanisms are found in the regulation of mammalian limb locomotion, suggesting that common strategies may be used to control the speed of animal movements in a diversity of species.

2. Neural Circuits Modulating the Larval Turning Behavior

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

References

[1] Kohsaka, H., Takasu, E., Morimoto, T. and Nose, A.:A group of segmental premotor interneurons regulates the speed of axial locomotion in *Drosophila* larvae. Current Biology, Volume 24, Issue 22, p2632-2642, (2014).

[2] Okusawa, S., Kohsaka, H. and Nose, A.: Serotonin and downstream leucokinin neurons modulate larval turning behavior in *Drosophila*. J Neurosci. 34, 2544-2558 (2014).

[3] Kohsaka, H. and Nose, A. Optogenetics in Drosophila. (a book chapter inhOptogeneticsh), Springer Verlag (2015)

33 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Noninvasive in vivo imaging of tumor cells in mouse auricles We developed methods of preparing xenograft model and imaging GFP-expressing cells to observe noninvasively cells in mouse auricles. In the previous studies, we imaged invasively the tumor exposed by dissection of skin and epithelium. By the dissection, blood flow was blocked, resulting in lack of supply of oxygen and nutrient. We, however, concern if homeostasis of their cells is maintained to elucidate biological phenomenon in imaging under ischemic condition. Therefore, we developed new noninvasive imaging methods. We selected the ear auricle of mouse for observation of tumor cells because of very thin (about 150-200 μm) and limited hypodermal tissue. We have developed a novel xenograft model which has tumor in auricle. SCID mice of 8-12 weeks old were used in our experiments. And then the tumor and cells in auricle were noninvasively imaged by spinning disk confocal (CSU) system equipped with automatic positioning stage, piezo actuator for objective and an EMCCD camera. We imaged GFP fluorescence in the MDA-MB-321-GFP-tub cells in tumor of ear auricle without injuring mice. The individual two cells in tumor were distinguished faintly with bright background of tumor fluorescence. We also took a montage view of tumor cover wide area (3x2 mm). The shape of a tumor appeared faintly at the depth $\geq 40\mu$m, suggesting the shape is background of a tumor located deeper. There are several bright spots in the diameter of $\sim 20\mu$m in the enlarged image, indicating those are single cells. We could successfully perform real time observation of GFP fluorescence in the breast cancer cells in noninvasive condition by a CSU system.

Selective removal of cancer stem cells Protease activated receptor 1 (PAR-1), has been known to be one of the most essential membrane protein that mediates intracellular signals promoting cell motility, which is closely related to cancer metastasis. Since the machinery of vesicles carrying this PAR-1 proteins plays a key role in signal transfer, we imaged the trafficking of PAR-1 carrying vesicles, mainly focused on the moment of endocytosis, to analyze the movement of activated PAR-1 after internalization. Our triple-view method consisting of dual-focus fluorescence and phase contrast optics, enabled us to track endocytotic vesicles in 3-dimension. Also, using confocal microscopy, we were able to diagnose the characteristic movements of PAR-1 proteins with respect to their relative position in a cell.

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

Determination of Power Stroke Distance Driven by Human Cytoplasmic Dynein Cytoplasmic dynein is a motor protein moving along microtubules toward the minus-end dominantly with 8.2nm step, and plays an important role in cellular processes. Dynein's conformational change, called 'power stroke', is assumed to generate driving forces moving along the microtubule. However, it has not been clarified the mechanism of how the power stroke contributes to individual steps. Thus, we measured the power stroke distance of single-headed dynein using optical tweezers. Results showed that the power stroke distance is less than 8.2nm, implying the following scenario; the attached head goes on power stroke, while the other head detaches, undergoes diffusive search and rebinds to the next site on microtubule.