II

Summary of activities in 2009

1 Theoretical Nuclear Physics Group

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

Member: Takaharu Otsuka, Tetsuo Hatsuda, Tetsufumi Hirano, Noritaka Shimizu and Shoichi Sasaki

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

Nuclear Structure Physics

In the Nuclear Structure group (T. Otsuka and N. Shimizu), quantum many-body problems for atomic nuclei, various issues on nuclear forces and their combinations are studied theoretically from many angles. The major subjects are the structure of unstable exotic nuclei, shell model calculations including Monte Carlo Shell Model, reactions between heavy nuclei, Bose-Einstein condensation, symmetries and quantum chaos, etc.

The structure of unstable nuclei is the major focus of our interests, and examples of the current subjects are the disappearance of conventional magic numbers and appearance of new ones. These phenomena are due to the change of the shell structure (shell evolution), and are largely due to nuclear forces such as the tensor force and the three-body force. Many papers with strong impacts have been published by our group in recent years, such as [1]. The structure of such unstable nuclei have been calculated by Monte Carlo Shell Model and conventional shell model [2], and their applications have been made in collaborations with experimentalists [3, 4]. We study also neutrino reactions with nuclei with astrophysical interest [5]. Relativistics Hartree-Fock calculations have been reported with the explicit inclusion of pions [6].

The mean-field based formulation of the Interacting Boson Model is a new original approach being developed by using thw Wavelet formalism [7].

A new type of ab initio calculations is being developed by using Monte Carlo Shell Model.

Quantum Hadron Physics

In Quantum Hadron Physics group (T. Hatsuda and S. Sasaki), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). Main research interests are the quark-gluon structure of hadrons, lattice gauge theories and simulations, matter under extreme conditions, quark-gluon plasma in relativistic heavy-ion collisions, high density matter, neutron stars and quark stars, chiral symmetry in nuclei, color superconductivity, and many-body problem in cold atoms and in graphene. Highlights in research activities of this year are listed below.

1. Lattice QCD studies of hadron structure [8]
2. Lattice QCD studies of the nuclear force [9]
3. Heavy-quarks in the quark-gluon plasma [10]
4. Phase transition in high density quark matter [11]
5. Boson-fermion mixture in ultracold atoms [12]
6. Non-equilibrium quantum field theory [13]

High Energy Hadron Physics

In High Energy Hadron Physics group (T. Hirano), the physics of the quark-gluon plasma and dynamics of relativistic heavy ion collisions are studied theoretically based on relativistic hydrodynamics and relativistic kinetic theories. Main subjects include (1) hydrodynamic description of the space-time evolution of the quark-gluon plasma, (2) transport description of hadrons and their dissipation, (3) analyses of the quark-gluon plasma through hard probes such as jets and heavy quarks/quarkonia [10, 16, 18], (4) initial states of high energy colliding hadrons/nuclei including color glass condensate [14], (5) electromagnetic probes of the quark-gluon plasma [15], and (6) viscous effects on hadronic observables [17].

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Member: Takeo Moroi, Tsutomu Yanagida, Koichi Hamaguchi, Yutaka Matsuo
Motoi Endo, Yosuke Imamura, Teruhiko Kawano

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 Dark Matter [1] [2] [3] [12] [13] [15] [16] [24]
   - 1.2 LHC [11] [14]
   - 1.3 Supersymmetry [20] [21] [23] [22] [25]
   - 1.4 Hadron Scattering Phenomena by Gauge/Gravity Correspondence
2. Superstring Theory.
   - 2.1 M-theory and BLG Model [4] [5]
   - 2.2 M-theory and AdS/CFT Correspondence [18] [17] [9]
   - 2.3 Duality [6]
   - 2.4 BPS State Counting and Crystal Melting [7]
   - 2.5 String Phenomenology [10]
   - 2.6 F-theory [19]

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3 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

1) Antimatter study at CERN's antiproton decelerator

Antiprotonic helium laser spectroscopy Atomic transition frequencies in antiprotonic helium (together with those in hydrogen) yield information on the Rydberg constant and the proton-to-electron mass ratio, thereby contributing to the CODATA 2006 recommended values of the fundamental physical constants.

In order to further improve the antiprotonic helium laser spectroscopy precision, we have developed new Doppler-free spectroscopy methods with which it should be possible to determine the (anti)proton-to-electron mass ratio with a relative standard uncertainty better than 10^{-10} (i.e., better than the current CODATA value) within a few years.

Antihydrogen Spectroscopic comparison of hydrogen and antihydrogen ($\bar{p} - e^+$) atoms is considered to be one of the most stringent tests of the CPT symmetry. At CERN, we can now routinely form antihydrogen atoms by mixing antiprotons and positrons, and our current goal is to capture antihydrogen atoms by using a superconducting octupole magnet system. At the same time, development of an "antihydrogen beam", with which we plan to measure the antihydrogen ground-state hyperfine splitting, is in progress.

$\bar{p}$-nucleus annihilation cross section at ultra-low energies At high energies, it is known that the $\bar{p}$-nucleus annihilation cross sections scale as $\sigma_{\rm ann} \propto A^{2/3}$, where A is the nuclear mass number. However, at very low energies, this scaling is expected to be violated, but no such measurements have been done due to the lack of ultra-low-energy antiproton beams. Using a radio-frequency quadrupole decelerator ("inverse" linac), we have started the $\sigma_{\rm ann}$ measurements at 100 keV.

2) Precision X-ray spectroscopy of kaonic atoms

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

X-ray spectroscopy of kaonic hydrogen In fiscal year 2009, we performed the measurement of kaonic hydrogen X-ray in the SIDDHARTA experiment at the DAΦNE storage ring in LNF, Italy. During the beam time from March to November, we also collected data with helium-4 target to tune the experimental setup. The expected performance of the silicon drift detectors was verified in the helium-4 target measurement. Moreover, we obtained consistent result on the $2p$-level shift of kaonic helium-4 atom with the E570 experiment at KEK in 2005, and published it in PLB. Meanwhile, the analysis of the hydrogen target data is now in progress to determine the $1s$-level shift and width of the kaonic hydrogen atom.

X-ray spectroscopy of kaonic helium 3 The kaonic helium 3 $2p$-level shift measurement, in addition to that of kaonic helium 4 given by KEK-PS E570 and very recently by SIDDHARTA, will give much more strong constraint to the kaon-nucleas interaction. The J-PARC E17, which is the first experiment to be carried out at J-PARC hadron hall, will be performed at K1.8BR beamline as a precision measurement of the shift. In fiscal year 2009, we have completed the preparation of beamline detectors and CDS (Cylindrical Detector System), and proceeded the kaon beam tuning of the K1.8BR beamline, R&D of the ^{3}He target and a new type of SDD. We will perform the kaonic helium 3 measurement in fiscal year 2010.

3) Study of kaonic nuclei

Study of kaonic nucleus via the stopped K^- reaction on helium 4 We have performed KEK-PS E549, to measure (semi-)inclusive ^{4}He($K^-_{stopped}, N$) spectra, and obtained strict upper limits for the formation of narrow $\bar{K}NNN$ states with total isospin $T = 0/1$. Meanwhile, the ^{4}He($K^-_{stopped}, YN/Yd$) semi-exclusive spectra exhibitted unresolved wide strengths which are well separable from multi-nucleon processes. They could be the signal of non-mesonic YN/YNN decay of strongly-bound $\bar{K}NN/\bar{K}NNN$ states, and the finalization of spectrum normalization, including the neutron detection efficiency study, is in progress to conclude the interesting problem. In fiscal year 2009, normalized Λp spectrum was provided, and the result of ^{4}He($K^-_{stopped}, n$) semi-inclusive measurement was finalized. As a byproduct, we have studied the branching ratios of non-mesonic two body weak decay modes of $^4_\Lambda$He hyper nucleus, $^4_\Lambda$He$\rightarrow d + d$ and $p + t$.

Search for K^-pp and K^-pn deeply-bound kaonic states at J-PARC The J-PARC E15, to be scheduled after E17 at K1.8BR beamline, will use the ^{3}He(K^-, n) reaction to search for K^-pp. E15 is a kinematically complete experiment in which all reaction products are detected exclusively for $K^-pp \rightarrow \Lambda p$ decay mode, and it aims to provide decisive information on the nature of the simplest kaonic nucleus. We have submitted an extension of the program to measure ^{3}He(K^-, p) spectrum to study K^-pn as well, and the extended part, P27, was approved and combined as a part of E15.

The experimental devices, which have many common parts with those used for E17, are now under construction.

4) Precision spectroscopy of pionic atoms

Precision spectroscopy of the 1s level of pionic atoms using the (d,^{3}He) reaction is a powerful method to study the $\langle q\bar{q} \rangle$ condensate, and to understand why the proton is so heavy compared to its constituents, the u, d quarks. A new experimental setup based on a dispersion-matched optics is being constructed at the BigRIPS facility of RIBF. In May 2009, we performed a test experiment to establish a method to accomplish the dispersion-matched optics and confirmed the experimental resolution was improved after applying the dispersion matching.

The next pionic atom spectroscopy experiment will be performed in fall 2010, and presently we are preparing detectors, optics and a data acquisition system for this experiment.

5) Study of muonium production targets

Ultra-slow polarized muon beam with the energy of 0.5∼30 keV is anticipated as a new "microscope for magnetism" for the investigation of the surface magnetism. The ultra slow muon beamline was established in the RIKEN RAL muon facility. In this site, 15∼20 /s ultra-slow muons can be generated while initial muon beam intensity reaches to 1.3×10^6 /s. In order to increase the intensity of the ultra-slow muons, improvements of the escaping efficiency of the muoniums from the formation target (3%), and laser ionization ($\sim 10^{-5}$) are needed.

In recent days, we can fabricate nano structures with the technique of material science and it is expected to improve escaping efficiency of muoniums. We are going to perform measurements of the efficiency by using new materials in 2010. Moreover, we will proceed understanding of the mechanism of muonium formation and behavior of muoniums near the surface.

4 Ozawa Group

Research Subjects: Experimental study of non-perturbative QCD

Member: Kyoichiro Ozawa

Study of quark-gluon-plasma at RHIC

In 6 years operation of Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), many new phenomena related to hot and dense nuclear matter have been discovered. We performed the PHENIX experiment at RHIC and produced many new results on a wide range of physics subjects, including charged and neutral hadron production, single electron production, event isotropy, and many other topics.

In spite of these fruitful results, there are still remaining questions to be answered to further characterize the state of matter formed at RHIC. In particular, chiral properties of the dense matter produced has not been obtained, and should be provided. For the study of the chiral properties, vector mesons, such as ϕ, ω and ρ are interesting mesons because the restoration of approximate chiral symmetry at high temperature may modify their mass and width. These modifications can be shown directly in the line shape of the e^+e^- mass spectra. Here, the measurements with lepton decays are essential, since leptons are not interact with the medium and carry direct information about conditions and properties of the medium. However, large background in electron pairs due to π^0 Dalitz decays and γ conversion make the measurement difficult in the past RHIC data. In this year, we have successfully installed and operated a new detector, which is called Hadron Blind Detector, to suppress the background. Data acquisition at RHIC-PHENIX is under way and we have started a preliminary analysis.

Study of mechanism of hadronic mass generation at J-PARC

The chiral property of QCD in dense($\rho \neq 0$) nuclear matter has also attracted wide interest in the field of hadron physics. In hot and/or dense matter, broken chirtal symmetry is subject to be restored either partially or completely and, hence, the properties of hadrons can be modified. To observe such an effect, measurements of the in-medium decay of vector mesons are highly desirable for the direct determination of the meson properties in matter. We are planning two new experiments at J-PARC to measure vector meson mass at normal nuclear density.

One new experiment aim to collect 100 times larger statistics of ϕ meson than that collected by the KEK experiment. We can discuss the velocity dependence of the mass spectra of vector mesons more precisely and compare with the theoretical predictions. We are also able to use larger and smaller nuclear targets as lead and proton, For this experiment, new detector based on Gas Electron Multiplier (GEM), which is originally developed at CERN, is under developing. Using GEM, we are investigating 2 dimensional tracker for high rate counting. A prototype is reconstructed and reasonable signals are observed. An test experiment is performed at LNS test beam line at Tohoku Univ. Incident angle dependence of position resolution is evaluated using an electron beam. As shown in Fig. 2.1.7, a position resolution of 150 μm is obtained for 30° of incident angle.

Also, we propose combined measurements of nuclear ω bound state and direct ω mass modification. Nuclear ω bound states are measured in p(π^-, n)ω reaction and decays of generated ω meson are also measured with $\omega \to \pi^0\gamma$ mode. Such exclusive measurement can supply essential information to establish partial restoration of the chiral symmetry in nucleus. We performed a test experiment to evaluate timing resolution of TOF counter for neutron measurements and the resolution of 60 ps is obtained. Several Monte Carlo simulations are performed based on known characteristics of detectors to evaluate final expected spectra. As results, expected final spectra are shown in Fig. 2.1.8.

Gas Electron Multiplier R&D for future experiments

We have studied Gas Electron Multiplier (GEM) for future experiments. For upgrade of Hadron Blind Detector, several gas mixtures of Ar and CF_4 are tested. In addition, we have tested GEM foils made by Tech-Etch Co. As a read-out electronics of GEM detectors, we have developed an ASIC chip which has pre-amplifier, shaper-amplifier, comparator, and sample-hold circuits. A proto-type chip is manufactured and will be tested soon.

5 Sakai (Hideyuki) Group

Research Subjects: Experimental Nuclear Physics

Member: Hideyuki Sakai, Kentaro Yako

We have been aiming to explore nuclear structure as well as nuclear reaction mechanisms by using an intermediate energy beam from accelerators. Particular emphasis is placed on the study of the spin degrees of freedom in nuclei. Major activities in the final year are summarized below.

ICHOR project: Isospin-spin responses in CHarge-exchange exOthermic Reactions

Spin-isospin response of nucleus is a unique excitation mode since it is related with mesons in nuclei and consequently it provides valuable information on nuclear forces. So far the research has been performed by using endothermic reactions by a stable beam such as (p, n) or (n, p), which is inevitably accompanied by a finite momentum transfer to nucleus. Such reactions hamper the study of spin-isospin responses in highly excited regions. We will try to overcome this difficulty by using exothermic reactions by an unstable beam such as (^{12}N, ^{12}C) or (^{12}B, ^{12}C). With this new experimental means, we pursue the study of spin-isospin responses in the highly excited region. Aiming to identify new spin excitation modes, we constructed a high energy resolution spectrometer SHARAQ dedicated to the exothermic reactions by unstable beams.

—First experiment at SHARAQ: Measurement of isovector spin-monopole resonance— The isovector spin-monopole resonance (IVSMR) has been a major topic in the study of spin-isospin responses in nuclei. The IVSMR is the $2\hbar\omega$ transition with $\Delta L = 0$, $\Delta S = 1$, and $\Delta T = 1$. Since the IVSMR is a breathing mode with spin and isospin changes, it can be related to the nuclear matter compressibility with spin and isospin degrees of freedom. In spite of the importance of the IVSMR, the experimental information is currently scarce. There are some experimental hints on the IVSMR for the β^- (or (p,n)) side, but few for the β^+ (or (n,p)) side. Therefore, we planned two experiments to establish the IVSMR by observing it in the β^+ channel, in which the physical background due to Gamow-Teller excitations are suppressed by excess neutrons. As a first step, we employed a slightly exothermic reaction of $(t, {}^3\text{He})$. The first physics measurement at SHARAQ was carried out successfully in November.

The triton beam of $T_t = 900$ MeV was produced by injecting the primary α beam onto a ^{9}Be target. The triton beam was acromatically transported to the SHARAQ target position and hits the ^{208}Pb and ^{90}Zr target. The ^{3}He particles from the target were momentum analyzed by SHARAQ and detected by the detectors at the focal plane. We have found a significant enhance of strength in the 0-degree spectrum, which indicates that this is the IVSMR (See Fig. 2.1.1). The detailed anaysis is in progress. The following experiement will be largely exothermic $({}^{12}\text{N}, {}^{12}\text{C})$ measurements, which would allow us to observe the IVSMR more clearly.

6 Komamiya group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) Detector development for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (3) Preparation for physics analyses in the ATLAS experiment at the LHC *pp* collider; (4) Data analyses for the BES-II experiment at BEPC-I, and TOF detector construction for BES-III experiment at BEPC-II; (5) Data analyses for the OPAL experiment at the LEP e^+e^- collider;

Member: Sachio Komamiya, Yoshio Kamiya

We, particle physicists, are entering an exciting period in which new paradigm of the field will be opened on the TeV energy scale by new discoveries expected in experiments at high-energy frontier colliders, LHC and ILC.

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to use superconducting accelerator structures. In 2007 March, the Reference Design Report was issued by the Global Design Effort (GDE) and hence the project has been accelerated as an international big-science project. The technical design will be completed in the end of 2012. We are working on ILC accelerator related hardware development, especially on the beam delivery system. We are developing the Shintake beam size monitor for the ATF2, which is a test accelerator system for ILC located at KEK. The Shintake beam size monitor is able to measure O(10)[nm] beam size, by using a high power laser interferometer. The electron beam is emitted to the interference fringe of the split laser beams. The total energy of photons, which are emitted from the inversed Compton scattering of beam electrons with the laser beam interference fringe, is measured by a multilayer CsI(Tl) detector in the down stream. The phase of the fringe is moved step-by-step, the total photon energy is measured in each step, and the beam size is extracted from a fitting of modulation pattern of the total photon energy as a function of the phase. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC.

2) Detector development for studying gravitational quantum bound states and searching for new medium range force using ultra-cold neutron beam: A detector to measure gravitational bound states of ultra-cold neutrons (UCN) is under way. We decided to use CCD's for the position measurement of the UCN's. The CCD is going to be covered by a B layer to convert neutron to charged nuclear fragments. The UCNs are going through a neutron guide of 100 $[\mu]$ height and their density is modulated in height as forming bound states within the guide due to the earth gravity. In 2008 we tested our neutron detector at ILL Grenoble. In 2009 we started the first experiment at ILL. We are analyzing the data. We will improve our detector and measure the modulation of the neutron density distribution in the next years.

3) ATLAS experiment at LHC: The epoch of new paradigm for particle physics is going to open with the experiments at LHC. LHC started its operation in the end of 2009. The high energy collision at 7 TeV (CMS) has been started in the end of March 2010. The ATLAS detector is now recording events at high energies. Some of our students work on data analysis at LHC. Search for supersymmetric particles with the missing transverse energy, and detector related and physics background are under study.

4) BES-II/-III experiment at IHEP: The group has considered the BES-III experiment at the Beijing e^+e^- collider BEPC-II as the candidate for the middle term project before ILC. We have made a research and development for TOF detector for the BES-III experiment together with IHEP, USTC. We successfully completed a test of over 500 photomultipliers in 1[T] magnetic field and they are already installed to the BES-II detector. We have studied the data analysis of baryon-pair production in $J\psi$ decay using 5.8M BES-II J/ψ events. Now BEPC-II is operating smoothly and BES-III detector is taking large samples of ψ' and J/ψ data.

5) OPAL experiment at LEP: It is the experiment at the highest energy e^+e^- collider LEP of CERN. The data taking with the OPAL detector was completed in the end of 2000. Important physics subjects at LEP are (a) Higgs boson searches, (b) Supersymmetric particle searches and (c) establishment of gauge interactions. We have extensively searched for the Higgs boson which was driven to a narrow mass range of 114-160 GeV.

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.

We started a new R and D study of a compact mobile anti-electron neutrino detector with plastic scintillators to be used at a nuclear reactor station, for the purpose of monitoring the power and plutonium content of the nuclear fuel. It can be used to monitor a reactor from outside of the reactor containment with no disruption of day-to-day operations at the reactor site. This unique capability may be of interest for the reactor safeguard program of the International Atomic Energy Agency(IAEA). We have built a prototype detetctor of a size of $1700 \times 667 \times 551$ mm^3 and weight of 270kg. A detailed Monte Carlo simulation and background measurement have shown that it can sense the on/off status of an ordinary nuclear power reactor station. It is waiting for test deployment at an appropriate reactor.

We are running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the TOKYO AXION HELIOSCOPE, aka Sumico. Sumico consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors. By now, we put upper limits of $g_{a\gamma\gamma} < (5.6–13.4) \times 10^{-10}\mathrm{GeV}^{-1}$ to axion - photon coupling constant for the axion mass $m_a < 0.27$ eV and 0.84 eV $< \mathrm{m_a} < 1.00$ eV. The latter is a newly explored mass region which CERN Axion Solar Telescope(CAST) group that started later has not reached yet. We planned to continue the measurement in which we scan the mass region from 1 eV upward.

An experiment is being prepared for a search for hidden photons kinetically mixing with the ordinary photons. The existence of the hidden photons and other hidden sector particles is predicted by extensions of the Standard Model, notably the ones based on string theory. The hidden photon is expected to come from the direction of the sun. It would be produced in the solar core or in the space by oscillation of the ordinary photon, and can transmute into the photon again in a long vacuum chamber in the laboratory. A photon sensor in the chamber would readily detects the ordinary photon. We plan to piggyback such a chamber onto the Sumico helioscope and track the sun to search for the hidden photons coming from the sun. We estimate that this kind of simple hidden photon detector is able to explore a parameter region of mixing angle vs. hidden photon mass beyond the existing limits. All the components required for the detector are now ready and waiting for the assembly.

A possible limit to the parameters of the hidden photon has also been estimated from the existing data of Sumico's solar axion search runs. It is found that it override the existing limits for the hidden photon mass around 1eV.

Another long-running project of our group is the direct experimental search for supersymmetric neutralino dark matter. The search has been suspended for the improvement of the CaF_2(Eu) scintillation detector in order to get still higher sensitivity for the possible feeble neutralino signals. The improvement includes the pulse shape analysis(PSA) for the discrimination between nuclear recoil events and electron recoil events. We found that PSA is possible with the CaF_2(Eu) scintillator although it is contradictory to the old report by UK group. Furthermore, a new attempt is made to develop organic liquid scintillator with fluorine content also aiming at a search for spin dependently interacting neutralino dark matter.

8 Aihara/Yokoyama Group

Research Subjects: Study of CP-Violation and Search for Physics Beyond the Standard Model in the B Meson System (Belle), Long Baseline Neutrino Oscillation Experiment (T2K), Neutrino-nucleus Interaction Measurement (SciBooNE), Dark Energy Survey at Subaru Telescope (Hyper Suprime-cam), and R&D for Hybrid Photodetectors and the ILC Silicon Detector Concept (SiD).

Staff Members: H. Aihara, M. Yokoyama, M. Iwasaki, H. Kakuno and T. Abe

One of the major research activities has been a study of CP-violation and a search for physics beyond the Standard Model in the B meson system using the KEK B-factory (KEKB). This past year we presented a precise measurement of the branching fraction for a flavor-changing neutral current decay $B \to X_s \ell^+ \ell^-$, where X_s is a hadronic system containing an s-quark and ℓ is an electron or a muon, based on a data sample containing 657M $B\bar{B}$ pairs. This decay mode is highly suppressed in the Standard Model and therefore a probe for searching new physics beyond the Standard Model. Combining the electron and muon modes, we find the branching fraction $Br(B \to X_s \ell^+ \ell^-) = [3.22 \pm 0.79(\text{stat.})^{+0.28}_{-0.25}(\text{syst.})] \times 10^{-6}$ for $M_{\ell^+\ell^-} > 0.2$ GeV/c^2. This is the most precise measurement of this decay mode. We have also continued to design a silicon vertex detector and the interaction region for the KEKB luminosity upgrade.

The T2K long baseline neutrino oscillation experiment has started in April 2009. We have constructed and operated the position (Eelectrostatic) and profile (Segmented Secondary Emission) monitors for the primary proton beams, the muon monitor in the secondary beamline, and near neutrino detectors. All the instruments have been working as expected. We have successfully observed neutrino interactions in both near neutrino detectors and Super-Kamiokande.

In order to reduce the uncertainty in the neutrino oscillation measurements, we have been analyzing data from SciBooNE, an experiment performed at Fermilab to study neutrino-nucleus interaction. We have measured the cross section of neutral current π^0 production, which is one of main sources of background in ν_e appearance search at T2K, as $\sigma(\text{NC}\pi^0)/\sigma(\text{CC}) = (7.7 \pm 0.5(\text{stat.})^{+0.5}_{-0.4}(\text{sys.})) \times 10^{-2}$.

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

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

SiD is a detector concept based on silicon tracking and a silicon-tungsten sampling calorimeter, complemented by a powerful pixel vertex detector, and outer hadronic calorimeter and muon system. Optimized forward detectors are deployed. In order to meet the ILC physics goals, we have designed the general purpose detector taking full advantage of the silicon technology. The Letter of Intent for SiD was validated as the detector concept at ILC by IDAG and ILC Research Director.

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9 Asai group

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

Member: S.Asai

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry and Extra-dimension.
  - Higgs: We are focusing on Higgs boson whose masses is lighter than 140 GeV. $H \rightarrow \gamma\gamma$, $\tau\tau$ and WW are the promising channels. We are contributes on these three modes.
  - SUSY: We contributes SUSY study at the ATLAS experiment as a convener. We have developed methods of the data-driven background estimation for all channels, and we found out that we can estimate background number//distributions from the data itself with accuracy of 10-30% even in the early of the state.
  - Missing Et and jet calibration: We are working on performance of the mET and jet calibration of the ATLAS detector.
  - Extra-dimension If the extra-dimension is compactified at a few TeV scale, Mini-black hole and KK excitation are interesting signals. We are study on these physics at the ATLAS experiments and have shown the ATLAS has good performance.

- (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:
  - Search for extra-dimension with positronium → invisible.
  - Search for CP violation of the lepton sector using positronium.
  - Precise measurement Search HFS of the positronium.
  - Developing high power (>500W) stable sub THz RF source
  - Spin-rotation of positronium

10 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Takashi Oka

Our main interests are many-body effects in electron systems, i.e., **superconductivity, magnetism and fractional quantum Hall effect**, for which we envisage a **materials design for correlated electron systems** and novel **non-equilibrium** phenomena should be realised. Studies in the 2009 academic year include:

- Superconductivity in repulsively interacting electron systems
  — Superconductivity in iron-oxypnictides with a disconnected Fermi surface [1,2]
  — Superconductivity in an aromatic crystal [3]
- Quantum Hall effect and physics of graphene
  — Optica Hall effect in graphene[4]
  — Quantum Hall effect in graphene: Topological aspects[5], edge states, Landau-level laser
  — Photovoltaic Hall effect in graphene[6]
  — Quantum dots in magnetic fields [7]
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  — Landau-Zener tunnelling in the breakdown of Mott's insulator [8,9]
  — Nonequilibrium steady states of photoexcited correlated electrons[10]
  — Numerical formalism for nonequilibrium [11]
  — Dynamics of superfluid-Mott insulator transition in cold atoms in optical lattices
- Realization of tight-binding photonic bands[12]

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11 Miyashita Group

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

Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita and Keiji Saito

1. Cooperative Phenomena in Long-Range Interacting Systems

So far, phase transitions of spin systems have been studied mainly on the fixed lattice. However, we pointed out that difference of sizes of the high-spin (HS) and the low-spin (LS) states causes lattice distortions. This degree of freedom of lattice deformation causes an effective long range order. We found that the critical property of this model belongs to the universality class of the mean-field model. We also found that its dynamical critical properties, such as the spinodal phenomena, are described by the corresponding mean-field theory. We analyzed the critical properties of divergence of the relaxation time near the spinodal point, and obtained asymptotic forms of the divergence and a finite size scaling form. We also pointed out that the threshold phenomena in the switching from LS state to HS state at a low temperature by photo-irradiation belong to this category. We performed Monte Carlo simulation of excitation process in the model with elastic interaction, and found that the scaling relation of the relaxation time describes its critical behavior.

We also pointed out that the boundary condition plays an essential role in long range interacting models. In particular, if we use the infinite-range model (Husimi-Temperley model), the distance between spins has no role, and the boundary condition has no sense. In contrast, in the present model, the open boundary condition causes significant different relaxation processes. We study that in what extent the mean-field description works in various long range models. We found that for a power law interacting model, there exists a parameter region in which the mean-field description does not work. It would be a very interesting problem to study static and dynamical critical properties of systems for which the thermodynamic limit does not exist.

2. Quantum Statistical Mechanics

In quantum systems, they show interesting non-classical behavior. As to the ordered states, the super-fluidity and super-conductivity are so-called off-diagonal long range order (ODLRO) which are specific to the quantum system. The coexistence of the ODLRO and the diagonal order such as the solidity of the particles has been one of the topics in the He system as the super-solid problem. We studied existence of the super-solid state by a quantum Monte Carlo simulation (stochastic series expansion method) on the soft-core Bose Hubbard model in a three-dimensional lattice (simple cubic). We observed successive phase transitions of the solid order and of the super-fluidity at finite temperatures, and also that the super-solid phase exists in a less-filled region, which is not the case in one- and two-dimensional systems. We also pointed out that importance of lattice structure for the super-solid state.

Coherent dynamics of quantum systems has also various characteristic features, and attracts interests from the view point of quantum information processing. We have studied such novel quantum phases and quantum responses. Parts of the subject are studied as an activity of the JST CREST project (Quantum-mechanical cooperative phenomena and their applications).

We study magnetic properties of itinerant electron systems described by the Hubbard model. When the system is in the so-called half-filled case, the system is in the Mott state where the total spin of the system is zero, while when an electron is removed from the half-filled state, the total spin of the system changes to the maximum value if the lattice satisfies a certain condition. This mechanism is called Nagaoka-ferromagnetism. We demonstrated an adiabatic change of the total spin by a mechanism inspired by the Nagaoka-ferromagnetism. There, we can produce a state with a large total spin but zero magnetization, which is called Dicke state. We studied the characteristics of this state and discussed how we observe the state. Moreover we studied the ground state of itinerant systems with particles of larger spins, e.g. $S = 1$ (Boson) and 3/2 (Fermion), etc., and found that the ground state has a degeneracy for the SU$(2S + 1)$ symmetry due to the symmetry among the particles with different magnetizations. It is expected that these new magnetic phenomena are realized in the optical lattice of the laser cooled atom systems.

The property of energy gap at the quasi-crossing point is important for manipulation of quantum states by an external field. We studied nontrivial degeneracy of eigenenergies uniaxial large spins with terms of the single-ion type anisotropy from the view point of a parity symmetry of magnetization. We also studied the gap opening phenomena for Floquet operator which describes the dynamics of periodically driven system. It has been known that periodic external field induces a kind of Rabi oscillation, and the frequency becomes zero at certain values of the amplitude of the AC field. This phenomenon is called the coherent destruction of tunneling (CDT). The CDT can be regarded as a degeneracy of eigenvalues of the Floquet operator. We found that the degeneracy comes from the time reversal symmetry of the AC field, and demonstrated a gap opening in asymmetric shape of the field. We also demonstrate a Landau-Zener analogue when we sweep the amplitude of AC field.

We studied dynamics of the transverse Ising model, and found a kind of quantum spinodal decomposition phenomena when we sweep the field fast in the ordered phase. We also studied the so-called quantum annealing by making use of the quantum fluctuation.

We also studied a control of the state by measurement procedures. Controls of photon state in micro-cavity with atom beams have been performed in experiments (Haroche group, France), and the measurement is a type of quantum non-demolition for the number distribution of photons, but when we measure states of atoms, the photon state changes to a number state. We studied time-dependence of the photon state by Jaynes-Cummings model, and investigated the statistical property of the ensemble of measurements.

We also studied properties of generalized Yang-Baxter relation in large spin system.

3. Formulations of Non-equilibrium Statistical Physics

We studied the formulism of time-evolution equation for systems contacting with the thermal bath. When we study the complex admittance in dissipative environments, we need time evolution of the autocorrelation function. We pointed out that the equation of motion of the autocorrelation function is the same as that of the density matrix. But the intial state must be treated properly. We make a formulation in which no assumption was made except for the second order perturbation of the strength of the interaction between the system and the thermal bath. We demonstrated the method and studied parameter dependence of the line width. We also compare formulations of the complex admittance by obtaining explicit forms.

We also studied fundamental mechanisms and statistical properties of the heat conductivity.

12 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Youichi Yanase

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-T_c superconductivity, Mott metal-insulator transition, magnetic systems, low-dimensional electron systems, mesoscopic systems, organic conductors, unconventional superconductivity, and Tomonaga-Luttinger liquid theory. The followings are the current topics in our group.

- High-T_c superconductivity
  High-T_c superconductors as a strongly correlated electron system.
  Inhomogeneity and two-gap features in high-T_c cuprates. [1]
  Phase diagram of multilayered cuprate superconductors.
- New superconductor: Iron-pnictide
  New mechanism for iron-pnictide superconductivity, "unscreening" effect of Coulomb interaction.
  Simple description of the nodeless and nodal s-wave gap functions in iron pnictides. [2]
  Normal-state spin dynamics of five-band model for iron pnictides. [3]
- Organic conductors
  Renormalization group study on quasi-one-dimensional superconductivity under magnetic field.
  Novel spin-liquid states in anisotropic triangular spin systems.
  Steady nonequilibrium state with competing charge orders under an electric field. [4]
- Theories of anisotropic superconductivity
  Antiferromagnetic order in the FFLO superconductivity. [5]

FFLO superconductivity in a random electron system. [6]
Angular-FFLO superfluidity in a cold-atom system. [7]

- Dirac Fermion systems
  Interband effects of magnetic field on Hall effects in Bi as a Dirac Fermion system. [8]
  Magneto-optical response of the Dirac Fermions in Bi.
- Electronic and spin states in frustrated systems
  Four-state classical Potts model with a novel type of frustrations as a model for rattling. [9]
  Ground states of the frustrated quasi-two-dimensional Hubbard model. [10]
- Kondo effect and heavy fermion systems
  Crossover from local Fermi liquid into heavy Fermi liquid. [11]
- Two-dimensional ^{3}He system on graphite
  Thermodynamic properties of the triangular Heisenberg model with two exchange couplings. [12]
  A new quantum liquid realized in the two-dimensional t-J-K model with ring-exchange interaction.
- Microscopic theory for the magnetic domain wall driving.

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13 Tsuneyuki Group

Research Subjects: Theoretical Condensed-matter physics

Member: Shinji Tsuneyuki and Yoshihiro Gohda

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

One of the major outcomes in FY2009 is a new method of electronic structure calculation of huge biomolecules based on the fragment molecular orbital (FMO) method, which we named FMO-LCMO method (S. Tsuneyuki et al., Chem. Phys. Lett. 476, 104 (2009)). The method not only makes it possible to calculate electronic energy spectrum and one-electron orbitals of huge biomolecules with little additional computational cost but also brings their physical interpretation.

We also succeeded in drastically improving computational efficiency of the Transcorrelated (TC) method. The TC method is a wave function theory utilizing explicitly correlated many-body wave functions and we have long been developing the method as an alternative to the density functional theory. By revising the algorithm of three-body integrals, we could decrease the order of the cpu cost and opened a pathway for its application.

In summary, our research subjects in FY2009 were as follows:

- New methods of electronic structure calculation
  - FMO-LCMO method: a new method of electronic structure calculation of huge biomolecules based on the fragment molecular orbital (FMO) method
  - Generalized anharmonic lattice model of crystals for investigating thermal conductivity
  - Efficient algorithm of diffusion Monte Carlo method on GPU
  - First-principles wavefunction theory for solids based on the Transcorrelated method
- Applications of first-principles electronic structure calculation
  - Electronic structure of Nitride semiconductors and their interface
  - Schottky contact on SiON/SiC(0001) surface
  - Oxygen vacancy and hydrogen impurities in $BaTiO_3$

14 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

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

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15 Uchida Group

Research Subjects: High-T_c superconductivity

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

1. Project and Research Goal

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

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

2. Accomplishment

(1) Ladder Cuprate

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

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

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

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

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

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

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

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

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

1) Granular structure of high-Tc superconductivity

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

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

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

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

16 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Toru HIRAHARA

Topics in our research group are (1) electronic/mass transports, (2) atomic/electronic structures, (3) phase transitions, (4) electronic excitations, (5) spin states and magnetism, and (6) epitaxial growths of coherent atomic/molecular layers/wires on semiconductor surfaces and nano-scale phases. Peculiar atomic arrangements and surface electronic states, characteristic of the surface superstructures and ultra-thin films, on semiconductor surfaces, are our platforms for studying physics of atomic-scale low-dimensional systems by using ultrahigh vacuum experimental techniques such as electron diffraction, scanning electron microscopy, scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy, *in-situ* 4-point-probe conductivity measurements with four-tip STM and monolithic micro-4-point probes, and surface mageto-optical Kerr effect measurements. Main results in this year are as follows.

(1) Surface electronic transport: Spin Hall effect of strong spin-orbit-interaction materials. Surface electronic states and their conductivity of topological insulators. Transport property of graphene. Metal-insulator transitions, hopping conduction, and a Mott insulator in surface states. Kondo effect in surface-state transport.

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

(3) Surface magnetism: Monolayer ferromagnetic surfaces. Diluted magnetic surface states.

(4) Construction of new apparatuses: Green's-function STM (low-temperature four-tip STM), Magneto-optical Kerr effect apparatus. Magneto-resistance with micro-four-point probes apparatus.

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17 Fukuyama Group

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

Member: Hiroshi Fukuyama, Tomohiro Matsui

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

1. **Dimensional crossover of the critical point in quantum systems:**

   It is an interesting open question to ask whether the critical point, i.e., the gas-liquid transition, exists in strictly 2D ^{3}He and, if so, when it restores as we decrease the confinement potential to 2D. The previous quantum many-body calculations predict interestingly that ^{3}He has the critical point but ^{4}He does not in pure 2D case. We have measured low-temperature heat capacities (C) of the second-, third- and fourth-layer ^{3}He adsorbed on a graphite surface preplated with monolayer ^{4}He to elucidate if the ground state of each layer is gas or liquid phase. The elucidation is based on the fact that the coefficient (γ) of T-linear term in $C(T)$ in degenerate fermion systems is determined by the surface area over which the fermions spread and the quasi-particle effective mass. Our data show that the second layer does not have the critical point, while the third- and fourth layers do and ^{3}He atoms form 2D paddles there when density is low ($\rho < 1.5$ nm^{-2}). Thus we conclude that the dimensional crossover from 2D to 3D for the ^{3}He critical point takes place in between the second and third layer.

2. **Other ongoing experiments on 2D ^{3}He:**

   We are preparing a new sample cell for high-precision heat capacity measurements of the possible order-disorder transition near $T = 1$ K in the second later ^{3}He on graphite using a ZYX exfoliated graphite substrate which has much larger micro-crystallite size than the previous one. The purpose of this experiment is to confirm the existence of such a commensurate phase, the 4/7 phase, at the expected density around which many interesting quantum phenomena are proposed to emerge at low temperatures. Designing of a LEED (low energy electron diffraction) experiment below 0.5 K is also undergoing in order to determine the structures of the commensurate phase unambiguously. A cryogen-free dilution refrigerator which will be used for these next generation experiments has been tested successfully with the lowest temperature of 12 mK and the cooling power of 200 μW at $T = 100$ mK.

3. **Fabrication and transport measurements of superconducting ultra-thin films:**

   Finite-temperature superconducting or superfluid transitions in 2D systems are explained by pair formation/dissociation of a free vortex and a free anti-vortex, which are topological defects, at T_{KT} below which the systems possess quasi long-rage ordering. Within this theory, called the Kosterlitz-Thouless (KT) theory, there exists a finite temperature range between T_{KT} and T_{c0}, the transition temperature expected from the mean field theory, where the system acquires finite amplitude of the order parameter but no phase coherence. In order to observe directly such an intermediate temperature region, we are conducting transport measurements of ultra-thin films of $Bi_2Sr_2CaCu_2O_{8+x}$, a layered cuprate high-T_c superconductor, fabricated with the micro-exfoliation technique. Gold electrodes are integrated with photolithography after the exfoliation. The ultra-thin films made in this manner are expected to be of higher quality in terms of atomically flat and clean surface and crystalline stress compared to those by other techniques such as molecular beam epitaxy or iron milling.

   We found in several samples measurable reduction of T_c by 3-8 K from that of bulk samples or the absence of T_c down to $T = 4$ K due to higher fluctuation in lower dimensions. The measured electrical resistance changes linearly with the reduced temperature, $\sqrt{(T_{c0} - T)/(T - T_{KT})}$. The exponent a in I-V characteristic $V \propto I^a$ increases from unity with decreasing temperature below T_{c0} and becomes three at $T = T_{KT}$. These data are consistent with the KT theory where resistance is determined by the density of unbound vortices. We are trying to fabricate samples with appropriate film thickness showing much lower but non-zero T_{KT} to see possible superconducting gap opening in $T_{KT} < T < T_{c0}$ with low temperature STS.

18 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

1. Strongly correlated two dimensional systems:
   We study magnetotransport in a high mobility Si two-dimensional electron system by *in situ* tilting of the sample relative to the magnetic field. A pronounced dip in the longitudinal resistivity is observed during the Landau level crossing process for noninteger filling factors. Together with a Hall resistivity change which exhibits the particle-hole symmetry, this indicates that electrons or holes in the relevant Landau levels become localized at the coincidence where the pseudospin-unpolarized state is expected to be stable. [Okamoto *et al.*, Phys. Rev. B **79**, 241302(R) (2009).]

   We have performed the cyclotron resonance (CR) measurements on two-dimensional electrons in a Si quantum well. At the electron density, both the CR scattering time $\tau_{\rm CR}$ and the transport scattering time τ_t exhibit a metallic temperature dependence down to 0.5 K. The ratio $\tau_t/\tau_{\rm CR}$ at 0.4 K shows the positive N_s dependence in the measured N_s region. [Masutomi *et al.*, Physica E **42**, 1184 (2010).]

   The valley splitting in Si two-dimensional electron systems is studied using Si/SiGe single quantum wells (QWs) with different well widths. The energy gaps for 4 and 5.3 nm QWs, obtained from the temperature dependence of the longitudinal resistivity at the Landau level filling factor $\nu = 1$, are much larger than those for 10 and 20 nm QWs. This is consistent with the well-width dependence of the bare valley splitting estimated from the comparison with the Zeeman splitting in the Shubnikov-de Haas oscillations. [Sasaki *et al.*, Appl. Phys. Lett. **95**, 122109 (2009).]

2. 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 as well as the application of scanning probe microscopy techniques.

19 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Shinichi Watanabe

We study light-matter interactions and many body quantum correlations in solids. In order to investigate the role of electron and/or spin correlations in the excited states as well as the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1THz∼4meV) frequency range where quasi-particle excitations and various collective excitations exist. A novel experimental technique such as THz magneto-optical spectroscopy is also developed to study the optical responses of quantum Hall systems and also the anomalous Hall effect in ferromagnets. The research summary in this year is as follows.

1. **High density electron-hole system :** We have investigated the exciton Mott-transition in Si by optical-pump and terahertz-probe experiments. Through the observation of 1s-2p transition of excitons, which locates around 3 THz for excitons in Si, we studied the formation dynamics of excitons from the photo-excited unbound electron-hole (e-h) pairs. The observed formation time of excitons is quantitatively explained by taking into account the intra- and inter-band electron-phonon scattering process. The 1s-2p transition energy hardly changes even when the e-h pair density exceeds the Mott transition density. This result makes a contrast with the conventional picture that the exciton binding energy continuously diminishes towards the Mott density.

2. **Quasi-1D organic conductor :** We have studied the photo-excited dynamics of a quasi-1D organic conductor $(TMTSF)_2PF_6$, which shows a metal-insulator transition below 12K accompanied by the emergence of a spin density wave(SDW) phase. Since the single particle excitation energy in the SDW phase, namely the SDW gap, is located in the THz frequency range, it is possible to investigate the photo-excited dynamics of the SDW order directly by THz time-domain spectroscopy. We have developed a reflection type optical-pump and THz-probe measurement system with a diffraction-limitted spatial resolution, which enables the measurements of organic conductor single crystals with their typical widths less than 1mm. After the ultrafast optical pulse excitation, the closing and recovery of the SDW gap is clearly observed. The recovery time of the SDW order diverges towards the SDW transition temperature, indicating a critical slowing down behavior.

3. **Optical Hall effect in the quantum Hall system :** We performed a terahertz frequency Faraday rotation measurement in the 2 dimensional electron gas system of a GaAs/AlGaAs heterostructure in the integer quantum Hall regime. The Faraday rotation angle is shown to exhibit a value determined by the fine-structure constant as prediced by theory(T. Morimoto et al., Phys. Rev. Lett. **103**, 116803,(2009).). Optical Hall conductivity $\sigma_{xy}(\omega)$ is obtained from the observed Faraday rotation angle, which exhibits a plateau-like behavior around the Landau-level filling $\nu = 2$. The result indicate that the carrier localization effect, a crucial ingredient in the integer QHE, affects the optical Hall conductivity even in the terahertz regime, namely, close to the cyclotron frequency.

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20 Theoretical Astrophysics Group

Research Subjects: Particle Astrophysics, Relativistic Astrophysics, Physics of Supernovae and High Density Matter, Observational Cosmology

Member: Yasushi Suto, & Atsushi Taruya

The Theoretical Astrophysics Group carries out a wide range of research programmes. However, astrophysics is a very broad field of research, and it goes without saying that our group alone cannot cover all the various important astrophysical research topics on hand; we therefore place particular emphasis on the following three areas of research - "Physics of the Early Universe", "Observational Cosmology", and "Paricle and Nuclear Astrophysics". Let us delve into the specifics of these areas below.

The understanding of the very early universe saw a sort of renaissance in 1980 's by applying the ideas of particle physics around the epoch close to the Planck time, of which the prime example is the inflationary universe scenario. On the basis of such recent development, "Physics of the Early Universe" aims at describing the birth of the universe within the language of physics. Our group activities include inflationary universe models, cosmological phase-transition and topological defects, big-bang nucleosynthesis, the cosmic no-hair conjecture and the fundamental problem of general relativity.

"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.

"Particle and Nuclear Astrophysics" explores the interfaces between particle physics, nuclear physics, and astrophysics. We place particular attention on the physics of supernovae. This includes a rich variety of micro- and macro-physics, for example, neutrino transport, equation of state of high density matter, r-process nucleosynthesis, convective instability, fast rotation of a stellar core, strong magnetic field, gravitational radiation, and so on. In particular, the mechanism of the Type II supernovae itself has not been properly explained for more than 40 years. It is, therefore, important to make clear the physics of supernova phenomena not only for astrophysics but also for other fields of elementary physics. We are currently working on the multi-dimensional aspects of supernovae such as rotating core collapse, asymmetric neutrino emission, convective energy transfer near the neutrino sphere, possibility of r-process nucleosynthesis in the hot bubble region, and gravitational radiation from an asymmetrically bouncing core. Additionally, we have also recently been working on the effects of magnetic fields and those of nuclear structural transitions on the explosion mechanism.

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;
2009

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

2008

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

2007

- The Rossiter effect of extrasolar transiting planetrary systems – perturbative approach and application to the detection of planetary rings
- Stability of flux compactifications and de Sitter thermodynamics
- Study of core-collapse supernovae in special relativistic magnetohydrodynamics
- Spectroscopic Studies of Transiting Planetary Systems
- The relation of the Galactic extinction map to the surface number density of galaxies
- Brane Inflation in String Theory

2006

- Numerical studies on cosmological perturbations in braneworld
- Inflationary braneworld probed with primordial black holes
- Galaxy Biasing and Higher-Order Statistics
- Probing circular polarization of Gravitational Wave Background with Cosmic Microwave Background Anisotropy
- Gravitational Collapse of Population III Stars

2005

- Brane gravity and dynamical stability in warped flux compactification
- Neutrino Probes of Galactic and Cosmological Supernovae
- Detectability of cosmic dark baryons through high-resolution spectroscopy in soft X-ray band

- Propagation of Ultra-High Energy Cosmic Rays in Cosmic Magnetic Fields
- The study of nuclear pasta investigated by Quantum Molecular Dynamics

2004

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

2003

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

21 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao, Peter Turner

Quantum information processing seeks to perform tasks which are impossible or not effective with the use of conventional classical information, by using quantum information described by quantum mechanical states. Quantum computation, quantum cryptography, and quantum communication have been proposed and this new field of quantum information processing has developed rapidly especially over the last 15 years. Entanglement is nonlocal correlation that appears in certain types of quantum states (non-separable states) and has become considered as a fundamental resource for quantum information processing. In our group, we investigate new properties of multipartite and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- Analysis of geometric measure of entanglement for multipartite states [1,2,3]
- Group theoretical study of quantum reference frames [4,5]
- Delocalization power of global unitary operation on quantum information [6]
- Resource overhead in distributed quantum information processing
- Distributed quantum computation using quantum butterfly networks

- Analysis of entanglement criterion: EVM vs, CMC
- Characterization of graphs in measurement based quantum computation
- Hopf fibrations and qubit entanglement
- Operational indistinguishability in quantum tomography
- Continuous variable t-designs
- Analysis of the asymptotic behavior of estimation errors in quantum tomography
- Analysis of Lindbrad master equation

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

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22 Ueda Group

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

Member: Masahito Ueda and Yuki Kawaguchi

We study theory of ultracold atoms and quantum information. In the former, we study Bose-Einstein condensation and Fermi superfluidity. In the latter, we study quantum information, quantum measurement, and are exploring information thermodynamics which investigates the thermodynamic energy cost on quantum information processing.

22.1 Quantum States of Ultracold Atoms

A possible Efimov trimer state in 3-component lithium 6

Efimov trimers are very special three-body bound states (triatomic molecules) whose existence relies purely on quantum mechanical effects. According to this effect, when 3 quantum particles have strong pair interactions, they can bind together even if the interaction cannot bind particles in a pairwise manner. This effect is purely quantum-mechanical and very general – it can occur for any quantum 3-body system, such as nucleons. It was prediced by nuclear physicist Vitaly Efimov 40 years ago. However, it has been observed only recently in cold-atom systems. This year was particular fruitful as Efimov trimer signatures were observed in several kinds of cold-atom systems, in particular in the case of a gas of lithium 6 atoms prepared in 3 different spin states. We analysed these experiments using the universal Efimov theory to check whether the observations could be interpreted as evidence of Efimov trimers, and found good qualitative agreement with the universal theory [1] and predicted the trimer energy. We are now working with experimentalists at the University of Tokyo to understand the non-universal features of these systems, as well as observing the trimers directly by measuring their energy.

Independent Control of Scattering Lengths in Multicomponent Quantum Gases

Recently, multicomponent degenerate gases have attracted broad interest. In such types of system, there are more than one interspecies scattering length which is crucial for the physical features of the system. In Ref. [2], we develop a method of simultaneous and independent control of different scattering lengths in ultracold multicomponent atomic gases. In our scheme the atoms are prepared in one bare hyperfine state as well as two dressed states given by the stimulated Ramman processes induced coupling between hyperfine states. We assume that there are two magnetic Feshbach resonance points which are close with each other. When the hyperfine states are dressed with each other, the energy levels of the dressed states can be controlled by the inter-hyperfine-level couplings. Therefore, the occurrence of the Feshbach resonances can be controlled by the stimulated Ramman process under a given magnetic field. We show that with this approach, at least two of the three scattering lengths in such a system can be independently controlled in a resonant way. The possible applications of our scheme in the systems with ^{40}K and ^{40}K-^{6}Li mixture are discussed. Our method can be used to engineer multi-component quantum phases and Efimov trimer states.

Non-Abelian vortices in a spinor Bose-Einstein condensate

Non-Abelian vortices are defined as quantized vortices with topological invariants classified by non-Abelian algebra, and they are now studied in various research arenas such as cosmology, high-energy physics, solid-state physics, and soft matter physics. The crucial distinction between Abelian and non-Abelian vortices manifests itself in their collision dynamics. We demonstrate the unique collision dynamics of non-Abelian vortices realized in the cyclic phase of a spin-2 spinor BEC, revealing that (i) unlike non-Abelian vortices, they do neither reconnect nor pass through each other but create a rung which bridges the colliding vortices, and (ii) linked Abelian vortices can unravel, while linked non-Abelian vortices cannot [3].

22.2 Quantum Information, Quantum Measurement, and Information Thermodynamics

Optimal Measurement on Noisy Quantum Systems

The most serious obstacle against realizing quantum computers and networks is decoherence that acts as a noise and causes information loss. Decoherence occurs when a quantum system interacts with its environment, and it is unavoidable in almost all quantum systems. Therefore, one of the central problems in quantum information science concerns the optimal measurement to retrieve information about the original quantum state from the decohered one and the maximum information that can be obtained from the measurement.

We identify an optimal quantum measurement that retrieves the maximum information about the expectation value of an observable $\hat{X}$ of $\hat{\rho}$ from the partially decohered state $\mathcal{E}(\hat{\rho})$. Here, $\hat{\rho}$ is an unknown quantum state and modeling of the noise is assumed to be given, and $\mathcal{E}(\hat{\rho}) \equiv \sum_i \hat{M}_i \hat{\rho} \hat{M}_i^{\dagger}$, where $\{\hat{M}_i\}$ are the Kraus operators that satisfy $\sum_i \hat{M}_i^{\dagger} \hat{M}_i = \hat{I}$. The information content that we use is the Fisher information, which has been widely used in estimation theory and is related to the precision of the estimation.

The primary finding of our study is that the optimal measurement for obtaining the Fisher information about $\langle \hat{X} \rangle \equiv tr[\hat{\rho}\hat{X}]$ is the projection measurement $\boldsymbol{P}_{\hat{Y}}$ corresponding to the spectral decomposition of an observable $\hat{Y}$ that is the solution to the operator equation $\mathcal{E}^\dagger(\hat{Y}) = \hat{X}$, where $\mathcal{E}^\dagger(\hat{Y}) \equiv \sum_i \hat{M}_i^\dagger \hat{Y} \hat{M}_i$ is the adjoint map of $\mathcal{E}$. Although the Fisher information depends on the unknown quantum state $\hat{\rho}$, the observable $\hat{Y}$ is independent of $\hat{\rho}$. Therefore, $\boldsymbol{P}_{\hat{Y}}$ is also independent of $\hat{\rho}$, and the optimal procedure to estimate $\langle \hat{X} \rangle$ is simply performing $\boldsymbol{P}_{\hat{Y}}$ to the noisy system [4].

Information Processing and Feedback Control in Small Nonequilibrium Systems

The fundamental lower bound of the energy cost needed for information processing processes such as the measurement or the information erasure has been an active topic of researches. A prominent result in this topic is the Landauer principle. In this research, we have rigorously determined the fundamental lower bound of the energy cost in terms of quantum statistical mechanics and quantum measurement theory. Our result includes the Landaurs principle as a special case, and serves as the generalized second law of thermodynamics which can be applied to information processing processes. This result was published in Physical Review Letters in 2009 [5], selected for Editor 's Suggestion, and highlighted in Physics.

Nonequilibrium statistical mechanics in small systems has seen a remarkable progress since 1990 's: the technology of manipulating small systems such as macromolecules has been developed, and some crucial theoretical results, such as the fluctuation theorem and the Jarzynski equality, have been found. According to the Jarzynski equality, which was found in 1997, the second law of thermodynamics can be expressed in terms of equality if all orders of the fluctuations (or cumulants) are taken into account. The Jarzynski equality includes the conventional second law of thermodynamics (inequality) as the property of its first cumulant. On the other hand, in a previous research, we have generalized the second-law inequality by including the term of the obtained information in the presence of feedback control.

In this research, we have generalized the Jarzynski equality to the situations in which small nonequilibrium systems are subject to feedback control. The generalized Jarzynski equality includes the term of obtained information, and straightforwardly reproduces the generalized second law which we derived before. Moreover, the generalized equality leads to the generalized fluctuation-dissipation theorem, in which the information and the dissipation (or the entropy production) are treated on an equal footing. Furthermore, we have derived another generalization of the Jarzynski equality, which includes the term of feedback efficacy. The feedback efficacy characterizes how efficiently we use the information to decrease the entropy production, and can be directly measured by experiments. The above results were published in Physical Review Letters [6].

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23 Makishima Group & Nakazawa Group

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

Member: Kazuo Makishima, Kazuhiro Nakazawa

We study cosmic and related high-energy phenomena in the X-ray and γ-ray frequencies, mainly using scientific satellites.

***Suzaku*, *Fermi*, and *MAXI*:** We utilize the *Suzaku* X-ray observatory, carrying the Hard X-ray Detector (HXD) which we developed jointly with other groups, and the *Fermi* gamma-ray space telescope launched in 2008. We also utilize all-sky data from *MAXI*, put onboard the International Space Station in July 2009.

Physics of Compact Objects: Mass accretion onto compact objects, including black holes, neutron stars, and white dwarfs, provides our favorite research subject. Utilizing wide-band *Suzaku* spectra, we have shown that some stellar-mass black holes [3] and active galactic nuclei have rather low angular momenta. Our *Suzaku* observations of aboutn 10 "magnetars" have revealed unusual hard X-ray components, extending to ~ 100 keV with very flat spectra, of which properties evolve with their age [5]. This emission may reflect interesting physics in the supposed ultra-strong magnetic fields, including electron-position pair production in the magnetosphere, their annihilation on the stellar surface, and "photon splitting" of the produced 511 keV photons.

Plasma Heating and Particle Acceleration: The universe is full of processes of plasma heating and particle acceleration. In fact, the most dominant known form of cosmic baryons exists in the form of X-ray emitting hot ($\sim 10^8$ K) plasmas associated with clusters of galaxies. There, large-scale magnetic structures, and their interactions with moving galaxies, are considered to be of essential importance [1]. Our search for non-thermal emission from merging clusters of galaxies have led to an unexpected discovery of unusually hot thermal emission. *Fermi* observations of molecular clouds revealed gamma-ray emission arising from the decay of π^0 particles, which are produced by cosmic-ray hadrons [2].

Particle Acceleration in Thunderclouds: From thunderclouds along the Japan Sea and at high mountains, we have so far detected more than a dozen events of gamma-ray showers with energies up to 10 MeV. Some of them last only for < 1 second, while others for 1–2 minutes [4]. Intense electric fields in thunderclouds are considered to accelerate electrons to relativistic energies, which then emit gamma-rays.

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

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24 Takase Group

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

Member: Yuichi Takase, Akira Ejiri, Yoshihiko Nagashima

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

Expermental research using three kinds of radio-frequency (RF) waves are being carried out in our group: (1) plasma heating using the high harmonic fast wave (HHFW) at 21 MHz, (2) plasma start-up from zero current using the electron cyclotron wave (ECW) at 2.45 GHz, and (3) current drive by the lower hybrid wave at 200 MHz.

A variety of nonlinear wave physics phenomena are observed during RF heating and current drive experiments. Parametric decay instability (PDI), which generates the lower sideband wave and the ion-cyclotron quasi-mode in addition to the incident pump wave, is often observed during HHFW heating experiments on TST-2. PDI is a local nonlinear phenomenon over the scale length of the RF power profile. However, nearly identical PDI spectra are observed at various locations regardless of the local magnetic field strength. By use of a new analysis technique (bispectral power analysis), the background physics of the nearly identical spectra was identified experimentally. The resonant lower sideband wave is produced by PDI and a beat modulation is generated by nonlinear coupling of the pump and lower sideband waves. A spectral broadening of the pump wave is often observed. The possibility of PDI driven spectral broadening was tested in RF power scan experiments. Since no significant dependence of the frequency width on RF power is observed, this possibility is unlikely.

In non-inductive start-up experiments using the ECW wave, it was found that the spontaneous formation of the ST configuration is induced earlier in deuterium plasmas than in hydrogen plasmas. The electron density and temperature were measured or estimated using various diagnostic methods. The temperature and density are high in the outboard peripheral region, and is low near the center of the plasma. The high pressure region has a banana shape. Such a pressure profile can be reproduced by a newly developed equilibrium code which can handle anisotropic pressure.

The Thomson scattering system was improved. The electron temperature profile was measured in inductively formed (Ohmic) discharges. The profile was peaked near the center. New polychromators were designed and fabricated, and a prototype detector system, consisting of an APD and a preamplifier, was tested. The FWHM of the output signal was 10 ns for the YAG laser pulse, and the measured noise agreed with theoretical estimates. These performances are sufficient for the planned multi-pass scattering scheme. A confocal spherical mirror system was investigated as a candidate for multi-pass optics. Analytic expressions to describe the features of the optics were obtained, and their accuracies were confirmed both numerically and experimentally. A reduced-scale test optics and a visible He-Ne laser were used (instead of the infra-red YAG laser) for this test.

Accessibility of the LHW to the core of TST-2 plasmas was studied using the TORIC-LH code, and the efficiency of current drive was estimated. The results demonstrate that the LHW can access the core of low density plasmas, and that the plasma current required to maintain the ST configuration can be driven by the existing RF power supply. In parallel, preparations of the facility of 200 MHz RF generators and transmission lines have progressed, a preliminary RF wave injection experiment was carried out.

25 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Yoich ASO

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

TAMA300 is a 300-m baseline laser interferometric gravitational wave detector constructed in Mitaka. We started the operation of the detector in 1999. The achieved sensitivity, $h \sim 3 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ at 700Hz to 1.5kHz, is sufficient to catch possible gravitational wave events in our galaxy. We are now expecting to start the next Japanese large-scale laser interferometer, LCGT.

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.

- Ground based laser interferometric gravitational wave detectors
  - Study of the next-generation laser interferometer, LCGT
  - Design of LCGT
- Space laser interferometer
  - Space laser interferometer, DECIGO
  - DECIGO pathfinder, DPF
  - Laser sensor for DPF
  - FP cavity for DPF
  - DPF gradiometer in space
  - Small size GW detector, SWIM
- Development of a gravitational wave detector using magnetic levitation
  - Gravitational wave detector using superconducting magnetic levitation
  - Magnetic field shielding for levitated detector
- High sensitive laser interferometer using non-classical light
  - High sensitive laser interferometer using squeezed light
  - Generation of the squeezed light
- Development of the ultra stable laser source
  - Laser stabilization using a cryogenic sapphire cavity
  - Study of the cavity support

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26 Sano Harada Group

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

Members: Masaki Sano and Takahiro Harada

Main research topics of our group are nonlinear dynamics, pattern formation in dissipative systems, nonequilibrium statistical mechanics, and biophysics. By closely studying oscillations, chaos, and turbulent behavior and fluctuations in fluidic, solidic, and granular materials as well as chemical reactions and biological systems, we wish to discover a diverse of novel phenomena and distils simple and universal laws underlying such phenomena. Our research are grounded on dynamical systems theory, statistical mechanics, soft matter physics, and laboratory experiments. The following are the representative research subjects in our laboratory.

1. Study of turbulence

(1) Search for the ultimate scaling regime in developed thermal turbulence

(2) Study of statistical properties and coherent structures in turbulence

(3) Turbulence - turbulence transition in electro hydrodynamic convection of liquid crystals

2. Nonlinear Dynamics and Chaos

(1) Pattern forming phenomena and their universalities in dissipative systems including granular materials

(2) Spatio-temporal dynamics in spatially extended dissipative systems

3. Nonequilibrium statistical mechanics and softmatter physics

(1) Fundamental studies on the nature of fluctuations and responses of system far from equilibrium

(2) Developing a general theory of measurements on small complex systems

(3) Manipulation of soft materials via novel optical trap techniques

(4) Softmatter physics on polymers, thermophoretic flows and other related topics

3. Dynamical aspects of biological systems

(1) Single molecule level measurement of DNA collapsing, DNA-protein interaction, and gene expression

(2) Study of slow dynamics in cellular functions

(3) Mechanical aspects of cell migration

(4) Pattern formation of bacteria

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27 Yamamoto Group

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

Member: Satoshi Yamamoto and Nami Sakai

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

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. Existence of WCCC clearly indicates a chemical diversity of low-mass star forming regions, which would probably reflect a variety of star formation. We are now studying how such chemical diversity is brought into the protoplanetary disks.

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooling HEB mixer using NbTiN and NbN in our laboratory. Our NbTiN mixer shows the noise temperature of 1700 K at 1.5 THz, which is well comparable to the results reported by other groups. The 0.8/1.5 THz HEB mixer receiver is now being developed, which will be used for astronomical observations with the ASTE 10 m telescope.

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28 Sakai (Hirofumi) Group

Research Subjects: Experimental studies of quantum optics and atomic/molecular 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) Generation of high-order sum and difference frequencies by adding an intense parallel- and perpendicular-polarized infrared laser field [1]

We demonstrate both efficient control of polarization and high tunability of high-order sum and difference frequencies generated by adding an intense parallel- and perpendicular-polarized infrared laser field. When 805 nm pulses from a Ti:sapphire laser system and 1300 nm pulses from an optical parametric amplifier (OPA) are combined with perpendicular polarizations, the sum frequencies with two or four OPA photons are generated stronger than those with one or three OPA photons. This observation directly reflects the difference in their polarizations of the generated sum frequencies. Sum frequencies absorbing up to eight OPA photons are also observed for the parallel polarizations. Our observations are successfully reproduced by the theoretical calculations with the Lewenstein model including a weighting factor.

(2) All-optical molecular orientation [2]

We report clear evidence of all optical orientation of OCS molecules with an intense nonresonant two-color laser field in the adiabatic regime. The technique relies on the combined effects of anisotropic hyperpolarizability interaction as well as anisotropic polarizability interaction and does not rely on the permanent dipole interaction with an electrostatic field. It is demonstrated that the molecular orientation can be controlled simply by changing the relative phase between the two wavelength fields. The present technique brings researchers a new steering tool of gaseous molecules and will be quite useful in various fields such as electronic stereodynamics in molecules, ultrafast molecular imaging and so on.

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

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

(4) Dependence of the generation efficiency of high-order sum and difference frequencies in the xuv region on the wavelength of an added tunable laser field [4]

We investigate the dependence of the generation efficiency of sum and difference frequencies in the xuv region on the wavelength of an added tunable laser field. The wavelength of the added field ranges from 600 nm to 1500 nm. The generation efficiency of sum and difference frequencies is dramatically enhanced when the wavelength of the added field is longer than that of the fundamental field for pure harmonics. The discussions are held to the added field with perturbative intensity first, and they are further extended to that with nonpertubative intensity.

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29 Nose Group

Research Subjects:Molecular Mechanism of Neural Network Formation

Member:Akinao Nose, Hiroshi Kohsaka and Etsuko Takasu

What is the physical basis of formation of the brain? The aim of our laboratory is to elucidate the molecular mechanism of neural development and function by using, as a model, the simple nervous system of the fruitfly, Drosophila. We focus on the synapses between motor neurons and their target muscles, and study the molecular mechanisms of how specific synaptic partners recognize each other and form synaptic connections. The following research plans are in progress.

1. Molecular mechanism of the neuromuscular target recognition

The proper functioning of the nervous system depends on precise interconnections of distinct types of neurons. Therefore, understanding how neurons specifically find and recognize their target cells is a central question in neuroscience. We have identified specific recognition molecules that are expressed in specific target cells and determine synaptic specificity.

1.1. Neural wiring by a negative signal: identification of a repulsive target cue that determines synaptic specificity.

The final matching of pre- and postsynaptic cells is thought to be mediated by specific molecular cues expressed on the target cells. While previous studies demonstrated essential roles of several target-derived attractive cues, less is known about the role of repulsion by non-target cells. In collaboration with Prof.

Hiroyuki Aburatani (Research Center of Advanced Science and Technology, University of Tokyo), we conducted single-cell microarray analysis of two neighboring muscles (called M12 and M13) in Drosophila, which are innervated by distinct motor neurons, by directly isolating them from dissected embryos. We identified a number of potential target cues that are differentially expressed between the two muscles, including M13-enriched Wnt4, a secreted protein of the Wnt family. When the function of Wnt4 was inhibited, motor neurons that normally connect with M12 formed smaller synapses on M12 but instead, inappropriately connected with M13. Conversely, forced expression of Wnt4 in M12 inhibited synapse formation by these motor neurons. These results suggest that Wnt4 generates target specificity by preventing synapse formation on a non-target muscle.

2. Live-imaging of synapse formation in vivo

Synapses are specialized junctions through which neurons signal to each other and to other target cells such as muscles and are crucial to the functioning of the nervous system. However, the mechanism of how the synapses form during development remains poorly understood. We applied live imaging of fluorescent fusion proteins expressed in the target cells to visualize the process of synapse formation in developing embryos.

2.1 Bidirectional recognition for neuronal matchmaking

The mechanism of how specific neural connections are formed in living animals is one of the significant topics in neuroscience. A traditional view is one-sided: motile growth cones of the presynaptic neurons actively search for the target cell, whereas the target cells wait still to be selected by adequate partner neurons. We found that not only presynaptic neurons but also postsynaptic target cells actively search for their partners during the formation of neural network. Such bidirectional recognition might be critical for the development of precise neural connections not only in Drosophila but also in other animals including humans.

30 Higuchi Group

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

Member: Hideo Higuchi and Motoshi Kaya

Changes in membrane morphology and membrane protein dynamics based on its fluidity are critical for cancer metastasis. However, this subject has remained unclear, because the spatial precision of previous in vivo imaging has been limited to the micrometer level and single molecule imaging is impossible. Here, we have imaged the membrane dynamics of tumor cells in mice with a spatial precision of 7-9 nm under a confocal microscope. A metastasis-promoting factor on the cell membrane, protease-activated receptor 1 (PAR1), was labeled with quantum dots conjugated with an anti-PAR1 antibody. Movements of cancer cells and PAR1 during metastasis were clearly observed in vivo. Images used to assess PAR1 dynamics were taken of representative cells for four stages of metastasis; i.e. cancer cells far from blood vessels in tumor, near the vessel, in the bloodstream, and adherent to the inner vascular surface in the normal tissues near tumor were photographed. The diffusion constant of PAR1 in static cells far from tumor blood vessels was smaller than in moving cells near the vessels and in the bloodstream. The diffusion constant of cells adhering to the inner vascular surface in the normal tissues was also very small. Cells formed membrane protrusion during migration. The PAR1 diffusion constant on these pseudopodia was greater than in other membrane regions in the same cell. Thus, the dynamics of PAR1 movement showed that membrane fluidity increases during intravasation, reaches a peak in the vessel, decreases during extravasation, and is also higher at locally formed pseudopodia.

Motile cilia at lateral ventricle are required for circulation of cerebrospinal fluid. The ciliary movement had so far been observed by the differential interference contrast (DIC) observation, but there was a problem that could not obtain the slice image. To analyze the ciliary motility in detail, we observed the cilia in a mice brain slice under a customized fluorescence microscope system with a high-speed confocal unit. The ependymal tissue section (200micro m in thickness) was prepared from the mice brain (postnatal days of six to 30). The labeling was carried out by adosorption of the organic fluorescence molecules (PKH:Sigma) to visualize the whole cilia form, or attachment of the polystyrene fluorescence nano-particles (Fluosphere: Invitrogen) to analyze detail ciliary movement by using spot tracking method. Motility and beating was analyzed with high temporal resolution (1.1ms) and nm-accuracy. The beat frequency of ciliary movement was 11-14Hz from 6th postnatal days to adult mice, and beating forms were changed with the postnatal days.

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