II

Summary of group activities in 2008

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
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 Nuclear Structure group (T. Otsuka and N. Shimizu), nuclear structure physics is studied theoretically in terms of the quantum many-body problem. 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, as studied extensively by using the Monte Carlo Shell Model. 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. A part of the review can be found in [1], while many papers with strong impacts have been published by our group in recent years. Effects on magnetic properties are discussed for exotic carbon isotopes [2].

A entirely new research project of the year is the mean-field based formulation of the Interacting Boson Model [3]. The mean-field models are good in obtaining intrinsic density ditributions, whereas the Interacting Boson Model is good for describing properties of excited states. We combined these two methods so that both merits can be utilized. The future of this project is quite promising.

The cluster structure can be stabilized by excess neutrons, as we have shown for 14C some years ago. This property has been shown to persist to 13C [4].

We have proposed a new type of ab initio calculations. This method is designed for the description of heavier nuclei.

We are working on the relation between symmtries and quantum chaos.

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. Highlights in research activities of this year are listed below.

1. Lattice QCD studies of hadron structure [5]
2. Lattice QCD study of the nuclear force [6]
3. Lattice QCD study of the quark-gluon plasma [7]
4. Phase transition in high density quark matter [8]

5. Confinement in Yang-Mills theory [9]
6. Hadrons in nuclear medium [10]

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 [11] (3) analyses of the quark-gluon plasma through hard probes such as jets and heavy quarks/quarkonia , (4) color glass condensate for high energy colliding hadrons/nuclei, and (5) electromagnetic probes of the quark-gluon plasma [12].

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Member: Tsutomu Yanagida, Yutaka Matsuo, Koichi Hamaguchi
Yosuke Imamura, Teruhiko Kawano, Taizan Watari

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. Superstring Theory.
   1.1 M-theory and 3-algebra [12] [21] [22] [23] [27] [40]
   1.2 M2-branes and Superconformal Chern-Simons theories [18] [24] [28] [31] [32] [34] [38]
   1.3 Gauge theories and gauge/string duality [9] [17] [26]
   1.4 String field theory [11] [15]
2. High Energy Phenomenology.
   3.1 Phenomenology of beyond the standard models [3] [8] [14] [19] [29] [30] [2] [4] [25] [5] [6] [7] [10] [13]
   3.2 Dark matter and Cosmic rays [33] [36] [39] [41] [37]
   3.3 String inspired models [1] [16] [35] [20]

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3 Sakai (Hideyuki) Group

Research Subjects: Experimental Nuclear Physics

Member: Hideyuki Sakai, Kentaro Yako

We are 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. Our expertise is various "spin-polarizations": spin-polarized beams ($\vec{p}$, $\vec{n}$ and $\vec{d}$), spin-polarized targets ($\vec{p}$ and $^{3}\vec{\mathrm{He}}$), and spin-polarization analysis of reaction products ($\vec{p}$, $\vec{n}$ and $\vec{d}$).

Major activities during the year are summarized below.

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

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 $(^{12}\mathrm{N}, ^{12}\mathrm{C})$ or $(^{12}\mathrm{B}, ^{12}\mathrm{C})$. 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 are constructing a high energy resolution spectrometer SHARAQ dedicated to the exothermic reactions by unstable beams. In this year, we completed the construction of SHARAQ and performed a commissioning by using the $T = 3.6$ GeV ^{14}N-beam. It was found out that (1) all the beam counters and the focal-plane detectors work fine, (2) the dispersion of SHARAQ is $(x|\delta) = 6.8$ m, consistent with the design value, and (3) the dispersion-matching technique is successuly applied (See Fig. 2.1.1).

—First experiment at SHARAQ: Measurement of isovector monopole resonance—

The isovector spin-monopole resonance (IVSMR) has long 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 will try 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. Our plan is to use a slightly exothermic reaction of $(t, ^{3}\mathrm{He})$. The triton beam of $T_t = 900$ MeV is produced by injecting the primary α beam onto a ^{9}Be target. The triton beam is acromatically transported to the SHARAQ target position and hits the ^{208}Pb or ^{90}Zr target. We proposed the beam time of 9 days and it was fully approved. The beam time is scheduled in 2010.

4 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

1) Precision laser spectroscopy of antiprotonic helium atoms at CERN's antiproton decelerator

Determination of proton-to-electron mass ratio 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.

Further improvements using Doppler-free spectroscopy In order to further improve the antiprotonic helium laser spectroscopy precision, we have developed, in 2008, three different methods to suppress the Doppler widths. They are, (1) two-color two-photon, (2) two-color saturation, and (3) single-color saturation methods. Sub- Doppler widths were observed in all these methods. By further refining one of these in coming years will make it 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).

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 The SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) project is currently in progress at the DAΦNE e^+e^- ring collider in LNF, Italy. Low energy kaons from DAΦNE beam line are stopped in a gaseous hydrogen target to produce the kaonic hydrogen atom. And the K-series x rays of the atom will be measured to a precision of a few eV to determine the shift and width of kaonic hydrogen $1s$-level with the best accuracy ever.

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, 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 start the kaonic helium 3 measurement in fiscal year 2009 at K1.8BR beamline. Construction of the beamline detectors, CDS (Cylindrical Detector System), ^{3}He target, and R&D of a new type of SDD are in progress.

3) Study of kaonic nuclei

Study of kaonic nucleus via the stopped K^- reaction on helium 4 In the $^4\mathrm{He}(K^-_{stopped}, YN/Yd)$ spectra measured in the KEK-PS E549, we have observed unresolved wide strength 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.

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 $^3\mathrm{He}(K^-, n/p)$ reaction to search for K^-pp and K^-pn. E15 is a kinematically complete experiment in which all reaction products are detected exclusively, and it aims to provide decisive information on the nature of the simplest kaonic nuclei. The experimental devices, which have many common parts with those used for E17, are now under construction, and the experiment is currently scheduled in year 2010∼2011.

4) Precision spectroscopy of pionic atoms

Precision spectroscopy of the $1s$ level of pionic atoms using the $(d,{}^3\mathrm{He})$ 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, and presently we are preparing the test experiment of the optics planned in May, 2009.

5 Ozawa Group

Research Subjects: Experimental study of non-perturbative QCD

Member: Kyoichiro Ozawa

We have three research activities.

- Study of quark-gluon-plasma and hadronic matter under high-temperature and high density condition at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory
- Study of mechanism of hadronic mass generation at J-PARC

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, properties of heavy flavor at dense matter have great interests, since heavy flavor has relatively large mass and be expected to have different behavior compared to light quarks. As a baseline measurements, we obtained cross section of charm and bottom generation separately in p+p collisions using two separated methods. We obtain the charm production cross section of $\sigma_{cc} = 544 \pm 39(\text{stat}) \pm 142(\text{syst}) \pm 200(\text{model})$ μb from dilepton invariant mass distribution. In addtion, we also measure a charm production cross section using single electron measurements and electron hadron correlation and we obtain the charm production cross section of and $\sigma_{cc} = 567 \pm 57(\text{stat}) \pm 224(\text{syst})$ μb. They are consistent with each other. The bottom production cross section of $\sigma_{bb} = 3.2 + 1.2\ -1.1$ (stat) $+1.4-1.3$ (syst) μb is also obtained. This is the first measurments at the current collision energy.

Study of mechanism of hadronic mass generation at J-PARC

Recently, the chiral property of QCD in hot($T \neq 0$) or dense($\rho \neq 0$) nuclear matter has attracted wide interest in the field of hadron physics. The dynamical breaking of chiral symmetry in the QCD vacuum induces an effective mass of quarks, known as constituent quark mass, which then determines the known mass of all the hadrons. In hot and/or dense matter, this broken 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 experimet 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 pricisely and compare with the theoretical predictions. We are also able to use larger and smaller nuclear targets as lead and proton, For this experimetn, new detector based on Gas Electron Multiplier (GEM), which is originally developped at CERN, is under developping. Using GEM, we are imvestigating 2 dimentional tracker for high rate counting. A prototype is reconstructed and reasonable signals are observed. An test experiment is performed at FUJI test beam line at KEK and detailed evaluation of postion resolution is done using an electron beam. As shown in Fig. 2.1.4, a position resolution of 100 μm is obtained.

In another experiment, 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. New neutron counter using TOF method is developped. The design of the neutron counter is shown in Fig. 2.1.5. Timing resolution of the counter is tested and we obtained 50 ps.

6 Komamiya group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) Data analysis for the BES-II experiment at BEPC-I, and TOF detector construction for BES-III experiment at BEPC-II; (3) Detector development for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (4) Preparation for physics analyses in the ATLAS experiment at the LHC pp collider; (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. 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. Also beam position monitors with a nano-meter position accuracy were developed with the KEK accelerator laboratory. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC.

2) 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 ia taking large samples of ψ' and J/ψ data.

3) 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 Li layer to convert neutron to charged nuclear fragments. The simulation studies on the quantum effects of UCN in a narrow slit with 100 [μ] height is also done. In 2008 we tested our neutron detector at ILL Grenoble. In 2009 we will start the first experiment at ILL.

4) ATLAS experiment at LHC: The epoc of new paradigm for particle physics is going to open with the experiments at LHC. LHC is going to be operated in 2009. The ATLAS detector is ready. Some of our students work on the preparation for physics analysis at LHC. Search for supersymmetric particles with the missing transverse energy, and detector related and physics background are under study.

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) W-boson physics. We have extensively searched for the Higgs boson at LEP. The Higgs boson was driven to a narrow mass range of 114-160 GeV. For supersymmetric particles searches the lower mass limit of the lightest neutralino, which is the most important candidate of the dark matter material, was set to be 38.0 GeV. The W boson mass was determined to be 80.412 ± 0.042 GeV (statistical and systematic errors combined).

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 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 $g_{a\gamma\gamma} < (5.6\text{–}13.4) \times 10^{-10}\text{GeV}^{-1}$ 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.

An R and D project of a resonance ionization mass spectroscopy, RIMS, is running aiming at neutrino detection by a trace analysis of an exotic atomic element produced by charged current interaction of an electron neutrino or an anti-electron neutrino on a nucleus in the target material. We first started with an analysis of metal contamination on a silicon wafer, which is a big issue in contemporary semiconductor industry and could potentially be improved by a use of RIMS. We introduced a blue LASER diode for the resonant excitation and a red LASER diode for the ionization, and successfully showed the effectiveness of the method by detecting a small amount of potassium vapor with a higher detection efficiency than the conventional ICP-mass spectroscopy. A clear discrimination of ^{39}K, ^{40}K and ^{41}K was demonstrated with a help of isotope shifts of the atomic levels. A hyperfine splitting of the 4s1/2 ground level was also observed clearly in each potassium isotope.

We also started a new R and D study of a compact mobile anti-electron neutrino detector with plastic scintillator 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 done a performance test of a plastic scintillator module, which is to be used as a building block of the detector. The basic design has been mostly completed with a help of computer simulation program.

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 for the discrimination between nuclear recoil events and electron recoil events. We are also studying a possibility of wavelength discrimination for the scintillation light. Furthermore, a new attempt is made to use quantum dots in the liquid scintillator to be deployed in the dark matter search. A quantum dot is a semiconductor whose excitons are confined in all three spatial dimensions. Upon excitation, it emits almost monochromatic light with a wavelength depending on its size. Its high quantum efficiency and tunable wavelength would be the advantage in making the scintillator. The scintillation light is confirmed in our preliminary experimental study by gamma-ray excitation.

8 Aihara 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), 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. Iwasaki, H. Kakuno, T. Abe, N. Hastings and T. Uchida

One of the major research activities has been a study of CP-violation in the B meson system using the KEK B-factory (KEKB). This past year we presented a measurement of CP violating asymmetries in the neutral B meson decaying to $K_S^0 K^+ K^-$. It was based on a data sample containing 657M $B\bar{B}$ pairs. By newly employing the time-dependent Dalitz plot analysis to the B^0 decays with $K_S^0 K^+ K^-$ final state, we directly measure the CP-violating phases in each significant decay channel, considering the interferences between them and potentially resolving two-fold ambiguity in the weak phases that arises in quasi-two-body time-dependent CP analyses. Evidence for CP violation at a significance of 3.9σ is found in the $B^0 \to \phi K_S^0$ decay and the result is consistent with the Standard Model expectation. We have also started to design a silicon vertex detector and the interaction region for the KEKB luminosity upgrade.

We have been working on the instrumentation of J-PARC beamline for T2K long baseline neutrino oscillation experiment. In particular, we have constructed and installed the position (Eelectrostatic) and profile (Segmentd Secondary Emission) monitors for the primary proton beams.

We have successfully developed 13-inch hybrid photodetector combining a large-format phototube technology and avalanche diode as photo-electron multiplier. 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 1.5 Giga pixel CCD camera (Hype 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. We have submitted Letter of Intent for SiD to ILC Research Director for validation of the detector concept.

1. Y. Nakahama, Ph.D.thesis "Measurement of CP -Violating Asymmetries in the Flavor-Changing Neutral Current Decays of the B Meson, " March, 2009.

2. T. Abe, "R&D status of large aperture Hybrid Avalanche Photo Detector," The 1st international conference on Technology and Instrumentation in Particle Physics (TIPP09), March 12-17, 2009, Tsukuba

3. H. Miyatake, T. Uchida, H. Fujimori, S. Mineo, H. Nakaya, H. Aihara, S. Miyazaki, "Prototype Readout Module for Hyper Suprime-Cam" ‘ 2008 IEEE Nuclear Science Symposium Conference Record ’, IEEE, 737-741, 2008.

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. $H \to \gamma\gamma$, $\tau\tau$ 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 (>100W) 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 2008 academic year include:

- Superconductivity in repulsively interacting electron systems
  — Superconductivity in iron-oxypnictides with a disconnected Fermi surface [1-3]
- Physics of Graphene
  — Quantum Hall effect in graphene: Topological aspects[4], edge states, Landau-level laser[5]
  — Photovoltaic Hall effect in graphene[6]
- Electron correlation effects in strong magnetic fields
  — Electron-molecule picture for 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]
  — Correlated electrons in intense laser lights[10,11]

— Dynamics of superfluid-Mott insulator transition in cold atoms in optical lattices[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. Novel Quantum States, Excited States, and Quantum Dynamics

In strongly interacting quantum systems, various interesting phases appear in the ground state. The coherent motion of quantum mechanics exhibits various characteristics which would play important roles in control 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 studied the properties of the super-solid state. We performed quantum Monte Carlo simulation (stochastic series expansion method) on the soft-core Hubbard model in a three-dimensional lattice (simple cubic), and observed successive phase transitions of the solid order and of the super-fluidity at finite temperatures. We also studied the ground state phase diagram as a function of the density of the particles. We found that the super-solid phase exists in a less-filled region, which has been denied in two-dimensional systems.

We study the magnetism of itinerant electron system on a lattice by using the Hubbard model. When an electron is removed from the half-filled state, the total spin of the system changes from zero to the maximum value if the lattice satisfies a certain condition (Nagaoka-ferromagnetism). We demonstrated an adiabatic change of this transition. Moreover we studied magnetic states of itinerant systems with larger spins, e.g. $S = 1$ (Boson) and 3/2 (Fermion), etc. These new magnetic phenomena could be realized in the optical lattice of the laser cooled atom systems.

We also studied nontrivial degeneracy of eigen-energies as a function of the transverse field in uniaxial large spins with terms of the single-ion type anisotropy which are models for single-molecular magnets. This degeneracy has been interpreted as an interference of the Berry phase. We showed that this degeneracy can be attributed to a parity symmetry of terms for the anisotropy. We also studied the distribution of the degenerate points in the parameter space of higher order terms for the anisotropy.

We studied the dynamics of magnetization under swept-field in the transverse Ising model, and found a kind of quantum spinodal decomposition phenomena with a collaboration of Professor Hans De Raedt of Groningen University and Professor Bernard Barbara of the Louis N´eel laboratory. In order to explain the size-independence of the magnetization process in fast sweepings, we introduced a new perturbation scheme for fast swept systems.

The transverse field is used in the quantum annealing to find the ground state of complicated systems. We studied the relation between the quantum fluctuation and the thermal fluctuation.

Besides the above topics, we studied control of photon state in micro-cavity with atom beams by studying a time-dependent Jaynes-Cummings model, and investigated the effect of observation on the photon state. We also studied generalized Yang-Baxter relation in large spin system with uniaxial anisotropy.

2. Phase Transition in Spin-Crossover Materials

We pointed out that the difference of the sizes of the high-spin (HS) and the low-spin (LS) states causes lattice distortions which interact through the elastic interaction. 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 are described by the corresponding mean-field theory (i.e., in the long-range interaction model) as well as the static critical property. We studied the excitation process from LS state to HS state at a low temperature by photo-irradiation. We found a threshold of the strength of the irradiation, below which the system stays in LS state and above which it jumps up to HS state. This threshold behavior can be regarded as a kind of spinodal phenomena. In short range model, the spinodal phenomenon is a crossover because the nucleation process smears a sharp transition in the relaxation time even in the infinite lattice. On the other hand, the present model exhibits threshold behavior as a true critical dependence. In order to analyze the scaling property of this singularity we studied the spinodal phenomena in a long-range-interaction system and obtained a finite scaling formula.

3. Formulations of Non-equilibrium Statistical Physics

We studied the formulism of time-evolution equation in contact with the thermal bath, and pointed out that the reduced density matrix of the equilibrium state of the total system gives the steady state of the reduced time-evolution equation. However, we also pointed out that the steady state of the quantum master equation obtained by the perturbation agrees with the reduced density matrix of the equilibrium state of the total system only in the leading order of the perturbation. That is, it only guaranties the zero-th order in the diagonal element, and the second order in the off-diagonal elements.

We also constructed concrete formula for the complex admittance which expresses the line shapes of the electron spin resonant (ESR). 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
  The t-J model as a mechanism for the oxide high-T_c superconductors.[1]
  Mott metal-insulator transition and superconductivity.
- New superconductor: Iron-pnictide
  New mechanism for iron-pnictide superconductivity, "unscreening" effect of Coulomb interaction.[2]
  Normal-state spin dynamics of five-band model for iron pnictides.[3]
- Organic conductors
  Dimensional crossover and superconductivity in quasi-one-dimensional organic conductors.[4]
  Novel spin-liquid state in an organic system induced by one-dimensionalization.
  Static nonequilibrium state of the competing charge orders under an electric field.[5]
- Theories of anisotropic superconductivity
  Superconductivity and antiferromagnetism in a non-centrosymmetric system.[6]
  FFLO superconductivity near an antiferromagnetic quantum critical point.[7]
  Anderson localization and superconductivity fluctuation in an impurity band.[8]
- Interband effects of magnetic field on Hall effects for Dirac fermion systems. [9]
- Electronic and spin states in frustrated systems
  Four-state classical Potts model with a novel type of frustrations as a model for rattling.
  Ground states of the frustrated quasi-two-dimensional Hubbard model.[10]
- Kondo effect and heavy fermion systems
  Fermi surface reconstruction with Kondo screening at quantum critical point.[11]
- Two-dimensional ^{3}He system on graphite
  A new quantum liquid realized in the two-dimensional t-J-K model with ring-exchange interaction.[12]
- Microscopic theory for the magnetic domain wall driving.[13]

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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.

Our research subjects in FY2008 were as follows:

- Applications of first-principles electronic structure calculation
  - Electronic structure of GaN and its interface
  - Stability and band profile of a SiON insulating layer on SiC(111)
  - Chemisorption mechanism of an SO_2 molecule on Ni
  - Two-Electron Reduction of a Rh-Mo-Rh Dithiolato Complex
  - Oxygen vacancy and hydrogen impurities in $BaTiO_3$
  - 3D C60 polymer
  - Phonon and thermodynamic properties of SiO_2 and TiO_2
- New methods of electronic structure calculation
  - First-principles wavefunction theory for solids based on the transcorrelated method
  - Electronic structure calculation of proteins based on the fragment molecular orbital method

14 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

We study the electronic structures of strongly correlated systems using high-energy spectroscopic techniques such as photoemission spectroscopy, x-ray absorption spectroscopy and 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), Kojima Kenji M. (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 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: Kondo effect and RKKY interaction in surface-state conduction. Surface-state conductivity of topological insulators. Metal-insulator transitions, hopping conduction, and a Mott insulator in surface states. Quantitative evaluation of surface-state conductivity from Fermi surface mapping. Quasi-ballistic transport at a Fe-silicide nanowires.

(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 Pb, Bi, and Ag 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):

Two-dimensional (2D) quantum fluids and solids with strong correlations and frustration,

Low temperature scanning tunneling microscopy and spectroscopy of 2D electron systems (2DES) and exotic superconductors.

Member: Hiroshi Fukuyama, Tomohiro Matsui

Our current interests are (i) new quantum phases with strong correlations and frustration in 2D ^{3}He, (ii) novel phenomena in Graphene, a single sheet of graphite, and (iii) Kosterlitz-Thouless transitions 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. **Novel quantum phases in 2D ^{3}He:**

   We are studying novel quantum phases in the second layer ^{3}He adsorbed on graphite preplated with monolayer ^{4}He. ^{3}He atoms localize at a commensurate 4/7 density ($\rho_{4/7} = 6.8\text{nm}^{-2}$) of the first layer. We made heat capacity measurements of this system in a wide temperature range of $0.3 < T < 80$ mK revealed various quantum phases exist at densities below and above $\rho_{4/7}$.

(a) **Various quantum phases at densities higher than the commensurate 4/7 phase**
In a relative density region of $1 \leq n \equiv \rho/\rho_{4/7} \leq 1.2$, newly added atoms form a degenerated self-bound Fermi liquid (puddles) of a density of 1.2 nm^{-2} in the third layer. This is in clear contrast to the absence of the gas-liquid transition in the first- and second-layers on graphite. It is followed by a first-order phase transition between the 4/7 phase and a high-density ferromagnetic incommensurate phase in the second layer. The coexistence region is from $n = 1.2$ to 1.4. Above $n = 1.4$, the pure incommensurate phase appears where the multiple-spin exchanges up to the six-spin exchange compete each other resulting in the frustrated ferromagnetism. We found that the three spin exchange tends to dominate with increasing density from quantitative analyses of the measured temperature dependences of heat capacities.

(b) **Zero-point vacancy phase at densities lower than the 4/7 phase**
At densities just below the 4/7 phase, on the other hand, the zero-point vacancies (ZPVs) are supposed to exist from our previous heat-capacity measurements. The ZPVs are atomic vacancies which exist stably and hop on crystalline lattice cites even at absolute zero. The spin-spin relaxation time (T_2) in this phase were measured with the spin-echo technique of pulsed-NMR in a longer time span than our previous measurements. We found that the echo amplitude decays exponentially with two time constants. Our analysis shows that such a non-single-exponential decay is not due to macroscopic two-phase coexistence between the 4/7 phase and a low density fluid phase but to the mosaic angle spread of the graphite substrate.

2. **STM/STS studies of graphene:**

Graphene is a monatomic sheet of carbon atoms in which the atoms are densely packed in a honeycomb lattice. The charge carriers behave as massless Dirac fermions due to the unique linear dispersion relation, which results in unusual electronic properties such as anomalous integer quantum-Hall-effect and weak anti-localization, *etc.*

We are studying two kinds of graphene samples, i.e., exfoliated graphene and epitaxial graphene. The exfoliated graphene is fabricated by exfoliating a graphite crystal on an insulating SiO_2 substrate, while the epitaxial graphene is epitaxially grown on an SiC surface.

(a) **STM studies of exfoliated graphene**
We fubricated a micro-structure of evaporated Au film around an exfoliated graphene sample to guide an STM tip successfully to the sample surface. Thanks to such a micro-structure, we succeeded in obtaining atomically resolved STM images of graphene with either hexagonal or triangular lattices in the ambient condition. However, it was found that we need to develop more careful cleaning process of resist residue after the micro-fabrication to obtain more reliable STM images.

(b) **LEED and STM studies of epitaxial graphene on SiC**
Graphene samples are fubricated on an Si-*rich* phase of 6H-SiC substrate by successive falsh-annealing up to 1600 K. LEED measurements of the resultant sample surfaces show clear diffraction spots of a few layers of graphene together with those of SiC, which indicates that flat graphene layers have been grown on SiC to some macroscopic extent. In fact, graphene regions with the $6\sqrt{3} \times 6\sqrt{3}$ structure, which is known to be characteristic of a few layer graphene on SiC, are observed at places with STM at $T = 79$ K .

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 performed systematic magnetotransport measurements on a very high mobility Si 2DES in the vicinity of the coincidence of the spin-up and spin-down LLs with $n = 0$ and 1, respectively.

   At low temperatures, the resistance peak having a strong anisotropy shows large hysteresis which is attributed to the Ising quantum Hall ferromagnetism. The peak is split into two peaks in the paramagnetic regime. A mean field calculation for the peak positions indicates that electron scattering is strong when the pseudospin is partially polarized. We also study the current-voltage characteristics which exhibit a wide voltage plateau. [Toyama *et al.*, Phys. Rev. Lett. **101**, 016805 (2008).]

   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.

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.

   Low-temperature Hall measurements have been performed on two-dimensional electron gases (2DEGs) induced by deposition of Cs or Na on *in situ* cleaved surfaces of *p*-type InAs. The surface donor level, at which the Fermi energy of the 2DEG is pinned, is calculated from the observed saturation surface electron density using a surface potential determined self-consistently. The results are compared to those of previous photoelectron spectroscopy measurements. [Minowa *et al.*, Phys. Rev. B **77**, 233301 (2008).]

   Magnetotransport measurements have been performed on two-dimensional electron gases formed at InAs(110) surfaces covered with a submonolayer of Fe. Hysteresis in the magnetoresistance, a difference in remanent magnetoresistance between zero-field-cooling procedures and field-cooling procedures, and logarithmic time-dependent relaxation after magnetic field sweep are clearly observed at 1.7 K for a coverage of 0.42 monolayer. These features are associated with spin-glass ordering in the Fe film. [Mochizuki *et al.*, Phys. Rev. Lett. **101**, 267204 (2008).]

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: 1)optically excited high density electron-hole systems in semiconductors, low dimensional systems such as 2) carbon nanotubes, 3) quasi-1D organic conductors, 4)superconductors, and 5) multi-ferroic materials. In order to investigate the role of electron correlations in the excited state as well as the ground state, we are focusing on the low energy electromagnetic responses in terahertz(THz) (1THz$\sim$4meV) frequency range where quasi-particle excitations and various collective excitations exist. A novel experimental technique such as THz Faraday rotation spectroscopy is also developed to study the optical responses of quantum Hall system and also anomalous Hall effect in ferromagnets.The research summary in this year is as follows.

1. **High density electron-hole system :**

   Photo-excited electron-hole(e-h) system in semiconductors exhibits various phases depending on their density and temperature, such as exciton gas, e-h plasma, e-h droplets(EHD). At low temperature, excitonic Bose Einstein condensation, or e-h BCS state is anticipated to exist. To investigate such variety of phases in e-h systems, we have developed a broadband terahertz spectroscopy technique which can directly access to the many-body electron correlation with ps temporal resolution. We applied the scheme to Si, the most well-known material which is also attractive for the study of high density e-h phenomena due to relatively long carrier lifetime and also due to the existence of electron-hole droplets. The formation dynamics of excitons is revealed by the 1s-2p Lyman transition of exciton that exist at 3THz. Formation of EHD is also studied through the observation of surface plasmon resonance(SPR) that exists in THz frequency range. The spatial condensation mechanism of EHD shows the spinodal decomposition behavior.

2. **Quasi-1D organic conductor :**

   We have studied the optical responses of quasi-1D organic conductor $(TMTSF)_2PF_6$ which shows metal-insulator transition below 12K accompanied by spin density wave formation. Since the single particle excitation energy in SDW phase is located in terahertz frequency range, it is possible to investigate the dynamics of SDW phase under photo-excitation by terahertz time domain spectroscopy. We have developed a reflection type optical-pump and THz-probe measurement system with diffraction-limitted spatial resolution, which allows one to measure small samples less than 1mm that is typical for organic conductor single crystals. After the ultrafast optical pulse excitation, a clear SDW gap collapse and revival is observed, of which relaxation time shows a slowing down behavior towards the transition temperature.

3. **THz Hall effect in ferromagnets and quantum Hall system**

   Transmission type terahertz polarization spectroscopy setup combined with a 7T superconductor magnet was developed to investigate the complex diagonal and off diagonal conductivity of materials. By using the developed system, we have measured the THz-Faraday rotation signal a perovskite itinerant ferromagnet, $SrRuO_3$ to reveal the origin of anomalous Hall effect. The results are interpreted in terms of Berry phase curvature of Bloch electron. The technique is also applied to 2 DEG system of a GaAs/AlGaAs heterostructure to study the quantum Hall effect.

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20 Theoretical Astrophysics Group

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

Member: Katsuhiko Sato, 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;
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:

- Remote extraction and destruction of asymmetrically spread qubit information [1]
- Thermal robustness of multipartite entanglement of 1-D spin 1/2 XY model [2,3]
- Group theoretical study of quantum reference frames [4,5,6,7]
- Authorized quantum computation [8]
- Geometric analysis of multipartite entanglement of symmetric states
- Nonlocality of Bipartite Unitary Operations
- Reference-frame-free communication with quantum spins
- Operational indistinguishability in quantum tomography
- Maximum-likelihood and Bayesian reconstruction schemes in quantum measurement tomography
- Altering descriptions of unitaries in mesurement-based quantum computation

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

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8. Y. Tanaka and M. Murao, *Authorized quantum computation*, arXiv:0903.2088 (quant-ph)

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 Knots in a Spinor Bose-Einstein Condensate

Topological objects are conjectured to play important roles in the formation of our universe. Among them, knot solitons have recently aroused the interest of cosmologists since Faddeev and Niemi suggested that knots might exist as stable solitons in a three-dimensional classical field theory. Knots are different from other familiar topological defects, such as vortices, monopoles, and skyrmions, in that knots are characterized by a linking number, or a Hopf invariant, while the others are characterized by winding numbers. Though there are many theoretical studies on knots, little is known about how to create such knots experimentally. In Ref. [1], we have shown that atomic BECs offer an ideal testing ground for investigating the dynamic creation and destruction of knots. In particular, we have shown that knots of spin textures can be created in the polar phase of a spin-1 BEC by using conventional magnetic field configurations, and proposed possible experimental schemes for generation and probe of knots.

22.2 Heteronuclear Fermionic Superfluids with Spin Degrees of Freedom

We present a theory of spinor superfluidity in a two-species heteronuclear ultracold fermionic atomic gas consisting of arbitrary half-integer spin and spin one-half atoms. In particular, we focus on the magnetism of the superfluid phase and determine the possible phases in the absence of a magnetic field. Our work demonstrates similarities between heteronuclear fermionic superfluids and spinor Bose-Einstein condensates at the mean-field level. Possible experimental situations are discussed [2].

22.3 d-Wave Collapse and Explosion of a Dipolar Bose-Einstein Condensate

We investigate the collapse dynamics of a dipolar condensate of ^{52}Cr atoms when the s-wave scattering length characterizing the contact interaction is reduced below a critical value. A complex dynamics, involving an anisotropic, d-wave symmetric explosion of the condensate, is observed. The atom number decreases abruptly during the collapse. We find good agreement between our experimental results and those of a numerical simulation of the three-dimensional Gross-Pitaevskii equation, including contact and dipolar interactions as well as three-body losses. The simulation indicates that the collapse induces the formation of two vortex rings with opposite circulations [3].

22.4 Miminal Energy Cost for Thermodynamic Information Processing

One of the pioneering work which related information to thermodynamics is Landauer's principle. It states that, in erasing H nat ($= H/\ln 2$ bit) of the Shannon information from a memory, at least $k_{\mathrm{B}}TH$ of heat should be dissipated into the environment with the same amount of work being performed on the memory. However, the proof of the Landauer's principle in terms of statistical mechanics was given in 2000, and the proof is valid only for symmetric memories. We have derived the minimal work that needs to be performed on a memory for information erasure. The lower bound of the work W_{eras} for the erasure is given by $W_{\mathrm{eras}} \geq k_{\mathrm{B}}TH - \Delta F$, where $-\Delta F$ is the free-energy difference of the memory during the erasure.

For the special case of the symmetric memory (i.e., $\Delta F = 0$), we obtain $W_{\rm eras} \geq k_{\rm B}TH$ in agreement with the Landauer's principle. However, when $\Delta F \neq 0$, the information erasure with $W_{\rm eras} < k_{\rm B}TH$, in particular with $W_{\rm eras} = 0$, is possible. We have also constructed a model in which the Landauer's principle for information erasure fails for an asymmetric memory. Moreover, we have derived the fundamental lower bound of the work $W_{\rm meas}$ for measurement: $W_{\rm meas} \geq -k_{\rm B}T(H-I)+\Delta F$, where I is the mutual information that is obtained by the memory during the measurement. The mutual information satisfies $0 \leq I \leq H$. For the special case of the error-free measurement ($I = H$) and the symmetric memory ($\Delta F = 0$), this inequality reduces to $W_{\rm meas} \geq 0$. In our inequalities, the information contents I and H and thermodynamic variables are treated on an equal footing. Our results are consistent with the second law of thermodynamics, and constitute a informatic generalization of the second law.

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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.

The *Suzaku* and *Fermi* satellites: We utilize the X-ray satellite *Suzaku* and the gamma-ray mission *Fermi* [7], launched in July 2005 and June 2008, respectively. For the former, we developed the Hard X-ray Detector (HXD), working in 10–600 keV, in collaboration with several domestic and US groups [2].

Physics of Compact Objects: Mass accretion onto compact objects provides our favorite research subject. Utilizing wide-band *Suzaku* spectra, we are constructing a unified "cool disk plus hot corona" view of mass-accreting black holes, including stellar-mass ones [1], ULX objects [3], and active galactic nuclei [4]. Our *Suzaku* observations of several "magnetars" have revealed unusual hard X-ray components, extending to $\sim$ 100 keV with very flat spectra [6]. This phenomenon is expected to provide a valuable probe into physics under extremely strong magnetic fields, exceeding the critical field (4.4×10^{13} G) at which the Landau-level separation for electrons becomes equal to $m_{\rm e}c^2$.

Plasma Heating and Particle Acceleration: The universe is full of processes of plasma heating and particle acceleration. The extended hard X-ray emission, which we detected from the Galactic center region, suggests the presence of ubiquitous particle acceleration in the interstellar space. Our search for non-thermal emission from merging clusters of galaxies have led to an unexpected discovery of unusually hot thermal emission [5]. *Fermi* observations of molecular clouds revealed gamma-ray emission arising from the decay of π^0 particles, which are produced by cosmic-ray hadrons. The *Suzaku* HXD has been shown to have a potential to detect neutrons produced in large solar flares.

Particle Acceleration in Thunderclouds: From thunderclouds along the Japan Sea and at high mountains, we detected nearly ten events of gamma-ray showers. Some of them last only for < 1 second, while others for 1–2 minutes. The gamma-ray spectrum extends to 10 MeV, and is sometimes accompanied by electrons. 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* (previously called *NeXT*). Scheduled for launch in 2013, it will carry out hard X-ray imaging observations and high-resolution X-ray spectroscopy. Our effort includes the development of "SpaceWire" technology, large BGO scintillators, and double-sided Si-strip detectors.

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24 Takase Group

Research Subjects: High Temperature Plasma Physics Experiments, Spherical Tokamak, 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.

Formation, heating and sustainment of the TST-2 spherical tokamak plasma

It is crucially important for ST to develop a scenario of plasma formation, heating and sustainment without the use of the central solenoid (CS). The physics of noninductive plasma initiation by RF power is being investigated on TST-2. Plasma is initiated and a small plasma current is formed by injection of microwave power at 2.45 GHz, which is resonant with electron cyclotron gyration. Once the plasma current reaches a threshold level, closed flux surfaces are formed spontaneously and the plasma current increases abruptly (current jump). Sustainment of the plasma current by radio-frequency power at 21 MHz was also demonstrated for the first time. Plasma heating by the high harmonic fast wave (HHFW) at 21 MHz is being investigated. A degradation of the heating efficiency was observed when a nonlinear process known as parametric decay was observed. The probes far from the exciting antenna detected stronger pump wave and broader frequency spectrum than probes near the antenna. The high beta plasma produced in ST is highly autonomous. Spontaneous deformation of the plasma by an instability and subsequent recovery are observed. This process involves nonlinear coupling of multiple modes leading to reconnection of magnetic field lines, and is called the internal reconnection event (IRE).

Formation of Ultra-High Beta Plasma by Plasma Merging

A new ST device, UTST, aiming at formation of ultra-high beta plasma by plasma merging, is now in operation. Two ST plasmas are formed by induction from external coils. Strong ion heating due to magnetic reconnection is expected to form one ST plasma with very high beta (30–50%). It is challenge to maintain the plasma in such a state for long enough time (exceeding the energy confinement time) after reconnection is over. This is planned to be accomplished by innovative methods of heating and current drive using RF waves (such as the HHFW) and neutral beam injection.

Collaborations

Collaborative experiments are being carried out on the JT-60U tokamak at Japan Atomic Energy Agency (JAEA). Plasma current sustainment by the bootstrap current, driven spontaneously by the pressure gradient, was demonstrated for the first time. Collaborations with larger ST devices NSTX (USA) and MAST (UK), as well as a high magnetic field tokamak device Alcator C-Mod (USA) are also being carried out. Experiments and data analysis focusing on the IRE were performed on MAST (Culham Lab., UK). The poloidal structure of the modes obtained from the three dimensional filamentary model showed coupling of multiple modes and suggested local deformation of the plasma which leads to collapse through magnetic reconnection. In a collaboration with Kyushu University and National Institute for Fusion Science, parametric-modulational interaction between the drift-wave fluctuation (7–8 kHz) and the azimuthally-symmetric sheared radial electric field structure (∼0.4 kHz) was observed in a cylindrical laboratory plasma. Bispectral analysis showed that nonlinear energy transfers from the drift wave to the sheared radial electric field occur.

25 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Masaki ANDO

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. Now the detection of the gravitational waves is one of the biggest challenges in the field of physics and astronomy.

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 can operate the detector for over 24 hours stably and continuously, and have accumulated over 3,000 hours data. We are now analyzing the obtained data searching for the gravitational waves from coalescing binaries, supernovae and pulsars. We are expecting to start the Japanese large-scale laser interferometer, LCGT, soon.

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 have just stared the theoretical and technical investigation for the realization of the DECIGO space detector.

We summarize the subjects being studied in our group.

- Ground based laser interferometric gravitational wave detectors
  - Current status of TAMA project
  - Study of the next-generation laser interferometer, LCGT
  - Caltech 40-m laser interferometer
- Space laser interferometer

  - Space laser interferometer, DECIGO
  - DECIGO pathfinder, DPF
  - Small size detector, SWIM

- Development of a gravitational wave detector using magnetic levitation
  - Gravitational wave detector using superconducting magnetic levitation
  - Experiments using permanent magnets

- Study of the precise measurements
  - Laser stabilization using optical fiber
  - Laser interferometer using squeezed light

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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 a particular 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 observe 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 radio telescopes such as Nobeyama 45 m telescope and IRAM 30 m telescope.

We have recently established a new chemistry occurring in the vicinity of a newly born star, which is called Warm Carbon Chain Chemistry (WCCC). We have found high abundances of various carbon-chain molecules in a lukewarm region near the protostar in L1527. This is very surprising, because carbon-chain molecules are known to exist in the early stages of cold starless cores. 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 variety of low-mass star forming regions, which would probably reflect a variety of star formation.

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 diffusion cooled HEB mixer using Nb and the phonon cooling HEB mixer using NbTiN 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. We are also studying bath-temperature dependence of the noise temperature in order to explore the mixing mechanism of the HEB mixer.

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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) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. (3) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (4) Ultrafast phenomena in atoms and molecules in the attosecond time scale. A part of our recent research activities is as follows:

(1) Laser-field-free molecular orientation [1]

We demonstrate laser-field-free molecular orientation with the combination of a weak electrostatic field and an intense nonresonant rapidly turn-off laser field, which can be shaped with the plasma shutter technique. We use OCS molecules as a sample. Molecular orientation is adiabatically created in the rising part of the laser pulse, and it is found to revive at around the rotational period of an OCS molecule with the same degree of orientation as that at the peak of the laser pulse in the virtually laser-field-free condition. This accomplishment means that a new class of molecular sample has become available for various applications.

(2) Field-free molecular orientation by an intense nonresonant two-color laser field with a slow turn on and rapid turn off [2]

We propose a practical and versatile technique to achieve completely field-free molecular orientation with an intense, nonresonant, two-color laser field with a slow turn on and rapid turn off. The technique is based on the combined effects of both anisotropic polarizability interaction and anisotropic hyperpolarizability interaction. Using a FCN molecule as a sample, we show that the orientation achieved adiabatically by the peak of the laser pulse can be successfully revived at the rotational period of the molecule with the same degree of orientation. The crucial importance of the sufficiently slow turn on of the laser pulse is emphasized to achieve the highest possible degree of orientation.

(3) Retrieving photorecombination cross sections of atoms from high-order harmonic spectra [3]

We observe high-order harmonic spectra generated from a thin atomic medium, Ar, Kr, and Xe, by intense 800-nm and 1300-nm femtosecond pulses. A clear signature of a single-atom response is observed in the harmonic spectra. Especially in the case of Ar, a Cooper minimum, reflecting the electronic structure of the atom, is observed in the harmonic spectra. We successfully extract the photorecombination cross sections of the atoms in the field-free condition with the help of an accurate recolliding electron wave packet. The present protocol paves the way for exploring ultrafast imaging of molecular dynamics with attosecond resolution. This work is the collaboration with Drs. Toshihito Umegaki, Toru Morishita, and Shinichi Watanabe from University of Electro-Communications, and Dr. Anh-Thu Le from Kansas State University.

(4) Alignment dependence of the structural deformation of CO_2 molecules in an intense femtosecond laser field [4]

Alignment dependence of structural deformation in the production process of multiply charged CO_2 molecules in an intense femtosecond laser field has been revealed by using aligned sample molecules. Our properly ordered observations clarify that the structural change takes place in the charge state of CO_2^{2+}. The bending angle decreases monotonically from the maximum value of 24° with the laser polarization parallel to the molecular axis to the minimum value of 16° with the polarization perpendicular to the molecular axis. The alignment dependence is discussed in terms of the field-induced nonadiabatic transition between the lowest two adiabatic states formed by the coupling between the electronically excited and the ground states of CO_2^{2+} ions.

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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: Myosin, kinesin and dynein in in vitro and cells

Member: Hideo Higuchi and Motoshi Kaya

Motor proteins, myosin, kinesin, and dynein, play roles in cell motility, vesicle transport, mitosis, and muscle contraction. To understand the molecular mechanisms of the motility, an in vitro motility assay and methods for detecting single molecules of purified motor proteins were developed Single kinesin-1, Cytoplasmic dynein and myosin-V move processively using 8, 8 and 36 nm steps, respectively, at a maximum velocity of 900, 800 and 500 nm/s and produce stall forces of 8, 8 and 2.5 pN. The movements of kinesin, dynein, and myosin V and VI have been explained by a‘‘ hand-over-hand ’’model. Physiological conditions in the cell environment are very different from those in in vitro assays. Therefore, it is crucial to measure the molecular functions of motor proteins in cells. We observed the transport of vesicles including Quantum dots after the endocytosis in cells under a fluorescence microscope. The vesicles moved along the membrane by transferring actin filaments and were then rapidly transported toward the nucleus along microtubules. The movement of the vecicles transported by myosin VI interacting with actin filaments consisted of 29- and 15-nm steps. The vesicles were then transported toward or away from the nucleus with successive 8-nm steps. Kinesin and dynein showed an interesting behavior of “ Stop and Go ” whereby they came to be almost paused briefly and then moved once again . This is in direct contrast to the smoothly continuous movement of them in an in vitro assay. Maximum velocity of kinesin in cells was faster than that in the in vitro assay. These results suggest that intracellular movements of motors are different from those in the in vitro assay.

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