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Department of Physics
School of Science
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Annual Report
2004
Summary of group activities

東京大学 大学院 理学系研究科・理学部
物理学教室

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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

Member: Takaharu Otsuka, Tetsuo Hatsuda, Naoyuki Itagaki, Shoichi Sasaki, and Sinji Ejiri

In the nuclear theory group, a wide variety of subjects are studied. The subjects are divided into two major categories. One is Nuclear Structure Physics and the other Hadron Physics。

Nuclear Structure Physics

In Nuclear Structure group (T. Otsuka and N. Itagaki), 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, cluster model and quantum chaos.
The structure of unstable nuclei is still the major focus of our interests, and the disappearance of N=20 magic gap was examined for Na and Mg isotopes by using the Monte Carlo Shell Model [1, 2]. In particular, the tensor force effects have been studied extensively from the viewpoints of the shell model and the mean-filed calculation, the chaos has been investigated as a possible origin of regularity, and the clustering has been studied including its competition with the shell structure [3, 4]. The former two subjects have no references yet. The collective motion has been studied from various microscopic angles based on Monte Carlo and pair-truncated shell model calculations [5, 6].

Hadron Physics

In Hadron Physics group (T. Hatsuda, S. Sasaki and S. Ejiri), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum choromodynamics (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, and color superconductivity.

Highlights in research activities of this year are listed below.

1. Physics of high density and/or high temperature matter
    - 1.1 QCD thermodynamics from lattice gauge simulations [7]
    - 1.2 Color superconductivity in quark matter [8, 9]
    - 1.3 Hadrons in quark-gluon plasma [10, 11]
2. QCD structure of hadrons
    - 2.1 Lattice QCD study of the penta-quark [12]
    - 2.2 Color molecular dynamics simulation the penta-quark [13]

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Member: Tohru Eguchi, Tsutomu Yanagida, Yutaka Matsuo,
Ken-Ichi Izawa, Yuji Sugawara, Yosuke Imamura, Teruhiko Kawano

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

We list the main subjects of our researches below.

1. Superstring Theory.
   - 1.1 Strings in curved background and D-branes [1, 3, 6, 7, 8, 9, 12, 16, 19, 20]
   - 1.2 String field theory [2, 13]
   - 1.3 p-adic strings [10, 17]
   - 1.4 AdS/CFT correspondence [11, 18]
2. Field Theory.
   - 2.1 Nonlinear gauge theories [14]
   - 2.2 Solitons in supersymmetric theories [22]
3. High Energy Phenomenology.
   - 3.1 Phenomenology of supersymmetric models [4, 15, 21]
   - 3.2 Particle cosmology [5, 23]

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3 Sakai 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.

Study of Gamow-Teller unit cross sections at 300 MeV

We are studying the behavior of pions in nuclei by measuring the total strength of the Gamow-Teller (GT) excitations in the $^{90}\mathrm{Zr}(p,n)$ and $^{90}\mathrm{Zr}(n,p)$ reactions at 300 MeV. An important ingredient is the GT unit cross section, which is used when measured GT cross sections are converted to the GT strengths. To obtain the GT unit cross section, we have measured the double differential cross sections for the $^{58}\mathrm{Ni}(p,n)$, $^{70}\mathrm{Zn}(p,n)$, $^{118}\mathrm{Sn}(p,n)$, and $^{120}\mathrm{Sn}(p,n)$ reactions at 300 MeV using the neutron time of flight facility at Research Center for Nuclear Physics. A mass number dependence of the GT unit cross section for the medium heavy nuclei at 300 MeV has been obtained for the first time. The GT unit cross section for $^{90}\mathrm{Zr}$ is estimated to be 3.45 ± 0.12 mb/sr. This value is consistent with the value we used previously, 3.5 ± 0.6 mb/sr while the accuracy is much improved.

Experimental test of Bell's inequality via the $(d, {}^2\mathrm{He})$ reaction

In 1935, Einstein, Podolsky and Rosen presented a paradox to quantum correlations and concluded that the quantum mechanical description of nature is incomplete. So-called hidden variables are introduced in the classical approach to describe the correlation. The Bell's inequality, discovered in 1964, shows that correlation produced by the hidden variables is weaker than that predicted by quantum mechanics. Since then many experimental tests on the Bell's inequality have been performed by using entangled photon pairs, while there are almost no severe tests in hadronic systems. To test the Bell's inequality in a two-proton system, we have measured the spin correlation between the two protons in $[{}^1\mathrm{S}_0]$ produced by the $^1\mathrm{H}(d, {}^2\mathrm{He})$ reaction. The violation of Bell's inequality is demonstrated with an accuracy of 2.9 standard deviations, which corresponds to a convidence level of 99.6%.

We are planning a similar measurement for the proton-neutron system. A neutron polarimeter system is under development.

Search for super narrow dibaryon via the p+d scattering

One of the interesting predictions of the quantum chromodynamics is the existence of six-quark states, i.e. dibaryons. No decisive conclusion has been drawn on the existence of the dibaryons after more than twenty years of experimental efforts. Recently Fil'kov *et al.* have found three narrow resonances in the p+d scattering data at the Institute for Nuclear Research. The resonances were claimed as candidates of super-narrow dibaryons, whose decay by the strong force was forbidden by the Pauli principle and the energy conservation law. We have performed an experiment to study the resonances with an order higher statistical accuracy under very low background condition by employing a liquid deuterium target and two magnetic spectrometers. No peaks are found in the missing mass spectra in the mass region of 1898 - 1952 MeV. Our analysis of the upper limit cross section excludes two out of three candidates with dibaryon masses of 1904 MeV and 1926 MeV. The candidate at 1942 MeV is not excluded.

4 Hayano Group

Research Subjects: Study of fundamental symmetries using exotic nuclei and exotic atoms.

Member: Ryugo S. Hayano, Takashi Ishikawa, Ryo Funakoshi and Eberhard Widmann

'Exotic nuclei' and 'Exotic atoms' are the keywords of Hayano group. We study deeply bound states of mesons (π^-, K^-, and η) and nuclei to investigate the partial restoration of chiral symmetry in the nuclear medium. We also use antihydrogen atoms (antiproton + positron), antiprotonic helium atoms (helium nucleus + antiproton + electron), antiprotonic helium ions (helium nucleus + antiproton) to study matter–antimatter symmetry (CPT) which is the most fundamental symmetry of nature.

- **Discovery of a strange tribaryon S^0(3115) at KEK**

  Motivated by theoretical predictions that kaons can form deeply-bound states in light nuclei, we performed a search for such states by stopping negative kaons (K^- meson) in a liquid helium target, and by measuring the energies of neutrons and protons emitted from the reaction. A monoenergetic peak was observed in ^{4}He($stopped K^-, p$) spectrum. This peak was interpreted as a new kind of tribaryon S^0(3115) with strangeness $S = -1$ and isospin $T = -1$.

- **High-precision tests of matter-antimatter symmetry at CERN-AD (Switzerland)**

  - **Antihydrogen**
    The antihydrogen atom is the bound state of an antiproton and a positron, and it is the antimatter counterpart of the hydrogen atom. In 2004, as the first step towards high-precision spectroscopy of antihydrogen, the ATHENA experiment attempted to perform laser-induced formation using a CO_2 laser to induce the radiative combination of a positron and an antiproton to produce antihydrogen with principal quantum number $n = 11$. Preliminary results indicate that we did not observe a high laser-induced formation rate, but there seems to be some indication that we produced $n = 11$ antihydrogen. Analysis of the data is still ongoing.
  - **Antiprotonic helium atom** Antiprotonic helium is an exotic metastable 3-body 'atom' (consisting of a helium nucleus, an antiproton, and an electron: He^{++}–$\bar{p}$–e^- (short $\bar{p}He^+$) discovered by our group, and is continuously studied in detail by using the laser-spectroscopy and microwave-spectroscopy techniques by the ASACUSA collaboration at CERN AD. In 2004, improvement of the precision of the laser spectroscopy by a factor of 10 was achieved by using a new narrow-band laser system calibrated and stabilyzed by an optical frequency comb. Potentially, we can reach a precision of 10^{-9} (1 ppb) for the antiproton-proton mass & charge comparison.
  - **Antiprotonic helium ion** In 2003 we succeeded in observing also metastable antiprotonic helium ions, two-body systems $^4He^{++}$–$\bar{p}$ (short $\bar{p}^4He^{2+}$) and $^3He^{++}$–$\bar{p}$ (short $\bar{p}^3He^{2+}$) and measured the density-dependent lifetime of various states. It was shown that the lifetimes of $\bar{p}^3He^{2+}$ against annihilation induced by collisions were shorter than those of $\bar{p}^4He^{2+}$, and decreased for states with larger pricipal quantum numbers. These results indicate that the laser spectroscopy of $\bar{p}He^{2+}$ may be possible, by inducing transitions between ionic states with different principal quantum numbers n and making use of n dependence of their lifetimes to detect the resonance signal. Since the energy levels of this highly-excited two-body system can be calculated to a much higher precision than the three-body system, it can be used to obtain theory-independent measurements of the antiproton charge and mass in the future.

- **Partial restoration of chiral symmetry in nuclei – study of the origin of proton mass at GSI (Germany)**

  Following the observation of partially restored chiral symmetry in nuclei, obtained by the study of deeply bound pionic Pb and pionic Sn atoms, we started a new experiment to study η–mesic nuclei. We are aiming at producing bound states of η meson and ^{11}B nucleus and measuring its binding energy and width. Purpose of this experiment is to extract further information on the chiral symmetry restoration in nuclear medium.

5 Sakurai Group

Research Subjects: Structures and Reactions of Extremely Neutron-rich Nuclei, and Nuclear Reactions Related with Astrophysical Phenomena

Member: Hiroyoshi Sakurai, Hironori Iwasaki

Research activities of our laboratory have covered a particular domain of nuclear physics, i.e., the field brought out by the advent of the radioactive isotope (RI) beams, emphasizing an isospin degree of freedom in nuclei. The recent developments of RI beams have opened an access to a drastically enlarged range of nuclear species as well as nuclear reactions involving such radioactive isotopes. Our research programs are coordinated to exploit these new opportunities and are directed to subjects related to 1) stability of nuclei and exploration of new domain of nuclear chart towards the drip lines, 2) exotic properties of nuclear structure and reactions of extremely neutron-rich nuclei, such as neutron halos and skins, magicity-loss, and appearance of new magic numbers, and 3) nuclear reaction rates and nuclear properties concerning the stellar nuclear synthesis.

The experiments are mainly performed using the RI beam facility RIPS (RIKEN Projectile-fragment Separator) at RIKEN. Several R&D studies have been focused on experimental simulations and detectors to be used for the RI Beam Factory (RIBF) project at RIKEN.

Our program in the fiscal year 2004 has covered the following subjects;

1. Particle stability and β-decay properties of very neutron-rich nuclei near the drip line.
2. Recoil shadow method for lifetime measurements of the low-lying excited states in ^{15,17}B and ^{17,18}C.
3. Proton inelastic scattering to investigate neutron-matter deformation of ^{16}C.
4. Proton inelastic scattering to determine low-lying level schemes in the very neutron-rich nuclei ^{74}Ni and ^{78}Zn.
5. Coulomb excitation of ^{76,78,80,82}Ge and quadrupole collectivity around N=50.
6. β spectroscopy of the proton-rich nuclei ^{46}Cr and ^{24}Si.
7. R&D studies for Zero-degree Forward Spectrometer at RIBF.
8. Development of strip Germanium telescope for in-beam gamma spectroscopy of fast-moving RI beams.
9. Development of TOF spectrometer for gamma spectroscopy of medium-heavy neutron-rich nuclei.
10. Precise measurements of Coulomb and nuclear breakup reactions of ^{11}Be.
11. Coulomb dissociation of ^{23}Al and ^{27}P to study key reactions of the rp-process path, ^{22}Mg(p,γ)^{23}Al and ^{26}Si(p,γ)^{27}P.

6 Komamiya Group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) TOF detector development for BES-III experiment at BEPC-II and data analysis for the BES-II experiment at BEPC-I; (3) Detector development for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutrons; (4)OPAL experiment at LEP e^+e^- collider; (5)research on astroparticle physics with balloon-borne high resolution spectrometer (BESS experiment);

Member: Sachio Komamiya, Tomoyuki Sanuki

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 be that uses superconducting accelerator structures, and hence the project has been accelerated as an international big-science project. We started various ILC accelerator simulations and hardware tests at KEK, especially on the cavities and the beam delivery system. We have been studying possible physics scenario and the large detector concept (GLD) 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 a candidate for the middle term project before ILC. We are starting research and development for TOF detector for the BES-III experiment together with IHEP, USTC and KEK. We are developing the test system of photomultipliers in 1[T] magnetic field. We have studied the data analysis of a search for CP violation using $J\psi \rightarrow \Lambda\bar{\Lambda}$ with BES-II data. In course of this analysis we are developing an efficient pattern recognition program for the charged particles in the BES-II drift chamber.

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 Ti/Li layers to convert a neutron into charged nuclear fragments. The simulation of the quantum effects of UCN in a narrow slit with 100 [μ] height is under way.

4) OPAL experiment: 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 114-250 GeV. For supersymmetric particle searches the lower mass limit of the lightest neutralino, which is the most important candidate of the dark matter material, was set to be 36.0 GeV. The W boson mass was determined to be 80.412±0.042 GeV (statistical and systematic errors combined).

5) BESS experiment: The spectrum of cosmic muon, proton and Helium were measured at various hight. These information is important for the calculation of the neutrino flux at Superkamiokande, hence it is valuable for the atmospheric neutrino oscillation analyses. The data was taken at the heights starting from 37 km (4.5 g/cm^2) to 27 km (30 g/cm^2) for the duration of about 11 hours in the 2001 BESS flight. The kinetic energy spectrum was measured from 0.5 GeV to 10 GeV with an accuracy of 8% for proton, 10% for Helium, and 20% for muon. This information is used for optimizing the simulation program for atmospheric muons and neutrinos. We optimized a computing code for hodronic interactions to reproduce muon spectrum observed at sea level and at mountain altitude with the BESS spectrometer. This modified interaction code would accurately calculate energy spectrum of Atmospheric neutrinos.

7 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

Various kinds of non-accelerator particle physics experiments have been performed and are newly being planned in our research group. They include the direct experimental search for supersymmetric neutralino dark matter running in an underground cell in the Kamioka Observatory.

Formerly, our cryogenic detectors, aka bolometers, of lithium fluoride and sodium fluoride gave stringent limits in the parameter plane of the neutralino-proton spin-dependent coupling($a_{\rm p}$) and neutralino-neutron spin-dependent coupling($a_{\rm n}$). The choice of the detector material is based on the fact that the fluorine is one of the best nuclides for the detection of spin-dependently interacting neutralinos. The sensitivity region of fluorine for the dark matter search is more or less orthogonal to the region of the widely used sodium(of NaI) when they are represented in $a_{\rm p} - a_{\rm n}$ plane.

In the new phase of our dark matter search project we started the development of the direction sensitive detectors as reported previously. In 2004, we again tried to go further with the fluorine target but with an ordinary CaF_2(Eu) scintillator. With carefully selected raw material for the scintillator and low radioactivity photomultipliers as well as high purity copper shielding, the limit to the spin dependent cross section is improved by an order of magnitude. In the $a_{\rm p} - a_{\rm n}$ plane, our result excluded DAMA's region allowed by their annual modulation observation.

We are also 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 AXION HELIOSCOPE. The axion helioscope consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors.

The AXION HELIOSCOPE is presently under modification to implement the buffer-gas handling system to make it sensitive to axions with a mass as high as the hadronic axion window at around 1 eV. We are also developing an automatic cable handling system for it to make long-term fully automated observations possible.

Another completely new project is an R and D of a neutrino detector with a resonance ionization spectroscopy. In a charged current interaction of an electron neutrino or an anti electron neutrino on a target nucleus, the atomic number Z of the nucleus is changed by ± 1. The neutrino detection, in this sense, is accomplished by a trace analysis of an exotic atomic element in the target material. The resonance ionization spectroscopy with a LASER is effective to the trace analysis.

8 Aihara Group

Research Subjects: Precision Measurements of CP-Violation in the B Meson System, Search for Physics Beyond the Standard Model using Rare B Decays, J-PARC Long Baseline Neutrino Oscillation Experiment (T2K), and R&D for Linear Collider Silicon Detector (SiD)

Members: H. Aihara, M. Iwasaki, H. Kakuno

The main research activity of our group has been a study of CP-violation in the B meson system and precision measurements of CKM matrix elements using the KEK B-factory (KEKB).

Direct CP Violation The first evidence for direct CP violation in B meson decay was reported by the Belle group in January 2004 in the disintegration of the B meson into two charged π mesons. From a sample of 152 million Bmeson pairs, Belle observed 264 anti-B meson decays but only 219 B meson decays, establishing direct CP violation with more than 99.8% probability. Most recently, Belle has found clear evidence of direct CP violation in the process of B mesons decaying to a K meson and a π meson. From a sample of 274 million B meson pairs, Belle found 1165 B meson decays but only 974 anti-B meson decays, establishing direct CP violation with a confidence level of more than 99.99%.

Hint of New Physics If the Standard Model is correct, several B meson processes other than the decay to $J/\psi K^0$ must show CP violation of a size that is determined by $\sin 2\phi_1$. A particularly interesting case is the decay into the ϕ meson and the K^0 meson. This process is believed to occur through a process involving so-called " quantum fluctuations " where the beauty quark within the B meson splits, for a brief instant, into a top quark and a W boson. It is possible that the top quark and/or W boson could occasionally be replaced by new particles that have never been seen and are not part of the Standard Model. Their hidden presence might appear as an anomalous value for $\sin 2\phi_1$, In summer 2003, the Belle group reported that the value of $\sin 2\phi_1$ determined using the ϕK^0 decay mode deviated significantly from the well-established value of $+0.736$ obtained from $J/\psi K^0$ decays. Further investigation requires a large data sample, and the experimenters are steaming ahead toward resolving what is probably the most serious challenge to the Standard Model in recent days. Using a 274 million B meson sample, the Belle group collected 175 ϕK^0 decays, and also extended its analysis to five other decay processes that are believed to behave similarly to the ϕK^0. Now, the value of $\sin 2q\phi_1$ after combining all these decays is $+0.43 \pm 0.11$, which represents a deviation from the Standard Model value with 99% probability. Further improvement of the measurement remains one of the most important issues in high energy physics.

T2K We have been involved in the next generation long-baseline neutrino oscillation experiment, JHFnu, which shoots off-axis neutrino beam from Tokai 50 GeV proton synchrotron to Super Kamiokande detector. We have been developing profile monitors for the primary proton beam. This past year we performed the beam test of the prototypes.

SiD Our R&D work also includes the design of Linear Collider beam delivery system, the interaction region and a general purpose detector based the silicon technology.

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- K.-F.Chen *et al.*,[Belle Collaboration] "Time-Dependent CP-Violating Asymmetries in $b \to s\bar{q}q$ Transitions," [arXiv:hep-ex/0504023]. submitted to PRD.
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9 Wadati Group

Research Subjects: Statistical Mechanics, Nonlinear Physics, Condensed Matter Physics

Member: Miki WADATI & Kazuhiro HIKAMI

We investigate fundamental problems in statistical mechanics and condensed matter physics. We aim to find and clarify novel phenomena, and to develop new non-perturbative analytical methods. Research themes of publications in 2001 are listed in the followings.

1. Bose–Einstein Condensation (BEC)
   (1) Ground State Properties of a Toroidally Trapped BEC
   (2) Free Expansion of a Bose-Einstein Condensate
   (3) Dynamics of a Wavefunction for the Attractive Nonlinear Schrödinger Equation under Isotropic Harmonic Confinement Potential
   (4) Statistical Mechanics of Bose–Einstein Condensation in Trap Potentials

2. Nonlinear Waves
   (1) Noncommutative Soliton
   (2) Cellular Automaton and Crystal Base
   (3) Lattice W Algebra and Integrable Systems
   (4) Quantum Soliton Equation and Baxter Equation

3. Non-Equilibrium Statistical Physics
   (1) Asymmetric Simple Exclusion Process
   (2) Stability of the Non-Equilibrium Steady States
   (3) Minority Game

4. Strongly Correlated Electron System
   (1) Thermodynamics in the Hubbard Model, t-J Model
   (2) Integrable Boundary Condition

5. Knot Theory and Low-Dimensional Topology
   (1) Hyperbolic Volume of Knot Complement
   (2) Quantum Gravity

6. Quantum Many-Body Problem
   (1) δ-function Bose gas
   (2) Calogero–Sutherland Model
   (3) Exclusion Statistics and Chiral Partition Function

7. Quantum Computing and Quantum Information
   (1) Geometric Aspects of Quantum Search
   (2) Multipartite entanglement and embeddings in algebraic geometry

8. Random Matrix
   (1) Polynuclear Growth Model
   (2) Random Walk

10 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Ryotaro Arita

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" should be possible. Specifically we study:

- Superconductivity in repulsively interacting electron systems
  - — High-T_C cuprates, Ru and Co compounds [1,2]
  - — How to optimize T_C through the "fermiology" [3,4]
  - — Spin-triplet superconductivity [1,2,4,5]
  - — Superconductivity in multi-orbital systems and correlated electron systems coupled to phonons [6,7]
- Magnetism in repulsively interacting electron systems
  - — Flat-band ferromagnetism in a designed organic polymer [8]
  - — Fullerene derivatives [9]
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  - — Landau-Zener tunnelling in the breakdown of Mott's insulator [10]
- Quantum Hall systems
  - — Interaction and effective mass in the fractional quantum Hall liquid [11]
  - — Integer quantum Hall effect in three dimensions [12]
  - — Electron-molecule picture for quantum dots in magnetic fields
- Electronic structure and correlation effects in hetero-interfaces
  - — Metal-induced gap states at metal/insulator interfaces [8,13]
  - — Metal-insulator transition on polar surfaces [8,14]
- Electronic structure of alkali-metal-loaded zeolites — "supercrystal" picture and magnetism [15]
- Electrons on periodic curved surfaces [16]

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11 Miyashita Group

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

Member: Seiji Miyashita and Keiji Saito

1. Magnetization Processes in Quantum Triangle Lattices

We studied the magnetization process in weakly XY-anisotropic antiferromagnetic Heisenberg spin systems. The magnetization processes of this type of model at finite temperatures were studied in their corresponding classical models, where we found very complicated successive phase transitions. They reflect magnetic-field-dependence of the entropy of various nearly degenerate ordered states of the models. We found that the quantum fluctuation causes the same effects on the stabilization of successive phases in the field in the ground state. We studied the quantum models in the approximation where use a $3 \times \infty$ lattice instead of the two-dimensional triangular lattice. This lattice can be studied by PWFRG method and DMRG method.

It has been found that this lattice is exactly the same as the system of alternate-triangle tube material. The existence of the gap between the ground state and the excited states is a matter of interest. Although in the regular triangle tube, the existence of the gap is known, in the present case there may be a ground state phase transition, which is under investigation.

2. Nature of Ferrimagnetic Order in Quantum Spin Systems

We have investigated types of ferrimagnetism in the ground state of quantum spin systems. The most familiar type is the Lieb-Mattis type in the antiferromagnetic model on bipartite lattices with different number of sublattice sites. On the other hand, in the case of frustrated lattices, the ground state spin configuration is often non-collinear, and they show a non-collinear ferrimagnetic states. In order to realize these types of ferrimagnetism in a lattice and to study the phase transitions between them, we investigate a lattice with frustrated interactions. We find that this model contains two types of ferrimagnetism as a function of the parameter. Furthermore we found that the system has an incommensurate spin configuration The wavelength of the oscillation changes with a parameter. The mechanism of this behavior is now under investigation.

3. Quantum Effects on the Charge Transfer Spin-Crossover Phenomena

As a new frontier of studies of the phase transition, phase transition of structure of materials due to charge transfer and also magnetic phase transition on such materials have been attracted interests. In some materials of this type, in the low temperature configuration the magnetic atoms are surrounded by non-magnetic atoms and the interaction between magnetic atoms is expected to be very small. Nevertheless, magnetic ordering occurs. Mechanism of this magnetic order is an interest problem. We have proposed that thermal fluctuation may assist the magnetic order. However this mechanism has been shown to be difficult at least in two-dimensional systems. Thus, we proposed alternate mechanisms including ones due to quantum fluctuation. We demonstrated that quantum mixing due to the DM interaction helps the magnetic order, and electron hopping also helps the order. We also studied effects of photo-irradiation on systems which shows the photomagnetism.

4. ESR Study on Nano-scale Molecular Magnets

We have developed a numerical method to obtain the ESR by means of direct numerical evaluation of the Kubo formula. We have studied characteristics of ESR absorption as functions of the frequency of the AC field ω and the strength of the static field H_0. In particular, we have studied the temperature dependence of total amplitude of the absorption of ESR of a molecular magnet V_15. At very high temperature, all the 15 spin gives independent data and we have 15 times of the absorption of single isolated spin. When the temperature decreases, due to the magnetic interaction the effective degree of freedom is reduced to 3 for a loosely coupled three spins. At further low temperatures, we found that the system shows various temperature dependence depending on the magnetization. We also find the dynamical shift, i.e., dependence of the absorption on the relative angle between the AC field and the system.

5. Mechanism of Slow Dynamics in Decorated Bond Systems

We also studied mechanism of reentrant phenomena and memory effect in a lattice consisting of frustrated decorated bond. There, we found that the time evolution of the spin becomes very slow due to a kind of dynamical metastability. We successfully evaluated the relaxation time by an analysis of distribution of configurations of a decorated bond. By this study we find that, although the equilibrium state is well defined, it may take very long time to reach it even in relatively simple systems.

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
  Superconductivity correlation length in the strongly correlated electron system.[1]
  Energy analysis of high-T_c superconductors.[2,3]
  Randomness and superconductivity fluctuation in high-T_c superconductors.
- Anisotropic superconductivity in Na_xCoO_2
  Spin triplet superconductivity in a multi-orbital model.[4,5]
  D-vector and multiple phase in a magnetic field.
  Superconductivity due to charge fluctuation.[6]
- Organic conductors
  Superconductivity and charge fluctuation in θ-type organic conductors.[7]
  Quantum melting due to geometrical frustration.[8]
- Theories of anisotropic superconductivity
  Electronic states in the vortex state.[9]
  Quasi-classical theory on the angle dependence of specific heat in a magnetic field.[10]
  Proximity effects of superconductivity and magnetism in the bilayered structure.
- Electronic and spin states in frustrated systems
  Superconductivity correlation in a triangular lattice.
  Charge order and superconductivity in a triangular lattice.
  Numerical simulation on the classical spin system with frustration.
- Metal-insulator transition
  Disorder operator in two-dimensional insulators.

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13 Tsuneyuki Group

Research Subjects: Theoretical Condensed-matter physics

Member: Shinji Tsuneyuki and Kazuto Akagi

Computer simulations, such as the first-principles molecular dynamics method, 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 ultra-high pressure or at surfaces.

In FY2004, we investigated chemical reactions in condensed water promoted by so-called proton relay, chemisorption of organic molecules on Si(001) surface, gigantic effective charge in hypervalent As_2Te_3, and the self-organization in N/Cu(001) surface. We also developed new methods of computer simulation of condensed matter as follows.

The Transcorrelated Method

The density functional theory (DFT) is one of the most popular bases of the first-principles simulations of materials nowadays, though its limitation, at least within the present approximation, has also been clarified: cohesive energy of solids are overestimated, van der Waals interaction is not reproducible, activation barrier of chemical reactions is underestimated, and electronic excitation spectrum is not correctly calculated for some narrow gap materials or strongly correlated electronic systems. The most significant problem is that we do not know how to improve the approximations adopted with DFT systematically in contrast to the wave function theory (WFT). To overcome these difficulties, we proposed a new method of first-principles simulation of solids based on the transcorrelated (TC) method. In the TC method, a Slater-Jastrow-type many-body wave function is fully optimized by solving a Hartree-Fock-like mean-field wave equation (TC-SCF equations) self-consistently.

We showed that, even with use of the simplest Jastrow function, total energy of the electron gas is surprisingly well reproduced for a wide range of the Wigner parameter r_s. We also demonstrated that excitation energy of a helium atom is accurately calculated within the scheme of the TC method. Since electronic correlation is taken into account through the Jastrow function, the band structure is much better than that obtained by the Hartree-Fock method for solids, i.e. no anomaly is observed at the Fermi surface of simple metals and the band gap of semiconductors is much improved.

Elastic Lattice Green's Function

Surface science is an important playground of DFT and the so-called first-principles molecular dynamics method, where we usually simulate a surface by a slab model with the periodic boundary conditions in three dimensions. If we consider large-scale self-organization at surfaces, however, the slab model is sometimes problematic, since the convergence of the elastic deformation energy is much slower than that of the electronic energy. Based on the pioneering work by Y. Saito in Keio University, we derived and implemented an elastic Green's function for an fcc crystal for surface simulation. We confirmed that the Green's function dramatically improves various elastic deformations and interactions within a thin slab model.

Replica-Exchange Molecular Dynamics

Structural optimization of complicated systems, like biomolecules, is another important and difficult problem of atomistic simulation of materials. Statistical sampling with so-called extended ensembles at present seems a hopeful tool for solving this problem. We developed the replica-exchange molecular dynamics method with the isobaric formalism and demonstrated that solidification of the Lennard-Jones particles is simulated more rapidly and systematically than parallel but independent simulations with the canonical ensemble. The present result suggests the usefulness of the replica exchange method for simulating the first-order structural phase transition, though further investigation is needed.

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14 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

The electronic structures of strongly correlated systems and complex materials are studied 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 [2], giant magnetoresistance, carrier-induced ferromagentism and spin/charge/orbital ordering [3] in strongly correalted systems such as transition-metal oxides, magnetic semiconductors, and their nano-structures.

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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 Iwao MATSUDA

Topics in our research group are (1) electronic/mass transports, (2) atomic/electronic structures, (3) phase transitions, (4) electronic excitations, and (5) 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 diffractions, scanning electron microscopy (STM), scanning tunneling micro/spectroscopy, photoemission spectroscopy, and in-situ 4-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes. Main results in this year are as follows.
(1) Surface electronic transport: Metal-insulator transitions, hopping conduction, and Hall effect in surface states. Quantitative evaluation of surface-state conductivity from Fermi surface mapping. Conductance of individual Cobalt silicide nanowires and metal-coated carbon nanotube tips.
(2) Surface phases ultra-thin films, and phase transitions: Order-disorder phase transition and charge-density-wave transition on various metal-induced surface superstructures of Si and Ge. Quantum-well state in Ultra-thin Pb film. Ge nanodots layer.
(3) Construction of new apparatuses: Green function STM (low-temperature four-tip STM). A new machine of conductivity measurement by photoemission spectroscopy.

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17 Fukuyama Group

Research Subjects: Low Temperature Physics:

Strong correlations, frustration effects and superfluidity in quantum fluids and solids, Low temperature scanning tunneling microscopy and spectroscopy for low-dimensional conductors and exotic superconductors.

Member: Hiroshi Fukuyama, Hiroshi Kambara

Our current interests are on (i) quantum many body phenomena such as strong correlation effects, frustrated magnetism and superfluidity in fluid and solid ^{3}He especially in two dimensions, (ii) electronic properties of low-dimensional conductors in high magnetic fields, (iii) exotic superconductors with non s-wave Cooper pairs, *etc.* We are investigating these topics experimentally at very low temperatures down to 50 μK.

1. **Strong correlation effects in 2D ^{3}He:**
   Monolayer ^{3}He adsorbed on a graphite surface is an ideal model system for strongly correlated two dimensional (2D) Fermions, Recently, we studied a rich quantum phase diagram of the second layer ^{3}He with four distinct quantum phases depending on density from heat-capacity and NMR measurements. At densities slightly lower than that for the 4/7 registered phase ($\rho_{4/7}$), there exists a quantum fluid phase possibly with the zero-point vacancies. On the other hand, there exists another quantum fluid phase either with the fluid over layer or interstitials in the 4/7 phase at densities slightly higher than $\rho_{4/7}$. As density increases further, ferromagnetic tendencies appear and the system undergoes a two-phase coexistence with the ferromagnetic phase.
2. **STM/STS studies of low dimensional conductors:**
   (a) **Visualization of the possible quantum Hall states at graphite surface:**
   Scanning tunneling spectroscopy (STS) measurements in high magnetic fields by use of an ultra-low temperature scanning tunneling microscope (ULT-STM) enable us to visualize spatial distributions of the possible localized and extended states of the quantum Hall state at quasi-two dimensional graphite surfaces. The localized states trapped circularly around a surface defect have expected width comparable to the magnetic length ($\sim$ 10 nm at 6 T). The width increases with decreasing field as expected.
   (b) **Graphite edge state:**
   The electronic local density of states (LDOS) was measured near single step edges at the surface of exfoliated graphite as a function of distance from the edges. A clear LDOS peak at an energy just below the Fermi level was found only near the zigzag edge but not the armchair one. The peak height develops with approaching the zigzag edge. These observations, which are in good agreement with the first-principles calculations by Tagami and Tsukada, indicate that we found the predicted "graphite edge state" experimentally for the first time.
   (c) **0D and 2D electronic systems at semiconductor surfaces:**
   It is known that a thin film of InAs epitaxially grown on a GaAs(111)A surface contains tetrahedral stacking faults. Inside and outside this tetrahedron, quasi 0-dimensional and 2-dimensional electronic states are formed on the surface. We started to study magnetic field dependencies of these electronic states with the ULT-STM as a collaboration with Hirayama group of NTT Basic Research Laboratories.
   (d) **An unconventional superconductor Sr_2RuO_4:**
   STM/STS studies of the spin-triplet superconductor Sr_2RuO_4 were carried out. We observed an antisymmetric LDOS structure below 100 meV at cleaved SrO planes. We also observed a large gap structure ($\Delta \sim 5$ meV) which is not related to the superconducting state. But its origin is still unknown. Further STM/STS studies are ongoing.
3. **Magnetotransport measurements of quasi 2D graphites:**
   Magnetotransport measurements for HOPG (highly oriented pyrolytic graphite) samples were done at temperatures down to 2 mK and in magnetic fields up to 14 T. Measured in-plane resistances increase logarithmically with decreasing temperature due to the electron-electron interaction in high fields and to weak localization in low fields. Also observed are quantum Hall-like plateaus in Hall resistance vs. magnetic field plot. This suggests the possible quantum Hall state realized in the quasi 2D electronic system in HOPG.

18 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Yukio Kawano

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

1. Magnetism in strongly correlated two dimensional systems:
(i) We have studied the magnetoresistance in a high-mobility Si-MOS sample down to low electron concentrations at which the longitudinal resistivity ρ_{xx} has an activated temperature dependence. The results indicate that a ferromagnetic instability does not occur even in the far insulating regime. (ii) We have performed electron spin resonance measurements for a Si/SiGe quantum well. In the parallel magnetic field, we observed a negative change in ρ_{xx}, which is opposite of the effect of electron heating. It can be attributed to the reduction of the spin polarization. (iii) We have investigated the magnetotransport in the strongly localized regime of GaAs 2D hole systems (2DHSs). Giant positive $B_{\perp}$-dependence of ρ_{xx} at $T = 100$ mK was observed for $B_{\rm tot} = 1$ T. We consider that it may be caused by the strong spin-orbit interaction in GaAs 2DHSs.

2. Exploration of novel properties of two-dimensional semiconductors and their application to new devices:
Our studies aim at revealing local transport and optical properties of quantum Hall conductors by means of scanning probe microscopes, Terahertz irradiations, etc. The three following techniques have been applied: (i) Infrared illumination: We have found that odd-filling-factor QHE states at 4.2K are induced by infrared illumination. We have also observed that this anomalous state exhibits an extremely long relaxation time of more than 10 min. (ii) Spatial mapping of 1/f noise: We have developed a novel technique for imaging 1/f-noise distributions in quantum Hall systems. This imaging system has made it possible to reveal the existence of two different types of 1/f noises. (iii) Time-resolved measurement of Terahertz photoresponses: We have found that "multiple-trapping process" of photoexcited carriers leads to a strong photoresponse of a THz detector based on a quantum Hall device.

3. Heat flow in quantum Hall systems:
We have observed Ettingshausen effect in the IQHE breakdown regime. Electron temperature difference across the current channel has been measured using two miniature Hall bars.

4. Two dimensional electrons at a cleaved semiconductor surface:
Low temperature in-plane magnetotransport measurements have been performed on adsorbate-induced electron systems formed at *in-situ* cleaved surfaces of p-type InAs. The Ag-coverage dependence of the surface electron density strongly supports a simple model based on a surface donor level lying above the conduction band minimum. The observations of the quantized Hall resistance and zero longitudinal resistivity demonstrate the perfect two dimensionality of the surface electron system. We also observed the Rashba effect due to the strong asymmetry of the confining potential well. The Shubnikov-de Haas oscillations were also observed for cleaved surfaces of p-InSb.

19 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Shinichi Watanabe

Our research interests are light-matter interactions and many body quantum correlations in optically excited semiconductors and low dimensional systems such as carbon nanotubes, organic conductors. Our study focuses on the low energy electromagnetic responses in the region of several meV, i.e., terahertz frequency region where various collective excitations exist. We also aim at studying the ultrafast dynamics of photo-induced phase transition in those low dimensional systems by THz conductivity measurements. R. Shimano started working at Physics Department, University of Tokyo in March, 2004. S. Watanabe joined our group in August, 2004.

The research summary in this year is as follows.

1. **Instrumental Developments**

   Rapid-sacn terahertz time domain spectroscopy
   Firstly, we have constructed a conventional terahertz time-domain spectroscopy setup. Optical rectification and eletro-optic detection scheme is used for the THz generation and detection, respectively. Determination of dielectric function in the frequency range between 0.5 to 2.5THz has become possible. Secondly, we introduced a rapid scan system, by shaking the optical delay for the gate pulse of electro-optic sampling. As a result, the data taking period is drastically reduced, typically within 0.2sec for 20psec scan range, and the *real-time* indication of THz waveform become possible. The scheme allows us to eliminate the effect of long term fluctuation of laser light.

   Terahertz Hall measurements
   Magneto-optical effect such as Faraday effect or magneto-optical Kerr effect enables us to investigate the ultrafast spin dynamics and transport properties under magnetic field, by optical means, i.e., without using electrodes. Recently, it has become possible to perform the magneto-optical measurements in THz frequency region. Because the phenomenon is equivalent to the high frequency ac Hall effect, the magneto-optical effect provides us deep insights into the dynamical properties of scattering processes of electrons under magnetic field. However, the magneto-optical signal, i.e., the polarization rotation and ellipticity of transmitted or reflected light is typically very small, of the order of mrad or less in the THz frequency regime. Accordingly, it is particularly important to develop a high sensitive detection scheme of polarization rotation and ellipticity. For this purpose, we have developed a scheme to control and modulate the circular polarization of a broadband THz pulse, which can be applied to high sensitive detection of circular dichroism in the THz region. The technique is based on the relative phase control of two THz pulses that are generated from optical rectification of ultrashort optical pulses in a ZnTe crystal. By changing the temporal separation of the optical pump pulses, continuous control of circular polarization from right to left is achieved in the frequency range from 0.3 to 2.5THz.

2. **Terahertz spectroscopy of carbon nanotubes**
   Carbon nanotubes are considered as one of the candidate materials for one dimensional electron system. Various exotic behaviors in optical and transport phenomena have been observed, while the dynamical aspects of transport properties are open problems. In order to clarify this issue, and to reveal the one dimensional nature of nanotubes, we started the study of THz electromagnetic responses of nanotubes.

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, & Shinji Mukohyama

Astrophysics is a very broad field of research, and it is hard to cover various important astrophysical research subjects in our group only. Therefore we are currently working on the three specific areas of research interest; "Physics of the Early Universe", "Observational Cosmology", and "Nuclear Astrophysics", all of which are definitely interrelated very closely. Let us describe more specifically the current interests and activities of our group in the above areas.

The understanding of the very early universe has made rapid progress in 1980's by applying the ideas of particle physics around the epoch close to the Planck time, one notable example of which 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 in a language of physics. Our group activities in this area include inflationary universe models, cosmological phase-transition and topological defects, big-bang nucleosynthesis, 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.

"Nuclear Astrophysics" is exploring the interface between nuclear physics and astrophysics, in particular the physics of supernovae. It 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 25 years. It is, therefore, quite 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.

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

2002

- Nuclear "pasta" in dense stars and its properties
- Supernova Neutrinos: Their Relic Background and Resonant Spin-Flavor Conversion
- Arrival Distribution of Ultra-High Energy Cosmic Rays and Implications for Their Source Candidates
- Non-linear evolution of the cosmological large scale structure from the local collapse model

2001

- The Universe with Extra Dimensions — From Kaluza-Klein Perspective to Brane World
- Gravitational Collapse of Rotating Massive Stars
- Effects of Neutrino Oscillation on Supernova Neutrino
- Resolving the Central Density Profile of Dark Matter Halos with Gravitational Lensing Statistics
- The Stability of Higher Dimensional Spacetime

2000

- Double inflation in supergravity and its observational implications
- Propagation of UHECRs in the inhomogeneous source model
- Effects of neutrino oscillation on the supernova neutrino spectrum
- A Biasing Model for Cosmological Two-Point Statistics and the Probability Distribution Function of Nonlinear Mass Fluctuations
- Genus Statistics for Large-Scale Structure as a probe of Primordial Random-Gaussianity and Nonlinear Stochastic Biasing
- Velocity Distribution Functions for Nonlinear Gravitationg Many-body Systems

21 Murao Group

Research Subjects: Quantum Information Theory

Members: Mio Murao and Damian Markham

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 10 years. Entanglement is a nonlocal correlation that appears in certain types of quantum states (non-separable states) and has been considered as the fundamental resource for quantum information processing. In our group, we are investigating new properties of multiparticle and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- *Entanglement convertibility for infinite dimensional pure bipartite states:* It is shown that the order property of pure bipartite states under SLOCC (stochastic local operations and classical communications) changes radically when dimensionality shifts from finite to infinite. In contrast to finite dimensional systems, where there are no pure incomparable states, the existence of infinitely many mutually SLOCC incomparable states is shown for infinite dimensional systems, even under the bounded energy and finite information exchange condition. These results show that the effect of the infinite dimensionality of Hilbert space, the "infinite workspace" property, remains even in physically relevant infinite dimensional systems.

- *Local copying and its relationship to local discrimination:* We obtain the necessary and sufficient conditions of a set of maximally entangled bipartite states in prime dimensional systems for creating two copies of a given unknown maximally entangled state drawn from the set, only using a known maximally entangled state and local operations and classical communications (LOCC). In prime dimensional systems, the set of the locally copiable maximally entangled states is equivalent to a subset of the canonical Bell states which are decomposable by simultaneous Schmidt decomposition. As a result of this, we show that local copying of the maximally entangled states is more difficult than local discrimination at least in prime dimensional systems.

- *Asymmetric qubit information sharing between two parties:* The necessary and sufficient conditions for deterministic extraction of qubit information encoded in bipartite states using only LOCC are presented. The conditions indicate that there is a way to asymmetrically share qubit information between two parties where one party's qubit can be only used as a remote "quantum key" to fully recover the original qubit information at the other party. A communication protocol which allows conditional transmission of qubit information using the non-copyable quantum key is proposed.

- *Local state discrimination and multipartite entanglement measures:* We present necessary conditions for the local, perfect discrimination of general multipartite states in terms of the global robustness of entanglement, the relative entropy of entanglement and the geometric measure. These lead to an upper bound to the number of orthogonal multipartite states that can be locally discriminated exactly. The bound is explicitly found for pure biparitite states and is shown to be tight for a set of generalized m-party GHZ states, adding evidence that W-states are more 'powerfully' entangled than GHZ states for this kind of task. Some known results are proved in a unified way.

- *The transition to infinite dimensions:* We study how and when large spin systems can indeed be treated as bosonic systems in the approach from finite to infinite dimensions. The mathematical basis of this transition is group contraction. Many theoretical tools exist for infinite dimensional systems, which do not exist for large spin systems. We hope to use this to develop rigorous analogy of homodyne measurements and other continuous variable operations for spin systems and see when a system really behaves as infinite dimensional.

- *One-way quantum computation and graph states:* In the one-way quantum computer, the computation carried out is defined by the set of measurement commands, and the graphs state. We investigate the relationship between the set of possible computations and the graph state and find a set of necessary conditions that the graph must satisfy to be consistent with a unitary computation. We hope to use this result to show how graph states can be used in cryptographic protocols.

22 Kobayashi Group

Research Subjects: Ultrafast and Nonlinear optical processes, Quantum Optics

Member: Takayoshi Kobayashi, Atsushi Yabushita, Akikatsu Ueki

Ultrashort pulse lasers are being developed to study ultrafast processes in condensed-phase materials including polymers, aggregates, and biological molecules. Quantum information and quantum optics are also studied.

1. Development of ultrashort pulse lasers
   - Control of the carrier-envelope phase and measurement
   - Generation of ultra-broadband light
2. Ultrafast spectroscopy
   - Oligothiophene
   - PIC J-aggregate
   - Porphyrin
   - Pump-probe anharmonic signal in a harmonic system induced by deformed wavepacket generated by an ultrashort pulse
   - Determination of Huang-Rhys factor associated with transition from excited state
3. Electric field modulation spectroscopy
   - Porphyrin J-aggregate, molecular crystal, and photosynthetic protein
   - Nonlinear absorptive spectroscopy of a single quantum dot
4. Quantum information
   - Generation of many-body entanglement and its application
   - Quantum key distribution using spontaneous emission parametric down conversion
   - Phase measurement beyond Heisenberg limit
   - Quantum high-pass and low-pass filters composed only of passive linear optical components

23 Makishima Group

Research Subjects: High Energy Astrophysics using Scientific Satellites, X-Ray Probing of the Universe, Development of Cosmic X-Ray/γ-Ray Instruments

Member: Kazuo Makishima, Motohide Kokubun

We study cosmic and solar high-energy phenomena in the X-ray and γ-ray frequencies, using scientific satellites launched by the Japan Aerospace Exploration Agency, as well as foreign missions.

Instrumental Developments: We have developed X-ray instruments onboard the solar mission *Yohkoh* (1991 – 2002), and the cosmic X-ray mission *ASCA* (1993 – 2001). We have also completed the Hard X-ray Detector (HXD-II) [1] onboard *Astro-E2*, to be launched in June-July 2005. The HXD-II has an unprecedented sensitivity to cosmic hard X-rays in the 10–600 keV range, and is expected to innovate our knowledge on high-energy astrophysics. We also develop future X-ray and gamma-ray technologies, including hard X-ray imagers with Fourier-synthesis optics, and ceramic inorganic scintillators.

Solar and stellar flares: We study solar flares using the X-ray and γ-ray data acquired with *Yohkoh* [2], and employing Monte-Carlo simulations. Our research activities also cover thermal X-ray emission from stellar coronae, and thermal/non-thermal radiations from their flares.

Physics of Neutron Stars: When a weakly magnetized neutron star accretes matter from its binary companion, optically-thick X-rays are emitted from its surface as well as the accretion disk around it. We have discovered that significant mass outflows take place when the mass accretion rate exceeds the critical value. Strongly magnetized neutron stars exhibit electron cyclotron resonance features in their spectra, which have enabled us to accurately measure their magnetic field intensities.

Physics of Black Holes: We are reinforcing our novel view, first obtained with *ASCA*, that "ultra-luminous compact X-ray sources" (ULXs) seen in nearby galaxies are massive ($\sim 100\ M_\odot$) stellar black holes under very high mass accretion rates [3]. We are constructing a unified description of high-accretion-rate black holes, including ULXs, ordinary black-hole ($\sim 10\ M_\odot$) binaries, and Narrow-Line type 1 Seyfert galaxies ($\sim 10^6\ M_\odot$).

Plasma Heating and Particle Acceleration in the Inter-Stellar Space: The inter-stellar space of our Galaxy, and those of other spiral galaxies [4], is filled with enigmatic diffuse hard X-ray emission which may be a composite of thermal and non-thermal signals. We have detected thermal and/or non-thermal diffuse X-rays from several globular clusters. The emission may arise when the clusters move through the Galactic halo and interact with the halo plasma.

Physics of Cluster of Galaxies: The X-ray emitting hot plasmas associated with clusters of galaxies constitute the most dominant known baryonic component in the universe. We have established with *ASCA* and *XMM-Newton* that these plasmas exist in the form of two-phase (hot and cool) media, and their radiative cooling is somehow suppressed. We attempt to explain these puzzles by invoking a magnetic field configuration like that of the solar corona. Then, kinetic energies of the member galaxies may be dissipated on the plasma by exciting magnetohydrodynamical turbulence, resulting in their continuous infall toward the cluster center.

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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

Members: Yuichi Takase, Akira Ejiri, Syun'ichi Shiraiwa, Kenichi Yamagishi

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 an international burning plasma experiment is ready to be constructed. 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 (defined as the ratio of the plasma pressure to the confining magnetic pressure), several times greater than the conventional tokamak. High beta plasma research using the ST approach is a rapidly developing field worldwide, and is being carried out in our group using the TST-2 spherical tokamak.

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

It is crucially important for ST to develop a scenario of plasma formation, heating and maintenance without the use of the central solenoid (CS) located on the inboard side of the torus. Several approaches are being investigated on TST-2. TST-2 was temporarily relocated to Kyushu University in 2003 in order to take advantage of the powerful microwave power (200 kW at 8.2 GHz). An ST plasma with a plasma current of 4 kA was successfully produced and maintained for 0.3 sec by microwave power. Magnetic reconstruction of this plasma indicated the existence of plasma current outside the last closed flux surface.

ST plasmas have very high dielectric constants compared to conventional tokamaks, and therefore, methods to diagnose, heat and drive current using different waves, such as the electron Bernstein wave (EBW) and the high harmonic fast wave (HHFW), must be developed. EBW heating based on the X-B mode conversion scenario was investigated. Over 100 kW of RF power was successfully injected into the plasma. Although some indications of heating were observed, only a small fraction (10–20%) of the injected power seemed to have contributed to heating. Possibilities of power loss at the plasma edge are being considered.

TST-2 is now located in a new experimental building on the Kashiwa Campus. Numerous improvements have been implemented, and it is now ready to start experiments with improved capabilities.

Collaborations

A completely CS-less plasma current start-up to 100 kA was achieved on the JT-60U tokamak at Japan Atomic Energy Research Institute (JAERI), using the same scenario as TST-2. The plasma current was generated even without a field null (where the poloidal magnetic field is zero), contrary to conventional belief. However, a strong ionization source, in this case by 1 MW of RF power, is required. A plasma current of 260 kA was maintained for 1 s by neutral beam current drive and self-driven bootstrap current alone. A ramp-up of plasma current from 215 to 310 kA was also achieved. An indication of bootstrap current overdrive was observed, as evidenced by a recharging of the CS. In a future experiment, plasma current ramp-up by bootstrap overdrive will be attempted.

Both coherent and turbulent fluctuations were studied on the JFT-2M tokamak at JAERI using three diagnostics: fast reciprocating Langmuir probes, two channels of reflectometers, and fast magnetic probes. A large scale coherent potential fluctuation around 10 kHz, observed last year, was identified as the Geodesic Acoustic Mode (GAM). Analysis showed that the bicoherence of the GAM fluctuations scaled as the squared envelope of the GAM fluctuations, as expected from theory.

Electron heating by HHFW was investigated on the Large Helical Device at the National Institute for Fusion Science. Central electron heating to 3.3 keV was observed when the starting electron temperature was 2.5 keV. However, no heating was observed when the starting temperature was 2.0 keV. This result is not inconsistent with the requirement to satisfy the Landau resonance condition for the wave to be absorbed effectively.

A collaboration on the NSTX spherical tokamak (Princeton Plasma Physics Laboratory) on CS-less start-up is also being carried out.

25 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave Physics, 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. We are now analyzing the obtained data searching for the gravitational waves from coalescing binaries, supernovae and pulsars.

We summarize the subjects being studied in our group.

- Laser interferometric gravitational wave detectors
  - Current status of TAMA project
  - Search for burst gravitational waves
  - Search for gravitational waves from SN1987A
  - Systematic analysis of TAMA monitoring signal
  - Study of the next-generation laser interferometer, LCGT
- Space laser interferometer
  - Space laser interferometer DECIGO
  - FP-DECIGO
- Study of thermal noise
  - Direct measurement of the thermal noise
  - Thermal noise caused by the inhomogeniously distributed loss
- Study of the precise measurement
  - Suspension point interferometer for vibration isolation
  - Development of the low-frequency vibration isolation system (SAS)
  - New vibration isolation system using magnetic levitation
  - Laser stabilization using optical fiber
  - Test of the law of gravitation at extremely small distance

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26 Sano Group

Research Subjects: Nonlinear Dynamics and Fluid Mechanics

Member: Masaki Sano and Yoshihiro Murayama

Our research group studies nonlinear dynamics and pattern forming phenomena in dissipative nonlinear systems. Oscillation, chaos, and turbulent behavior of fluid, solid, granular systems, chemical reactions and biological systems are investigated based on dynamical system's theory and laboratory experiments. Through these efforts we search for novel phenomena, and to develop new methods in understanding complex phenomena arising in the systems far from equilibrium. The followings are main subjects of our study.

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

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

3. Dynamical aspects of biological systems

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

(2) Collective behavior of the activities in biological neural assemblies

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27 Yamamoto Group

Research Subjects: Submillimeter-wave Astronomy, Physical and Chemical Evolution of Interstellar Molecular Clouds, Laboratory Spectroscopy of Interstellar Molecules

Member: Satoshi Yamamoto & Tomoharu Oka

Molecular clouds are birthplaces of new stars, and understanding their physical and chemical properties provides us with fundamental bases for detailed studies on star formation, which is an elementary process in evolution of the Galaxy. With this in mind, we are studying submillimeter-wave astronomy as well as the laboratory microwave spectroscopy, as described below.

Our group is running the Mt. Fuji submillimeter-wave telescope in order to explore formation processes, detailed structure, and chemical evolution of molecular clouds. The main reflector of the telescope has a diameter of 1.2 m, and the telescope is enclosed in a space frame radome with a Gore-Tex membrane. We have developed a superconductor mixer receiver with high sensitivity for this telescope to observe the spectral lines of the atomic carbon (CI) ($^3P_1 -^3 P_0$ 492 GHz; $^3P_2 -^3 P_1$ 809 GHz). The telescope system was installed at the summit of Mt. Fuji (el. 3700 m) in July 1998, and we started astronomical observations from November 1998 in a remote way by using a commercial satellite communication system. The Mt. Fuji submillimeter-wave telescope is being operated as a research project of Research Center for the Early Universe (RESCEU) in collaboration with researchers of National Astronomy Observatory, National Space Development Agency, and Fukui University.

With this telescope, we are conducting large scale mapping observations of the 492 GHz line of CI toward a number of molecular clouds in our Galaxy. Until now we have observed various sources including dark clouds, giant molecular clouds and translucent clouds. Total observing area is more than 50 square degrees, which is the largest survey of the CI line so far made. Furthermore, a few representative clouds (Orion A, Orion B, M17, and DR21) have been mapped with the 809 GHz line of CI. By comparing the CI distribution with the CO distribution, we are studying formation and evolution of molecular clouds in detail.

In addition, our group has developed the portable 18 cm submillimeter-wave telescope (POST18). The main purpose of this telescope is a survey of the CI 492 lines over the Milky Way. In 2002, we accomplished the first observation of the CI line with this telescope at the Pampa la Bola site (alt. 4800 m) in Chile. In 2003, we have successfully conducted the CI line observation toward the southern Milky Way. With the result, we are studying formation and evolution of molecular clouds in the galaxy scale.

Furthermore, we are developing a hot electron bolometer (HEB) mixer that can be used at 1.5 THz for a survey of the NII fine structure line. For this purpose, we have newly introduced an electron beam lithography system and a mixer fabrication system in our laboratory. With these equipments, we fabricated a diffusion-cooled type HEB mixer using Nb as a superconductor material, and confirmed that this mixer shows a good response at 800 GHz. We are also developing a phonon-cooled type HEB mixer using NbTiN.

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28 Sakai (Hirofumi) Group

Research Subjects: Experimental study 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 pulses. (3) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation) and ultrafast phenomena in atoms and molecules. (4) Attosecond pulses generated with high-order harmonics and their reliable measurements. (5) Structures and dynamics of molecules studied by the laser induced Coulomb explosion. Some of our research activities in the academic year of 2004 are as follows:

(1) Enhancement of molecular orientation with combined electrostatic and intense, nonresonant laser fields

We have already succeeded in the proof-of-principle experiments of one-dimensional and three-dimensional orientation of molecules with combined electrostatic and intense, nonresonant laser fields. However, it is indispensable to further increase the degree of orientation in order to use a sample of oriented molecules in applications. In the last academic year, we designed a new apparatus where a higher electrostatic field can be applied. With the help of detailed simulations of ion trajectories, we paid special attention to the design of the electrodes and their surroundings so that the fragment ions arrive at the detector in a correct manner.

In this academic year, after we constructed the apparatus and confirmed that it worked as expected, the experiments to enhance the degree of molecular orientation are ongoing. With a sample of OCS molecules diluted (5%) with He gas, a backing pressure of 10 atm., an electrostatic field of 4.4 kV/cm, and a laser peak intensity of 1.7×10^{12} W/cm^2, we have already succeeded in achieving higher degree of orientation than that achieved in the proof-of-principle experiments. Although the laser peak intensity, which was limited by the damage threshold of the polarizing beamsplitter cube, was only 2/3 of that used in the proof-of-principle experiments, the achieved higher degree of orientation shows the efficacy of a higher electrostatic field than that used in the proof-of-principle experiments by more than one order of magnitude. We aim to further enhance the degree of orientation by increasing the laser peak intensity up to around 2.6×10^{12} W/cm^2.

(2) Controlling high-order harmonic generation from nonadiabatically aligned molecules

A sample of aligned molecules is an ideal quantum system to investigate the quantum phenomena associated with molecular symmetries. This is illustrated by HHG from aligned molecules. Here, we employ the nonadiabatic alignment technique to align molecules with a relatively high rotational temperature of several tens K. We introduce a novel methodology that we observe both ion yields and harmonic signals under the same experimental conditions. Thereby, we can disentangle the contributions from each step in the three-step model for HHG from molecules.

Some of the major results obtained so far are as follows: (1) We confirm that high-order harmonic generation characteristics reflect the symmetry of the HOMO of the sample molecule. (2) Characteristic modulation patterns of both ion yields and harmonic signals measured as a function of the pump-probe delay are successfully explained by our original formulae determined by the valence orbital of the molecules.

(3) As the most remarkable result, we report the first demonstration of quantum interference of electron de Broglie waves evidenced by HHG from aligned CO_2 molecules. (4) In order to explain the destructive interference observed for CO_2 molecules, we successfully extend the two point emitters model, which was originally proposed for a diatomic molecule, to a triatomic molecule. (5) We propose that simultaneous observations of both ion yields and harmonic signals can serve as a new route to probe the instantaneous structure of the molecular systems.

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[2] Takayuki Suzuki, Shinichirou Minemoto, and Hirofumi Sakai, Appl. Opt. **43**, 6047-6050 (2004).

[3] Tsuneto Kanai, Shinichirou Minemoto, and Hirofumi Sakai, Nature **435**, 470-474 (2005).

29 Kuwajima Group

Research Subjects: Protein Folding, Molecular Chaperones, Protein Stability, Physicochemical Studies of Biological Macromolecules

Member: Kunihiro Kuwajima, Kosuke Maki, & Kimiko Saeki

We are studying mechanisms of *in vitro* protein folding and mechanisms of molecular chaperone function. Our goals are to elucidate the physical principles by which a protein organizes its specific native structure from the amino acid sequence and to elucidate how these principles are utilized or qualified by the molecular chaperones in a biogical cell. To this end, we are using various physicochemical, protein engineering, and computational techniques, including rapid reaction techniques, mutational analysis, and molecular dynamics simulations.

To investigate whether the structure partially formed in the molten globule folding intermediate of goat α-lactalbumin is further organized in the transition state of folding, we constructed a number of mutant proteins and performed Φ-value analysis on them. We studied the equilibrium unfolding transitions and kinetic refolding and unfolding reactions of the mutants using equilibrium and stopped-flow kinetic circular dichroism techniques. The results have indicated that the folding nucleus in the transition state of goat α-lactalbumin is not extensively distributed over the α-domain of the protein, but very localized in a region that contains the Ca^{2+}-binding site and the interface between the C-helix and the β-domain. It is concluded that the specific docking of the α- and β-domains at a domain interface is necessary for this protein to organize its native structure from the molten globule intermediate.

We investigated the kinetic refolding of a mutant (F99S/M153T/V163A) of green fluorescent protein, which is known to mature more efficiently than the wild-type protein, from the acid-denatured state; refolding was observed by chromophore fluorescence, tryptophan fluorescence, and the far-UV circular dichroism, using a stopped-flow technique. In this study, we demonstrated that the kinetics of the refolding of the mutant have at least five kinetic phases, and involve nonspecific collapse within the dead time of a stopped-flow apparatus and the subsequent formation of an on-pathway intermediate with the characteristics of the molten globule state. We also demonstrated that the slowest phase and a major portion of the second slowest phase were rate-limited by slow prolyl isomerization in the intermediate state, and this rate limitation accounts for a major portion of the observed kinetics in the folding of green fluorescent protein.

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30 Nose Group

Research Subjects: Mechanism of Neural Network Formation

Member: Akinao Nose, Takako Morimoto-Tanifuji 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

1.1. Genome-wide search for target recognition molecules by microarray

To systematically identify novel genes involved in neuromuscular target recognition, we performed microarray analysis. We compared the expression of genes in two neighboring muscles, 12 and 13, which are innervated by distinct motor neurons, and identified 200 genes that are differentially expressed. We are now conducting functional analyses of some of these genes, in particular, those encoding transmembrane or secreted proteins.

1.2. Live imaging of neuromuscular target recognition

We investigated the dynamics of the membrane protein Capricious (Caps), which we previously identified as a target recognition molecule in this system. We found that CAPS-GFP concentrates at the tips of myopodia, protrusions extended by muscles, just before and during the period when motoneurons initiate contact with muscles. Presentation of a target recognition molecule at the tips of cellular protrusions such as myopodia may be an efficient way to ensure correct interaction between pre- and postsynaptic cells and suggest for an active role played by the postsynaptic muscles in target recognition.

2. Molecular Mechanisms of Synaptogenesis

2.1. Role of postsynaptic CaMKII on synaptogenesis

During synaptogenesis, synaptic proteins are rapidly assembled into both pre- and postsynaptic sites that are capable of high fidelity transmission. Interaction between the presynaptic neuron and its postsynaptic target cell(s) is essential for the development of synapses. To elucidate the role of postsynaptic cells in synaptogenesis, activity of calcium/calmodulin-dependent protein kinase II (CaMKII) was manipulated specifically in the postsynaptic cell using GAL4-UAS expression system and its effect on the synapse formation at developing Drosophila neuromuscular junction was examined. Together with the investigation into localization of synaptic proteins, we found that increased postsynaptic CaMKII activity enhances not only postsynaptic but also presynaptic maturation in function and morphology. We propose two significant functions of postsynaptic CaMKII during synaptogenesis - retrograde modulation of presynaptic properties and coordinated regulation of pre- and postsynaptic maturation. Currently, we are further examining the molecular mechanisms of retrograde signaling. We also found the development-stage dependent effect of postsynaptic CaMKII modification on the synapse maturation.