ISSN 0910-0709

*Department of Physics*

*School of Science*

*University of Tokyo*

# Annual Report

# 2001

# 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, Stochastic Configuration Method, Relativistic Mean Field Calculation
Quark-gluon Plasma, Lattice QCD simulations, Structure of Hadrons

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

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

Among various subjects of the Nuclear Structure Physics, we have studied mostly, during the past one year, (1) Structure and reaction of unstable nuclei, (2) Monte Carlo Shell Model, (3) various new approaches to the nuclear many-body problems.

(1) Unstable nuclei stand for the nuclei far from the beta stability line. We are studying various features of such nuclei. This year, a systematic study has recently been made for unstable nuclei around A=30, focusing upon varying shell gap, vanishing magic number and anomalous deformation, by applying the Monte Carlo shell model described above [1, 2, 3]. We found that magic numbers of unstable nuclei can be quite different systematically from those of stable nuclei, and this difference has a robust origin [3]. Significant influences of the spin-isospin interaction are also for magnetic moments and Gamow-Teller transitions.

(2) We have proposed, several years ago, the Quantum Monte Carlo Diagonalization (QMCD) method for solving many-body problems. This method enables us to generate, through a Monte Carlo process, a small number of many-body bases which are important to the final solution. The method therefore can be characterized as *importance truncation scheme* [1, 2, 4]. Thus, this study is expected to produce enormous progress in our understanding of nuclear structure. This kind of studies are referred to as Monte Carlo Shell Model.

(3) The molecular structure of unstable nuclei is studied extensively also [5]. A new method treating loosely bound particles, called Stochastic Configuration Method, is developed also. The relativistic mean field approaches are studied from some new perspectives as well.

## Hadron Physics

In Hadron Physics group (T. Hatsuda and S. Sasaki), 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 matter
   - 1.1 Color superconductivity in quark matter [7]
   - 1.2 Chiral symmetry restoration in hot and dense matter [8, 9]
2. Quark-gluon plasma and its signature [10, 11]
3. QCD structure of hadrons
   - 3.1 Lattice QCD simulations for excited baryons, and chiral symmetry in baryon spectrum [12]
   - 3.2 High energy QCD processes and structure functions [13]
   - 3.3 Baryon mixings in QCD sum rules [14]

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# 2 Theoretical Particle and High Energy Physics Group

**Research Subjects:** The Unification of Elementary Particles & Fundamental Interactions

**Member:** Kazuo Fujikawa, 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. In addition to these topics, we also study various problems in quantum field theory, ¿from the viewpoints of both continuum and lattice approaches.

We list the main subjects of our researches below.

1. String Theory
   - 1.1 Calabi-Yau Compactification [1, 2, 3, 28, 39]
   - 1.3 String Field Theory and Tachyon Condensation [26, 27, 34, 35, 36, 37, 42, 43, 44, 45, 46, 47, 48, 49, 50]
   - 1.3 Noncommutative Geometry [17, 18, 33]
   - 1.4 String Theory in Various Backgrounds [20, 21, 22, 23, 38, 40, 41]
2. High Energy Phenomenology
   - 2.1 Models in Higher Dimensional Spacetime [19, 24, 25, 31, 32, 51, 52, 53, 54, 55]
   - 2.1 Particle Cosmology [6, 7, 8, 9, 15, 16]
   - 2.2 The Phenomenology of Supersymmetric Models [4, 5, 29, 30]
3. Quantum Field Theory
   - 3.1 Lattice Gauge Theory [12, 13, 14]
   - 3.2 Fundamental Problems in Field Theory [10, 11]

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# 3 Sakai Group

**Research Subjects:** Experimental Nuclear Physics

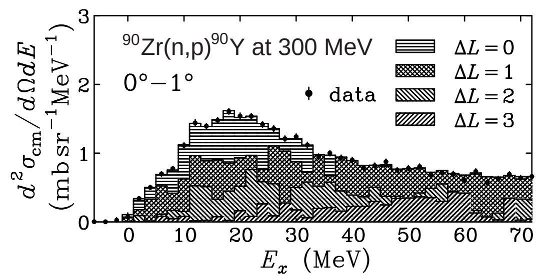
**Member:** Hideyuki Sakai, Atsushi Tamii

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 "polarizations": polarized beams ($\vec{p}$, $\vec{n}$ and $\vec{d}$), polarized targets ($\vec{p}$ and $^3\vec{\mathrm{He}}$), and polarization analysis of reaction products ($\vec{p}$, $\vec{n}$ and $\vec{d}$).

Major activities during the year are summarized below.

1. Measurement of the $^{90}$Zr$(n,p)$ reaction at $E_n$=300 MeV has been carried out by employing the newly constructed $(n,p)$ facility. The $\Delta L$=0 transition strength has been extracted by the multipole decomposition analysis (MDA) as shown in the figure below. After subtracting the spin monopole (SM) contribution, we have identified a $\beta^+$ Gamow-Teller (GT) strength of $S_{\beta+}$=3.1±0.4±0.8±0.5 up to $E_x$=31 MeV.

   By combining the $S_{\beta+}$ strength with the $S_{\beta-}$ strength formerly obtained by the $^{90}$Zr$(p,n)$ measurement, the GT quenching factor has been found to be $Q$=0.83±0.06. By this $Q$ value the Landau-Migdal parameter can be derived as $g'_{\mathrm{N}\Delta} = 0.26 \sim 0.09$. The $g'_{\mathrm{N}\Delta}$ value allows us, for the first time, to estimate quantitatively the critical density of pion condensation which may be realized in neutron stars.




2. How the effect of three nucleon force (3NF) appears in nuclear reactions is one of interesting subjects in nuclear physics. We are studying the effect of 3NF by comparing high precision data of nucleon-deuteron elastic scattering with predictions of recent Faddeev calculations using modern nucleon-nucleon forces. Following three studies have been pursued.

   a) The $\vec{d}$-$p$ elastic scattering has been measured at $E_d$=140, 200, and 270 MeV for cross sections and deuteron analyzing powers as well as the deuteron to proton polarization transfer coefficients at 270 MeV. Clear signature of 3NF is being obtained for the cross section data. However, apparent discrepancies, especially in tensor analyzing powers and proton induced polarization, clearly indicate deficiency in the spin-dependent part of the 3NF. It has been revealed that 3NF models are required to satisfy the chiral symmetry to reproduce the data.

   b) 3NF effects at $E_p$=392 MeV are studied by measuring the $\vec{p}$-$d$ elastic scattering. Obtained analyzing powers show larger deviation from the prediction of Faddeev calculations than that of low energy. Induced deuteron polarizations and proton to deuteron polarization transfer coefficients are poorly reproduced by the calculation.

   c) 3NF effects in a Coulomb free system have been studied by measuring the differential cross sections and analyzing powers of the $\vec{n}$-$d$ elastic scattering at $E_n$=245 MeV. Faddeev calculations incorporating 3NF have reproduced the cross section slightly better than those without 3NF. They still, however, underestimate the data, which might be an indication of relativistic effects at this energy.

3. The spin structure of the three nucleon bound systems, $^3$He and $^3$H, in high momentum region has been studied by measuring analyzing powers of the $\vec{d}d \to {}^3\mathrm{He}\,n, {}^3\mathrm{H}\,p$ reactions. The tensor analyzing powers are not reproduced by one nucleon exchange (ONE) model calculations at forward scattering angles. The result implies deficiency in the present spin wave functions of the three nucleon systems.

# 4 Hayano Group

**Research Subjects:**

(1) ASACUSA project (Atomic Spectroscopy and Collisions Using Slow Antiprotons) at CERN. (2) Study of deeply bound pionic atoms in $^{207}$Pb, $^{205}$Pb and $^{115,119,123}$Sn nuclei at GSI. (3) Spectroscopy of hypernuclei.

**Member:** Ryugo S. Hayano, Takashi Ishikawa, Eberhard Widmann, Nobuhiro Yamanaka, Makoto C. Fujiwara, Masaki Hori, and Kiyoshi Tanida

- **Precision laser and microwave spectroscopy of antiprotonic helium at CERN-AD**

  Within the framework of the ASACUSA collaboration we are performing precision laser and microwave spectroscopy of antiprotonic helium (an exotic three-body system consisting of a helium nucleus, an antiproton, and an electron: $\mathrm{He}^{++}$–$\overline{\mathrm{p}}$–$\mathrm{e}^-$ (short $\overline{\mathrm{p}}\mathrm{He}^+$) at the Antiproton Decelerator (AD) of CERN. The antiproton occupies highly excited metastable states with lifetimes of the order of microseconds, thus enabling their study with laser and microwave spectroscopy.

  In 2001 we continued the laser spectroscopy of $\overline{\mathrm{p}}{}^4\mathrm{He}^+$, and systematically investigated also $\overline{\mathrm{p}}{}^3\mathrm{He}^+$ for the first time. Using a Radio Frequency Qadrupole Decelerator (RFQD) to further reduce the energy of antiprotons, we could measure the transition wavelength at about a factor 1000 lower densities, thus reducing the systematic error coming from the extrapolation to zero density that was needed before. The preliminary analysis indicates that we will be able to improve our experimental precision to $\sim 8\times10^{-8}$ in the best case. As before, for the majority of transitions we found agreement with the most precise three-body calculations that include QED corrections up to order $\alpha^4$ at the same level. This is an impressive test on the accuracy of the variational calculations. Assuming the correctness of both experiment and calculations, the agreement can be used to perform a CPT test on the equality of proton and antiproton charge and mass, since the theory uses the numerical values of the proton that are much more precisely known. From the preliminary data analysis we expect to improve the constraint on the equality of proton and antiproton charge and mass by a factor 3 over our previous value to $\sim$ 20 ppb ($2\times10^{-8}$).

  A step further in the precision spectroscopy of $\overline{\mathrm{p}}\mathrm{He}^+$ is the investigation of level splittings arising from the magnetic interaction of its constituents. Due to the magnetic moment of the electron and antiproton, the levels in $\overline{\mathrm{p}}\mathrm{He}^+$ are split into a quadruplet, where the dominant splitting (called *hyperfine* (HF) splitting) arises from the interaction of the $\overline{\mathrm{p}}$ *angular* momentum (that is large because $L\sim35$) and the electron spin. Using a two-laser microwave triple resonance technique, we could in 2001 for the first time observe two microwave-induced transitions within the $(37,35)$ state. The measured frequencies (accuracy $\sim 2\times10^{-5}$) agree with recent three-body QED calculations on the level of $<6\times10^{-5}$. The difference corresponds to the precision of the theories which is limited by the omission of terms of order $\alpha^2\sim5\times10^{-5}$. This measurement provides an important benchmark for the three-body QED calculations, and the higher precision of the experimental value calls for their improvement.

- **Deeply-bound pionic states in Pb and Sn nuclei**

  By the study of deeply bound pionic states in the recoil-less $^{208,206}$Pb(d,$^3$He) reaction we determined the s-wave part of the pion-nucleus potential. From this study it was found that the mass of $\pi^-$ meson is increased by 27 MeV inside the Pb nuclei.

  A new series of systematic measurements of $1s$ states of $\pi^-$ by the (d,$^3$He) reaction with Sn targets ($^{116,120,124}$Sn) was carried out in 2001 at GSI. For each of the pionic Sn atoms with the mass number of 115, 119, 123, the binding energy of the $1s$ state was measured with a precision of about 25 keV.

  From this experiment we can deduce the iso-scaler parameter of the s-wave part of the pion-nucleus interaction potential. This parameter is regarded as a unique signal of the restoration of the chiral-symmetry in the 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, Nori Aoi

Research activities covered by our laboratory are 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, 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.

- Production and identification of new neutron-rich isotopes, $^{34}$Ne, $^{36}$Na and $^{43}$Si, and particle instability of $^{33}$Ne and $^{36}$Na.
- In-beam gamma spectroscopy for the exotic structure of very neutron-rich nuclei.
  1. Magicity loss at $N$=20 and large deformation.
     Large deformation of $^{34}$Mg via the intermediate energy Coulomb excitation method, and energy determination of the first excited state for $^{30}$Ne by means of a liquid hydrogen target via the proton inelastic scattering.
  2. De-coupling of proton- and neutron-matter deformations.
     neutron-matter deformations for $^{32}$Mg via the proton inelastic scattering, and proton-matter deformations by a new technique, Doppler-shift-attenuation method, for life time measurements of excited states in light and neutron-rich nuclei.
  3. Magicity at $N$=50: Coulomb excitation of $^{84}$Se.
  4. Development of Germanium telescope for in-beam gamma ray spectroscopy in inverse reactions.
- Breakup reactions with very neutron-rich nuclei.
  1. Coulomb and nuclear breakup reactions with $^{17}$B for its exotic structure and soft collective modes.
  2. Exotic cluster structures of $^{12,14}$Be via nuclear breakup reactions.
- beta spectroscopy of $^{46}$Cr.
- Key reactions of nuclear synthesis in astrophysical phenomena.
  1. Coulomb dissociation of $^{23}$Al to study a key reaction of the rp-process path, $^{22}$Mg(p,$\gamma$)$^{23}$Al.
  2. Coulomb dissociation of $^{15}$C to study a key reaction of the CNO neutron cycle in low-mass AGB stars, $^{14}$C(n,$\gamma$)$^{15}$C.
  3. Application of transfer reactions to radiative capture reactions in stellar evolutions, $^{7}$Be(p,$\gamma$)$^{8}$B, $^{8}$B(p,$\gamma$)$^{9}$C, $^{12}$C(n,$\gamma$)$^{13}$C by means of the ANC method.

# 6 Komamiya Group

**Research Subjects:** (1)OPAL experiment at LEP $e^+e^-$ collider;(2) preparation for experiment at the linear $e^+e^-$ collider JLC;(3)research on astroparticle physics with balloon-borne high resolution spectrometer (BESS experiment);(4) Detector researches and developments for future particle physics experiments.

**Member:** Sachio Komamiya, Tomoyuki Sanuki

1) OPAL experiment:The elementary particle physics experiment of a large international collaboration using the highest energy $e^+e^-$ collider LEP is running at 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 lower limit of the Higgs Boson of the Standard Model was set to be 114 GeV (95% C.L.). From the precise measurement of the electro-weak interaction at LEP and other accelerators, the upper mass limit of the Higgs boson was obtained to be about 200 GeV. Therefore the Higgs boson should exist within the narrow mass range of 114-200 GeV. For the Minimal Supersymmetric Standard Model (MSSM) the lightest Higgs boson was excluded in the large MSSM parameter space, so that it is restricted into rather narrow parameter space. 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 36.3 GeV. This limit is quite independent of the models. The W boson mass was determined to be $80.468 \pm 0.053 \pm 0.039$ GeV (statistical and systematic errors) by the OPAL experiment alone. The combined W boson mass for the four LEP experiments is $80.450 \pm 0.039$ GeV (statistical and systematic errors combined). Anomalous interactions of the W boson was searched for, and strict limits were set for these interactions.

2) Preparation for the $e^+e^-$ linear collider JLC: JLC is the energy frontier machine for $e^+e^-$ collisions in the near future. We have been studying the possible physics and experiments at JLC.

3) BESS experiment: To calculate the accurate atmospheric neutrinos spectra in a study of neutrino oscillation, it is essential to know the accurate primary cosmic-ray fluxes up to about 1 TeV, as well as atmospheric muon spectra at various altitudes which correlate directly to the hadronic interactions. The BESS spectrometer had provided to observe proton and helium spectra up to 100 GeV. We upgraded the BESS detector to improve the rigidity resolution and muon/electron separation. Balloon experiment was performed to observe cosmic-ray fluxes at Fort Sumner, New Mexico (cutoff rigidity is 4.2 GV), in September 2001. Because of gradually descendant of the balloon (pressure changed from 4.5 $g/cm^2$ to 33 $g/cm^2$), very precise measurement of the cosmic-ray fluxes were made at various altitudes.

4) Detector R&D: We are starting research and development for possible detectors in the future experiments. The group has considered the BES-III experiment at the Beijing $e^+e^-$ collider BEPC-II as the candidate for the middle term project before JLC. We have studied the possibility of the search for a rare decay $\tau^\pm \to \mu^\pm \gamma$ at BES-III. Development of photon detector for the CsI calorimeter system is considered.

# 7 Minowa Group

**Research Subjects:** Experimental Particle Physics without Accelerators

**Member:** MINOWA, Makoto and INOUE, Yoshizumi

The direct experimental search for supersymmetric particle dark matter is running in an underground cell in the Kamioka Observatory.

The detector consists of 8 pieces of 20-gram lithium fluoride bolometers. The fluorine is estimated to be one of the best nuclide for the detection of spin-dependently interacting neutralinos. The fluorine for the dark matter search is complementary to the widely used sodium(of NaI) when their sensitivity is represented in the parameter plane of the neutralino-proton spin-dependent coupling($a_{\mathrm{p}}$) and neutralino-neutron spin-dependent coupling($a_{\mathrm{n}}$)

On the basis of the measurement in Kamioka limits were obtained on normalized point-like cross section for the spin-dependently interacting neutralino incident on a single proton. The new limits are better in the higer mass region than those previously obtained by the measurement in the Nokogiriyama underground cell. We also derived the limits in the $a_{\mathrm{n}}$–$a_{\mathrm{p}}$ plane and excluded a part of the parameter space allowed by the measurement of UK dark matter collaboration with NaI detectors.

A still more sensitive new detector for the dark matter search is under development by us. Anthracene and stilbene scintillators have directional anisotropies in the scintillation efficiency for heavy charged particles. This feature of the scintillators could be used to detect the motion of the dark matter particles relative to the earth improving the sensitivity to the dark matter detection.

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 if its mass is a few electronvolts. 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.

We have made the experiment in which the magnetic field region is filled with the cold conversion buffer gas. We got upper limits to the coupling constant of axions to photons in $m_a$ region less than 0.26 eV, which are currently the world's best limits. We also put limits on the axion flux coming from the various celestial objects for the first time by the ground-based direct search.

# 8 Aihara Group

**Research Subjects:** Study of CP-Violation in the $B$ Meson System, Precise Measurements of CKM Matrix Elements, Search for Physics Beyond the Standard Model in the $B$ Meson, R&D for Silicon Detectors, and R&D for Linear Collider

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

The main research activity of our group has been a study of CP-violation in the $B$ meson system using the KEK $B$-factory (KEKB). This past year we presented a measurement of the Standard Model $CP$ violation parameter $\sin 2\phi_1$ based on a 29.1 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance. One neutral $B$ meson was fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ or $J/\psi K^{*0}$ decay and the flavor of the accompanying $B$ meson was identified from its decay products. From the asymmetry in the distribution of the time intervals between the two $B$ meson decay points, we determined $\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$. We conclude that we have observed $CP$ violation in the neutral $B$ meson system [1].

We have also measured $B_d^0$ and $B^\pm$ lifetimes [2] and $B_d^0 - \overline{B_d}^0$ mixing using the silicon vertex detector [3] that our group built and has been responsible for operating.

In addition to $B$ physics, we have performed high precision measurements of the charmed meson lifetimes and searched for $D^0 - \overline{D}^0$ mixing [4], taking advantage of the high statistics data and the superb performance of the silicon vertex detector.

The goal of our instrumentation R&D program has been to develop the next generation vertex detector for the Belle experiment. We have investigated radiation-hardness of CMOS preamplifier based on deep sub-micron technology and fabricated readout preamplifier VLSI chip based on 0.35 micron process. We have verified that the 0.35 micron chip is radiation hard up to 20 Mrad [5], which is well beyond the total radiation dose expected for several years of the $B$-factory operation. We have been fabricating a new silicon vertex detector for the Belle upgrade.

Also this year we have started R&D program for a linear collider experiment. Our initial interest includes a simulation work for the beam delivery system, a study of a machine-detector interface (or an interaction region) and a design of the silicon-only tracker.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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. Spin Chains
   (1) Integrable Vertex Models
   (2) Magnetization, Correlation Function and Riemann–Hilbert problem
4. Strongly Correlated Electron Systems
   (1) Thermodynamics in the Hubbard Model, $t$-$J$ Model
   (2) Integrable Boundary Conditions
5. Knot Theory and Low-Dimensional Topology
   (1) Hyperbolic Volume of Knot Complement
   (2) Quantum Gravity
6. Quantum Many-Body Problem
   (1) $\delta$-function Bose gas
   (2) Calogero–Sutherland Model
   (3) Exclusion Statistics and Chiral Partition Function
   (4) Hard-core Bose gas
7. Quantum Computing and Quantum Information
   (1) Geometric Aspects of Quantum Search
   (2) Multipartite entanglement and embeddings in algebraic geometry
   (3) Quantum Cloning
8. Random Matrix
   (1) Mesoscopic Fluctuation

# 10 Tsukada Group

**Research Subjects: Theory of Solid Surface and Interface,**

**Theory of Artificial Nano-Structures,**

**Development of Computational Material Science**

**Member:Masaru Tsukada, Ryo Tamura**

A new method for the first-principles calculation of electronic structure of surface under strong field and current is developed. The mechanism of atom extraction by the tip and nano-scale point contact formation are clarified by this method. The concept of eigen-channels for the quantum transport through atom bridges is developed by this method. Ultrasoft pseudopotential method for the first-principles molecular dynamics is developed with the implementation of the core orthogonalization and the generalized gradient correction. The method is applied to the problems as the substitutional penetration of adsorbed Ge on Si(001) surface, the molecular chemisorption of acetylene on Si(001) surface, quantum dynamics of dimers of Si (001) surface and a new symmetry broken structure of Si(111) $\sqrt{3}\times\sqrt{3}$ - Ag. Interaction of water clusters with clean or hydrogenated Si(001) surfaces is investigated by the first-principles molecular dynamics. An important concept obtained by the calculations is the proton relay dissociation of water molecules on solid surfaces. The first-principles density functional calculations as well as numerical Greens function method are applied to various problems related nano-structures and surface science. The problems we studied this year include the structure and hydrogenation of $C_{36}$ clusters, the transport properties of carbon nanotube metal-semiconductor junctions, effect of the tip on the noncontact atomic force microscopy ( ncAFM ) images , the phase transition of Si(111)$\sqrt{3} \times \sqrt{3}$-Ag surface, quantum transport through atomic wires and $C_{60}$. Successful development of the new numerical algorithm for the integration of the time-dependent Kohn-Sham equation has been also achieved. We examined the structures and energies of isomers of $C_{36}$ with the first-principles density functional calculation based on the real space finite-element method (FEM). Two hydrogenation way up to octahydrogenation was revealed. The theoretical nc-AFM image by the density functional calculation reproduced excellently the experimental image of Si(111)$\sqrt{3} \times \sqrt{3}$-Ag surface, if the thermal average of the images of the two IET phases is taken into account. The influence of the tip on the nc-AFM image is revealed by the theoretical calculation. Mechanism of damping and dissipation of the cantilever oscillation is theoretically analyzed, and the relation with non-conservative atomic process is clarified. The transport property of the semiconductor metal nano-tube junction is investigated with the effects of the atomic structures. We found that the junction becomes a backward diode. Electron transmission through a $C_{60}$ molecular bridge is studied and a loop current feature is found, when the electron energy is near the degenerate molecular levels. We developed an efficient method for solving the time dependent Kohn-Sham equation in real space and real time. Applying this method to He atom and Be atom, we confirmed the efficiency and accuracy of the method.

N.Sasaki, S.Watanabe, H.Aizawa and M.Tsukada: Simulation of interaction force between Si tip and Si(111) -Ag surface of IET structure in noncontact AFM, Surf. Sci. 493 (2001) 188–193

N.Watanabe and M.Tsukada: Efficient method for simulating quantum election dynamics under the time dependent Kohn Sham equation, Phys. Rev. E 65 (2002) 036705

S.Nakanishi and M.Tsukada: Quantum Loop Current in a C60 Molecular Bridge, Phys. Rev. Lett. 87 (2001) 126801

K.Tagami, N.Sasaki, and M.Tsukada: Simulated nc-AFM images of Si(001)surface with nanotube tip, Appl. Surf. Sci. 172 (2001) 301–306

N.Kobayashi, M.Aono and M.Tsukada: Conduction channels of Al wires at finite bias, Phys. Rev. B 64 (2001) 121402

M. Gauthier, N. Sasaki, and M. Tsukada: Dynamics of the cantilever in noncontactdynamic force microscopy: The steady-state approximation and beyond, Phys. Rev.B 64 (2001) 085409

R.Tamura: Backward diode composed of a metallic and semiconducting nanotube,Phys. Rev. B 64 (2002) 201404

# 11 Aoki Group

**Subject:** Theoretical condensed-matter physics

**Members:** Hideo Aoki, Ryotaro Arita

Our main interests are in many-body effects in electron systems, incl. what we call "materials design for correlated electron systems":

• Superconductivity in repulsively interacting electron systems
— Numerical and analytic studies for the Hubbard model in 2D and 3D[1]
incl. models for high-$T_C$ cuprates and organic conductors[2],
— Spin-triplet superconductivity in oxides[3] and organic metals[4],
— how to optimize $T_C$ through the "fermiology"[1,5,6]

• Magnetism in repulsively interacting electron systems
— Ferro- and antiferromagnetism in 2D and 3D,
— Electron-correlation-dominated magnetotransport[7],
— Flat-band ferromagnetism in an organic polymer[8]

• Quantum Hall systems
— Effective mass and Fermi liquid properties in the fractional quantum Hall liquid[9],
— Integer quantum Hall effect, Hofstadter butterfly and field-induced spin-density wave in three dimensions [10]

• Mesoscopic and hetero systems
— Electron-molecule picture for quantum dots,
— Electron correlation effects at surfaces and interfaces[11]

• Electrons on periodic curved surfaces — topological band structure[12]


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# 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, materials with spin, charge and orbital degrees of freedom, unconventional superconductivity, and Tomonaga-Luttinger liquid theory. The followings are the current topics in our group.

- High-$T_c$ superconductivity
  Numerical studies of Stripe states in the two-dimensional $t$-$J$ model.
  Pseudo-gap phenomena in high-$T_c$ superconductors.
  Low temperature specific heat and entropy in the $t$-$J$ model and its spin-charge separation.
  Extension of Gutzwiller approximation to clarify the effect of strong correlation.
- Electronic states and instabilities in $d_{x^2-y^2}$-wave superconductivity
  Quasiparticle states and magnetism around nonmagnetic and magnetic impurities.
  Antiferromagnetic vortex core and its charging effect.
  Other orders coexisting with d-wave superconductivity.
- Triplet superconductivity in $Sr_2RuO_4$
  Triplet superconductivity due to antiferromagnetic spin fluctuation.
  Microscopic mechanism of triplet superconductivity.
- Electronic states in frustrated systems
  Verwey transition in magnetite.
  Strongly correlated electron system on a triangular lattice.
  Melting of CDW state due to frustration in $PrBa_2Cu_4O_8$.
- Spin excitations in two-dimensional insulators
  Spin waves and high-energy spin excitations in RVB or $\pi$-flux states.
- One-dimensional systems
  Impurities in spin-Peierls systems.
  Coexistence between $2k_F$ SDW and $2k_F$ CDW in the quarter-filled organic conductors and its crossover.
  Organic materials with a spin gap.
  New correlation functions in one-dimensional electron systems.


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[11] M. Saito and M. Ogata: J. Phys. Soc. Jpn. **71**, 721-724 (2002). "Midgap States in Disordered Spin-Peierls Systems"

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# 13 Tsuneyuki Group

**Research Subjects:** Theoretical condensed-patter physics

**Member:** Shinji Tsuneyuki

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.

Our activity of this year includes:

- New method of electronic-structure calculation
  - Applications of the transcorrelated method for small atoms and molecules, and also for the Hubbard model.
    Transcorrelated Hamiltonian $\mathcal{H}_{tc} = (1/F)\mathcal{H}F$ is a kind of similarity transform of the many-body Hamiltonian $\mathcal{H}$ with the Jastrow function $F$, which represent electron correlation explicitly. If $\Psi = FD$ is the exact eigenstate of $\mathcal{H}$, $D$ is the eigenstate of $\mathcal{H}_{tc}$ and so the eigenvalues are the same with each other. Since $\mathcal{H}_{tc}$ includes at most three-body operator, we can estimate its expectation value with the Slater determinant $D$ without Monte Carlo sampling. We showed that this transcorrelated method works well for small atoms and molecules, and also for the Hubbard model with $F$ being the Gutzwiller factor. We also found that CI (configuration interaction) for $\mathcal{H}_{tc}$ converges much faster than that for $\mathcal{H}$.
- Surface and interface
  - First-principles study of unsaturated cyclic-hydrocarbon on Si(001) surface and its chemical reaction.
    In collaboration with Yoshinobu group at the Institute for Solid State Physics (ISSP), the University of Tokyo, we are studying electronic and structural properties of unsaturated cyclic-hydrocarbon on Si(001) surface. We predicted that additional reaction of halogen molecules will proceed as in gas phase at low coverage, while it will be prohibited at high coverage by geometrical hindrance.
  - First-principles study of inter nitrogen interaction energy of Cu(100)-$c(2 \times 2)$N surface.
    We calculated nitrogen interaction energy of Cu(100)-$c(2 \times 2)$N surface to clarify the mechanism of the self-organization observed by Komori group at ISSP.
  - First-principles study of electronic states localized at grain boundaries in semiconductors.
    We studied electronic structure at the grain boundary of silicon with first-principles method, especially focusing on the formation of localized state at the grain boundary. Some results of the previous calculations are found to be artifacts of the model Hamiltonian adopted so far.
- Materials under high pressure
  - First-principles study of a high-pressure hydrous phase, $\delta$-AlOOH.
    $\delta$ phase of AlOOH, synthesized by Ohtani group at Tohoku University very recently, is a candidate of minerals which carry $H_2O$ water in the lower mantle. It has specific features like large bulk modulus and strange anisotropy of the elastic constant. We studied the materials with the first-principles molecular dynamics method and found that symmetric hydrogen bonds will explain such features. This finding will have general importance when we consider hydrogen atoms in oxides.

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Y. Yoshimoto and S. Tsuneyuki: First-principles study of inter nitrogen interaction energy of Cu(100)-$c(2 \times 2)$N surface, Surf. Sci., in press.

# 14 Nagasawa Group

**Research Subjects:** Optical Spectroscopy on Semiconductors and Carbon Nanotubes

**Member:** Nobukata Nagasawa and Nobuko Naka

Current studies are devoted to following subjects.

- Search for excitonic Bose condensate in the semiconductor $Cu_2O$

  Excitons in $Cu_2O$ are one of the most favorite candidate to realize the Bose condensate of quasiparticles. We established a new approach to create a cold and dense exciton system by employing exciton traps and two-photon loading. The phase space density of the exciton system has been estimated to be 0.1 at the maximum.

  - Two-photon diagnostics of stress-induced exciton traps [3]
  - Two-photon spectroscopy of paraexcitons [3]
  - Observation of highly diffusive zero-momentum orthoexcitons [1]
  - Examination of the nonlinear exciton kinetics in the trap [6]

- Optical spectroscopy of carbon nanotubes formed in Zeolite single crystals

  Tang et al. have developed a method to grow mono-sized, aligned and single-walled carbon nanotubes of about 0.4 nm diameter inside micro-channels of a Zeolite single crystal. Interesting features related to the superconductivity have been recently reported on this material. Following works are performed as collaboration with Tokyo Instruments, Inc. and Prof. Z. K. Tang of Hong Kong University of Science and Technology.

  - Symmetry consideration of the optical transitions based on the band calculation by the LDA method [2, 4]
  - Spectroscopic study on linear visible emission under laser light irradiation at room temperature [4]
  - Observation of the nonlinear emission and second harmonic processes [4]
  - 3D microscope tomographic studies of the photo-induced effect on the emission in nanoscale spatial resolution using Nanofinder®
  - Electrical transport and photo-induced current-modulation measurements [5]


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# 15 Tarucha Group

**Research Subjects:** Low-dimensional electron transport, Electronic properties of artificial atoms and molecules, Spin effects and many-particle interactions in semiconductor nanostructures

**Member:** Seigo Tarucha, Keiji Ono

1. Electronic propertries of articificial atoms: We previously observed obeyance of Hund's first rule (favoring total spin maximal) for two-dimensional (2D) harmonic quantum dots. We extend the study to Hund's second rule (favoring total angular momentum maximal), and find that this rule is only observed when the dot has an ideal 2D harmonic confinement. However, this is not the case for many of real dots since imperfection in the harmonic confinement as well as the screening effect lifts the shell degeneracy.

   We assign the electronic configurations of a few-electron ground states in a high magnetic field to study the strong correlation effect, and find a systematic set of stable ground states, which compare well to magic number states characterized by special numbers of total angular momentum.

   We develop a new theory for the Kondo effect associated with singlet-triplet degeneracy in a quantum dot to reveal the competition between Hund's coupling inside the dot and the singlet coupling to the external leads. We also observe a two-stage Kondo effect, using a quantum dot prepared by a novel epitaxial growth technique. This Kondo effect arises from two different couplings between two channels in the leads and a singlet-triplet Kondo state.

2. Electronic properties of artificial two-dot molecules: We find for fairly strongly coupled artificial molecules that a single electron tunneling current is significantly small for a specific electronic configurations. We interpret this being due to isospin blockade. The isospin (IS) is defined for difference of number of electrons between the bonding and antibonding states. When the $|IS| > 1/2$ between the N and N-1 electron states, transition between the two states is forbidden.

   We observe spin blockade due to Pauli exclusion in the tunneling characteristics of a vertically weakly coupled quantum dot system when two same spin electrons occupy the lowest energy state in each dot. Spin blockade only occurs in one bias direction when there is asymmetry in the electron operation of the two dots, leading to current rectification. This spin blockade is collapsed by applying a magnetic field to open up a new spin-triplet current carrying channel.

3. Transport properties of quantum wires: We observe negative Coulomb drag resistance for coupled two quantum wire system when one of the two wires has a very low electron density. In this case dragged are holes in the other wire. This is well understood by assuming a sliding Wigner crystal in the wire with a very low electron density, since correlating holes are then induced in the other wire with a fairly high electron density.

4. Ballistic spin injection to semiconductor: We study hot, ballistic electron spin transport in a Co(emitter) /AlO(tunnel junction)/Fe(base)/GaAs(collecor) spin valve transistor. Due to strong anisotropy of spin density of states in Fe above 1 eV, hot electrons in the base can be highly spin polarized. However, there was a technical problem to produce such electrons. Thanks to the high quality tunnel junction, we succeed in producing high-energy electrons($> 1.2eV$)in the Fe base, and observe for the first time strong enhancement of spin polarization.

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# 16 Fujimori Group

**Research Subjects:** Photoemission Spectroscopy of Condensed Matter, Electronic Structure Studies of Correlated Systems

**Member:** Atsushi Fujimori

The electronic structures of strongly correlated systems and complex materials are studied using electron spectroscopic techniques such as photoemission, inverse-photoemission and x-ray absorption spectroscopies. We investigate metal-insulator transitions, magnetic fluctuations, mass renormalization, spin and charge density modulations, narrow-gap and pseudogap formation, electron-phonon coupling, etc., in $d$- and $f$-electron systems (transition-metal and rare-earth compounds, respectively) in one, two and three dimensions. Particular emphasis is made on novel phenomena near metal-insulator transitions including high-temperature superconductivity and giant magnetoresistance. Low-energy electronic structures near the Fermi level are studied using high-resolution photoemission. Angle-resolved photoemission is used to study band dispersions and Fermi surfaces.

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# 17 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. The surfaces we are interested in are covered by a variety of surface superstructures with various kinds of adsorbates. Peculiar atomic arrangements and surface electronic states, characteristic of the surface superstructures, 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, scanning tunneling micro/spectroscopy, photoemission spectroscopy, electron energy-loss spectroscopy, and in-situ 4-point-probe conductance measurements. Main results in this year are as follows.

**(1) Surface electronic transport**: measurements with micro-4-point probes (under collaboration with Denmark Technical Univ. ), and with a four-tip STM for nano-scale 4-point probe measurements, correlation with surface phase transitions or epitaxial growths.

**(2) Surface phases and phase transitions**: one-dimensional surface superstructures of Si(111)-$4 \times 1$-In and Si(111)-$5 \times 2$-Au (under collaboration with Yonsei Univ. (Korea)). 2D surface charge-density-wave transitions on Pb- or Sn-covered Si(111)-$\sqrt{3} \times \sqrt{3}$. 2D metals on Si(111)-$\sqrt{3} \times \sqrt{3}$-Ag and its derivatives, $\sqrt{21} \times \sqrt{21}$ phases.

**(3) Surface electronic excitations**: plasmons in surface-state bands.

**(4) Epitaxial growths of atomic/molecular layers**: perfect layer-by-layer growth of Bi films on Si, unwetting growth of Ag on Si.


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# 18 Fukuyama Group

**Research Subjects:** Low Temperature Physics:

Low temperature properties of liquid and solid $^3$He, Ultra-low temperature scanning probe microscope, Two-dimensional rare-gas solids, Superconductivity and charge density waves in low dimensional conductors.

**Member:** Hiroshi Fukuyama, Hiroshi Kambara, and Christopher Bäuerle

Our current research interests are (i) quantum many body phenomena such as nuclear magnetic orderings and superfluidity in liquid and solid $^3$He especially in two dimensions (2D), (ii) structural phase transitions in 2D rare-gas solids, (iii) exotic superconductors and charge density waves in low dimensional conductors, and etc. We are investigating these topics at very low temperatures down to several tens micro kelvin.

1. **Construction of a new ultra-low temperature scanning tunneling microscope (ULT-STM)**
An STM that works with an atomic resolution at ultra-low temperatures (T $>$ 50 mK) in high magnetic fields (B $\leq$ 6 T) has been constructed and tested. An STM head is made of non-magnetic silver based alloys, and is attached to the mixing chamber of a dilution refrigerator (DR). Clean sample surfaces are prepared either by cleavage or by repeated cycles of Ar ion sputtering and annealing in an ultra-high vacuum chamber. The resultant surfaces can be evaluated by low energy electron diffraction in the same chamber. A bottom loading mechanism enables us to change the samples and STM tips quickly without warming the DR above 2 K and to cool it back to the base temperature within 3 hours. We obtained atomically resolved imaging and tunneling spectroscopy capabilities of this new instrument which allows us to study new 2D physics in a variety of samples ranging from exotic superconductors with low $T_c$ to 2D rare-gas solids adsorbed on various substrates.

2. **Unconventional superconductivity in $Sr_2RuO_4$**
We have prepared scanning tunneling spectroscopy studies of the spin-triplet superconductor $Sr_2RuO_4$ with the ULT-STM. Single crystals of $Sr_2RuO_4$ were cleaved along the ab plane at 8 K in the UHV chamber. We found that the resultant surfaces were clean and flat from the low energy electron diffraction studies. Spatial information of the quasiparticle density of states, i.e., the superconducting gap structure, near the quantized vortices in magnetic fields will be reported near future.

3. **Quantum spin liquid state in 2D solid $^3$He**
The "quantum spin liquid (QSL)" state is suggested as the ground state of the low density second-layer solid $^3$He adsorbed on a graphite surface from a previous heat capacity measurement in zero magnetic field which shows a double peak structure. It is theoretically suggested that, with increasing magnetic field, the QSL phase changes into a long-range ordered phase called the "uuud phase" above a certain threshold field, which is a measure of the spin gap of the QSL phase, accompanied by a finite temperature phase transition. To study this unusual ground state, we have constructed a powerful and compact nuclear demagnetization refrigerator for heat capacity measurements of 2D $^3$He at temperatures below 200 $\mu$K in magnetic fields below 1 T.

4. **Search for a superfluidity in 2D $^3$He films**
So far, theoretically predicted 2D superfluidity in monolayer $^3$He has not been observed experimentally. This is because the temperature range in previous searches was limited above 1 mK due to localized $^3$He atoms trapped in heterogeneities of Grafoil substrate or because the single crystalline size (? 10 nm) of Grafoil is shorter than the expected superfluid coherence length (? 100 nm). To overcome these problems, we have constructed a high performance nuclear demagnetization refrigerator and characterized the ZYX grade exfoliated graphite which has at least ten times longer crystalline size than Grafoil. NMR measurements are now under going to search for the possible 2D and quasi 2D superfluidity in $^3$He films.

# 19 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 two-dimensional systems formed in the semiconductor interfaces such as silicon metal-oxide-semiconductor field-effect transistors (Si-MOSFET) and GaAs/AlGaAs heterostructures.

The current topics are following:

1. Magnetism in 2D electron solids and the Aharonov-Bohm effect:
   We study exchange interactions in the quantum solid phase formed in strongly correlated two dimensional electron systems. The nature of the interactions between neighboring spins can be controlled using the magnetic flux through the exchange path. Experimental results on the magnetic field dependence of the thermal activation energy in Si-MOSFET's had been explained by a model based on this effect (Okamoto et al. (1998) at Gakushuin University). We extend our research on this phenomenon to other semiconductor materials. In this year, we have developed a sample preparation system, cryostats and measuring systems in our new laboratory.

2. Metal-insulator transition in strongly correlated two-dimensional systems:
   A metal-insulator transition in 2D systems attracts a great deal of attention since it seems to contradict an important result of the scaling theory that the conductance of a disordered 2D system at zero magnetic field goes to zero for $T \to 0$. To clarify the electronic state in the metallic phase, we study magnetotransport in silicon two dimensional electron systems formed in Si-MOSFET's and Si/SiGe quantum wells at low temperatures.

3. Dynamics of nonequilibrium electrons in quantum Hall conductors:
   We study dynamics of nonequilibrium electrons in quantum Hall conductors through application of local probe techniques. The following techniques have been newly developed:

   (i) Imaging of cyclotron radiation

   We have achieved imaging of cyclotron radiation associated with inter-Landau-level transitions of electrons, which provides density profiles of nonequilibrium electrons. A combination of this technique with conventional resistance measurements has enabled us to clarify electronic properties in the vicinity of current contacts.

   (ii) Local electrometer using a small Hall device

   We have developed a novel technique for obtaining electrostatic potential images, which exploits the magnetoresistance oscillation of a two-dimensional electron system in a small Hall device.

# 20 Theoretical Astrophysics Group

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

**Member:** Katsuhiko Sato, Yasushi Suto, Tetsuya Shiromizu & Atsushi Taruya

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;

The Universe with Extra Dimensions — From Kaluza-Klein Perspective to Brane World (2001)
Gravitational Collapse of Rotating Massive Stars (2001)
Effects of Neutrino Oscillation on Supernova Neutrino (2001)
Resolving the Central Density Profile of Dark Matter Halos with Gravitational Lensing Statistics (2001)
The Stability of Higher Dimensional Spacetime (2001)
Double inflation in supergravity and its observational implications (2000)
Propagation of UHECRs in the inhomogeneous source model (2000)
Effects of neutrino oscillation on the supernova neutrino spectrum (2000)
A Biasing Model for Cosmological Two-Point Statistics and the Probability Distribution Function of Nonlinear Mass Fluctuations (2000)
Genus Statistics for Large-Scale Structure as a probe of Primordial Random-Gaussianity and Nonlinear Stochastic Biasing (2000)
Velocity Distribution Functions for Nonlinear Gravitationg Many-body Systems (2000)
The cosmological redshift-space distortion on two-point statistics of high-z objects (1999)
Gravitational lens theory from the wave-optics viewpoint and its application to gravitational wave astronomy (1999)
Gravitational particle productions in the early universe (1999)

Thermodynamics properties of nuclear “Pasta” in super dense matter (1999)
Dynamics of cosmological phase transition and evolution of global strings (1998)
The gamma-ray burst as a probe of cosmic star formation history and ultra-high energy cosmic rays (1998)
Imprints of Structure Formation on Cosmic Microwave Background (1998)
Topological Defects in the Early Universe (1998)
Modeling Galaxy Formation in a Hierarchical Universe (1998)
Quantum creation of the universe with the inner space (1998)
Phase transitions in high-density matter and neutron star evolution (1997)
Cosmological implications of the abundances of clusters of galaxies (1997)
Effects of axisymmetric explosion in collapse-driven supernovae (1997)
Hybrid inflation and axionic isocurvature fluctuations in supergravity (1997)
Asymptotic structure of time-like infinity (1997)

# 21 Murao Group

## Research Subjects: Quantum Information Theory

## Member: Mio Murao

In our group, we are investigating new properties of multiparticle entanglement and the use of these properties as resources for quantum information processing. M. Murao started working at University of Tokyo in October, 2001.

**Quantum information processing and entanglement:** Quantum information processing seeks to perform tasks which are impossible or not efficient 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 nonlocal correlation appearing in certain types of quantum states (non-separable states) consisting of several subsystems. A non-separable state cannot be represented by a product state of constituent subsystems. Entanglement is sometimes called "quantum correlation", since it is genuine correlation of quantum systems and does not exist in classical systems. It has been considered as the fundamental resource for quantum information processing to be more effective than classical information processing. As the result of intensive study of entanglement (especially in the last 5 years), entanglement of bipartite two-level systems (two qubit systems) is now understood quite well. However, there are still many open questions regarding the entanglement of multiparticle and multi-level systems.

**The current projects:**

- **The properties and applications of multiparticle entanglement:** We had proposed two quantum information processing schemes using multiparticle entanglement, remote quantum information distribution protocol [1] and remote quantum information concentration protocol [2]. We have analyzed the multiparticle entangled states used for these protocols and found new properties. In particular, the multiparticle entangled state used in [2] is a bound entangled state, which had previously been considered "useless" for quantum information processing as a single state. This is the first example of the effective use of a single bound entangled state for quantum information processing. Recently, we have shown that several different types of entangled states, including a single bound entangled state, can be used for remote quantum information concentration. This is in contrast to remote information distribution, which requires a certain type of entanglement. We have analyzed the asymmetry of quantum information distribution and concentration from the viewpoint of required entanglement. We have been investigating a new quantum information processing system using this property. A part of this work has been done in collaboration with Dr. V. Vedral of Imperial College, London.

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  [2] Mio Murao and Vlatko Vedral, Remote information concentration using a bound entangled state, Phys. Rev. Lett. 86, 352-355 (2001).

- **Photonic state quantum information processing under realistic circumstance:** Photonic states are promising candidates for the realization of quantum information processing, especially for quantum communications. Teleportation experiments have been already demonstrated using two different types of entangled photonic states. However experimental preparations are often far from the ideal conditions required to perform perfect quantum information processing. Therefore we are investigating how to perform effective quantum information processing using realistic resources for photonic systems, i.e. non-perfect photon detectors, non-perfect entangled states. A part of this work is in collaboration with Prof. Sam Braunstein and Dr. Kae Nemoto of the University of Wales.

# 22 Kobayashi Group

**Research Subjects:** Ultrafast and Nonlinear Optical Processes, Quantum Optics

**Member:** Takayoshi Kobayashi, Takao Fuji, Akikatsu Ueki

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

1. **Development of ultrashort pulse lasers**

   i. **Generation of the shortest 3.9 fs visible pulses by noncollinear optical parametric amplifier (NOPA)**: We demonstrate the generation of a continuous, simultaneously phase-matched 250-THz parametrically amplified spectrum. The resultant visible near-IR signal-wave pulses were compressed to a 4-fs duration by a micromachined f lexible mirror.

   ii. **Controlling the carrier-envelope phase of ultrashort light pulses with optical parametric amplifiers**: The phase link between signal, idler, and pump waves in a parametric interaction allows generation of an idler pulse with a phase independent of that of the input pulse. It is suggested that the use of a white-light seeded optical parametric amplifier as a self-stabilized source of few-cycle pulses, in which the phase of the electric field is exactly reproduced in each laser shot.

2. **Real-time spectroscopy for molecular vibration**

   i. **Vibrational dynamics in photoisomerization**: The photoisomerization dynamics of azobenzene derivative is studied using sub-5-fs laser pulses. Time-frequency analysis of molecular vibration modes reveals that the photoisomerization is described by a multi-dimensional model.

   ii. **Observation of Breather in polyacetlenes**: *Trans*-polyacetylene with a degenerate ground state has a nonlinear excitation of soliton after photoexcitation, due to the electron-phonon coupling. The excess energy of an excited electron-hole pair over a soliton-pair creation energy induces a *breather* (bound solition) oscillation characterized by collective stretching vibration of the carbon-carbon bonds. A time-frequency analysis of pump-probe signal shows that instantaneous frequencies of stretching modes are modulated for $\sim$50 fs after excitation and the modulation period is $44\pm3$ fs consistent with the theoretical expectation, clearly verifying the breather.

   iii. **Vibrational coherence persisting after internal conversion and vibrational relaxation in cyanine dye molecules**: Vibrational coherence after internal conversion from the higher-lying excited singlet state to the first excited singlet state ($S_n \rightarrow S_1$) and vibrational relaxation in cyanine dye molecules in solution are observed with two-color pump–probe experiments with the 20-fs time resolution.

3. **Midinfra red of time-resolved spectroscopy**: Time-resolved induced absorption spectrum in infrared region in the excited state of polydiacetylenes was investigated using the femtosecond near and mid infrared spectroscopy.

4. **Study of nonlinear ultrashort pulse propagation**: A nonlinear ultrashort pulse propagation in a solution of cyanine dye was measured by second-harmonic-generation FROG (SHG FROG). Decrease of the instantaneous frequency of the pulse was observed. This phenomena is explained by dynamic Stokes shift.

5. **Scanning near-field optical microscope(SNOM)**: A layered sample of J-aggregates of the dye pseudoisocyanine bromide in an ethylene glycol/water glass layer was studied with a scanning near-field optical microscopy (SNOM) developed in our group. The absorption and fluorescence spectra of the sample were measured at $50\times50$ scanned sample points at 8 K within 5 minutes. The fluorescence dynamics was measured by the optical Kerr-gate method, which verified the excitation-energy transfer to optically forbidden states.

6. **Quantum optics and quantum information**

   i. **Quantum teleportation and quantum information**: Opical parametric oscillator for generating squeezed light were constracted. The ratio of squeezing was 2 dB. To generate EPR pair, we controlled the phase of the squeezing.

# 23 Makishima Group

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

**Member:** Kazuo Makishima, Motohide Kokubun

We study cosmic and solar high-energy phenomena in the X-ray and $\gamma$-ray frequencies, using scientific satellites launched by the Institute of Space and Astronautical Science (ISAS), as well as foreign missions.

**Instrumental Developments:** We have developed the Hard X-ray Telescope (HXT) onboard the *Yohkoh* mission launched in August 1991, and the Gas Imaging Spectrometer (GIS) for the *ASCA* mission launched in February 1993. We also developed the Hard X-ray Detector (HXD) onboard the ASTRO-E mission. Although the launch of ASTRO-E by the M-V-4 rocket of the ISAS was unsuccessful, its recovery mission, ASTRO-E II, to be launched in January 2005, has been approved. We have hence started rebuilding the HXD as HXD-II.

**Solar and stellar flares:** Using *Yohkoh*, we have found that the wide-band spectral energy distribution of solar flares, ranging from soft X-rays to MeV gamma-rays, are controlled by four independent parameters; the overall flare size, the relative dominance of thermal signals, the spectral slope in hard X-rays, and the dominance of gamma-rays compared to hard X-rays. By analyzing the spectral and spatial data of the intense limb flare which occurred on 1998 August 18, we have identified three characteristic emission components, one emitted from top of the flaring magnetic loops, while the others from the loop foot-points. We also investigate stellar X-ray emission and stellar flares.

**Physics of Black Holes:** Through *ASCA* observations, we have obtained firm pieces of evidence that the ultra-luminous compact X-ray sources, found in arm regions of nearby galaxies, are massive ($\sim 100\ M_\odot$), accreting, black holes [2]. In particular, we have discovered clear spectral state transitions from two such objects, and furthermore, found evidence for a 31 hour periodicity from one of them. The period is consistent with the binary period of a massive mass-exchanging close binary.

We have discovered that the optically-thick accretion disk in black-hole binaries can take three characteristic states. They are (in the increasing order of accretion rate); a standard accretion disk, a standard disk strongly modified by Comptonization, and an optically-thick advection-dominated disk. Our analysis of the data of some Narrow-Line type 1 Seyfert galaxies suggest that they are in the same Compton-dominated state as described above.

**Particle Acceleration in the Inter-Stellar and Inter-Galactic Space:** Diffuse, probably non-thermal, X-ray emission has been detected from several galaxy groups, as well as from the entire region of our Galactic bulge. We have successfully detected three extended thermal X-ray components from the central region of M31. Their temperatures are 0.1, 0.3 and 0.9 keV.

We study particle and field energy densities in the lobes of radio galaxies, by comparing the synchrotron radio flux and the inverse-Compton X-ray flux. We have discovered that the particle energy density generally much exceed that in the magnetic field [3].

**Physics of Cluster of Galaxies:** We have developed a novel view of the cluster core region [1] . The ingredients are; hierarchical or scale-free dark-matter distribution; two-temperature plasma structure; metal escape from galaxies to the intra-cluster space; and magnetohydrodynamic energy transfer from galaxies to the intra-cluster plasma. The concept can provide a promising alternative to the cooling flow hypothesis that is becoming unrealistic

We have discovered that an elliptical galaxy NGC 1550 resides in a large-scale dark matter distribution, exhibiting a mass-to-light ratio as high as $\sim 300$. Thus, the object is a promising dark-cluster candidate.


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2. Makishima, K., Kubota, A., Mizuno, T., Ohnishi, T., Tashiro, M. et al.: The Nature of Ultra-Luminous Compact X-ray Sources in Nearby Spiral Galaxies, *Astrophys. J.* **535**, 632 (2000)

3. Tashiro, M., Makishima, K., Iyomoto, N., Isobe, N., & Kaneda, H.: X-Ray Measurements of the Field and Particle Energy Distributions in the West Lobe of the Radio Galaxy NGC 1316 (Fornax A)、*Astrophys. J. Lett.* **546**, 19 (2001)

# 24 Takase Group

**Research Subjects:** High Temperature Plasma Physics Experiments, Spherical Tokamak, MHD Stability, RF Heating and Wave Physics, Advanced Plasma Diagnostics Development, Fluctuations and Transport

**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.

**Study of spherical tokamak plasmas**

A high temperature, high beta plasma is a typical example of nonlinear complex system that exhibits interesting collective phenomena. The internal reconnection event (IRE) is an MHD phenomenon that is peculiar to the ST. Besides the previously reported IRE, more benign events which have no positive current spikes and ones with small magnetic fluctuations have been observed. Some events are accompanied by a rapid ion temperature increase but have little effect on global confinement.

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. To detect the EBW outside the plasma, the EBW must be mode-converted to an electromagnetic wave. Hence, in order to estimate the electron temperature from EBW emission, it is necessary to determine the conversion efficiency, which depends on the density scale length. A new instrument which measures the density profile and EBW emission simultaneously was used to measure the radiation temperature of 150 eV and a conversion efficiency of 40%, leading to an electron temperature of 370 eV. For heating the plasma we are investigating a method that utilizes the HHFW. A two-strap poloidal loop antenna was installed and a high power transmitter with 200 kW output power was commissioned. Heating experiments are scheduled to start in 2002.

A 4-beam correlation method is being developed to measure the ultra-fine structure of fluctuations. Analysis of the visible emission data suggests that the edge fluctuations are dominant and they have a long correlation length ( $> 100$ mm) parallel to the magnetic field, and a short perpendicular correlation length (10–20 mm). A PIN-switched 3-chord interferometer at 104 GHz was used to observe the broadening of the density profile during an IRE. A feasibility test of an AM interferometer at 50 GHz was also carried out. The edge electron temperature of 35 eV and a density of $2 \times 10^{18}\,\mathrm{m}^{-3}$ were measured using the double probe technique. A Si(Li) X-ray detector was installed to measure the core electron temperature by pulse height analysis.

**Theory of radial electric field structure bifurcation**

The radial electric field has an important role in improving plasma confinement. Bifurcation of the radial electric field structure is being studied. Various types of radial electric field structures were found for the same boundary condition. Accessibility of the solutions was deduced from an analysis of the transition dynamics.

**Collaborations**

Plasma current rampup from 350 to 400 kA by lower hybrid waves and neutral beam heating was demonstrated on the JT-60U tokamak (Japan Atomic Energy Research Institute). A bremsstrahlung emission profile was measured by an array of 84-channel photomultipliers in the Large Helical Device (National Institute for Fusion Science). Collaborations on the NSTX spherical tokamak (Princeton Plasma Physics Laboratory) were carried out on plasma heating by the HHFW, development of a new electron temperature diagnostic using EBW emission, and development of a new fluctuation diagnostic using correlation microwave reflectometry.

# 25 Tsubono Group

**Research Subjects:** Experimental Relativity, Experimental Gravitation, Gravitational Wave Physics, Laser Interferometer

**Member:** Kimio TSUBONO, Keita KAWABE 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 2000. The achieved sensitivity, $h \sim 5 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ 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. Last summer we performed 2-month data taking run and collected over 1,000 hours data. We are now analyzing the obtained data searching for the gravitational waves from coalescing binaries using matched filtering technique with templates of chirping signal.

We summarize the subjects being studied in our group.

- Laser interferometric gravitational wave detectors
  - TAMA project
  - Diagnosis of the TAMA detector
  - Search for gravitational waves from SN1987A
  - Suspension point interferometer for vibration isolation
  - Study of the next generation laser interferometer
  - GEO600 project
- Experimental study of relativity
  - Test of the space isotropy
- Study of thermal noise
  - Study of the thermal noise due to the inhomogeniously distributed loss
  - Measurement of the intrinsic Q of low-loss materials
  - Direct measurement of the thermal noise in the mirrors
- Study of the precise measurement
  - Development of the low-frequency vibration isolation system (SAS)
  - Development of the TAMA SAS suspension system

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# 26 Sano Group

**Research Subjects:** Nonlinear Dynamics and Fluid Mechanics

**Member:** Masaki Sano

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 measurement of DNA collapsing, DNA-protein interaction, and gene expression

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

# 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 triple band superconductor mixer receiver 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) and that of the carbon monoxide (CO) ($J = 3 - 2$ 345 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 dark clouds like HCL2, L183, and $\rho$ Oph, giant molecular clouds like Ori A, Ori B, W3, L1495, DR21, NGC1333, and Rosette molecular cloud, infrared dark clouds, and translucent clouds. Total observing area is about 35 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 to this, our group is developing the transportable 18 cm submillimeter-wave telescope. The main purpose of this telescope is to survey the 492 and 809 GHz CI lines over the Milky Way. From the result, we can study formation and evolution of molecular clouds in the galaxy scale. Last year, we have conducted the test run twice at the Pampa la Bola site (alt. 4800 m) in the northern Chile.

We are also studying rotational spectra of transient molecules in the laboratory with the submillimter-wave spectroscopy and Fourier transform millimeter-wave (FTMW) spectroscopy. Particularly we have extended observable frequency of the FTMW spectrometer up to 85 GHz in order to cover fundamental molecules which are important in astrochemistry. With this spectrometer, the rotational spectra of the ethyl radical has Recently been detected for the first time. We determined the molecular constants including hyperfine interaction constants in the $K_a$=0 state accurately. We have also observed the rotational spectrum of the FCO radical with the FTMW spectrometer, from which we estimated the barrier of the tunneling motion.


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# 28 Sakai (Hirofumi) Group

**Research Subjects**: Experiemental study of quantum optics and atomic/molecular physics

**Members**: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between the strong nonresonant laser field and the induced dipole moment 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) Structures and dynamics of molecules studied by the laser induced Coulomb explosion.

The summary of our research activities in the academic year of 2001 is as follows:

**(1) Controlling the orientation of polar molecules with combined electrostatic and pulsed, nonresonant laser fields**

The experimental realization of molecular orientation to arrange *any* polar molecules in a "head-versus-tail" order is a challenging subject and should greatly expand the range of applications in stereodynamical studies of chemical reaction dynamics. Recently, Friedrich and Herschbach suggested exploiting combined electrostatic and nonresonant induced dipole forces to enhance the orientation of polar molecules. We have demonstrated the experimental evidence of molecular orientation of *common* molecules such as OCS and HCl based on their scheme. To achieve molecular orientation, we apply nanosecond fundamentals from an injection-seeded Nd:YAG laser and utilize an extraction field of a time-of-flight (TOF) mass spectrometer also as an electrostatic field of the above scheme. Therefore, the polarization direction of the YAG laser is parallel to the TOF axis. To see the degree of orientation at the peak of the YAG laser pulses, we irradiate intense femtosecond Ti:sapphire laser pulses with the polarization parallel to the TOF axis. Here we concentrate on the results for OCS molecules. We observe the typical TOF spectra. First we focus on the $S^{3+}$ signals. When the YAG laser is not applied, the forward and backward signals look almost symmetric, indicating that the molecules are randomly oriented. However, when we apply the YAG laser, they look asymmetric, which we interpret as the result that more than half the OCS molecules are oriented with their S atoms directed toward the detector. We can confirm our interpretation by observing the change of the signal magnitude of counterpart fragment, e.g., $CO^{+}$. As we expected, the backward signal was larger than the forward signal. As expected theoretically, the degree of orientation became larger for the higher intensity of the YAG pulse, the larger magnitude of electrostatic field, and the lower rotational temperature.

**(2) Optimization of quantum processes in atoms and molecules by the feedback-controlled pulse-shaping technique**

It is one of the ultimate goals in atomic and molecular physics to optimize the excitation rate and ionization rate of atoms and molecules, the yield of a specific fragment out of some photodissociated products, and more generally a specific quantum state in atoms and molecules. The feedback-controlled pulse-shaping technique is promising to maximize the desired result. We have developed such a system consisting of a femtosecond pulse shaper, feedback signals, and evolutionary algorithm. The evolutionary algorithm was optimized by applying it to the optimization of second harmonic generation with femtosecond pulses. We have already succeeded in optimizing a specific fragmentation channel produced from the Coulomb explosion of $I_2$ molecules by intense femtosecond Ti:sapphire laser pulses.

**(3) Alignment of van der Waals molecules**

We have succeeded in aligning van der Waals molecules such as $Xe_2$, $Kr_2$, and $Ar_2$ by a strong, non-resonant, nanosecond laser field. The alignment was observed by photodissociating the molecules with a femtosecond laser pulse and detecting the direction of the photofragments by two-dimensional imaging techniques. By utilizing our alignment and/or orientation technique, we aim to evaluate some fundamental properties of van der Waals molecules such as polarizabilities, dipole moments, and structures, which have not been well studied.

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# 29 Kuwajima Group

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

**Member:** Kunihiro Kuwajima, Munehito Arai, & Kimiko Saeki

We are studying the mechanism of *in vitro* protein folding and the mechanism of molecular chaperone action. 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 biological cell. For this purpose, we are using various physicochemical and protein engineering techniques including rapid reaction techniques.

We have studied the refolding kinetics of $\alpha$-lactalbumin in the presence of wild-type GroEL and its ATPase-deficient mutant D398A at various concentrations of nucleotides (ATP and ADP). We have evaluated the apparent binding constant between GroEL and the $\alpha$-lactalbumin refolding intermediate quantitatively by numerical simulation analysis of the $\alpha$-lactalbumin refolding curves in the presence and absence of GroEL. The binding constant showed a cooperative decrease with an increase in ATP concentration, whereas the binding constant decreased in a noncooperative manner with respect to ADP concentration. For the D398A mutant, the ATP-induced decrease in the affinity occurred much faster than the steady-state ATP hydrolysis by this mutant, suggesting that the ATP binding to GroEL rather than the ATP hydrolysis was responsible for the cooperative decrease in the affinity for the target protein. We thus analyzed the nucleotide-concentration dependence of affinity of GroEL for the target protein by an allosteric (MWC) model in which GroEL underwent an ATP-induced cooperative conformational transition between the high-affinity and low-affinity states for the target protein. The transition midpoint of the ATP-induced transition of GroEL has been found to be around 30 $\mu$M, and this is in good agreement with the midpoint evaluated in other structural studies of GroEL. The results of the analysis based on the MWC model have also shown that the observed difference between the ATP- and ADP-induced transitions of GroEL is brought about by a small difference in an allosteric parameter (the ratio of the nucleotide affinities of GroEL in the high-affinity and the low-affinity states), i.e., 4.1 for ATP and 2.6 for ADP.


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# 30 Nose Group

**Research Subjects:**Molecular 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 by using techniques of biophysics and molecular genetics. We are trying to identify molecules that function during neural wiring by using, as a model, the simple nervous system of a fruitfly, Drosophila. We are currently conducting the following research projects.

1. Molecular Mechanisms of Axon Guidance

1.1. Neuromuscular target recognition molecules, Connectin and Capricious

By using the enhancer trap method, we identified two genes, Connectin and Capricious, that encode cell surface proteins with leucine-rich repeat. During the formation of neuromuscular connectivity, these molecules are expressed in different subsets of neuromuscular synaptic partners. Loss-of-function or ectopic expression of these molecules alter neuromuscular target specificity, indicating their roles in selective synapse formation. We are currently studying the roles of these molecules during selective synapse formation more in detail and also trying to identify the downstream signaling mechanisms of these molecules.

1.2. Gain of function mutant screening

To systematically identify novel genes involved in axon guidance, we adopted a recently developed genetic method, gain-of-function mutant screening. We isolated genes whose ectopic expression in all muscles or neurons cause defects in axon projection and/or synaptogenesis. By molecularly characterizing these genes, we have identified several molecules that are implicated in axon guidance and/or synaptogenesis. We are currently studying the function of these genes.

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. We are also investigating the effect of postsynaptic CaMKII modification on the synaptic response at different developmental stages.