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Department of Physics

School of Science

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Annual Report

2005

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

目 次

1 Theoretical Nuclear Physics Group

Subjects: Structure and reactions of unstable nuclei, Monte Carlo Shell Model, Molecular Orbit Method, Mean Field Calculations, Quantum Chaos
Quark-Gluon Plasma, Lattice QCD simulations, Structure of Hadrons

Member: Takaharu Otsuka, Tetsuo Hatsuda, Naoyuki Itagaki, Sinji Ejiri 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 PhysicsB

Nuclear Structure Physics

In Nuclear Structure group (T. Otsuka, N. Shimizu and N. Itagaki), nuclear structure physics is studied theoretically in terms of the quantum many-body problem. The major subjects are the structure of unstable exotic nuclei, shell model calculations including Monte Carlo Shell Model, cluster model and quantum chaos. @ The structure of unstable nuclei is the major focus of our interests, and the disappearance of N=20 magic gap was examined for Na and Mg isotopes by using the Monte Carlo Shell Model [1, 3, 4, 5, 6]. In particular, the tensor force effects have been studied extensively from the viewpoints of the shell model and the mean-filed calculation, indicating robust and charateristic effects on the shell evolution [4]. The chaos has been investigated as a possible origin of regularity, and the relativistic approach was studied [2]. The clustering has been studied including its competition with the shell structure[7, 8]. The collective motion has been studied from various microscopic angles based on Monte Carlo and pair-truncated shell model calculations [9].

Hadron Physics

In Hadron Physics group (T. Hatsuda, S. Ejiri 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 and/or high temperature matter
   - 1.1 QCD thermodynamics from lattice gauge simulations [10, 11, 12, 13, 14]
   - 1.2 Color superconductivity in quark matter [15, 16]
   - 1.3 Hadrons in quark-gluon plasma [17]
2. QCD structure of hadrons
   - 2.1 Lattice QCD study of the excited hadrons [18, 19, 20]
   - 2.2 Phenomenology of strange tribaryons [21]

References

[1] G. Neyens, M. Kowalska, D. Yordanov, K. Blaum, P. Himpe, P. Lievens, S. Mallion, R. Neugart, N. Vermeulen, Y. Utsuno, and T. Otsuka : “Measurement of the Spin and Magnetic Moment of 31Mg: Evidence for a Strongly Deformed Intruder Ground State”, Phys. Rev. Lett., **94**, 022501 (2005).

[2] M. Serra, T. Otsuka, Y. Akaishi, P. Ring and S. Hirose : “Relativistic Mean Field Models and Nucleon-Nucleon Interactions”, Prog. Theor. Phys. **113**, 1009-1046, (2005).

[3] Vandana Tripathi, S. L. Tabor, P. F. Mantica, C. R. Hoffman, M. Wiedeking, A. D. Davies, S. N. Liddick, W. F. Mueller, T. Otsuka, A. Stolz, B. E. Tomlin, Y. Utsuno, and A. Volya : “^{29}Na: Defining the edge of the island of inversion for Z=11”, Phys. Rev. Lett., **94**, 162501 (2005).

[4] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe and Y. Akaishi : “Evolution of Nuclear Shells due to the Tensor Force”, Phys. Rev. Lett., **95**, 232502 (2005).

[5] B. Fornal, S. Zhu, R.V.F. Janssens, M. Honma, R. Broda, *et al.* : “Yrast structure of neutron-rich Ti-53”, Phys. Rev. **C72**, 044315, (2005).

[6] M. Belleguic, F. Azaiez, Z. Dombradi, *et al.* : “Search for neutron excitation across the N=20 shell gap in 25-29Ne”, Phys. Rev. **C72**, 054316, (2005).

[7] N. Itagaki, H. Masui, M. Ito, and S. Aoyama : “Simplified modeling of cluster-shell competition”, Phys. Rev. C **71**, 064397 (2005).

[8] Tz. Kokalova, N. Itagaki, W. von Oertzen, and C. Wheldon : “Signatures for multi-alpha-condensed states”, Phys. Rev. Lett. in press.

[9] K.Higashiyama,N.Yoshinaga,andK.Tanabe: “New band mechanism of doubly-odd nuclei around mass 130”, Phys. Rev. C**72**, 024315 (2005).

[10] K. Yagi, T. Hatsuda and Y. Miake : “Quark-gluon plasma: From big bang to little bang”, (Cambridge monographs on particle physics, nuclear physics and cosmology, vol.23) Cambridge Univ. Press (2005) 446 pp.

[11] S. Ejiri, F. Karsch, E. Laermann and C. Schmidt : “The isentropic equation of state of 2-flavor QCD” , Phys. Rev. **D73**, 054506 (2006).

[12] M. Döring, S. Ejiri, O. Kaczmarek, F. Karsch and E. Laermann : “Screening of heavy quark free energies at finite temperature and non-zero baryon chemical potential” , Euro. Phys. J. **C46**, 179 (2006).

[13] S. Ejiri, F. Karsch and K. Redlich : “Hadronic fluctuations at the QCD phase transition” , Phys. Lett. **B633**, 275 (2006).

[14] Shinji Ejiri : “Lee-Yang zero analysis for the study of QCD phase structure” , Phys. Rev. **D73**, 054502 (2006).

[15] Mei Huang : “Spontaneous current generation in g2SC phase” , Phys.Rev.D73, 045007(2006).

[16] A. P. Balachandran, S. Digal and T. Matsuura : “Semi-superfluid strings in high density QCD”, Phys. Rev. D **73**, 074009 (2006)

[17] T. Hatsuda : “In-medium spectral functions from lattice QCD”, Eur. Phys.J. **C43** (2005) 45-49.

[18] K. Sasaki and S. Sasaki : “Excited baryon spectroscopy from lattice QCD: finite size effect and hyperfine mass splitting” , Phys. Rev. **D72** (2005) 034502.

[19] K. Sasaki, S. Sasaki and T. Hatsuda : “Spectral analysis of excited nucleons in lattice QCD with maximum entropy method” , Phys. Lett. **B623** (2005) 208-217.

[20] N. Ishii, T. Doi, Y. Nemoto, M. Oka, H. Suganuma : “Spin 3/2 penta-quarks in anisotropic lattice QCD”, Phys. Rev. D**72**, 074503 (2005).

[21] Y. Maezawa, T. Hatsuda and S. Sasaki : “Strange tribaryons as nona-quark states”, Prog. Theor. Phys. **114**, 317 (2005).

2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

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

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

We list the main subjects of our researches below.

1. Superstring Theory.
   - 1.1 Flux compactification [8]
   - 1.2 2-dimensional conformal field theories [13]
   - 1.3 Strings in curved background and D-branes [3, 9, 14]
   - 1.4 AdS/CFT correspondence [4, 17, 10, 18]
2. Field Theory.
   - 2.1 Supersymmetric Field Theories [5, 7, 12, 15]
3. High Energy Phenomenology.
   - 3.1 Phenomenology of supersymmetric models [2, 6, 11, 19]
   - 3.2 Particle cosmology [1, 16]

References

[1] M. Kawasaki and T. Yanagida, "511-keV gamma ray from moduli decay in the galactic bulge," Phys. Lett. **B624** (2005) 162.

[2] M. Ibe, K. I. Izawa, Y. Nakayama, Y. Shinbara and T. Yanagida, "Conformally sequestered SUSY breaking in vector-like gauge theories," Phys. Rev. D **73**, 015004 (2006)

[3] Y. Nakayama, S. J. Rey and Y. Sugawara, "D-brane propagation in two-dimensional black hole geometries," JHEP **0509**, 020 (2005).

[4] Y. Tachikawa, "Five-dimensional supergravity dual of a-maximization," Nucl. Phys. B **733** (2006) 188.

[5] T. Okuda and Y. Ookouchi, "Higgsing and superpotential deformations of ADE superconformal theories," Nucl. Phys. B **733** (2006) 59.

[6] M. Ibe, K. I. Izawa, Y. Nakayama, Y. Shinbara and T. Yanagida, "More on conformally sequestered SUSY breaking," Phys. Rev. D **73**, 035012 (2006).

[7] T. Kawano, Y. Ookouchi, Y. Tachikawa and F. Yagi, "Pouliot Type Duality via a-Maximization," Nucl. Phys. B **735** 1 (2006).

[8] T. Eguchi and Y. Tachikawa, "Distribution of flux vacua around singular points in Calabi-Yau moduli space," JHEP **0601** (2006) 100.

[9] Y. Hikida. and T.-S. Tai, "D-instantons and Closed String Tachyons in Misner Space," JHEP **0601**, 054 (2006).

[10] K. Okamura, Y. Takayama and K. Yoshida, "Open spinning strings and AdS/dCFT duality," JHEP **0601**, 112 (2006).

[11] M. Tanimoto and T. Yanagida, "A Higher-dimensional origin of the inverted mass hierarchy for neutrino," Phys. Lett. **B633** (2006) 567.

[12] R. Suzuki and Y. Tachikawa, "More anomaly-free models of six-dimensional gauged supergravity," J. Math. Phys. (in press)

[13] Y. Imamura, H. Isono and Y. Matsuo, "Boundary states in the open string channel and CFT near a corner," Prog. Theor. Phys. **115** (2006) (in press).

[14] Y. Imamura, "Large N vector quantum mechanics and bubbling supertube solutions," Prog. Theor. Phys. **115** (2006) 797-813.

[15] Y. Nakayama, "Index for orbifold quiver gauge theories," Phys. Lett. B **636**, 132 (2006).

[16] F. Takahashi and T. Yanagida, "Unification of dark energy and dark matter," Phys. Lett. **B635** (2006) 57.

[17] Y. Imamura, "Baryon vertices in AdS black hole backgrounds," Prog.Theor.Phys. **115** (2006) 815-826.

[18] H.-Y. Chen and K. Okamura, "The anatomy of gauge/string duality in Lunin-Maldacena background," JHEP **0602**, 054 (2006).

[19] M. Ibe, K. I. Izawa, Y. Shinbara and T. T. Yanagida, "Minimal supergravity, inflation, and all that,"

3 Sakai (Hideyuki) Group

Research Subjects: Experimental Nuclear Physics

Member: Hideyuki Sakai, Kentaro Yako

We are aiming to explore nuclear structure as well as nuclear reaction mechanisms by using an intermediate energy beam from accelerators. Particular emphasis is placed on the study of the spin degrees of freedom in nuclei. Our expertise is various "spin-polarizations": spin-polarized beams ($\vec{p}$, $\vec{n}$ and $\vec{d}$), spin-polarized targets ($\vec{p}$ and $^3\vec{\mathrm{He}}$), and spin-polarization analysis of reaction products ($\vec{p}$, $\vec{n}$ and $\vec{d}$).

Major activities during the year are summarized below.

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

—SHARAQ spectrometer

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

—Intermediate states involved in nuclear double beta decay

The double β decay with two neutrinos in the final state ($2\nu\beta\beta$ decay) is an allowed second-order weak process which has been observed for a number of nuclei, while that with no neutrinos in the final state ($0\nu\beta\beta$ decay) is a lepton number violating process forbidden in the standard model. $0\nu\beta\beta$ decay is of particular interest because the rate of the decay is related to a neutrino mass through nuclear matrix element. Since the nuclear matrix element is available only by theoretical calculations, the validity of calculations is tested by comparing the predicted $2\nu\beta\beta$ matrix elements with those obtained by decay measurement. The calculated $2\nu\beta\beta$ nuclear matrix element depends on the Gamow-Teller (GT) matrix elements from the mother nucleus to the intermediate states of daughter nucleus, and those from the granddaughter nucleus to the intermediate states. Our aim is to obtain the GT strength distribution experimentally up to 50 MeV exciation energy by using the most reliable reaction probe, i.e., the (p, n) and (n, p) reactions (See Fig. **??**). The (p, n) measurements at 300 MeV on ^{48}Ca, ^{76}Ge, ^{100}Mo, and ^{116}Cd nuclei have been performed using the neutron time of flight facility at Research Center for Nuclear Physics.

Experimental test of Bell's inequality in proton-neutron system

In 1935, Einstein, Podolsky and Rosen presented a paradox to quantum correlations and concluded that the quantum mechanical description of nature is incomplete. So-called hidden variables are introduced in the classical approach to describe the correlation. The Bell's inequality, discovered in 1964, shows that correlation produced by the hidden variables is weaker than that predicted by quantum mechanics. Since then many experimental tests on the Bell's inequality have been performed by using entangled photon pairs, while there are almost no severe tests in hadronic systems. This year, we tested the Bell's inequality in the proton-neutron system by measuring the spin correlation between the proton-neutron pair in [^{1}S$_0$] produced by the ^{1}H(d, pn) reaction. The measurement was performed at the RIKEN accelerator research facility. The polarization of the proton was analyzed by EPOL located at the focal plane of magnetic spectrograph SMART. The neutron polarization was analyzed by a newly constructed neutron polarimeter SMART-NPOL. Data analysis is in progress.

Three-body force observed in the deuteron-proton scattering

How the effect of three neucleon force (3NF) appears in nuclear reactions is one of the interesting subjects in nuclear physics. We are studying the effect of 3NF by compareing high precision data of deuteron-proton scattering with predictions of recent Faddeev calculations using modern nucleon nucleon forces. We performed measurements of the analyzing powers and the polarization transfer coefficients for the $d + p \to p + p + n$ reaction at $E_d = 270$ MeV.

4 Hayano Group

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

Member: Ryugo S. Hayano and Takashi Ishikawa

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

Antihydrogen and antiprotonic helium atoms – precision study of the CPT symmetry at CERN's antiproton decelerator (AD)

- Antiprotonic helium:

  We used a new pulse-amplified CW laser with an integrated absolute frequency calibration utilizing an optical frequency comb to precisely measure transition frequencies of antiprotonic helium 3 and helium 4 atoms. We then compared the results with the state-of-the-art three-body QED theory calculations, and determined the antiproton-to-electron mass ratio. The $\bar{p}$ mass precision is now close to that of the proton-to-electron mass ratio, and p and $\bar{p}$ masses agree within a relative precision of 2×10^{-9}. This is the highest-precision test of CPT in baryonic systems.

- Antihydrogen:

  Microwave (ground-state hyperfine splitting) and laser ($1s - 2s$) spectroscopic studies of antihydrogen are promising tools to test the CPT symmetry to the highest-possible precision. For the ground-state hyperfine splitting spectroscopy, a new antihydrogen source using a superconducting two-frequency radio-frequency trap, is being developed. For the $1s - 2s$ laser spectroscopy, a neutral-atom trap based on superconducting octupole coils is under construction.

Exotic-atom spectroscopy – the origin of the proton mass

- η-nucleus bound state:

  In 2004, we established that the $1s$ binding energy of pionic atoms, produced by the Sn(d,^{3}He) reaction, can be used to quantitatively determine the degree of partial chiral symmetry restoration in nuclear media. In 2005, we extended this method to study η-nucleus bound states. Data taking was completed, and the data are being analyzed.

- Deeply-bound kaon-nucleus system:

  In 2004, we found an evidence for the production of a 'strange-tribaryon' state, in the ^{4}He(stopped K^-, p) reaction at KEK (E471). This is a candidate of the "deeply-bound kaonic nuclei" predicted by Akaishi and Yamazaki. In 2005, we upgraded the E471 detector, by adding time-of-flight detectors optimized for protons, and collected high-statistics data (E549). The data are being analyzed.

- Precision spectroscopy of kaonic-helium $3d \to 2p$ X-rays:

  If the kaon-nucleus potential is as deep as predicted by Akaishi and Yamazaki, a large strong-interaction shift of some 10 eV is expected for the $3d \to 2p$ X-rays of kaonic helium atoms. Theories which do not accommodate the deeply-bound states predict very small shift of < 0.1 eV. We therefore carried out an experiment at KEK (E570) to measure the kaonic-helium Balmer X-rays (6.4 keV) using silicon-drift X-ray detectors. The goal is to achieve a precision of 2 eV. Data taking was completed at the end of 2005, and the data are being analyzed.

5 Komamiya group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) Data analysis for the BES-II experiment at BEPC-I, and TOF detector construction for BES-III experiment at BEPC-II; (3) Detector development for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (4) Preparation for physics analyses in the ATLAS experiment at the LHC pp collider; (5) Data analyses for the OPAL experiment at the LEP e^+e^- collider; (6) Research on astroparticle physics with balloon-borne high resolution spectrometer (BESS experiment);

Member: Sachio Komamiya, Tomoyuki Sanuki

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to be that uses superconducting accelerator structures, and hence the project has been accelerated as an international big-science project. We are working on ILC accelerator simulations and hardware development, especially on the beam delivery system. We have been studying possible physics scenario and the large detector concept (GLD) for an experiment at ILC.

2) BES-II/-III experiment at IHEP: The group has considered the BES-III experiment at the Beijing e^+e^- collider BEPC-II as the candidate for the middle term project before ILC. We are starting research and development for TOF detector for the BES-III experiment together with IHEP, USTC and KEK. We successfully performed a test of over 500 photomultipliers in 1[T] magnetic field. We have studied the data analysis of a search for CP violation using $J\psi \to \Lambda\bar{\Lambda}$ using BES-II data. In course of this analysis we are developing an efficient pattern recognition program for the charged particles in the BES-II drift chamber.

3) Detector development for studying gravitational quantum bound states and searching for new medium range force using ultra-cold neutron beam: A detector to measure gravitational bound states of ultra-cold neutrons (UCN) is under way. We decided to use CCD's for the position measurement of the UCN's. The CCD is going to be covered by Ti/Li layers to convert neutron to charged nuclear fragments. The simulation of the quantum effects of UCN in a narrow slit with 100 [μ] height is under way.

4) ATLAS experiment at LHC: Some of our students started to work on the preparation for physics analysis at LHC. Search for supersymmetric particles and search for the effects of hidden extra-dimensions are being studied.

5) OPAL experiment at LEP: It is the experiment at the highest energy e^+e^- collider LEP of CERN. The data taking with the OPAL detector was completed in the end of 2000. Important physics subjects at LEP are (a) Higgs boson searches, (b) Supersymmetric particle searches and (c) W-boson physics. We have extensively searched for the Higgs boson at LEP. The Higgs boson was driven to a narrow mass range of 114-250 GeV. For supersymmetric particles searches the lower mass limit of the lightest neutralino, which is the most important candidate of the dark matter material, was set to be 38.0 GeV. The W boson mass was determined to be 80.412$\pm$ 0.042 GeV (statistical and systematic errors combined).

6) BESS experiment: The spectrum of cosmic muon, proton and Helium were measured at various hight. These information is important for the calculation of the neutrino flux at Superkamiokande, hence it is valuable for the atmospheric neutrino oscillation analyses. The data was taken at the heights starting from 37 km (4.5 g/cm^2) to 27 km (30 g/cm^2) for the duration of about 11 hours in the 2001 BESS flight. The kinetic energy spectrum was measured from 0.5 GeV to 10 GeV with an accuracy of 8% for proton, 10% for Helium, and 20% for muon. This information is used for optimizing the simulation program for atmospheric muons and neutrinos. In order to measure momentum of primary cosmic ray particles in the range of 100 GeV to 1 TeV, the tracking detector system was upgraded by installing a new Jet-chamber and a outer precision tracking detector. In the October 2002 flight in Canada, the primary high momentum cosmic ray flux was measured up to about 1 TeV range.

6 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

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

We employed a CaF_2(Eu) scintillator for the search experiment. The choice of the detector material is based on the fact that the fluorine is one of the best nuclides for the detection of spin-dependently interacting neutralinos. With carefully selected raw material for the scintillator and low radioactivity photomultipliers as well as high purity copper shielding, we put stringent limits in the parameter plane of the neutralino-proton spin-dependent coupling($a_{\rm p}$) and neutralino-neutron spin-dependent coupling($a_{\rm n}$). The sensitivity region of fluorine for the dark matter search is more or less orthogonal to the region of the widely used sodium(of NaI) when they are represented in $a_{\rm p} - a_{\rm n}$ plane. Our result excluded a considerable part of DAMA's region in the $a_{\rm p} - a_{\rm n}$ plane allowed by their annual modulation observation.

It is essential to reduce the background of the measurements in order to get still higher sensitivity for the possible feeble neutralino signals. We found one of the leading background sources is Eu, the dopant of the scintillator. One may need to enrich the Eu to get rid of the production of radioactive impurities by ambient thermal neutrons.

We are also running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the AXION HELIOSCOPE. The axion helioscope consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors. Previously, we put upper limts of $g_{a\gamma\gamma} < (6.8 - 10.9) \times 10^{-10}\mathrm{GeV}^{-1}$ to axion - photon coupling constant for the axion mass less than 0.27 eV.

The axion helioscope is presently under modification to implement the buffer-gas handling system to make it sensitive to axions with a mass as high as the hadronic axion window at around 1 eV.

Another project is an R and D of a neutrino detector with a resonance ionization spectroscopy. In a low-energy charged current interaction of an electron neutrino or an anti-electron neutrino on a target nucleus, the atomic number Z of the nucleus is changed by ± 1. The neutrino detection, in this sense, is accomplished by a trace analysis of an exotic atomic element in the target material. The resonance ionization spectroscopy with a LASER is effective to the trace analysis. To start with, we introduced a quadrapole mass spectrometer and tried to detect a trace of helium atoms produced by an α-emitting radioactive souce ^{241}Am. Even with the conventional elctron-impact ionization, it was possible to detect the helium atoms quantitatively.

7 Aihara Group

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

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

Precision Measurements of CP Violation in the B Meson System We have performed improved measurements of CP-violation parameters $\sin 2\phi_1^{\rm eff}$ and $\mathcal{A}_f$ for $B^0 \to \phi K^0$, $\eta' K^0$, $K_S^0 K_S^0 K_S^0$, $K_S^0 \pi^0$, $f_0 K_S^0$, ωK_S^0 and $K^+K^-K_S^0$ decays. These charmless decays are dominated by $b \to s$ flavor-changing neutral currents and are sensitive to possible new CP-violating phases. We do not see any significant deviation between the results for each $b \to s$ mode and those for $B^0 \to J\psi K^0$. Since some models of new physics predict such effects, our results can be used to constrain these models. However, many models predict smaller deviations which we cannot rule out with the current experimental uncertainty. Therefore, further measurements with larger data samples are required in order to search for new, beyond the SM, CP-violating phases in the $b \to s$ transition.

Search for Physics Beyond the Standard Model using Rare B Decays We have updated the measurement of the inclusive $b \to s\ell^+\ell^-$ branching fraction using a sample of 152 million $B\overline{B}$ pairs. The measurement is based on a semi-inclusive technique to reconstruct $B \to X_S \ell^+\ell^-$, where X_S is a hadronic system containing an s quark and ℓ is an electron or a muon. The X_S hadronic system consists of one $K^\pm$ or K_S^0 and up to four pions (at most one pion can be neutral). The weighted average of the branching fractions for the electron and muon channels, assuming the individual branching fraction to be equal for $M_{\ell^+\ell^-} > 0.2$ GeV$/c^2$, yields $\mathcal{B}(B \to X_S \ell^+\ell^-) = (4.11 \pm 0.83^{+0.85}_{-0.81}) \times 10^{-6}$. This result is in good agreement with the Standard Model prediction of $(4.18 \pm 0.70) \times 10^{-6}$.

T2K We have been involved in the next generation long-baseline neutrino oscillation experiment, T2K, which shoots off-axis neutrino beam from Tokai 50 GeV proton synchrotron to Super Kamiokande detector. We have developed profile and position monitors for the primary proton beam.

SiD SiD is a detector concept based on silicon tracking and a silicon-tungsten sampling calorimeter, complemented by a powerful pixel vertex detector, and outer hadronic calorimeter and muon system. Optimized forward detectors are deployed. In order to meet the ILC physics goals, we have designed the general purpose detector taking full advantage of the silicon technology. Our R&D program includes development of a silicon tracker and a 5Tesla superconducting solenoid.

Dark Energy Survey at Subaru Telescope We are proposing to construct a large CCD camera as a prime focus instrumentation of Subaru telescope to conduct a wide-field weak lensing survey. With this survey, we can determine characteristic of Dark Energy which is believed to be responsible for acceleration of the preset-day expansion of the universe.

- K. Abe *et al.* (Belle Collaboration), Time-Dependent CP Asymmetries in $b \to sq\bar{q}$ Transitions and $\sin 2\phi_1$ in $B^0 \to J/\psi K^0$ Decays with 386 Million $B\bar{B}$ Pairs, arXiv:hep-ex/0507037].
- H. Aihara, "Rare Decays of B and D Mesons and Flavor Physics," Italian Physical Society, International School of Physics "Enrico Fermi" CP Violation from quarks and leptons, 19-29 July 2005, Varenna, Italy
- M. Iwasaki *et al.* [Belle Collaboration], "Improved Measurement of Electroweak Penguin Process $B \to X_s \ell^+\ell^-$," Phys. Rev. D**72** 092005 (2005).
- H. Aihara, "The Silicon Detector Concept," 2005 International Linear Collider Physics and Detector Workshop, Snowmass, Colorado, August 14-27, 2005.

8 Wadati Group

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

Member: Miki WADATI & Kazuhiro HIKAMI

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

1. Bose–Einstein Condensation (BEC)
   - (1) Ground State Properties of a Toroidally Trapped BEC
   - (2) Free Expansion of a Bose-Einstein Condensate
   - (3) Dynamics of a Wavefunction for the Attractive Nonlinear Schrödinger Equation under Isotropic Harmonic Confinement Potential
   - (4) Statistical Mechanics of Bose–Einstein Condensation in Trap Potentials
2. Nonlinear Waves
   - (1) Noncommutative Soliton
   - (2) Cellular Automaton and Crystal Base
   - (3) Lattice W Algebra and Integrable Systems
   - (4) Quantum Soliton Equation and Baxter Equation
3. Non-Equilibrium Statistical Physics
   - (1) Asymmetric Simple Exclusion Process
   - (2) Stability of the Non-Equilibrium Steady States
   - (3) Minority Game
4. Strongly Correlated Electron System
   - (1) Thermodynamics in the Hubbard Model, t-J Model
   - (2) Integrable Boundary Condition
5. Knot Theory and Low-Dimensional Topology
   - (1) Hyperbolic Volume of Knot Complement
   - (2) Quantum Gravity
6. Quantum Many-Body Problem
   - (1) δ-function Bose gas
   - (2) Calogero–Sutherland Model
   - (3) Exclusion Statistics and Chiral Partition Function
7. Quantum Computing and Quantum Information
   - (1) Geometric Aspects of Quantum Search
   - (2) Multipartite entanglement and embeddings in algebraic geometry
8. Random Matrix
   - (1) Polynuclear Growth Model
   - (2) Random Walk

9 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Takashi Oka

Our main interests are many-body effects in electron systems, i.e., **superconductivity, magnetism and fractional quantum Hall effect**, for which we envisage a "materials design for correlated electron systems" should be possible. Specifically we study:

- Superconductivity in repulsively interacting electron systems
  - — How to optimize T_C through the "fermiology" [1]
  - — Superconductivity in Ru and Co compounds [2]
  - — Effect of charge fluctuations [3]
  - — Superconductivity in multi-orbital systems
  - — Coexistence of electron-phonon and electron-electron interactions [4]
- Magnetism in repulsively interacting electron systems
  - — Flat-band ferromagnetism in a designed organic polymer
- Nonempirical methods for strongly correlated systems
  - — Projector Monte Carlo method[5]
  - — Materials design for correlated systems and estimation of interaction parameters
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  - — Landau-Zener tunnelling in the breakdown of Mott's insulator [6]
- Quantum Hall systems
  - — Interaction and dimensionality in the quantum Hall system
  - — Electron-molecule picture for quantum dots in magnetic fields[7]
- Electronic structure and correlation effects in hetero-interfaces
  - — Metal-induced gap states at metal/organic interfaces [8]
  - — Metal-insulator transition on polar surfaces
- Electrons on periodic curved surfaces [9]

[1] Hideo Aoki: Triplet superconductivity, *Physica B* **374-375**, 229 (2006).

[2] K. Kuroki, Y. Tanaka and R. Arita: Competition between singlet and triplet pairing in $Na_xCoO_2{\cdot}yH_2O$, *Phys. Rev. B* **71**, 024506 (2005).

[3] S. Onari, R. Arita, K. Kuroki and H. Aoki: Triplet superconductivity induced by charge fluctuation in the extended Hubbard model, *J. Phys. Soc. Jpn* **74**, 2579 (2005); S. Onari, R. Arita, K. Kuroki, H. Aoki: Superconductivity from long-range interaction, *Phys. Rev. B* **73**, 014526 (2006).

[4] M. Tezuka, R. Arita and H. Aoki: Density-matrix renormalization group study of pairing when electron-electron and electron-phonon interactions coexist *Phys. Rev. Lett.* **95**, 226401 (2005).

[5] R. Arita and K. Held: Orbital-selective Mott-Hubbard transition in the two-band Hubbard model, *Phys. Rev. B* **72**, 201102(R) (2005); Crossover from d-wave to p-wave pairing in the t-t' Hubbard model at zero temperature, *Phys. Rev. B* **73**, 064515 (2006).

[6] T. Oka, N. Konno, R. Arita and H. Aoki: Breakdown of an electric-field driven system: a mapping to a quantum walk, *Phys. Rev. Lett.* **94**, 100602 (2005); Takashi Oka and Hideo Aoki: Ground-state decay rate for the Zener breakdown in band and Mott insulators, *Phys. Rev. Lett.* **95**, 137601 (2005).

[7] Y. Nishi, P.A. Maksym, D.G. Austing, T. Hatano, L.P. Kouwenhoven, H. Aoki and S. Tarucha: Intermediate low spin states in a few-electron quantum dot in the $\nu \leq 1$ regime, *Phys. Rev. B* (in press).

[8] M. Kiguchi, R. Arita, G. Yoshikawa, Y. Tanida, S. Ikeda, S. Entani, I. Nakai, H. Kondoh, T. Ohta, K. Saiki and H. Aoki: Metal-induced gap states in epitaxial organic-insulator/metal interfaces, *Phys. Rev. B* **72**, 075446 (2005).

[9] M. Koshino and H. Aoki: Electronic structure of an electron on the gyroid surface, a helical labyrinth, *Phys. Rev. B* **71**, 73405 (2005).

10 Miyashita Group

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

Member: Seiji Miyashita and Keiji Saito

1. Novel phases originated in the quantum interactions

We studied various new types of quantum phases in spin systems. We are interested in phases which have nonzero magnetization. Although familiar type of ferrimagnetism is the Lieb-Mattis type in the antiferromagnetic model on bipartite lattices with different number of sublattice sites or different sizes of spin, there exists another type whose ground state spin configuration is non-collinear in the case of frustrated lattices. We have found a model which contains the two types of ferrimagnetism as a function of the parameter. We found that the nature of spin order is different from ordinary ferrimagnets. We also propose a structure of molecular magnets with the latter type of ferrimagnetism which show new types of spin dynamics in the ground state. We also found a model in which quantum fluctuation enhances the magnetic order. A ground state phase transition between the gapfull and gapless phases in the so-called spin tube is also found.

2. Quantum magnetic processes

The magnetization processes of a system composed by ferromagnetic dimers and antiferromagnetic dimers are studied. This model shows a metamagnetic property which can be explained the so-called Tachiki-Yamada model using renormalized parameters in the magnetic field. We studied the dependence of effective parameters using a kind of local decimation process in quantum systems, and explained the over all dependence of the magnetization process on the field and temperature.

We studied dynamical magnetization process of the transverse Ising model in the ordered ground state under the sweeping of magnetic field. We found a kind of collective motion which does not depend on the size of the system. We also studied the dependence of the critical transverse field on the size of spin S.

3. Quantum dynamics

We have studied properties of quantum dynamics and manipulation in nanoscale molecular magnets and related materials, where the Landau-Zener mechanism plays important role. In order to study further on the quantum dynamics, we have started a crest project in JST on "Quantum-mechanical cooperative phenomena and their applications".

For quantum information processes, the manipulation of qubits which is a local unit of the system is important. We derived analytic formula of the probability of non-adiabatic tunneling in a system where qubits interact with boson systems.

4. Thermal conductivity of quantum magnets

The mechanism of thermal conductivity due to the spin interaction is one of the hot topics in strongly interacting spin systems. Using a non-equilibrium green function method, we found non-symmetric thermal flow in a system where a gapfull system and a gapless system are contacted.

6. Phase transitions in spin-crossover complexes

As a new frontier of studies of the phase transition, phase transition of structure of materials due to the spin-crossover and/or charge transfer have been attracted interests. The properties of photo-excited state at low temperatures have been also studied extensively. Furthermore the composite phase transitions of the spin structure and magnetic structure is a hot topic. We have found a metastable branch of the high spin state at low temperatures which is much below the thermal hysteresis. The related experiment has also been done and gave a strong support of the existence of the branch. We also develop a theory to study the both phase transitions in a unified way and studied the static and dynamical properties of this type of materials. We also developed analysis on the spin transition and magnetic transition of the Prussian-blue analogue by taking into account the sublattice structure of the material. Effects of lattice vibration have been also studied.

7. Slow relaxation in frustrated systems

In frustrated system, the dynamics of ordering process is often very slow. In most cases it is due to a kind of energetically trap at metastable state. However, we found that there is a another type of slow down. That is, a kind of entropy-induced slow down occurs in a frustrated system which shows a reentrant phase transition. We have analyzed the mechanism. We found the so-called thermal annealing method does not help to find the low temperature stable state, but the quantum annealing does. We are studying the underlying mechanism of this process. As another example, we have studied the slow relaxation in the Kagome lattice with Ising-like Heisenberg antiferromagnets, where the macroscopically degenerate ferromagnetic ordered state appears. In the ordered state, we found slow relaxation mechanism due to the macroscopically degenerate states which are characterized by so-called weather-vane loop.

8. Gas-liquid phase transition and hydrodynamics

In order to study the generation bubble of gas in the gas-liquid phase transition we developed a theoretical scheme combining the fluid dynamics equations (Navier-Stokes equation) and the equation of state of material (van der Waals equation) and demonstrated the bubble generation by point heating and various properties during the generation.

9. Random matrix and quantum chaos

We also studied the random matrix theorem to study the relation between the obits in the classical mechanics and quantum chaos. We also studied distribution of separation of repulsive energy crossings in the random matrices.

11 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Youichi Yanase

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

- High-T_c superconductivity
  Superconductivity correlation length in the strongly correlated electron system.[1]
  Mott metal-insulator transition and superconductivity.
  Energy analysis of high-T_c superconductors.[2]
  Randomness and superconductivity fluctuation in high-T_c superconductors.
- Anisotropic superconductivity in $Na_xCoO_2{\cdot}yH_2O$
  Spin triplet superconductivity in a multi-orbital model.[3]
  D-vector and multiple phase in a magnetic field.[4]
  Superconductivity due to charge fluctuation.[5]
- Organic conductors
  Quantum melting due to geometrical frustration.[6,7]
  New type charge ordering in quasi-two-dimensional organic conductors.[8,9]
  Charge ordering and spin degrees of freedom.[10]
  One-dimensional organic systems with localized spins.[11]
- Theories of anisotropic superconductivity
  Quasi-classical theory on the angle dependence of specific heat in a magnetic field.[12]
  New state of Sr_2RuO_4 in high magnetic fields.[13]
  Proximity effects of superconductivity and magnetism in heterostructures.
- Electronic and spin states in frustrated systems
  Superconductivity correlation in a triangular lattice.[14]
  Numerical simulation in classical XY spin systems with frustration.
- Novel quantities in electronic systems
  Disorder operator in two-dimensional insulators.
  Artificial electric field in Fermi liquids.[15]
- Kondo effect in quantum dots

[1] T. Koretsune and M. Ogata: J. Phys. Soc. Jpn. **74**, 1390-1393 (2005).
[2] Y. Yanase and M. Ogata: J. Phys. Soc. Jpn. **74**, 1534-1543 (2005).
[3] M. Mochizuki, Y. Yanase and M. Ogata: J. Phys. Soc. Jpn. **74**, 1670-1673 (2005).
[4] Y. Yanase, M. Mochizuki and M. Ogata: J. Phys. Soc. Jpn. **74**, 2568-2578, 3351-3364 (2005).
[5] H. Watanabe and M. Ogata: J. Phys. Soc. Jpn. **74**, 2901-2904 (2005).
[6] J. Merino, H. Seo, and M. Ogata: Phys. Rev. B **71**, 125111-1-125111-5 (2005).
[7] H. Seo, J. Merino, H. Yoshioka and M. Ogata: J. Phys. Soc. Jpn. **75**, 051009 (2006).
[8] M. Kaneko and M. Ogata: J. Phys. Soc. Jpn. **75**, 014710 (2006).
[9] H. Watanabe and M. Ogata: J. Phys. Soc. Jpn. **75**, No. 6 (2006).
[10] Y. Tanaka and M. Ogata: J. Phys. Soc. Jpn. **74**, 3283-3287 (2005).
[11] C. Hotta, M. Ogata and H. Fukuyama: Phys. Rev. Lett. **95**, 216402-1 - 216402-5 (2005).
[12] M. Udagawa, Y. Yanase and M. Ogata: Phys. Rev. B **71**, 024511-1-024511-11 (2005).
[13] M. Udagawa, Y. Yanase and M. Ogata: J. Phys. Soc. Jpn. **74**, 2905-2908 (2005).
[14] T. Koretsune and M. Ogata: Phys. Rev. B **72**, 134513-1-134513-6 (2005).
[15] R. Shindou and K-i. Imura: Nucl. Phys. B **720**, 399 (2005).

12 Tsuneyuki Group

Research Subjects: Theoretical Condensed-matter physics

Member: Shinji Tsuneyuki and Kazuto Akagi

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

Our research subjects in FY2005 were as follows:

- Electronic structures and chemical reactions at surfaces
  - Effect of strong electric field on organic molecules chemisorbed on Si(100)
  - Organic chemistry on Si surfaces
- Impurity effect in ferroelectrics
  - Impurity state of Mn-doped perovskite
  - Role of impurity hydrogen in $BaTiO_3$
- Structura/electronic transition of materials under ultra-high pressure
  - Insulator-metal transition of YH_3under high pressure
  - 3D C60 polymer synthesized under high pressure
- New methods of electronic structure calculation
  - First-principles wavefunction theory for solids based on the transcorrelated method
  - First-principles calculation of Hubbard parameter by constrained DFT with Maximally localized Wannier function

13 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

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

[1] O. Rösch, O. Gunnarsson, X. J. Zhou, T. Yoshida, T. Sasagawa, A. Fujimori, Z. Hussain, Z.-X. Shen and S. Uchida: Polaronic Behavior of Undoped high-T_c Cuprates, Phys. Rev. Lett. **95** (2005) 227002–1-4.

[2] T. Yoshida, K. Tanka, H. Yagi, A. Ino, H. Eisaki, A. Fujimori and Z.-X Shen: Direct Observation of the Mass Renormalization in $SrVO_3$ by Angle-Resolved Photemission Spectroscopy, Phys. Rev. Lett. **95** (2005) 146404–1-4.

[3] M. Kobayashi, Y. Ishida, J. l. Hwang, T. Mizokawa, A. Fujimori, J. Okamoto, K. Mamiya, Y. Takeda, T. Okane, Y. Saitoh, Y. Muramatsu, A. Tanaka, H. Saeki, H. Tabata and T. Kawai: Characterization of Magnetic Components in the Diluted Magnetic Semiconductor $Zn_{1-x}Co_xO$ by X-ray Magnetic Circular Dichroism, Phys. Rev. B **72** (2005) 201201(R)–1-4.

14 Uchida Group

Research Subjects: High-T_c superconductivity

Member: Uchida Shin-ichi (professor), Kojima Kenji M. (research associate)

1. Project and Research Goal

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

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

2. Accomplishment

(1) Ladder Cuprate

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

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

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

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

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

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

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

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

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

1) Granular structure of high-Tc superconductivity

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

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

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

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

15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Iwao MATSUDA

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

(1) Surface electronic transport: Metal-insulator transitions, hopping conduction, and Hall effect in surface states. Quantitative evaluation of surface-state conductivity from Fermi surface mapping. Conductance of individual Cobalt silicide nanowires and metal-coated carbon nanotube tips.

(2) Surface phases, ultra-thin films, and phase transitions: Order-disorder phase transition and charge-density-wave transition on various metal-induced surface superstructures of Si and Ge. Quantum-well state in ultra-thin Pb, Bi, and Ag films. Ge nanodots layer.

(3) Construction of new apparatuses: Green's-function STM (low-temperature four-tip STM). Metal-coated carbon nanotube STM tips.

[1] C. Liu, I. Matsuda, R. Hobara, and S. Hasegawa: *Interaction between adatom-induced localized states and a quasi-two-dimensional electron gas*, Physical Review Letters **96**, 036803 (Jan 2006).

[2] A. Konchenko, I. Matsuda, S. Hasegawa, Y. Nakamura, and M. Ichikawa: *Observation of Quantum Confinement in Ge nanodots on an oxidized Si surface*, Physical Review B **73**, 113311(Mar 2006).

[3] I. Matsuda, T. Hirahara, M. Konishi, C. Liu, H. Morikawa, M. D'angelo, S. Hasegawa, T. Okuda, and T. Kinoshita: *Evolution of Fermi surface by electron doping into a free-electron-like surface state*, Physical Review B **71**, 235315 (Jun 2005).

[4] T. Hirahara, I. Matsuda, C. Liu, R. Hobara, S. Yoshimoto, and ShujiHasegawa: *Direct measurement of the Hall effect in a free-electron-like surface state*, Physical Review B, in press (2006).

[5] H. Okino, I. Matsuda, R. Hobara, Y. Hosomura, S. Hasegawa, and P. A. Bennett: *In situ resistance measurements of epitaxial cobalt silicide nanowires on Si(110)*, Applied Physics Letters, **86**, 233108 (Jun 2005).

[6] I. Matsuda, T. Hirahara, M. Ueno, R. Hobaram and S. Hasegawa: *Electrical Conduction through a Monatomic Step*, Journal de Physique IV **132**, 57 (Apr 2006).

[7] M. Dfangelo, M. Konishi, I. Matsuda, C. Liu and S. Hasegawa: *Alkali metal-induced Si(111)-*$\sqrt{21} \times \sqrt{21}$ *structure: the Na case*, Surface Science **590**, 162-172 (Oct 2005).

[8] T. Nagao, S. Yaginuma, M. Saito, T. Kogure, T. Ohno, S. Hasegawa, and T. Sakurai: *Strong Lateral Growth and Crystallization via Two-dimensional Allotropic Transformation of Semi-metal Bi Film*, Surface Science **590**, L247-252 (Sep 2005).

[9] H. Konishi, S. Honda, M. Kishida, Y. Murata, T. Yasuda, D. Maeda, K. Tomita, K. Motoyoshi, S. Yoshimoto, R. Hobara, I. Matsuda, J.-G. Lee, H. Mori, K. Oura, S. Hasegawa, and M. Katayama: *Synthesis of Metal-Alloy Nanowires toward Functional Scanning Probe Microscope*, Japanese Journal of Applied Physics **45**, 3690-3692 (Apr 2006).

[10] Y. Murata, S. Yoshimoto, M. Kishida, D. Maeda, T. Yasuda, T. Ikuno, S. Honda, H. Okado, R. Hobara, I. Matsuda, S. Hasegawa, K. Oura, and M. Katayama: *Exploiting Metal Coating of Carbon Nanotubes for Scanning Tunneling Microscopy Probes*, Japanese Journal of Applied Physics **44**, 5336-5338 (Jul 2005).

[11] S. Yoshimoto, Y. Murata, R. Hobara, I. Matsuda, M. Kishida, H. Konishi, T. Ikuno, D. Maeda, T. Yasuda, S. Honda, H. Okado, K. Oura, M. Katayama, and S. Hasegawa: *Electrical Characterization of Metal-Coated Carbon-Nanotube Tips*, Japanese Journal of Applied Physics **44**, L1563-L1566 (Dec 2005).

[12] S. Yamazaki, I. Matsuda, H. Okino, H. Morikawa and S. Hasegawa: *Electrical Conduction on Various Au/Si(111) Surface Superstructures*, e-Journal of Surface Science and Nanotechnology **3**, 497 (Dec 2005)

16 Fukuyama Group

Research Subjects: Low Temperature Physics (Experiment):
Two-dimensional (2D) quantum fluids and solids with strong correlations and frustration; Low temperature scanning tunneling microscopy and spectroscopy of 2D electron systems (2DES) and exotic superconductors.

Member: Hiroshi Fukuyama, Hiroshi Kambara

Our current interests are (i) new quantum phases with strong correlations and frustration in 2D ^{3}He. (ii) 2DES in high magnetic fields and unconventional superconductors. We are investigating these materials at very low temperatures down to 50 μK, using various experimental techniques such as NMR, calorimetry, STM/STS, *etc.*

1. **Novel quantum phases in 2D ^{3}He:**

   Monolayer ^{3}He adsorbed on a graphite surface is an ideal system for studying strongly correlated 2D Fermion systems. The magnetic ground state of the second-layer registered phase of ^{3}He is believed to be the gapless quantum spin-liquid. We are studying the rich quantum phase diagram in this system from heat-capacity and NMR measurements in a wide temperature and density region.

   A Fermi fluid existing at a low density region gradually transforms to the Mott localized phase with increasing density to the 4/7 registered phase ($\rho_{4/7}$). Unusual density dependences of measured magnetization and demagnetization field coefficient imply importance of ferromagnetic short range spin correlations. In the region just above $\rho_{4/7}$, an excess magnetization decreases towards zero below 500 μK. This is indicative of a possible phase transition to the spin-singlet ordered phase.

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

   (a) **Real-space imaging of the quantum Hall states at graphite surface:**
   We succeeded to observe spatial distributions of the local density of states (LDOS) of a quasi 2DES near point defects at graphite surface with STM/STS. A clear contrast between localized and extended states which correspond to the valley and peak energies of the Landau levels indicates the existence of quantum Hall state at graphite surface. The experimental localized LDOS is in good agreement with a spatial distribution of a calculated wave function for a single electron in 2D in a Coulomb potential under magnetic fields.

   (b) **STM/STS studies of Landau quantization in 2DES in semiconductors:**
   The Landau quantization of 2DES confined in a InAs thin film on a GaAs or InAs substrate was observed with STS. We also observed a curious DOS oscillation with periodicity of 60 meV in the positive energy range, which could be due to electron confinement with a Schottky barrier at the InAs-GaAs interface.

   (c) **Graphite edge state:**
   The graphite "edge state", which was theoretically predicted, was confirmed experimentally by LDOS measurements of graphite surfaces near monoatomic step edges with STM/STS. A clear peak in LDOS was observed at energies below E_F by $20 - 100$ meV only near the zigzag edges, while such a peak was not observed near the armchair edges.

3. **STM/STS studies of unconventional superconductors:**

   (a) **Surface electronic states of Sr_2RuO_4:**
   We studied surface electronic properties of the spin-triplet superconductor Sr_2RuO_4 with STM/STS. A large gap structure ($\Delta \sim 5$ meV) in the LDOS is always observed on an SrO plane cleaved at low temperatures. This structure would originate from the surface reconstruction with rotation of the RuO_2 plane underneath the SrO plane. On the other hand, surface cleaved at room temperature shows a DOS proportional to the square root of energy ($\sqrt{V}$) which is characteristic of the disordered electronic state in Anderson localization.

4. **Construction of the second generation very-low temperature STM:**

   We have started to design and construct a new very-low temperature STM. An entirely home-made STM head designed as extremely compact (ϕ=26 mm) worked quite well at 77 K in the test measurement.

17 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Yukio Kawano

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

1. Two dimensional electrons at cleaved semiconductor surfaces:
At the surfaces of InAs, conduction electrons can be induced by submonolayer deposition of other materials. Research on electrons at semiconductor surfaces has great future potential because of the variety of adsorbates and the application of scanning probe microscopy techniques. Recently, we have successfully performed the first low-temperature ($T = 1.5$ K) magnetotransport measurements on Ag-induced electron systems (ESs) formed at in situ cleaved surfaces of p-type InAs. In this year, we extended the study to various adsorbates. (a) For Fe-induced 2DESs, strong positive magnetoresistance was observed in the in-plane magnetic field configuration. The resistivity increases by a factor of 2 when B reaches 9 T. We consider that exchange interactions between localized moments of adsorbed Fe atoms and 2D electrons play an essential role. (b) The quantum Hall effect is observed for Ge-induced 2DESs. (c) The positive magnetoresistance due to the suppression of weak antilocalization is observed in the weak perpendicular magnetic field region. The magnetoresistance curve for an Au-induced 2DES is different from that for a Ge-induced 2DES. This is associated with the spin-orbit scattering of an Au atom.

2. Strongly correlated two dimensional systems:
(i) We have performed cyclotron resonance measurements for a Si/SiGe quantum well. The ratio of the obtained scattering time τ to τ_0 deduced from zero-field mobility increases with decreasing electron concentration and approaches unity in the metal-insulator transition region. (ii) The resistivity change due to electron spin resonance (ESR) absorption is investigated in the high-mobility two-dimensional electron system formed in the Si/SiGe heterostructure. Results for a specific Landau level configuration demonstrate that the primary cause of the ESR signal is a reduction of the spin polarization, not the effect of electron heating. The longitudinal spin relaxation time T_1 is obtained to be of the order of 1 ms in an in-plane magnetic field of 3.55 T. The suppression of the effect of the Rashba fields due to high-frequency spin precession explains the very long T_1.

3. Exploration of novel properties of two-dimensional semiconductors and their application to new devices:
Our studies aim at revealing local transport and optical properties of quantum Hall conductors by means of scanning probe microscopes, Terahertz irradiations, etc.

18 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Shinichi Watanabe

We study light-matter interactions and many body quantum correlations in optically excited high density electron-hole systems in semiconductors, low dimensional systems involving carbon nanotubes, quasi-1D organic conductors. Currently, we are focusing on the low energy($\sim$ meV) electromagnetic responses, i.e., in terahertz(THz) frequency range where the responses are dominated by free carriers, quasi-particle excitations, and/or various collective excitations.

The research summary in this year is as follows.

1. **Instrumental Developments**

   THz time domain spectrscopy at low temperature and in high magnetic field
   In order to perform THz time domain spectroscopy(TDS) at low temperature and in high magnetic field, we have improved the dynamic range of THz spectroscopy. By using a p-type InAs for THz generation, THz radiation with the electric field amplitude of 10kV/m is generated. A shot-noise level balanced detector is developed for electo-optic sampling of THz pulse. These improvements on THz generation and detection allow us to obtain the dynamic range of THz-TDS as 5×10^4 in amplitude, which could compensate the transmission loss due to the multiple windows of the superconducting magnet.

   THz ellipsometry
   Magneto-optical effect such as Faraday effect or magneto-optical Kerr effect enables us to investigate the ultrafast spin dynamics and transport properties under magnetic field, by optical means, i.e., without using electrodes. We have developed the magneto-optical measurements scheme in THz frequency range, by highly sensitve THz ellipsometry. Polarization rotation as low as 0.1mrad can be deteced in the frequency range between 0.5THz to 2.5THz.

   THz spectroscopy in subwavelength space region
   We have examined an aperture type THz microscopy in order to apply the technique to small samples in subwavelength size. An aperture which diameter is smaller than the wavelength, is attached on a sample. Transmissivity is obatined by comparing the sample with an aperture and a blank aperture. We have applied the technique to determine the dielectric function of doped semiconductors, in the frequency range between 0.5THz to 2.5THz. FDTD simulation analysis of the transmitted THz spectrum is performed and compared with the experimental results.

2. **THz spectroscopy of one-dimensional system**

   Carbon Nanotube
   Carbon nanotubes are considered as one of the promissing materials for one dimensional electron systems. Various exotic behaviors in optical and transport phenomena reflecting 1D nature have been observed. The dynamical aspects of transport properties, and photo-excited dynamics are also important issues to understand the many body effects in such 1D electron system. In this context, we are studying the low energy ($\sim$ meV) electromagnetic responses of ground state and photo-excited state of nanotubes. By using THz-TDS, the dielectric response of nanotubes in the relevant frequency range has been investigated.

   Quasi-1D Organic Conductor
   $(TMTSF)_2PF_6$ is a quasi-1D organic conductor which exibits metal-insulator transition at 12K accompanied with spin density wave(SDW) formation. For the study of the photo-excited dynamics of SDW phase, and photo-induced phase transition in such low temperature exotic phases, we have developed a reflection type THz-TDS.

19 Theoretical Astrophysics Group

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

Member: Katsuhiko Sato, Yasushi Suto, Atsushi Taruya, & Shinji Mukohyama

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

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

"Observational Cosmology" attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of the recent and future data provided by COBE, ASCA, the Hubble telescope, SUBARU, and large-scale galaxy survey projects is quite important both in improving our understanding of the present universe and in determining several basic parameters of the universe which are crucial in predicting the evolutionary behavior of the universe in the past and in the future. Our current interests include nonlinear gravitational evolution of cosmological fluctuations, formation and evolution of proto-galaxies and proto-clusters, X-ray luminosity and temperature functions of clusters of galaxies, hydrodynamical simulations of galaxies and the origin of the Hubble sequence, thermal history of the universe and reionization, prediction of anisotropies in the cosmic microwave background radiation, statistical description of the evolution of mass functions of gravitationally bound objects, and statistics of gravitationally lensed quasars.

"Nuclear Astrophysics" is exploring the interface between nuclear physics and astrophysics, in particular the physics of supernovae. It includes a rich variety of micro- and macro-physics, for example, neutrino transport, equation of state of high density matter, r-process nucleosynthesis, convective instability, fast rotation of a stellar core, strong magnetic field, gravitational radiation, and so on. In particular, the mechanism of the Type II supernovae itself has not been properly explained for more than 25 years. It is, therefore, quite important to make clear the physics of supernova phenomena not only for astrophysics but also for other fields of elementary physics. We are currently working on the multi-dimensional aspects of supernovae such as rotating core collapse, asymmetric neutrino emission, convective energy transfer near the neutrino sphere, possibility of r-process nucleosynthesis in the hot bubble region, and gravitational radiation from an asymmetrically bouncing core.

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;
2005

- Brane gravity and dynamical stability in warped flux compactification
- Neutrino Probes of Galactic and Cosmological Supernovae
- Detectability of cosmic dark baryons through high-resolution spectroscopy in soft X-ray band
- Propagation of Ultra-High Energy Cosmic Rays in Cosmic Magnetic Fields
- The study of nuclear pasta investigated by Quantum Molecular Dynamics

2004

- Strong Gravitational Lenses in a Cold Dark Matter Universe
- Effect of Rotation and Magnetic Field on the Explosion Mechanism and Gravitational Wave in Core-Collapse Supernovae

- ”Bulk Fields in Braneworld”
- “Gravitational collapse and gravitational wave in the brane-world”
- Magnetohydrodynamical Simulation of Core-Collapse Supernovae
- A Search for the Atmospheric Absorption in the Transiting Extrasolar Planet HD209458b with Subaru HDS
- Baryogenesis and Inhomogeneous Big Bang Nucleosynthesis
- The large-scale structure of SDSS quasars and its cosmological implication

2003

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

2002

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

2001

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

2000

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

20 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Damian Markham

Quantum information processing seeks to perform tasks which are impossible or not effective with the use of conventional classical information, by using quantum information described by quantum mechanical states. Quantum computation, quantum cryptography, and quantum communication have been proposed and this new field of quantum information processing has developed rapidly especially over the last 10 years. Entanglement is nonlocal correlation that appears in certain types of quantum states (non-separable states) and has become considered as the fundamental resource for quantum information processing. In our group, we are investigating new properties of multipartite and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- *Entanglement distances and local access of information:* We investigate the relationship between distance-like entanglement measures and the ability to access information locally when it is spread to many separate parties. We give an explicit bound on how well we can discriminate a set of states, given only local access to them, in terms of the entanglement. This is then translated to a bound on how well we can use these states to encode and decode information in the local setting. The overall result is an explicit statement of how information access is limited by the presence of entanglement. This work should allow the development of protocols to make use of this fact, for example in quantum secret sharing. Further this work offers an operational interpretation to these distance-like entanglement measures, which are defined and understood only as abstract mathematical properties of states. [1]

- *Local copying and local discrimination as a study of non-locality of a set of states:* We focus on the non-locality concerning local copying and local discrimination, especially for a set of orthogonal maximally entangled states in prime dimensional systems, as a study of non-locality of a set of states. As a result, for such a set, we completely characterize deterministic local copiability and show that local copying is more difficult than local discrimination. From these results, we can conclude that lack algebraic symmetry causes extra non-locality of a set of states. [2]

- *Local discrimination – one-way classical communication vs. two-way classical communication:* The power of quantum information processing often depends on weather two-way classical communication channel is available, or only one-way classical communication channel is available. For example, distillable entanglement and quantum channel capacity depend on weather we are allowed one-way classical communication and two-way classical communication in addition to local operations. However, such an example had not been known on local discrimination problems. We investigated local discrimination of an entangled state from a completely mixed state, and showed that local distinguishability also depends on whether one-way classical communication, or two-way communication is available.

- *Robustness of entanglement in low-rank noises:* The robustness of entanglement describes how strong a given state‘s entanglement is against noises. The effects of noises to a quantum state can be modeled by mixing an additional density matrix with the original density matrix of the state. The rank of the additional density matrix describes the number of different possible unitary operations introduced by the noises. We investigated the effects of low rank noises for multipartite entangled states. We have proven that the noises represented by a rank smaller than the Schmidt number of the multipartite entangled states minus one cannot destroy entanglement completely.

- *Control of Quantum Information Flow and One-way Quantum Computation:* We investigate how quantum information can be maintained, manipulated and controlled in multiparty settings. In particular we look at one-way quantum computation, where initially the information is spread by entanglement across the whole system, then controlled and manipulated through a series of measurements and feed-forward steps. We investigate conditions on the entanglement of these systems, and the measurements allowed, and what feed forward is necessary to not loose the quantum information.

- *Entanglement in many-body systems:* In the last few years a lot of effort has been made in understanding the presence and role of entanglement in various areas of physics. For example, it has been associated to critical phenomena in condensed matter physics, symmetry breaking in high energy physics and hawking radiation. We consider a thermal system with a highly entangled ground state, intuitively it makes sense that if the temperature is low enough, the population of the ground state is high enough to keep the mixed state entangled. This intuition is made exact and we derive critical temperatures, below which, we are guaranteed entanglement. We investigate this effect for a range of Hamiltonians. We then relate this to other critical phenomena in solid state physics.

- *Mixed state asymmetric quantum information sharing:* We show a way to asymmetrically share qubit information in a mixed bipartite state such that it can be fully extracted with unit probability at one of the qubits but not at the other as long as using LOCC (local operations and classical communications). As an application of this scheme, we present a remote quantum communication switch protocol, which allows conditional transmission of quantum information. Entanglement properties behind this protocol are investigated.

- *A quantum lock protocol:* We proposed a quantum lock protocol for authentication, which is composed of a quantum key state, a verification key state, and a quantum lock state created by a authenticator. The states of two keys are connected by a Pauli unitary operation, which is encoded in the quantum lock, represented by a maximally entangled state. The authenticator distributes the quantum key to a user and a verification key to the verifier and the quantum lock to the user and the verifier. The verifier customizes the quantum lock such that the authenticators information about the quantum key and the unitary operation is not enough to prove the authentication of the quantum key. Our protocol fully deals with quantum information, since all the states of the keys and the lock are kept unknown throughout the protocol.

- *Blind quantum computation:* Blind quantum computation is a computation which a user performs a unitary operation given by a supplier without knowing the identity of the operation by using measurement based quantum computation. Since the anonymous unitary operation can be only "undone" by the supplier, blind quantum computation can be useful for cryptographic applications. We have shown that universal blind quantum computation is impossible and also any blind computation is impossible in the teleportation model of quantum computation.

- *High Precision measurements using quantum optical states:* We study energy efficiency of high precision measurements using quantum optical systems. We use higher order annihilation-creation operators to describe the measurements. We found that the energy division method using entanglement, which enhances accuracy of the measurement in low order operator cases, makes the precision worse with the higher order operators. We also found that a special cat state which works better in higher order operator cases.

[1] M. Hayashi, D. Markham, M. Murao, M. Owari and S. Virmani, Phys. Rev. Lett. **96** (2006), 040501

[2] Masaki Owari, Masahito Hayashi, quant-ph/0509062

21 Kobayashi Group

Research Subjects: Ultrafast and Nonlinear optical processes, Quantum Optics

Member: Takayoshi Kobayashi, Atsushi Yabushita, Akikatsu Ueki

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

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

22 Makishima Group

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

Member: Kazuo Makishima, Motohide Kokubun

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

The *Suzaku* satellite: In collaboration with several domestic and US groups, we have developed the Hard X-ray Detector (HXD) [2] which has an unprecedented sensitivity to cosmic hard X-rays in the 10–600 keV range. The *Suzaku* satellite, carrying onboard the HXD and CCD cameras (coupled to X-ray telescopes), has been launched successfully by an M-5 rocket on 2005 July 10. Performance-verification observations with *Suzaku* were completed in the first 9 months.

Cosmic Nucleosysnthesis: X-ray observations provide powerful diagnostics to cosmic nucleosynthesis, from individual stars to clusters of galaxies. Our observation of a planetary nebula with the *Suzaku* CCD camera revealed an extreme carbon overabundance relative to oxygen. This is a rare occasion where the carbon-rich material produced deep inside an evolved star is being witnessed [1]. Using *XMM-Newton* and near-infrared data, we discovered that the stellar masses in a dozen clusters of galaxies are much more centrally concentrated than their nuclear products, namely ion in the X-ray emitting plasma. This suggests that galaxies have fallen to the cluster center over the Hubble time, presumably due to magneto-hydro-dynamic interactions with the plasma.

Physics of Compact Objects: Mass accretion onto compact objects is our favorite research subject [3], and extensive *Suzaku* studies have started. From two binary X-ray pulsars, the HXD successfully detected spectral features due to electron cyclotron resonance. Rotation-powered pulsars, including the Crab pulsar in particular, provided accurate calibration to the HXD timing function. Combining the HXD and the CCD camera data, several black-hole binaries (including the prototypical Cygnus X-1) were detected over an extremely wide energy band, from ~ 0.3 keV to ~ 300 keV. We keep our quest for the nature of enigmatic Ultra-Luminous X-ray sources (ULXs) in nearby galaxies, candidates for intermediate-mass black holes. A dozen active galactic nuclei also enabled the *Suzaku* detection at least up to 100 keV.

Plasma Heating and Particle Acceleration: Using *Suzaku* and other missions, we are revealing that vast inter-stellar and inter-galactic space is a site of ubiquitous plasma heating and particle acceleration. Examples include; giant flares around young stars; colliding stellar winds; and globular clusters moving through the Galactic halo gas. *Suzaku* observations have demonstrated that the Galactic plane near the Galactic center is filled with hot thermal X-ray emission (detected with the CCD camera), and non-thermal hard X-ray signals (detected with the HXD). The origin of these "Galactic diffuse X-ray emissions" is still unclear. Using *Suzaku*, we are searching clusters and groups of galaxies for non-thermal emission from the anticipated relativistic particles.

Future Instrumentation: We are making various attempts toward future instrumentation. These include Fourier-sysnthesis gamma-ray imagers [4], coded-mask imagers employing small-pixel inorganic scintillators, and new single- and poly-crystalline and inorganic scintillators. Some of them are meant for the future mission called *NeXT* (New X-ray Telescope), which is being planned as a successor to *Suzaku*.

1. Murashima, M., Kokubun, M., Makishima, K., Kotoku, J., Murakami, H., Matsushita, K., *et al.*: "*Suzaku* Reveals He-burning Products in the X-ray Emitting Planetary Nebula BD +30° 3639", *Astrophys. J. Lett.*, in press (2006)
2. Kokubun, M., Abe, K., Ezoe, Y., Fukazawa, Y., Hong, S., Inoue, H., Itoh, T., Kamae, T., Kasama, D., Kawaharada, M. *et al.*: "Improvements of the *Astro-E2* Hard X-ray Detector (HXD-II)", *IEEE Trans. Nuc. Sci.* **51**, 1991-1996 (2005)
3. Kubota, A., Ebisawa, K., Makishima, K., & Nakazawa, K.: "On the Temperature Profile of Radiatively Efficient Geometrically Thin Disks in Black Hole Binaries with the *ASCA* GIS ", *Astrophys. J.* **631**, 1062-1071 (2005)
4. Miyawaki, R., Niko, H., Okada, Y., Kokubun, M., Makishima, K., Negoro, H., Kotoku, J., Terada, Y. *et al.*: "High Resolution Fourier Synthesis Hard X-Ray Imaging Based on CdTe Strip Detectors", *IEEE Trans. Nucl. Sci.* **52**, 2052-2057 (2005)

23 Takase Group

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

Members: Yuichi Takase, Akira Ejiri

Thermonuclear fusion, the process that powers the sun and stars, is a promising candidate for generating abundant, safe, and clean power. In order to produce sufficient fusion reactions, isotopes of hydrogen, in the form of hot and dense plasma, must be confined for a long enough time. A magnetic configuration called the tokamak has reached the level where the International Thermonuclear Experimental Reactor (ITER) would be constructed to study the behavior of burning plasmas. However, improvement of the cost-effectiveness of the fusion reactor is still necessary. The spherical tokamak (ST) offers a promising approach to increasing the efficiency by raising the plasma beta (the ratio of plasma pressure to magnetic pressure). High beta plasma research using ST is a rapidly developing field worldwide, and is being carried out in our group using the TST-2 spherical tokamak. TST-2 is now located in a new experimental building in Kashiwa Campus. Numerous improvements to power supplies and RF heating systems have been implemented, and experimental activities have resumed with upgraded capabilities in 2005.

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

It is crucially important for ST to develop a scenario of plasma formation, heating and maintenance without the use of the central solenoid (CS). Several approaches are being investigated on TST-2. Noninductive plasma initiation was achieved by injection of RF power at 2.45 GHz in the presence of a vertical magnetic field with positive decay index. A doubling of plasma current was observed by additional injection of RF power at 21 MHz. Plasma heating by the high harmonic fast wave (HHFW) was also investigated. A clear evidence of electron heating was observed when HHFW with an appropriate wavenumber (toroidal mode number of 10) was excited, consistent with absorption of HHFW power by electron Landau damping and transit time damping. The excited HHFW can be measured by magnetic probes located outside the plasma, and by a reflectometer which measures modulation of the reflected microwave from the wave induced density oscillation inside the plasma. Heavy scattering of HHFW and nonlinear decay of HHFW were indicated by the measured frequency spectra.

The high beta plasma produced in ST is highly autonomous. Spontaneous deformation of the plasma by an instability and subsequent recovery are observed. This process involves reconnection of magnetic field lines, and is called the reconnection event (RE). A large increase in ion temperature is observed, confirming ion acceleration and thermalization predicted by theory. The deformation and the loss of electron thermal energy were studied by measuring the spatial profile of soft X-ray emission. It was found that the RE process starts around a normalized radius of 0.1, and tends to occur when the pressure gradient exceeds a critical value, suggesting that the instability is driven by the pressure gradient. Magnetic fluctuation measurements reveal oscillations at 10 kHz and harmonics, with toroidal mode numbers of 1 and 2, consistent with predictions of 3-dimensional MHD simulation.

Formation of Ultra-High Beta Plasma by Plasma Merging

A new ST device, UTST, aiming at formation of ultra-high beta plasma by plasma merging is under construction. Two ST plasmas will be formed by induction from external coils. Strong ion heating due to magnetic reconnection is expected to form one ST plasma with very high beta (30–50%). Access to the second stability regime becomes much easier using this unique method. It is a challenge to maintain the plasma in such a state for long enough time (exceeding the energy confinement time) after reconnection is over. This is planned to be accomplished by innovative methods of heating and current drive using RF waves (such as the HHFW) or neutral beam injection. Fabrication of the vacuum vessel and the coils have completed. and experiments will start in 2006.

Collaborations

Collaborative experiments are being carried out on the JT-60U tokamak at Japan Atomic Energy Agency (JAEA). Plasma current sustainment by the bootstrap current, driven spontaneously by the pressure gradient, was demonstrated. Compared to previous results, the duration of constant current with zero loop voltage was much longer, and therefore, a much clearer evidence of fully bootstrap driven discharge was obtained.

24 Tsubono Group

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

Member: Kimio TSUBONO and Masaki ANDO

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

TAMA300 is a 300-m baseline laser interferometric gravitational wave detector constructed in Mitaka. We started the operation of the detector in 1999. The achieved sensitivity, $h \sim 3 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ at 700Hz to 1.5kHz, is sufficient to catch possible gravitational wave events in our galaxy. We can operate the detector for over 24 hours stably and continuously, and have accumlated over 3,000 hours data. We are now analyzing the obtained data searching for the gravitational waves from coalescing binaries, supernovae and pulsars.

A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era. We have just stared the theoretical and technical investigation for the realization of the DECIGO space detector.

We summarize the subjects being studied in our group.

- Laser interferometric gravitational wave detectors
  - Current status of TAMA project
  - Data analysis of the TAMA data
  - Systematic analysis of TAMA monitoring signal
  - Study of the next-generation laser interferometer, LCGT
- Space laser interferometer
  - Space laser interferometer DECIGO
  - FP-DECIGO
  - Laser stabilization using optical fiber
  - Study of the movable devices
- Study of the precise measurement
  - Suspension point interferometer for vibration isolation
  - New vibration isolation system using magnetic levitation

references

[1] B Abbott et al. (LIGO Scientific collaboration), T Akutsu at al. (TAMA Collaboration), Joint LIGO and TAMA300 search for gravitational waves from inspiralling neutron star binaries, Phys. Rev. D (2006, in press), gr-qc/0512078

[2] Y. Aso, M. Ando, S. Otsuka and K. Tsubono: Active vibration isolation using a Suspension Point Interferometer, Journal of Physics: Conference Series **32** (2006) 451-456.

[3] S. Kawamura, et al., The Japanese space gravitational wave antenna.DECIGO, Class. Quantum Grav. **23**-8 (2006) S125-S131.

[4] B Abbott et al. (LIGO Scientific collaboration), T Akutsu at al. (TAMA Collaboration), Upper limits from the LIGO and TAMA detectors on the rate of gravitational-wave bursts, Phy. Rev. D **72**-12 (2005) 122004.

25 Sano Group

Research Subjects: Nonlinear Dynamics and Fluid Mechanics

Member: Masaki Sano and Yoshihiro Murayama

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

1. Study of turbulence

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

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

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

2. Nonlinear Dynamics and Chaos

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

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

3. Dynamical aspects of biological systems

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

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

References

1. M. Matsuo: Violation of a Fluctuation-Dissipation Relation in Fragile Glasses, J. Phys. Soc. Jpn. Vol.74, 2128 (2005).
2. A. Awazu FForword and Backword Drift Motions and Inversion of Drift Directions in a Partially Driven Lattice Gases. J. Phys. Soc. Jnp. 74, 3127 (2005).
3. H. Wada, Y. Murayama and M. Sano: Nonlinear elasticity of single collapsed polyelectrolytes, Phys. Rev. E 72 041803 (2005).
4. S. Tatsumi, M. Sano, A. G. Rossberg: Observation of stable phase jump lines in convection of a twisted nematic liquid crysta, Phys. Rev. E, 73 (1), 011704 (2006).
5. Y. Kobayashi and M. Sano: Aggregated spots and waving loops in a reaction-advection-diffusion system with a global coupling, Phys. Rev. E 73, 015104(R) (2006).
6. T. Mashiko, T. Segawa, M. Sano and Y. Tsuji: Simultaneous measurements of velocity fields in thermal turbulence by USV and PIV , Flow Measurement and Instrumentation 17, 107-112 (2006).
7. Y. T. Maeda and M. Sano: Regulatory Dynamics of Synthetic Gene Networks with Positive Feedback, J. Mol. Biol, in press (available online) (2006).

26 Yamamoto Group

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

Member: Satoshi Yamamoto and 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. Toward this goal, we are conducting observational studies in the millimeter- and submillimeter-wave region.

Our group operated the Mount Fuji Submillimeter-wave Telescope on the top of Mount Fuji (alt. 3770 m) from 1998 to 2005. With this telescope, we explored formation processes, detailed structure, and chemical evolution of interstellar molecular clouds by observing the fine structure lines of the atomic carbon ($^3P_1-^3P_0$ 492 GHz; $^3P_2-^3P_1$ 809 GHz). Owing to the high sensitivity of our superconductor receiver, the fully remote controlled operation, and the excellent observing condition from Mount Fuji, we were able to observe more than 50 square degrees of the sky with the 492 GHz line. This is the largest survey of the atomic carbon line so far made. Furthermore, a few representative clouds such as Orion A, Orion B, and NGC1333 were mapped with the 809 GHz line. By comparing the distribution of the atomic carbon lines with the CO distribution, we have been studying formation and evolution of molecular clouds in detail. The Mount Fuji Submillimeter-wave Telescope is a research project of Research Center for the Early Universe (RESCEU) in collaboration with researchers of National Astronomy Observatory and other Japanese institutes.

In addition, our group has developed a transportable 18 cm submillimeter-wave telescope in order to conduct a survey of the 492 GHz line of the atomic carbon over the Milky Way. In 2003, we successfully operated the telescope at Pampa la Bola (alt. 4800 m) in Chile, and observed the southern Milky Way in the atomic carbon line. From the result, we are studying molecular cloud formation in the galaxy scale [1].

We are also studying chemical evolution of star forming regions with the Nobeyama 45 m telescope and Nobeyama Millimeter Array. Particularly we are interested in behaviors of complex organic molecules ($HCOOCH_3$, $(CH_3)_2O$, etc.) in hot cores around low mass protostars. These molecules can be used as potential tracers to study the early stage of protostellar evolution. In fact, we have detected the $HCOOCH_3$ line from an extremely young low-mass protostar, NGC1333 IRAS4B [2].

Along with the above observational studies, we are developing a hot electron bolometer (HEB) mixer that can be used at 1.5 THz for a survey of the fine structure line of N^+. Fur this purpose, we have introduced an electron beam lithography system and a mixer fabrication system in our laboratory, and have started fabrication of a diffusion-cooled type HEB mixer using Nb as a superconductor and a phonon-cooled type HEB mixer using NbTiN.

[1] T. Oka, K. Kamegai, M. Hayashida, M. Nagai, M. Ikeda, N. Kuboi, K. Tanaka, L. Bronfman, and S. Yamamoto: Atomic Carbon in the Southern Milky Way, Astrophys. J., **623**, 889-896 (2005).

[2] N. Sakai, T. Sakai, and S. Yamamoto: Detection of $HCOOCH_3$ toward a Low-Mass Protostar NGC1333, Pub. Astron. Soc. Japan, **58**, L15-L18 (2006).

27 Sakai (Hirofumi) Group

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

Member: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) Controlling quantum processes in atoms and molecules using shaped ultrafast laser pulses. (3) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation) and ultrafast phenomena in atoms and molecules. (4) Attosecond pulses generated with high-order harmonics and their reliable measurements. (5) Structures and dynamics of molecules studied by the laser induced Coulomb explosion. Some of our research activities in the academic year of 2005 are as follows:

(1) Enhancement of molecular orientation in the adiabatic regime and its extension to the nonadiabatic regime

In the last fiscal year, we developed a new apparatus, in which a higher electrostatic field can be applied, and confirmed that it worked as expected. In this fiscal year, with a sample of OCS molecules diluted (5%) with He gas to avoid cluster formation, a backing pressure of 10 atm., an electrostatic field of 4.4 kV/cm, and a laser peak intensity of 4.1×10^{12} W/cm^2, we succeeded in achieving higher degree of orientation than that achieved in the proof-of-principle experiments.

In precise spectroscopic measurements and experiments including the observation of photoelectrons, it is desirable to prepare a sample of oriented molecules in the field-free condition. Noting that molecules can be oriented with combined electrostatic and intense, nonresonant laser fields in the adiabatic regime, we propose that we use a shaped pulse which has a relatively long rising edge compared to the rotational period of the molecule and is suddenly switched off at the peak of the pulse. Thereby, in the laser-field-free condition after the shaped pulse, we can expect the same degree of orientation as that could be adiabatically achieved at the peak of the pulse. The feasibility of this approach was recently confirmed by our numerical studies.

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

In the last fiscal year, we succeeded in the demonstration of quantum interference of electron de Broglie waves during high-order harmonic generation (HHG) from aligned CO_2 molecules. In this fiscal year, we have investigated ellipticity dependence of HHG from nonadiabatically aligned N_2, O_2, and CO_2 molecules. For experimental observations, we employ parallel and perpendicular configurations for which the molecular axis is parallel and perpendicular to the major axis of the elliptical polarization, respectively. We have found that the harmonic intensity decreases more rapidly in the parallel configuration than in the perpendicular configuration as the ellipticity is increased. These observations are consistent with intuitive expectations based on the shapes of the valence orbitals and successfully reproduced by our theoretical model. The quantum interference in the recombination process was also observed in the ellipticity dependence of HHG. Specifically, the ellipticity dependence of the 31st harmonic intensity from aligned N_2 molecules measured in the parallel configuration shows a clear dip at linear polarization (ellipticity $\varepsilon \sim 0$). The dip is due to the destructive interference and explained by our theoretical calculations. The ellipticity dependence provides us with rich information about underlying physics of HHG and can serve as a probe for ultrafast dynamic imaging of molecular structures.

(3) Utilizing ion images for the learning-loop optimal control of quantum processes in molecules and its application to the nonadiabatic molecular alignment

We developed a technique with which two-dimensional ion images can be used as feedback signals and applied it to the optimal control of nonadiabatic alignment of N_2 molecules. We maximized the degree of alignment around the half revival. As optimized pulses, we obtained a single ultrashort (almost transform-limited) pulse in some cases, and a doubly-peaked pulse in other cases. We investigated the effect of doubly-peaked pulses by integrating the time-dependent Schrödinger equation numerically and found that the doubly-peaked pulses are more effective for the molecular alignment just after the pump pulse, which is equivalent to that around the full revival, than for that around the half revival. Therefore, we measured the degree of alignment just after the pump pulse as a function of the interval between the two pulses produced by an interferometer equipped with an optical delay. We found that there is an optimum interval between the two pulses, which is consistent with our numerical simulations. In this study, experiments and theoretical calculations worked mutually complementarily and we obtained important information about the formation mechanism of rotational wave packets.

[1] Tsuneto Kanai, Shinichirou Minemoto, and Hirofumi Sakai, Nature (London) **435**, 470–474 (2005).

[2] Takayuki Suzuki, Shinichirou Minemoto, and Hirofumi Sakai, The Review of Laser Engineering **33**, 322–328 (2005).

[3] Haruka Tanji, Shinichirou Minemoto, and Hirofumi Sakai, Phys. Rev. A **72**, 063401 (2005).

28 Kuwajima Group

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

Member: Kunihiro Kuwajima & Kosuke Maki

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

The recombinant form of goat α-lactalbumin has a significantly faster unfolding rate compared to the authentic form, although the two molecules differ only in an extra methionine at the N-terminus of the recombinant. The mechanism of the destabilization caused by this residue was investigated through the combined use of kinetic experiments and molecular dynamics simulations. Unfolding simulations for the authentic and recombinant forms at 398 K (10 trajectories of 5 ns for each form, 100 ns total) precisely reproduced the experimentally observed differences in unfolding behavior. In addition, experiments reproduced the destabilization of a mutant protein, T38A, faithfully as predicted by the simulations. This bidirectional verification between experiments and simulations enabled the atomically detailed description of the role of the extra methionine residue in the unfolding process.

We collected quantitative kinetic data on early and late stages of folding in non-two-state proteins from the literature, and studied the relationship between the kinetics of the two stages. There was a surprisingly high correlation between the rate constants of these stages. The correlation coefficient of the logarithmic rate constants was as high as 0.97, which could not be caused by chance. We also studied relationships of the logarithmic rate constants of the two stages with native three-dimensional structures represented by the residue-residue contact map. There were again surprisingly high correlations between the logarithmic rate constants and the number of non-local contact clusters obtained from the contact maps. Because the number of non-local contact clusters represents overall arrangement of substructures in a native protein, the results strongly suggested the importance of the arrangement of the substructures for the kinetics of both early and late stages of protein folding.

[1] T. Oroguchi, M. Ikeguchi, K. Saeki, K. Kamagata, Y. Sawano, M. Tanokura, A. Kidera & K. Kuwajima: Atomically detailed description of the unfolding of α-lactalbumin by the combined use of experiments and simulations. *J. Mol. Biol.* (2005) **354** 164-172.

[2] K. Kamagata & K. Kuwajima: Surprisingly high correlation between early and late stages in non-two-state protein folding. *J. Mol. Biol.* (2006) **357** 1647-1654.

29 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 and function by using, as a model, the simple nervous system of the fruitfly, Drosophila. We focus on the synapses between motor neurons and their target muscles, and study the molecular mechanisms of how specific synaptic partners recognize each other and form synaptic connections. The following research plans are in progress.

1. Molecular mechanism of the neuromuscular target recognition

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

To systematically identify novel genes involved in neuromuscular target recognition, we performed microarray analysis. We compared the expression of genes in two neighboring muscles, 12 and 13, which are innervated by distinct motor neurons, and identified 200 genes that are differentially expressed. We conducted functional analyses of genes encoding transmembrane or secreted proteins and showed that Wnt4, a secreted protein of WNT family plays a major role in target specificity.

1.2. Live imaging of neuromuscular target recognition

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

2. Molecular Mechanisms of Synaptogenesis

2.1. Role of postsynaptic CaMKII on synaptogenesis

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