ISSN 0910-0709

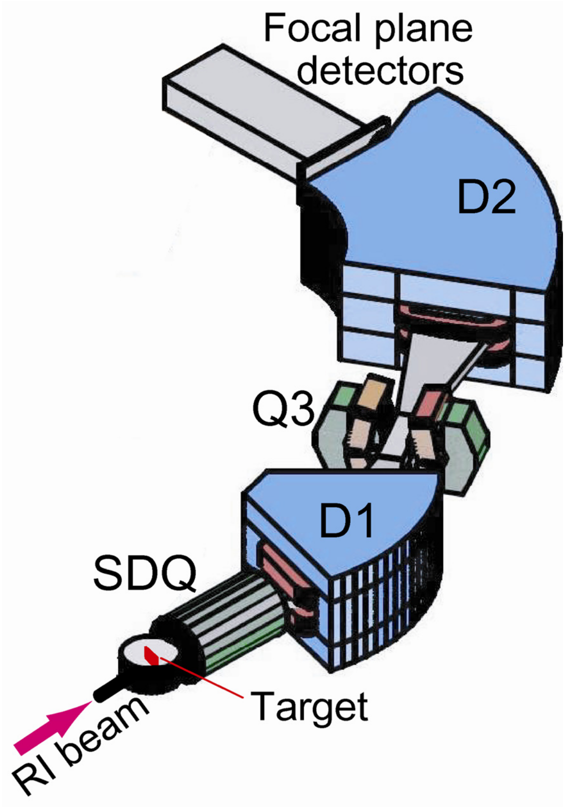
Department of Physics
School of Science
The University of Tokyo

Annual Report

2006

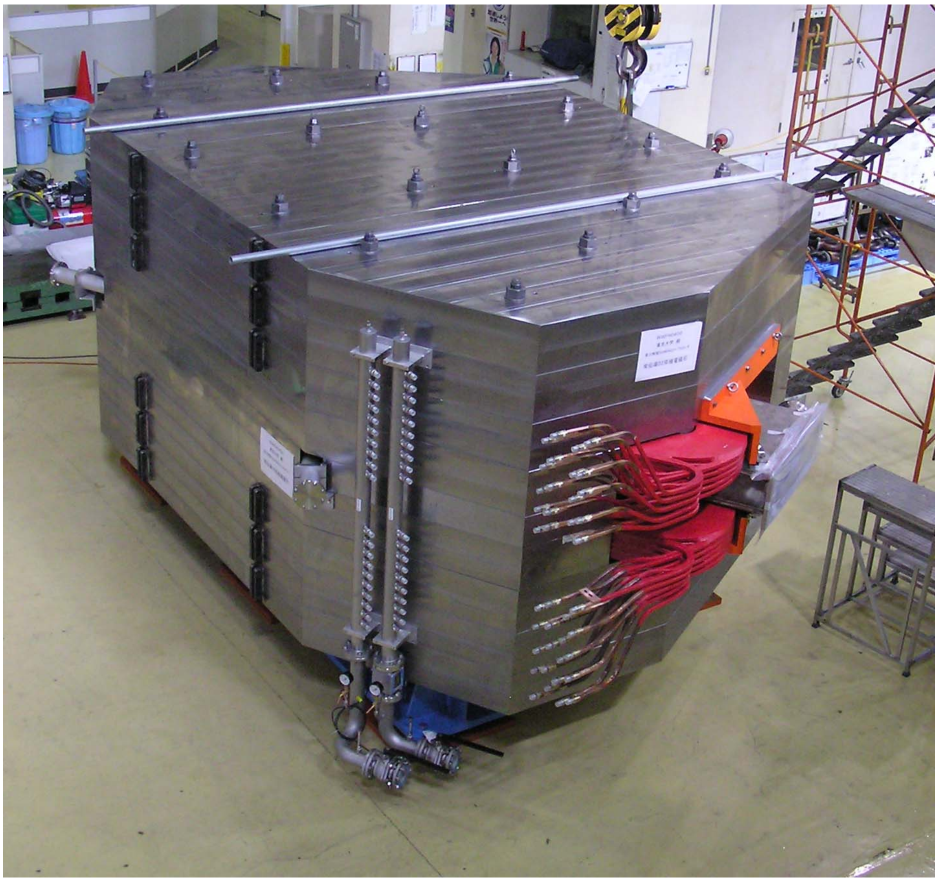
平成18年度 年次研究報告

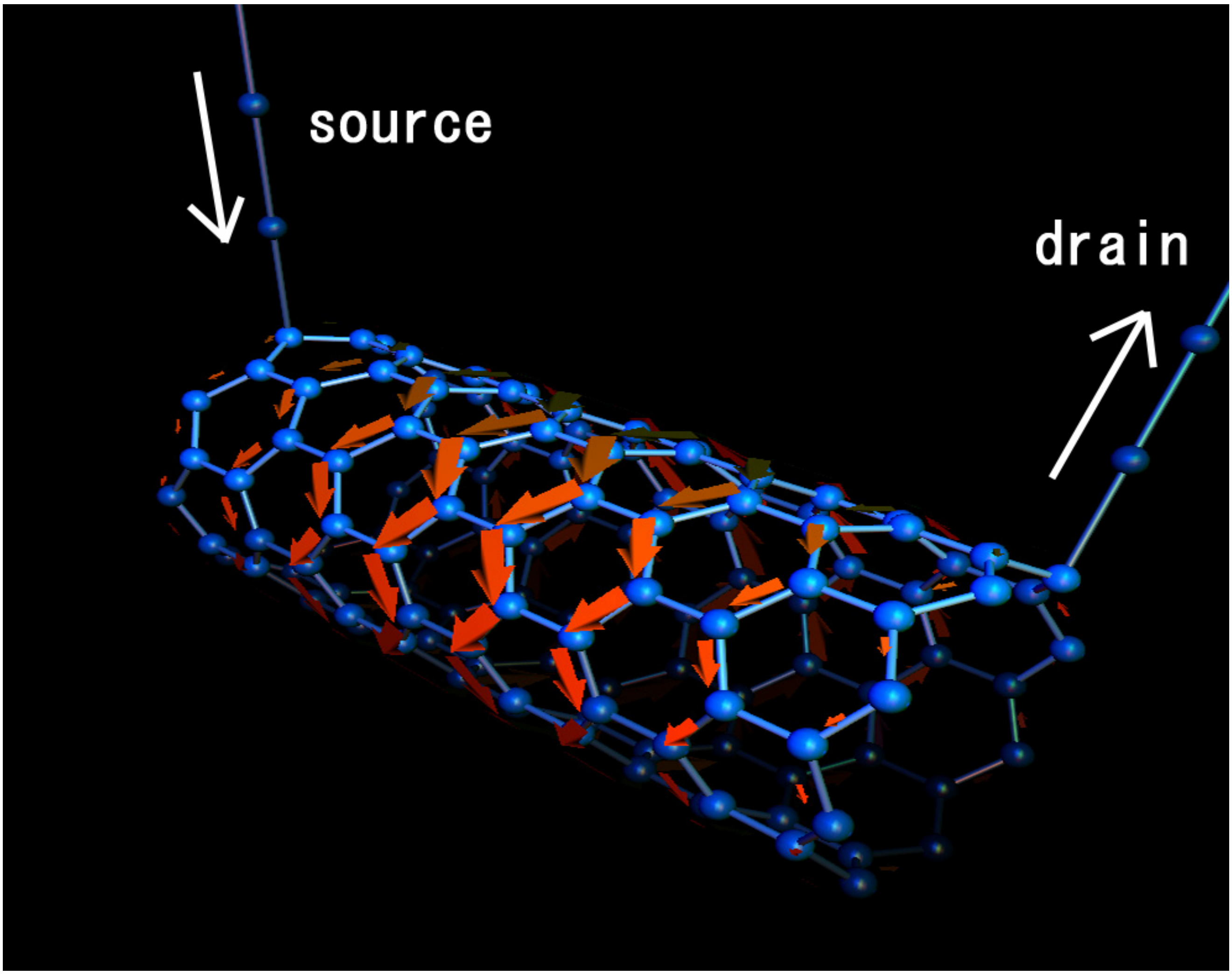
東京大学 大学院　理学系研究科・理学部
物理学教室



(a) Artistic illustration of the SHARAQ spectrometer.

The magnetic spectrometer SHARAQ dedicated to the radio isotope beam experiments is being constructed under the ICHOR program (see Sakai Hideyuki group). It consists of a super conducting doublet quadrupole magnet (SDQ), a dipole magnet (D1), a quadrupole magnet (Q3) and a dipole magnet (D2) and its total weight is about 500 tons. The SHARAQ spectrometer having the maxmum rigidity of 6.8 Tm with dispersion of 5.86 m is designed to achieve a good momentum resolution of 14,700 as well as a dispersion matching mode operation in lateral and angle directions. **(Sakai Hideyuki group in collaboration with CNS)**


(b) Photograph of the D2 dipole magnet (300 tons).



A carbon nanotube with source and drain electrodes attached is schematically shown. When a current is injected from the electrode, a quantum loop current (red arrows) is theoretically predicted to be induced around the tube, whose magnitude is orders of magnitude greater than that for the current across the electrodes. **(Aoki group)**

II

Summary of group activities in 2006

1 Theoretical Nuclear Physics Group

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

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

In the nuclear theory group, a wide variety of subjects are studied. The subjects are divided into three major categories: Nuclear Structure Physics, quantum hadron physics and high energy hadron physics.

Nuclear Structure Physics

In Nuclear Structure group (T. Otsuka, N. Shimizu and N. Itagaki (till June 2006)), nuclear structure physics is studied theoretically in terms of the quantum many-body problem. The major subjects are the model of the nuclear force, structure of unstable exotic nuclei, shell model calculations including Monte Carlo Shell Model, cluster model and quantum chaos.

In particular, we studied extensively the tensor force effects in the nuclear force from the viewpoints of the shell model and the mean-filed calculation, indicating robust and characteristic effects on the shell evolution [1, **?**].

The nuclear structure of various nuclei are studied using the nuclear shell model [3]. Through the shell-model calculation and Monte Carlo Shell Model, we achieved many collaboration with experimental groups [4, 5] and the contribution in astrophysics [6].

In the relativistic mean field (RMF) model, we constructed a new Lagrangian consisting of one-meson exchange terms and point coupling terms [7].

Quantum Hadron Physics

In Quantum Hadron Physics group (T. Hatsuda and S. Sasaki), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD).

Main research interests are the quark-gluon structure of hadrons, lattice gauge theories and simulations, matter under extreme conditions, quark-gluon plasma in relativistic heavy-ion collisions, high density matter, neutron stars and quark stars, chiral symmetry in nuclei, 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 [8]
    - 1.2 Color superconductivity in quark matter [10]
    - 1.3 Hadrons in quark-gluon plasma [9]
2. QCD structure of hadrons
    - 2.1 Lattice QCD study of bound state signature [11]
    - 2.2 Lattice QCD studies of hadronic interaction and decay [12, 13]
3. Cold atomic gas
    - 3.1 BEC-BCS crossover in the unitary regime [14]

High Energy Hadron Physics

In High Energy Hadron Physics group (T. Hirano), the physics of the quark-gluon plasma and dynamics of relativistic heavy ion collisions are studied theoretically based on relativistic hydrodynamics and relativistic kinetic theories. Main subjects include (1) hydrodynamic description of the space-time evolution of the quark-gluon plasma, (2) transport description of hadrons and their dissipation (3) analyses of the quark-gluon plasma through hard probes such as jets and heavy quarkonia, and (4) color glass condensate for high energy colliding hadrons/nuclei.

References

[1] T. Otsuka, T. Matsuo, and D. Abe, "Mean Field with Tensor Force and Shell Structure of Exotic Nuclei" Phys. Rev. Lett. 97, 162501 (2006)

[2] A. Brown, T. Duguet, T. Otsuka, D. Abe, and T. Suzuki, "Tensor interaction contributions to single-particle energies" Phys. Rev. C 74, 061303 (2006)

[3] M. Horoi, B. A. Brown, T. Otsuka, M. Honma, and T. Mizusaki, "Shell model analysis of the ^{56}Ni spectrum in the full pf model space" Phys. Rev. C 73, 061305(R) (2006)

[4] A. Gade, B. A. Brown, D. Bazin, C. M. Campbell, J. A. Church, D. C. Dinca, J. Enders, T. Glasmacher, M. Horoi, Z. Hu, K. W. Kemper, W. F. Mueller, T. Otsuka, L. A. Riley, B. T. Roeder, T. Suzuki, J. R. Terry, K. L. Yurkewicz, and H. Zwahlen, "Evolution of the $E(1/2_1^+) - E(3/2_1^+)$ energy spacing in odd-mass K, Cl, and P isotopes for N=20-28" Phys. Rev. C 74, 034322 (2006)

[5] L. Gaudefroy *et al.*, "Reduction of the Spin-Orbit Splittings at the N=28 Shell Closure" Phys. Rev. Lett. 97, 092501 (2006)

[6] T. Suzuki, S. Chiba, T. Yoshida, T. Kajino and T. Otsuka, " Neutrino-nucleus reactions based on new shell model Hamiltonians " Phys. Rev. C74, 034307 (2006).

[7] S. Hirose, M. Serra, P. Ring, T. Otsuka and Y. Akaishi, "Relativistic mean field model based on realistic nuclear forces" Phys. Rev. C 75, 024301 (2007)

[8] Y. Maezawa, N. Ukita, S. Aoki, S. Ejiri, T. Hatsuda, N. Ishii and K. Kanaya (WHOT-QCD Collaboration), "Heavy-Quark Free Energy, Debye Mass, and Spatial String Tension at Finite Temperature in Two Flavor Lattice QCD with Wilson Quark Action," Phys. Rev. D **75**, 074501 (2007).

[9] H. Iida, T. Doi, N. Ishii, H. Suganuma and K. Tsumura, 'Charmonium properties in deconfinement phase in anisotropic lattice QCD," Phys. Rev. D **74**, 074502 (2006).

[10] T. Hatsuda, M. Tachibana, N. Yamamoto and G. Baym, "New critical point induced by the axial anomaly in dense QCD," Phys. Rev. Lett. **97**, 122001 (2006).

[11] S. Sasaki and T. Yamazaki, "Signatures of S-wave bound-state formation in finite volume," Phys. Rev. D **74**, 114507 (2006).

[12] C. Dawson, T. Izubuchi, T. Kaneko, S. Sasaki and A. Soni, "Vector form factor in K(l3) semileptonic decay with two flavors of dynamical domain-wall quarks," Phys. Rev. D **74**, 114502 (2006).

[13] K. Yokokawa, S. Sasaki, T. Hatsuda and A. Hayashigaki, "First lattice study of low-energy charmonium-hadron interaction," Phys. Rev. D **74**, 034504 (2006).

[14] Y. Nishida and D. T. Son, "An epsilon expansion for Fermi gas at infinite scattering length," Phys. Rev. Lett. **97**, 050403 (2006)

2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Member: Tohru Eguchi, Tsutomu Yanagida, Yutaka Matsuo, Koichi Hamaguchi
Yuji Sugawara, Yosuke Imamura, Teruhiko Kawano, Taizan Watari

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

We list the main subjects of our researches below.

1. Superstring Theory.
   - 1.1 2-dimensional conformal field theories [2, 19, 29, 30]
   - 1.2 Quantum gravity and matrix models [3, 32]
   - 1.3 Theory of membranes [1, 18]
2. Gauge theories and gauge/string duality
   - 2.1 Superconformal field theories and AdS/CFT [17, 20, 27, 28, 31, 33]
   - 2.2 Spin chains and classical strings [9, 22, 23, 24, 25, 26]
   - 2.3 Brane realization of gauge theories [14, 15, 16]
3. High Energy Phenomenology.
   - 3.1 Phenomenology of beyond the standard models [8, 13, 21]
   - 3.2 Particle cosmology [4, 5, 6, 7, 10, 11, 12, 34, 35, 36, 37, 38]

References

[1] Y. Aisaka and Y. Kazama, "Towards pure spinor type covariant description of supermembrane: An approach from the double spinor formalism," JHEP **0605** (2006) 041.

[2] T. Eguchi, Y. Sugawara and A. Taormina, "Liouville field, modular forms and elliptic genera," JHEP **0703**, 119 (2007)

[3] Y. Hatsuda and Y. Matsuo, "Symmetry and integrability of non-singlet sectors in matrix quantum mechanics", J. Phys. A **40**, 1633 (2007).

[4] W. Buchmuller, K. Hamaguchi, M. Ibe and T. T. Yanagida, "Eluding the BBN constraints on the stable gravitino," Phys. Lett. B **643** (2006) 124.

[5] W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, "Gravitino dark matter in R-parity breaking vacua," JHEP **0703** (2007) 037.

[6] M. Endo, K. Hamaguchi and F. Takahashi, "Moduli-induced gravitino problem," Phys. Rev. Lett. **96** (2006) 211301.

[7] M. Endo, K. Hamaguchi and F. Takahashi, "Moduli / inflaton mixing with supersymmetry breaking field," Phys. Rev. D **74** (2006) 023531

[8] K. Hamaguchi, M. M. Nojiri and A. de Roeck, "Prospects to study a long-lived charged next lightest supersymmetric particle at the LHC," JHEP **0703** (2007) 046.

[9] Y. Hatsuda and K. Okamura, "Emergent classical strings from matrix model," JHEP **0703**, 077 (2007)

[10] M. Ibe, Y. Shinbara, T.T. Yanagida, "A New Inflation Model with Anomaly-mediated Supersymmetry Breaking," Phys.Lett.B642:165-170,2006.

[11] M. Ibe, Y. Shinbara and T. T. Yanagida, "The Polonyi problem and upper bound on inflation scale in supergravity," Phys. Lett. B **639**, 534 (2006)

[12] M. Ibe, Y. Shinbara and T. T. Yanagida, "A new inflation model with anomaly-mediated supersymmetry breaking," Phys. Lett. B **642**, 165 (2006)

[13] M. Ibe, T. Moroi, T.T. Yanagida, "Possible Signals of Wino LSP at the Large Hadron Collider," Phys.Lett.B644:355-360,2007.

[14] Y. Imamura, H. Isono, K. Kimura, M. Yamazaki, "Exactly marginal deformations of quiver gauge theories as seen from brane tilings", to appear in Prog. Theor. Phys., hep-th/0702049

[15] Y. Imamura, “Global symmetries and ’t Hooft anomalies in brane tilings”, JHEP**12**(2006)041,

[16] Y. Imamura, “Anomaly Cancellations in Brane Tilings”, JHEP**06**(2006)011,

[17] F. Koyama and F. Yagi, “Quantum moduli space of the cascading Sp(p+M) x Sp(p) gauge theory,” Prog. Theor. Phys. 117 (2007) 487-499.

[18] P.-M. Ho and Y. Matsuo, “A toy model of open membrane field theory in constant 3-form flux,” arXiv:hep-th/0701130, General Relativity and Gravitation, to appear.

[19] Y. Nakayama, S. J. Rey and Y. Sugawara, “Unitarity meets channel-duality for rolling / decaying D-branes,” JHEP **0608**, 014 (2006)

[20] Y. Nakayama, “Index for supergravity on AdS(5) x T**(1,1) and conifold gauge theory,” Nucl. Phys. B **755**, 295 (2006)

[21] H. Nakajima and Y. Shinbara, “Solutions to large B and L breaking in the Randall-Sundrum model”, Phys. Lett. **B648** (2007) 294.

[22] K. Okamura and K. Yoshida, “Higher loop Bethe ansatz for open spin-chains in AdS/CFT,” JHEP **0609**, 081 (2006)

[23] H. Y. Chen, N. Dorey and K. Okamura, “Dyonic giant magnons,” JHEP **0609**, 024 (2006)

[24] H. Y. Chen, N. Dorey and K. Okamura, “On the scattering of magnon boundstates,” JHEP **0611**, 035 (2006)

[25] K. Okamura and R. Suzuki, “A perspective on classical strings from complex sine-Gordon solitons,” Phys. Rev. D **75**, 046001 (2007)

[26] H. Y. Chen, N. Dorey and K. Okamura, “The asymptotic spectrum of the $\mathcal{N} = 4$ super Yang-Mills spin chain,” JHEP **0703**, 005 (2007)

[27] J. Raeymaekers and K.P. Yogendran, “Supersymmetric D-branes in the D1-D5 background,” J. High Energy Phys. JHEP12(2006)022.

[28] J. Raeymaekers, “Open string attractors,” J. High Energy Phys. JHEP04(2007)075.

[29] Y. Sugawara, “Aspects of infalling D-branes in two-dimensional black hole,” Mod. Phys. Lett. A **22**, 83 (2007).

[30] T.-S. Tai, “Winding String Dynamics in a Time-Dependent Beta Deformed Background,” Prog. Theor. Phys. **116** (2006) 965-974.

[31] T.-S. Tai and S. Yamaguchi, “Correlator of Fundamental and Anti-symmetric Wilson loops in AdS/CFT Correspondence,” JHEP **0702** 035, (2007).

[32] T.-S. Tai, “Classical c=1 Tachyon Scattering and 1/2 BPS Correlators,” Prog. Theor. Phys. **117** (2007) 795-801.

[33] S. Benvenuti, L. A. Pando Zayas and Y. Tachikawa, “Triangle anomalies from Einstein manifolds,” Adv. Theor. Math. Phys. **10** (2006) 395

[34] M. Endo, K. Kadota, K. A. Olive, F. Takahashi, T.T. Yanagida, “The Decay of the Inflaton in No-scale Supergravity,” JCAP 0702:018,2007.

[35] M. Endo, F. Takahashi, T.T. Yanagida, “Spontaneous Non-thermal Leptogenesis in High-scale Inflation Models,” Phys.Rev.D74:123523,2006.

[36] M. Endo, M. Kawasaki, F. Takahashi, T.T. Yanagida, “Inflaton decay through supergravity effects,” Phys.Lett.B642:518-524,2006.

[37] M. Kawasaki, F. Takahashi, T.T. Yanagida, “The Gravitino-overproduction problem in inflationary universe,” Phys.Rev.D74:043519,2006.

[38] M. Kawasaki, F. Takahashi, T.T. Yanagida, “Gravitino overproduction in inflaton decay.” Phys.Lett.B638:8,2006.

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. Aiming to identify new spin excitation modes, we are constructing a high energy resolution spectrometer SHARAQ dedicated to the exothermic reactions by unstable beams. SHARAQ will be completed in 2007.

—Intermediate states involved in nuclear double beta decay

The double β decay of nuclei is the rarest process confirmed so far in nature. It is a second-order weak process, described by successive virtual Gamow-Teller transitions from the mother nucleus to the intermediate nucleus, and then from the intermediate to the daughter nucleus, emitting two neutrinos. 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. The GT strength distributions give information through which intermediate states the decay occurs. The ^{116}Cd(p, n) and ^{116}Sn(n, p) measurements at 300 MeV were performed Research Center for Nuclear Physics, Osaka University. It has been found that for the decay of ^{116}Cd, the ground state of the intermediate ^{116}In has the most important contribution to the decay matrix element.

Spin correlation in entangled two-nucleon 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. Although there are many experimental tests of quantum mechanical correlations by using entangled photon pairs, there are almost no severe tests in hadronic systems. Completed the study of the spin correlation between the two-proton system, we tested the quantum mechanical correlation 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 by using the magnetic spectrograph SMART at the RIKEN accelerator research facility, employing two polarimeters EPOL and SMART-NPOL. The two polariztion measurements were performed in the space-like region from each other. It is shown that the spin correlation survives even if the proton-neutron pair is separated by several meters, which is 10^{15} times larger than the range of nuclear force.

4 Hayano Group

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

Member: Ryugo S. Hayano (Takashi Ishikawa)[1]

'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. In 2006, we published the value for antiproton-to-electron mass ratio to be $1836.152\,674 \pm 0.000\,005$, which is almost as precise as the present proton-to-electron mass ratio. Our result was recently incorporated to the CODATA 2006 adjustment of fundamental constants; by including our result in the fit (assuming the CPT symmetry), the precision of proton-to-electron mass ratio has been improved from 1836.152 672 61(85) (CODATA 2002) to 1836.152 672 47(80) (CODATA 2006).
- 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 has been constructed, and has been commissioned at CERN during 2006.

Exotic-atom spectroscopy – the origin of the proton mass

- η-nucleus bound state:
  We have already 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. We have now extended this method to study η-nucleus bound states. As the first step of the data analysis, we have recently deduced the elementary cross section $p(d,^3\text{He})\eta$ using the data taken in 2005 at GSI, Darmstadt, Germany.
- Precision spectroscopy of kaonic-helium $3d \rightarrow 2p$ 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 $3d \rightarrow 2p$ 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. We are now approaching the final stage of the data analysis, and the final result will be published soon.

[1] On medical leave.

5 Ozawa Group

Research Subjects: Experimental study of non-perturbative QCD

Member: Kyoichiro Ozawa

We have three research activities.

- Study of quark-gluon-plasma and hadronic matter under high-temperature and high density condition at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory
- Study of mechanism of hadronic mass generation at KEK and J-PARC
- R&D of new detector for future J-PARC experiment

Study of quark-gluon-plasma at RHIC

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

In spite of these fruitful results, there are still remaining questions to be answered to further characterize the state of matter formed at RHIC. In particular, chiral properties of the dense matter produced has not been obtained, and should be provided. For the study of the chiral properties, $\phi(1020)$ is an interesting meson because the restoration of approximate chiral symmetry at high temperature may modify its mass and width. These modifications can be shown directly in the line shape of the $\phi \longrightarrow e^+e^-$ peak. Here, the measurements with lepton decays are essential, since leptons are not interact with the medium and carry direct information about conditions and properties of the medium. To realize such measurements, baseline measurements in $p+p$ collisions are important for comparison. In this year, we focused on the analysis of $\phi \longrightarrow e^+e^-$ in $p+p$ collisions.

Figure 2.1.12 shows the e^+e^- invariant mass distribution. There are clear two peaks around the ω mass and the ϕ mass. The mass peak and width values agree with the values from the Particle Data Group and experimental mass resolution. We proved PHENIX detector has good mass resolution to detect the mass modification in Au+Au collisions.

Study of mechanism of hadronic mass generation at J-PARC

Recently, the chiral property of QCD in hot(T$\neq$ 0) or dense($\rho \neq 0$) nuclear matter has attracted wide interest in the field of hadron physics. The dynamical breaking of chiral symmetry in the QCD vacuum induces an effective mass of quarks, known as constituent quark mass, which then determines the known mass of all the hadrons. In hot and/or dense matter, this broken symmetry is subject to be restored either partially or completely and, hence, the properties of hadrons can be modified. To observe such an effect, measurements of the in-medium decay of vector mesons are highly desirable for the direct determination of the meson properties in matter. We performed an experiment at KEK and are planning a new experiment at J-PARC to measure vector mesons at normal nuclear density.

As shown in Fig. 2.1.12, we observed an excess in the lower mass region of ϕ meson peak. the excess is observed only the slowly moving component in larger nuclear target. The result is consistent with a view that limited number of mesons decay inside nucleus and have mass-modification by density effect.

R&D of new detector for future J-PARC experiment

We have performed an R&D for future J-PARC experiment. The development of new detector based on Gas Electron Multiplier (GEM), which is originally developped at CERN. Using GEM, we are imvestigating photon detector for Cherenkov counter and 2 dimentional tracker for high rate counting. A prototype of the photon detector is constructed and tested at Hiroshima university.

6 Komamiya group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) Data analysis for the BES-II experiment at BEPC-I, and TOF detector construction for BES-III experiment at BEPC-II; (3) Detector development for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (4) Preparation for physics analyses in the ATLAS experiment at the LHC pp collider; (5) Data analyses for the OPAL experiment at the LEP e^+e^- collider; (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 use 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 completed a test of over 500 photomultipliers in 1[T] magnetic field. We have studied the data analysis of a search for CP violation using $J\psi \rightarrow \Lambda\bar{\Lambda}$ and other processes of baryon pair productions 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 a Li layer to convert neutron to charged nuclear fragments. The simulation studies on the quantum effects of UCN in a narrow slit with 100 [μ] height is also done.

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 114-200 GeV. For supersymmetric particles searches the lower mass limit of the lightest neutralino, which is the most important candidate of the dark matter material, was set to be 38.0 GeV. The W boson mass was determined to be 80.412 ± 0.042 GeV (statistical and systematic errors combined).

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.

7 Minowa Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

Various kinds of astro-/non-accelerator/low-energy particle physics experiments have been performed and are newly being planned in our research group.

We are running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the TOKYO AXION HELIOSCOPE. 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 limits 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. We have successfully tested an automatic buffer-gas pressure control system at the operating temperature. The helioscope will soon become ready for the new search deployment.

Another long-running project of our group is the direct experimental search for supersymmetric neutralino dark matter in an underground cell of the Kamioka Observatory. We employed a CaF_2(Eu) scintillator aiming at a search for spin-dependently(SD) interacting neutralinos. Our results put a stringent limit to the SD cross section competitive to the world records on it. The search has been suspended for the improvement of the CaF_2(Eu) scintillation detector in order to get still higher sensitivity for the possible feeble neutralino signals.

The third project is an R and D of a neutrino detector with a resonance ionization mass spectroscopy, RIMS. The neutrino detection is accomplished by a trace analysis of an exotic atomic element produced by charged current interaction of an electron neutrino or an anti-electron neutrino on a nucleus in the target material. This year, we introduced a variable wavelength blue LASER diode and examined the effectiveness of the method by trying to detect a small amount of potassium vapor. The next step is to find out a way to get a high detection efficiency.

We also started a new R and D of a compact antineutrino detector with plastic scintillator to be used at a nuclear reactor station, for the purpose of monitoring the power and plutonium content of the nuclear fuel. It can be used to monitor a reactor from outside of the reactor containment with no disruption of day-to-day operations at the reactor site. This unique capability may be of interest for the reactor safeguard program of the International Atomic Energy Agency(IAEA), as well as for the precision monitoring of the antineutrino flux in the close vicinity of a reactor in a short baseline neutrino oscillation experiment for the determination of the mixing angle θ_{13}.

8 Aihara Group

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

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

The main research activity of our group has been a study of CP-violation in the B meson system using the KEK B-factory (KEKB). This past year we presented a measurement of CP violating asymmetries in the neutral B meson decaying to the $\rho\pi$ state using a time-dependent Dalitz plot analysis. It was based on a 414/fb data sample containing 449M $B\bar{B}$ pairs. Combining our analysis with information on charged B decay modes, we performed a full Dalitz and isospin analysis and obtained a constraint on the CKM angle ϕ_2, 68 deg.$< \phi_2 <$ 95 deg. at the 68.3% confidence interval for the ϕ_2 solution consistent with the standard model (SM). We have also been conducting the analysis of flavor changing neutral current processes such as $B^0 \to K_S K_S$ and $B \to X_S \ell^+ \ell^-$ to probe physics beyond the Standard Model.

We are working on the instrumentation of J-PARC beamline for T2K long baseline neutrino oscillation experiment. In particular, we have done R&D for the position and profile monitors for the primary proton beams. We have also developed beamline simulations. We have also successfully developed 13-inch hybrid photodetector combining a large-format phototube technology and avalanche diode as photo-electron multiplier.

We have started the five-year program to construct a 1.5 Giga pixel CCD camera (Hype Suprime-Cam) to be mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct extensive wide-filed deep survey to investigate weak lensing. This data will be used to develop 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy.

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

1. K. F. Chen *et al.* [Belle Collaboration], "Observation of time-dependent CP violation in $B^0 \to \eta' K^0$ decays and improved measurements of CP asymmetries in $B^0 \to \phi K^0, K_S^0 K_S^0 K_S^0$ and $B^0 \to J/\psi K^0$ decays," Phys. Rev. Lett. **98**, 031802 (2007) [arXiv:hep-ex/0608039].
2. H. Aihara *et al.*, "Belle SVD2 vertex detector," Nucl. Instrum. Meth. A **568**, 269 (2006).
3. H. Nakayama *et al.*, "Development of a 13-in. Hybrid Avalanche Photo-Detector (HAPD) for a next generation water Cherenkov detector," Nucl. Instrum. Meth. A **567**, 172 (2006).
4. A.Kusaka, Ph.D. thesis : Measurement of CP-Violating Asymmetries in the Neutral B Meson Decaying to the $\rho\pi$ State Using a Time Dependent Dalitz Plot Analysis.
5. K.Yamada, Master's thesis : Research and Development of Segmented Secondary Emission Beam Monitors for J-PARC Neutrino Beamline.

9 Wadati Group

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

Member: Miki Wadati & Kazuhiro Hikami

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

1. Bose–Einstein Condensation (BEC)
   (1) Ground State Properties of a Toroidally Trapped BEC
   (2) Free Expansion of a Bose-Einstein Condensate
   (3) Dynamics of a Wavefunction for the Attractive Nonlinear Schrödinger Equation under Isotropic Harmonic Confinement Potential
   (4) Statistical Mechanics of Bose–Einstein Condensation in Trap Potentials
2. Nonlinear Waves
   (1) Noncommutative Soliton
   (2) Cellular Automaton and Crystal Base
   (3) Lattice W Algebra and Integrable Systems
   (4) Quantum Soliton Equation and Baxter

Equation

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

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

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

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

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

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

10 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, 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"[1,2]; Effects of spin and charge fluctuations [3]
  — Superconductivity in multi-orbital systems [4]
  — Coexistence of electron-phonon and electron-electron interactions [5]
- Magnetism in repulsively interacting electron systems
  — Flat-band ferromagnetism in a designed organic polymer
- Carbon systems
  — Quantum Hall effect in graphene [6]
  — Loop current in carbon nanotubes [7]
  — Carbon nanoribbons
- Quantum Hall systems
  — Interaction and dimensionality in the quantum Hall system
  — Electron-molecule picture for quantum dots in magnetic fields [8]
- Electronic structure and correlation effects in hetero-interfaces
  — Interface states at metal/organic interfaces [9] and polar surfaces
- Electronic structure of periodic nanostrucutures
  — "Supercrystal" picture in alkali-metal-loaded zeolites
  — Electrons on periodic curved surfaces
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  — Landau-Zener tunnelling in the breakdown of Mott's insulator [10]
  — Correlated electrons in intense laser lights

[1] Hideo Aoki: Superconductivity in highly correlated systems, in H. Akai, A. Hosaka, H. Toki and F. B. Malik (eds): *Condensed Matter Theories* Vol. 21 (Nova Science, 2007), Chapter 14.

[2] H. Aoki: Fermiology and interaction in unconventional superconductors, *Physica C* **437-438**, 11 (2006).

[3] S. Onari, R. Arita, K. Kuroki, H. Aoki: Superconductivity from long-range interaction — a crossover between the electron gas and the lattice model, *Phys. Rev. B* **73**, 014526 (2006).

[4] S. Sakai, R. Arita, K. Held and H. Aoki: Quantum Monte Carlo study for multiorbital systems with preserved spin and orbital rotational symmetries, *Phys. Rev. B* **74**, 155102 (2006).

[5] 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); M. Tezuka: An improved initialization procedure for the density-matrix renormalization group, *J. Phys. Soc. Jpn* **76**, 053001 (2007).

[6] Y. Hatsugai, T. Fukui and H. Aoki: Topological analysis of the quantum Hall effect in graphene, *Phys. Rev. B* **74**, 205414 (2006).

[7] N. Tsuji, S. Takajo and H. Aoki: Large orbital magnetic moments in carbon nanotubes generated by resonant transport, *Phys. Rev. B* **75**, 153406 (2007).

[8] 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, *PRB* **74**, 033306 (2006).

[9] M. Kiguchi, G. Yoshikawa, K. Saiki, R. Arita and H. Aoki: Metal induced gap states at tetratetracontane/Cu interface, *Journal de Phys. IV* **132**, 199 (2006).

[10] 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).

11 Miyashita Group

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

Members: Seiji Miyashita, Keiji Saito, Hiroko Tokoro (JSPS) and Keigo Hijii (JST)

1. Phase Transition in Spin-Crossover Materials

We studied cooperative properties of spin-crossover materials, where responses to light-irradiation have attracted a lot of interest. In particular, the so-called LIESST (light-induced excited spin state trapping) phenomena have been extensively studied. In order to trap the excited state for a long time, the system needs a kind of metastability. In the atomic level, the unit of the material has an energy-barrier between the high-spin (HS) and the low-spin (LS) states which provides a mechanism of metastability. However, we found the existence of a metastable state in the thermodynamic free energy. This metastability is caused by the cooperativity of the molecules. We studied the properties of this metastability in various cases including the Prussian blue analogues. This metastable state was also found in an experiment which was done in the collaboration with the Ohkoshi-group in the department of chemistry, We proposed that the difference between the atomic metastability and the thermodynamic metastability would appear in the dependence of relaxation processes on the initial values. The existence of the thermodynamic metastability causes a non-monotonic relaxation. We also studied the origin of the cooperativity, and we found that the elastic distortion energy due to the variation of the size of the molecule plays an important roll.

2. Slow Relaxation in Highly Frustrated Systems

We studied the mechanism of slow relaxation caused by the entropy origin. The temperature dependence of the effective coupling of frustrated decorated bond structure causes the reentrant phase transition. We have pointed out the dynamics of the ordering becomes very slow due to the mechanism of spin-screening effect. There it is very difficult to find the ground state of the system by using the thermal annealing methods. Then, we studied how the quantum annealing works to find the ground state in this system and demonstrated in some simple cases. There, the adiabatic transition plays an important role. We also studied the slow relaxation in the Ising-like kagome antiferromagnetic Heisenberg model which exhibits a thermodynamical phase transition with the symmetry breaking phenomenon of the magnetization. In this system, reflecting the macroscopic degeneracy as the characteristic of the corner-sharing frustrated systems, a slow relaxation process exists even after the magnetization reaches to the equilibrium value. We studied this process by observing the number of the weathervane loops which represents the variety of the degenerate states. We found the a kind of entropy-induced ordering process, and obtained characteristics of the slow relaxation.

3. Novel Quantum Phenomena

We have studied novel quantum phases. In the last year, we studied the conditions for the existence of the "super-solid state". We investigated the effect of frustration of the interaction, the soft-core effect, and also the effect of inhomogeneity of the interaction. Especially, we found that the superfluid density have maximum value when the effective potential that additional particle feel becomes flat. We also studied phase diagram of the extended Bose-Hubbard model.

The localization of the electrons in one-dimensional tight-binding model was also studied in collabaration with the Nagaosa-group in applied physics department. When the magnetic system has frustrated interaction or the DM interaction, a spiral spin structure may appear. This structure affects the electron conduction. In particular, we found that the electron state may localize when the spiral is incommensurate with the lattice.

The energy gap at the avoided level crossing plays important role in the control the quantum state by external field. The gap changes with the external parameter continuously including zero which means gapless. This mechanism has been studied in term of the Berry phase. We have studied it from the view point of the spin parity. We also studied the similar behavior in the eigenvalue of the Floquet operator when the system is under the periodically oscillating field.

4. Quantum Dynamics

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

In the last year, we studied dynamical properties of the transverse Ising model under the sweeping field, and also the spin-wave propagation through the domain wall in the Ising-like Heisenberg model, where we find that the transverse component is reflected by the domain wall, while the longitudinal component propagates though it. These studies were done in the collaboration with De Readt group in the Groningen University.

As we mentioned above, to find the ground state is difficult in some frustrated systems where the entropy-origin slow dynamics takes place. We studied the quantum annealing method to find the ground state, and found that it efficiently works. We discussed the quantum annealing process from the view points of the adiabatic theorem of the quantum mechanics.

Manipulation of quantum particle by motion of potential well is important in microscopic operations of quantum lattice systems. We studied properties of conveyance of quantum particles by a moving potential-well. In particular, we study how the potential-well traps a particle when we sweep the potential-well. We also studied how the potential-well carries up the particle over a hill, i.e., from a region where the potential energy is low to a region of high potential energy. There, we found that the tunneling effect reduces the carried amount. This process is well described by the Landau-Zener mechanism. Effects of potential sweep in other potential shapes were also studied. The dynamics of particle density of non-interacting Fermi particle system under the sweeping potential-well was also studied and found the effect of the position of the Fermi level.

We studied the effects of quantum dissipation in the Landau-Zener mechanism. At zero temperature, we found that the transition probability can be completely soluble with both phononic bath and spin-bath. Especially when the thermal environment interacts with the spin-component where the driving field is applied, the probability is bath-independent and coincides with the original Landau-Zener probability.

Classical and Quantum correspondence of chaos was studied with the semiclassical periodic orbit theory. Quantum mechanics does not have the sensitivity to the initial state which is the characteristic of classical chaos. However, as well known, the quantum counterparts of classically chaotic systems show the universality in the level statistics which is well described by random matrix. We studied this empirical universality focusing on form factor.

12 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Youichi Yanase

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

- High-T_c superconductivity
  Superconductivity correlation in the strongly correlated electron systems.
  Mott metal-insulator transition and superconductivity.[1]
  Randomness and superconductivity fluctuation in high-T_c superconductors.[2]
- Multi-orbital superconductivity in $Na_xCoO_2 \cdot yH_2O$ [3-6]
- Organic conductors
  Quantum melting due to geometrical frustration.[7,8]
  New-type charge ordering and superconductivity in two-dimensional organic conductors.[9,10]
  Dimensional crossover and superconductivity in quasi-one-dimensional organic conductors.[11]
  Novel spin-liquid state in an organic system.[12]
- Theories of anisotropic superconductivity
  Superconductivity and antiferromagnetism in a non-centrosymmetric system.[13]
  New states of Sr_2RuO_4 in magnetic fields.
- Electronic and spin states in frustrated systems
  Effects of carrier doping in a Kagomé lattice.
  Numerical simulation in classical XY spin systems with frustration.
- Novel quantities in electronic systems
  Disorder operator in two-dimensional insulators.[14]
- Kondo effect and heavy fermion systems
  Kondo effects in quantum dots.[15]
  Fermi surface reconstruction with Kondo screening at quantum critical point.[16]
- Two-dimensional ^{3}He system on graphite
  Spin-liquid state at half-filling.
  Effects of ring-exchange interaction on the two-dimensional t-J model.

[1] H. Yokoyama, M. Ogata and Y. Tanaka: J. Phys. Soc. Jpn. **75**, 114706 (2006).
[2] Y. Yanase: J. Phys. Soc. Jpn.**75**, 124715 (2006).
[3] M. Mochizuki and M. Ogata: J. Phys. Soc. Jpn. **75**, 113703 (2006).
[4] M. Mochizuki and M. Ogata: J. Phys. Soc. Jpn. **76**, 013704 (2007).
[5] M. Mochizuki, H. Q. Yuan and M. Ogata: J. Phys. Soc. Jpn. **76**, 023702 (2007).
[6] M. Ogata: J. Phys.: Condens. Matter **19**, 145282 (2007).
[7] H. Seo, J. Merino, H. Yoshioka and M. Ogata: J. Phys. Soc. Jpn. **75**, 051009 (2006).
[8] H. Seo, K. Tsutsui, M. Ogata and J. Merino: J. Phys. Soc. Jpn. **75**, 114707 (2006).
[9] M. Kaneko and M. Ogata: J. Phys. Soc. Jpn. **75**, 014710 (2006).
[10] H. Watanabe and M. Ogata: J. Phys. Soc. Jpn. **75**, 063702 (2006).

[11] Y. Fuseya, M. Ogata: submitted to J. Phys. Soc. Jpn..
[12] Y. Hayashi and M. Ogata: J. Phys. Soc. Jpn. **76**, 053705 (2007).
[13] Y. Yanase and M. Sigrist: J. Phys. Soc. Jpn.**76**, 043712 (2007).
[14] R. Shindou, K-i. Imura, and M. Ogata: Phys. Rev. B **74**, 245107 (2006).
[15] D. Matsubayashi and M. Eto, Phys. Rev. B **75**, 165319 (2007).
[16] H. Watanabe and M. Ogata: arXiv:0704.1722, submitted to Phys. Rev. Lett..

13 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 FY2006 were as follows:

- Electronic structures and chemical reactions at surfaces
  - Organic chemistry on Si surfaces: precursor states and Markovnikov's rule for chemical reaction
  - Effect of strong electric field on organic molecules chemisorbed on Si surfaces
- Impurity effect in ferroelectric perovskites
  - Charge-state effect on hydrogen impurities in $BaTiO_3$
  - Temperature dependence of the charge state of Mn impurities in $SrTiO_3$
- Structura/electronic transition of YH_3 under ultra-high pressure
- Electronic structure analysis of proteins by the LCMO scheme
- New methods of electronic structure calculation
  - First-principles wavefunction theory for solids based on the transcorrelated method
  - Construction of model hamiltonian of materials from first principles and its application to excitation spectrum

14 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

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

[1] K. Tanaka, W.S. Lee, D.H. Lu, A. Fujimori, T. Fujii, Risdiana, I. Terasaki, D. J. Scalapino, T.P. Devereaux, Z. Hussain and Z.-X. Shen: Distinct Fermi-Momentum Dependent Energy Gaps in Deeply Underdoped Bi2212, Science **314** (2006) 1910-1913.

[2] K. Mamiya, T. Koide, A. Fujimori, H. Tokano, H. Manaka, A. Tanaka, H. Toyosaki, T. Fukumura and M. Kawasaki: Indication of Intrinsic Room-Temperature Ferromagnetism in $Ti_{1-x}Co_xO_{2-\delta}$ Thin Film: An X-Ray Magnetic Circular Dichroism Study, Appl. Phys. Lett. **89** (2006) 062506–1-3.

[3] M. Takizawa, H. Wadati, K. Tanaka, M. Hashimoto, T. Yoshida, A. Fujimori, A. Chikamatsu, H. Kumigashira, M. Oshima, K. Shibuya, T. Mihara, T. Ohnishi, M. Lippmaa, M. Kawasaki, H. Koinuma, S. Okamoto and A. J. Millis: Photoemission from Buried Interfaces in $SrTiO_3/LaTiO_3$ Superlattices, Phys. Rev. Lett. **97** (2006) 057601–1-4.

15 Uchida Group

Research Subjects: High-T_c superconductivity

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

1. Project and Research Goal

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

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

2. Accomplishment

(1) Ladder Cuprate

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

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

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

3) The origin of the insulating phase dominating the whole $x-P$ phase diagram is most likely the charge

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

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

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

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

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

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

1) Granular structure of high-Tc superconductivity

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

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

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

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

16 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA, Iwao MATSUDA, and Toru HIRAHARA

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] N. Nagamura, I. Matsuda, N. Miyata, T. Hirahara, S. Hasegawa, and T. Uchihashi: *Quasi-quantum-wire states in an epitaxial Ag film on a one-dimensional surface superstructure*, Physical Review Letters **96**, 256801 (Jun 2006).

[2] T. Hirahara, T. Nagao, I. Matsuda, G. Bihlmayer, E. V. Chulkov, Yu. M. Koroteev, P. M. Echenique, M. Saito, and S. Hasegawa: *Role of Spin-Orbit Coupling and Hybridization Effects in the Electronic Structure of Ultrathin Bi Films*, Physical Review Letters **97**, 146803 (Oct 2006).

[3] S. Yoshimoto, Y. Murata, K. Kubo, K. Tomita, K. Motoyoshi, T. Kimura, H. Okino, R. Hobara, I. Matsuda, S. Honda, M. Katayama, and S. Hasegawa: *Four-Point Probe Resistance Measurements Using PtIr-Coated Carbon Nanotube Tips*, Nano Letters **7**, 956 (May 2007).

[4] Y. Nakayama, I. Matsuda, S. Hasegawa, and M. Ichikawa: *Quantum regulation of Ge nanodot state by controlling barrier of the interface layer*, Applied Physics Letters **88**, 253102 (Jun 2006).

[5] T. Hirahara, T. Nagao, I. Matsuda, G. Bihlmayer, E. V. Chulkov, Yu. M. Koroteev, and S. Hasegawa: *Quantum-well states in ultrathin Bi films from angle-resolved photoemission spectroscopy and first-principles calculations study*, Physical Review B **75**, 035422 (Jan 2007).

[6] T. Hirahara, I. Matsuda, R. Hobara, S. Yoshimoto, and S. Hasegawa: *Direct measurement of the Hall effect in a free-electron-like surface state*, Physical Review B **73**, 235332 (Jun 2006).

[7] C. Liu, I. Matsuda, M. D'angelo, and S. Hasegawa: *Self-Assembly of Two-Dimensional Nanoclusters: From Surface Molecules to Surface Superstructure*, Physical Review B **74**, 235420 (Dec 2006).

[8] H. Konishi, Y. Murata, W. Wongwiriyapan, M. Kishida, K. Tomita, K. Motoyoshi, S. Honda, and M. Katayama, S. Yoshimoto, K. Kubo, R. Hobara, I. Matsuda, S. Hasegawa, M. Yoshimura, J.-G. Lee and H. Mori: *High-yield synthesis of conductive carbon nanotube tips for multiprobe scanning tunneling microscope*, Review of Scientific Instruments **78**, 013703 (Jan 2007).

[9] R. Hobara, N. Nagamura, S. Hasegawa, I. Matsuda, Y. Yamamoto, K. Ishikawa, and T. Nagamura: *Variable-Temperature Independently-Driven Four-Tip Scanning Tunneling Microscope*, Review of Scientific Instruments **78**, 053705 (May 2007).

[10] R. Hobara, S. Yoshimoto, S. Hasegawa, and K. Sakamoto: *Dynamic electrochemical-etching technique for tungsten tips suitable for multi-tip scanning tunneling microscopes*, e-Journal of Surface Science and Nanotechnology **5**, 94 (Apr 2007).

17 Fukuyama Group

Research Subjects: Low Temperature Physics (Experimental):

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

Member: Hiroshi Fukuyama, Hiroshi Kambara

Our current interests are (i) new quantum phases with strong correlations and frustration in 2D ^{3}He. (ii) quantum phenomena in 2DES like the quantum Hall effect and (iii) superconductivity with unconventional Cooper pairing. We are investigating these phenomena at very low temperatures down to 50 μK, using various experimental techniques such as NMR, calorimetry, STM/STS, *etc.*

1. **Novel quantum phases in strongly correlated fermions in 2D:**
   (a) **Zero-point vacancies in 2D ^{3}He:**
   We obtained a thermodynamic evidence for the zero-point vacancies (ZPVs), which are atomic vacancies hopping on crystalline lattice cites even at absolute zero, in monolayer solid ^{3}He adsorbed on a graphite surface. Our heat capacity measurements at densities (ρ) just below that ($\rho_{4/7}$) for the low-density commensurate phase (the 4/7 phase) show anomalies associated with the 2D hole band created by the strong correlation effects. Various theoretical analyses support the ZPV scenario even quantitatively.
   (b) **Spin dynamics in 2D ^{3}He near localization:**
   We are investigating spin dynamics of 2D ^{3}He near localization with the spin echo technique of pulsed-NMR. The density dependence of measured spin-spin relaxation time (T_2) shows a "V" shaped minimum at $\rho_{4/7}$. The increase of T_2 at $\rho \leq \rho_{4/7}$ can be understood as the motional narrowing due to doping the ZPVs and that at $\rho \geq \rho_{4/7}$ as the exchange narrowing due to the interlayer exchange with an overlayer.
2. **STM/STS studies of 2DES:**
   (a) **Real-space imaging of the quantum Hall state at graphite surface:**
   Previously we demonstrated that spatial distributions of the electronic states in the quantum Hall regime can be mapped in nm scale with STS near point defects at graphite surface. We have extended this investigation to graphite surfaces with many defects created by Ar-ion sputtering. In addition to the localized state with a central peak and a satellite ring (Type-I) which had been observed near the point defects, we found another state with a different distribution consisting only of the satellite ring (Type-II). Theoretical calculations for 2DES in magnetic fields show that the Type-I and Type-II states correspond to the localized states in Coulomb and harmonic potentials, respectively.
   (b) **STM/STS studies of 2DES in semiconductors:**
   In our previous STS measurements on the 2DES confined in an InAs thin film on a GaAs substrate, a strange oscillation of the density of states (DOS) with a 60 meV periodicity was found in the positive energy range. We have studied the origin of this oscillation in detail by changing the InAs film thickness, inserting an undoped GaAs thin layer in between the film and substrate, and replacing the substrate from GaAs to InAs. It was concluded that the oscillation is caused by modulation of the tunnel probability in the presence of the Schottky barrier between the film and substrate.
3. **STM/STS studies of unconventional superconductors:**
   (a) **Impurity-induced resonant states in a d-wave superconductor:**
   We studied the temperature dependence of impurity-induced resonant states in Zn-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ to identify the origin of the sharp near-zero-energy peak observed in STS experiments. We found that the resonant peak survives even at $T = 52$ K which is much higher than the estimated Kondo temperature ($\sim$ 15 K). This result supports the impurity-scattering resonance scenario.
   (b) **Surface electronic states of Sr_2RuO_4:**
   Surface electronic states of the spin-triplet superconductor Sr_2RuO_4 have been studied with STS. A large gap structure ($\Delta \sim 5$ meV) in the tunnel spectrum is always observed at surface SrO planes cleaved at low temperatures possibly because of the surface reconstruction. On the other hand, surfaces cleaved or exposed at room temperature show a disordered DOS with 3D correction term of Anderson localization.

18 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

1. Two dimensional electrons at cleaved semiconductor surfaces:
   At the surfaces of InAs and InSb, conduction electrons can be induced by submonolayer deposition of other materials. 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. However, a high magnetic field above 10 T was required for the observation of the QH effect. In this year, we extended the study to InSb surfaces. The quantum Hall effect was observed even at low magnetic fields around 2 T. The surface electron density and the electron mobility exhibit strong dependence on the Ag-coverage and the annealing temperature in the range of 15-40 K. The annealing effect suggests that the surface morphology strongly affects the properties of the two-dimensional electron systems.

2. Strongly correlated two dimensional systems:
   We have studied anisotropic magnetotransport in a silicon quantum Hall system. By controlling the angle of the magnetic field with respect to the two dimensional plane, the ratio of the Zeeman energy to the cyclotron gap can be adjusted. At the angle, where the Landau levels ($n = 1, \uparrow$) and ($n = 0, \downarrow$) have the same energy, giant anisotropy of the longitudinal resistivity was found. With decreasing temperature, the longitudinal resistivity in the direction parallel to the in-plane magnetic field steeply increases while that in the perpendicular direction decreases. The results might be related to the formation of a striped spin density wave.

3. Spin current in the quantum Hall regime detected by dynamic nuclear polarization:
   We have studied the spin current and heat flow in the spin-resolved quantum Hall regime around Landau level filling factor $\nu = 3$ in GaAs/AlGaAs two-dimensional electron systems (2DESs). First, we demonstrated that dynamic nuclear polarization (DNP) can be caused by a change in T_e in the breakdown regime at $\nu = 3$. The sample used has a narrow channel, where the width varies stepwise along the electron flow. We found that electron cooling (heating) causes the polarization of nuclear spins against (toward) the external magnetic field at liquid helium temperatures. Secondly, spin current perpendicular to the electric current was investigated in the transition regions of $2 < \nu < 3$ and $3 < \nu < 4$. A specially designed Hall bar was used in order to detect DNP in the vicinity of one of the edges after applying a large electric current. The observed polarity of DNP, which depends on those of the electric current and magnetic field, indicates that the directions of the spin current and the Hall electric field are the same for $\nu > 3$, but are opposite for $\nu < 3$. It is suggested that the spin of the majority carriers of the dissipative current determines the direction of the spin current.

19 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Shinichi Watanabe

We study light-matter interactions and many body quantum correlations in: 1)optically excited high density electron-hole systems in semiconductors, low dimensional systems such as 2) carbon nanotubes, 3) quasi-1D organic conductors, 4)superconductors, and 5) strongly correlated electron systems. In order to investigate the dynamics of phase transition in those materials, we are focusing on their low energy electromagnetic responses in terahertz(THz) (1THz$\sim$4meV) frequency range where quasi-particle excitations and various collective excitations exist. The research summary in this year is as follows.

1. **THz spectroscopy**
   (1)**Carbon nanotubes:** Carbon nanotubes are considered as one of the promising materials for the study of one dimensional electronic systems. The dynamical aspects of their transport properties, and photo-excited dynamics are important issues to understand the Coulomb correlation in such 1D electron system. In this context, we are studying the low energy ($\sim$ meV) electromagnetic responses of their ground state and photo-excited state. We determined the complex dielectric function of HiPco

single-wall carbon nanotubes (SWNTs) by terahertz time-domain spectroscopy in the broad spectral range from 0.2 to 20 THz. Real part of the dielectric function exhibits extremely large and positive value at low frequency below 2THz, indicating the response of small gap SWNTs.
(2)**Superconductors:** Vortex lattice, or glass in superconductor can be recognized as a new class of material phase which can be controlled by external perturbation such as magnetic field or temperature. We study the interaction among the vortices and their dynamics as well as the quasi-particle dynamics by THz conductivity measurements. A clear gap at 1.1THz is observed in NbN film of T_c=15K, which disappears with increasing the applied magnetic field. The conductivity spectrum is analyzed based on effective medium theory.
(3)**Multiferroics:** Antiferromagnetic resonance is observed in multiferroic material $DyMnO_3$, where ferroelectric and antiferromegnetic order coexist at low temperature. The correlation between ferroelectricity and magnetism is systematically examined in THz frequency range, in order to investigate the collective excitation of the ferroelectric order.

2. **Instrumental Developments**
(1)**THz time domain ellipsometry at low temperature and under high magnetic field:** THz time domain ellipsometry at low temperature as low as 1.6K and under high magnetic field as high as 7T is achieved. The available frequency range is between 0.2 to 2THz, which covers the BCS gap of conventional superconductors, antiferromagnetic resonances, and cyclotron frequencies in typical semiconductors such as Si, InAs, GaAs under the relevant magnetic field. A high sensitive polarization spectroscopy, namely the THz time domain ellipsometry, is combined with this system, which allows one to measure the magneto-optical Faraday rotation angle as small as 0.5mrad.
(2)**Broadband THz spectroscopy system:** In order to extend the conventional THz spectroscopy range of 0.2 to 3THz of which upper limit is restricted by the laser pulse width 160fs, we installed a much shorter femtosecond laser system with pulse width of 14fs. By adopting the optical rectification and dipole antenna for THz generation and detection scheme, we suceeded in obtaining a broad spectral range of 0.5 to 30THz(600μm to10μm), which covers interesting response range of those abundant materials listed above.
(3)**Development of compact THz spectroscopy system:** Compact and mobile terahertz time domain spectroscopy (THz-TDS) measurement system is quite useful as one can perform the measurements anywhere including what conventional setup cannot be accessible, e.g. inside a cryogenic system with no optical windows. Also useful is a diffraction-limited THz imaging system with high spatial resolution, as one can quantitatively extract the spectroscopic information of small objects, particularly when their sizes are in the order of mm, comparable to the wavelength of THz waves. For this purpose, we have developed a very compact THz-TDS imaging system with high diffraction-limited spatial resolution, which is designed so as to put the whole system except for pump and probe laser lines inside a cryostat with 25 millimeter diameter sample space.

20 Theoretical Astrophysics Group

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

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

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

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

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

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

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;
2006

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

2005

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

2004

- Strong Gravitational Lenses in a Cold Dark Matter Universe
- Effect of Rotation and Magnetic Field on the Explosion Mechanism and Gravitational Wave in Core-Collapse Supernovae
- "Bulk Fields in Braneworld"
- "Gravitational collapse and gravitational wave in the brane-world"
- Magnetohydrodynamical Simulation of Core-Collapse Supernovae
- A Search for the Atmospheric Absorption in the Transiting Extrasolar Planet HD209458b with Subaru HDS

- Baryogenesis and Inhomogeneous Big Bang Nucleosynthesis
- The large-scale structure of SDSS quasars and its cosmological implication

2003

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

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

21 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 a fundamental resource for quantum information processing. In our group, we investigate new properties of multipartite and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- Relationship between LOCC copying and LOCC discrimination of maximally entangled states [1]
- Two-way classical communication remarkably improves LOCC distinguishability
- Multipartite distance like measure of entanglement for a class of symmetric states
- A computable bound of deterministic LOCC discrimination in a multipartite system

- Entanglement and local information access for graph states [2]
- Local encoding of classical information onto quantum states [3]
- Remote destruction of spread qubit information
- Generalization of measurement based quantum computation
- Searching for the maximally entangled tripartite state
- Survival of entanglement in thermal states [4]
- The role of entanglement in quantum information and in statistical physics [5]
- Entanglement in one dimensional spin systems
- Enhancement of security by using blind quantum computation

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

References

1. Masaki Owari, Masahito Hayashi, *Local Copying and local discrimination as a study for non-locality of a set of states*, Physical Review A, **74**, 032108 (2006)
2. D. Markham, A. Miyake and S. Virmani, *Entanglement and local information access for graph states*, arXiv:quant-ph/0609102 (to appear in N. J. Phys.)
3. Y. Tanaka, D. Markham and M. Murao, *Local encoding of classical information onto quantum states* arXiv:quant-ph /0702190 (to appear in J. Mod. Opt.)
4. D. Markham, J. Anders, V. Vedral and M. Murao, *Survival of entanglement in thermal states*arXiv:quant-ph/0606103
5. J. Anders, D. Markham, V. Vedral and M. Hajdusek, *How much of one-way computation is just thermodynamics?* arXiv:quant-ph/0702020
6. M. Owari, S. L. Braunstein, K. Nemoto, Mio Murao, *ϵ-convertibility of entangled states and extension of Schmidt rank in infinite-dimensional systems*, arXiv:quant-ph/0609167

22 Makishima Group & Nakazawa 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, Kazuhiro Nakazawa

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) [1,2] 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. After the initial performance-verification phase, the first guest-opservation cycle of *Suzaku* was completed in the end of March 2006.

Physics of Compact Objects: Mass accretion onto compact objects is our favorite research subject, and extensive *Suzaku* studies have been carried out. From two binary X-ray pulsars, the HXD successfully detected spectral features due to electron cyclotron resonance [4]. Rotation-powered pulsars, including the Crab pulsar in particular, provided accurate calibration to the HXD timing function. Combining the ~ 0.3 keV to ~ 200 keV spectra of several black-hole binaries (including the prototypical Cygnus X-1) obtained with *Suzaku*, were have discovered that their spectra require, in terms of thermal Compton scenario, at lest two different optical depths. 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 yielded the *Suzaku* detection at least up to 100 keV. In particular, the data from the type 2 Seyfert galaxy NGC 4945 has provided valuable information on the geometry of obscring materials.

Cosmic Nucleosysnthesis: X-ray observations provide powerful diagnostics to cosmic nucleosynthesis, from individual stars to clusters of galaxies. Our observations of a planetary nebula with the *Suzaku* CCD camera revealed an extreme carbon overabundance relative to oxygen [3]. This is a rare occasion where the carbon-rich material produced deep inside an evolved star is being witnessed. Using *Suzaku* and *XMM-Newton* data of a fair number of clusters of galaxies, we discovered that Oxygen in their hot X-ray emitting plasma is much more widely distributed than Silicon and Iron. This can be explained if their member galaxies have been falling to the cluster centers over the Hubble time, presumably due to magneto-hydrodynamic interactions with the plasma.

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, coded-mask imagers employing small-pixel inorganic scintillators, new single- and poly-crystalline and inorganic scintillators, and avalanche photo diodes. Some of them are meant for the future mission called *NeXT* (New X-ray Telescope), which is being planned as a successor to *Suzaku*, hopefully to be launch in 2012.

1. Takahashi, T., Ezoe, Y., Fukazawa, Y., *et al.*: "Hard X-Ray Detector (HXD) on Board Suzaku", *Publ. Astr. Soc. Japan* **59**, S35-S51 (2007)
2. Kokubun, M., Makishima, K., *et al.*: "In-Orbit Performance of the Hard X-Ray Detector on Board Suzaku", *Publ. Astr. Soc. Japan* **59**, SS53-S76
3. Murashima, M., Kokubun, M., Makishima, K., *et al.*: "*Suzaku* Reveals He-burning Products in the X-ray Emitting Planetary Nebula BD +30° 3639", *Astrophys. J. Lett.*, **647**, L131-L134 (2006)
4. Terada, Y., Mihara, T., Nakajima, M., Suzuki, M., Isobe, N., Makishima, K., Takahashi, H., Enoto, T., Kokubun, M., Kitaguchi, T., (21): "Cyclotron Resonance Energies at a Low X-Ray Luminosity: A0535+262 Observed with *Suzaku*", *Astrophys. J. Lett.* **648**, L139-L142 (2006)

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. Our group is tackling the problem of creating and sustaining a high beta plasma using a variety of approaches.

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). The physics of noninductive plasma initiation by RF power in the presence of a vertical magnetic field with positive decay index is being investigated on TST-2. Analysis based on single particle orbits has successfully reproduced the main features of the experimental dependences on the magnetic geometry and the magnetic field strength, showing that the plasma current maximizes when $R\Omega_p$ becomes comparable to the electron thermal velocity, where R is the major radius of the plasma and Ω_p is the cyclotron frequency evaluated with the poloidal magnetic field. Plasma heating by the high harmonic fast wave (HHFW) is also being investigated. A nonlinear process known as parametric decay was observed by both RF magnetic probes and microwave reflectometry. A clear evidence of electron heating, as evidenced by increased soft X-ray emission, was observed only when parametric decay activity was made sufficiently weak by pushing the plasma inward.

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 mode structure is being revealed by simultaneous singular value decomposition (SVD) analysis of soft X-ray and magnetic data. Internal modes as well as external modes, which are consistent with predictions of nonlinear MHD simulations, have been identified in TST-2. On MAST it was found that the electron pressure gradient increases to $dP/dr \sim 9 \times 10^3$ Pa/m before an RE and relaxes to $dP/dr \sim 4 \times 10^3$ Pa/m after an RE, suggesting that the instability is driven by the pressure gradient.

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 has been constructed and plasma formation experiments have started. 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.

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 using the newly developed constant surface flux control algorithm, which eliminates the possibility of inductive current drive. Collaborations with larger ST devices NSTX (USA) and MAST (UK) are also being carried out.

24 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Masaki ANDO

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

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

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
  - Systematic analysis of TAMA monitoring signal
  - Search for continuous gravitational waves from unknown pulsars
  - Study of the next-generation laser interferometer, LCGT
- Space laser interferometer
  - Space laser interferometer DECIGO
  - DECIGO pathfinder
  - Small size detector SWIM
- Study of the precise measurements
  - Laser stabilization using optical fiber
  - Study of magnetic levitation
- Study of the thermal noise
  - Study of the thermal noise in a space interferometer
  - A new analysis method for the thermal noise caused by an inhomogeneous distributed loss

references

[1] Kazuhiro Yamamoto, Masaki Ando, Keita Kawabe, and Kimio Tsubono: Theoretical approach to thermal noise caused by an inhomogeneously distributed loss: Physical insight by the advanced modal expansion, Phys. Rev. D (2007) in press.

[2] Tomomi Akutsu, and the TAMA Collaboration, Results of the search for inspiraling compact star binaries from TAMA300's observation in 2000-2004, Phys. Rev. D **74**-12 (2006) 122002.

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. K. Takeuchi: Can the Ising critical behavior survive in non-equilibrium synchronous cellular automata?, Physica D, 223, 146-150 (2006).
2. A. Awazu and K. Kaneko : Pulse Replications and Spatially Differentiated Structure Formation in One dimensional lattice dynamical System, Mathematical Bioscience, 201, 90-100 (2006).
3. H. Shiba, J. R.-Felsot, Y. Takahashi, Y. Murayama, Q. Ouyang, and M. Sano: Elastic Convection in Vibrated Viscoplastic Fluids, Phys. Rev. Lett. 98, 044501 (2007).
4. K. Takeuchi and M. Sano: Role of unstable periodic orbits in phase transitions of coupled map lattices, Phys. Rev. E, 75, 036201 (2007).
5. S. Toyabe, H. R. Jiang, T. Nakamura, Y. Murayama and M. Sano: Experimental Test of a New Equality: Measuring Heat Dissipation in an Optically Driven Colloidal System, Phys. Rev. E 75, 011122 (2007).
6. Y. Murayama, H. Wada, R. Ishida, and M. Sano: Unfolding Dynamics of Single Collapsed DNA Molecules, Prog. Theo. Phys. Suppl. 165, 144-163 (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. A part of our recent research activities is as follows:

(1) Laser field free molecular orientation with combined electrostatic and shaped laser fields

The control of the spatial direction of molecules is especially important for molecular control experiments as well as stereodynamics of chemical reactions. In fact, a sample of aligned or oriented molecules is an ideal anisotropic quantum system to investigate many interesting phenomena such as multiphoton ionization and high-order harmonic generation, which are related to symmetry and directions of a molecule, and are spatially averaged out with randomly oriented molecule. As for the molecular orientation, we have already succeeded in the proof-of-principle experiments of one-dimensional and three-dimensional orientation of molecules with combined electrostatic and intense, nonresonant laser fields. These experiments were performed in the adiabatic regime, where the pulse width of the laser field is rather long compared to the rotational period of the molecules. In this case, the degree of molecular orientation follows the temporal profile of the laser pulse and reaches the maximum at the peak of the laser pulse.

On the other hand, 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. Such a suddenly switched-off pulse can be shaped with the plasma shutter technique. 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 and the proof-of -principle experiment is now in progress in our lab.

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

We have developed an original technique to generate ultrashort light pulses in the XUV region by using high-order harmonic generation (HHG) from aligned molecules. First, we have succeeded in the optimal control of multiphoton ionization processes in aligned I_2 molecules with time-dependent polarization pulses. This means that we have developed the most advanced technique to control tunnel ionization which is the first step of HHG. Second, our novel technique to observe both ion yields and harmonic signals under the same experimental conditions enabled us to observe the first clear evidence of quantum interference of electron de Broglie waves in the recombination process, i.e., the third step of HHG from aligned CO_2 molecules. Third, we applied the polarization gate technique to HHG from non-adiabatically aligned N_2 molecules. Contrary to our expectations based on ellipticity dependence of HHG from aligned molecules, we have found that the spectral width of each harmonic tends to be broader when the molecular axis is perpendicular to the major axis of elliptical polarization. Theoretical calculations show that our observations are characteristic of time-dependent polarization pulses. This means that molecular alignment can be used as an important control parameter in addition to the carrier envelope phase when we generate attosecond pulses with polarization gated few-cycle pulses.

[1] Yutaka Nomura, Tsuneto Kanai, Shinichirou Minemoto, and Hirofumi Sakai, "Efficient generation of high-order sum and difference frequencies in the xuv region by combining a weak longer-wavelength field," Phys. Rev. A **75**, 041801(R) (4 pages) (2007).

[2] Shinichirou Minemoto and Hirofumi Sakai, "Anomalous angular distribution of fragment ions from rare-gas diatomic molecules with intense, femtosecond, near-infrared laser pulses," Phys. Rev. A **75**, 033413 (6 pages) (2007).

[3] Tsuneto Kanai, Shinichirou Minemoto, and Hirofumi Sakai, "Ellipticity dependence of high-order harmonic generation from aligned molecules," Phys. Rev. Lett. **98**, 053002 (4 pages) (2007).

28 Kuwajima Group

Research Subjects: Protein Folding, Molecular Chaperones, Protein Stability, Physico-chemical 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 equilibrium and kinetics of canine milk lysozyme folding/unfolding were studied by peptide and aromatic circular dichroism and tryptophan fluorescence spectroscopy. The Ca^{2+}-free apo form of the protein exhibited a three-state equilibrium unfolding, in which the molten globule state is well populated as an unfolding intermediate. A rigorous analysis of the holo protein unfolding, including the data from the kinetic refolding experiments, revealed that the holo protein also underwent three-state unfolding with the same molten globule intermediate. Although the observed kinetic refolding curves of both forms were single-exponential, a burst-phase change in the peptide ellipticity was observed in both forms, and the burst-phase intermediates of both forms were identical to each other with respect to their stability, indicating that the intermediate does not bind Ca^{2+}. This intermediate was also shown to be identical to the molten globule state observed at equilibrium. The ϕ-value analysis, based on the effect of Ca^{2+} on the folding and unfolding rate constants, showed that the Ca^{2+}-binding site was not yet organized in the transition state of folding. A comparison of the result with that previously reported for α-lactalbumin indicated that the folding initiation site is different between canine milk lysozyme and α-lactalbumin, and hence the folding pathways must be different between the two proteins. These results thus provide an example of the phenomenon wherein proteins that are very homologous to each other take different folding pathways. It is also shown that the native state of the apo form is composed of at least two species that interconvert into each other.

[1] S. Enoki, K. Maki, T. Inobe, K. Takahashi, K. Kamagata, T. Oroguchi, H. Nakatani, K. Tomoyori & K. Kuwajima: The Equilibrium unfolding intermediate observed at pH 4 and its relationship with the kinetic folding intermediates in green fluorescent protein. *J. Mol. Biol.* (2006) **361**, 969-982.

[2] H. Nakatani, K. Maki, K. Saeki, T. Aizawa, M. Demura, K. Kawano, S. Tomoda & K. Kuwajima: Equilibrium and Kinetics of the Folding and Unfolding of Canine Milk Lysozyme. *Biochemistry* (2007) **46**, 5238-5251.

29 Nose Group

Research Subjects: Molecular Mechanism of Neural Network Formation

Member: Akinao Nose, Hiroshi Kohsaka and Etsuko Takasu

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

1. Molecular mechanism of the neuromuscular target recognition 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.

2. Molecular Mechanisms of Synaptogenesis 2.1 Live imaging of neuromuscular synaptogenesis Cell adhesion molecules (CAMs) have been proposed to mediate interactions between innervating axons and their targets. However, such interactions have never been directly observed in vivo. We studied the function and dynamics of Fasciclin2, a homophilic CAM expressed both pre- and postsynaptically during the formation of neuromuscular synapses in Drosophila. By live-imaging of functional Fas2-GFP, we showed that postsynaptic Fas2 accumulates at the synaptic contact site soon after the arrival of the nerve. The accumulation of postsynaptic Fas2 was dependent on its extracellular domain and the presence of axonal Fas2, consistent with recruitment by presynaptic Fas2. This notion was further supported by photobleaching experiments, which demonstrated presynaptic-Fas2-dependent reduction of postsynaptic Fas2 motility. In fas2 mutants, we found reduced postsynaptic accumulation of glutamate receptors and Dlg/PSD-95, a scaffolding protein known to bind Fas2. These results suggest that Fas2 mediates trans-synaptic adhesion that is necessary for the initiation of postsynaptic assembly.

2.2. Innervation and activity dependent changes in postsynaptic oxidative metabolism The level of mitochondrial energy metabolism is highly correlated with neuronal activity to ensure the balance of energy consumption and production. Yet it remains largely unknown whether this relationship holds in the postsynaptic cell during synaptogenesis when it receives increasing amount of inputs from the presynaptic neuron. We have studied the changes in postsynaptic oxidative metabolism by monitoring the redox of mitochondrial flavoproteins during neuromuscular synaptogenesis. Flavoproteins cycle between fluorescent and non-fluorescent states as they are oxidized and reduced in the respiratory chain. We found that the postsynaptic muscle cells spontaneously emit green autofluorescence transients originating in flavoproteins under blue light excitation. The fluorescence transient is dependent on external Ca^{2+} and correlates with an increase in intracellular Ca^{2+} concentration. Notably, the rate of transients in muscle cells increases during synapse formation presumably through a contact with motoneuronal axon. The rate is also influenced by the magnitude of synaptic inputs. Thus, our results indicate that presynaptic cells dynamically regulate the level of postsynaptic energy metabolism during the early stage of neuromuscular synapse formation.