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Department of Physics
School of Science
University of Tokyo

Annual Report
2003
Summary of group activities

東京大学 大学院 理学系研究科・理学部
物理学教室

目 次

1 Theoretical Nuclear Physics Group

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

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

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

Nuclear Structure Physics

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

(1) Exotic (Unstable) nuclei stand for the nuclei far from the beta stability line. We are studying various features of such nuclei. This year, a systematic study has recently been made for unstable nuclei around A=30, focusing upon varying shell gap, vanishing magic number and anomalous deformation, by applying the Monte Carlo shell model described below. We found that magic numbers of unstable nuclei can be quite different systematically from those of stable nuclei, and this difference is one of the consequences of the shell evolution [1, 2, 3]. The tensor interaction has been shown to have significant effect on the shell evolution. Significant influences of the spin-isospin interaction are also for magnetic moments and Gamov-Teller transitions [4].

(2) We have proposed, several years ago, the Quantum Monte Carlo Diagonalization (QMCD) method for solving many-body problems. This method enables us to generate, through a Monte Carlo process, a small number of many-body bases which are important to the final solution. The method therefore can be characterized as *importance truncation scheme*. Thus, this study is expected to produce enormous progress in our understanding of nuclear structure. This kind of studies are referred to as Monte Carlo Shell Model (MCSM) [1, 2, 3].

(3) The molecular structure of unstable nuclei is studied extensively also [5, 6]. The quantum chaos and symmetry are shown to be closely connected. The relativistic mean field approaches are studied from some new perspectives as well.

Hadron Physics

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

Main research interests are the quark-gluon structure of hadrons, lattice gauge theories and simulations, matter under extreme conditions, quark-gluon plasma in relativistic heavy-ion collisions, high density matter, neutron stars and quark stars, chiral symmetry in nuclei, and color superconductivity.

Highlights in research activities of this year are listed below.

1. Physics of high density and/or high temperature matter
    - 1.1 Hadrons in quark-gluon plasma [7, 8]
    - 1.2 Color superconductivity in quark matter [9]
    - 1.3 Superfluidity, pion condensation and chiral restoration in srrong coupling QCD [10, 11]
    - 1.4 Induced critical phenomena in strong coupling QCD [12]
2. QCD structure of hadrons
    - 2.1 Axial structure of the nucleon in lattice QCD simulations [13]
    - 2.2 Lattice QCD study of the penta-quark

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2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

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

The main research interests at our group are in superstring theory, quantum theory of gravity and unification theories. Superstring theory, supersymmetric field theories, topological field theories and conformal field theories are analyzed relating to the fundamental problems of interactions. In the field of high energy phenomenology, supersymmetric unified theories are extensively studied and cosmological problems are also investigated. In addition to these topics, we also study various problems in quantum field theory, from the viewpoints of both continuum and lattice approaches.

We list the main subjects of our researches below.

1. String Theory
   1.1 Supersymmetric Gauge Theories, Topological String Theories and Superstrings [1, 2, 3, 4, 27, 32, 35, 36, 37]
   1.2 String Field Theory [21, 22, 23, 24, 30]
   1.3 Strings and D-branes on Curved Backgrounds [5, 6, 15, 16, 19, 20, 25, 28, 31, 33, 34, 38, 39, 41]
2. High Energy Phenomenology
   2.1 Particle Cosmology [7, 8, 9, 17, 26, 40, 42, 43, 44]
   2.2 Supersymmetric Unification Models [14, 18, 45]
3. Quantum Field Theory
   3.1 Anomalies and Fundamental Problems in Field Theory [10, 11, 12, 13, 29]

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3 Sakai Group

Research Subjects: Experimental Nuclear Physics

Member: Hideyuki Sakai, Kentaro Yako

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

Major activities during the year are summarized below.

Study of three-nucleon force effects via the n+d scattering

How the effect of three nucleon force (3NF) appears in nuclear reactions is one of the interesting subjects in nuclear physics. Up to now, the 3NF effects have been discussed by comparing the experimental data of p+d scattering with Faddeev calculations of n+d scattering since it is difficult to incorporate the Coulomb force into the calculation. In order to make clear how the Coulomb force affects the p+d scattering process, we have measured the n+d elastic scattering at $E_n = 250$ MeV covering a wide angular region of $\theta = 10°$–$180°$. The result shows clear difference between the n+d and p+d data indicating the Coulomb force effects.

Search for super narrow dibaryon via the p+d scattering

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

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

In 1935, Einstein, Podolsky and Rosen presented a paradox to quantum correlations and concluded that the quantum mechanical description of nature is incomplete. So-called hidden variables are introduced in the classical approach to describe the correlation. The Bell's inequality, discovered in 1964, shows that correlation produced by the hidden variables is weaker than that predicted by quantum mechanics. Since then many experimental tests on the Bell's inequality have been performed by using entangled photon pairs, while there are almost no severe tests in hadronic systems. To test the Bell's inequality in a two-proton system, we have measured the spin correlation between the two protons in $[{}^1\mathrm{S}_0]$ produced by the ${}^{12}\mathrm{C}(d, {}^2\mathrm{He})$ reaction. The Bell's inequality will be tested with an accuracy of more than four standard deviations.

Elastic scattering between the RI beam and the polarized proton target

A polarized solid proton target system has been developed to study structures of unstable nuclei. The first nucleus studied was ^{6}He, which is considered to have neutron skin structure. The analyzing powers for the $\vec{p}$+^{6}He elastic scattering have been measured for the first time at 71 MeV/A at angles between 40° and 80° in the center of mass frame. The polarization of the proton target was ∼20%. The present analysis suggests that the spin-orbit potential of ^{6}He is located more outward by 0.8 fm than that of ^{6}Li.

Study of Gamow-Teller unit cross sections at 300 MeV

We are studying the behavior of pions in nuclei by measuring the total strength of the Gamow-Teller (GT) excitations in the ${}^{90}\mathrm{Zr}(p, n)$ and ${}^{90}\mathrm{Zr}(n, p)$ reactions at 300 MeV. An important ingredient is the GT unit cross section, which is used when measured GT cross sections are converted to the GT strengths. To obtain the GT unit cross section, we have developed a new neutron detection system in the neutron time of flight facility at Research Center for Nuclear Physics. The commissioning runs confirmed a good energy resolution of ∼700 keV at 300 MeV.

4 Hayano Group

Research Subjects: Study of fundamental symmetries using exotic atoms.

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

'Exotic Atom' is the keyword of Hayano group. Namely, we use antihydrogens (antiproton + positron), antiprotonic helium atoms (helium nucleus + antiproton + elecrtron), pionic atoms (negative pion + nucleus), etc., and study fundamental symmetries of nature.

- **High-precision tests of matter-antimatter symmetry at CERN-AD (Switzerland)**
  - **Antihydrogen** "Production and spectroscopy of antihydrogen" is funded by the "Grant-in-Aid for Specially Promoted Research" of MEXT (5-year project started in 2003), Japan, and is being carried out at the antiproton decelerator (AD) at CERN (Geneva, Switzerland). The ultimate goal of antihydrogen spectroscopy is to test matter-antimatter symmetry (CPT) to very high precision. In 2002, our ATHENA experiment succeeded to produce a large number of cold antihydrogen atoms, and published the result in Nature. From 2003, we are working on CO2-laser-stimulated recombination of antihydrogen atoms, the first step towards the future laser spectroscopy.
  - **Antiprotonic helium atom** Antiprotonic helium is an exotic metastable 3-body 'atom' (consisting of a helium nucleus, an antiproton, and an electron: He^{++}–$\bar{p}$–e^- (short$\bar{p}He^+$)) serendipitously discovered by our group, and is currently studied in detail by using the laser-spectroscopy technique by the ASACUSA collaboration at CERN AD. We have recently reached a precision of 10^{-8} (10 ppb). This result provides the most stringent antiproton-proton mass & charge comparison. The antiprotonic helium atom spectroscopy is also funded by the Specially Promoted Research.
  - **Antiprotonic helium ion** In 2003 we succeeded in observing also metastable antiprotonic helium ions, a two-body system He^{++}–$\bar{p}$ (short $\bar{p}He^{++}$), and measured the density-dependent lifetime of various states. Preliminary results show that the ions can also be used for laser spectroscopy. Since the energy levels of this highly-excited two-body system can be calculated to a much higher precision than the three-body system, it can be used to obtain theory-independent measurements of the antiproton charge and mass in the future.

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

  Recently, it has been recognized that the spectroscopy of 'deeply-bound' pionic atoms can provide a crucial information to understand the origin of 'proton mass'. We have succeeded to produce 1s states of pionic Pb and pionic Sn by using the (d,^{3}He) reaction, and, for the first time, to quantitatively demonstrate that chiral symmetry is partially restored in nuclei. This is an important step toward understanding why a proton can acquire a large mass of $\sim$ 1GeV/c^2, while the u and d quarks, the proton ingredients, are nearly massless.

  Our next goal is to bind an η meson to a nucleus, measure the binding energy, and extract further information on the chiral symmetry restoration.

- **Search for strange tri-baryons at KEK**

  Motivated by theoretical predictions that kaons can form deeply-bound states in light nuclei, we conducted a search for such states by stopping negative kaons (K^- meson) in a liquid helium target, and by measuring neutrons and protons emitted from the reaction. A tantalizing result showing a strong evidence for the existence of hitherto unknown strange tribaryon has been obtained. Analyses are underway.

5 Sakurai Group

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

Member: Hiroyoshi Sakurai, Hironori Iwasaki

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

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

Our program in the year 2003 has covered the following subjects;

1. Development of RI beams in the vicinity of ^{54}Ca and ^{78}Ni using a 63AMeV ^{86}Kr beam.
2. Particle stability and β-decay properties of very neutron-rich nuclei near the drip line.
3. In-beam shadow method for lifetime measurements of the 2^+ state in ^{16}C.
4. Proton inelastic scattering to investigate neutron-matter deformation of ^{16}C.
5. Proton inelastic scattering to determine low-lying level schemes in the very neutron-rich nuclei ^{74}Ni and ^{78}Zn.
6. Coulomb excitation of ^{76,78,80,82}Ge and quadrupole collectivity around N=50.
7. β spectroscopy of the proton-rich nuclei ^{46}Cr and ^{23,24}Si.
8. R&D studies for Zero-degree Forward Spectrometer at RIBF.
9. Development of strip Germanium telescope for in-beam gamma spectroscopy of fast-moving RI beams.
10. Development of TOF spectrometer for gamma spectroscopy of medium-heavy neutron-rich nuclei.
11. Precise measurements of Coulomb and nuclear breakup reactions of ^{11}Be.
12. Coulomb dissociation of ^{23}Al and ^{27}P to study key reactions of the rp-process path, ^{22}Mg(p,γ)^{23}Al and ^{26}Si(p,γ)^{27}P.

6 Komamiya group

Research Subjects: (1) Preparation for experiment at the linear e^+e^- collider GLC;(2)OPAL experiment at LEP e^+e^- collider;(3) preparation for data analysis for the ATLAS experiment at LHC (4)research on astroparticle physics with balloon-borne high resolution spectrometer (BESS experiment);(5) Detector researches and developments for future particle physics experiments.

Member: Sachio Komamiya, Tomoyuki Sanuki

1) Preparation for the e^+e^- linear collider GLC: GLC is the energy frontier machine for e^+e^- collisions in the near future. We started various GLC accelerator simulations and plan to help hardware tests at KEK. We have been studying possible physics and experiments at GLC. In the FY2002 the ACFA Linear Collider Project Report was completed. The whole picture of the Linear Collider Project is described in this report (http//:lcdev.kek.jp/ProjReport/). The report includes expected physics, detector design, accelerator design and R&D, civil engineering, site studies, cost evaluation, international organization, benefit of the project, and a roadmap to realize the project. As for the accelerator simulation studies for the design we are involved in the following two projects; (a) An accelerator energy upgrade scheme would use C-band technology up to about 500 GeV, with X-band accelerating structures filling the remaining space in the tunnel for the future upgrade. The C-band technology for the main linac is the realistic backup option of the X-band, since the fabrication and operation tolerance of C-band is looser than those for the X-band but the acceleration gradient for X-band is higher. The simulation study demonstrated that main linac using both C-band and X-band technologies in series should work without major problems. (b)The estimation of the beam scattering by residual gas or by thermal photons in the Linear Collider main linac was performed. The estimation of emittance increase due to the beam scattering will be studied using these results.

2) OPAL experiment:The elementary particle physics experiment of a large international collaboration using the highest energy e^+e^- collider LEP is running at CERN. The data taking with the OPAL detector was completed in the end of 2000. Important physics subjects at LEP are (a) Higgs boson searches, (a) Supersymmetric particle searches and (c) W-boson physics. We have extensively searched for the Higgs boson at LEP. The lower limit of the Higgs Boson of the Standard Model was set to be 114 GeV (95% C.L.). From the precise measurement of the electro-weak interaction at LEP and other accelerators, the upper mass limit of the Higgs boson was obtained to be about 200 GeV. Therefore the Higgs boson should exist within the narrow mass range of 114-200 GeV. For the Minimal Supersymmetric Standard Model (MSSM) the lightest Higgs boson was excluded in the large MSSM parameter space, so that it is restricted into rather narrow parameter space. For supersymmetric 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. This limit is quite independent of the models. The W boson mass was determined to be80.490 ± 0.065 GeV by the OPAL experiment alone. The combined W boson mass for the four LEP experiments is 80.412 ± 0.042 GeV (statistical and systematic errors combined). Anomalous interactions of the W boson was searched for, and strict limits were set for these interactions.

3) 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.

4) Detector R&D: We are starting research and development for possible detectors in the future experiments. The group has considered the BES experiment at the Beijing e^+e^- collider BEPC as the candidate for the middle term project before GLC. We have measured the $J/\psi \to \Lambda\bar{\Lambda}$ decay branching fraction and

the CP violation parameters for this process. Development of TOF system for particle identification is started.

7 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

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

Formerly, our cryogenic detectors, aka bolometers, of lithium fluoride and sodium fluoride gave stringent limits in the parameter plane of the neutralino-proton spin-dependent coupling($a_{\rm p}$) and neutralino-neutron spin-dependent coupling($a_{\rm n}$), which excluded a part of the parameter space not excluded by UK Dark Matter Collaboration. The choice of the detector material is based on the fact that the fluorine is one of the best nuclides for the detection of spin-dependently interacting neutralinos. The sensitivity region of fluorine for the dark matter search is more or less orthogonal to the region of the widely used sodium(of NaI) when they are represented in $a_{\rm p} - a_{\rm n}$ plane.

In the new phase of our dark matter search project we started the development of the direction sensitive detectors. Anthracene and stilbene scintillators have directional anisotropies in the scintillation efficiency for heavy charged particles. This feature of the scintillators could be used to detect the motion of the dark matter particles relative to the earth improving the sensitivity to the dark matter detection.

We have experimentally proved that the scintillation efficiency of carbon recoils in stilbene scintillator is anisotropic with respect to its crystallographic axis. Then, we carried out a pilot run for the dark matter search with 116g stilbene crystal in Kamioka Observatory. With the crystal fixed to the earth, we searched the modulation of the light output. Although no modulation signal was found, we obtained the spin-independent neutralino-proton cross section upper limit of 7.4 pb for the neutralinos with mass 50 GeV under the spherical isothermal halo model. The present results are the first limit in the world derived from the directional signature of WIMPs. The limit is rather looser than the present best limit in the world because of the small size of the detector crystal and the higher background rate yet to be eliminated. However, it demonstrated the effectiveness of the method of direction sensitive search for the dark matter with an implementation of the anisotropic organic scintillation crystal.

We are also running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the AXION HELIOSCOPE. The axion helioscope consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors.

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

8 Aihara Group

Research Subjects: Study of CP-Violation in the B Meson System, Search for Physics Beyond the Standard Model in the B Meson, JHFnu Long Baseline Neutrino Oscillation Experiment, and R&D for Linear Collider

Members: H. Aihara, M. Iwasaki

The main research activity of our group has been a study of CP-violation in the B meson system and precision measurements of CKM matrix elements using the KEK B-factory (KEKB). This past year we presented an improved measurement of the Standard Model CP violation parameter $\sin 2\phi_1$ based on 152 million B-anti$B$ pairs collected at the $\Upsilon(4S)$ resonance. One neutral B meson was fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ or $J/\psi K^{*0}$ decay and the flavor of the accompanying B meson was identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we determined $\sin 2\phi_1 = 0.733 \pm 0.057(\text{stat}) \pm 0.028(\text{syst})$[1].

We have present an improved measurement of CP-violation parameters in $B^0 \to \phi K^0_S, K^+K^-K^0_s$, and $\eta' K^0_S$. We find that the observed CP asymmetry ($S = -0.96 \pm 0.50^{+0.09}_{-0.11}$) in the $B^0 \to \phi K^0_S$ decay differs from the standard model (SM) expectation by 3.5 standard deviations, while the other cases are consistent with the SM[2].

We have also reported the first observation of CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ decays. We find that the CP-violating asymmetry amplitudes Apipi = +0.58+/-0.15(stat)+/-0.07(syst) and Spipi = -1.00+/-0.21(stat)+/-0.07(syst). We rule out the CP-conserving case, Apipi=Spipi=0, at a level of 5.2 standard deviations. We also find evidence for direct CP violation with a significance at or greater than 3.2 standard deviations for any Spipi value.

We are involved in the next generation long-baseline neutrino oscillation experiment, JHFnu, which shoot off-axis neutrino beam from Tokai 50 GeV proton synchrotron to Super Kamiokande detector. We have been developing profile monitors for the primary proton beam.

Our R&D work also includes the design of Linear Collider beam delivery system, the interaction region and the central tracker based on the silicon strip detectors.

1. K. Abe *et al.* [Belle Collaboration], "Measurement of CP-violation parameter $\sin 2\phi_1$ with 152 million $B\overline{B}$ pairs," [arXiv:hep-ex/0308036].

2. K. Abe *et al.* [Belle Collaboration], "Measurement of time-dependent CP-violating asymmetries in $B^0 \to \phi K^0_S, K^+K^-K^0_S$, and $\eta' K^0_S$ decays," Phys. Rev. Lett. **91**, 261602 (2003). [arXiv:hep-ex/0308035].

3. K. Abe *et al.* [Belle Collaboration], "Observation of Large CP violation and evidence for direct CP violation in $B^0 \to \pi^+\pi^-$ decays," [arXiv:hep-ex/0401029].

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 Tsukada Group

Research Subjects: Theory of Solid Surface and Interface

Theory of Artificial Nano-Structures

Development of Computational Material Science

Member: Masaru Tsukada, Katsunori Tagami

New methods for theoretical calculations of quantum transport properties of nanodevices have been developed, which include the first-principles recursion transfer matrix method (FP-RTM), numerical Lipman-Schwinger method, real space finite element method, and density functional tight-binding method combined with the non-equilibrium Green's function (DFTB-NEGF). Using these methods, the transmission spectra through several metallic atomic wires and organic molecules (low-gap oligoporphyrin, wide-gap benzothiophene-based oligomer, phenalenyl radical, and high-spin phenoxyradical molecules) have been clarified. Based on these calculations, we have proposed novel functions accessible in the single molecular devices, e.g., unimolecular MRAM, molecular solenoid, chemical sensor, spin filter, and so on. In addition, we have found the significance of the contact structure at the molecule/electrode interface in the quantum transport properties.

We have analyzed the attractive features recently observed on the graphite surface in Fukuyama Lab. We revealed the reason why the number of Landau peaks on the graphite surface decreases compared to that formed inside the crystal. In addition, we found that the existence of defects at the graphite edge forms the electronic superlattice structures, which explains well the $\sqrt{3} \times \sqrt{3}$ patterns observed by the scanning tunneling microscopy.

Publications

K.Tagami and M.Tsukada: Interface Sensitivity in Quantum Transport through Single Molecules, Nano Letters, 4 (2004) 209-212.

K.Tagami,M.Tsukada,Y.Wada, T.Iwasaki and H.Nishide: Electronic transport of benzothiophene-based chiral molecular solenoids studied by theoretical simulations, J. Chem. Phys.,119 (2003) 7491-7497.

K. Tagami, M. Tsukada, T. Matsumoto, T. Kawai: Electronic transport properties of free base tape porphyrin molecular wires studied by selfconsistent tight binding calculations, Phys. Rev. B67 (2003) 2453241-2453247.

K.Tagami and M. Tsukada: Chemical contact promising for coherent transport through tape porphyrin molecular bridges, e-J. Surf. Sci. Nanotech. 1 (2003) 45-49.

K.Tagami and M.Tsukada: Current controlled magnetism in T-shape tape porphyrin molecular bridges, Curr. Appl. Phys., 3 (2003) 439-444.

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K.Tagami and M.Tsukada: Spintronic Transport through Polyphenoxyl Radical Molecules, J. Phys. Chem. B. 108 (2004) 6441-6444.

T.Matsui, H.Kambara, Y.Niimi, K.Tagami, M.Tsukada, and H.Hukuyama: STS Observation of Landau Levels at Graphite Surfaces, Phys. Rev. Lett. , submitted.

Y.Niimi, T.Matsui, H.Kambara, K.Tagami, M.Tsukada and H.Fukuyama: Scanning tunneling microscopy and spectroscopy studies of graphite edges, Appl. Surf. Sci., in press.

11 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Ryotaro Arita

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

- Superconductivity in repulsively interacting electron systems incl. models for high-T_C cuprates
  - — How to optimize T_C through the "fermiology" [1-3]
  - — Spin-triplet superconductivity [4]
  - — Magnetic-field induced triplet pairing [5]
- Magnetism in repulsively interacting electron systems
  - — Flat-band ferromagnetism in an organic polymer [6,8]
- Electronic structure of alkali-metal-loaded zeolites — "supercrystal" picture and magnetism[7,8]
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  - — Landau-Zener tunnelling in the breakdown of Mott's insulator [9]
- Quantum Hall systems
  - — Interaction and effective mass in the fractional quantum Hall liquid [10],
  - — Integer quantum Hall effect and butterfly spectra in three dimensions [11]
  - — Electron-molecule picture for quantum dots in magnetic fields,
- Electronic structure of hetero-interfaces
  - — Metal-induced gap states on metal/insulator interfaces [12]
  - — Metal-insulator transition in polar surfaces [13]
- Electrons on periodic curved surfaces [14]

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12 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Youichi Yanase

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

- High-T_c superconductivity
  Extended Gutzwiller approximation for the two-dimensional t-J model.[1]
  Pseudo-gap phenomena in high-T_c superconductors.[2]
  Low temperature specific heat and entropy in the t-J model and its spin-charge separation.
  Kinetic energy gain in the two-dimensional Hubbard model.[3]
  Electronic states around the vortex core.[4]
- Triplet superconductivity in Sr_2RuO_4
  Microscopic theory within a three-band model.[5]
  Electronic states in the vortex state under a magnetic field parallel to the plane.[6]
- Anisotropic superconductivity in Na_xCoO_2
  $d_{x^2-y^2}+d_{xy}$-wave superconducting state in frustrated t-J model.[7]
  f-wave superconducting state due to charge fluctuation.[8]
  f-wave superconducting state in a multi-orbital model.
- Organic conductors
  Coexistence between charge order and spin Peierls state.[9]
  Superconductivity due to charge fluctuation in θ-type organic conductors.[10]
- Electronic states in frustrated systems
  Strongly correlated electron system on a triangular lattice.[11]
  Ising spin chain hidden in a spin-ice system.[12]
- One-dimensional systems
  Nature of carries in one-dimensional Hubbard model.
  Hidden order parameter in a ladder spin system.

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13 Tsuneyuki Group

Research Subjects: Theoretical condensed-patter physics

Member: Shinji Tsuneyuki and Kazuto Akagi

Computer simulations, such as the first-principles molecular dynamics method, enable us to investigate properties and behavior of materials beyond the limitation of experiments, or rather to predict them before experiments. Our main subject is to develop and apply such techniques of computational physics to investigate basic problems in condensed matter physics, especially focusing on prediction of material properties under ultra-high pressure or at surfaces.

Self-organization of N/Cu(001) surface

One of the promising ways for realizing ordered structure for nano devices is to use nano-scale self-organization at surfaces. Nitrogen-chemisorbed Cu(001) surface is an example of such self-organization, where nitrogen-covered region form square islands of typically ~5nm×5nm size and the islands are regularly arranged with leaving a thin network of clean surface region. We are investigating the mechanism of the self-organization by first-principles theoretical calculations.

This interesting self-organization is probably driven by competition of two interactions. One is the short-range attractive interaction among nitrogen atoms at the surface with electronic origin, and the other is the long-range elastic interaction caused by the strain of nitrogen-chemisorbed region. The former is necessary for the nitrogen atoms to form islands, while the latter limits the size of each island and probably causes the regular arrangement of the islands. By calculating the total energy of various types of nitrogen-chemisorbed surface, we confirmed that chemisorbed nitrogen atoms exhibit attractive interaction in effect. We also performed large-scale first-principles calculation of model surfaces to find spontaneous formation of clean surface region on the full-coverage and ideal N/Cu(001) surface. It was also found that the chemisorption of nitrogen atoms change the surface stiffness.

New method of electronic-structure calculation: the transcorrelated method

We are developing a new method of calculating the total energy and electronic state of solids within the wave function theory. The method was originally proposed for molecules by S. F. Boys and N. C. Handy more than 30 years ago and named the transcorrelated method. In this method, total wave function is written by a product of a Slater determinant and a Jastrow factor, the latter of which is a function of electron-electron distance and so represents the electron correlation effect. In spite of the many-body character of the trial wave function, we can optimize the one-electron wave function in the Slater determinant by solving a self-consitent equation with at most three-body integral.

We have demonstrated that the electron correlation effect in small molecules or electron gas is efficiency treated by the transocorrelated method. Its application to realistic crystals is, however, difficult and has not been reported, since the three-body integrals indispensable for the self-consistent calculation is difficult to calculate. In this FY, we formulated the transcorrelated method with the Bloch orbitals for crystals and showed that all the integrals are efficiently evaluated by the Fast Fourier Transformation. We started coding a program for crystal calculation and demonstrated that our prototype code with plane waves reproduces the total energy of an isolated atoms and molecule calculated by a gaussian basis set.

We are also investigating the following issues.

- Chemisorption of unsaturated cyclic-hydrocarbon molecules on Si(001) Surface
- Atomic diffusion in SiO_2
- Carrier doping effects in $SrTiO_3$

Y. Yoshimoto and S. Tsuneyuki, First principles study of inter-nitrogen interaction energy of Cu(100)-c(2x2)N surface, International Journal of Quantum Chemistry 91, 211-215 (2003).

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14 Tarucha Group

Research Subjects: Electronic properties of artificial atoms and molecules, Spin effects and correlations in semiconductor nanostructures, Physics and technologies for quantum computing with quantum dots

Member: Seigo Tarucha, Keiji Ono

1. **Electronic Properties of Artificial Atoms and Molecules**

   — **The Kondo physics**: We have observed the enhanced Kondo effect associated doublet-doublet degeneracy (SU(4)) as well as singlet-triplet degeneracy (S-T) in a quantum dot both induced by B field. Lifting of the degeneracy leads to quenching of the Kondo effect in a symmetric (asymmetric) manner with respect to the B field for the SU(4) (S-T) Kondo effect.

   — **Strong correlation effects**: Application of strong B fields makes dominant the effect of electron correlation especially in a few-electron (N) quantum dot, and the concept of the electron molecule predicts that the molecule is stabilized at certain magic-number angular momenta and total spins. For $N = 5$ have observed consecutive transitions between stable states via unstable states as a function of B field, i.e. between two $S = 5/2$ pentagonal electron molecules via $S = 3/2$ states.

   — **Molecular phase**: A technique of rotating a sample in a dilution refrigerator is developed to study the effects of titling B field on the electronic states. This technique is useful to increase in-plane B field with keeping constant vertical B field. For a double dot system increase in the in-plane B field leads to reduction in the tunnel coupling. We have applied this technique to a strongly coupled double dot system to confirm the formation of molecular phase, which refers to filling of tunnel-coupled bonding and antibonding states. With increasing in-plane field, we have observed lowering of molecular phase energy, reflecting the reduction of tunnel coupling.

2. **Nuclear Spin Effects in Quantum Dots**

   — **Dynamical coupling of an electron spin to nuclear spin ensembles**: We previously observed nuclear spin effects for lifting Pauli blockade in a double dot system. The lifting of the blockade is observed as a small leakage current induced by application of small magnetic field, and the leakage current shows a hysteresis loop with respect to the sweep directions of B field. We have studied in detail the temporal response of this leakage current, and found that the low current of the hysteresis loop indicates depolarization of nuclei, whereas the high current arises from polarized nuclei.

3. **Transport Properties of Quantum Wires**

   — **Negative Coulomb drag**: Negative Coulomb drag was previously observed for parallel couple wires (drive and drag wires), and we discussed that particle-like electron states in the drive wire are dressed by correlation holes. To explore this effect we have performed drag experiments for similar coupled wires but containing a quantum dot in the drive wire. We have observed negative drag when a Coulomb oscillation peak appears in the drive wire, indicating that correlation holes are dragged by single electron tunneling events. The drag is only promoted in the drag wire near the barrier regions of the dot, and low compressibility of the drag wire is necessary for the negative drag to occur.

4. **Spin Control for Implementing Quantum Computing**

   —**Single spin ESR**: An electron spin in a quantum dot can be coherently manipulated using a local ESR technique. This enables experiments on a decoherence time and Rabi oscillations. g-factor for a GaAs-based vertical quantum dot is a key parameter for ESR. We have initially observed clear Zeeman splitting in experiments of Coulomb diamonds for various in-plane DC magnetic fields, and derived the g-factor of -0.23. This value is significantly smaller than that for bulk GaAs probably due to the influence of AlGaAs barriers. With this knowledge a single spin ESR experiment is under operation.

M. Rontani et al: Molecular phases in coupled quantum dots, Phys. Rev. B **69**, 85327 (2004).

K. Ono et al: Nuclear-spin-induced oscillatory current in spin-blockaded quantum dots, to be published in Phys. Rev. Lett. (2004).

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15 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

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

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16 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 (with N. Fujiwara and N. Môri, ISSP, U. of Tokyo).

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).

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) Manipulation of THz Optical Spectrum in High-T_c Cuprates

The high-T_c cuprate superconductors can be regarded as a superlattice of Josephson coupled superconducting layers along the c-axis. As a consequence, a collective excitation mode, Josephson plasma mode, is observed in the THz region for polarization parallel to the c-axis. However, the Josephson plasma is a longitudinal mode which does not directly couple with the THz radiation. We have demonstrated that, upon application of a magnetic field parallel to the layers, a new transverse Josephson plasma mode appears in the c-axis optical conductivity spectrum of underdoped $YBa_2Cu_3O_{6.6}$. This mode originates from the periodic modulation of Josephson coupling strength between layers with and without Josephson vortices. The mode frequency is shown to be variable with changing the field intensity and oxygen content (doping concentration).

(3) Control of Competition between Static Stripe and Superconductivity Phase

The stripe order is the one that is obviously competing with the d-wave superconducting order in high-T_c cuprates. Although the stripe order has been identified only in La-based cuprates, it is the only known order which exists in the highly doped superconducting region ($x \sim 0.12$) in the cuprate phase diagram, so it is a candidate for the phase microscopically coexisting with the superconducting phase in other cuprate superconductors.

The pressure effect on T_c and the Hall coefficient has been investigated in the static stripe-ordered phase of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. We have demonstrated that hydrostatic pressure quite effectively controls the competition between the static stripe and high-T_c SC phases. In this compound the static stripe is most stable and in turn T_c is much reduced. We showed that hydrostatic pressure of only 0.1GPa is enough to suppress the stripe order and to enhance T_c dramatically. The uniaxial pressure experiment indicates that the pressure effect is caused primarily by the in-plane compression (in collaboration with S. Arumugam and N. Môri).

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

The STM/STS collaboration with J. C. Davis' group in UC Berkeley 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) Modulation of LDOS induced by vortex cores

The SC order parameter is suppressed inside a vortex core with a radius of ∼10Å where the electronic excitations show a pseudogap and antiferromagnetic correlation is enhanced. We find that the additional QP states are generated by quantized vortices which show up as a four unit cell 4×4 "checkerboard" pattern.

3) 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.

17 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Iwao MATSUDA

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

(1) Surface electronic transport: metal-insulator transitions and anisotropic surface-state conductivity, measured with micro-4-point probes at variable temperatures, and with a four-tip STM .

(2) Surface phases and phase transitions: Quasi-one dimensional metallic surfaces; Si(111)-4×1-In, Si(557)-Au. Two-dimensional metals; Si(111)-$\sqrt{3} \times \sqrt{3}$-Ag, Au, $\sqrt{21} \times \sqrt{21}$.

(3) Construction of new apparatuses: Green function STM (low-temperature four-tip STM).

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18 Fukuyama Group

Research Subjects: Low Temperature Physics:

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

Member: Hiroshi Fukuyama, Hiroshi Kambara

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

1. **Strong correlation effects in 2D ^{3}He:**

   Monolayer ^{3}He adsorbed on a graphite surface is an ideal model system for studying strongly correlated two dimensional (2D) Fermions, where one can tune interactions and hence correlations by changing particle density over a wide range without introducing disorder. Recently, we discovered a new quantum phase at densities slightly lower than that for the 4/7 registered phase in the second layer ^{3}He from high precision heat-capacity measurements. The new phase is conceived as a hole (zero-point vacancy) doped Mott localized phase and presumably a uniform phase. We observed a heat capacity anomaly near 30 mK in this phase indicating the spin polaron effect due to quantum mechanical hoppings of the holes. In this sense, 2D ^{3}He system has an intriguing resemblance to strongly correlated 2D electron systems such as high T_c cuprates. NMR measurements to study magnetic susceptibility and spin dynamics in the new phase are now in progress.

2. **STM/STS studies of electronic states in low dimensional conductors:**

   (a) **STS observations of Landau levels at graphite surfaces:**
   Scanning tunneling spectroscopy (STS) measurements were made on surfaces of two different kinds of graphite samples, Kish graphite and highly oriented pyrolytic graphite (HOPG), at very low temperatures (60 mK) and in high magnetic fields (6 T). We observed a series of peaks in the tunnel spectra, which are associated with Landau quantization of the quasi 2D electrons and holes in graphite in magnetic fields. Almost field independent Landau levels fixed near the Fermi energy, which are characteristic of the graphite crystalline structure, were directly observed for the first time. Calculations of the local density of states at the graphite surfaces allow us to identify Kish graphite as bulk graphite and HOPG as graphite with finite thickness effectively.

   (b) **STM/STS studies of graphite edges:**
   The electronic local density of states (LDOS) was studied near single step edges at the surface of exfoliated graphite. In the STM experiments, we observed the $(\sqrt{3} \times \sqrt{3})R30^\circ$ and honeycomb superstructures near both the zigzag and armchair edges. Theoretical calculations based on the non-orthogonal tight-binding model show that the coexistence of the two superstructures is due to admixing of the two types of edge. In the STS measurements, we found a clear LDOS peak at an energy just below the Fermi level only near the zigzag edge. This is the first experimental observation of the graphite "edge state" theoretically predicted for graphene ribbons.

   (c) **Magnetotransport measurements of graphite:**
   Quantum Hall effect like plateaus in the Hall resistance and metal-insulator transitions were observed for HOPG in magnetotransport measurements at low temperatures ($T > 0.5$ K) and in high magnetic fields ($B < 9$ T). The former will be closely related to the 2D nature of the electronic states in HOPG as was demonstrated by our Landau level observations with STS. We

are now preparing to extend these measurements to much lower temperatures ($T > 1$ mK) and higher fields ($B < 15$ T).

19 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Yukio Kawano

We study low temperature electronic properties of two-dimensional systems formed in the semiconductor interfaces.

The current topics are following:

1. Magnetism in strongly correlated two dimensional systems:
A zero-magnetic-field metal-insulator transition can be observed in strongly correlated two dimensional systems, such as Si electron systems and GaAs hole systems. We are investigating the relationship between the stability of the metallic state and the spin degree of freedom. We have found that the metallic state remains in a Si/SiGe sample even in the fully spin polarized regime, while it is suppressed in Si-MOSFETs and GaAs hole systems located in strong in-plane magnetic field. We also study magnetic states in the insulating phase where the formation of a Wigner solid and exchange interactions among neighboring electrons are expected. The perpendicular component of the magnetic field should drastically change the nature of the exchange interactions due to the Aharonov-Bohm effect.

2. Dynamics of nonequilibrium electrons in quantum Hall conductors:
Our studies aim at revealing local transport and optical properties of quantum Hall conductors by means of scanning probe techniques. The three following techniques have been applied: (i) Scanning near-field THz microscope: Imaging of cyclotron radiation emitted from quantum Hall devices has made it possible to specify locations where the QHE breaks down. (ii) Scanning electrometer: We have developed a novel technique for obtaining high-resolution images of electrostatic potential distribution. This exploits gate effect in a quantum Hall device by a charged nano-probe. In addition, we have constructed a new system for mapping spatial distribution of noise voltage. (iii) Hybrid system combining THz microscope and scanning electrometer: With this system, we have obtained clear images of intra- and inter-Landau-level scattering.

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

4. Multi-subband electronic state of InAs surfaces:
We have measured magnetoresistance of a SiO_2-sputtered InAs surface. The results show that damage-induced electrons are distributed from the surface to $\sim 0.3\mu$m in depth and disappear after annealing at 150 °C. On the other hand, the electron density in the inversion layer is found to increase after sputtering and annealing.

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

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

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

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

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

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;
Non-Gravitational Heating of Galaxy Clusters in a Hierarchical Universe (2003)
Discoveries of Gravitationally Lensed Quasars from the Sloan Digital Sky Survey (2003)
One, Two, Three – measuring evolved large scale structure of the Universe (2003)
Higher-order Statistics as a probe of Non-Gaussianity in Large Scale Structure (2003)
Primordial black holes as an imprint of the brane Universe (2003)
Probing the Extra Dimensions with Gravitational Wave Background of Cosmological Origin (2003)
Nuclear "pasta" in dense stars and its properties (2002)
Supernova Neutrinos: Their Relic Background and Resonant Spin-Flavor Conversion (2002)
Arrival Distribution of Ultra-High Energy Cosmic Rays and Implications for Their Source Candidates (2002)
Non-linear evolution of the cosmological large scale structure from the local collapse model (2002)
The Universe with Extra Dimensions — From Kaluza-Klein Perspective to Brane World (2001)
Gravitational Collapse of Rotating Massive Stars (2001)
Effects of Neutrino Oscillation on Supernova Neutrino (2001)
Resolving the Central Density Profile of Dark Matter Halos with Gravitational Lensing Statistics (2001)
The Stability of Higher Dimensional Spacetime (2001)
Double inflation in supergravity and its observational implications (2000)

Propagation of UHECRs in the inhomogeneous source model (2000)
Effects of neutrino oscillation on the supernova neutrino spectrum (2000)
A Biasing Model for Cosmological Two-Point Statistics and the Probability Distribution Function of Nonlinear Mass Fluctuations (2000)
Genus Statistics for Large-Scale Structure as a probe of Primordial Random-Gaussianity and Nonlinear Stochastic Biasing (2000)
Velocity Distribution Functions for Nonlinear Gravitationg Many-body Systems (2000)
The cosmological redshift-space distortion on two-point statistics of high-z objects (1999)
Gravitational lens theory from the wave-optics viewpoint and its application to gravitational wave astronomy (1999)
Gravitational particle productions in the early universe (1999)
Thermodynamics properties of nuclear "Pasta" in super dense matter (1999)

21 Murao Group

Research Subjects: Quantum Information Theory

Members: Mio Murao and Damian Markham

In our group, we are investigating new properties of multi-particle and multi-level entanglement and the use of these properties as resources for quantum information processing. M. Murao started working at University of Tokyo in October, 2001 and D. Markham started working at University of Tokyo in February, 2004.

Quantum information processing and entanglement: Quantum information processing seeks to perform tasks which are impossible or not efficient with the use of conventional "classical" information, by using "quantum" information described by quantum mechanical states. Quantum computation, quantum cryptography, and quantum communication have been proposed and this new field of quantum information processing has developed rapidly especially over the last 10 years. Entanglement is nonlocal correlation appearing in certain types of quantum states (non-separable states) consisting of several subsystems. A non-separable state cannot be represented by a product state of constituent subsystems. Entanglement is sometimes called "quantum correlation", since it is genuine correlation of quantum systems and does not exist in classical systems. It has been considered as the fundamental resource for quantum information processing to be more effective than classical information processing. As the result of intensive study of entanglement (especially in the last 5 years), entanglement of bipartite two-level systems (two qubit systems) is now understood quite well. However, there are still many open questions regarding the entanglement of multiparticle and multi-level systems.

The current projects:

- **The properties and applications of entanglement in discrete systems**

  Asymmetric quantum information sharing between two parties: The necessary and sufficient conditions for extracting quantum information of an unknown qubit which has been shared by two spatially separated qubits using only local operations and classical communications are obtained. The conditions indicate that there is a way to asymmetrically share quantum information between two parties where one party's qubit can only be used as a key (quantum key) to recover the original quantum information at the other party. A protocol which allows secure conditional transmission of quantum information using both classical and quantum keys is presented.

- **The properties and applications of entanglement in infinite dimensional systems**

  Entanglement Generation from Thermal Spin States via Unitary Beam Splitters: We investigate the entanglement generated by passing a thermal spin state through a beam splitter. In the infinite temperature case this can be seen as creating distillable entanglement from a maximally mixed state through unitary operations. It is the truncation of the state that allows for entanglement generation. The output entanglement is investigated for different temperatures and it is found that more randomness - in the form of higher temperature - is better for this set up.

  Extension of Schmidt rank in infinite dimensional systems Nielsen's theorem for entanglement convertibility under local operations and classical operations (LOCC) and Vidal's theorem for stochastic LOCC (SLOCC) are extended to infinite dimensional systems in fully mathematical ways by redefining LOCC and introducing a concept of ϵ-convertibility. A pair of monotones which indicate rapidity of convergence of Schmidt coefficients and is an extension of Schmidt rank to infinite dimensional pure bipartite states have been presented. The states with polynomially dumping Schmidt coefficients are shown to belong to a higher entanglement class in terms of SLOCC than the states with exponentially damping ones and their relationship to entanglement embezzling is investigated.

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

22 Kobayashi Group

Research Subjects: Ultrafast and Nonlinear optical processes, Quantum Optics

Member: Takayoshi Kobayashi, Masakatsu Hirasawa, Takao Fuji, Akikatsu Ueki

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

1. Development of ultrashort pulse lasers

1. Development of Synchronously-pumped double-pass visible NOPA.
2. Numerical simulation of short pulse propagation in NOPA.
3. Investigation of novel crystals for NOPA.
4. Self-stabilization of the absolute phase (carrier-envelope phase: CEP).

2. Real-time spectroscopy for the study of molecular vibration

1. Polydiacetylene (PDA-3BCMU).
2. Psudoisocyanine (PIC) J-aggregates.
3. Coherent control of molecular dynamics.
4. Naphthalocyanines (Si, Cu).
5. Ultrashort pulse chirp characterization utilizing molecular vibrations.
6. Green fluorescent protein (GFP).
7. The charge transfer (CT) excitation in tin phthalocyanine.
8. Organic-inorganic layered semiconductor.
9. Numerical simulation of the molecular vibrational phase.

3. Electric field modulation spectroscopy with multi-channel lock-in amplifier:

New method of electric field modulation spectroscopy was developed, where simultaneous measurements in spectrum saves time substantially and also makes it possible to investigate extensively.

4. Quantum optics and quantum information

1. Generation of broadband photon pairs and its application to absorption spectroscopy.
2. Photon number fluctuation and correlation in frequency domain in a optical fiber.
3. Quantum interference in the multi-mode optical parametric oscillator.
4. Four-photon correlation.
5. Quantum key distribution using the spontaneous parametric down conversion (SPDC).

23 Makishima Group

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

Member: Kazuo Makishima, Motohide Kokubun

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

Instrumental Developments: We have developed the Hard X-ray Telescope (HXT) onboard the *Yohkoh* mission (August 1991 – December 2002), and the Gas Imaging Spectrometer (GIS) for the *ASCA* mission (February 1993 – March 2001). We are also developing the Hard X-ray Detector (HXD-II) [1] onboard *ASTRO-E2*, to be launched soon in February 2005. The HXD-II has an unprecedented sensitivity to cosmic hard X-rays in the 10–600 keV range, and is expected to innovate our knowledge on high-energy astrophysics. We also develop future X-ray and gamma-ray technologies, including hard X-ray imagers with Fourier-synthesis optics, ceramic inorganic scintillators, and avalanche photo diodes.

Solar and stellar flares: We study solar flares using the X-ray and γ-ray data acquired with *Yohkoh*, and employing Monte-Carlo simulations. By analyzing the deep X-ray imaging data obtained with *Chandra*, we have discovered diffuse thermal/non-thermal X-ray emission associated with several massive star-forming regions. The phenomenon may result from shocks in the stellar winds from massive young stars.

Physics of Black Holes: We are reinforcing our novel view, first obtained with *ASCA*, that "ultra-luminous compact X-ray sources" (ULXs) seen in nearby galaxies are massive ($\sim 100\ M_\odot$) stellar black holes under very high mass accretion rates. We are constructing a unified description of high-accretion-rate black holes [2], including ULXs as well as ordinary black-hole binaries ($\sim 10\ M_\odot$) and Narrow-Line type 1 Seyfert galaxies ($\sim 10^6\ M_\odot$). It invokes four different accretion-disk states; the optically-thin disk state, the standard-disk state, the Comptonized-disk state, and the slim-disk state.

Plasma Heating and Particle Acceleration in the Inter-Stellar Space: As established with a series of Japanese and foreign cosmic X-ray satellites, the inter-stellar space of our Galaxy is filled with enigmatic diffuse hard X-ray emission, which is a composite of thermal and non-thermal signals. We have detected similar emission from the Galactic bulge, from the central region of M31, and even from a few globular clusters. These diffuse high-energy photons may represent some unknown form of inter-stellar high-energy process, leading to the plasma heating and particle acceleration.

Physics of Cluster of Galaxies: The X-ray emitting hot plasmas associated with clusters of galaxies constitute the most dominant known baryonic component in the universe. We have established with *ASCA* and *XMM-Newton* that these plasmas exist in the form of two-phase (hot and cool) media, and their radiative cooling is somehow suppressed. We attempt to explain these puzzles by invoking a magnetic field configuration like that of the solar corona. Then, kinetic energies of the member galaxies may be dissipated on the plasma by exciting magnetohydrodynamical turbulence. This process is expected to enhance galaxy mergers within each cluster, which in turn may explain the presence of isolated elliptical galaxies each surrounded by a huge gravitational potential halo [3].

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24 Takase Group

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

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

Thermonuclear fusion, the process that powers the sun and stars, is a promising candidate for generating abundant, safe, and clean power. In order to produce sufficient fusion reactions, isotopes of hydrogen, in the form of hot and dense plasma must be confined for a long enough time. A magnetic configuration called the tokamak has reached the level where an international burning plasma experiment is ready to be constructed. However, improvement of the cost-effectiveness of the fusion reactor is still necessary. The spherical tokamak (ST) offers a promising approach to increasing the efficiency by raising the plasma beta (defined as the ratio of the plasma pressure to the confining magnetic pressure), several times greater than the conventional tokamak. High beta plasma research using the ST approach is a rapidly developing field worldwide, and is being carried out in our group using the TST-2 spherical tokamak.

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

It is crucially important for ST to develop a scenario of plasma formation, heating and maintenance without the use of the central solenoid (CS) located on the inboard side of the torus. Several approaches are being investigated on TST-2. TST-2 was temporarily relocated to Kyushu University in order to take advantage of the powerful microwave power (200 kW at 8.2 GHz). An ST plasma with a plasma current of 4 kA was successfully produced and maintained for 0.3 sec using the 8.2 GHz microwave power. This plasma had a line integrated density of $n_e l = 0.3 \times 10^{18}\,\mathrm{m}^{-2}$.

Coils located on the outboard side, normally used to keep equilibrium, were used in combination with the 8.2 GHz microwave power to create a plasma with up to 9.5 kA of plasma current. This was the first demonstration of a completely CS-less plasma formation. It is noteworthy that plasma current was generated even without a field null (where the poloidal magnetic field is zero), contrary to conventional belief.

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

Collaborations

A systematic study of conditions necessary for CS-less start-up (gas input, RF power, location of EC resonance, etc.) was carried out on the JT-60U tokamak at Japan Atomic Energy Research Institute (JAERI). An indications of bootstrap current overdrive was observed, but further confirmation is needed. Demonstration of bootstrap overdrive will relax requirements for current drive systems substantially.

Both coherent and turbulent fluctuations were studied on the JFT-2M tokamak at JAERI using three diagnostics: fast reciprocating Langmuir probes, two channels of reflectometers, and fast magnetic probes. A large scale coherent potential fluctuation around 10 kHz, similar to what is expected for the Geodesic Acoustic Mode (GAM) was observed in an Ohmically heated plasma. Two characteristic fluctuations were observed in a neutral beam heated H-mode plasma. The high frequency mode around 300 kHz is the high frequency mode, possibly the ballooning mode, often observed in high recycling steady H-mode. The intermediate frequency mode around 80 kHz may be the GAM, but is not positively identified.

Particle transport was studied by injecting impurity pellets and measuring the transient response of visible light emission with high temporal and spatial resolutions on the Large Helical Device at National Institute for Fusion Science. Transport can be described by a diffusion-convection model with a spatially constant diffusion coefficient and a convective velocity which is directed inward where the electron density gradient is finite. The convection velocity was found to be strongly dependent on both electron density and impurity ion charge, whereas the diffusion coefficient was weakly dependent on them.

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

25 Tsubono Group

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

Member: Kimio TSUBONO and Masaki ANDO

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

TAMA300 is a 300-m baseline laser interferometric gravitational wave detector constructed in Mitaka. We started the operation of the detector in 1999. The achieved sensitivity, $h \sim 3 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ at 700Hz to 1.5kHz, is sufficient to catch possible gravitational wave events in our galaxy. We can operate the detector for over 24 hours stably and continuously. Last year, we performed 2-month data taking run and collected over 1,000 hours data. We are now analyzing the obtained data searching for the gravitational waves from coalescing binaries, supernovae and pulsars.

We summarize the subjects being studied in our group.

- Laser interferometric gravitational wave detectors
  - TAMA project
  - Search for burst gravitational waves
  - Search for gravitational waves from SN1987A
  - Suspension point interferometer for vibration isolation
  - Study of the next-generation laser interferometer
  - Space laser interferometer DECIGO
- Study of thermal noise
  - Direct measurement of the thermal noise
  - Thermal noise caused by the inhomogeniously distributed loss
- Study of the precise measurement
  - Development of the low-frequency vibration isolation system (SAS)
  - New vibration isolation system using magnetic levitation

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26 Sano Group

Research Subjects: Nonlinear Dynamics and Fluid Mechanics

Member: Masaki Sano and Yoshihiro Murayama

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

1. Study of turbulence

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

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

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

2. Nonlinear Dynamics and Chaos

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

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

3. Dynamical aspects of biological systems

(1) Single molecule level measurement of DNA collapsing, DNA-protein interaction, and gene expression
(2) Collective behavior of the activities in biological neural assemblies

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27 Yamamoto Group

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

Member: Satoshi Yamamoto & Tomoharu Oka

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

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

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

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

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

We are also studying rotational spectra of transient molecules in the laboratory with the Fourier transform millimeter-wave (FTMW) spectroscopy. Our spectrometer covers the frequency range up to 85 GHz with sufficient sensitivity for transient molecules. With this spectrometer, the rotational spectra of the ethyl radical, the vinyl radical, the cyclopropyl radical have been detected.

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28 Sakai (Hirofumi) Group

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

Member: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between the strong nonresonant laser field and the induced dipole moment of the molecules. (2) Controlling quantum processes in atoms and molecules using shaped ultrafast laser pulses. (3) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation) and ultrafast phenomena in atoms and molecules. (4) Attosecond pulses generated with high-order harmonics and their reliable measurement. (5) Structures and dynamics of molecules studied by the laser induced Coulomb explosion. Some of our research activities in the academic year of 2003 are as follows:

(1) Controlling the orientation of molecules with combined electrostatic and intense, nonresonant 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 the last fiscal year, we demonstrated that polyatomic molecules such as 3,4-dibromothiophene can be three-dimensionally oriented with combined electrostatic and intense elliptically-polarized laser fields. By three-dimensional orientation, we mean controlling all of the three Euler angles which determine the spatial direction of a molecule. Although we succeeded in a proof-of-principle experiment, it is indispensable to further increase the degree of orientation in order to use a sample of oriented molecules in applications. Therefore, we started the development of a new apparatus to increase the degree of orientation. The key is to increase the magnitude of an electrostatic field. Based on the detailed simulations of ion trajectories, we carefully designed the new apparatus so that the fragment ions arrive at the detector in a correct manner.

(2) Generation and control of time-dependent polarization pulses

In the last fiscal year, we developed a closed-loop pulse shaping system by the combination of a femtosecond pulse shaper and genetic algorithm. By removing polarizers from the pulse shaper, the system can generate and control time-dependent polarization pulses. We also developed a polarization characterization system called POLLIWOG (POLarization Labeled by Interference versus Wavelength of Only a Glint). These homemade systems enable us to perform experiments in optimal control of quantum processes in molecules and get invaluable information to understand underlying physics in the interaction between time-dependent polarization pulses and molecules. We are now developing a technique to shape desired time-dependent polarization pulses based on the combination of the direct comparison between the target pulse and the result of a polarization characterization measurement and an adaptive learning loop with genetic algorithm. This technique is indispensable to verify the validity of theoretically predicted time-dependent polarization pulses required in many applications including selective preparation of one of the enantiomers, attosecond generation, control of tunnel ionization and so on.

(3) Efficient generation of high-order sum and difference frequencies in the XUV region by combining a weak longer-wavelength laser field

We have succeeded in the efficient generation of high-order sum and difference frequencies in the XUV region. The intensity of the combined filed is lower than that of the fundamental field for high-order harmonic generation by more than two orders of magnitude. In fact, high-order harmonics cannot be generated by only the combined field. The key feature of the present experiments is that the wavelength of the combined field ($\lambda = 1064$ nm) is longer than that of the fundamental field ($\lambda \sim 800$ nm). Our results demonstrate a great advantage of the longer-wavelength combined field. Our approach can be a useful approach to generate XUV radiation whose wavelengths cannot be covered by only the fundamental field. Furthermore, the present experimental results are supported by the theoretical calculations based on our extended version of the Lewenstein model, by which the effect of the combined field can be studied in an appropriate manner. Our calculations also show that there are some wavelength regions of the combined field favorable to the efficient generation of high-order sum and difference frequencies.

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29 Kuwajima Group

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

Member: Kunihiro Kuwajima, Kosuke Maki, & Kimiko Saeki

Recently, we studied the relationships between the folding rate constants of globular proteins and their native three-domensional structures. What determines the folding rate of globular proteins, and how does it relate to protein hydration? Most proteins that have more than 100 amino acid residues are non-two-state proteins, which accumulate a molten globule-like intermediate at an early stage of kinetic refolding. Is such an intermediate a productive folding intermediate or kinetically trapped misfolded species? These issues are essential for fully elucidating the molecular mechanisms of protein folding.

To address the above issues, we have collected the kinetic folding data for non-two-state and two-state globular proteins reported in the literature, and investigated the relationships between the folding kinetics and the native three-dimensional structure of these proteins. We have found that the folding rates from the unfolded state to the intermediate and from the intermediate to the native state both show significant correlations with the native backbone topology of a protein. The correlation coefficients were comparable to that previously found for the two-state folders. From these results, (1) protein folding is in general occurs in a hierarchical manner, by which the backbone topology forms first, then the formation of the specific packing structure follows, and (2) the molten globule-like folding intermediates observed in many non-two-state folding proteins are real productive folding intermediates.

Based on a comparison of the folding rates of the non-two-state and two-state folders, it was also found that they are similarly dependent on the parameters reflective of the native backbone topology. This suggests that the mechanisms behind non-two-state and two-state folding are essentially identical. The present results lead us to propose a unified mechanism of protein folding. The hierarchical folding is a general mechanism of protein folding, and reflects the hierarchy of the native three-dimensional structure, as embodied in the case of non-two-state folding with an accumulation of the intermediate. Apparently, two-state folding is merely a simplified version of hierarchical folding caused either by an alteration in the rate-limiting step of folding or by destabilization of the intermediate.

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30 Nose Group

Research Subjects: Molecular Mechanism of Neural Network Formation

Member: Akinao Nose, Takako Morimoto-Tanifuji and Etsuko Takasu

What is the physical basis of formation of the brain? The aim of our laboratory is to elucidate the molecular mechanism of neural development by using techniques of biophysics and molecular genetics. We are trying to identify molecules that function during neural wiring by using, as a model, the simple nervous system of a fruitfly, Drosophila. We are currently conducting the following research projects.

1. Molecular Mechanisms of Axon Guidance

1.1. Neuromuscular target recognition molecules, Connectin and Capricious

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

1.2. Gain of function mutant screening

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

2. Molecular Mechanisms of Synaptogenesis

2.1. Role of postsynaptic CaMKII on synaptogenesis

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