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Department of Physics
School of Science
University of Tokyo

Annual Report

2002

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

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

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

Nuclear Structure Physics

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

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

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

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

Hadron Physics

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

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

Highlights in research activities of this year are listed below.

1. Physics of high density matter
   - 1.1 Chiral symmetry in dense matter [1, 2]
   - 1.2 Critical end point in hot and dense matter [3]
2. Quark-gluon plasma and its signature [4, 5, 6, 7]
3. Fundamental aspects of confimenment and chiral symmetry in QCD [8, 9]
4. QCD structure of hadrons
   - 3.1 Lattice QCD simulations for excited baryons, and chiral symmetry in baryon spectrum [10]
   - 3.2 High energy QCD processes and structure functions [11]

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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 and Superstrings [1]
   - 1.2 Strings and D-branes on Curved Backgrounds [2, 16, 17, 40, 48, 49]
   - 1.3 String Field Theory [23, 24, 31, 32, 33, 34, 36, 37]
   - 1.4 String Theories on PP-waves and Holographic Dualities [18, 19, 20, 21, 22, 38, 39, 41, 42, 43]
   - 1.5 Noncommutative Geometry and Mathematical Physics [14, 35]
2. High Energy Phenomenology
   - 2.1 Particle Cosmology and Supersymmetric Unification Models [3, 4, 5, 6, 7, 44, 50, 51]
   - 2.2 Models in Higher-dimensional Space-time and Brane World [13, 15, 25, 26, 27, 28, 29, 30, 45, 46, 47]
3. Quantum Field Theory
   - 3.1 Lattice Gauge Theory [8, 9, 10, 11, 12]
   - 3.2 Fundamental Problems in Field Theory

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3 Sakai Group

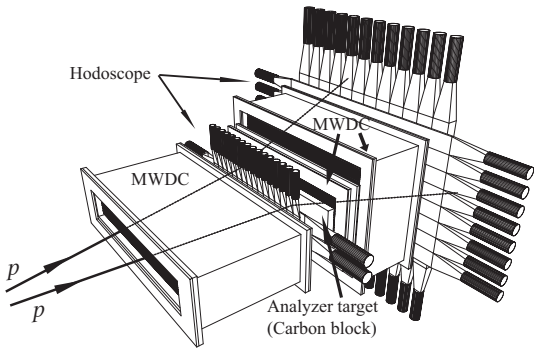
Research Subjects: Experimental Nuclear Physics

Member: Hideyuki Sakai, Atsushi Tamii

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

Major activities during the year are summarized below.

1. Measurement of the ^{90}Zr(n,p) reaction at E_n=300 MeV has been carried out by employing the newly constructed (n,p) facility. The reduced matrix element of the Gamow-Teller transition, $B(\mathrm{GT}^+)$, has been extracted. By combining the β^+ Gamow-Teller strength ($\Sigma B(\mathrm{GT}^+)$) with the β^- one, which was formerly obtained by the ^{90}Zr(p,n) measurement, the GT quenching factor has been found to be Q=0.89±0.06. From this Q value the Landau-Migdal parameter can be derived as $g'_{\mathrm{N}\Delta} = 0.24 \pm 0.10$. The $g'_{\mathrm{N}\Delta}$ value allows us, for the first time, to estimate quantitatively the critical density of pion condensation which may be realized in neutron stars.
2. How the effect of three nucleon force (3NF) appears in nuclear reactions is one of interesting subjects in nuclear physics. Up to now, the 3NF effects in the intermediate energy region have been discussed by comparing the experimental data of p-d scattering and Faddeev calculations of n-d scattering since it is very 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 an intermediate energy of E_n = 250 MeV. This year we have succeeded in measuring the n-d elastic scattering at forward angles by employing a deuterated liquid scintillator as an active target. Preliminary result shows that some characteristic difference between the n-d and p-d data. The effects of the Coulomb force will be quantitatively extracted as well as the 3NF and other contributions such as relativistic effects.
3. 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 narrow resonances in the p-d scattering data at the Institute for Nuclear Research. Since the observed widths were as small as 3 MeV and were equivalent to the experimental mass resolution, 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. The existence of the resonances is not confirmed up to now. Detailed analysis is in progress.
4. We have been constructing two new experimental apparatuses. One is a focal plane polarimeter, EPOL, for measuring polarization of two protons simultaneously (see the Figure). The EPOL will be used for studying a long-standing question on the quantum mechanics, called EPR paradox, by measuring spin correlations in a hadronic system. The other is a polarized solid proton target system for studying structures of unstable nuclei. The first nucleus to be measured is ^{6}He, which is considered to have neutron skin structure. Both experiments are scheduled in this year.



Schematic view of the spin-correlation polarimeter EPOL.

4 Hayano Group

Research Subjects:

(1) ATHENA project (Production and spectroscopy of cold antihydrogen) at CERN.

(2) ASACUSA project (Atomic Spectroscopy and Collisions Using Slow Antiprotons) at CERN.

(3) Study of deeply bound pionic atoms in ^{207}Pb, ^{205}Pb and ^{115,119,123}Sn nuclei at GSI.

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

Production of cold antihydrogen

We have succeeded to produce a large number of antihydrogen atoms, by mixing antiprotons and positrons under cryogenic conditions in a so-called nested Penning trap. Clear signatures of antihydrogen annihilations were obtained by detecting antiproton annihilations (using Si detectors) and positron annihilations (using CsI detectors), occurring at the same place at the same time. This work was done in the ATHENA international collaboration at CERN AD.

Antiprotonic helium

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

In 2002 we extended the precision laser spectroscopy of antiprotonic helium by studying various states in $\overline{p}^4He^+$ and $\overline{p}^3He^+$ at ultra-low densities by using a Radio Frequency Qadrupole Decelerator (RFQD) to further reduce the energy of antiprotons. At these low densities the collision-induced shift of the transition energies becomes negligible compared to other systematic errors. We have thus improved the constraint on the equality of proton and antiproton charge and mass by a factor 5 over our previous value to ~ 10 ppb (1×10^{-8}).

Deeply-bound pionic atoms reveal the origin of proton mass

A proton, which consists of massless gluons and nearly massless $u-, d-$ quarks, dynamically acquires its large mass. Here, the quark condensate $| < \bar{q}q > |$ is considered to play a role similar to the Higgs particle, and hence experimental detection of the effect of the condensate is of particular importance.

We have recently succeeded to precisely measure the binding energies of deeply-bound pionic-Sn states ($1s$ states of pionic ^{115,119,123}Sn atoms), and determined the in-medium isovector scattering length b_1, which turned out to be significantly different from the vacuum value. We then used theoretical relations to deduce the ratio of in-medium vacuum condensate to the vacuum value to be, $| < \bar{q}q > |_\rho / | < \bar{q}q > |_0 = 0.66 \pm 0.06$, which agree fairly well with theoretical expectations. This is one of the first clear indications of the importance of quark condensate in hadron physics.

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.

- Particle stability and β-decay properties of very neutron-rich nuclei near the drip line
  1. Production and identification of new neutron-rich isotopes, ^{34}Ne, ^{36}Na, and ^{43}Si, and particle instability of ^{33}Ne, ^{36}Na, and ^{39}Mg.
  2. β-decay lifetime and β-delayed neutron multiplicities of the neutron drip-line nuclei ^{19}B, ^{22}C, and ^{23}N.
- In-beam gamma spectroscopy for the exotic structure of very neutron-rich nuclei.
  1. Doppler-shift attenuation method and in-beam γ attenuation method for life time measurements of excited states in light neutron-rich nuclei ^{12}Be and ^{16}C.
  2. Proton inelastic scattering to investigate neutron-matter deformation of ^{16}C and ^{34}Mg and to determine low-lying level schemes in very neutron-rich nuclei ^{27}F and ^{30}Ne.
  3. Coulomb excitation of ^{46}Cr, ^{50}Fe, and ^{54}Ni and investigation of M_n/M_p ratios in T=1 nuclei.
  4. One-nucleon transfer reactions ^{12}Be(α,t)^{13}B and ^{22}O(α,t)^{23}F to investigate single-particle states in neutron-rich nuclei
  5. Development of Germanium telescope for in-beam gamma ray spectroscopy in inverse reactions.
- Coulomb and nuclear breakup reactions of ^{11}Li, ^{14}Be, and ^{17}B for soft collective modes in neutron-rich nuclei.
- β spectroscopy of ^{46}Cr.
- Key reactions of nuclear synthesis in astrophysical phenomena.
  1. 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.
  2. Coulomb dissociation of ^{15}C to study a key reaction of the CNO neutron cycle in low-mass AGB stars, ^{14}C(n,γ)^{15}C.
  3. Application of transfer reactions to radiative capture reactions in stellar evolutions ^{7}Be(p,γ)^{8}B, ^{7}Be(p,γ)^{9}C, and ^{12}C(n,γ)^{13}C by means of the ANC method.

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/RMdraft/). 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 400 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, (b) Supersymmetric particle searches and (c) W-boson physics. We have extensively searched for the Higgs boson at LEP. The lower limit of the Higgs Boson of the Standard Model was set to be 114 GeV (95% C.L.). ¿From the precise measurement of the electro-weak interaction at LEP and other accelerators, the upper mass limit of the Higgs boson was obtained to be about 200 GeV. Therefore the Higgs boson should exist within the narrow mass range of 114-200 GeV. For the Minimal Supersymmetric Standard Model (MSSM) the lightest Higgs boson was excluded in the large MSSM parameter space, so that it is restricted into rather narrow parameter space. For supersymmetric 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 36.3 GeV. This limit is quite independent of the models. The W boson mass was determined to be 80.490 ± 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 .

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

7 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

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

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

In 2002, we use NaF crystals as bolometers instead of LiF crystals. ^{23}Na (natural abundance 100 %) has a large expectation value of the neutron spins than ^{7}Li (natural abundance 92.5 %). If ^{23}Na is used in combination with ^{19}F, better sensitivities in the $a_{\rm p}$–$a_{\rm n}$ plane can be reached with a single detector. In addition, the background below 20 keV from ^{3}H produced by the neutron capture of ^{6}Li (natural abundance 7.5 %) during the development in the surface laboratory can be avoided.

On the basis of the measurement in Kamioka we obtained more stringent limits in the $a_{\rm p}$–$a_{\rm n}$ plane for certain mass of neutralinos than those of the first results with LiF bolometer at Kamioka Observatory, and this result as well as the first result with LiF bolometer excluded a part of the parameter space which is not excluded by UK Dark Matter Collaboration.

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

The scintillation efficiency of carbon recoils in stilbene scintillator was mesured down to 45 keV using neutrons from ^{7}Li(p,n)^{8}Be and ^{252}Cf . Anisotropy responce was confirmed in low energy regions. The variation of the quenching factor is about 10%, that could produce the possible “dark matter signal”.

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.

In 2002, the AXION HELIOSCOPE is directed toward the soft gamma ray repeater SGR 1900+14 to search for axions produced in it with its very strong magnetic field. Although no gamma ray burst was reported during the run on the SGR 1900+14, we put a limit of $d\Phi_a/dE_a < 4.8 \times 10^{13}\mathrm{keV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}$ (95% CL) on the axion flux coming from it for the first time.

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 85 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 $\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{syst})$. With this direct measurement and other indirect constraints based on the Standard Model, we conclude that Kobayashi-Maskawa model has been established[1,3].

We have also presented an improved measurement of CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ decays based on a 78 fb^{-1} data sample. We reconstruct one neutral B meson as a$B^0 \to \pi^+\pi^-$ CP eigenstate. We apply an unbinned maximum likelihood fit to the distribution of the time intervals between the two B meson decay points. The fit yields the CP-violating asymmetry amplitudes Apipi = +0.77+/-0.27(stat)+/-0.08(syst) and Spipi = -1.23+/-0.41(stat)+0.08/-0.07(syst). We obtain confidence intervals for CP-violating asymmetry parameters Apipi and Spipi based on a frequentist approach. We rule out the CP-conserving case, Apipi=Spipi=0, at the 99.93% confidence level[2,4].

We have also measured B^0_d and $B^\pm$ lifetimes and $B^0_d - \overline{B_d}^0$ mixing [3] and, for the first time, have measured the electroweak penguin Process $B \to X_s\ell^+\ell^-$. We have determined the branching fraction of the process to be $Br(B \to X_s\ell^+\ell^- = (6.1 \pm 1.4^{+1.4}_{-1.2}) \times 10^{-6}$[5].

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. 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.

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2. K. Abe *et al.* [Belle Collaboration], "Evidence for CP-violating asymmetries $B^0 \to \pi^+\pi^-$ decays and constraints on the CKM angle ϕ_2," arXiv:hep-ex/0301032.
3. Tomonobu Tomura "Study of Time Evolution of B Mesons at the KEK B Factory."(Ph.D. Thesis)
4. Takeshi Nakadaira "Study of CP Asymmetry in the Neutral B Meson Decays to Two Charged Pions." (Ph.D. Thesis)
5. J. Kaneko *et al.* [Belle Collaboration], "Measurement of the electroweak penguin process $B \to X_S\ell^+\ell^-$," Phys. Rev. Lett. **90**, 021801 (2003) [arXiv:hep-ex/0208029].

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 2002 are listed in the followings.

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

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

3. Spin Chain
   (1) Integrable Vertex Model
   (2) Magnetization, Correlation Function and Riemann–Hilbert problem

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
   (3) Quantum Cloning

8. Random Matrix
   (1) Mesoscopic Fluctuation

10 Tsukada Group

Research Subjects: Theory of Solid Surface and Interface

Theory of Artificial Nano-Structures

Development of Computational Material Science

Member: Masaru Tsukada, Ryo Tamura

New methods for theoretical calculations of electronic structure and atomic/electronic processes of surface and nano-structures under finite field and current have been developed. These methods include the first-principles molecular dynamics method, first-principles recursion transfer matrix method(FP-RTM), numerical Lipman-Schwinger method, real space finite element method, computational method for the time-dependent Kohn-Sham equation, as well as density functional tight-binding method combined with the non-equilibrium Green's function (DFTB-NEGF). The first-principles molecular dynamics method with ultrasoft pseudopotential developed in our group is called TAPP package and kept extending its users community and ever incresing its applicability. The method is applied to various problems in materials science, in particular surface and nanostructure science. So far studied problems include the substitutional penetration of Ge on Si(001), quantum dynamics of dimers of Si (001) surface and a new symmetry broken structure of Si(111) $\sqrt{3}\times\sqrt{3}$ -Ag, and the proton relay dissociation of water molecules on solid surfaces. We also developed first-principles theoretical simulation method for the noncontact atomic force microscopy (ncAFM) images. This method can reproduce excellently the experimentally observed ncAFM images of Si(111)$\sqrt{3}\times\sqrt{3}$-Ag surface including even its temperature dependence. The influence of the tip on the nc-AFM image is revealed by the theoretical calculation. Mechanism of damping and dissipation of the cantilever oscillation is theoretically analyzed, and the relation with irreversible atomic processes is clarified. On the othe hand, the FP-RTM method is the extension of the density functional theory for the non-equilibrium open systems. The mechanism of atom extraction by the tip and nano-scale point contact formation were clarified by this method. The concept of eigen-channels for the quantum transport through nano-structures have been also developed. This method as well as simpler DFTB-NEGF has been applied to various problems related nano-structure and surface science. The problems we studied include transport properties of carbon nanotubes and atom or molecular bridge structures connecting nano-electrodes. Quantum transport through atomic wires, C_{60}, and molecular bridges like tape-porphyrin have been theoretically analysed. Electron transmission through a C_{60} molecular bridge shows a large loop current, when the electron energy is near the degenerate molecular levels. The transport property of the semiconductor metal carbon nano-tube junction is investigated with the effects of the atomic structures. The junction is found to be a backward diode. Development of the new numerical algorithm for the integration of the time-dependent Kohn-Sham equation has been also achieved. We developed an efficient method for solving the time dependent Kohn-Sham equation in real space and real time. Applying this method to Benzine, CNT, or diamond crystal, we confirmed the efficiency and accuracy of the method.

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K. Tagami and M. Tsukada: Current-controlled magnetism in T-shape tape-porphyrin molecular bridges Curr. App. Phys., in press.

K. Tagami and M. Tsukada: Theoretical Predictions of Electronic Transport Properties of Differently Conjugated Porphyrin Molecular Wires, Jpn. J. Appl. Phys., in press.

11 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Ryotaro Arita

Our main interests are in 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" is possible:

- Superconductivity in repulsively interacting electron systems incl. models for high-T_C cuprates [1,2]
  - — How to optimize T_C through the "fermiology" [3-5]
  - — Spin-triplet superconductivity [6]
  - — Organic superconductors [7]
  - — Magneto-tunnelling tomography of the pairing symmetry [8]
- Magnetism in repulsively interacting electron systems
  - — Flat-band ferromagnetism in an organic polymer [9]
- Electronic structure of alkali-metal-loaded zeolites — Supercrystal [10]
- Electronic structure of hetero-interfaces
  - — Metal-induced gap states at metal/insulator interfaces [11]
- Nonequilibrium and nonlinear phenomena in strongly correlated electron systems
  - — Universal Landau-Zener tunnelling in the breakdown of Mott insulator [12]
- Quantum Hall systems
  - — Interaction and BCS states in the fractional quantum Hall liquid [13],
  - — Optical properties [14],
  - — Integer quantum Hall effect and Hofstadter butterfly in three dimensions [15-17]
  - — Field-induced SDW in three dimensions [18]
- Electrons on periodic curved surfaces [19]

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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
  Numerical studies of Stripe states in 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.
- Electronic states in $d_{x^2-y^2}$-wave superconductivity
  Quasiparticle states and magnetism around nonmagnetic and magnetic impurities.
  Electronic states around the vortex core.[9]
- Triplet superconductivity in Sr_2RuO_4[8]
- Electronic states in frustrated systems[14]
  Verwey transition in magnetite.[3]
  Strongly correlated electron system on a triangular lattice.[6,13]
  Exact calculation of the ground-state entropy in a kagomé ice.[7]
- One-dimensional systems
  Nature of carries in one-dimensional Hubbard model.[10]
  Coexistence between charge order and spin Peierls state.[11]
  Hidden order parameter in a ladder spin system.

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[12] M. Ogata and A. Himeda: J. Phys. Soc. Jpn. **72**, 374 (2003). "Superconductivity and antiferromagnetism in an extended Gutzwiller approximation for t-J model: effect of double-occupancy exclusion"

[13] T. Koretsune and M. Ogata: preprint. "Ferromagnetism on the frustrating lattices"

[14] M. Ogata: preprint. "Superconducting states in frustrating t-J model: A model connecting high-T_c cuprates, organic conductors and Na_xCoO_2"

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.

New method of electronic-structure calculation: the transcorrelated method
We are trying to develop a new method of treating many-fermion systems within the wave function theory. The method was originally proposed by S. F. Boys and N. C. Handy about 30 years ago and named the transcorrelated method. In this method, total wave function is written by a product of a Slater determinant and the 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 the efficiency of the method by calculating total energy of small atoms, a hydrogen molecule with various bond length and several sizes of one-dimensional ionic Hubbard models. We have also shown that the Koopmans' theorem holds for the transcorrelated method.

Application of the transcorrelated method to crystals in continuum space is quite difficult because of the three-body numerical integration appearing in the SCF equation. Thus we first applied the method for the jellium mode. We found that the total energy calculated by QMC is reproduced surprisingly well by the transcorrelated method for a wide range of electron density. Based on this calculation, we have proposed new non-local exchange-correlation energy functional for the density functional theory.

Carrier doping effects in $SrTiO_3$
We investigated carrier-doping effects on the structural phase transitions in $SrTiO_3$ first-principles calculations. We found that the instabilities of the cubic phase to both the TiO_6-octahedron rotated phase and the ferroelectric phase are modulated characteristically by the electron-doping and the hole-doping. The results of the calculations are consistent with a previous experiment in which carrier electrons were introduced by impurity-doping or photo-irradiation. We are now trying to explain the huge photo-enhancement of dielectric constant in quantum paraelectric materials like $SrTiO_3$.

Atomic structures and vibrational spectra of NO/Pt(111)
The chemisorption structure of NO molecules on Pt(111) surface has not been clarified, or rather it has been misunderstood for long, although it is an important system for a catalytic reaction. We have specified the coverage dependence of the structure by first-principles total energy calculations. Especially at high coverage, NO molecules was found to have two chemisorption sites, the hollow site and the a-top site. We have also shown that the high-coverage structure shows large intensity transfer between two peaks in infrared absorption/reflection spectra, which is in harmony with experimental results showing a single absorption/reflection peak.

A hydrogen bond under high pressure: δ-AlOOH and δ-$Al_{1-2x}Mg_xSi_xOOH$
AlOOH is an important substance in subducting sedimentary rocks, and could possibly serve as a water reservoir in the Earth's lower mantle. Its high-pressure phase shows specific features like anomalously large bulk modulus and strange anisotropy of the elastic constant. By first-principles molecular dynamics simualtions, we have found that symmetric hydrogen bonds will explain such features. We have also shown that the same effect of hydrogen bonds appears in contaminated phase, δ-$Al_{1-2x}Mg_xSi_xOOH$.

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14 Nagasawa Group

Research Subjects: Optical Spectroscopy on Semiconductors and Carbon Nanotubes

Member: Nobukata Nagasawa and Nobuko Naka

Current studies are devoted to following subjects.

- Search for excitonic Bose condensate in semiconductor Cu_2O

  Excitons in Cu_2O are one of the most favorable candidate to realize the Bose-Einstein condensation (BEC) of quasiparticles. We established a new approach to create a cold and dense exciton system by employing exciton traps and two-photon loading. New optical phenomena suggesting the bosonic stimulation into the lowest energy state of the stress-induced exciton trap were observed, where the phase space density of the exciton system was estimated to be over 1. Temporal properties of the phenomena are consistent with the characteristic feature of the excitonic Bose-Einstein Condensate.

  - Two-photon temporal and spatial diagnostics of stress-induced exciton traps [1, 3, 6]
  - Bosonic stimulation of excitons to the BEC state [7]

- Optical spectroscopy of carbon nanotubes formed in Zeolite single crystals

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

  - Nano-scale microscope spectroscopy on emission [2]
  - Electrical transport and photo-induced current-modulation measurements [4, 5]

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15 Tarucha Group

Research Subjects: Electronic properties of artificial atoms and molecules, Spin effects and correlations in semiconductor nanostructures

Member: Seigo Tarucha, Keiji Ono

1. **Electronic Properties of Artificial Atoms**

   — **Dynamics of a few-electron states**: We use an electrical pump and probe technique to investigate energy relaxation in a quantum dot. The relaxation for the one-electron state occurs from a 2p state (excited) to a 1s state (ground) with phonon emission, whereas for the two-electron state, it occurs from a spin triplet (excited) to a spin singlet (ground) with spin-flip as well as phonon emission. The observed relaxation time is a few nsec for the one-electron case, and longer for the larger relaxation energy. The enhanced relaxation time is assigned to "phonon bottleneck effect". The two-electron relaxation time is as long as 200μsec, indicating that the degree of spin freedom is well isolated from the surrounding. This can be a good news for possible applications to spintronics

   — **The Kondo physics**: We observe the Kondo effect only associated with the spin triplet state, and the evaluated Kondo temperature is consistent with the theoretical prediction. We also develop a theoretical model of a coupled quantum dot to understand "Kondo chessboard", which only appears for a planar quantum dot in a weak magnetic field.

   — **Strong correlation effects**: We fabricate a quantum dot having a low-electron density to study the correlation effects in a high magnetic field, and find that the two-electron ground state undergoes a transition from a spin singlet state to a triplet state, then to a novel state. This state is associated with a state having a larger angular momentum, which is only favored by strong correlations.

2. **Electronic Properties of Artificial Two-dot Molecules**

   — **Filling of molecular phase**: For fairly strongly coupled artificial molecules we find molecular phases which include electrons in both of the bonding and antibonding orbital states under a perpendicular magnetic field. This arises from certain antibonding states being favored by magnetic field.

   — **Nuclear spin effects**: We find evidence of nuclear spin effects for lifting Pauli blockade in a double dot system. This is associated with spin flip-flop hyperfine interactions, whose strength can be manipulated as a function of magnetic field and bias voltage by adjusting the energy mismatch between the electron spins and nuclear spins. We use this to demonstrate nuclear spin memory operation.

3. **Transport Properties of Quantum Wires**

   — **Negative Coulomb drag**: We propose a Wigner crystallization model to account for the negative Coulomb drag previously observed for a coupled quantum wire system. The numerical simulation reproduces the experiment qualitatively.

   — **Coupled quantum wire-dot**: We fabricate a quantum wire incorporating a quantum dot with tunable coupling to the quantum wire to study the 1D-0D-1D transport physics. We observe clear Coulomb oscillations in the weak coupling region, and interference effect for the 1D propagating wave in the strong coupling region. These are both associated with the two potential barriers forming the dot.

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

   — **ESR technology build-up**: We fabricate an ESR cavity to study a g-factor and dephasing time of electron spin. We first apply the technique to a 2D electron gas to derive the g-factor (=-0.38) and a lower bound (7ns) of dephasing time. We also find significant contribution from hyperfine coupling to nuclear spins.

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16 Fujimori Group

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

Member: Atsushi Fujimori

The electronic structures of strongly correlated systems and complex materials are studied using electron spectroscopic techniques such as photoemission, inverse-photoemission and x-ray absorption spectroscopies. We investigate high-temperature superconductivity, metal-insulator transitions, giant magnetoresistance, spin and charge ordering, pseudogap formation, etc., in d- and f-electron systems (transition-metal and rare-earth compounds, respectively) in one, two and three dimensions. Particular emphasis is made on novel phenomena near metal-insulator transitions. Low-energy electronic structures near the Fermi level are studied using high-resolution photoemission and angle-resolved photoemission.

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J. Matsuno, T. Mizokawa, A. Fujimori, Y. Takeda, S. Kawasaki and M. Takano: Different Routes to Charge Disproportionation in Perovskites-Type Fe Oxides, Phys. Rev. B **66** (2002) 193103.

K. Okazaki, T. Mizokawa, A. Fujimori, E.V. Sampathkumaran, M.J. Martinez-Lope and J.A. Alonso: Crossover in the Nature of the Metallic Phases in the Perovskite-Type RNiO$_3$, Phys. Rev. B **67** (2003) 073101.

17 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 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 a dominant s-wave component which has been 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 remarkable enhanced 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 by Pressure

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 Zn (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 highlight are as follows:

1) Granular structure of high-Tc superconductivity

The STM observation of "gap map" has been extended to underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$. The result reveals an apparent segregation of the electronic structure into SC domains of ∼3mm size with local energy gap smaller than 50meV, located in an electronically distinct background ("pseudogap" phase) with local gap larger than 50meV but without phase coherence of pairs.

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) Quasiparticle interference

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). The result indicates the special relationship between real-space and momentum-space electronic structure.

18 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Iwao MATSUDA

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

(1) Surface electronic transport: a metal-insulator transition and anisotropic surface-state conductivity, measurements with micro-4-point probes at variable temperatures, and with a four-tip STM for nano-scale 4-point probe measurements.

(2) Surface phases and phase transitions: quenching and modifying of the Peierls transition at Si(111)-4×1-In surface superstructure. Formation of one-dimensional metallic systems on vicinal Si(111) surfaces. Two-dimensional metals on Si(111)-$\sqrt{3} \times \sqrt{3}$-Ag and its derivatives, $\sqrt{21} \times \sqrt{21}$ phases.

(3) Construction of new apparatuses: Ultra-high-energy/momentum-resolution photoemission spectroscopy (PES) apparatus. Fermi-surface mapping PES apparatus.

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19 Fukuyama Group

Research Subjects: Low Temperature Physics:
Frustrated magnetism and superfluidity in solid and fluid ^{3}He, Ultra-low temperature scanning tunneling microscopy, Two-dimensional rare-gas solids, Exotic superconductors.

Member: Hiroshi Fukuyama, Hiroshi Kambara and Christopher Bäuerle

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

1. **Nuclear magnetism of 2D solid ^{3}He:** Solid monolayers of ^{3}He adsorbed on graphite are ideal 2D quantum spin systems with nuclear spin 1/2. The gapless "quantum spin liquid" ground state has been strongly suggested in our previous heat capacity measurement for the low density second-layer commensurate phase (4/7 phase) in zero magnetic field. We obtained preliminary heat capacity data for the 4/7 phase adsorbed on graphite preplated with ^{4}He monolayer in magnetic fields up to 0.65 T down to 200 μK. The different first layer seems to result in a slightly different temperature dependence of heat capacity but again a double peak structure similar to that observed previously.

2. **Mott-Hubbard transition in 2D ^{3}He:** Fluid monolayers of ^{3}He absorbed on graphite are ideal 2D Fermi fluids where one can vary interactions between the ^{3}He quasiparticles from the Fermi gas regime to a strongly correlated one by increasing areal density over a wide range. Very large mass enhancement of the quasiparticles, *i.e.* $m^*/m \approx 20$, was observed in our preliminary heat-capacity measurements for high density 2D fluid ^{3}He near the critical density for the 4/7 phase. It suggests the Mott-Hubbard transition between the 2D ^{3}He fluid and the 4/7 commensurate phase.

3. **Search for possible superfluidity (BCS transition) in 2D ^{3}He:** In order to search for possible superfluidity in 2D ^{3}He well below 1 mK, we are testing a new ZYX exfoliated graphite substrate which has a larger single crystalline size than the expected superfluid coherence length ($\gtrsim$ 100 nm). We have confirmed that monolayer solid ^{3}He adsorbed on ZYX can be cooled successfully down to 200 μK through NMR measurements of the nuclear magnetic susceptibility.

4. **Characterization and STM study of ZYX exfoliated graphite:** We characterized ZYX exfoliated graphite (ZYX) by measuring the surface area and electrical resistivity as a function of density. It was observed with STM that ZYX has much larger single crystalline size ($\approx$ 200 nm) than that of Grafoil ($\approx$ 10 nm) which is a commonly used adsorption substrate at ultra low temperatures. Our results show that ZYX has reasonably large surface area and good thermal conductance to be used in heat capacity or NMR experiments of 2D ^{3}He samples at temperatures below 1 mK.

5. **Construction of a high performance nuclear demagnetization refrigerator (NDR):** We could greatly improve the performance of our newly constructed NDR. The lowest temperature we can reach is now 51 μK. This is one of the four most powerful NDRs in the world.

6. **Construction of a new ultra-low temperature scanning tunneling microscope (ULT-STM):** We have finally succeeded in obtaining expected performances of a new versatile dilution refrigerator based ULT-STM which has been under construction in the last several years. It works at temperatures down to 30 mK, in magnetic fields up to 6 T and under ultra high vacuum (UHV) with an atomic resolution. It has wide applicability since one can transfer new samples, after surface preparation and characterization in UHV, keeping low temperature and UHV environments and can cool them to the lowest temperatures within 3 hrs.

20 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 2D electron solids and the Aharonov-Bohm effect:
   We study exchange interactions in the quantum solid phase formed in strongly correlated two dimensional electron systems. The nature of the interactions between neighboring spins can be controlled using the magnetic flux through the exchange path. Experimental results on the magnetic field dependence of the thermal activation energy in Si-MOSFET's had been explained by a model based on this effect. In this year, we have extended our research to p-type GaAs 2D systems.

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

3. Dynamics of nonequilibrium electrons in quantum Hall conductors:
   Our studies aim at revealing local transport and optical properties of quantum Hall conductors by means of scanning probe techniques. The two 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. With this technique, we proceed research on electronic process relating to the QHE breakdown. (ii)Scanning electrometer We have developed a novel technique for obtaining high-resolution images of electrostatic potential distribution. This exploits gate effect for a quantum Hall device by a charged nano-probe.

4. Multi-subband electronic state of InAs surface inversion layers
   We have investigated basic properties of multi-subband electronic state of InAs surface inversion layers. We found the in-plane effective mass in the first subband is larger than that in the second subband by a factor of 3.

21 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 & Shigehiro Nagataki

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;
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)
Dynamics of cosmological phase transition and evolution of global strings (1998)
The gamma-ray burst as a probe of cosmic star formation history and ultra-high energy cosmic rays (1998)
Imprints of Structure Formation on Cosmic Microwave Background (1998)
Topological Defects in the Early Universe (1998)
Modeling Galaxy Formation in a Hierarchical Universe (1998)
Quantum creation of the universe with the inner space (1998)

22 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao

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.

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:** We had proposed two quantum information processing schemes using multiparticle entanglement, remote quantum information distribution protocol [1] and remote quantum information concentration protocol [2]. We have analyzed the multiparticle entangled states used for these protocols and found new properties. In particular, the multiparticle entangled state used in [2] is a bound entangled state, which had previously been considered "useless" for quantum information processing as a single state. This is the first example of the effective use of a single bound entangled state for quantum information processing. Recently, we have shown that several different types of entangled states, including a single bound entangled state, can be used for remote quantum information concentration. This is in contrast to remote information distribution, which requires a certain type of entanglement. We have analyzed the asymmetry of quantum information distribution and concentration from the viewpoint of required entanglement. In the extreme case, encoding requires entanglement and global operations but decoding can be performed using only local operations and classical communications without any entanglement. This strong asymmetry may suggest the possibility of quantum"one-way function" in terms of entanglement. We are investigating a new quantum protocols using this quantum one-way function. A part of this work has been done in collaboration with Dr. V. Vedral of Imperial College, London.

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

- **The properties and applications of entanglement in photonic continuous variable systems:** Photonic states are promising candidates for the realization of quantum information processing, especially for quantum communications. Teleportation experiments have been already demonstrated using two different types of entangled photonic states, a discrete variable (or finite dimensional) type like spin systems and a continuous variable (or infinite dimensional) type. We concentrate on the continuous variable type and are investigate how to perform effective discrete quantum communication using realistic entangled photonic continuous variable states, i.e. two mode finitely-squeezed entangled states. A part of this work is in collaboration with Prof. Sam Braunstein and Dr. Kae Nemoto of the University of Wales.

23 Kobayashi group

Research Subjects: Ultrafast and Nonlinear Optical Processes, Quantum Optics

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

1. Development of ultrashort pulse lasers

i. Generation of the shortest 3.9 fs visible pulses by noncollinear optical parametric amplifier (NOPA): We have demonstrated the generation of a continuous, simultaneously phase-matched 250-THz parametrically amplified spectrum. The resultant visible near-IR signal-wave pulses are compressed to a 3.9-fs duration with a flexible mirror.

ii. Novel crystals for NOPA Novel crystals of KABO($K_2Al_2B_2O_7$) and CLBO($CsLiB_6O_{10}$) were evaluated for NOPA. They are promising for ultra-broadband amplification form infrared to visible frequency.

iii. Time evolution of super-broadbanded spectrum in a filament A mechanism of super-continuum generation has been studied with both experiment and numerical calculation. The results strongly suggest that stimulated Raman scattering contribute to filament formation and spectral broadening.

iv. Generation of Ultra-broadband THz light The bandwidth of THz light is limited by the temporal width of pump light. We have utilized sub-5-fs pulse to generate ultra-broadband THz light.

v. Controlling the carrier-envelope phase of ultrashort light pulses with optical parametric amplifiers: The phase link between signal, idler, and pump waves in a parametric interaction allows the generation of an idler pulse with a phase independent of that of the input pulse.

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

i. J-aggregates: Pseudoisocyanine (PIC) molecules in concentration solutions form J-aggregates. Although PIC has been known to have week coupling system between electron and molecular vibration, temporal oscillation of transmittance due to molecular vibrations has been clearly observed. The observed modes are assigned to out-of-plane vibrations that contribute J-aggregate formation.

ii. Polydiacetylene: PDA-3BCMU (blue phase) derived from polydiacetylene is one of the π-conjugated polymers, where had been dispute about the excited state. This work determined the time scale of relaxation processes and demonstrated that the excited state of PDA-3BCMU is not entirely a butatriene-type structure.

iii. Green fluorescent protein (GFP): The GFP emits green fluorescence (500 nm) involving the proton transfer. In order to investigate the molecular dynamics of vibrations related to the proton transfer we have prepared the pump-prove experiment by a 400-nm femtosecond laser.

iv. Tin phthalocyanine: Tin phthalocyanine (SnPc) film evaporated on a substrate has been investigated by 5-fs ultrafast laser system. The SnPc film shows strong 2nd harmonics vibration of Pc macro-cycle breathing mode, which is originated from electronic excitation state (Q-band).

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

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

4. Quantum optics and quantum information

i. Photon-number squeezed state in a fiber: We have demonstrated numerically that the photon-number squeezing in a optical fiber can be achieved with practicable parameters. The experiment is in progress.

ii. Non-locally coupled photon-pair generation: Optical parametric oscillator has been found to show a periodic pattern in two-photon correlation, which is a quite new feature of photon correlation.

iii. Verification of two-photon correlation in frequency domain: We have demonstrated that self parametric down conversion generates a pair of photons with quantum correlation in frequency domain. New applications of the novel correlation are under progress.

iv. Theoretical study of quantum teleportation: A coherent basis method have been developed to discuss the effects of non-ideal elements of the experimental conditions, such as inefficiencies of the Bell measurement, loss, and thermal noise in the nonlinear crystal used for producing entangled pairs.

v. Inter-atomic entanglement enhanced by an optical cavity: In a multi-mode optical cavity electric field have been found to enhance the degree of entanglement between the two atoms, which is possibly useful for quantum computation, teleportation, and cryptograpy.

24 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 Institute of Space and Astronautical Science (ISAS), as well as foreign missions.

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

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

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

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

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

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

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

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

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25 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 β (ratio of the plasma pressure to the confining magnetic pressure), several times greater than the conventional tokamak. High β 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. TST-2 will be temporarily relocated to Kyushu University in 2003 to perform current drive experiments using the electron Bernstein wave (EBW) at 8.2 GHz. It will be relocated again to the new Kashiwa Campus by the end of academic year 2003.

Study of ST plasmas

A high temperature, high β plasma is a typical example of nonlinear complex system that exhibits interesting collective phenomena. A typical example of self-organization seen in the ST is an MHD phenomenon called the internal reconnection event (IRE). Plasma deforms and reaches a relaxed state by magnetic reconnection. As a result, particles and electron thermal energy are lost, but a large increase in the impurity ion temperature, typically from 100 eV to 400 eV, is observed.

ST plasmas have very high dielectric constants compared to conventional tokamaks. Therefore, methods to diagnose, heat and drive current using different waves, such as EBW and high harmonic fast wave (HHFW), must be developed. To detect EBW emission outside the plasma, EBW must be mode converted to an electromagnetic wave. A new diagnostic, combining a radiometer to measure the radiation and a reflectometer to determine the mode conversion efficiency, was developed. The central electron temperature of $T_e \simeq 300$ eV has been deduced, consistent with T_e measured by soft X-ray pulse height analysis. A more direct method of measuring T_e by Thomson scattering of laser light is currently being developed. HHFW heating experiments have begun, with up to 200 kW of RF power injected from the antenna. A broadening of the frequency spectrum, most likely caused by scattering of HHFW by density fluctuations in the plasma edge region, has been observed.

Theory of electric field structural formation

A peaked structure in the radial electric field (E_r) profile is observed in plasma biasing experiments using electrodes. The E_r profile depends sensitively on plasma non-uniformities. Because the peak of the single-peak structure appears at the outermost peak location of a multiple-peak structure, measurement of the E_r structure can be used to estimate the shear viscosity.

Collaborations

An advanced tokamak plasma with high confinement and very high self-driven current fraction (over 90%) was obtained by RF and NB heating and current drive, combined with induction provided by vertical field and shaping coils, on the JT-60U tokamak (Japan Atomic Energy Researcg Institute). The "fishbone" current drive antenna has been developed for stability improvement, and particle fuelling and transport are being studied using an impurity pellet injector on the LHD helical device (National Institute for Fusion Science). Collaborations on the NSTX spherical tokamak (Princeton Plasma Physics Laboratory) on HHFW heating and EBW emission were carried out in 2002. A CS-less ramp-up experiment is being planned for the academic year 2003.

26 Tsubono Group

Research Subjects: Experimental Relativity, Experimental Gravitation, 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. This spring 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
  - Numerical calculation method for the thermal noise
  - Study of the thermal noise in some metals
- Study of the precise measurement
  - Development of the low-frequency vibration isolation system (SAS)
  - New vibration isolation system using magnetic levitation
  - Study of passive damping using permanent magnets

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27 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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28 Yamamoto Group

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

Member: Satoshi Yamamoto & Tomoharu Oka

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

Our group is running the Mt. Fuji submillimeter-wave telescope in order to explore formation processes, detailed structure, and chemical evolution of molecular clouds. The main reflector of the telescope has a diameter of 1.2 m, and the telescope is enclosed in a space frame radome with a Gore-Tex membrane. We have developed a triple band superconductor mixer receiver for this telescope to observe the spectral lines of the atomic carbon (CI) ($^3P_1 - ^3P_0$ 492 GHz; $^3P_2 - ^3P_1$ 809 GHz) and that of the carbon monoxide (CO) ($J = 3 - 2$ 345 GHz). The telescope system was installed at the summit of Mt. Fuji (el. 3700 m) in July 1998, and we started astronomical observations from November 1998 in a remote way by using a commercial satellite communication system. The Mt. Fuji submillimeter-wave telescope is being operated as a research project of Research Center for the Early Universe (RESCEU) in collaboration with researchers of National Astronomy Observatory, National Space Development Agency, and Fukui University.

With this telescope, we are conducting large scale mapping observations of the 492 GHz line of CI toward a number of molecular clouds in our Galaxy. Until now we have observed dark clouds like HCL2, L183, and ρ Oph, giant molecular clouds like Ori A, Ori B, M17, W3, DR21, NGC2264, NGC1333, and Rosette molecular cloud, infrared dark clouds, and translucent clouds. Total observing area is more than 40 square degrees, which is the largest survey of the CI line so far made. Furthermore, a few representative clouds (Orion A, Orion B, M17, and DR21) have been mapped with the 809 GHz line of CI. By comparing the CI distribution with the CO distribution, we are studying formation and evolution of molecular clouds in detail.

In addition to this, our group is developing the transportable 18 cm submillimeter-wave telescope. The main purpose of this telescope is a survey of the CI 492 lines over the Milky Way. From the result, we can study formation and evolution of molecular clouds in the galaxy scale. In September 2002, we have accomplished the first observation of the CI 492 GHz line with this telescope at the Pampa la Bola site (alt. 4800 m) in Chile.

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 studying rotational spectra of transient molecules in the laboratory with the Fourier transform millimeter-wave (FTMW) spectroscopy. Particularly we have extended observable frequency of the FTMW spectrometer up to 85 GHz in order to cover fundamental molecules which are important in astrochemistry. With this spectrometer, the rotational spectra of the ethyl radical, the vinyl radical, the cyclopropyl radical have been detected. the FTMW spectrometer, which would be useful for the upper atmosphere chemistry.

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29 Sakai (Hirofumi) Group

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

Members: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between the strong nonresonant laser field and the induced dipole moment of the molecules. (2) Controlling quantum processes in atoms and molecules using shaped ultrafast laser pulses. (3) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation) and ultrafast phenomena in atoms and molecules. (4) Attosecond pulses generated with high-order harmonics and their reliable measurement. (5) Structures and dynamics of molecules studied by the laser induced Coulomb explosion. The summary of our research activities in the academic year of 2002 is as follows:

(1) Three-dimensional orientation of asymmetric top molecules using electrostatic and elliptically polarized laser fields

We have demonstrated three-dimensional orientation of asymmetric top molecules with the combination of electrostatic and elliptically polarized laser fields. We use 3,4-dibromothiophene as a sample molecule. The supersonic molecular beam is intersected by the orientation pulse (Nd:YAG, $\lambda = 1064$ nm, $\tau = 12$ ns, $I \sim 3 \times 10^{12}$ W/cm^2) and the probe pulse (Ti:sapphire, $\lambda \sim 800$ nm, $\tau \sim 50$ fs, $I \sim 1.4 \times 10^{14}$ W/cm^2) between the repeller and the extractor plates of the time-of-flight (TOF) mass spectrometer. The extraction field (1000 V/cm) of the TOF spectrometer serves also as the electrostatic field for the molecular orientation. The YAG pulse is elliptically polarized in order to achieve three-dimensional orientation. The 12-ns duration of the YAG pulse ensures that the orientation proceeds in the adiabatic regime. Three-dimensional orientation is evidenced by performing two experiments. The degree of three-dimensional alignment is evaluated from the ion images observed with the major axis of the elliptical polarization parallel to the detector plane. The degree of orientation is measured from the TOF spectra obtained with the major axis perpendicular to the detector plane.

(2) Optimal control of multiphoton processes in molecules with time-dependent polarization pulses

We have developed a closed-loop pulse shaping system with a spatial light modulator, where even a time-dependent polarization pulse can be generated and controlled. A time-dependent polarization pulse is demonstrated and characterized by a homemade POLLIWOG (POLarization Labeled by Interference versus Wavelength of Only a Glint) system. We apply the developed pulse shaping system to the active control of multiphoton ionization processes in *aligned* I_2 molecules. We perform two kinds of control experiments. First we show the ability to selectively produce specific multiply-charged molecular ions. Second we investigate a correlation between a femtosecond time-dependent polarization pulse and the production efficiency of evenly- or oddly-charged molecular ions. We achieve much better controllability of the correlation with a time-dependent polarization pulse than with a pulse having a fixed ellipticity. Our experiments point to some new directions in optimal control studies with molecular systems.

(3) Polarizability anisotropies of rare gas van der Waals dimers studied by laser-induced molecular alignment

The molecular alignment technique utilizing the interaction between the intense nonresonant laser field and the induced dipole moment is applied to the homonuclear rare gas dimers Rg_2 (Rg = Ar, Kr, and Xe). The degree of alignment is investigated by Coulomb exploding Rg_2 and by measuring the angular distributions of the fragment ions. At the same peak intensity of the laser field, the degree of alignment $\ll\cos^2\theta\gg$ becomes larger in order of Ar_2, Kr_2, and Xe_2, reflecting the order of magnitudes of their polarizability anisotropy $\Delta\alpha$. By taking I_2 molecules as a reference, $\Delta\alpha$ of Ar_2, Kr_2, and Xe_2 are estimated to be 0.5, 0.7, and 1.3 Å^3, respectively.

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30 Kuwajima Group

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

Member: Kunihiro Kuwajima, Kaname Mogami, & Kimiko Saeki

We are studying the mechanism of *in vitro* protein folding and the mechanism of molecular chaperone action. Our goals are to elucidate the physical principles by which a protein organizes its specific native structure from the amino acid sequence and to elucidate how these principles are utilized or qualified by the molecular chaperones in a biological cell. For this purpose, we are using various physicochemical and protein engineering techniques including rapid reaction techniques.

We have studied the ATP-induced allosteric structural transition of GroEL using small angle X-ray scattering and fluorescence spectroscopy, and the kinetics of the transition of GroEL induced by ATP have been observed directly by stopped-flow X-ray scattering for the first time. The ATP-induced fluorescence kinetics at various ATP concentrations (< 400 μM) occur before ATP hydrolysis by GroEL takes place and are well explained by a kinetic allosteric model, which is a combination of the conventional transition state theory and the Monod-Wyman-Changeux model, and we have successfully evaluated the equilibrium and kinetic parameters of the allosteric transition, including the binding constant of ATP in the transition state of GroEL.

The folding mechanism of proline-free staphylococcal nuclease (SNase (pro−)) was investigated using the double-jump stopped-flow methods (interrupted refolding, and interrupted unfolding). We have found that there are at least two accessible pathways on the free energy landscape of SNase (pro−) folding, starting from a macroscopically single unfolded-state ensemble. Our results suggest that multiple parallel-pathway folding of a protein that has a unique amino acid sequence is more general than previously expected.

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31 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.