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The University of Tokyo

Annual Report

2022

令和４年度 年次研究報告

東京大学 大学院　理学系研究科・理学部
物理学教室

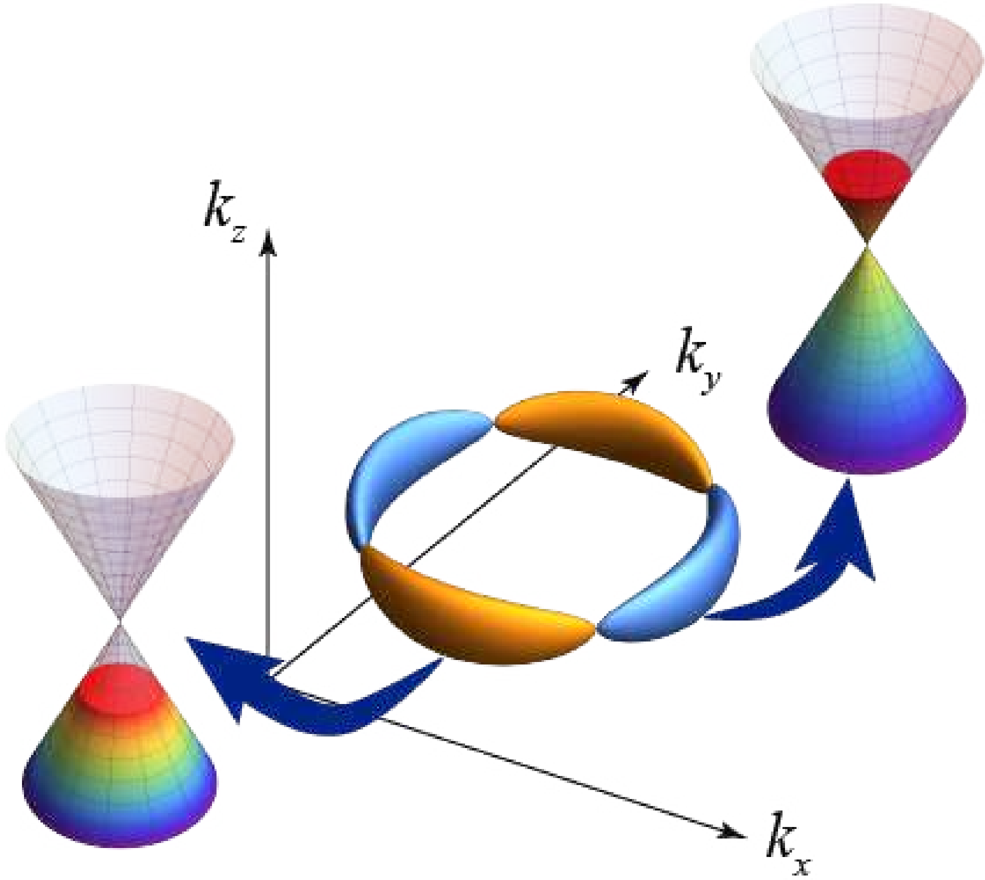

図 1: 擬１次元有機伝導体 HMTSF-TCNQ の電荷密度波（CDW）状態におけるフェルミ面の模式図。第一原理計算の結果から、この物質はギャップのないディラック電子系のノード（ディラックコーンの頂点）が波数空間で連続的に存在している状態、つまりノーダルライン半金属であることが明らかになった。さらにノードのエネルギーは波数空間内で少しだけ上下するために、下図のように波数空間内の位置によって電子のフェルミ面 (青い部分) とホールのフェルミ面 (橙の部分) が交互に出現する。電子とホールが共存するので半金属である。HMTSF-TCNQ の実験で見られる大きな軌道反磁性とその奇妙な温度依存性は、この特異なフェルミ面によって説明可能である。（尾崎壮駿ほか、小形研究室）

Schematic figure of the Fermi surface in the charge density wave (CDW) state of quasi-one dimensional organic conductor HMTSF-TCNQ. From the first-principles calculation, it is shown that this material has a ground state in which the nodes of gapless Dirac electron systems exist continuously in momentum space, or a nodal line semimetal. Furthermore, since the energy of the nodes changes slightly in the momentum space, the electron Fermi surface (blue part) and the hole Fermi surface (orange part) appear alternately depending on the position in the momentum space, as shown in the figure. It represents a semimetallic state because electrons and holes coexist. The large diamagnetism and its unconventional temperature dependence observed experimentally in HMTSF-TCNQ can be explained using this characteristic Fermi surface. (Soshun Ozaki et al, Ogata group)

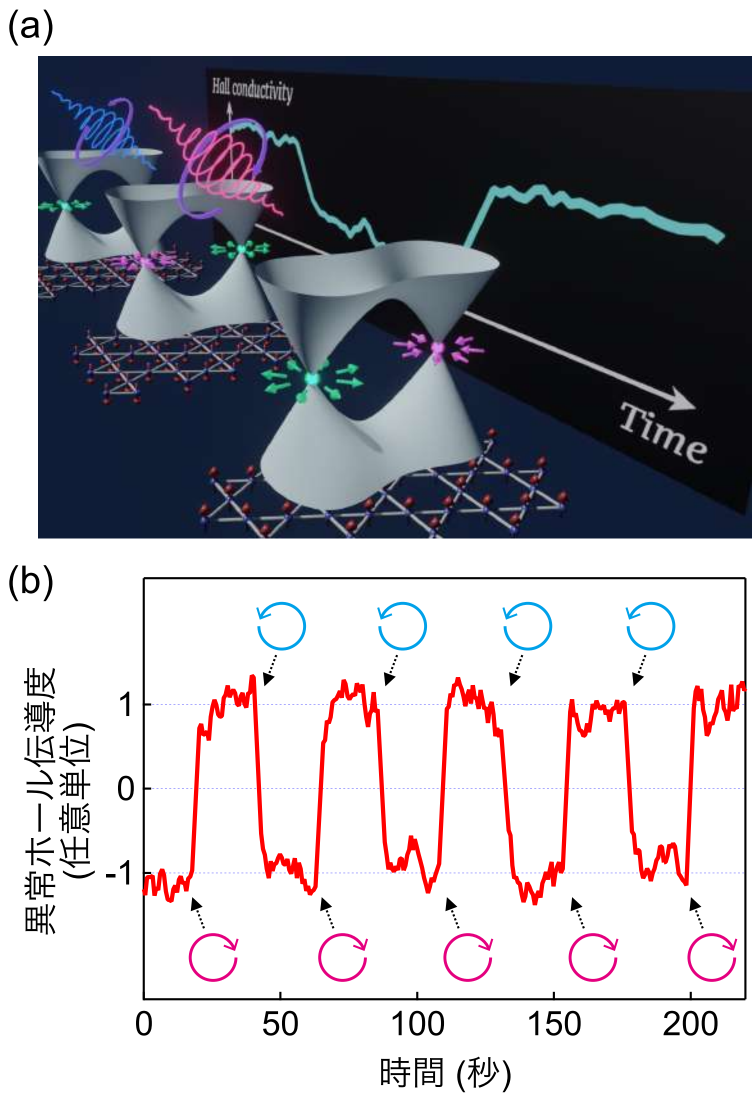

図 2: (a) カゴメ格子を有する $Co_3Sn_2S_2$ は、特徴的なバンド構造（図中グレーのコーン）に由来して物質中の電子が質量ゼロのワイル粒子として振る舞う、ワイル半金属の一種である。$Co_3Sn_2S_2$ に円偏光の光（青や赤の螺旋）を照射することで、この物質が持つ強磁性の磁化とワイル粒子のカイラリティ（右巻き：ピンク、左巻き：緑）を繰り返し自在に反転することに成功した。(b) 右回り円偏光 (ピンク)、左回り円偏光 (水色) を繰り返し照射した際の異常ホール伝導度の時間変化。円偏光のヘリシティを変えることで、ワイル粒子のカイラリティと対応する異常ホール伝導度の符号が繰り返し反転している。（島野研究室）

(a) $Co_3Sn_2S_2$, which has a kagome lattice, is a Weyl semimetal in which the electrons behave as massless Weyl particles due to the characteristic band structure (gray cones in the figure). By irradiating $Co_3Sn_2S_2$ with circularly polarized light (blue and red spirals), the ferromagnetic magnetization and the chirality of Weyl cones in this material (right-handed: pink, left-handed : Green) were successfully reversed repeatedly. (b) Time evolution of anomalous Hall conductivity under repeated irradiation with left-handed (light blue) and right-handed (pink) circularly polarized light, which shows repeated flips. (Shimano Group)

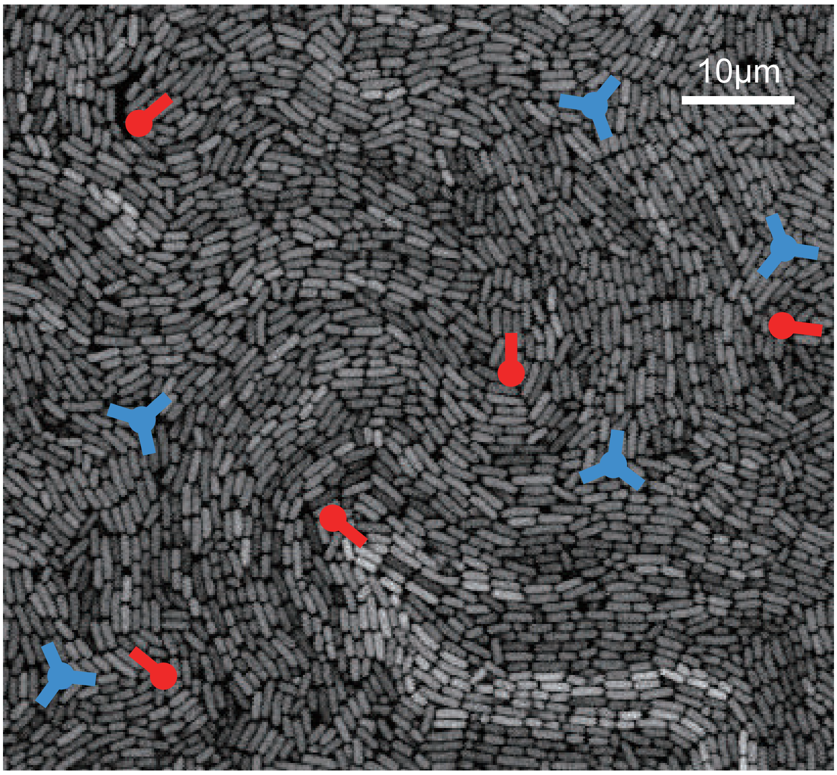

図 3: 大腸菌集団に生じる液晶的配向秩序とトポロジカル欠陥。トポロジカル欠陥の箇所に大腸菌が引き寄せられ、コロニーが局所的に隆起することが見出された。 従来知見では巻き数 $-1/2$ の欠陥からは細胞が逃避することが期待されていたが、本研究では $-1/2$ 欠陥にも細胞が引き寄せられていた。我々は、細胞が鉛直方向に傾くことで極性秩序が生じていることを発見し、それによる極性起因力によって $-1/2$ 欠陥への細胞流を説明することに成功した。T. Shimaya and K. A. Takeuchi, PNAS Nexus **1**, pgac269 (2022).（竹内研究室）
Liquid crystalline orientation order and topological defects in colonies of *Escherichia coli*. Topological defects were found to attract bacteria, increasing the local colony height at the locations of the defects. While existing theory predicted that cells should be repelled from defects of winding number $-1/2$, our experiments showed the opposite. We found that vertical tilting of cells led to the formation of polar order, and the force induced by this polarity turned out to be the key to account for the cell in-flux toward $-1/2$ defects. T. Shimaya and K. A. Takeuchi, PNAS Nexus **1**, pgac269 (2022). (Takeuchi Group)

II

Summary of group activities in 2022

1 Fukushima Group

Research Subjects: QCD phase diagram, Confinement, Lattice simulation, Neutron star, Chiral anomaly

Member: Kenji Fukushima and Arata Yamamoto

In Theoretical Hadron Physics group, many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include quark-gluon plasma in relativistic heavy-ion collisions, lattice gauge simulations with classical and quantum computing, matter under extreme conditions, neutron stars, etc.

Highlights in research activities of this year are listed below:

1. New confinement mechanism with imaginary rotation
2. Quantum sampling in lattice gauge theories
3. Lattice gauge theory at nonzero baryon density
4. Neutron star equation of state and the gravitational wave signals
5. Trace anomaly and the speed of sound in dense nuclear/quark matter

2 Liang Group

Research Subjects: Quantum many-body theories in nuclear and cold-atom physics

Member: Haozhao Liang and Hiroyuki Tajima

In our group, we study the properties of atomic nuclei and neutron stars based on various nuclear many-body theories. In particular, one of the main research themes is nuclear density functional theory (DFT), which aims at understanding both ground-state and excited-state properties of thousands of nuclei in a consistent and predictive way. Our research interests also include the microscopic foundation of nuclear DFT, the interdisciplinary applications in nuclear astrophysics, particle physics, condensed matter physics, etc., and the relevant studies in general quantum many-body problems. To this end, a cold atomic gas can be regarded as an ideal testing ground for many-body theories because of its controllability. In this regard, we are also interested in investigating novel many-body phenomena and developing quantum many-body theories through the comparisons with cold-atom experiments.

Highlights in research activities of this year include:

1. Charge symmetry breaking force in nuclear DFT
2. Functional renormalization group approach to DFT
3. Neutron-star properties and nuclear structure
4. Nuclear mass predictions with machine learning
5. A systematic calculation of β-decay half-lives
6. A Kohn-Sham scheme based neural network for nuclear systems
7. Cooper multiplet correlations
8. Density-induced BCS-BEC crossover and its three-body counterpart
9. Polarons and clusters in ultracold atoms and their applications to nuclear systems
10. Non-Hermitian topological unitary p-wave Fermi superfluid
11. Multi-particle tunneling transport in strongly-correlated systems
12. Andreev reflection through nonlinear radio-frequency transport

3 High Energy Physics Theory Group

Research Subjects: Particle Physics and Cosmology

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo

We are working on various topics in particle physics and cosmology, such as physics beyond the Standard Model, dark matter, baryogenesis, inflation, phenomenology of supersymmetric models, grand unified theories, string theory, supersymmetric field theories, conformal field theories, holography, entanglement entropy, and so on. Specific subjects studied in this academic year are summarized below:

1. Phenomenology
   - 1.1. Vacuum stability in SUSY models [1]
   - 1.2. Vacuum stability in inflation models [2]
   - 1.3. Axion detection at the ILC [3]
   - 1.4. Dark matter searches in compact stars [4, 5, 6]
   - 1.5. New physics searches at the MUonE experiment [7]
   - 1.6. Supersymmetric Grand Unified Theories [8]
   - 1.7. Electric dipole moments in supersymmetric standard model [9]
   - 1.8. Dipole moments in vector-like lepton models [10]
   - 1.9. Muon anomalous magnetic dipole moment at the ILC [11]
2. Superstring theory and formal aspects of quantum field theories
   - 2.1. AGT correspondence of supergroup gauge theories [12]
   - 2.2. Bethe equations of 2d conformal field theory [13]
   - 2.3. Generalized symmetry [14, 15, 16, 17]
   - 2.4. Defect/boundary conformal field theories [18, 19, 20]
   - 2.5. Narain CFTs and error-correcting codes [21]

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4 Nakamura Group

Research Subjects: Spectroscopic study of hypernuclei and related hadron/nuclear physics

Member: Satoshi N. Nakamura and Sho Nagao

Nuclear Experimental Group (NEX) started research activities under a new structure with the arrival of Prof. Nakamura in April 2022 and Assistant Prof. Nagao in September.

We are performing experimental research in modern nuclear physics to understand quantum many-body systems interacting with the strong interaction. To this end, we are conducting experiments of hypernuclei which are composed of nucleons (protons and neutrons) and hyperons (with strange quarks), by making full use of particle accelerators in Japan and abroad.

Quantum many-body systems in which the strong interaction plays an important role include; baryons, which consist of quarks including protons and neutrons; (hyper)nuclei as baryonic many-body systems; and neutron stars, the densest objects in the universe, which are gravitationally bound baryon many-body systems and may be described as "giant nuclei" whose masses are supported by the baryon interaction. Those quantum many-body systems have size scales from 1 fm (10^{-15} m) to 10 km (10^4 m), spanning 19 orders of magnitude. In order to understand these in a unified manner based on the baryon interaction, which extends the nuclear force, we have been conducting experiments at 1) Jefferson Laboratory (JLab) in the United States, 2) Johannes Gutenberg University Mainz, Germany (MAMI), and 3) Research Center for Electron Photon Science, Tohoku University (ELPH). These facilities have high-energy, high-intensity electron accelerators capable of producing strange quarks. In addition to the above, we are leading hypernuclear experiments using the next-generation π meson beams at the High-Intensity High-Resolution beamline (HIHR), which is being prepared as a next-generation flagship project at the hadron experimental facility of J-PARC in Tokai.

Currently, there are four key issues to be solved in hypernuclear research: 1) the hyperton puzzle, 2) the existence or non-existence of atomic number zero hypernuclei (nnΛ), 3) charge symmetry breaking of Lambda hypernuclei, and 4) the hyperon puzzle (why heavy neutron stars exist). We are promoting research to solve these puzzles through the following experiments.

- Spectroscopic study of Λ hypernuclei at Jefferson Lab
  - Search of a neutral hypernuclei, nnΛ
  - Electro-production of hyperons
  - Electro-production of η' mesons
  - High-precision spectroscopy of Λ hypernuclei with the $(e, e'\mathrm{K}^+)$ reaction
- Decay π^- spectroscopy of electro-produced hypernuclei at MAMI
  - Precise measurement of mass of hypertriton
  - Precise measurement of electron beam energy
- Study of light hypernuclei at ELPH
  - Lifetime measurement of hypernuclei
  - Study of the Λn interaction by the Final State Interaction measurement
- Design of the next generation experiment with the (π, K) reaction at HIHR, J-PARC

5 Yokoyama(M)-Nakajima Group

Research Subjects: Experimental Particle Physics and Particle Astrophysics

Member: Masashi Yokoyama, Yasuhiro Nakajima, and Kota Nakagiri

The main focus of our group is the study of neutrino properties and research using neutrinos as a probe. We are leading experiments using Super-Kamiokande and Hyper-Kamiokande detectors and the J-PARC accelerator.

T2K long-baseline neutrino oscillation experiment

We have been studying neutrino oscillations with the T2K long-baseline neutrino experiment. In T2K, intense neutrino and anti-neutrino beams produced using the J-PARC accelerator complex are measured with the SK detector, 295 km away. Our current major research goal is the search for a new source of CP symmetry violation in neutrino oscillations.

We have been leading the project to upgrade near neutrino detectors for the reduction of uncertainties associated with understanding of neutrino interactions. This year, we finished the mechanical assembly of a new neutrino detector named SuperFGD. The SuperFGD detector will be installed in the experimental hall and start taking data by the end of 2023.

Super-Kamiokande experiment

Super-Kamiokande is the world's largest underground detector for neutrino physics and nucleon decay. In the summer of 2022, we added 27 tons of $Gd_2(SO_4)_3$ to increase the Gd concentration in Super-Kamiokande from 0.011% achieved in 2020 to 0.033%. The addition of gadolinium improves the detection efficiency of neutrons. Utilizing this new capability, we aim for the world's first observation of supernova relic neutrinos.

Hyper-Kamiokande

In order to significantly extend the reach in the neutrino physics and the proton decay search beyond T2K and SK, the next-generation water Cherenkov detector, Hyper-Kamiokande is under construction. The Hyper-Kamiokande will be a large water Cherenkov detector with a cylindrical tank 68 meters in diameter and 71 meters deep, filled with 260,000 tons of ultrapure water. Our group is leading the design and construction of the Hyper-Kamiokande detector system. We are also testing the performance of the photomultiplier tubes and developing calibration methods.

R&D of particle detectors for future experiments

We have been developing new particle detectors for future experiments. One example is a Time Projection Chamber (TPC) using an organic liquid as a medium for precise measurement of reactor neutrinos and supernova neutrinos. Another is the search for neutrinoless double-beta decay with ^{160}Gd, utilizing ultra-high purity Gd technology developed for the SK-Gd project.

6 Asai group

Research Subjects: (1) Particle Physics with the energy frontier accelerators (LHC) (2) Physics analysis in the ATLAS experiment at the LHC: (Higgs, SUSY and Extra-dimension) (3) Particles Physics without accelerator using high intensity of Photon (4) Positronium and QED (5) Quantum Technology and Artificial Intelligence (AI)

Member: S.Asai, A.Ishida

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry, and new diboson resonances(WW and $\gamma\gamma$).
  - Higgs: After the discovery of Higgs Boson, We are measuring the Yukawa coupling precisely.
  - SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.4 and 1.5TeV, respectively.
- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Dark matter indirect search with multi-wavelength photons.
  - Search for Photon-Photon scattering with XFEL.
  - Search for WISPs in various wavelengths with high-power light sources.
  - Basic study for Bose-Einstein condensation of positronium.
  - Search for vacuum birefringence.
  - Search for vacuum diffraction with an XFEL and high power laser beams.
  - Precision measurement of the energy spectrum in the orthopositronium decay.
  - Measurement of Positronium Hyper-fine splitting.
  - Search for weakly coupling neutral particles with ortho-positronium.
  - Search for CP violation with ortho-positronium.
  - Search for the invisible decay of ortho-positronium.
  - Lifetime measurement of ortho-positronium.
  - Search for solar axions with Fe-57 resonant absorption.
- (3) Quantum Technology and Artificial Intelligence (AI) for application to fundamental physics.
  - Optimization problems (database search and gradient estimation).
  - Performance evaluation and improvement of quantum machine learning model with repetitive structure.

7 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Hiroyasu Matsuura

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-T_c superconductivity, Mott metal-insulator transition, topological materials, Dirac electron systems in solids, thermoelectric materials with large response, organic conductors, and magnetic systems with frustration and/or spin-orbit interactions. The followings are the current topics in our group.

- Dirac electron systems in solids [1]
- Thermal transport phenomena [2-6]
- Theories on superconductivity [7,8]
- Orbital magnetic effects [9-11]
- Theories on organic conductors [12,13]
- Physics of chirality [14,15]

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8 Tsuneyuki Group

Research Subjects: Theoretical Condensed-Matter Physics

Member: Shinji Tsuneyuki and Takahiro Ishikawa

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

One such new method is first-principles lattice dynamics calculations considering the anharmonicity. We have developed a scheme for modeling the phonon Hamiltonian with third and higher-order anharmonicity from the first principles and applied the self-consistent-phonon method to calculate the lattice thermal conductivity and thermal expansivity. This year, we improved and used the method for calculating the complex permittivity of crystals in the THz region.

Another important method is the so-called data assimilation for crystal structure exploration. We newly applied the method to amorphous materials and successfully accelerated its precise structural simulation.

Major research topics in FY 2022 are as follows.

- First-principles study of dielectric functions in rutile TiO_2
- Dielectric function calculations for molecular condensed systems by machine learning of dipole moments
- Theoretical calculations of laser ablation considering electronic entropy effects
- Data assimilation method for crystal structure exploration
- Data assimilation method for amorphous structure exploration
- Structure search using evolutionary algorithms
- Exploration of trinitrotoluene (TNT) degradation process
- Search for superconducting phases in the lanthanum-boron-hydrogen and lanthanum-boron-nitrogen systems
- Superconductivity in hydride perovskites
- Electronic structure calculation with explicitly correlated wave functions

9 Todo Group

Research Subjects: Development of simulation algorithms for strongly-correlated systems; Application of machine learning technique to materials science; Fundamental theory of quantum computer; Novel state and critical phenomena in strongly correlated systems; Thermalization and non-equilibrium dynamic of quantum many-body systems; Quantum computing and quantum algorithms; Development of open-source software for next-generation parallel simulations

Member: Synge Todo, Tsuyoshi Okubo, Hidemaro Suwa, and Shinichiro Akiyama

To know the state of matter, one can solve the many-body Schrödinger equation and obtain the partition function of statistical mechanics. However, even with the computational power of modern supercomputers, the many-body Schrödinger equation cannot be solved exactly. Therefore, an essential key in computational physics is to re-express the original equations in a form that facilitates simulation without losing physically critical properties in the original equations, such as symmetry and quantum correlations.

We are exploring novel computational physics methods based on sampling methods such as the Monte Carlo algorithm, path integrals to represent quantum fluctuations, information compression using the singular value decomposition and the tensor networks, statistical machine learning, etc. By entirely using these powerful numerical methods, we aim to elucidate various exotic states, phase transitions, and dynamics in quantum many-body systems, from quantum spin systems to actual materials. Also, we are studying the basic theory of quantum computers and quantum machine learning algorithms and working on developing and releasing open-source software for next-generation large-scale simulations.

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[2] Yuichi Motoyama, Tsuyoshi Okubo, Kazuyoshi Yoshimi, Satoshi Morita, Takeo Kato, Naoki Kawashima, TeNeS: Tensor Network Solver for Quantum Lattice Systems, Comp. Phys. Comm. **279**, 108437 (10pp) (2022).

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10 Katsura Group

Research Subjects: Condensed Matter Theory and Statistical Physics

Member: Hosho Katsura and Yutaka Akagi

In our group, we study various aspects of condensed matter and statistical physics. In particular, our research focuses on strongly correlated many-body systems in and out of equilibrium, which would give rise to a variety of novel phases. We study theoretically such systems, with the aim of predicting intriguing quantum phenomena that have no counterpart in weakly-interacting systems and cannot be understood within standard approaches. Our work involves a combination of analytical and numerical methods. We are currently interested in (i) topological phases of matter, (ii) quantum magnetism, (iii) dissipative quantum many-body systems, and (iv) non-ergodic dynamics in non-integrable systems. In addition, we are also interested in the mathematical aspects of the above-mentioned fields. Our research projects conducted in FY 2022 are the following:

- Topological phases of matter
  - Symmetry-protected quantization of complex Berry phases in non-Hermitian systems [1]
  - Duality, criticality, anomaly, and topology in quantum spin-1 chains [2]
- Quantum magnetism
  - CP^2 skyrmion crystals in an SU(3) magnet with a Dzyaloshinskii-Moriya type interaction [3]
  - Semi-classical simulation of spin-1 quantum magnets [4]
- Nonequilibrium quantum dynamics
  - Quantum many-body scars of spinless fermions in higher dimensions [5]
  - Liouvillian gap and single spin-flip dynamics in the dissipative Fermi-Hubbard model [6]
- Mathematical and statistical physics
  - Spontaneously broken supersymmetric fracton phases with fermionic subsystem symmetries [7]
  - Flat-band ferromagnetism in the SU(N) Hubbard and Kondo lattice models [8]

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11 Kabashima Group

Research Subjects: Statistical mechanics of disordered systems and its application to information science

Member: Yoshiyuki Kabashima, Takashi Takahashi, Xiangming Meng

We are working in a cross-disciplinary field between statistical mechanics and information science. Our research interests include error-correcting codes, cryptography, CDMA multi-user detection, data compression, compressed sensing, sparse modeling, high-dimensional statistics, probabilistic inference, neural networks, random matrix, machine learning, spin glasses, etc.

The followings are highlights in our research activities in AY 2022:

1. Performance analysis of ℓ_1-reguralized linear regression for Ising model selection
2. Average case analysis of Lasso under ultra-sparse conditions
3. Statistical mechanics analysis of general multi-dimensional knapsack problems
4. Replicated simulated annealing with a global-best reference for efficient hardware implementation
5. Performance analysis of iterative self-training with linear classifier
6. Analysis of ensemble learning
7. Analysis of eigenspace of sample covariance matrices
8. Compressive sensing using diffusion models

12 Tsuji Group

Research Subjects: Theory of condensed matter physics, nonequilibrium quantum many-body systems

Member: Naoto Tsuji and Kazuaki Takasan

We are interested in nonequilibrium physics of quantum many-body systems and statistical mechanics. The aim is to realize a new order or new physical property by driving quantum systems out of equilibrium. At first sight, it sounds unlikely to happen because energy injected by an external drive would turn into heat, which would destroy all the interesting properties of quantum many-body systems that might emerge at low energies. However, contrary to our intuition, recent studies have found various possibilities such that novel states of matter that can never be realized in equilibrium do emerge out of equilibrium. We are trying to understand their mechanism and explore the frontier of nonequilibrium condensed matter physics.

In the academic year of 2022, we worked on the following projects:

- Dynamics of superconductors
  - Higgs mode in superconductors and nonlinear responses [1]
  - Optical amplification of third harmonic generation in superconductors [2]
  - Floquet states in superconductors [3, 4]
- Dynamics of open quantum many-body systems
  - Analysis of energy current based on quantum master equations
  - Feedback control of quantum many-body systems
  - Quantum active matter
- DC-electric-field- and current-induced quantum phases [5, 6]
- Nonlinear response of quantum many-body systems [7]
- Dynamics of topological phases [8]

[1] Naoto Tsuji, "Collective modes in superconductors: a new perspective from nonlinear terahertz responses", CCES seminar (online), IBS Center for Correlated Electron Systems (CCES), Seoul National University, March 2023.

[2] Naoto Tsuji, "Higgs-mediated nonlinear optical response and its amplification in superconductors", Novel Quantum States in Condensed Matter 2022 (NQS2022), YITP, Kyoto, November 2022.

[3] Huanyu Zhang, Kazuaki Takasan, Naoto Tsuji, "Floquet Many-body Theory for Driven BCS Superconductors: With Potential Application to the Nonlinear Responses", FoPM Symposium 2023, University of Tokyo (Tokyo, Japan), February 2023.

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13 Ashida Group

Research Subjects: Condensed matter theory, Theoretical quantum optics

Member: Yuto Ashida and Kazuki Yokomizo

This group focuses on theoretical studies at the intersection of quantum many-body physics and quantum optics. We have been studying physics of open and out-of-equilibrium systems, where quantum systems interact with external world and thus feature nonunitary dynamics. We employ the ideas/methods, including field theory, renormalization group, topology, and variational approach. In addition, we are interested in physical phenomena in the corresponding classical systems and their potential applications. We have also been doing studies related to machine learning and physics. We list research/review papers published in the academic year of 2022 below.

- Non-Hermitian physics, open quantum systems [1, 2, 4]
- Strongly interacting quantum light-matter systems [3, 5, 8]
- Statistical physics, machine learning [6, 7]

[1] K. Yokomizo, T. Yoda, and S. Murakami, Non-Hermitian waves in a continuous periodic model and application to photonic crystals, Physical Review Research **4**, 023089 (May 2022).

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14 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Ryota AKIYAMA

Surfaces/interfaces of materials and atomic-layer materials are platforms of our research where rich physics is expected due to the low-dimensionality, symmetry breaking, a wide variety of structures, and direct access for measurements. (1) Charge/spin/mass transports including superconductivity and spin current, (2) atomic/electronic structures, (3) phase transitions, (4) spin states and spintronics, and (5) epitaxial growths of coherent atomic/molecular layers/wires on surfaces of metals, semiconductors, topological materials, and nano-scale phases such as surface superstructures, ultra-thin films including atomic-layer materials such as graphene and transition metal dichalcogenides. We use various kinds of ultrahigh-vacuum experimental techniques, such as electron diffraction, scanning electron microscopy(SEM), scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy(PES), *in-situ* four-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes, and surface magneto-optical effects apparatuses. Main results in this year are as follows.

(1) Surface transport and magnetism:
- soft-magnetic skyrmions at interfaces/heterostructures at ferromagnetic topological insulators and magnetic interaction therein.
- 2D superconductivity at α-Sn layers on a topological crystalline insulator
- non-reciprocal photocurrent at Rashba surfaces induced by irradiation of circularly polarized light
- surface transport of $SrTiO_3$ influenced by electron beam irradiation
- Ferromagnetic states at Yb-intercalated graphene

(2) Surface phases and atomic-layer materials:
- Epitaxial growth of ultra-flat SnTe and PbTe films on $SrTiO_3$(001)

(3) New methods:
- Fabrication of a four-point probe UHV system with tunneling-spectroscopy capability
- Fabrication of a UHV-MBE system with polarization-controlled mid-infrared irradiation

[1] R. Akiyama, R. Ishikawa, K. Akutsu-Suyama, R. Nakanishi, Y. Tomohiro, K. Watanabe, K. Iida, M. Mitome, S. Hasegawa, S. Kuroda: *Direct probe of ferromagnetic proximity effect at the interface in SnTe/Fe heterostructure by polarized neutron reflectometry*, The Journal of Physical Chemistry Letters **13**, 8228-8235 (Aug, 2022).

15 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

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

1. Two dimensional electrons at cleaved semiconductor surfaces:
   At the surfaces of InAs and InSb, conduction electrons can be induced by submonolayer deposition of other materials. Recently, we have performed in-plane magnetotransport measurements on in-situ cleaved surfaces of p-type substrates and observed the quantum Hall effect which demonstrates the perfect two dimensionality of the inversion layers. Research on the hybrid system of 2D electrons and adsorbed atoms has great future potential because of the variety of the adsorbates and the application of scanning probe microscopy techniques.

   To explore exotic physical phenomena related to spin at a semiconductor surface, magnetic-adatom induced two dimensional electron systems are investigated by using low-temperature scanning tunneling microscopy and spectroscopy combined with transport measurements.

2. Superconductivity of monolayer films on cleaved GaAs surfaces:
   Recently, we studied the effect of the parallel magnetic field $H_\parallel$ on superconductivity of monolayer Pb films on GaAs(110). Superconductivity was found to occur even for $H_\parallel = 14$ T, which is much higher than the Pauli paramagnetic limiting field H_P. The observed weak $H_\parallel$ dependence of the superconducting transition temperature T_c is explained in terms of an inhomogeneous superconducting state predicted for 2D metals with a large Rashba spin splitting.

   We have studied nonreciprocal charge transport in superconducting ultrathin films. For ultrathin Pb and Al films grown on the cleaved surface of GaAs (110), the antisymmetrized second harmonic magnetoresistance was observed, which suggests that rectification effect occurs in the superconducting ultrathin films. Moreover, to clarify the origin of the rectification effect, we made the observation of the cleaved GaAs surface using a scanning electron microscope. We found that an asymmetric edge structure causes the rectification effect, which is called vortex ratchet.

3. Formation of Dirac cones in ultrathin Bi films
   Magnetotransport measurements have been performed on ultrathin Bi films grown on GaAs(110). While large positive magnetoresistance is observed at low temperatures, the Hall resistance is found to be extremely small. This is explained by the cancellation of contributions of electrons and holes, which are estimated to have close density and mobility values. By analogy with graphene near the charge neutral point, magnetotransport properties are discussed in relation to the formation of Dirac cones.

16 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Naotaka Yoshikawa

We study light-matter interactions and many body quantum correlations in solids, aiming at light-control of many-body quantum phases. In order to investigate the role of electron and/or spin correlations in the excited states as well as in the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1 THz$\sim$4 meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research highlights in FY2022 are as follows.

1. **Nonequilibrium dynamics of superconductors:** We have investigated the photoexcited nonequilibrium dynamics of high-T_c cuprate superconductors and iron-based superconductors through the observation of collective modes. In La-based compounds, $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, the signature of light-induced superconductivity was identified though the emergence of light-induced plasma edge was observed above T_c upon the near-infrared optical pulse excitation, with the plasma frequency almost identical to that of Josephson plasma frequency in the superconducting phase. The induced-plasma edge was identified up to the onset temperature of the charge stripe order, indicating the intimate interplay between the stripe order and superconductivity.

2. **Nonequilibrium dynamics of charge density wave system:** We investigated a thin film of transition metal dichalcogenide (TMD) 3R-$Ta_{1+x}Se_2$ which shows a charge density wave(CDW) order at low temperatures. The dynamics of the CDW order parameter was studied by time-resolved measurements of amplitude mode oscillation. Nonthermal melting of the CDW order induced by the intense THz pulses was revealed with the injected THz pulse energy far below the thermal energy required to heat the system up to the CDW onset temperature.

3. **Floquet engineering of Dirac electron systems:** Floquet states in Dirac electron system in Bi were investigated by irradiating the circular polarized mid infrared light pulses. In particular, we discovered that a new type of Weyl nodes appears at the one photon resonance position, which dominates the light-induced anomalous Hall effect in three-dimensional Dirac electron system.

4. **All optical switching of chirality and magnetization in a ferromagnetic Weyl semimetal:** $Co_3Sn_2S_2$, which has a kagome lattice, is a Weyl semimetal in which the electrons behave as massless Weyl particles due to the characteristic band structure. By irradiating $Co_3Sn_2S_2$ with circularly polarized light, we succeeded in all optical switching of the magnetization and the chirality of Weyl cones.

References

[1] Kota Katsumi, Morihiko Nishida, Stefan Kaiser, Shigeki Miyasaka, Setsuko Tajima, Ryo Shimano: Absence of the superconducting collective excitations in the photoexcited nonequilibrium state of underdoped $YBa_2Cu_3O_y$, arXiv.2209.01633.

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[4] Yoshua Hirai, Naotaka Yoshikawa, Masashi Kawaguchi, Masamitsu Hayashi, Shun Okumura, Takashi Oka, Ryo Shimano: Anomalous Hall effect of light-driven three-dimensional Dirac electrons in bismuth, arXiv.2301.06072.

[5] Morihiko Nishida, Kota Katsumi, Dongjoon Song, Hiroshi Eisaki, Ryo Shimano: Light-induced coherent interlayer transport in stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, arXiv.2303.01961.

17 Takagi-Kitagawa Group

Research Subjects: Physics of Correlated Electron Systems

Member: Hidenori Takagi, Kentaro Kitagawa, Naoka Hiraoka

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2022 included, $3d$-electron superconducting materials under high pressure, $4f$ lanthanoide honeycomb-lattice compounds with interplay of electron correlations and strong spin orbit coupling, spin liquids, and instrumental development of ultrahigh-pressure magnetometry devices.

Realization of spin liquid, where quantum spins fluctuates at absolute zero, should be a milestone in the field of quantum spin physics. After a theoretical achievement of the exactly solvable spin liquid state on a honeycomb lattice, by Alexei Kitaev, a materialization of this Kitaev Honeycomb Model (KHM) has been intensively pursuit. One dimensional spin liquid has been commonly accepted, while in two or three dimensions, typical known frustrated quantum spin liquid materials, like triangular compounds, is not based on an exactly solvable lattice model. We have been focussed on a two-dimensional honeycomb iridate, $H_3LiIr_2O_6$, and discovered that $H_3LiIr_2O_6$ is indeed spin liquid, as the first material of such a liquid, down to 50 mK by specific heat, magnetic susceptibility, and nuclear magnetic resonance experiments.

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\mathrm{eff}} = 1/2$ quantum pseudo spins of Ir eighther on two-dimensional honecomb lattice or on three-dimensional hyper-honeycomb lattice would be a main route. Two kinds of Majorana fermions represent KHM and they are particles on the exactly solved ground state. Since our discovery is an only spin liquid on Kitaev system, and no report was given to proof two Majorana particles. We will pursuit realization of the ”true” Kitaev material. For this purpose, we are exploring a new route to Kitaev physics, by exploring Lanthanoid honeycomb materials. For example, α, β-type Na_2PrO_3 are newly suggested candidates for a platform having an antiferromagnetic Kitaev-type interaction. We have clarified α-Na_2PrO_3 (two-dimensional) exhibits metamagnetic behavior which would be related to the theoretically expected behavior for the antiferromagnetic Kitaev spin liquid and its proximate. We further clarified that β-Na_2PrO_3 shows a significant short-range ordering above the antiferromagnetic transition temperature, implying that frustration takes place in this three-dimensional hyperhoneycomb compound. We further explore other $4f$ Lanthanoid honeycomb materials as a new field for quantum magnetism in combination with Material Informatics and traditional crystal growth techniques.

To further accelerate quantum magnetism research in different ways, we apply ultrahigh pressure on such candidate materials to modify the ground state. However, it has been difficult to evaluate magnetic samples above a few giga pascals. We have recently developed a highly sensitive technique to conduct magnetometry under very high pressures up to 9 GPa using an opposed-anvil type cell, which can detect a weak volume susceptibility as small as $\sim 10^{-4}$. The high-pressure cell has an optimized geometry to yield a reduced background in the magnetic response, one order of magnitude smaller than those for previously reported high-pressure cells in a commercial SQUID magnetometer. This year, we started making a redesigned Moissanite anvil cell realizing even better resolutions and/or higher pressure. Using this state-of-the-art experimental technique, we pursue novel magnetism under pressure.

18 Hayashi Group

Research Subjects: Quantum spintronics/optics

Member: Masamitsu Hayashi, Masashi Kawaguchi

In solids, it is understood that the spin angular momentum of electrons plays an important role in, for example, magnetism, superconductivity, electrical transport and optical properties of solids. In addition to electrons and photons, magnons (magnetic excitation), phonons (lattice vibration), and other excitations in solids possess spin angular momentum. We want to understand the dynamics of particles and waves with spin and how they influence the physical properties of solids.

- Spin current generation
  - Spin magnetic moment current in Dirac materials[4]
  The spin transport properties of Dirac Hamiltonian systems is studied using Bismuth as a model case. We find the spin Hall conductivity takes a maximum near the Dirac point and decreases with increasing carrier density. The sign of the spin torque conductivity is the same regardless of the position of the Fermi level. These features can be accounted for quantitatively using a Dirac Hamiltonian model if spin current is defined as a flow of spin magnetic moment. The results demonstrate that the giant spin magnetic moment, with an effective g factor that approaches 100, is responsible for the spin Hall effect in Bi.

- Chiral magnetism
  - Current induced domain walls in ferrimagnetic TbFeCo alloy[2]
  The direction to which domain walls move in a ferrimagnetic TbFeCo alloy changes when the Tb concentration crosses the magnetization compensation point. Interestingly, the domain walls move along (against) the current flow for FeCo-rich (deficient) films. These results suggest that two competing torques act on the domain walls in the Tb-based ferrimagnets (TbFeCo), causing the domain wall velocity to be more than one order of magnitude smaller than that of Gd-based ferrimagnets.

- Magnon-phonon coupling
  - Highly non-reciprocal transmission of surface acoustic waves[5]
  We find the transmission of surface acoustic waves (SAWs) in ferromagnetic/non-magnetic/ferromagnetic tryilayers is non-reciprocal. The SAW transmission amplitude depends on its propagation direction when the two ferromagnetic layers are coupled antiferromagnetically. The degree of such SAW non-reciprocity increases with increasing exchange coupling strength. These results show the potential of interlayer exchange coupled synthetic antiferromagnets for viable acoustic nonreciprocal transmission devices, such as circulators and isolators.

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[4] Z. Chi, G. Qu, Y.-C. Lau, M. Kawaguchi, J. Fujimoto, K. Takanashi, M. Ogata, M. Hayashi, Spin Hall effect driven by the spin magnetic moment current in Dirac materials. Phys. Rev. B 105, 214419 (2022).

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19 Kobayashi Group

Research Subjects: quantum sensing and mesoscopic physics

Member: Kensuke Kobayashi and Kento Sasaki

The development of nanotechnology since the 1980s has given rise to mesoscopic physics. This field aims to control various properties of matter using tiny electronic circuits (= mesoscopic systems) made from semiconductors, metals, superconductors, and magnetic materials. Developments in this field have led to the possibilities of various quantum technologies. One of these is quantum sensing, a precision measurement technique based on the principles of quantum mechanics. Our goal is to construct precise condensed matter physics based on quantum sensing.

Using color center quantum sensors, we are developing a single quantum spin microscope for diverse quantum sensing applications. This technique can quantitatively image the distribution of magnetic fields and temperature on a sub-micron scale in various environments. Such a technique has never existed in condensed matter physics. Many essential and fascinating topics, such as non-equilibrium transport, spin glass, topological edge states, and persistent currents, lie ahead.

In FY2022, we addressed the following research topics:

- Floquet engineering using pulse driving in a diamond two-level system
- Spin state readout optimization in a diamond quantum sensor
- Demonstration of geometric non-adiabatic dynamics
- Development of hexagonal boron-nitride quantum sensors
- Accurate magnetic field imaging using nanodiamond quantum sensors using machine learning
- Lock-in thermography using diamond quantum sensors
- Observation of quantum vortices in superconductors
- Magneto-optic Kerr effect measurement in a quantum spin microscope
- Microwave imaging

- Nonlinear conduction in magnetic tunnel junctions
- Determination of the Kondo temperature in quantum dots

Published papers:

[1] Y. Nakamura, *et al., AIP Advances* **12** (5), 055215 (2022).

[2] M. Tsukamoto, *et al., Scientific Reports* **12** (1), 13942 (2022).

[3] S. Nishimura, *et al., Physical Review Applied* **18** (6), 064023 (2022).

[4] K. Ogawa, *et al., Journal of the Physical Society of Japan* **92** (1), 014002 (2023).

[5] M. Shinozaki, *et al., Physical Review* B **107** (9), 094436 (2023).

20 Nakatsuji-Sakai Group

A new era in quantum materials research arises, featuring discoveries of novel topological phases of matter and interdisciplinary approaches. Our research activities focus on designing and synthesizing new materials with emergent quantum properties that have never been seen before, then exploring the physics and functionalities of such properties with our world-leading measurement facilities. We aim to lead the innovative quest for new quantum materials that bear a far-reaching impact not only on basic science but also on our everyday life in the future.

Major research themes:
1. Solid-state analogs of relativistic particles and new quantum phenomena in strongly correlated topological phases and frustrated magnets
2. Room-temperature topological transport in magnetic materials
3. Non-Fermi-liquid behavior and exotic superconductivity in multipolar Kondo materials

Summary of research subjects in 2022

1. Room-temperature tunneling magnetoresistance in an all-antiferromagnetic memory device [4]
Magnetoresistive random access memory (MRAM) has the potential to revolutionize computer memory by offering ultrafast, high-density, and energy-saving data storage and processing. A critical step to realizing such a possibility is to improve MRAM's operation speed and integration density; both factors are currently limited by the ferromagnetic materials used for this technology. Antiferromagnets have recently emerged as promising constituents for future ultrahigh-speed on-chip MRAM, owing to their thousandfold faster spin dynamics and lack of a stray field. However, a critical challenge to address is demonstrating the tunneling magnetoresistance (TMR) in all-antiferromagnetic MRAM, which is essential as a reading protocol. In this study, we report the observation of a finite room-temperature TMR in all-antiferromagnetic spintronics devices comprising Mn_3Sn, which breaks the common belief that TMR is directly related to interfacial spin polarization, and thus is restricted to ferromagnetic materials. This first-of-its-kind demonstration not only pushes the boundaries of operation speed in magnetic memory but also lays a firm foundation for advancing all-antiferromagnetic MRAM toward commercialization.

2. Full electrical switching of antiferromagnet unlocks unprecedented speed and capacity for spintronic devices [2]
Spintronic applications make a great leap forward by turning to antiferromagnets. Antiferromagnetic memories are insensitive to stray fields and can operate hundreds of times faster than their ferromagnetic counterparts. These unique characteristics open the door to high-speed, high-density, and low-power data processing. A major obstacle, though, is the difficulty in controlling the antiferromagnetic spin structure, which limits the device' s performance. In this study, we achieved full electrical switching of the antiferromagnetic Mn_3Sn for the first time, enabled by applied 0.2% tensile strain owing to the lattice mismatch with the substrate. Such switching maximizes the device's operating speed and dramatically simplifies the device configuration, setting down a vital milestone in antiferromagnetic spintronics.

3. Large piezomagnetic effect allows strain control of antiferromagnet [3]
Identifying effective control knobs for antiferromagnets is key to pushing forward their spintronic applications. In this study, we found sizable piezomagnetic effect in the topological antiferromagnet Mn_3Sn, famous for its nearly magnetization-free anomalous Hall effect. This piezomagnetic effect enables an applied strain as small as about 0.1% to reverse the sign of the anomalous Hall signal by rotating the underlying spin structure. The effective strain control of the anomalous Hall effect complements the conventional means, such as a magnetic field and electric current, and will be indispensable for widening the scope of topological antiferromagnetic spintronics.

4. Ultrafast dynamics of the Anomalous Hall effect in the topological antiferromagnet Mn_3Sn [5]
The large, magnetization-free anomalous Hall effect in Mn_3Sn makes the material highly promising for achieving all-antiferromagnetic memory devices with unprecedented operation speed and minimal energy consumption. Previous research using THz time-domain spectroscopy found that the nonequilibrium AHE in the THz-regime resembles the static AHE and is nearly dissipation-free at room temperature. This result suggests that the observed THz-scale AHE could be used for the electrical readout of high-speed magnetic memory. To realize this perspective, a sub-picosecond time-resolved investigation is necessary to clarify the origin of the nonequilibrium AHE and its interplay with the time evolution of the underlying magnetic order. Our new study investigates the dynamics of AHE in Mn_3Sn using ultrashort optical pulses with sub-100fs time resolution. By comparing the experimental results with microscopic calculations, we conclude that the intrinsic Berry-curvature mechanism is responsible for the nonequilibrium AHE. This work demonstrates that nonequilibrium dynamics can provide essential clues to the microscopic mechanism of anomalous transport.

5. Fabrication and thermal stability of nanoscale grains of the Weyl antiferromagnet Mn_3Sn [1]
A key step towards the integration of Mn_3Sn into electronics is to establish the functionality of the material with nanoscale dimensions. In this study, we fabricated isolated island-like structures of Mn_3Sn with diameters of one to several hundred nanometers through deposition of Mn_3Sn on a Si/SiO_2 substrate kept at a high temperature [1]. By connecting the islands using an extra aluminum conducting layer, we were able to measure the transport properties of the grains in series, confirming that they exhibit the large anomalous Hall effect indicative of the time-reversal symmetry breaking magnetic structure. The stability of the magnetic orientations of these islands under ambient temperature was confirmed through the transport measurements, indicating promise for functional nanoscale devices based on Mn_3Sn.

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21 Theoretical Astrophysics Group

Research Subjects: Observational Cosmology, Extrasolar Planets, Star Formation, high-energy astrophysics, and Artificial Intelligence

Member: Yasushi Suto, Naoki Yoshida, Kotaro Fujisawa , Kana Moriwaki & Tilman Hartwig

The Theoretical Astrophysics Group conducts a wide range of research programmes. Observational cosmology is our primary research area, but we also pursue other forefront topics such as extrasolar planets, star formation, high-energy astrophysics, and artificial intelligence.

"Observational Cosmology" attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of recent and future data provided by Planck, Hubble Space Telescope, ALMA, and wide-field galaxy surveys such as Subaru Hyper-Suprime-Cam survey are very 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 evolution of the universe. Our current interests include non-linear 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, statistics of gravitationally lensed quasars, and the chemical formation history of the Milky Way.

Astronomical observations utilizing large ground-based telescopes discovered distant galaxies and quasars that were in place when the Universe was less than one billion years old. We can probe the evolution of the cosmic structure from the present-day to such an early epoch. Shortly after the cosmological recombination epoch when hydrogen atoms were formed, the cosmic background radiation shifted to infrared, and then the universe would have appeared completely dark to human eyes. A long time had to pass until the first generation stars were born, which illuminated the universe once again and terminate the cosmic Dark Ages. We study the formation of the first stars and blackholes in the universe. The first stars are thought to be the first sources of light, and also the first sources of heavy elements that enable the formation of ordinary stellar populations, planets, and ultimately, the emergence of life. We perform simulations of structure formation in the early universe on supercomputers. Direct and indirect observational signatures are explored considering future radio and infrared telescopes. We study the formation and mixing of the first heavy elements in the universe. Comparing the predictions of our simulations to observations allows us to better understand the nature of the underlying physical processes.

Can we discover a second earth somewhere in the universe? This puzzling question used to be very popular only in science fictions, but is now regarded as a decent scientific goal in the modern astronomy. Since the first discovery of a gas giant planet around a Sun-like star in 1995, more than 4000 exoplanets have been reported as of March 2021. Though most of the confirmed planets turned out to be gas giants, the number of rocky planet candidates was steadily increasing, which therefore should give the affirmative answer to the above question. Our approaches towards that exciting new field of exoplanet researches include the spin-orbit misalignment statistics of the Rossiter-MacLaughlin effect, simulations of planet-planet scattering, simulations of tidal evolution of the angular momentum of the planetary system, photometric and spectroscopic mapping of a surface of a second earth and detection of possible biomarker of habitable planets.

To maximise the information gain from astrophysical observations and numerical simulations, we also apply and develop state-of-the-art machine learning techniques. We use supervised machine learning algorithms to classify observations of metal-poor stars, quasars, and satellite galaxies of the Milky Way. We improve existing deep learning methods with a new class of activation functions that allow users to improve the extrapolation properties of their neural networks. Artificial intelligence (AI) is a rapidly evolving field with many promising applications. To better understand the social impact of AI research, we also collaborate with social scientists to better understand the impact and public attitudes towards AI research.

Let us summarize this report by presenting recent titles of the PhD and Master's theses in our group;

2022

- Formation and evolution of star clusters and galaxies in the early Universe
- Understanding Atmospheric Escape of Hot Jupiters Using Radiation Hydrodynamics Simulations
- Neutron-capture element enrichment of early galaxies

2021

- Study on the effect of supernova fallback on the neutron star diversity
- Gravitational hierarchical three-body systems with an invisible inner binary: application to binary black-hole search and their dynamical stability
- Analysis of the Large-Scale Structure of the Universe Using Cosmological Simulations and Machine Learning
- Planetary systems predicted from the ALMA disks: planet-disk evolution and long-term orbital stability of multi-planets
- Structure Formation of the Universe with Fuzzy Dark Matter
- Dispersal mechanism of proto-planetary disks

2020

- Observational signatures from tidal disruption events of white dwarfs
- Multiwavelength Signals From Pulsar-Driven Supernovae
- Measuring stellar rotation periods and stellar inclinations of kepler solar-type stars

2019

- Observational characterization of protoplanetary disks, exo-rings, and Earth-twins in exoplanetary systems
- Non-sphericities and alignments of clusters and central galaxies from cosmological hydrodynamical simulation: theoretical predictions and observational comparison
- Probing Cosmic Star-Formation History with Blind Millimetre Searches for Galaxy Emission Lines
- Photoevaporation process of giant planets
- Dilution of heavy elements in galaxies and its implications

2018

- Stellar Inclinations from Asteroseismology and their Implications for Spin-Orbit Angles in Exoplanetary Systems
- Numerical Investigations on Explosion Mechanisms of Core-collapse Supernovae
- Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev-Zel′dovich Effect
- Photoevaporation of Protoplanetary Disks and Molecular Cloud Cores in Star-Forming Regions
- Numerical Algorithms for Astrophysical Fluid Dynamics
- Radial velocity modulation of an outer star orbiting an unseen inner binary: analytic perturbation formulae in a three-body problem to search for wide-separation black-hole binaries
- The distribution and physical properties of emission line galaxies in the early universe
- Diversities out of the observed proto-planetary disks: migration due to planet-disk interaction and architecture of multi-planetary systems

2017

- Formation of supermassive stars and black holes via direct gravitational collapse of primordial gas clouds
- Formation and growth of massive black holes in the early universe
- Measuring Dynamical Masses of Galaxy Clusters with Stacked Phase Space
- GCM simulation of Earth-like planets for photometric lightcurve analysis
- Tidal disruption events of white dwarfs caused by black holes
- Radio, Submillimetre, and Infrared Signals from Embryonic Supernova Remnants

22 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao and Hayata Yamasaki

Quantum mechanics allows a new type of information represented by quantum states which may be in a superposition of 0 and 1 state. Quantum information processing seeks to perform tasks that are impossible or not effective with the use of conventional classical information, by manipulating quantum states to the limits of quantum theory. Examples are quantum computation, quantum cryptography, and quantum communication.

We consider that a quantum computer is not just a machine to run computational algorithms but also a machine to perform any operations allowed by quantum mechanics. We analyze what kinds of new properties and effects may appear in quantum systems by using quantum computers to improve our understanding of quantum mechanics from an operational point of view. We also investigate applications of quantum properties and effects such as entanglement for information processing, communication, quantum learning, and quantum manipulations by developing quantum algorithms and quantum protocols.

This year, our group consisted of faculty members, Mio Murao (Professor), Hayata Yamasaki (Assistant Professor), postdoctoral researchers, Bartosz Regula (JSPS foreign postdoctoral fellow), Philip Taranto (JSPS foreign postdoctoral fellow), Hlér Kristjánsson (Postdoctoral researcher), graduate students, Wataru Yokojima (D3), Yutaka Hashimoto (D1), Yu Tanaka (D1), Timothy Forrer (D1), Satoshi Yoshida (M2) and Tatsuki Odake (M1). Our projects engaged in the academic year of 2022 were the following:

- Distributed quantum information processing
  - Distribution of non-local gates between networks of quantum computers (By Forrer, Murao)
  - Distributed quantum computing with entanglement-assisted packing processes (By Forrer, Murao)
- Quantum machine learning and Quantum learning
  - Quantum state generation via binary decision diagram (By Tanaka, Yamasaki, Murao)
  - Quantum neural networks with coherent control (by Kristjánsson, Yamasaki, Murao)
  - Quantum simulation of unitary comparison (By Hashimoto, Murao)
  - Quantum ridgelet transform (by Yamasaki)
- Higher-order quantum computation
  - Algorithm for transforming Hamiltonian dynamics (By Odake, Kristjánsson, Soeda, Murao)
  - Deterministic exact algorithm for inverting qubit-unitary operations (By Yoshida, Murao)
  - Catalytic supermaps (by Kristjánsson, Yoshida, Taranto, Murao)
- Indefinite causal order
  - Decomposition of unitarily extendable n-partite processes (by Yokojima, Kristjánsson, Murao)

  - Simulatability of quantum switch using definite causal order (by Kristjánsson, Taranto, Murao)

- Quantum thermodynamics
  - Landauer vs. Nernst: what is the true cost of cooling a quantum system (By Taranto)

- Quantum resource theories
  - Irreversibility of quantum entanglement (By Regula)
  - Tight constraints on the probabilistic convertibility of quantum states (By Regula)

- Quantum error correction
  - Low-depth random Clifford circuits for quantum coding against Pauli noise (By Yamasaki)
  - Time-efficient constant-space-overhead fault-tolerant quantum computation (By Yamasaki)

23 Ueda Group

Research Subjects: Bose-Einstein condensation, fermionic superfluidity, topological phenomena, open quantum systems, information thermodynamics, quantum information, measurement theory, machine learning

Member: Masahito Ueda and Masaya Nakagawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controllable systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose-Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied nonunitary dynamics of atomic gases subject to dissipation and/or measurement backaction, classification of phases of matter in nonequilibrium open systems, quantum Hall effect and vortex lattices in synthetic gauge fields, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems and the formulations of state reduction dynamics and Hamiltonian estimation in light of information flow under measurements and feedback controls. Furthermore, we have recently tackled an understanding of AI and machine learning from a viewpoint of physics. We list our main research subjects in FY2022 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Embedding of the Yang-Lee quantum criticality in open quantum systems [1]
  - Universal properties of dissipative Tomonaga-Luttinger liquids [2]
  - Eigenstate thermalization in long-range interacting systems [3]
- Unification of quantum physics, statistical mechanics, information theory, and machine learning
  - Fundamental theory for training deep neural networks [4, 5, 6]
  - Universal thermodynamic uncertainty relation in nonequilibrium dynamics [7]
  - Control of a quantum rigid body using reinforcement learning [8]

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[7] Liu Ziyin and Masahito Ueda, Phys. Rev. Research **5**, 013039 (2023).

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24 Yokoyama (J) Group

Research Subjects: Theoretical Cosmology and Gravitational Waves

Member: Jun'ichi Yokoyama, Kohei Kamada, and Ryusuke Jinno

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We have also been working on gravitational wave data analysis to prepare for completion of KAGRA. Below is the list of topics studied during the academic year 2021.

Early Universe Cosmology

- Vacuum decay in the Lorentzian path integral
- One-loop correction on the primordial curvature perturbation from single-field inflation
- Schwinger reheating through the helical gauge field amplification
- Backreaction on the axion inflation from the charged particle production
- Chiral effects in cosmology

- Baryogenesis in the axion inflationary scenario
- Precise calculation of the cosmic birefringence
- Baryogenesis from sphaleron decoupling
- Condition of the PBH formation with conditional probability
- Time evolution of the primordial magnetic field
- Baryon isocurvature perturbation from primordial magnetic field
- Production of radiation, dark matter, and baryon asymmetry in quintessential inflation with hierarchical right-handed neutrinos
- Reheating in the R^2 inflation model with massive right-handed Majorana neutrinos
- Ruling out PBH formation in the single-field inflation models
- Machine learning post-Minkowskian integrals
- Borel resummation in stochiastic inflation
- First order phase transition in the early Universe
- Gradient flow method for the construction of saddle-point solutions

Gravitational wave analysis

- Noise removal method with environmental monitors
- Observational constraints on cosmic string with particle and gravitational wave emission
- Exploration of light dark matter

Time-domain astronomy

- Observation of the flare from red dwarf stars with Tomo-e Gozen camera

25 Ejiri Group

Research Subjects: high temperature plasma physics experiments, spherical tokamak, wave heating and current drive, nonlinear physics, collective phenomena, fluctuations and transport, advanced plasma diagnostics development

Member: Akira Ejiri, Naoto Tsujii

In our laboratory, we conduct research on magnetically confined torus plasma with the goal of realizing nuclear fusion energy. In addition to conducting experimental research using the TST-2 device at the Kashiwa Campus, we are also conducting joint research with National Institutes for Quantum and Radiological Science and Technology (QST), National Institute for Fusion Science (NIFS), Kyushu University, and the University of Tsukuba. We are also conducting joint research with overseas institutions such as Tokamak Energy. In TST-2, we use powerful wave heating to generate a highly non-linear self-organized plasma through fast electron generation and current drive. Our laboratory is working on various physics of waves and fast electrons.

TST-2 is a spherical tokamak (ST) with the major radius of 0.36 m and the minor radius of 0.23 m. The maximum plasma current is 120 kA for inductive operation and 27 kA for non-inductive operation using radio frequency waves. At TST-2, we mainly use the Lower-Hybrid Wave (LHW) to study non-inductive current drive. In 2022, we started experiments using a new off-midplane launch LHW antenna. Initial experiments showed improvement in the heating efficiency at the plasma core as it was designed. The x-ray radiation was also observed to be small compared to the previously studied top launch scenario, which indicated that LHW driven fast electron losses were reduced. The efficiency for LHW current drive can be also limited by parasitic LHW loss mechanisms at the edge. Ion heating was observed in correlation with parametric decay activities. Fast electron losses were studied by measuring thick-target x-ray radiation at the target limiter. Theoretically, fast electron energy is expected to increase with major radius around the low-field side scrape-off layer (SOL) if the electrons are accelerated at the high-field side. During the outer-midplane antenna pulse, the x-ray flux increased by an order of magnitude when the target limiter was moved outward across the SOL. In contrast, during the top antenna pulse, the intensity increased slightly before it decreased by a factor of five. Fast electron transport model is being developed to explain the observed characteristics. Impurity generation at the LHW antenna can be a problem since radiation by high-Z impurities may cool the plasma and density may increase in an uncontrolled way. Mo radiation was observed to increase linearly during the outer-midplane antenna pulse near the antenna and drop promptly when the power was turned off. Hot plasma finite element full-wave simulation was developed to perform realistic simulation of LHW excitation.

Diagnosis and suppression of runaway electrons are important issues in a tokamak fusion reactor. The fast electron characteristics may be studied by measuring the instabilities driven by fast electrons. We have observed instabilities with magnetic probes during the plasma current ramp-down in TST-2. During the period when instabilities were observed, no visible radiation was observed and only x-ray radiation was observed, suggesting that only fast electrons remain. Coherent magnetic fluctuations were observed over a wide range of frequencies from several tens of MHz to several hundreds of MHz, which may help understand fast electron transport during this time.

To improve the startup reliability of superconducting tokamaks, we study EC (Electron Cyclotron) wave-assisted Ohmic startup in the Trapped Particle Configuration (TPC). In FY2022, to quantitatively understand the TPC start-up characteristics, we modeled the fast electron transport using the collisionless kinetic equation and estimated the parameter regime for successful start-up. It was predicted that the low neutral pressure limit increased at high power for pure EC start-up and that the low pressure limit decreased at stronger vertical magnetic field strength. Introduction of small loop voltage did not significantly alter this parametric dependence. The predictions were consistent with TST-2 experimental results.

Microwave polarimeter is developed to measure directly the internal current profile of LHW driven plasmas. In 2022, the diagnostic principle was verified by measuring the known toroidal magnetic field. We have also developed a double-pass Thomson scattering system, a compact magnetic probe and spectroscopy.

Particle transport over a very long period of time is studied in QUEST at the Kyushu University. In 2022, we have upgraded the Thomson scattering diagnostic to measure the discharge for tens of minutes. We found that it took about 300 seconds for the EC driven plasma to reach a steady state. This time scale is thought to represent the time scale for the particles to interact with the wall.

26 Yamamoto Group

Research Subjects: Millimeter- and submillimeter-wave Astronomy, Star and Planet Formation, Chemical Evolution of Interstellar Molecular Clouds

Member: Satoshi Yamamoto and Yoko Oya

Molecular clouds are birthplaces of new stars and planetary systems, which are being studied extensively as an important target of astronomy and astrophysics. Although the main constituent of molecular clouds is a hydrogen molecule, various atoms and molecules also exist as minor components. The chemical composition of these minor species reflects formation and evolution of molecular clouds as well as star formation processes. It therefore tells us how each star has been formed. We are studying star formation processes from such an astrochemical viewpoint.

Since the temperature of a molecular cloud is $10 - 100$ K, an only way to explore its physical structure and chemical composition is to observe the radio wave emitted from atoms, molecules, and dust particles. Particularly, there exist many atomic and molecular lines in the millimeter/submillimeter wave region, and we are observing them toward formation sites of Solar-type protostars mainly with ALMA (Atacama Large Millimeter/submillimeter Array).

So far, it has well been recognized that an envelope/disk system of a Solar-type protostar shows a significant chemical diversity. One distinct case is so called Warm Carbon Chain Chemistry (WCCC), which is characterized by rich existence of various unsaturated carbon-chain molecules such as C_2H, C_4H, and HC_5N. A prototypical source is L1527 in Taurus. Another distinct case is so called hot corino chemistry, which is characterized by rich existence of various saturated organic molecules such as CH_3OH, $HCOOCH_3$, and C_2H_5CN. A prototypical source is IRAS 16293–2422 in Ophiuchus. Recently, sources having the both characteristics have also be found. Such chemical diversity would reflect the star formation history of each source, more specifically, a duration time of the starless core phase.

We are now studying how such chemical diversity is brought into protoplanetary disks by using ALMA. For the WCCC source L1527, we have found that carbon-chain molecules only exist in an infalling-rotating envelope outside its centrifugal barrier ($r = 100$ AU), while SO preferentially exists around the centrifugal barrier. For the hot corino source IRAS 16293–2422, OCS traces an infalling-rotating envelope, while saturated organic molecules such as CH_3OH and $HCOOCH_3$ trace the centrifugal barrier. Hence, chemical compositions drastically change across the centrifugal barrier of the infalling gas. Since a protostellar disk is formed inward of the centrifugal barrier, the chemical diversity at an envelope scale (~ 1000 au) is indeed inherited in the disk forming region (~ 100 au). Then, what is the initial chemical condition of the Solar System? Is it a common occurrence in our Galaxy? To answer these questions, the ALMA large program FAUST (Fifty AU Study of the chemistry in the disk/envelope system of Solar-like protostar) is ongoing.

Furthermore, we are now incorporating machine-learning techniques to explore the physical and chemical structures in an unbiased way.

Note: Our group is closed on March 31, 2023 due to formal retirement of Satoshi Yamamoto. Yoko Oya already moved Kyoto University on Oct.1, 2022.

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27 Sakai (Hirofumi) Group

Research Subjects: Experimental studies of atomic, molecular, and optical physics

Members: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (3) Ultrafast phenomena in atoms and molecules in the attosecond time scale. (4) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. A part of our recent research activities is as follows:

(1) All-optical control of pendular qubit states with nonresonant two-color laser pulses [1]

Practical methodologies for quantum qubit controls are established by two prerequisites, i.e., preparation of a well-defined initial quantum state and coherent control of that quantum state. Here we propose a new type of quantum control method, realized by irradiating nonresonant nanosecond two-color (ω and 2ω) laser pulses to molecules in the pendular (field-dressed) ground state. The two-color field nonadiabatically splits the initial pendular ground state $|\tilde{0},\tilde{0}\rangle$ to a superposition state of $|\tilde{0},\tilde{0}\rangle$ and $|\tilde{1},\tilde{0}\rangle$, whose relative probability amplitudes can be controlled by the peak intensity of one wavelength component (ω) while the peak intensity of the other component (2ω) is fixed. The splitting of the quantum paths is evidenced by observing degrees of orientation of ground-state selected OCS molecules by the velocity map imaging technique. This quantum control method is highly advantageous in that any type of polar molecules can be controlled regardless of the molecular parameters, such as rotational energy, permanent dipole moment, polarizability, hyperpolarizability, and hyperfine energy structures.

(2) Ultrafast X-ray photoelectron diffraction from free molecules: Simulations of diffraction profiles from transient intermediates in the elimination reaction of $C_2H_4I_2$ [2]

We have performed the simulations of C1s X-ray photoelectron diffraction (XPD) profiles from $C_2H_4I_2$, bridged and classical anti-forms of C_2H_4I intermediates and C_2H_4 products to capture structures of transient intermediates in the elimination reaction of $C_2H_4I_2$, under our ultrafast X-ray photoelectron diffraction (UXPD) scheme for free molecules using soft X-ray free-electron laser (SXFEL). In the UXPD scheme, the sample molecules are aligned in advance by near-infrared (NIR) laser with ns pulse duration before applying a pump-probe method. Then, we have considered alignment control of $C_2H_4I_2$ by using the elliptically polarized NIR laser to realize the UXPD experiments for the free molecules. As the results of simulations of XPD profiles from the laser-aligned $C_2H_4I_2$ molecules, we have demonstrated the two-dimensional (2D) color maps of the C1s XPD profiles from $C_2H_4I_2$, C_2H_4I, and C_2H_4. The 2D color maps have revealed that the transient C1s XPD profiles from the bridged-form and classical anti-form C_2H_4I intermediates exhibit remarkable differences, reflecting different intra-molecular scattering pathways of C1s photoelectrons within the intermediates. Thus, the present result has proved that UXPD for the free molecules has an advantage, compared with other traditional diffraction methods.

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28 Gonokami Group

Research Subjects: Experimental studies on light-matter interaction in many-body quantum systems, optical phenomena in artificial nanostructures, and development of laser based coherent light sources

Member: Makoto Gonokami and Junji Yumoto

We explore new aspects of many-body quantum systems and their exotic quantum optical effects by designing light-matter interactions. Our current target topics consist of a wide variety of matters, including excitons and electron-hole ensembles in semiconductors, and ultra-cold atomic gases. In particular, we have been investigating the phase of Bose-Einstein condensation of excitons, which has not been experimentally proven while considered as the ground state of an electron-hole ensemble. Based on quantitative spectroscopic measurements, the temperature and density of the excitions are determined in a quasi-equilibrium condition where they are trapped in a highly pure crystal kept below 1 K. We are now investigating a stable Bose-Einstein condensate of dark excitons at the low temperature. We also study lthe mechanism of laser ablation by femtosecond lasers. Furthermore, we are now developing novel coherent light sources and spectroscopic methods. We achieved precision measurements of the refractive index of materials in an EUV region using techniques of higher-order harmonics generation. We also developed laser-based angle resolved photoemission spectroscopy using time-of-flight photoelectron analyzer.

The group activities of this year are as follows:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   - 1.1. Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   - 1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases
2. Investigation for non-trivial optical responses and development of applications:
   - 2.1. Exploring the mechanism of laser ablation by femtosecond lasers
3. Development of novel coherent light sources and spectroscopic methods:
   - 3.1. EUV precision spectroscopy using higher-order harmonics
   - 3.2. Laser-based angle resolved photoemission spectroscopy
   - 3.3. Institute for Photon Science Technology

29 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Kentaro Komori

Gravitational waves has a potential to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars or binary black holes; 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 and improve detectors.

In Japan, we are constructing a large-scale cryogenic gravitational-wave antenna, named KAGRA, at Kamioka underground site. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200 Mpc. A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

The current research topics in our group are followings:

- KAGRA gravitational wave detector
- Space laser interferometer, DECIGO and precursor missions
- Development of TOBA (Torsion Bar Antenna)

- Dark Matter Seach
- High-precision experiments on relativity and opto-mechanics

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30 Bamba Group

Research Subjects: High-energy astrophysics, mainly utilizing X-ray/Gamma-ray observatories in orbit. Targets are, supernova remnants, black-holes, neutron-stars, magnetars, white dwarfs, active galactic nucleus, and so on.

Member: Associate Prof: Aya Bamba, Assistant Prof: Hirokazu Odaka (– December), Kouichi Hagino (January –)

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants, compact stars such as neutron stars and blackholes, and active galactic nucleus. Such high energy objects emit X-rays and gamma-rays, thus we observe such high energy photons using balloons and satellites. This year we focused our research specifically on neutron stars (NSs), supernova remnants, and NS-NS merger remnants, as well as the development of coming missions, XRISM, GRAMS, and cipher.

Neutron stars are compact stars, as dense as nuclei, and have quite large dipole magnetic field of $\sim 10^{12-15}$ Gauss. Neutron stars accreted from companion stars are ideal to study with high X-ray luminosities. We have made wide band spectroscopy of the bright accreting neutron star, Cen X-3, and succeeded to resolve the orbital and rotational variabilities. With this analysis, we found that the original emission from the neutron star is stable and the absorption partially cover the neutron star make the complicated time variability. We have made similar analysis to another accreting pulsar, Her X-1, and derived the geometric structure of emission column. We also made the first systematic study of wide-band spectroscopy of nebulae of pulsars. Supernova remnants distribute heavy elements and cosmic rays into the space, and makes the diversity of the universe. It is unknown which environmental parameters changes the spectrum and acceleration efficiency of cosmic rays. We have made spatially resolved spectroscopy of the young SNR, Kepler's remnant, and found that there are two regime to determine the acceleration efficiency; the low medium environment with high shock speed and strong magnetic field due to the interaction between shocks and interstellar medium.

We will launch our next generation satellite, XRISM on Japanese fiscal year 2023, and now in preparation. We also have a plan to launch balloon experiment for engineering demonstration experiments of GRAMS.

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31 Kusaka Group

Research Subjects: Observational Cosmology, Cosmic Microwave Background (CMB) Observation, Dark Matter Search. (1) Study of Inflation in the early universe and the evolution of the universe through gravitational lensing using Polarbear and Simons Array experiment; (2) Design, Development, and Construction of Simons Observatory aiming to study Inflation, evolution of the universe, Neutrinos, Dark Energy, and Dark Radiation; (3) Research and Development of technologies for Simons Observatory and CMB-S4; (4) Dark matter search using Magnon.

Member: A. Kusaka and K. Kiuchi

- POLARBEAR experiment and its successor, Simons Array, are optimized to measure both inflationary signature and the gravitational lensing effect in CMB polarization. POLARBEAR experiment has concluded its observation campaign, and Simons Array experiment started the osbervation. Our focus is on data analysis as well as the development and characterization of the continuously-rotating half-wave plate (HWP) enabling accurate measurement of CMB polarization.
- Simons Observatory experiment is under constraction, with the first light expected in two years. We plan to deploy an array of what we call "small aperture telescopes," which are dedicated for the inflationary signal, and a six-meter "large aperture telescope," which enables observation for Neutrinos and the dark content of the universe. We are primarily focusing on the design and development for the small aperture telescope.
- Research and Development for the next generation experiments such as Simons Observatory and CMB-S4 are crucial component of our research program. We specifically work on superconducting technologies used in the detectors, cryogenic bearing system for HWP, and anti-reflection coating for high-index optical material. We also develop techniques for high-performance computation (HPC) enabling data analysis for new experiments producing order-of-magnitude larger data volume than the current instruments.
- Dark matter accounts for about 80% of the matters in the Universe. Axion is one of the candidates of the dark matter. In searching for relatively light dark matters such as axion, detectors free from standard quantum limit (SQL), which constrains the sensitivity of conventional methods, play an important role. We are developing Magnon Q-bit hybridized system to overcome SQL aiming at the axion dark matter search.

32 Takeuchi Group

Research Subjects: Experimental statistical physics for non-equilibrium systems

Members: Kazumasa A. Takeuchi and Daiki Nishiguchi

We aim to explore statistical physics of out-of-equilibrium phenomena experimentally. Using soft and living matter, such as liquid crystal, colloids, and granular materials, as well as bacteria, we carry out experiments that we design to capture underlying physical principles, in addition to the understanding of specific phenomena we observe. As a result, we deal with diverse subjects in the group, sometimes enjoying interesting connections in between. More specifically, we carried out the following projects among others in the academic year 2022:

(1) Non-equilibrium phenomena in soft matter systems
(1-1) Observation of 3D dynamics of topological defect lines in nematic liquid crystal [2]
(1-2) Negative viscosity and spontaneous flow formation of liquid crystal turbulence
(1-3) Sponge-like granular media
(1-4) Model experiment of stochastic particle transport

(2) Non-equilibrium phenomena in living systems
(2-1) Physics underlying heterogeneity of bacterial community
(2-2) Glass transition of bacterial populations [8]
(2-3) Magnetic response of collective motion of bacteria

(3) Approaches based on nonlinear science
(3-1) Route to turbulence in an active fluid model under confinement
(3-2) Algorithm to measure large deviations in non-equilibrium interfaces

More detailed information can be found at the group's website, `https://lab.kaztake.org/`

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33 Mio Group

Research Subjects: Application of lasers

Member: Norikatsu Mio

Mio Group is conducting research on lasers and their applications. Since the laser was invented in 1960, the laser technology has been widely used in various fields as a fundamental technology that supports modern society, thus is extremely important and indispensable for communication, information technology, material processing and so on. In addition, state-of-the-art photon technology was used in the first observation of a gravitational wave in 2015; photon science and technology work as an important bridge between academia and society.

Our laboratory belongs to Institute for Photon Science and Technology (IPST), where various researches are conducted to deepen science and to promote collaboration with industry. IPST has many members in addition to our laboratory; all of them are working closely together to promote research and education(http://www.ipst.s.u-tokyo.ac.jp).

Physics on laser material processing

The processes such as cutting and welding, using lasers are called laser processing. Since advances in laser sources have made it possible to use high-power ultraviolet light and to control pulse widths and wavelengths more freely, the development of new processing has become possible.

However, the actual phenomena are non-equilibrium, open systems, and the interaction between laser light and materials is in a region that cannot be explained by a perturbative approach. The goal of this project is to advance our understanding of this phenomenon and to develop its application.

We are now investigating the non-linear effects on laser beam propagation for laser material processing and the applications of the fine-processing using femto-sesond laser pulses.

KAGRA project

More than seven years have already passed since gravitational waves were actually detected. The number of events detected to date reaches 90 and observations of gravitational waves become important to build a new picture of the universe.

In Japan, KAGRA is being constructed in the Kamioka Mine in Gifu Prefecture. KAGRA takes advantage of the quiet underground environment and incorporates cryogenic technology. to improve its sensitivity.

Currently, we are cooperating with LIGO in the U.S. and VIRGO in Europe. KAGRA is being improved to join international joint observation called O4 (scheduled to start in May 2023). Our group is involved in developing the laser source of KAGRA. Now, a new solid-state laser that has higher power and stability is being evaluated for replacing the current laser source.

34 Nose Group

Research Subjects:Formation and function of neural networks

Member:Akinao Nose and Teruyuki Matsunaga

The aim of our laboratory is to elucidate the mechanisms underlying the formation and function of neural networks, by using as a model, the simple nervous system of the fruitfly, *Drosophila*. A part of our recent research activity is summarized below.

1.Extraction of bouton-like structures from neuropil calcium imaging data.

The neuropil, the plexus of axons and dendrites, plays a critical role in operating the circuit processing of the nervous system. Revealing the spatiotemporal activity pattern within the neuropil would clarify how the information flows throughout the nervous system. However, calcium imaging to examine the circuit dynamics has mainly focused on the soma population due to their discrete distribution. Here, we propose a new method to decompose calcium imaging data of the neuropil into populations of bouton-like synaptic structures with a standard desktop computer. To extract bouton-like structures from calcium imaging data, we introduced a new type of modularity, a widely used quality measure in graph theory, and optimized the clustering configuration by a simulated annealing algorithm, which is established in statistical physics. To assess this method’s performance, we conducted calcium imaging of the neuropil of *Drosophila* larvae and established artificial neuropil imaging datasets. We applied the decomposition procedure to the artificial and experimental calcium imaging data and extracted individual bouton-like structures successfully. Based on the extracted spatiotemporal data, we analyzed the network structure of the central nervous system of fly larvae and found it was scale-free. These results demonstrate that neuropil calcium imaging and its decomposition could provide new insight into our understanding of neural processing.

2. A neuromechanical model for *Drosophila* larval crawling based on physical measurements.

Animal locomotion requires dynamic interactions between neural circuits, the body (typically muscles), and surrounding environments. While the neural circuitry of movement has been intensively studied, how these outputs are integrated with body mechanics (neuromechanics) is less clear, in part due to the lack of understanding of the biomechanical properties of animal bodies. Here, we propose an integrated neuromechanical model of movement based on physical measurements by taking *Drosophila* larvae as a model of soft-bodied animals. We first characterized the kinematics of forward crawling in *Drosophila* larvae at a segmental and whole-body level. We then characterized the biomechanical parameters of the larvae, namely the contraction forces generated by neural activity, and passive elastic and viscosity of the larval body using a stress-relaxation test. We established a mathematical neuromechanical model based on the physical measurements described above, which succeeded in quantitatively reproducing the kinematics of larval locomotion that were obtained experimentally and the observation of optogenetic studies reported previously. Furthermore, the model predicted a significant contribution of intersegmental connections in the central nervous system, which contrasts with a previous study. In conclusion, we generated a neurochemical model based on physical measurement to provide a new foundation to study locomotion in soft-bodied animals and soft robot engineering.

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35 Higuchi Group

Research Subjects:Protein dymamics in vitro,cells and mice

Member:Hideo Higuchi and Motoshi Kaya

35.1 Oscillation by the minimum model system of flagella

Bending of cilia and flagella occurs when axonemal dynein molecules on one side of the axoneme produce force and move toward the microtubule minus end. These dyneins are then pulled back when the axoneme bends in the other direction, meaning oscillatory back and forth movement of dynein during repetitive bending of cilia/flagella. There are various factors that may regulate the dynein activity, e.g. the nexin-dynein regulatory complex, radial spokes, and central apparatus. In order to understand the basic mechanism of dynein’ s oscillatory movement, we constructed a simple model system composed of microtubules, outer-arm dyneins, and crosslinks between the microtubules made of DNA origami. Electron microscopy showed pairs of parallel microtubules crossbridged by patches of regularly arranged dynein molecules bound in two different orientations, depending on which of the microtubules their tails bind to. The oppositely oriented dyneins are expected to produce opposing forces when the pair of microtubules have the same polarity. Optical trapping experiments showed that the dynein- microtubule -DNA-origami complex actually oscillates back and forth after photolysis of caged ATP. Intriguingly, the complex, when held at one end, showed repetitive bending motions. The results show that a simple system composed of ensembles of oppositely oriented dyneins, microtubule s, and inter- microtubule crosslinkers, without any additional regulatory structures, has an intrinsic ability to cause oscillation and repetitive bending motions.

35.2 Quantitative evaluation of intracellular vesicle diffusion in weakened cells.

When cells are exposed to an unsuitable environment for growth, they become weakened and the survival rate after a period decreases. Weakened cells show changes in their state, such as shape contraction, compared to healthy cells, and these changes in cell state are considered to contribute to the survival rate of the cells. However, it is not known in detail how the state of weakened cells differs from that of healthy cells. In this study, we focused on intracellular vesicle diffusion as a parameter to quantify the change in state when cells are weakened. Two methods were used to weaken cells: intracellular generation of reactive oxygen species (ROS) and exposure of cells to an ATP-depleted environment. First, when ROS is generated in cells, the ”fluctuation value” in the cell decreases in the phase contrast image of the cell, and the ”fluctuation value” is an index of the degree of cellular damage, which has already been reported in our laboratory. However, the actual meanings of the fluctuation value have not been reported. We have therefore tracked intracellular vesicles in cells which have decreased fluctuation values and calculated the diffusion coefficient, and the decrease rate in vesicle diffusion was found to be approximately the square of that in the fluctuation value, indicating that the decrease in vesicle diffusion is one of the causes of the decrease in fluctuation value. Next, we also calculated the vesicle diffusion coefficient for cells exposed to ATP-depleted environment and found that it decreased significantly and was correlated with the survival rate. Thus, the vesicle diffusion coefficient was found to be a characteristic quantity of ATP-depleted cells. To further elucidate the mechanism by which the diffusion coefficient of vesicles decreased, we examined the positional relationship between vesicles and the cytoskeleton by fluorescence observation and found that the cytoskeleton was located near the extremely slow-moving vesicles, suggesting that the cytoskeleton was involved in the decrease in the diffusion coefficient of vesicles.

36 Okada Group

Research Subjects: Biophysics, cell biology, super-resolution microscopy, live cell imaging and single molecule imaging.

Member: Yasushi Okada, Sawako Enoki and Keigo Ikezaki

Our primary goal is to answer the very basic question "What is life". To answer this question , we are trying to fill the gap between the world of molecules and the world of living cells. Direct measurement of molecules in living cells would serve as a basic technology to fill this gap. Thus, we have been working on the development of the technologies for the visualization and non-invasive measurement of the molecular processes in living cells. High-speed, super-resolution live-cell imaging and single-molecule measurement in living cells are the two main technologies we develop.

By using these technologies, we are trying to understand the regulatory mechanisms of motor proteins during axonal transport. Despite the many studies in the past decades by our group and others, it is still unclear how the biophysical properties of motor proteins are related to their biological functions. For example, a point mutation in kinesin-1 can cause hereditary spastic paraplegia, but it is unclear why this mutation selectively affects neurons in the longest tract in the aged patients.

Through these studies and development, we have realized the importance of the cellular states, and our microscope technologies can also be applied to the measurement of the cellular states. Thus, we have proposed a project for the visualization, prediction and control of cellular states. We are now leading this project, and the project members in our lab are working on the development of the technologies to visualize and control cellular states.

This year, we had progress in development of several microscope-related technologies. For example, we have collaborated with Miyawaki-lab in RIKEN for the development and application of a new, highly photostable green fluorescent protein, StayGold. This enabled a three-dimensional super-resolution live cell imaging for longer period without photobleaching.

We also applied our superresolution imaging technologies to solve various biological quesitons. One example is the analysis of the distribution of the force sensor protein Pkd1 on the surface of the nodal immotile cilia. The asymmetric distribution of this protein solved the long-lasting mystery of the mechanism of the left-right symmetry breaking in the development of our body.

37 Furusawa Group

Research Subjects: Theoretical Biophysics, Evolutionary Biology, Complex Systems

Member: Chikara Furusawa and Yusuke Himeoka

Biological systems have both robustness and plasticity, a property that distinguishes them from artificial systems and is essential for their survival. Biological systems exhibit robustness to various perturbations, including noise in gene/protein expressions and unexpected environmental changes. Simultaneously, they are plastic to the surrounding environment, changing their state through processes such as adaptation, evolution and cell differentiation. Although the coexistence of robustness and plasticity can be understood as a dynamic property of complex and interacting networks consisting of a large number of components, the mechanisms responsible for the coexistence are largely unknown.

Our work extracts the universal features of cellular dynamics responsible for robustness and plasticity in biological systems. We describe the systems using a relatively small number of degrees of freedom with the macroscopic state variables. We expect that such a description will provide novel methods for the prediction and control of complex biological systems.

The current research topics in our group are followings:

1. Laboratory evolution of bacterial cells to analyze dynamics of phenotype-genotype mappings
2. Construction of macroscopic state theory describing adaptation and evolution of biological systems
3. Theoretical analysis of evolutionary process under dynamically changing environments
4. Metabolic simulation for understanding growth and lag-phase
5. Development of a method to characterize animal morphology using machine learning

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