ISSN 0910-0709

Department of Physics
School of Science
The University of Tokyo

Annual Report

2024

令和 6 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

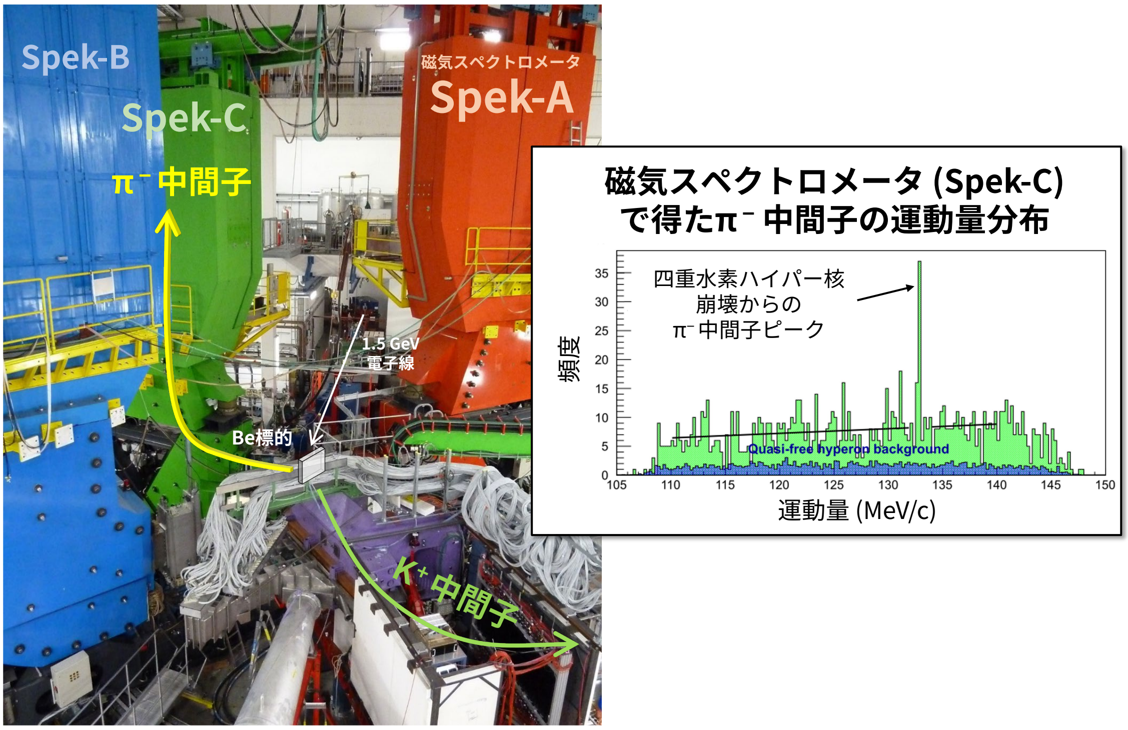

図 1: 写真はドイツ・マインツ大学にある電子加速器施設 MAMI にあるセットアップである。赤、青、緑に彩られた Spek-A、B, C と呼ばれるビルの 4 階ぐらいの高さがある磁気スペクトロメータと手前にある紫色の Kaos スペクトロメータが見える。ベリリウム標的に撃ち込まれた 1.5 GeV の電子によりストレンジクォークと反ストレンジクォークが対生成され、ストレンジクォークを含むラムダハイパー原子核が作られる。この際、反ストレンジクォークは K^+ 中間子となり Kaos スペクトロメータで検出される。生成されたラムダハイパー核が標的内で静止し、二体崩壊することによって放出される π^- 中間子を Spek-A, C で精密測定することにより親であるラムダハイパー核の質量を求めることができる。右図に示す π^- 中間子の運動量分布に見える鋭いピークは ${}^4_\Lambda$H（四重水素ラムダハイパー核）に対応し、世界最高分解能、精度の測定に成功した。さらに標的を工夫することにより未だに質量と寿命が同時に理解されていない ${}^3_\Lambda$H(三重水素ラムダハイパー核）の測定にも成功しており、最終的な解析を進めている。（中村研究室）
This photo shows the experimental setup at the electron accelerator facility MAMI at Johannes Gutenberg University Mainz in Germany. Visible in the image are the large magnetic spectrometers Spek-A, B, and C ―each approximately four stories tall and colored red, blue, and green― and the purple-colored Kaos spectrometer in the foreground. When 1.5 GeV electrons are incident on a beryllium target, strange – antistrange quark pairs are produced. A Λ hypernucleus containing a strange quark is formed, while the accompanying antistrange quark becomes a K^+ meson, which is detected by the Kaos spectrometer. The produced Λ hypernucleus comes to rest in the target and undergoes a two-body decay. By precisely measuring the emitted π^- mesons with the Spek-A and Spek-C spectrometers, the mass of the parent Λ hypernucleus can be determined. The sharp peak observed in the π^- momentum distribution, shown in the figure on the right, corresponds to ${}^4_\Lambda$H (hyperhydrogen-4), marking a successful measurement with the world' s highest resolution and precision. By optimizing the target design, the experiment also succeeded in measureing ${}^3_\Lambda$H (hypertriton), whose mass and lifetime have not yet been simultaneously understood. Final analysis of the data is currently in progress. (Nakamura Group)

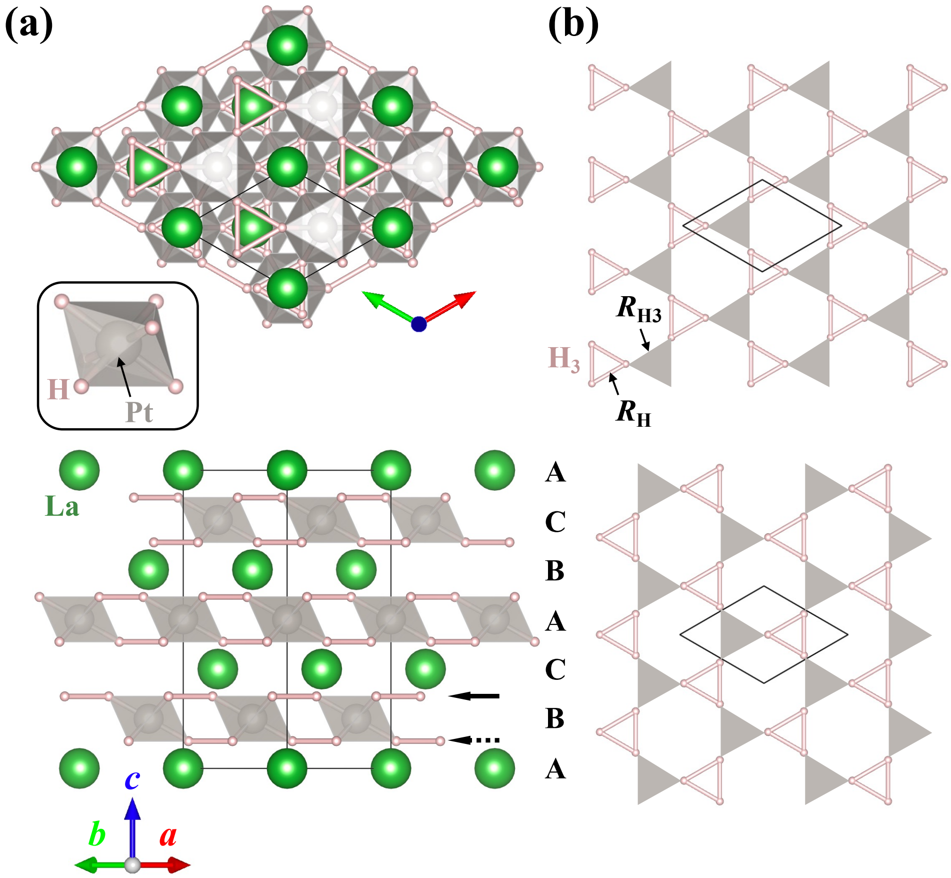

図 2: (a) 進化的アルゴリズム、ニューラルネットワークポテンシャル計算、密度汎関数を用いた第一原理計算の連携によって得られた 20 GPa における新規水素化物超伝導体 $LaPtH_6$ の結晶構造。Allen-Dynes の式を使って計算した超伝導転移温度は 18.7 K となる。八面体 PtH_6 層と La 層が c 軸方向に ABCABC で積層した構造となっている。(b) c 軸から見た H 層の様子。上図と下図はそれぞれ (a) の実線矢印と点線矢印に対応する。H_3 ユニットが平面内に配列し、H 原子の 2 次元カゴメ格子が形成されている。（常行研究室）

(a) Crystal structure of the novel hydride superconductor $LaPtH_6$ at 20 GPa, predicted through a combination of evolutionary algorithms, neural network potential calculations, and first-principles calculations based on density functional theory. The superconducting critical temperature, calculated using the Allen-Dynes formula, is 18.7 K. The structure consists of alternating layers of octahedral PtH_6 units and La atoms, stacked along the c-axis in an ABCABC sequence. (b) Top view of the hydrogen layers along the c-axis, corresponding to the solid and dashed arrows in (a). H_3 units are arranged within the plane, forming two-dimensional Kagome lattices of hydrogen atoms. (Tsuneyuki Group)

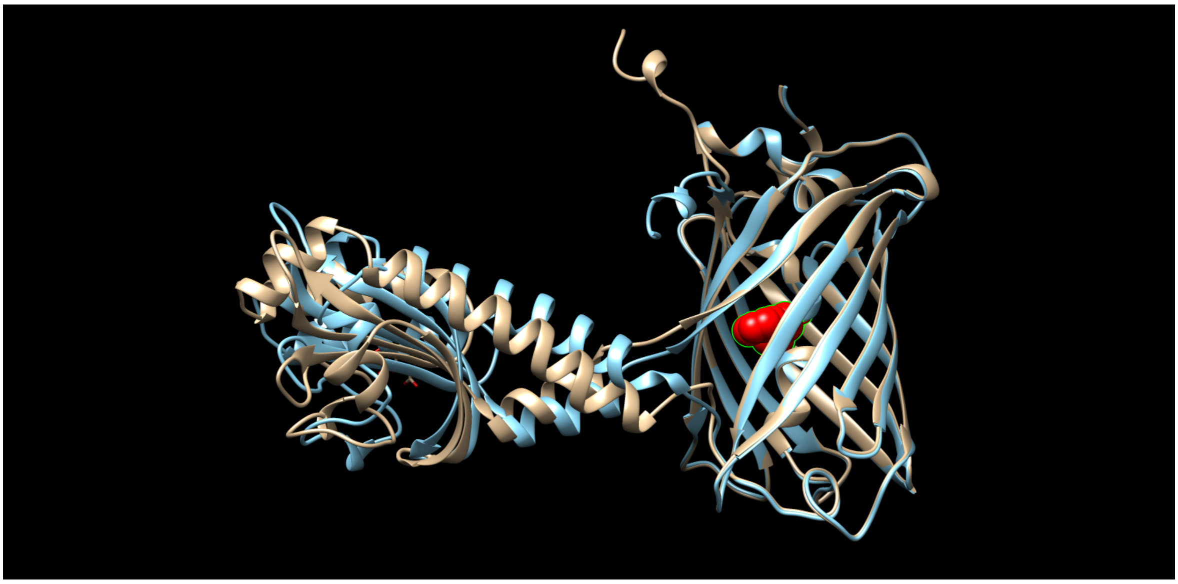

図 3: 蛍光寿命バイオセンサーの設計。蛍光タンパク質は樽型の構造をしており (右側)、中に蛍光色素団（赤色）を埋め込むことで周囲の水分子との衝突や振動によるエネルギー緩和を防ぎ、明るく蛍光を発することができる。樽の胴板に相当するβシートの一つを、蛍光色素団に直接接している場所で切断し、センサータンパク質（左側）を挿入した。センサータンパク質は、標的分子と結合することで構造が変化する（水色→薄い金色）。これにより、蛍光色素団周囲の環境が変化し、蛍光寿命が変化する。AlphaFold2 による推定構造。C. Zhong *et al.*, Cell Rep Meth **4**, 100902 (2024)（岡田研究室）

Design of fluorescence lifetime biosensor. The fluorescent protein has a barrel-shaped structure (right) with an embedded fluorophore (red) that emits bright fluorescence by preventing both collisional and vibrational energy relaxation. A β-sheet stave directly contacting the fluorophore was cleaved to insert a sensor protein (left). When this sensor binds its target, its conformation changes (cyan to pale gold), altering the fluorophore's environment and its fluorescence lifetime. Structure predicted by AlphaFold2. C. Zhong *et al.*, Cell Rep Meth **4**, 100902 (2024) (Okada Group)

序

東京大学大学院理学系研究科物理学専攻・理学部物理学科の令和 6 年度（2024 年 4 月–2025 年 3 月）年次研究報告をお届けします。この小冊子が物理学教室で広く行われている多彩で活発な研究・教育の現状を知っていただく手がかりになれば幸いです。

最初に、新しく入ってこられた教員ですが、教授として、有田亮太郎氏（物性理論：本学先端科学技術研究センター）、山崎雅人氏（素粒子物理学理論：本学国際高等研究所カブリ数物連携宇宙研究機構）、准教授として、相川清隆氏（量子光学・原子分子物理学：東京工業大学）、鈴木大介氏（原子核物理学実験：理化学研究所）、助教として、光山隼史氏（川口研：Max-Planck-Institute of Biochemistry）、川﨑拓也氏（相川研：東京工業大学）、髙倉理氏（日下研：高エネルギー加速器研究機構）、渡邉光氏（有田研：本学先端科学技術研究センター）、苅田裕也氏（竹内研：Max Planck Institute for Evolutionary Biology）が着任されました。また、髙木英典教授が物質・材料研究機構 ICYS センター長（フェロー）、西口大貴助教（竹内研）が東京科学大学准教授、赤城裕助教（桂研）がお茶の水女子大学講師、石田明助教が産業技術総合研究所主任研究員、松浦弘泰助教（小形研）が産業技術総合研究所主任研究員、山崎隼太助教（村尾研）が本学情報理工学系研究科准教授として転出されました。また、木内健司助教（日下研）が退職されました。また、酒井広文教授、小形正男教授、三尾典克教授が本年度定年を迎えられました。

本年度も教室関係者の活発な研究・教育活動の結果、多くの方が受賞されています。吉田直紀教授がフィリップ・フランツ・フォン・シーボルト賞を、常行真司教授が第 21 回本多フロンティア賞を、髙木英典教授が米国物理学会（APS） James C. McGroddy Prize for New Materials を、山崎雅人教授が、国際基礎科学会議 Frontiers of Science Award (Mathematics) を、小形正男教授が日本物理学会第 30 回論文賞を、酒井明人講師、永田夏海助教（濱口研）が第 2 回 AAPPS-JPS Award を、肥後友也特任准教授が第 3 回 AAPPS-JPS Award を、森脇可奈助教（吉田研）が第 3 回羽ばたく女性研究者賞（マリア・スクウォドフスカ＝キュリー賞） 最優秀賞を、大森寛太郎助教（松尾研）が国際基礎科学会議 Frontiers of Science Award (Physics) を、横溝和樹助教（蘆田研）、野下剛氏（松尾研）が第 19 回日本物理学会若手奨励賞を、山田恭平氏（日下研、現プリンストン大）が第 26 回高エネルギー物理学奨励賞を、小林研究室の皆様が令和 6 年度「秀でた利用成果」優秀賞（文部科学省 ARIM）を受賞されました。

また、KRISTIANO Jason 氏、塚本萌太氏、吉村耕平氏、永瀬慎太郎氏、水野るり惠氏が令和 6 年度理学系研究科研究奨励賞（博士課程）を、中根美七海氏、柳澤広登氏、小川宏太朗氏、吉岡大地氏が同研究奨励賞（修士課程）を、金澤貴弘氏、辻圭汰氏、岡田樹氏が令和 6 年度理学部学修奨励賞を受賞しました。

ここ 2 〜 3 年で、定年を迎えられる教員が多く、教室の陣容が急速に変化してきました。昨年度から数えて今年度の終わりまで考えると退職・移動される教授は 9 名におよび、それと入れ替わる形で多くの新たな先生方が来られております。実に教室全体の約 1/4 が入れ替わる形になりました。今後新しい変化が様々な形で表れてくると思われます。

令和 2 年度から始まった物理学教室と産業界との連携はますます発展しています。JSR 株式会社との包括連携に基づいた共同研究の基盤活動は、理学部 1 号館中央棟 3 階にオープンした協創オフィス「JSR・東京大学協創拠点 CURIE」を起点として、教室内の先生との交流を生み、複数の共同研究に繋がっています。この包括連携により、物理学専攻は社会に深く浸透した様々な材料の学理探究を通して普遍的真理と新たな学問領域を見出し、一方 JSR はサイエンスに基づく新たな高機能材料の開発を推進していきます。また、物理学専攻の博士課程学生を対象とした給付型フェローシップである、「JSR フェローシップ」もこれまで何名もの学生に給付され、彼らの研究活動を支援しています。JSR 社との社会連携は令和 7 年からさらに 3 年延長されることが決まりました。これまでの活発な活動が高く評価された形になりました。

また令和 3 年度から IBM 量子コンピューターの実機（ソフトウェア）を用いた量子ネイティブ人材育成を開始していますが、令和 4 年度からは浅野キャンパスに設置された IBM 量子コンピューターの実機に触れる教育内容に拡充して行っています。

令和 4 年 10 月に、サスティナブル量子 AI 研究拠点が、JST 共創の場形成支援プログラム (COI-NEXT) の政策重点分野 (量子技術分野) に採択されました。これは、東京大学・慶應大学・理化学研究所・OIST・シカゴ大学をはじめ川崎市や多数の参画企業が一体となり研究開発を進めるもので、量子機械学習・量子シミュレーション・量子計測デバイスを結合した量子 AI 技術を創出、量子 HPC 基盤の構築を目指しています。

物理学教室は、今後も社会における基礎科学の新たな役割を模索しつつ、持続可能な基礎研究・教育の実現に向けて努力してまいります。令和 6 年度よりは東大基金にも参加し、得られた資金をもとに先輩の先生方、卒業生の皆様、ならびに関係各位との交流をさらに深めていきたいと考えております。皆様には、引き続きご指導ご鞭撻をお願い申し上げます。

この年次研究報告は、中島康博准教授、酒井明人講師、中村ちか子氏のご尽力によって編集作成されました。この場を借りて感謝いたします。

2025 年 5 月 1 日
物理学専攻 専攻長・物理学科 学科長
松尾 泰

II

Summary of group activities in 2024

1 Fukushima Group

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

Member: Kenji Fukushima, Arata Yamamoto, and Syo Kamata

In Theoretical Hadron Physics group, many-body quantum problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include the 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. Z_3 gauge theory as an effective model of QCD.
2. Quantum computing in the Z_2 gauge theory.
3. Numerical analysis of the Higgs-confinement transition with non-local operators.
4. Inhomogeneous state with chiral symmetry breaking in the imaginary-rotating system.
5. Signature for the inhomogeneous state in the relativistic heavy-ion collision via the HBT interferometry.
6. Research of nuclear matter properties using the QCD-based functional renormalization group.
7. Analysis of the equation of state and the neutron star mass-radius distributions in the machine-learning method.
8. Path-integral formulation and the WKB approximation for the diffusion generative model.
9. Gravitational wave analysis with the equation of state with crossover to quark matter.
10. Inversion of polarization of rotating matter under strong magnetic fields.
11. Unified description of the sound speed and the trace anomaly in various high-density 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. Cooper quartet correlations near the surface of $N = Z$ nuclei
2. Response of asymmetric nuclear matter with finite nucleon numbers
3. Possibly heaviest $N = Z$ doubly-magic nucleus

4. Quantum computation for two-valence neutron nuclei
5. Non-relativistic trace anomaly in dense three-color fermionic matter
6. P-wave Bose polaron picture of neutrons in alpha matter
7. Free-field approaches to boundary RCFT_2
8. Probing supersymmetry-like transport of Goldstino in an ultracold Bose-Fermi mixture
9. Fluctuations and Fano-Feshbach resonance in a two-band superconductor
10. Non-Hermitian P-wave Fermi superfluid with the inelastic three-body loss
11. Thermomagnetic spin transport through the magnetic junctions

3 High Energy Physics Theory Group

Research Subjects: Particle Physics and Cosmology

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo, Masahito Yamazaki

We are working on a wide range of topics in particle physics and cosmology, such as physics beyond the Standard Model, dark matter, baryogenesis, inflation, phenomenology of supersymmetric models, astroparticle physics, neutrinos, axion, string theory, supersymmetric field theories, conformal field theories, generalized symmetries, and so on. Specific subjects studied in this academic year are summarized below:

1. Phenomenology
   - 1.1. ALP dark matter [1]
   - 1.2. Neutron star temperature observation and new physics search [2]
   - 1.3. Inflation [24]
   - 1.4. Collider physics [13]
   - 1.5. Dark matter direct detection [21, 22]
   - 1.6. Neutrino physics [26, 27, 15, 16]
   - 1.7. Nucleon decay in grand unified theories [17, 18]
   - 1.8. Leptogenesis [23, 29]
   - 1.9. Phase transition [25]
   - 1.10. Supernova [14]
   - 1.11. Quantum anomaly detection [3]
   - 1.12. Quantum parton shower [9]
2. Superstring theory and formal aspects of quantum field theories
   - 2.1. Invariants of Calabi-Yau manifolds and the BPS/CFT correspondence [19, 20]
   - 2.2. Generalized symmetries [31, 32, 33, 34]
   - 2.3. Classification of two-dimensional CFTs [35]
   - 2.4. Fractonic quantum field theories [36]
   - 2.5. Solvable models with non-Abelian holonomy and their symmetries [28]
   - 2.6. Lorentz-invariant spinor wave packet [30]
   - 2.7. θ angle and topology in Yang-Mills theories [6, 4]
   - 2.8. Non-invertible symmetries [5]
   - 2.9. BPS states counting [7]

2.10. Integrability of large-charge sectors [10]
2.11. Phenomenology of quantum gravity [11, 8]
2.12. Phenomenological implications of positivity bounds in gravitational scattering amplitudes [12]

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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

The Nuclear EXperimental physics group (NEX) consists of two research groups: the Nakamura Group, led by Professor Nakamura and Assistant Professor Nagao with four master's course students, and the Suzuki Group, newly established by Associate Professor Suzuki, who joined in December 2024. The NEX group is concurrently affiliated with the Quark Nuclear Science Institute (QNSI), established in July 2024, and is leading international collaborative research through the development of the International Quantum Physics Network. This section summarizes the research activities of the Nakamura Group.

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
  - Design of the next generation experiment of decay π^- spectroscopy
- Decay π^- spectroscopy of electro-produced hypernuclei at MAMI
  - Precise measurement of mass of hypertriton
  - High-precision measurement of electron beam energy using synchrotron radiation interference
  - High precision calibration of magnetic spectrometers
- Study of light hypernuclei at RARiS
  - Lifetime measurement of hypernuclei
  - Study of the Λn interaction by the Final State Interaction measurement
- Study of hypernuclei at J-PARC
  - Lifetime measurement of light hypernuclei
  - Spectroscopy of Ξ hypernuclei
  - Research and Development for the spectroscopy of Λ hypernuclei with the (π^+, K^+) reaction
  - Design of the next generation experiment with the (π, K) reaction at HIHR, J-PARC

5 Suzuki Group

Research Subjects: Experimental nuclear physics: exotic nuclei, nuclear matter and nuclear astrophysics

Member: Daisuke Suzuki

Our laboratory specializes in nucleon many-body physics. We are promoting research on nuclei, nuclear matter, and nuclear astrophysics using quantum beams of radioactive isotopes (RI). In particular, focusing on spectroscopic and reaction experiments of asymmetric nuclei with an imbalance of neutrons and protons, we are challenging various problems in modern nuclear physics, from microscopic systems of extremely short-lived nuclei to macroscopic objects such as neutron stars and explosive astrophysical phenomena.

Nuclear physics is a very broad academic field whose main theme is the formation and evolution of hadronic matter in the universe. Nucleon many-body systems, which are our laboratory's area of expertise, i.e., atomic nuclei and nuclear matter, are quantum many-body systems composed of protons and neutrons (collectively called nucleons) that appear in the low-energy limit of quantum chromodynamics (QCD). Although it is a seemingly simple system involving only the *ud* sector, it is known to be a many-body system where direct calculations based on QCD are extremely difficult. In particular, the nuclear force acting between nucleons and many-body correlations in the medium are very complex, with many mysteries remaining and serving as a source of unexpectedly diverse physical phenomena.

While nucleon many-body physics was historically limited to the study of stable nuclei on Earth, technological innovations in heavy-ion RI beam (beams in which the nuclei of heavy ions are replaced with RI) facilities, which emerged in the 1990s, have made it possible to artificially generate extremely short-lived nuclei and nuclear matter that do not exist on Earth using RI beams accelerated to approximately 10% to 70% of the speed of light, and to conduct quantum scattering experiments. Particularly with the successful operation of the RI Beam Factory (RIBF) of RIKEN Nishina Center, the world's first third-generation facility, a global rush to construct RI beam facilities is currently underway.

We are tackling various problems related to three themes: (1) exotic nuclei, (2) nuclear matter, and (3) nuclear astrophysics, through RI beam experiments using electroweak probes (electromagnetic and weak forces) and hadron probes (strong force). Furthermore, we are actively participating in the RIBF Upgrade Project as a medium- to long-term project. This project is an innovative attempt to pioneer the intensity frontier of RI beams by applying beam recycling technology based on a storage ring to RI beam generation for the first time.

Our activities in FY2024 include:

- Investigating shape transition, triaxiality, and octupole deformation using in-beam γ-ray spectroscopy.
- Studying mirror symmetry beyond the proton dripline.
- Addressing the spectroscopic factor quenching problem.
- Researching the nuclear equation of state through heavy ion collision (SπRIT project) and isoscaler giant monopole resonance measurement.
- Exploring the origin of molybdenum elements in the Universe.
- Developing a 3D γ-ray tracking germanium detector (GT-5 project).
- Organizing the international symposium PCM2025 at the University of Aizu to discuss updates and perspectives on nuclear structure studies.
- Organizing the international workshop ADRIB25 for discussions on the RIBF Upgrade Project.

6 Yokoyama(M)-Nakajima Group

Research Subjects: Experimental Particle Physics and Particle Astrophysics

Member: Masashi Yokoyama, Yasuhiro Nakajima, and Kota Nakagiri

Our group primarily focuses on studying the properties of neutrinos and using them as probes for research. We are leading experiments with the Super-Kamiokande and Hyper-Kamiokande detectors, as well as the J-PARC accelerator.

T2K long-baseline neutrino oscillation experiment

We are currently conducting research on neutrino oscillations through the T2K long-baseline neutrino experiment. This experiment measures intense neutrino and antineutrino beams produced by the J-PARC accelerator complex, which are then detected by the Super-Kamiokande detector located 295 km away. Our primary goal is to identify a new source of CP symmetry violation in neutrino oscillations.

We have been leading the upgrade of the near neutrino detectors to reduce uncertainties in neutrino interaction modeling. This year, we began neutrino beam data taking with the fully instrumented SuperFGD detector. We are leading its operation, calibration, and data analysis, aiming at precise measurements of electron neutrino interactions and neutrino oscillations.

Super-Kamiokande experiment

Super-Kamiokande (SK) is the largest underground detector in the world for studying neutrino physics and nucleon decay. In the summer of 2022, we added 27 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ to increase the concentration of gadolinium in Super-Kamiokande from 0.011% achieved in 2020 to 0.033%. By increasing the gadolinium concentration, we have improved the detection efficiency of neutrons.

Our group has been leading the search for the diffuse supernova neutrino background (DSNB) using the enhanced neutron detection capability of Super-Kamiokande, aiming for the world's first observation of these neutrinos. We are also developing a new calibration method based on neutron captures on gadolinium. Furthermore, we are preparing a nuclear physics experiment to improve our understanding of neutrino-nucleus interactions and enhance the sensitivity of DSNB searches.

Hyper-Kamiokande

The next-generation water Cherenkov detector, Hyper-Kamiokande, is currently under construction. It will significantly extend the reach of neutrino physics and the search for proton decay beyond what is possible with T2K and Super-Kamiokande. Hyper-Kamiokande will feature a cylindrical tank measuring 68 meters in diameter and 71 meters in depth, containing 260,000 tons of ultrapure water. Our group has been leading the design and construction of the Hyper-Kamiokande detector system, as well as testing the performance of 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 of our focus is the search for neutrinoless double-beta decay with ^{160}Gd, utilizing ultra-high purity Gd technology developed for the SK-Gd project.

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.

- Thermal transport phenomena [1–3]
- Strongly correlated electron systems [4]
- Altermagnet [5]
- Spin-orbit interaction [6,7]
- Orbital magnetic effects [8]
- Theories on organic conductors [9–11]
- Physics of chirality [12–13]

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[13] K. Ohe, H. Shishido, M. Kato, S. Utsumi, H. Matsuura, and Y. Togawa: Phys. Rev. Lett. **132**, 056302 (2024). "Chirality-induced selectivity of phonon angular momenta in chiral quartz crystals"

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 calculations based on the density functional theory (DFT). We are also developing new methods that go beyond the limitations of classical MD and DFT to study the electronic, structural, and dynamical properties of materials.

This academic year, we improved two methods for crystal structure exploration. One is the method based on the evolutionary algorithm, where we introduced neural network potentials for atomic interactions to accelerate the calculation. We applied the method to several hydrides to find new superconducting materials. The other is the data-assimilated molecular dynamics method (DAMD), which utilizes powder X-ray/neutron diffraction data to accelerate structural exploration by the simulated annealing method. We showed that large-scale DAMD applies to so-called multi-phase materials containing two or more different crystal grains.

We also developed a machine-learning method for molecular dipole moments in liquids and polymers. This method successfully calculated the permittivity of liquid alcohols, propylene glycol, and polypropylene glycol at the THz frequency range, where the electronic dipole moment couples and changes with molecular motion and structural deformation.

Another important development is the Green function method in the framework of the transcorrelated method, which utilizes explicitly correlated wave functions to treat electron correlation. We confirmed that the Green function method improves the ionization energy and the charge density distribution in the ionic Hubbard model.

Besides the topics mentioned above, we applied the superconducting density functional theory to a doped perovskite hydride to find the critical effect of spin fluctuation, applied first-principles path-integral molecular dynamics to H_2O ice under high pressure to clarify the nuclear quantum effects on its elastic property, and developed a hydrodynamic simulation of laser ablation to find 100fs ultra-short laser pulse cause less thermal damage compared to the 10ps short laser pulse.

9 Todo Group

Research Subjects: Development of simulation algorithms for strongly-correlated systems; Novel state and critical phenomena in strongly correlated systems; Quantum computing and quantum algorithms; Machine learning and statistical mechanics; Development of open-source software for next-generation parallel simulations

Member: Synge Todo, Hidemaro Suwa, Tsuyoshi Okubo, Sayan Mukherjee, Atsushi Iwaki, Tatsuya Sakashita

To understand the state of matter, the many-body Schrödinger equation must be solved to obtain the partition function in statistical mechanics. However, even with the computational power of modern supercomputers, solving this equation completely is difficult. Therefore, a crucial issue in computational physics is reconstructing the original equation in a form that is easy to simulate while preserving the physically important properties, such as symmetry and quantum correlations, inherent in the original equation.

At Todo Laboratory, we have been studying various quantum many-body systems ranging from quantum spin systems to real matter and even quantum computers by making full use of sampling methods such as Monte Carlo methods, representation of quantum fluctuations based on path integrals, singular value decomposition, information compression using tensor networks, statistical machine learning methods, etc. We have also been developing new techniques to simulate quantum many-body systems. We aim to elucidate the unique states, phase transitions, and dynamics of various quantum many-body systems, from quantum spin systems to real materials, and even quantum computers.

We are also developing and releasing open-source software for next-generation large-scale simulations. We are also involved in the "Quantum Software" endowed course and the "Sustainable Quantum AI" program of the JST's Co-creation Field Formation Support Program. In addition, through the "Quantum Software" endowed chair and the JST Center for Sustainable Quantum AI Research and Development, he is actively engaged in researching and developing quantum algorithms and quantum machine learning methods based on sampling and tensor networks.

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[3] Y. Alexeev *et al.*, Quantum-centric supercomputing for materials science: A perspective on challenges and future directions, Future Generation Computer Systems **160**, 666–710 (2024).

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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 conduct theoretical research on fundamental problems in condensed matter and statistical physics, with a particular focus on strongly correlated quantum many-body systems, both in and out of equilibrium. Our goal is to understand and predict novel quantum phases and emergent phenomena that arise in these systems. To this end, we use a combination of analytical and numerical methods. We are currently exploring topics such as (i) low-dimensional correlated systems, (ii) topological magnetism, (iii) open quantum many-body systems, and (iv) nonequilibrium dynamics in integrable and non-integrable systems. In addition, we are interested in the mathematical aspects of the above-mentioned fields. Our research projects conducted in FY 2024 are the following:

- Low-dimensional correlated systems
  - Ground-state phase diagram of the Hubbard model on a trimer ladder [1]
  - Spontaneous breaking of U(1) symmetry at zero temperature in one dimension [2]
- Topological magnetism
  - Electric field induced thermal Hall effect of triplons in quantum dimer magnets [3]
  - High harmonic generation from electrons moving on topological spin textures [4]
  - Gravitational wave analogues in spin nematics and cold atoms [5]
- Open quantum many-body systems
  - Late-time dynamics of two particles with two-body losses in one dimension [6]
- Mathematical and statistical physics

- Quantum many-body scars in spin models with Dzyaloshinskii-Moriya interaction [7]
- Integrability and a precursor of chaos in disorder-free Sachdev-Ye-Kitaev models [8]
- Weak ergodicity breaking in non-integrable models [9, 10]

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[9] M. Nakagawa, H. Katsura, and M. Ueda, Phys. Rev. Research **6**, 043259 (2024).

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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

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 2024:

1. Quantum effects in spin glass models with rotationally invariant random interactions
2. Analysis of SGD dynamics for principal component analysis
3. Analysis of iterative thresholding algorithm
4. Correlation between secondary structure and robustness to environmental changes in lattice proteins
5. Analysis of retrieval dynamics in the Hopfield model with three-body interactions
6. Analysis of intracellular signal transduction pathways using transfer entropy
7. Analysis of under-bagging method
8. Analysis of ensemble-learning-based variable selection methods
9. Analysis of self-distillation in linear models
10. Statistical mechanics derivation of information criterions

12 Tsuji Group

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

Member: Naoto Tsuji, Kazuaki Takasan, and Shohei Imai

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 2024, we mainly worked on the following projects:

- Dynamics of superconductors
  - Higgs mode in superconductors and nonlinear responses
  - Collective modes in multiband superconductors with Lifshitz invariant
  - Nonequilibrium phase transition in periodically driven superconductors
  - Superconducting nonlinear Hall effect
- Dynamics of open quantum many-body systems
  - Quantum active matter
  - Steady states of boundary-driven quantum spin systems with partial solvability [3]
  - Strongly correlated electron systems coupled to quantum electromagnetic fields
- Quantum many-body scar states [5]
- Dynamical response of quantum many-body systems
  - Attosecond physics in solids [4]
  - KPZ universality class in integrable spin chains [6]
  - THz pulse driven dynamics in Weyl semimetals [1]
  - Nonlinear response based on AdS/CFT correspondence [2]
- Tensor train methods for quantum many-body problems
- Many-body excitons and magnetic orders

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[3] Chihiro Matsui, Naoto Tsuji, “Boundary dissipative spin chains with partial solvability inherited from system Hamiltonians”, Phys. Rev. B **110**, 224306 (2024).

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[5] Shohei Imai and Naoto Tsuji, “Quantum many-body scars with unconventional superconducting pairing symmetries via multibody interactions”, Phys. Rev. Research **7**, 013064 (2025).

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13 Ashida Group

Research Subjects: Condensed matter theory, Theoretical quantum information/optics

Member: Yuto Ashida and Kazuki Yokomizo

This group focuses on theoretical studies at the intersection of quantum many-body physics and quantum information/optics. We have been studying the physics of open and out-of-equilibrium systems, where quantum systems interact with the 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 2024 below.

- Open quantum systems [1, 5, 9]
- Strongly interacting quantum light-matter systems [2, 4]
- Statistical physics, machine learning [8]
- Ultracold atoms [6, 7]
- Transport phenomena [3]

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14 Arita Group

Research Subjects: Condensed Matter Theory

Member:Ryotaro Arita and Hikaru Watanabe

We are studying condensed matter physics using non-empirical methods. Our goal is to predict unique material properties originating from non-trivial electronic states and to pioneer unexplored areas in materials science through extensive calculations for diverse materials. This approach not only aims to uncover new principles, laws, and concepts in physics but also sets the stage for groundbreaking advancements in materials design. We are also developing cutting-edge computational methodologies that promise unprecedented precision in materials design.

Major research topics in AY 2024 are as follows.

1. Development and application of first-principles methods for magnetic materials [1]
2. Magnetic structure prediction and high throughput materials search for functional magnets [2]
3. Development and application of first-principles methods for superconductors [3,4,5,6]
4. *Ab initio* derivation of effective low-energy models for magnetic materials [7]
5. Exotic responses of spin-orbital coupled systems [8]
6. Non-perturbative studies on strongly correlated electron systems [9]
7. Crystal structure prediction at finite temperatures [10]
8. Topological materials [11, 12]

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15 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:
- Anomalous Hall effect at sandwich structures consisted of magnetic topological insulators and topological crystalline insulator
- 2D superconductivity at α-Sn layers on a topological crystalline insulator
- Non-reciprocal photocurrent at Rashba surfaces induced by irradiation of circularly polarized light
- Ferromagnetism and superconductivity at Yb-intercalated graphene
- Conductivity of highly N-doped surface layer on SiC crystal

(2) New methods:

- Fabrication of a four-point probe UHV system with tunneling spectroscopy and quantum Shot noise measurements
- Development of probes for spin injection and spin detection
- Fabrication of a UHV-MBE system with polarization-controlled mid-infrared irradiation

[1] Ibuki Taniuchi, Ryota Akiyama, Rei Hobara, and Shuji Hasegawa: *Surface Circular Photogalvanic Effect in Tl-Pb Monolayer Alloys on Si(111) with Giant Rashba Splitting*, ACS Nano **19**, 3147-3154 (Jan, 2025).

[2] Shuji Hasegawa: *Surface and Interface Physics Driven by Quantum Materials*, Applied Physics Express **17**, 050101 (pp.20) (Jun, 2024).

[3] Shuji Hasegawa: *Surface and Edge States of Quantum Materials*, Coshare Science **03**, 01 (Feb, 2025).

16 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 of the GaAs substrate causes the rectification effect, which is called vortex ratchet.

17 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∼4 meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research topics in FY2024 are as follows.

1. **Light-induced superconducting-like state in high-T_c cuprate superconductors:** We performed a comprehensive study on the light-induced superconductivity phenomenon in cuprate superconductors, $La_{1.6-x-y}Nd_ySr_xCuO_4$, by using near-infrared optical-pump and terahertz-probe spectroscopy. The light-induced plasma edge was observed in the *c*-axis terahertz reflectivity for all the samples above T_c, regardless of long-range charge order(CO) or short-range charge density wave (CDW) order while showing a strong correlation with the coherence length of the CO/CDW order. The frequency of light-induced plasma edge coincides with that of Josephson plasma resonance in $La_{2-x}Sr_xCuO_4$ at the similar doping in the low-temperature superconducting phase, imposing a strong constraint on the interpretation of the phenomenon.

2. **Study of collective mode in iron-based superconductors:** We studeid the collective mode behavior of iron-based superconductors, $FeSe_{1-x}Te_x$, by using terahertz third harmonic generation technique. In FeSe, a distinct collective mode resonance was indentified substantially below the superconducting gap. By comparing with the theoretical analysis based on the multi-orbital model of pairing interactions, the observed mode is accounted for the the Bardasis-Schrieffer mode, corroborating that the superconducting order parameter in FeSe is described by the admixture of *s*-wave and *d*-wave paring channels.

3. **Floquet engineering of Dirac electron systems:** We have aimed at realizing Floquet states in Dirac electron system in thin films of $Co_3Sn_2S_2$. Upon the irradiation of circular polarized mid-infrared light pulses, we observed the light-induced anomalous Hall effect as manifested by the transient Faraday rotation signal in the terahertz frequency range. The light-induced optical Hall conductivity shows $1/\omega^3$ dependence against the driving frequency ω, in accordance with the Floquet theory that predicts the light-induced Floquet-Weyl state with further strong driving fields.

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[2] Kohei Fujiwara, Kazuma Ogawa, Naotaka Yoshikawa, Koji Kobayashi, Kentaro Nomura, Ryo Shimano and Atsushi Tsukazaki: Giant antisymmetric magnetoresistance arising across optically controlled domain walls in the magnetic Weyl semimetal $Co_3Sn_2S_2$, Commun. Mater. **5**, 239 (2024).

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18 Hayashi Group

Research Subjects: Condensed matter physics

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 currents and chiral magnetism
  - Decoding the magnetic bit positioning error in a ferrimagnetic racetrack[4]
  Current-driven motion of magnetic domain walls is one of the key technologies for developing storage class memory devices. Extensive studies have revealed a variety of material systems that exhibit high-speed and/or lower power propagation of the domain walls driven by electric current. However, few studies have assessed the reliability of the operations of the memory technology. Here, we decode the errors associated with writing and shifting domain walls using nanosecond current pulses in a 5-micrometer-wide wire composed of a Pt/GdFeCo bilayer. We find that writing a domain wall at the edge of the wire causes a bit positioning error of 0.3 micrometers, whereas the shifting process induces an error of 0.1 micrometers per a 2-nanosecond-long current pulse. The error correlation among successive shifting is negligible when the current drive is sufficiently large. These features allow reliable operation of highly packed domain walls in a ferrimagnetic racetrack.

- Strong coupling in solids
  - Magnon-phonon coupling of synthetic antiferromagnets in a surface acoustic wave cavity resonator[5]
  a surface acoustic wave (SAW) cavity resonator is used to study the coupling of acoustic magnons in a synthetic antiferromagnet (SAF) and phonons carried by SAWs. The SAF is composed of a CoFeB/Ru/CoFeB trilayer, and the scattering matrix of the SAW resonator is studied to assess the coupling. We find that the spectral line width of the SAW resonator is modulated when the frequency of the excited magnons approaches the SAW resonance frequency. Such a change in the spectral linewidth can be well reproduced using macrospin-like model calculations. From the model analyses, we estimate the magnon − phonon coupling strength to be ~ 9.9 MHz at a SAW resonance frequency of 1.8 GHz: the corresponding magnomechanical cooperativity is ~ 0.66. As the spectral shape hardly changes in a CoFeB single-layer reference sample, these results show that SAF provides an ideal platform to study magnon − phonon coupling in an SAW cavity resonator.

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19 Kobayashi Group

Research Subjects: Quantum sensing and mesoscopic physics

Member: Kensuke Kobayashi and Kento Sasaki

The advancement of nanotechnology since the 1980s has paved the way for mesoscopic physics, which seeks to manipulate the properties of matter using miniature electronic circuits—so-called mesoscopic systems—composed of semiconductors, metals, superconductors, and magnetic materials. Progress in this field has opened up new avenues for various quantum technologies. Among them, quantum sensing—a precision measurement technique grounded in the principles of quantum mechanics—has emerged as an auspicious approach. Our research aims to establish a new framework for precision condensed matter physics based on quantum sensing.

We focus on quantum sensors based on color centers, such as nitrogen vacancy (NV) centers in diamond and boron vacancies in hexagonal boron nitride (hBN). We are developing a single quantum spin microscope for various quantum sensing applications. This technique enables quantitative imaging of magnetic field and temperature distributions at submicron scales under multiple conditions. Such a capability has been unprecedented in the field of condensed matter physics. This approach holds promise for exploring various compelling topics, including non-equilibrium transport, spin glasses, topological edge states, and persistent currents.

The primary research topics in FY2024 are as follows.

- Systematic characterization of nanoscale hBN quantum sensor spots created by helium-ion microscopy [1]
- Nano-diamond quantum thermometry assisted with machine learning [2]
- Wideband wide-field imaging of spin-wave propagation using diamond quantum sensors [3]
- Quantitative imaging of nonlinear spin-wave dynamics using diamond quantum sensors
- Superconducting vortex nucleation induced by self-Field of current
- Imaging stress distribution under high pressure using diamond quantum sensors
- Observation of antiferromagnetic domain wall in Mn_3Sn using scanning diamond quantum sensor

Published papers:

[1] H. Gu, M. Tsukamoto, Y. Nakamura, S. Nakaharai, T. Iwasaki, K. Watanabe, T. Taniguchi, S. Ogawa, Y. Morita, K. Sasaki, K. Kobayashi, *Physical Review Applied* **22,** 054026 (2024).

[2] K. Yamamoto, K. Ogawa, M. Tsukamoto, Y. Ashida, K. Sasaki, K. Kobayashi, *Applied Physics Express* **18,** 025001 (2025).

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20 Nakatsuji-Sakai Group

Research Subjects: Condensed Matter Experiment

Member: Satoru Nakatsuji and Akito Sakai

Our research group is advancing a new phase in quantum materials science, where fundamental discoveries are increasingly connected with emerging quantum technologies through interdisciplinary collaboration. We focus on the design, synthesis, and characterization of quantum materials that exhibit novel macroscopic properties. These materials are integrated into thin-film-based devices, enabling us to probe novel quantum functionalities and assess their technological potential. By forging direct links between quantum phenomena and practical applications, our mission is to lead the creation of material platforms that drive both scientific discovery and innovation in computing, sensing, and energy-saving technologies.

Major research themes:

1. Quantum transport in magnetic topological materials
2. Coherent quantum spin transport in antiferromagnetic spintronics
3. Strange metal and exotic superconductivity in strongly correlated electron systems

Summary of research subjects in 2024

1. Fabrication of single-crystalline $YFeO_3$ films with large antiferromagnetic domains [1]
Antiferromagnets have attracted considerable interest in fields such as spintronics, magnonics, and ultrafast magnetism. However, issues with sample quality and the presence of structural domains complicate quantitative studies of antiferromagnetic thin films, which limit their application in these areas. In this study, we successfully fabricated high-quality, twinning-free (110)-oriented $YFeO_3$ films using pulsed laser deposition. Our results show that spin rotation under high magnetic fields aligns well with the two-sublattice approximation model. The films feature an atomically flat surface with a step-terrace morphology. We also observed a longitudinal magneto-optic Kerr (MOKE) rotation of 10 millidegrees at room temperature, consistent with previous reports based on bulk single crystals. The in-plane anisotropy of the Kerr response matches the magnetic anisotropy measured by SQUID techniques.The strong MOKE signal enables imaging of antiferromagnetic domains and their reversal, with domain sizes exceeding 100 micrometers. These high-quality $YFeO_3$ thin films are promising for the development of antiferromagnetic spintronics and the exploration of spin-related phenomena in thin films and interfaces.

2. Manipulation of Weyl antiferromagnet Mn_3Sn by interlayer magnetic coupling [2]
The Weyl antiferromagnet Mn_3Sn exhibits large responses like the anomalous Hall effect with tiny magnetization and is expected to be utilized in next-generation spintronics. The control of the magnetic properties of Mn_3Sn is a critical technique, and manipulation using several means, including external magnetic field, spin-orbit torque, and strain, has been demonstrated. In this study, we demonstrated the manipulation of the magnetic state in Mn_3Sn by interlayer magnetic coupling and revealed unique properties of this effect. We found that the observed coupling phenomena were induced not by the tiny magnetization but by the chiral antiferromagnetic order of Mn_3Sn. Moreover, the unidirectional magnetic anisotropy resulting from interfacial coupling can be easily applied in any direction owing to its small demagnetizing field. This effect can play a key role in realizing all-antiferromagnetic memory devices.

3. Large Anomalous Nernst effect in polycrystalline ferromagnets with nodal web band structure [3]
We explored the anomalous Nernst effect (ANE) in chemically substituted Fe_3(Ga, Al) and Fe_3(Al, Si) compounds, which are promising for thermoelectric and spintronic applications due to their topological band structure. Our study revealed that $Fe_3Ga_{1-x}Al_x$ polycrystals display a remarkably large and robust ANE signal ($\sim 5.7\ \mu$V/K) over a wide range of chemical compositions, demonstrating that the underlying topological "nodal web" feature remains intact despite significant atomic substitutions. The substitution of Ga with the more abundant and cost-effective aluminum further highlights the potential of $Fe_3Ga_{1-x}Al_x$ as a promising material for scalable, energy-harvesting thermoelectric technologies.

4. Large spontaneous anomalous Nernst effect in kagome ferromagnet Fe_3Sn thin film[4]
The anomalous Nernst effect (ANE) is a representative transverse thermoelectric effect that holds promise for developing low-cost, large-area, and flexible thermoelectric devices. It is suitable for applications in heat flux sensors and energy harvesting. In this work, we investigate the thin-film kagome ferromagnet Fe_3Sn, which exhibits a novel topological electronic structure characterized by a nodal plane. We fabricated high-quality (0001)-oriented Fe_3Sn epitaxial thin films and successfully observed a large spontaneous ANE in these thin films, with a response comparable to bulk samples. Moreover, we assessed the transverse electromotive force per unit heat flux under an out-of-plane heat current, matching the configuration used in heat flux sensors, and demonstrated a sensitivity one order of magnitude greater than that of conventional ferromagnetic materials. Our findings underpin the thermoelectric application of the Fe_3Sn binary system, which utilizes cost-effective elements.

5. Multipole-drive superconductivity in $PrTi_2Al_{20}$ [5]
Since the discovery of unconventional superconductivity in the early 20th century, expanding the landscape and understanding its mechanism have been central themes in quantum materials research worldwide. The ultimate goal of realizing superconductivity at room temperature and under everyday conditions can revolutionize today's technologies, from electrical grids with no loss and new computing techniques to ultra-fast, energy-efficient transportation. Recent research has extensively explored the link between superconductivity and the coexistence of ordered states beyond conventional long-range spin order, generating significant interest. In this study, we focus on $PrTi_2Al_{20}$, which provides a unique and fascinating platform to explore how high-rank multipoles can generate superconductivity in the absence of spin degrees of freedom. We comprehensively characterized the superconducting state through highly challenging thermodynamic experiments, uncovering key insights into the superconducting pairing symmetry. Through La-doping, we identified an intimate link between the multipolar order parameter and superconducting pairing symmetry via chemical tuning, revealing a phase diagram that contrasts sharply with that of the extensively studied

spin-fluctuation-driven superconductors. This study is a crucial step in characterizing and showcasing the unique properties of multipole-driven superconductivity.

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21 Theoretical Astrophysics Group

Research Subjects: Observational Cosmology, High-Energy Astrophysics , and Artificial Intelligence

Member: Naoki Yoshida, Kana Moriwaki & Erika Ogata

The Theoretical Astrophysics Group conducts a wide range of research programs. We pursue a variety of topics such as observational cosmology, galaxy formation and evolution, high-energy astrophysics, quantum computing and artificial intelligence.

Observational Cosmology attempts to understand the evolution of the universe based on the observational data in various wavebands. The proper interpretation of recent and upcoming observational data provided by JWST, ALMA, Euclid, SPHEREx, and Subaru PFS is 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 and ionization and thermal history of the universe and reionization.

Astronomical observations 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 and galaxies were born, which illuminated the universe once again and terminate the cosmic Dark Ages. We explore direct and indirect observational signatures from those objects that can be obtained in future observations. Comparing the predictions of our simulations to observations allows us to better understand the nature of the underlying physical processes.

To maximise the information gain from astrophysical observations and numerical simulations, we also explore several new techniques. We develop supervised machine learning models to analyze noisy observational data. With the aim of utilizing quantum computers in the future for faster computation, we are also working on the development of new computational methods.

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

2024

- Kinetic Simulations of Pulsar Magnetosphere in Interacting Binary Systems
- Impact of Reionization History on Constraining Primordial Gravitational Waves with Cosmic Microwave Background B-modes
- Probing Cosmic Large Scale Structure with Voids

- Long-Term Evolution and Dispersal of Protoplanetary Disks
- The nature of dark matter probed by strong gravitational lensing
- Three-dimensional Radiation Hydrodynamics Simulations of Wandering Black Holes: Effects of Anisotropic Radiation Feedback in Dusty-Gas

2023

- Binary blackhole mergers induced by dynamical interaction of hierarchical triple systems
- Observational studies of stellar rotation using high precision photometric data
- White Dwarf Populations from a Semi-Analytical Star Formation Model

2022

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

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 are in a superposition of 0 and 1 states. Quantum information processing seeks to perform tasks that are impossible or ineffective with conventional classical information by manipulating quantum states. Examples are quantum computation, quantum cryptography, quantum communication, and quantum sensing.

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, Philip Taranto, Zane Marius Rossi (JSPS foreign postdoctoral fellow), Jisho Miyazaki, graduate students, Yu Tanaka (D3), Wataru Yokojima (D3), Timothy Forrer (D2), Satoshi Yoshida (D2), Kosuke Matsui (D1), Natsuto Isogai (M2), Ryotaro Niwa (M1), Ben Yardan Jumoorty (Research student) and an intern, Noah Eckstein (Harvard University). We engaged in active collaborations with colleagues at the University of Toronto, MIT, North Carolina State University, Sorbonne Université, University of Gdańsk, Université Paris-Saclay, Perimeter Institute, University of Geneva, University of Illinois Urbana-Champaign, Foxconn, IBM Quantum, Tamkang University, NTT, NII, Ritsumeikan University, the Chinese University of Hong Kong, and TU Wien.

Our projects engaged in this academic year were the following:

Quantum Machine Learning and Quantum Algorithms
– Advantage of quantum machine learning from general quantum computational advantages (Yamasaki, Isogai, Murao)
– Parallel quantum signal processing via polynomial factorization (Rossi)
– Modular quantum signal processing in many variables (Rossi)
– Quantum state preparation using counting oracles (Tanaka, Yamasaki, Murao)
– Dequantization of period-finding algorithms using binary decision diagrams (Tanaka, Yamasaki, Murao)
– Teleportation using multiple copies of input quantum states (Yoshida, Murao)
– Analysis of quantum protocols using large language models (Jumoorty, Murao)

Higher-Order Quantum Computation and Quantum Learning
– Storage and retrieval of higher-order quantum channels (Yokojima, Miyazaki, Murao)
– Quantum algorithms for learning spectral moments of quantum channels (Niwa, Taranto, Rossi, Murao)
– Quantum functional protocols (Forrer, Miyazaki, Taranto, Murao)
– Analytical lower bound on the number of queries of higher-order transformations of unitaries (Odake, Yoshida, Murao)
– No-go theorem on quantum switch simulation (Odake, Yoshida, Taranto, Murao)
– Universal algorithm for transforming Hamiltonian eigenvalues (Odake, Taranto, Murao)
– Equivalence between fidelities of port-based teleportation and unitary estimation (Yoshida, Murao)

Quantum Error Correction and Quantum Error Suppression
– Coherent information for Calderbank-Shor-Steane codes under decoherence (Niwa)
– Constant-overhead magic state distillation (Yamasaki)
– Robust error accumulation suppression of quantum circuits (Odake, Taranto, Murao)

Distributed Quantum Information Processing
– Reduction of qubit usage in entanglement distillation protocols (Matsui, Yamasaki, Murao)
– Computing entanglement costs of nonlocal operations using algebraic geometry (Miyazaki)

Quantum Resource Theories
– Estimation of imaginarity of quantum states (Miyazaki)
– Proof of generalized quantum Stein's lemma and the second law of quantum resource theories (Yamasaki)
– Efficiently cooling quantum systems with finite resources (Taranto)
– Analysis of unitary interactions preserving states of quantum open systems (Eckstein, Taranto, Murao)

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, 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 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 FY2024 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Topology of discrete quantum feedback control [1]
  - Exact eigenstates and weak ergodicity breaking in multicomponent Hubbard models [2]
  - Yang-Lee zeros in quantum phase transitions and their relation with entanglement transitions [3]

- Unification of quantum physics, statistical mechanics, information theory, and machine learning
  - Universal upper bound on work extractable from isolated quantum many-body systems [4]
  - Nonequilibrium dynamics in an evolutionary game on a regular graph [5]

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24 J. Yokoyama Group

Research Subjects: Theoretical Cosmology and Gravitation

Member: Jun'ichi Yokoyama

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. Yokoyama served as the Director of RESCEU from April 2023, but since November 2023, he has also been the Director of the Kavli Institute for the Physics and Mathematics of the Universe. He continues his duties at the Graduate School of Science as an adjunct professor.

Cosmology of the early universe and gravitation

- One-loop correction on the primordial curvature perturbation from single-field inflation and primordial black hole formation
- Real-time analysis of vacuum decay in the presence of a black hole
- Roles of the Higgs field during reheating after R^2 inflation.
- $f(R)$ gravity in the Einstein-Cartan theory.
- Scale free gravity and cosmology

Observational cosmology

- Cosmic birefringence as a probe of dark components
- Distance measurement to the Andromeda galaxy
- Time domain astronomy using Tomo-e Gozen

Gravitational wave analysis

- Noise removal by nonlinear independent component analysis
- LVK collaboration papers

25 Ejiri-Tsujii 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 FY2024, a movable molybdenum target rod with a thermocouple was fabricated to measure the energy flux of the fast electrons generated by the LHW. As a result, it was found that a non-negligible power of about 10 % of the incident LHW power reaches the target, and that the power varies depending on the antenna used and the measurement position. When the plasma current is maintained, bursts occasionally appear in the hard X-ray (HX) signal, and their energy reaches about half of the total X-ray energy during the discharge, and may be important in the current drive process. As a new measurement method, we have developed the line integrated Thomson scattering method, and initial experimental results have been obtained in one line of sight. In theoretical research, we are developing a new wave calculation method using integral form dielectric tensor. In a joint research project with QST, we are analyzing the heating and equilibrium during electron cyclotron wave assisted startup, and confirmed that the theory and the experimental results in TST-2 are not inconsistent. In joint research with Kyushu University, we have continued to improve the performance of the Thomson scattering diagnostic.

26 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) Observation of the alignment and orientation dynamics of state-selected OCS Molecules in a field-free space

We applied a plasma shutter developed for two-color laser pulses to state-selected OCS molecules and observed the dynamics of their alignment and orientation after the laser pulse was rapidly blocked. This year, due to the degradation of the LD used to excite the femtosecond Ti:sapphire laser amplification system for plasma generation, unfortunately, we could not utilize sufficient output power. Consequently, increasing the cross-sectional area of the femtosecond pulse on the ethylene glycol sheet was difficult. As a result, to prevent self-breakdown of the ethylene glycol, we had to limit the pulse energy of the two-color laser pulse consisting of the fundamental wave (wavelength $\lambda = 1064$ nm) and the second-harmonic wave

(λ = 532 nm) of the nanosecond Nd:YAG laser. Despite this limitation, the achieved orientation degree upon applying the plasma shutter was approximately 2.5 times higher than that observed in the proof-of-principle experiment (K. Oda *et al.*, Phys. Rev. Lett. **104**, 213901 (2010)). Additionally, as discussed later, the observed dynamics of alignment and orientation indicated the presence of a residual electric field to some extent after applying the plasma shutter.

The alignment dynamics after ultrafast blocking of the two-color laser pulse using the plasma shutter was found to be consistent with the results reported in the paper on the development and performance evaluation of the plasma shutter (Je Hoi Mun *et al.*, Opt. Express **27**, 19130–19140 (2019)), specifically Fig. 3. Three quantum revivals were observed within one rotational period. On the other hand, for the first time worldwide, we successfully observed the orientation dynamics after ultrafast blocking of the two-color laser pulse applied to state-selected OCS molecules. We confirmed that the orientation degree returned to approximately the same level as before laser pulse blocking after nearly one rotational period. Additionally, modulations in the orientation were observed for the first time around $T_{\mathrm{rot}}/4$ and $3T_{\mathrm{rot}}/4$.

The observed results qualitatively agreed with the numerical solutions of the time-dependent Schrödinger equation, assuming the rotational ground state of the OCS molecule, thereby verifying the validity of our observations. Furthermore, the effect of the residual electric field (less than approximately 10%) after laser pulse blocking was clarified. It was found that the quantum revival period was delayed by a few picoseconds compared to the field-free case. Additionally, the intensity ratio of the orientation signals observed around $T_{\mathrm{rot}}/4$ and $3T_{\mathrm{rot}}/4$, which is symmetric in the absence of a residual field, became asymmetric when a residual electric field was present.

(2) Proposal for an all-optical method for enantioselective orientation of chiral molecules

In the all-optical molecular orientation control method reported above, the highest orientation degree is achieved when the orientation dynamics is purely adiabatic. However, in recent years, it has been found that even when using two-color pulses with a pulse width of approximately 10 ns, the orientation dynamics is not purely adiabatic. To maximize the degrees of orientation in such cases, Sakai group proposed not only optimizing the intensity ratio of the two-wavelength pulses (Mun and Sakai, Phys. Rev. A **98**, 013404 (2018)) but also utilizing a combination of a linearly polarized fundamental wave and an elliptically polarized second-harmonic wave (Hossain and Sakai, J. Chem. Phys. **153**, 104102 (2020)).

In molecular orientation control, numerical calculations have generally assumed a relative phase of 0 (or π) to maximize the asymmetry of the potential. This year, by selecting a relative phase $\Phi = \pi/4$, the fact that the sign of the hyperpolarizability tensor's off-diagonal component differs between L- and D-enantiomers enables a technique for enantioselective orientation of chiral molecules, where L- and D-enantiomers — related as mirror images — can be oriented in opposite directions. Furthermore, by selecting $\Phi = 5\pi/4$, the relative orientation of L- and D-enantiomers can be easily switched between up/down and left/right compared to the case when $\Phi = \pi/4$.

27 Aikawa Group

Research Subjects: Levitated optomechanics

Member: Kiyotaka Aikawa, Takuya Kawasaki

We experimentally explore single nanoparticles optically levitated in vacuum. Recently, we realize feedback cooling on all the external degrees of freedom of a single nanoparticle, with one degree of freedom being cooled to the ground state. We have realized time-of-flight free-expansion measurements of the velocity distribution of a levitated nanoparticle and elucidated that cooling the angular motions is crucial to explore the velocity distribution near the ground state. In future, we aim at employing these techniques to explore the quantum behaviors of a nanoparticle as well as its application to sensing beyond current technologies. The main research subjects in FY2024 are as follows:

- Construction of a new apparatus for multi-particle experiments
- Construction of a new apparatus for a hybrid quantum system
- Exploring the application of a nanoparticle to sensing

28 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 140 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 (B-DECIGO, SILVIA)
- Development of TOBA (Torsion Bar Antenna)
- Dark Matter Seach
- High-precision experiments on relativity and opto-mechanics

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29 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 nuclei, and so on.

Member: Aya Bamba and Kouichi Hagino

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants (SNRs), compact stars such as white dwarfs, neutron stars, and black holes, active galactic nuclei, and so on. Such energetic objects emit bright X-rays and/or gamma-rays, thus we observe such high energy photons using rockets, balloons, and satellites. We also develop detectors for future X-ray/Gamma-ray missions, such as GRAMS and XRPIX, and so on.

The group main activities of this year are as follows:

1. Observations of high energy cerestal objects
   - Supernova remnants are one of the main players to distribute heavy elements in the universe. We have suceeded to map the Doppler shift/broadening of Fe K shell lines in one of the youngest Galactic core-collapse SNR, Cassiopeia A (SN 1682) with XRISM, which we successfully launched on 2023. The map shows quite asymmetric expansion, suggesting incomplete shell structure. It may have connection with the supernova explosion mechanism called neutrino-driven supernova.
   - We observed an active galactic neuclei, PDS456, with XRISM. Surprisingly, we have detected several absorption lines with different redshift value (z =0.1–0.3). It means that the ultra fast outflow from the central supermassive blackhole is very asymmetric and clumpy.
2. Developments of future missions
   - We develop the liquid Ar detector for cosmic MeV gamma-ray detection. We found that impurities in liquid Ar prevents successful signal detection. We have successfully removed the impurities and detected the signal.
   - We have proceed development of XRPIX detector for the future hard X-ray mission. In this year, we suceeded to operate the XRPIX with onchip ADC, without degradation of energy resolution.

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30 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 S. Takakura

- 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 observation. 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 construction and test observations. We are deploying 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. Current our focus is on the analysis of commissioning data of first 2 telescopes at Chile site and on fabrication of the 4th 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.

31 Takeuchi Group

Research Subjects: Experimental statistical physics for non-equilibrium systems

Members: Kazumasa A. Takeuchi, Daiki Nishiguchi, Yuya Karita

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, through such keywords as active matter, non-equilibrium phase transitions, topology, etc. More specifically, we carried out the following projects among others in the academic year 2023:

(1) Non-equilibrium phenomena in soft matter systems
(1-1) Rigidity transition of a highly compressible granular medium [3]
(1-2) Model experiment of stochastic particle transport
(1-3) Direct observation of reconnecting liquid-crystalline topological defects [1]
(1-4) Rheotaxis of self-propelled colloid

(2) Non-equilibrium phenomena in living systems
(2-1) Active matter phases in bacteria [2, 5]
(2-2) Route to turbulence for collective motion of bacteria [6]
(2-3) Seeking for a topological mode in active matter
(2-4) Physical origin of heterogeneity in bacterial biofilms
(2-5) Model experimental system of porous soil for studying microbial life therein
(2-6) Collective state of magnetotactic bacteria
(2-7) Collective motion of animals as anti-predator behavior

(3) Theoretical approaches
(3-1) Kardar-Parisi-Zhang universality class in integrable spin chains [4]
(3-2) Capturing spatiotemporal chaos by reservoir computing

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

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32 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 prepared a project to apply this technology to advanced semiconductor manufacturing processes, and our propozal has been approved and decided to begin in fiscal year 2025.

KAGRA project

Almost ten years have already passed since gravitational waves were actually detected. The number of events detected to date reaches 200 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 has joined the first part of the international joint observation called O4a which began on May 24, 2023 and ended January 16, 2024. It is a very unfortunate matter, but KAGRA was significantly affected by the Noto Earthquake in January 2024. At present, it has finally recovered from the damage, and its sensitivity has greatly improved.

33 Konishi Group

Research Subjects:Metasurface, Metamaterials, Nonlinear optics, Laser processing

Member:Kuniaki Konishi and Haruyuki Sakurai

We are investigating new physical phenomena caused by the interaction of light with nano- and micro-scale ultra-fine artificial structures fabricated by state-of-the-art microfabrication techniques, and their application to optical control. Furthermore, based on condensed matter physics, we are exploring the scientific principles of laser processing to understand why light can break things and are developing new methods for fabricating micro three-dimensional structures using state-of-the-art ultrashort pulsed lasers.

As a member of UTokyo Research Institute for Photon Science and Laser Technology, we are also working to create a new system for the rapid transfer of new technologies developed by our laboratory to the real industry.

Exploration of new phenomena and the physics of artificial nanostructures and their application to optical control

Artificial nanostructures that are smaller than the wavelength of light can be used to create new physical phenomena and to control light based on the new concept of manipulating the interaction with light through the "shape" of appropriately designed nanostructures. We are exploring new phenomena in such artificial nanostructures, elucidating their mechanisms, and applying them to light sources. In particular, we are aiming to apply our light source to the vacuum ultraviolet region with wavelengths below 200 nm and terahertz waves with frequencies near 1 THz, which are in need of the development of control methods.

Creation of micro three-dimensional structures by ultrashort pulse laser and their application to electromagnetic wave control

It is a well-known fact that when a material is exposed to intense laser light, the material is dRecent advances in laser technology have made it possible to generate intense and stable ultrashort pulsed lasers that can not only drill and cut objects, but also fabricate micron-order fine three-dimensional (3D) structures that are difficult to fabricate by other methods. Since the structures fabricated by such advanced technology are smaller than electromagnetic waves, such as millimeter waves and terahertz waves, they can be utilized as functional materials for new electromagnetic wave control by fabricating appropriate structures. In this research, we are developing such laser-based 3D structure fabrication technology and at the same time, developing new functional materials using such technology, and we recommend its application to various fields such as astrophysics and next-generation wireless technology (Beyond 5G and 6G).

Elucidating the Principles of Laser Processing

It is a well-known fact that when a material is exposed to intense laser light, the material is destroyed, and in fact, laser processing is an important fundamental technology that supports the current industry. On the other hand, the mechanism by which ultrashort laser pulses, in particular, cause material destruction remains unclear. When intense pulsed light that causes material destruction is incident on a material, what kind of process is used to transfer the energy of the light to the material? How does this energy propagate through the electron and lattice systems inside the material, and what triggers the dramatic and irreversible phenomenon of destruction? To find answers to these questions, we have developed state-of-the-art optical control techniques and various measurement methods, and are conducting research by making full use of these techniques. Through this research, we aim not only to elucidate the mechanism of laser-induced material destruction but also to use this knowledge to advance laser processing technology further.

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. Segment-specific axon guidance by Wnt/Fz signaling diversifies motor commands in *Drosophila* larvae

Functional diversification of homologous neuronal microcircuits is a widespread feature observed across brain regions as well as across species, while its molecular and developmental mechanisms remain largely unknown. We address this question in *Drosophila* larvae by focusing on segmentally homologous Wave command-like neurons, which diversify their wiring and function in a segment-specific manner. Anterior Wave (a-Wave) neurons extend axons anteriorly and connect to circuits inducing backward locomotion, whereas posterior Wave (p-Wave) neurons extend axons posteriorly and trigger forward locomotion. Here, we show that Frizzled receptors DFz2 and DFz4, together with the DWnt4 ligand, regulate the segment-specific Wave axon projection. DFz2 knock-down (KD) not only reroutes Wave axons to posterior neuromeres but also biases its motor command to induce forward instead of backward locomotion as tactile response. Thus, segment-specific axon guidance diversifies the function of homologous command neurons in behavioral regulation. Since control of anterior-posterior (A-P) axon guidance by Wnt/Fz-signaling is evolutionarily conserved, our results reveal a potentially universal molecular principle for formation and diversification of the command system in the nerve cord. Furthermore, this work indicates that sensorimotor transduction can be rerouted by manipulating a single gene in a single class of neurons, potentially facilitating the evolutionary flexibility in action selection.

2. Synchronous multi-segmental activity between metachronal waves controls locomotion speed in *Drosophila* larvae

The ability to adjust the speed of locomotion is essential for survival. In limbed animals, the frequency of locomotion is modulated primarily by changing the duration of the stance phase. The underlying neural mechanisms of this selective modulation remain an open question. Here, we report a neural circuit controlling a similarly selective adjustment of locomotion frequency in *Drosophila* larvae. *Drosophila* larvae crawl using peristaltic waves of muscle contractions. We find that larvae adjust the frequency of locomotion mostly by varying the time between consecutive contraction waves, reminiscent of limbed locomotion. A specific set of muscles, the lateral transverse (LT) muscles, co-contract in all segments during this phase, the duration of which sets the duration of the interwave phase. We identify two types of GABAergic interneurons in the LT neural network, premotor neuron A26f and its presynaptic partner A31c, which exhibit segmentally synchronized activity and control locomotor frequency by setting the amplitude and duration of LT muscle contractions. Altogether, our results reveal an inhibitory central circuit that sets the frequency of locomotion by controlling the duration of the period in between peristaltic waves. Further analysis of the descending inputs onto this circuit will help understand the higher control of this selective modulation.

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35 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

At the heart of our research lies the fundamental question, 'What is life?'. We believe that to answer this question, we must bridge the gap between the world of molecules and living cells. Direct measurement of molecules in living cells is crucial in this endeavor. Therefore, we have been tirelessly developing 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 leading technologies we have developed to address this profound question.

This year, we achieved several significant breakthroughs in our research. We developed a generalized design strategy for fluorescence lifetime biosensors using mTurquoise2, enabling quantitative measurements of small molecules such as ATP, cAMP, citrate, and glucose in living cells ([9]). This design approach addresses the challenges of traditional biosensors by offering better quantitation and multi-target detection capabilities.

In collaboration with the Miyawaki laboratory at RIKEN, we continued our work on super-photostable fluorescent proteins. Zhang from our laboratory demonstrated that fusion proteins of the monomeric, photostable green fluorescent protein mStayGold with various cellular proteins do not adversely affect protein localization or function. These fusion proteins enable super-resolution imaging techniques, including stimulated emission depletion (STED) microscopy, with unprecedented observation duration.

Addressing the limitations of fluorescence microscopy, particularly for light-sensitive samples such as iPS cells, Inutsuka developed a label-free imaging method called polarization-based differential phase contrast (pDPC) ([11]). This technique achieves approximately 100 nm spatial resolution and 8 ms/frame temporal resolution, comparable to our previously developed spinning disk super-resolution fluorescence microscope. The pDPC method successfully visualized dynamic subcellular structures such as ER and mitochondrial cristae in living cells without fluorescent labeling. Furthermore, Kondratiev and Inutsuka demonstrated the application of machine learning to pDPC images for automated cell cycle classification ([12]).

In the area of single-molecule analysis, Takanami, in collaboration with the Kabashima laboratory, developed a novel algorithm combining Expectation-Maximization and particle filtering to detect shape anisotropy from individual molecular trajectories ([3]). This method overcomes the limitations of traditional approaches by extracting shape information from experimentally feasible trajectory lengths, offering new insights into the conformational states of biomolecules in living cells.

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36 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, lag-phase, and death.

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37 Kawaguchi Group

Research Subjects: Biophysics

Member: Kyogo Kawaguchi, Shunshi Kohyama

The Kawaguchi group aims to elucidate diverse biological and physical phenomena from a physical perspective. Currently, the lab investigates a wide range of topics, from intracellular phenomena and cell populations to biological evolution and emergent phenomena in AI, through theoretical approaches, numerical simulations, data analysis, and collaboration with experiments.

The main research themes for the current fiscal year are as follows:

- **Patterns and evolution of vertebral counts in tetrapods:** Vertebral counts are crucial evolutionary indicators, likely involving Hox genes, though details remain unclear. Analysis of data from 388 tetrapod species confirmed known patterns (e.g., constancy in thoracic/lumbar counts) and discovered new ones, such as correlations between distant regions (cervical-sacral) and avian-specific anterior-posterior balance relationships. Connections between vertebral counts and Hox gene structure were also demonstrated.

- **Theory for predicting intracellular molecular assemblies:** Proteins and RNA assemble into droplet-like structures (membraneless organelles) via liquid-liquid phase separation (LLPS). We constructed a simulation-based theoretical model to predict interactions, particularly for intrinsically disordered regions (IDRs), that drive this formation. Furthermore, we proposed indicators to predict mixing or separation between different IDR sequences and showed that there might be an upper limit to the variety of droplet types that can coexist within a cell.

- **Chromatin structure and histone modifications:** Chromatin structure within the cell nucleus is regulated by histone modifications such as acetylation, but the detailed mechanisms are not fully understood. Using experiments with reconstituted chromatin, we revealed that acetylation increases structural fluctuations, leading to a more open chromatin state. We also showed that these modification patterns alone can reproduce structures similar to those observed in vivo.

- **Membrane phase separation and protein dynamics in bacterial cell division:** Bacterial cell membranes contain specific lipid regions (membrane domains) where proteins accumulate during division. Using artificial cell membranes (GUVs) to replicate membrane phase separation states, we clarified that proteins select specific membrane domains and form patterns. Moreover, we uncovered a bidirectional interaction where protein assembly, in turn, reorganizes the membrane structure.

- **Percolation model for emergent phenomena in neural networks:** In large-scale neural networks, new abilities can suddenly appear ("emergent phenomena") once model size exceeds a certain threshold. Noting the similarity to phase transitions in physics, we conducted experiments training networks on artificial languages, showing a strong correlation between the acquisition of grammatical rules and rapid improvements in task performance. We further explained this phenomenon theoretically using a percolation model from physics, demonstrating its ability to predict scaling laws related to the amount of training data.

- **Universality of dynamical phase transitions in Brownian motion:** We provided the first demonstration that "dynamical phase transitions," phenomena characteristic of non-equilibrium systems, exist universally in the fundamental stochastic process of Brownian motion. For instance, we theoretically proved that particles undergo a first-order phase transition between localized and delocalized states when the spatial dimension exceeds four. We also showed that even in one-dimensional systems, a second-order dynamical phase transition can occur by carefully choosing the observable. These findings offer new perspectives for understanding non-equilibrium statistical mechanics and diffusion models in AI.

年次研究報告　2024年度

2025年 5 月 30 日

東京大学大学院理学系研究科・理学部
物　理　学　教　室

発　行　　松 尾 泰

編　集　　中 島 康 博
酒 井 明 人
中 村 ち か 子