RIKEN QUANTUM COMPUTING

RIKEN Center for Quantum Computing

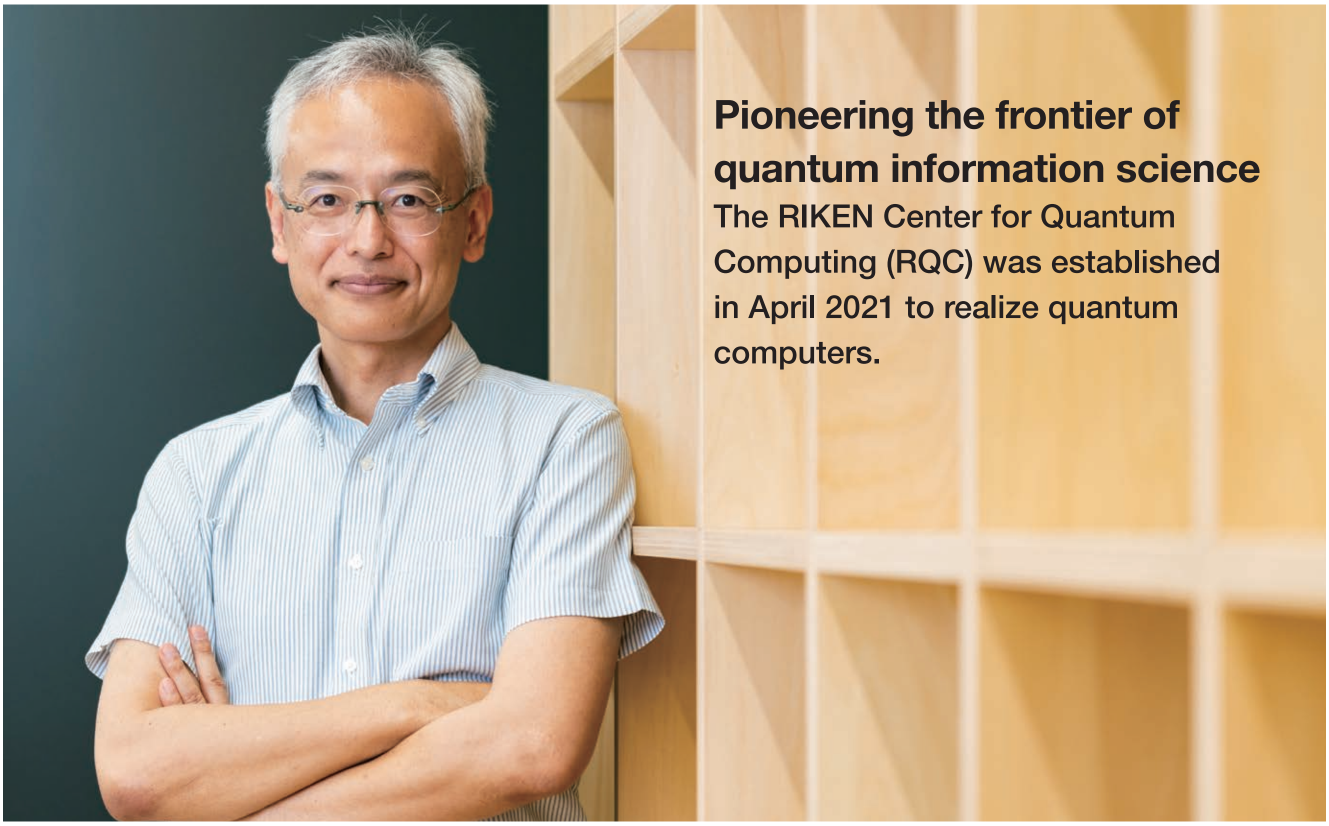
Activity Report

RIKEN

Published May 2023

Contents

Director's Greetings



Pioneering the frontier of quantum information science

The RIKEN Center for Quantum Computing (RQC) was established in April 2021 to realize quantum computers.

Quantum mechanics, which was born in the early 20th century, has evolved through the efforts of numerous researchers and contributed to the development of science and technology over a broad range of areas. However, from the perspective of quantum information science, which has rapidly gained attention since the end of the last century, it has become clear that humans have not yet fully mastered quantum mechanics. That is, quantum mechanics and quantum technology are expanding their scope to information science and technology, fields that they have had limited contact with thus far, as they seek to uncover potentially transformative computing resources.

Even in the research and development of quantum computers, the major physical platform has not yet been narrowed down worldwide. At RQC, we have invited leaders in the fields of superconducting, optical, and semiconductor quantum computers, which are relatively advanced. By conducting research and development on different approaches simultaneously, we hope to enhance opportunities for mutual discovery and learning and create new ideas through the synergy effect. In addition, RQC has other experimental research teams developing basic technology for quantum information processing using atoms and electrons, as well as several theoretical teams working on research fields such as quantum computing theory, quantum algorithms, quantum architecture, and quantum software. Diverse talents collaborate from basics to applications, from experiments to theories, aiming for breakthrough research every day.

Furthermore, RQC serves as the headquarters and quantum computer development hub at the core of all ten of the Quantum Technology Innovation Hubs that were set up based on the National Quantum Technology Innovation Strategy promoted by the Japanese government. As such, it is engaging in activities for promoting advances and collaborations in Japanese quantum technology research and development. Through the cross-industry-government-academia base activities, by sharing knowledge across specialized fields and deepening lateral collaboration, we aim to accelerate the innovation cycle, contribute to the development of science and technology, and contribute to society.

In RQC, three new teams will be launched in the fiscal year 2023. We will further deepen collaboration with researchers inside and outside of RIKEN, conduct multifaceted discussions through the gathering of researchers with diverse ideas and expertise, nurture talents to lead the next generation of quantum technology, and work together as a center to conduct research and development towards the realization of quantum computers.

RIKEN Center for Quantum Computing

The RIKEN Center for Quantum Computing (RQC) will broaden quantum technology's potential by engaging in coherent research and development that encompasses everything from hardware to software, and fundamental science through to applications, with the aim of realizing quantum computers as innovative information processing units based on the principles of quantum mechanics.

The RQC will launch three new teams in fiscal 2023, giving it a lineup of 18 research teams in total. It is promoting the development of quantum computers with various physics-related teams that cover the superconducting method, the optical method, the semiconductor method and so on, as well as research and development by theoretical teams that cover quantum algorithms, quantum computation theory and other fields.

RIKEN Center for Quantum Computing

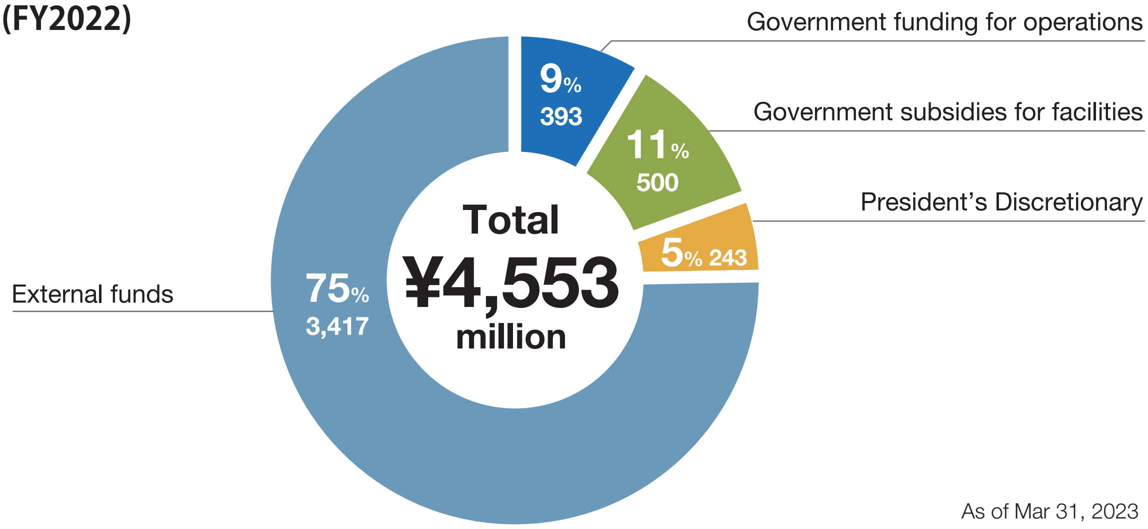
Director: Yasunobu Nakamura
Deputy director: Akira Furusawa, Shinichi Yorozu

- **RQC Advisory Council**
- **Superconducting Quantum Electronics Research Team:** Yasunobu Nakamura
- **Superconducting Quantum Simulation Research Team:** Jaw-Shen Tsai
- **Superconducting Quantum Electronics Joint Research Unit:** Eisuke Abe
- **Superconducting Quantum Computing System Research Unit:** Yutaka Tabuchi
- **Hybrid Quantum Circuits Research Team:** Atsushi Noguchi
- **Optical Quantum Computing Research Team:** Akira Furusawa
- **Optical Quantum Control Research Team:** Hidehiro Yonezawa [Est. Jul.1st 2023]
- **Quantum Many-Body Dynamics Research Team:** Takeshi Fukuhara
- **Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team:** Erika Kawakami
- **Semiconductor Quantum Information Device Research Team:** Seigo Tarucha
- **Semiconductor Quantum Information Device Theory Research Team:** Daniel Loss
- **Quantum Computing Theory Research Team:** Keisuke Fujii
- **Quantum Information Physics Theory Research Team:** Franco Nori
- **Quantum Computational Science Research Team:** Seiji Yunoki
- **Quantum Computer Architecture Research Team:** Hayato Goto [Est. Apr.1st 2023]
- **Analytical Quantum Complexity RIKEN Hakubi Research Team:** Tomotaka Kuwahara
- **Mathematical Quantum Information RIKEN Hakubi Research Team:** Bartosz Regula [Est. Apr.1st 2023]
- **RIKEN RQC-FUJITSU Collaboration Center:** Yasunobu Nakamura
- **Office of the Center Director:** Shinichi Yorozu

Superconductivity | Optics | Atoms | Electrons | Semiconductor | Theory | Administration

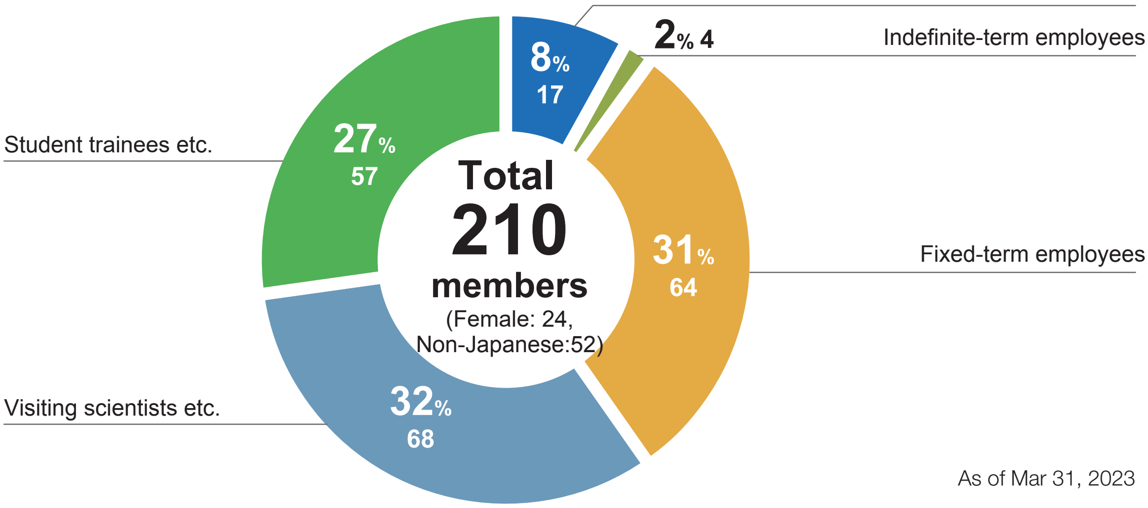
RIKEN Center for Quantum Computing (Continued)

Budget (FY2022)



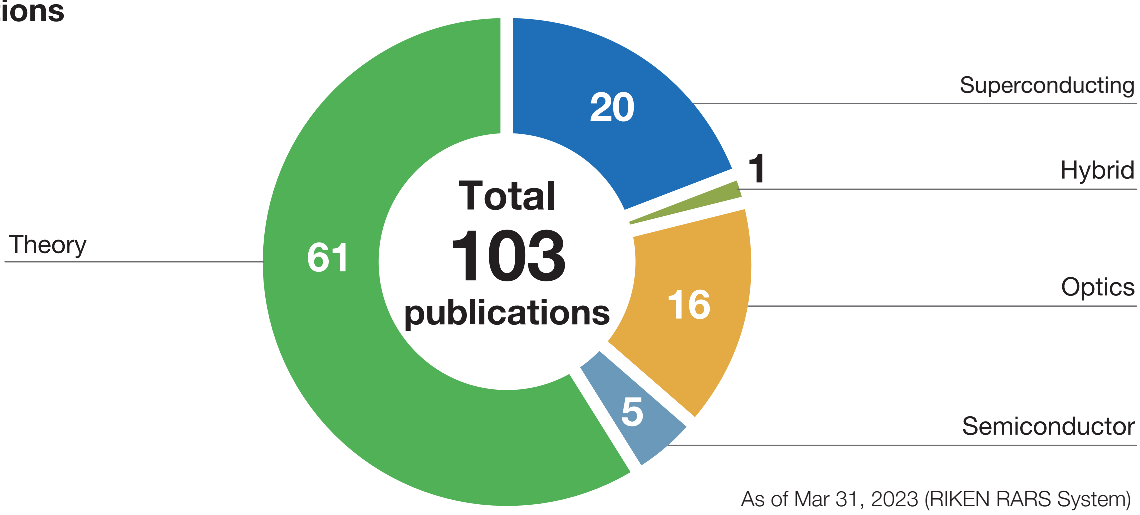
As of Mar 31, 2023

Members



As of Mar 31, 2023

Publications



As of Mar 31, 2023 (RIKEN RARS System)

RQC Colloquiums and RQC Seminars

FY2022 RQC Colloquium

At the RQC, we regularly invite renowned researchers and hold RQC Colloquiums. RQC Colloquiums were held 10 times in fiscal 2022, and vigorous discussions took place as a result of making the events known to other centers as well, not just the RQC.

No.	Date	Speaker	Affiliation	Title
1st	Apr. 20, 2022	Prof. John Martinis	UC Santa Barbara	Building a Quantum Computer
2nd	May 18, 2022	Prof. Andrew Dzurak	UNSW Sydney	Silicon-based quantum computing: The path from the laboratory to industrial manufacture
3rd	Jun. 15, 2022	Prof. Adam Kaufman	JILA	Quantum science with microscopically controlled arrays of two-electron atoms
4th	Jul. 13, 2022	Prof. Isaac Chuang	MIT	From spin physics to quantum algorithms
5th	Sep. 7, 2022	Dr. Zachary Vernon	Xanadu	Fault-tolerant photonic quantum computing
6th	Oct. 5, 2022	Prof. Alexandre Blais	Institut Quantique, Université de Sherbrooke	Measuring the quantum state of superconducting qubits
7th	Nov. 2, 2022	Prof. Jonathan Home	ETH Zürich	Scaling quantum computing with trapped ions
8th	Dec. 7, 2022	Dr. James Clarke	Intel	From a Grain of Sand to a |Quantum> Bit of Information
9th	Jan. 11, 2023	Prof. Antoine Browaeys	Laboratoire Charles Fabry, Institut d'Optique, CNRS	Exploring the many-body problem with assembled atoms
10th	Mar. 15, 2023	Prof. Peter van Loock	University of Mainz	Optical quantum information processing

FY2022 RQC Seminar

Additionally, at the RQC we also hold RQC Seminars, which each PI organizes independently. RQC Seminars were held 28 times in fiscal 2022, and vigorous discussions that went beyond the team framework were held, with the aim of making breakthroughs related to the research and development of quantum computers.

No.	Date	Speaker	Affiliation
9th	Jun. 8, 2022	Dr. Tomotaka Kuwahara	RIKEN RQC
10th	Jul. 29, 2022	Prof. Junichiro Kono	Rice University
11th	Aug. 16, 2022	Prof. Anton Frisk Kockum	CHALMERS UTS
12th	Aug. 26, 2022	Prof. Ievgen Arkhipov	Palacky University
13th	Sep. 1, 2022	Prof. Henning Schomerus	Lancaster University
14th	Sep. 12, 2022	Dr. Dan Gunlycke	U.S. Naval Research Lab.
15th	Oct. 28, 2022	Dr. Dany Lachance-Quirion	Nord Quantique
16th	Nov. 1, 2022	Prof. Yueh-Nan Chen	National Cheng Kung Univ.
17th	Nov. 4, 2022	Dr. Po-Chen Kuo	National Cheng Kung Univ.
18th	Nov. 10, 2022	Prof. Stephen Hughes	Queen's University
19th	Nov. 14, 2022	Prof. Yosuke Nakata	Osaka University
20th	Nov. 18, 2022	Dr. Alessandro Ferreri	Forschungszentrum
21st	Nov. 22, 2022	Mr. Zane Marius Rossi	MIT Quanta Group
22nd	Nov. 25, 2022	Prof. Valerio Scarani	NUS

No.	Date	Speaker	Affiliation
23rd	Dec. 20, 2022	Prof. Christian Flindt	Aalto University
24th	Jan. 20, 2023	Dr. Vittorio Vitale	ICTP
25th	Jan. 31, 2023	Dr. Xianjing Zhou	RIKEN RQC
26th	Feb. 13, 2023	Ms. Polina Kofman	NU Karazin
27th	Feb. 21, 2023	Dr. Enrico Russo	Messina Univ.
28th	Feb. 22, 2023	Prof. Kay Brandner	Univ. of Nottingham
29th	Mar. 8, 2023	Dr. Marcello Dalmonte	ICTP
30th	Mar. 14, 2023	Prof. Fabio Marchesoni	INFN Perugia
31st	Mar. 16, 2023	Prof. Pulak Kumar Ghosh	Presidency Univ.
32nd	Mar. 17, 2023	Dr. Kaoru Mizuta	RIKEN RQC
33rd	Mar. 22, 2023	Mr. Alberto Mercurio	DST
34th	Mar. 24, 2023	Mr. Fabio Mauceri	DST
35th	Mar. 30, 2023	Dr. Vyacheslav Misko	VUB
36th	Mar. 31, 2023	Dr. Masanori Hanada	Univ. of Surrey

Collaborations

International

[Europe]
- Aalto University
- Chalmers University of Technology
- Copenhagen University
- Delft University of Technology (TU Delft)
- Interuniversity Microelectronics Centre (IMEC)
- Johannes Gutenberg University Mainz
- Palacky University
- Qutech
- University of Basel
- Walther Meissner Institute (WMI)

etc.

[North America]
- Argonne National Lab
- Intel Corporation
- Massachusetts Institute of Technology (MIT)
- Nord Quantique
- University of Notre Dame

etc.

[Asia, Oceania]
- Center for Axion and Precision Physics Research, Institute for Basic Science
- Electronics and Telecommunications Research Institute (ETRI)
- Hunan Normal University
- Moscow Institute of Physics and Technology(MIPT)
- National Tsing Hua University (NTHU)
- Taiwan Semiconductor Research Institute (TSRI)
- The University of New South Wales(UNSW)
- University of Technology Sydney(UTS)

etc.

National

[Research Institute]
- National Astronomical Observatory of Japan (NAOJ)
- National Institute of Advanced Industrial Science and Technology (AIST)
- National Institute of Information and Communications Technology (NICT)

etc.

[National University Corporations]
- Keio University
- Nagoya University
- Okinawa Institute of Science and Technology Graduate University (OIST)
- Osaka University
- Shizuoka University
- The University of Tokyo
- Tohoku University
- Tokyo Institute of Technology
- Tokyo Medical and Dental University
- Tokyo University of Science

etc.

[Private business]
- Fujitsu Ltd.
- Hitachi.Ltd.
- Mitsubishi Electric Corporation
- Nikon Corporation
- Nippon Electric Company, Ltd.
- Nippon Telegraph and Telephon Corporation (NTT)
- TOSHIBA CORPORATION

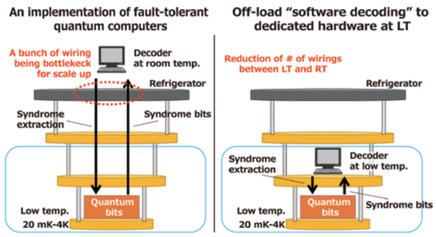
etc.

Press Releases

April 1, 2022

A Quantum Error Correction Methodology toward Lattice Surgery

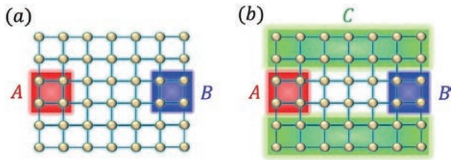
Superconducting Quantum Computing System Research Unit



April 26, 2022

It takes three to tangle: long-range quantum entanglement needs three-way interaction

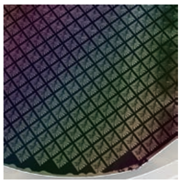
Analytical Quantum Complexity RIKEN Hakubi Research Team



August 25, 2022

Researchers demonstrate error correction in a silicon qubit system

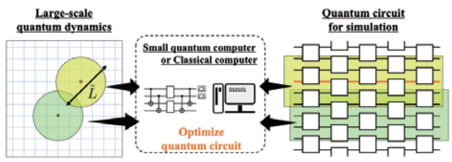
Semiconductor Quantum Information Device Research Team



October 6, 2022

Local variational quantum compilation of a large-scale Hamiltonian dynamics

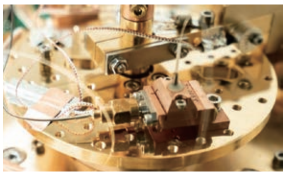
Quantum Computing Theory Research Team



October 31, 2022

Quantum arbitrary waveform generator

Optical Quantum Computing Research Team

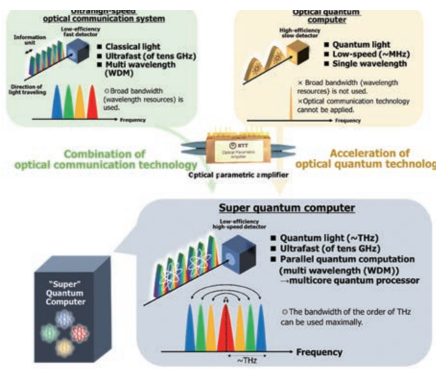


March 6, 2023

43-GHz real-time optical quantum signal detection for ultrafast quantum computation

Toward super quantum computers with optical high-speed communication technologies

Optical Quantum Computing Research Team



Awards

April 20, 2022

Dr. Seigo Tarucha awarded Commendation by Minister of Education, Culture, Sports, Science and Technology

Dr. Seigo Tarucha, Team Leader, Semiconductor Quantum Information Device Research Team, has been awarded the Commendation for Science and Technology (Research Category) by the Minister of Education, Culture, Sports, Science and Technology (2022). This Commendation is awarded to honor individuals who have achieved outstanding results in research and development, promotion of understanding, and other areas related to science and technology. Dr. Seigo Tarucha was awarded the Commendation for his work: "Research on the Physics of Semiconductor Quantum Information and its Applications in Quantum Computing."

August 28, 2022

Mr. Ivan Grytsenko awarded ULT2022 Best Poster Award

Mr. Ivan Grytsenko, Technical Scientist for the Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team, has been awarded the ULT2022 Best Poster Award (International Conference on Ultra Low Temperature Physics 2022). This Award is administered by the IUPAP (International Union of Pure and Applied Physics), the Japan World Exposition 1970 Commemorative Fund, and the Inoue Foundation for Science, and it was awarded to Mr. Grytsenko for his work: "Using a cryogenic tunable resonance circuit to image-charge detection of surface electrons on He II."

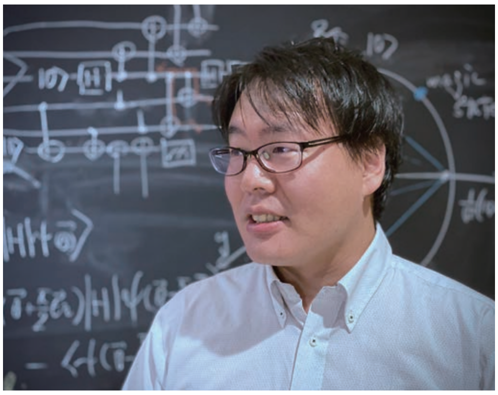
November 21, 2022

Dr. Franco Nori selected as Clarivate Highly Cited Researcher 2022

Dr. Franco Nori, Team Leader at the Quantum Information Physics Theory Research Team, has been selected as a Clarivate Highly Cited Researcher 2022, as announced by Clarivate Analytics. Highly Cited Researchers are selected in each field of research, as the authors of papers that rank in the top 1% based on number of citations in Clarivate Analytics' Essential Science Indicators database.

December 15, 2022

Dr. Keisuke Fujii awarded the Japan Society for the Promotion of Science (JSPS) Prize



Dr. Keisuke Fujii, Team Leader, Quantum Computing Theory Research Team, has been awarded the 19th (FY2022) JSPS (Japan Society for the Promotion of Science) Prize. This Prize is awarded to young researchers aged under 45 in all fields of the humanities, social sciences and natural sciences, who are recognized as having achieved particularly outstanding academic results through papers, books, and other research achievements published in academic journals and similar publications inside and outside Japan. Dr. Fujii was awarded the JSPS Prize for his work: "Pioneering Research on Quantum Computing Theory and Quantum Software for the Realization of Quantum Computers."

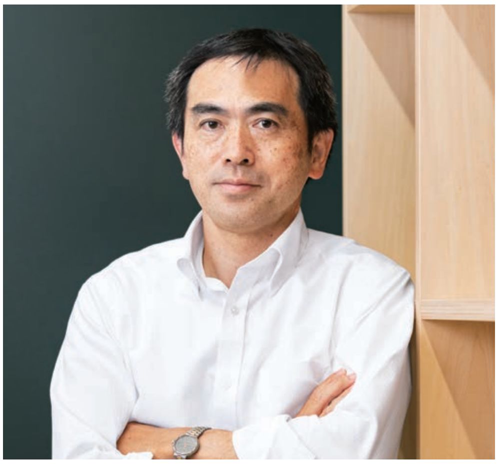
January 1, 2023

Dr. Franco Nori awarded PQE-2023 Lamb Award

Dr. Franco Nori, Team Leader, Quantum Information Physics Theory Research Team, has been awarded the Lamb Award at the PQE-2023, which was hosted by the Physics of Quantum Electronics (PQE) conference. The Lamb Award is presented annually for outstanding contributions to the field of laser science and quantum optics. Dr. Nori received the award for his work: “Pioneering contributions to quantum optics, quantum electronics, and quantum information.”

March 3, 2023

Dr. Akira Furusawa awarded Incentive Award in the 38th Telecommunications Advancement Foundation Award (Telecom System Technology Award)

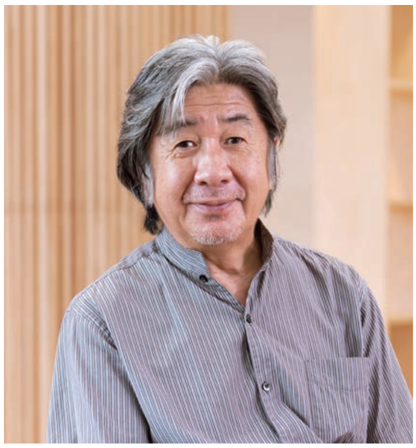


Dr. Akira Furusawa, Deputy Director of RQC, has been awarded an Honorable Mention in the 38th Telecommunications Advancement Foundation Award (Telecom System Technology Award). This award is granted by the Telecommunications Advancement Foundation, and is given to research papers and works related to information and telecommunications that have made significant contributions and achievements to the advancement, development, and standardization of information and telecommunications from technical and engineering perspectives. The name of the paper that won the award is: “Fabrication of low-loss quasi-single-mode PPLN waveguide and its application to a modularized broadband high-level squeezer.”

March 13, 2023

Dr. Yasunobu Nakamura and Dr. Jaw-Shen Tsai awarded a Japan Academy Prize

Dr. Yasunobu Nakamura, Director of RQC, and Dr. Jaw-Shen Tsai, Team Leader, Superconducting Quantum Simulation Research Team, have been awarded a Japan Academy Prize. Each year, up to nine Japan Academy Prizes are awarded to persons who have achieved notable research landmarks or who have authored particularly outstanding academic papers or books. The title of Dr. Nakamura and Dr. Tsai’s work is: “Pioneering Research Works on Superconducting Qubits and their Quantum Control (Joint Research).”



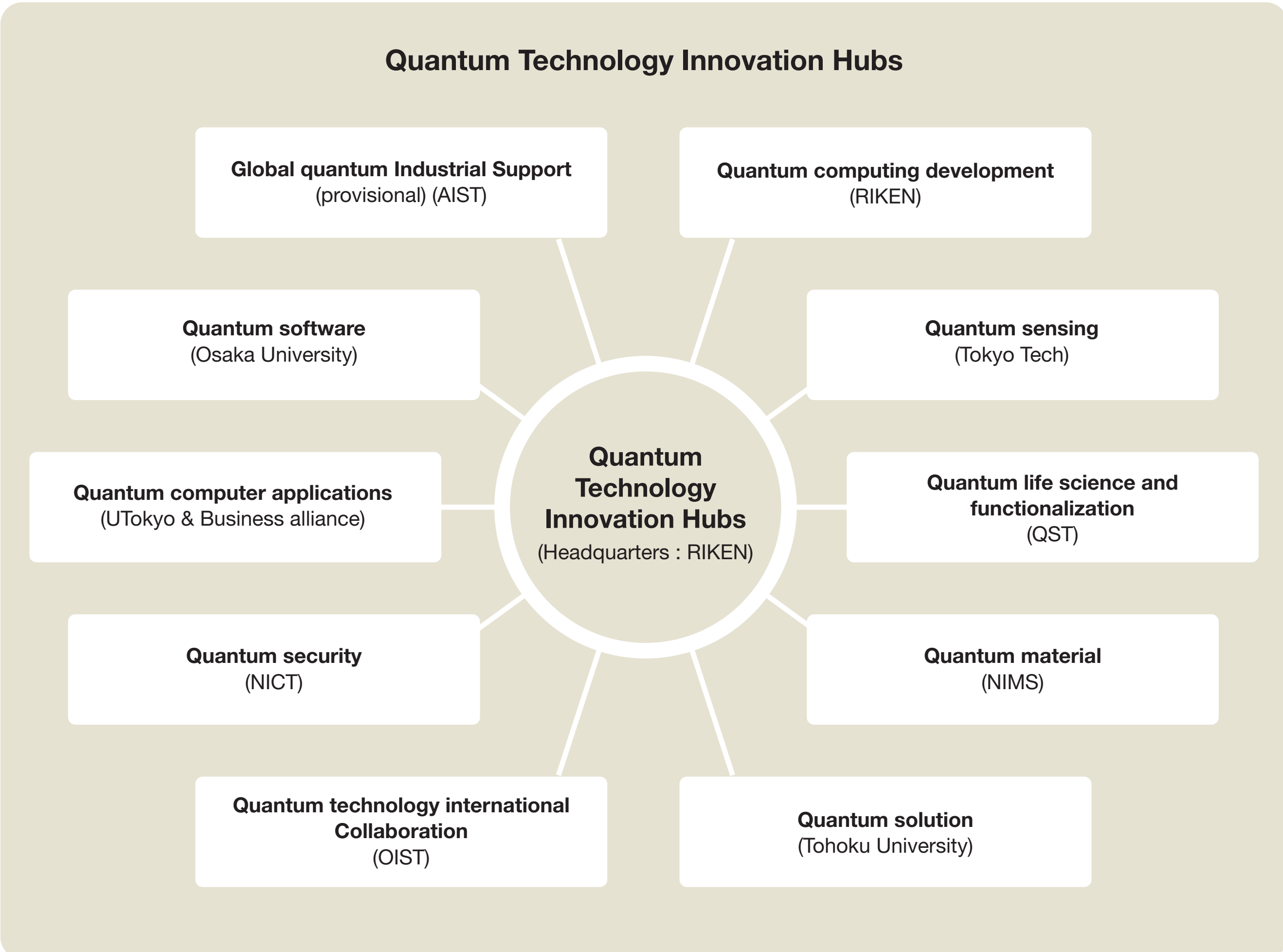
Quantum Technology Innovation Hubs

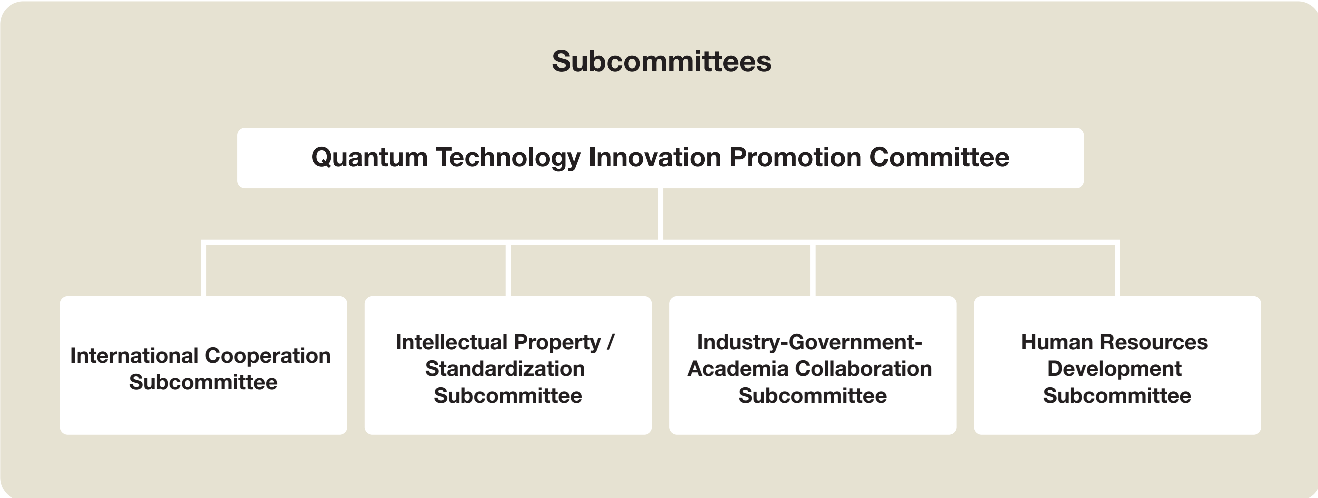
QIH
Quantum Innovation Hubs

As the core organization of the 10 Quantum Innovation Hubs (QIH), RIKEN brings all the hubs together as one to accelerate the social implementation of quantum technology

QIH were established as hubs for streamlining the engagement of industry, government and academia in everything from basic research on quantum technology through to technology verification, intellectual property management and human resources development, from the perspective of securing and strengthening Japan's international competitiveness, on the basis of government strategies known as the National Quantum Technology Innovation Strategy (January 2020) and the Vision of Quantum Future Society (April 2022).

As the core organization of the QIH, RIKEN performs a headquarters function that strives for coordination among the 10 hubs. Additionally, within the 10 domestic hubs, RIKEN is active as a quantum computing development hub that aims to realize and establish quantum computer systems.





The positioning of the respective subcommittees

With an eye on the social implementation of quantum technology, the QIH established and operate the Quantum Technology Innovation Promotion Committee as a meeting framework for undertaking joint recommendations and promotions. Four subcommittees where the hubs exchange views on challenges, and share awareness and strategies, are established beneath the Promotion Committee.

- International Cooperation Subcommittee: Holds international symposiums, and promotes international collaborations such as international joint research
- Intellectual Property / Standardization Subcommittee: Shares strategies between the hubs on intellectual property and international standardization
- Industry-Government-Academia Collaboration Subcommittee: Promotes industry-government-academia collaborations aimed at the social implementation of quantum technology
- Human Resources Development Subcommittee: Strengthens entries by young researchers, and human resources development that transcends institutions and research fields

Pick up Activities

Quantum Innovation 2022, an international symposium concerning quantum science and technology innovation, was held on November 28-30, 2022 as one part of the QIH activities. This Symposium, which was held mainly online, served as a valuable platform for disseminating information. Over the three-day period it featured approximately 91 lectures, two panel discussions, and sessions for young participants with 64 presentations by young researchers, and attracted remote participation from approximately 50 countries and a total of approximately 1,100 individuals.

Quantum Innovation 2022, November 28-30, 2022 (at the broadcasting venue)

Quantum Technology Innovation Hubs (Continued)

In addition, the QIH are also focusing on outreach activities to promote the training and retention of personnel who will carry quantum computing and quantum technology into the future, and partnerships with the industrial community.

Images showing Welcome to the mysterious world of Quantum, a summer vacation science event held on August 11-13, 2022, at the Science Museum

Exhibition at Nano tech 2023, which was held on February 1-3, 2023, at Tokyo Big Sight

Toshio Tonouchi (Ph.D.), Coordinator

Selected Publications

1 Toshio Tonouchi *et al.*, "A fast method of verifying network routing with back-trace header space analysis", IEEE/IFIP IM 2015
2 CS Hong, Toshio Tonouchi ed., Internet for Changing Business and New Computing Services: 12th Asia-Pacific Network Operations and Management Symposium, APNOMS 2009, LNCS 5787
3 Yoshinori Watanabe *et al.* "UTRAN O&M Support System with Statistical Fault Identification and Customizable Rule Sets", NOMS 2008
4 Nicholas Damianou, Naranker Dulay, Emil Lupu, Morris Sloman, Toshio Tonouchi, "Tools for Domain-Based Policy Management of Distributed Systems", IEEE/IFIP NOMS 2002
5 Toshio Tonouchi *et al.*, "An Implementation of OSI Management Q3 Agent Platform for Subscriber Networks", IEEE Int Conf on Communication (ICC) 1997

Brief resume

1990 B.S. in Information Science, The University of Tokyo
1992 M.S. in Information Science, The University of Tokyo
1992 Researcher, C&C Systems Research Laboratories, NEC Corporation
1999 Visiting Researcher, Imperial College
2004 Principal Researcher, Internet System Research Laboratories, NEC Corporation
2008 Ph.D. (Information Science), Osaka University
2011 Senior Principal Researcher, Service Platform Research Laboratories, NEC Corporation
2018 Director, Council for Science, Technology and Innovation, Cabinet Office
2020 Deputy Manager, Planning Office for the Quantum Computing Center
2021 Research Administrator, Office of the Center Director, RIKEN Center for Quantum Computing
2022 Coordinator, Office of the Center Director, RIKEN Center for Quantum Computing (-present)

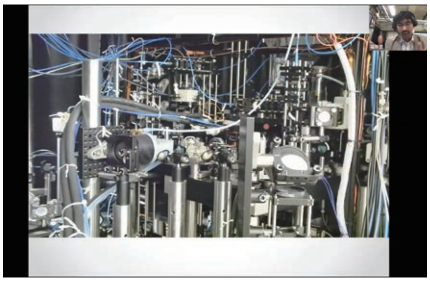
Dr. Toshio Tonouchi is angaged in work of the head quaters of QIH as a coordinator.

RQC FY2022 Pick Up Topics

RIKEN Open Campus

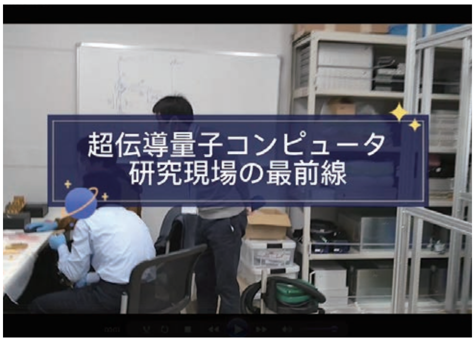
RIKEN Wako Open campus was held on April 23, 2022. The RQC implemented a variety of content to inform the public about quantum computer research and development.

Science lecture by Dr. Yorozu.



Virtual Lab tour by Dr. Abe and Dr. Fukuhara.

Lab tour by Dr. Kawakami

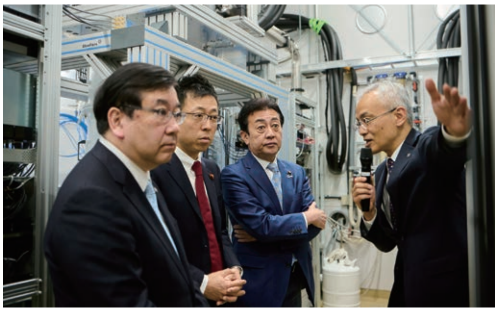


Youtube video released by Dr. Tabuchi

Launch of and Opening Ceremony for Japan's superconducting quantum computing cloud service

On March 27, 2023, RIKEN installed and launched the cloud service of a domestically-built superconducting quantum computer, which was made by a joint-research group composed of Japanese universities, research institutes and businesses, for external parties. In addition, that same day, RIKEN also held an Opening Ceremony for members of industry, government and academia related to the project, and introduced the research and conducted a tour of the quantum computer hardware. The event was covered by a wide range of media, including newspapers and TV broadcasters.

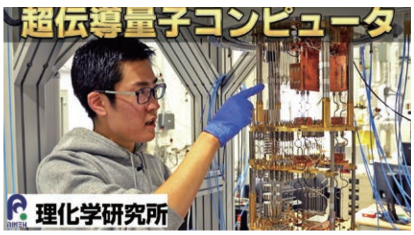
Commemorative Photo of Participants at the Opening Ceremony



Tour of the Quantum Computer

YouTube Video Release

In order to promote understanding of quantum computers, RIKEN collaborated with the famous Japanese YouTuber Ichiken to make a video introducing superconducting quantum computer research and development, in cooperation with the Superconducting Quantum Simulation Research Team, and released it on YouTube.



Superconducting Quantum Electronics Research Team

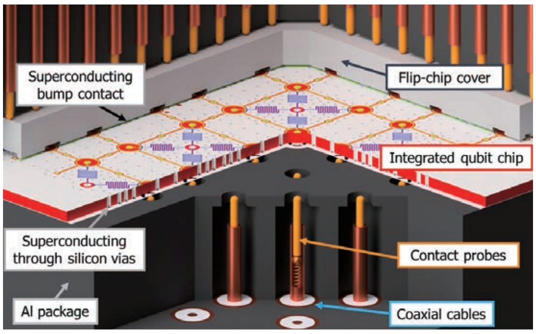
Keywords: Quantum computing, Superconducting circuits, Josephson junction, Microwave quantum optics, Circuit quantum electrodynamics

Research Outline

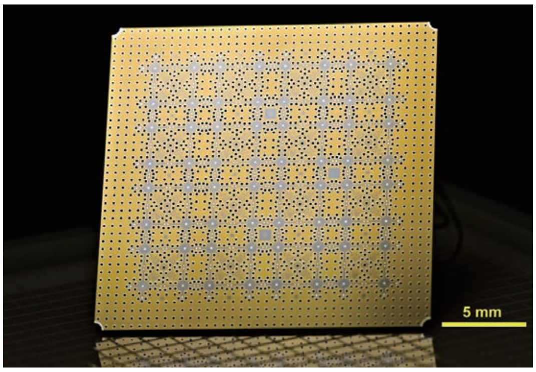
Our team, in collaboration with other teams in RQC as well as collaborators outside RIKEN, is conducting research and development on superconducting quantum circuits for quantum computing and other quantum technologies. Currently, our focus is on the development of a superconducting quantum computing platform with integrated qubits. For a scalable implementation of qubits on a chip, we design and fabricate a two-dimensional array of fixed-frequency transmon qubits on a Si wafer with superconducting through-silicon vias. The control and readout ports for the all-microwave architecture are brought vertically from the backside of the chip as an array of coaxial cables and connected to the chip with spring contacts. In parallel, we are setting up dilution refrigerators, control hardware and software.

We also investigate various phenomena and techniques in microwave quantum optics, where superconducting qubits strongly coupled to a resonator and/or a waveguide are used as a tool for controlling microwave photons stored or transmitted. The topics include microwave photon emitters/receivers, non-reciprocal devices using Josephson junctions, nonlinear microwave quantum optics, and parametric amplification. They can be both research targets and tools for other experiments.

Through those activities, we deepen our understanding further and master superconducting quantum electronics, which we believe leads us to next breakthroughs.



Schematics of the package for an integrated superconducting-qubit circuit



Photograph of a 64-qubit chip

Yasunobu Nakamura (Ph.D.), RQC Director, Team Leader

Selected Publications

1 S. Kono, K. Koshino, Y. Tabuchi, A. Noguchi, and Y. Nakamura, “Quantum non-demolition detection of an itinerant microwave photon”, *Nature Physics* 14, 546 (2018).
2 O. Astafiev, A. M. Zagoskin, A. A. Abdumalikov, Jr., Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J.S. Tsai, “Resonance fluorescence of a single artificial atom”, *Science* 327, 840 (2010).
3 T. Yamamoto, K. Inomata, M. Watanabe, K. Matsuba, T. Miyazaki, W. D. Oliver, Y. Nakamura, and J. S. Tsai, “Flux-driven Josephson parametric amplifier”, *Appl. Phys. Lett.* 93, 042510 (2008).
4 I. Chiorescu, Y. Nakamura, C.J.P.M. Harmans and J.E. Mooij, “Coherent quantum dynamics of a superconducting flux-qubit”, *Science* 299, 1869 (2003).
5 Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, “Coherent control of macroscopic quantum states in a single-Cooper-pair box”, *Nature* 398, 786 (1999).

Brief resume

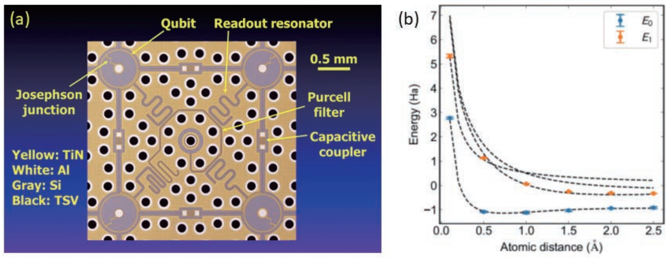
1992 Researcher, Fundamental Research Laboratories, NEC Corporation
1997 Senior Researcher, Fundamental Research Laboratories, NEC Corporation
2001 Principal Researcher, Fundamental Research Laboratories, NEC Corporation (-2005)
2001 Visiting Researcher, Department of Applied Physics, Delft University of Technology (-2002)
2002 Researcher, Frontier Research System, RIKEN (-2013)
2005 Research Fellow, Fundamental and Environmental Research Laboratories, NEC Corporation (-2012)
2012 Professor, Research Center of Advanced Science and Technology, The University of Tokyo (-2022)
2014 Team leader, RIKEN Center for Emergent Matter Science
2020 Group Director, RIKEN Center for Emergent Matter Science
2021 Director, RIKEN Center for Quantum Computing (-present)
2022 Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo (-present)

Recent Achievements

Demonstration of NISQ algorithms on a superconducting quantum computing chip

We have developed and been testing 16- and 64-qubit chips. As for the control and readout, we have achieved a single-qubit and two-qubit gate fidelities of 99.96% and 99.1%, respectively, and a readout fidelity of 99.0% as the best values. For the all-microwave architecture with fixed-frequency transmon qubits, frequency collisions between neighboring qubits and resonators are a critical issue. We are currently testing local laser annealing of individual qubits to reduce the deviations of the qubit frequencies from the targeted values.

We have implemented small-scale NISQ applications by partially using one of the 16-qubit chips. The examples are the subspace-search variable quantum eigensolver (SSVQE) and subspace variational quantum simulator (SVQS).



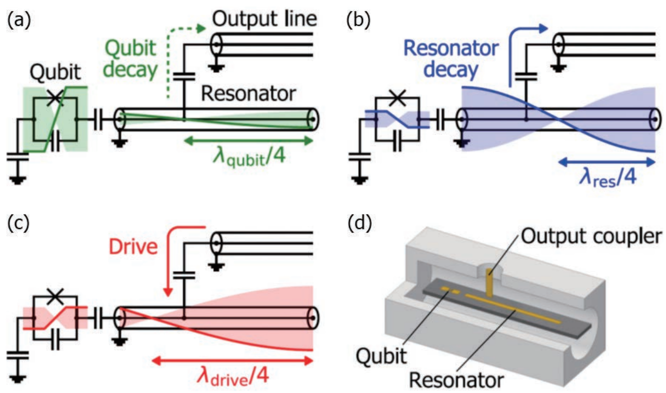
(a) Unit-cell structure of our chip. A larger chip can be constructed by tiling the unit cell. (b) Energy levels of the ground and first-excited states of a hydrogen molecule obtained by SSVQE as a function of the distance between two atoms.

K. Heya *et al.*, “Subspace variational quantum simulator”, Phys. Rev. Research 5, 023078 (2023).

Fast, high-fidelity readout and reset of superconducting qubits

Fast, high-fidelity readout and reset of a qubit are critical for improving the performance of superconducting quantum computers towards fault-tolerant quantum computing. We invented an “intrinsic Purcell filter” and applied it to the dispersive readout of a transmon qubit. The compact notch-type filter implemented by using the internal mode structure of a readout resonator suppresses qubit relaxation through the resonator, while enabling fast readout of the qubit strongly coupled. We demonstrated qubit readout with a 40-ns readout pulse and 99.1% assignment fidelity in a 3D implementation. Later with a planar device, we further improved the numbers to 36 ns and 99.6%, respectively. The circuit also works for microwave-controlled fast unconditional reset of the qubit.

Y. Sunada *et al.*, “Fast readout and reset of a superconducting qubit coupled to a resonator with an intrinsic Purcell filter”, Phys. Rev. Appl. 17, 044016 (2022). Editors’ Suggestion



(a)-(c) Mode structures at the relevant frequencies. The mode at the qubit frequency has a node at the output coupling. (d) Schematic of the device implemented in a 3D cavity.

Core members

(Research Scientist) **Shuhei Tamate**
(Research Scientist) **Alexander Badrutdinov**
(Special Postdoctoral Researcher) **Chung Wai Sandbo Chang**
(Postdoctoral Researcher) **Zhiguang Yan**
(Postdoctoral Researcher) **Rui Li**
(Postdoctoral Researcher) **Chih-Chiao Hung**
(Postdoctoral Researcher) **Zhiling Wang**
(Postdoctoral Researcher) **Shiyu Wang**
(Visiting Researcher) **Ryo Sasaki**
(Visiting Researcher) **Peter Anthony Spring**
(Senior Technical Staff) **Koichi Kusuyama**
(Technical Staff I) **Koh-ichi Nittoh**
(Technical Staff I) **Laszlo Szikszai**
(Technical Staff I) **Harumi Hayakawa**

Superconducting Quantum Simulation Research Team

Keywords: Superconductivity, Josephson effect, Macroscopic quantum coherence, Superconducting qubit, Superconducting quantum information processing

Research Outline

We are conducting research aimed at realizing superconducting quantum computers and quantum simulators. Here, one-way quantum computers and gate-model quantum computers are considered. Superconducting qubit possesses high degree of freedoms in the circuit design and ability to local control as well as readout quantum states.

We proposed an integration method for superconducting qubit circuits that can be easily packaged using conventional planar wiring and are working on a prototype of such a quantum chip [Image 1]. This is a quasi-two-dimensional network that connects qubits using local 3D wire crossing utilizing superconducting air bridges [Image 2]. Using this circuit method, we prototyped a 100-bit superconducting computer and confirmed that it fits on a 20mm square chip.

Operations of superconducting computers require periodic initialization of qubits. We have proposed a new circuit scheme that initializes superconducting qubits at high speed and has succeeded in prototyping. This circuit scheme is realized by connecting a superconducting resonator with a variable attenuation rate to a qubit.

Quantum computer using Bosonic code has an ability to correct errors relatively easily. It protects quantum information from errors by utilizing the infinite degrees of freedom of the resonator. We are conducting research on Kerr parametric oscillators (KPO) to realize the cat code using superconducting circuits, which is one of the practical bosonic codes.

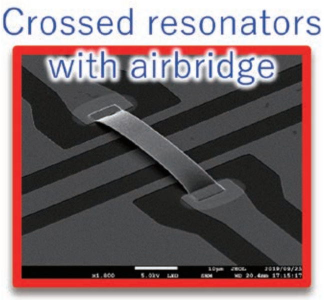


Image 2. Photograph of wire crossing with airbridge in the pseudo 2D network

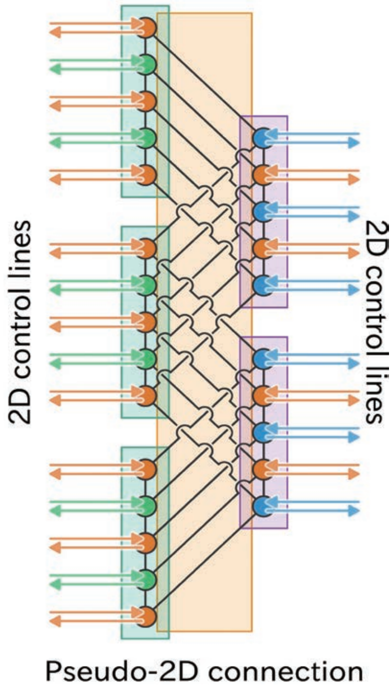
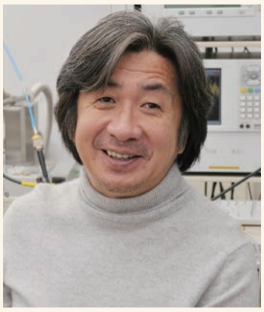


Image 1. Qubits connected by pseudo-2D network



Jaw-Shen Tsai (Ph.D.), Team Leader

Selected Publications

1 H. Mukai, K. Sakata, S.J. Devitt, R. Wang, Y. Zhou, Y. Nakajima, and J.S. Tsai, "Pseudo-2D superconducting quantum coupling circuit for the surface code: proposal and preliminary tests", *New Journal of Physics*, 22, 043013 (2020)

2 A. O. Niskanen, K. Harrabi, F. Yoshihara, Y. Nakamura, S. Lloyd and J. S. Tsai, "Quantum Coherent Tunable Coupling of Superconducting Qubits", *Science*, 316, 723 (2007)

3 T. Yamamoto, Yu. Y. Pashkin, O. Astafiev, Y. Nakamura, and J. S. Tsai, "Demonstration of conditional gate operation using superconducting charge qubits", *Nature*, 425, 941 (2003)

4 Yu. A. Pashkin, T. Yamamoto, O. Astafiev, Y. Nakamura, D. V. Averin and J. S. Tsai, "Quantum oscillations in two coupled charge qubits", *Nature*, 421, 823 (2003)

5 Y. Nakamura, Yu. A. Pashkin, J. S. Tsai, "Coherent Control of Macroscopic Quantum States in a Single-Cooper-pair Box", *Nature*, 398, 786 (1999)

Brief resume

1975 Bachelor of Arts degree in Physics at University of California at Berkeley
1983 Ph.D. State University of New York at Stony Brook
1983 Research Scientist, Microelectronics Research Laboratories, NEC
2001 Fellow, Nano Electronics Research Laboratories, NEC
2001 Team Leader, Macroscopic Quantum Coherence Team, RIKEN
2012 Group Director, Single Quantum Dynamics Research Group, RIKEN
2012 Team Leader, Macroscopic Quantum Coherence Research Team, RIKEN
2014 Team Leader, Superconducting Quantum Simulation Research Team, RIKEN
2015 Professor, Department of Physics, Tokyo University of Science (-present)
2022 Professor, Research Institute for Science and Technology, Tokyo University of Science (-present)

Recent Achievements

100-bit superconducting quantum computer

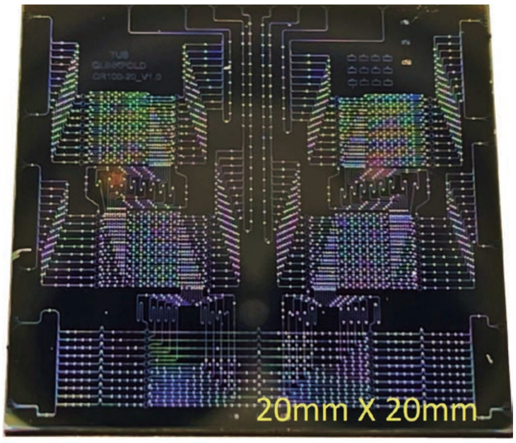


Image 1. Photograph of a 100-bit superconducting quantum computer. Conventional flat wiring can be used for wiring to each qubit.

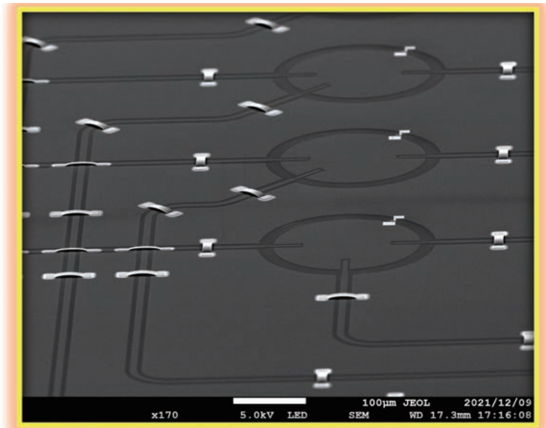


Image 2. Partial magnified view of the 100-bit chip. Quantum bits and air bridges are visible.

We proposed a new integration scheme for superconducting qubit circuits that can be easily packaged using conventional planar wiring and are working on a prototype of such a quantum chip [Image 1]. This is a quasi-two-dimensional network that connects qubits using local 3D wire crossing utilizing superconducting air bridges [Image 2]. Using this circuit method, we prototyped a 100-bit superconducting computer and confirmed that it fits on a 20mm square chip.

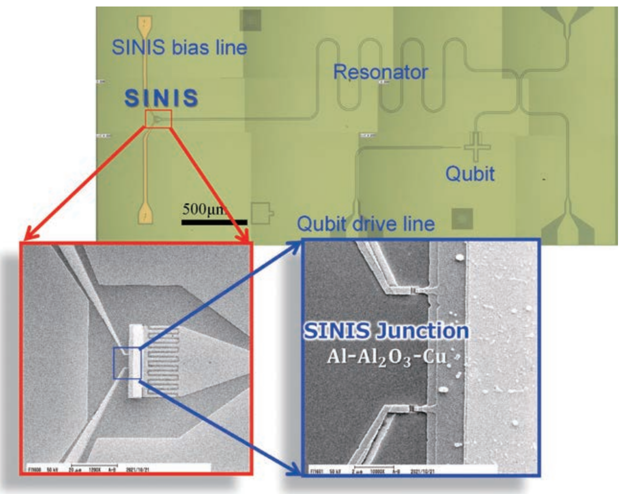
In this circuit, all the qubits are located on the periphery of the chip, which means that conventional planar microwave interconnect technology can be applied, eliminating the need for advanced 3D interconnect technology. The qubits are coupled by a network of alternating crossed resonators, and nearest neighbor junctions are realized.

High-speed initialization of superconducting qubit

Operations of superconducting computers require periodic initialization of qubits. We have proposed a new circuit scheme that initializes superconducting qubits at high speed and has succeeded in prototyping. This circuit scheme is realized by connecting a superconducting resonator with a variable attenuation rate to a qubit.

The Q factor of the resonator is set to a high value during normal operation of the qubit, so that the lifetime of the qubit is not affected by the resonator. And during initialization of the qubit, the Q factor of the resonator is set to a low value, allowing for fast initialization. This is achieved by connecting a SINIS junction to the resonator. In such a circuit, applying a bias voltage to the SINIS junction induces photon-assisted tunneling, which causes a drastic reduction in the Q-value of the resonator.

In our experiments, fast initialization in 180 ns with 99.5% accuracy was achieved.



Fast initialization circuit photo. Superconducting qubits are connected to a superconducting resonator containing a SINIS junction.

Core members

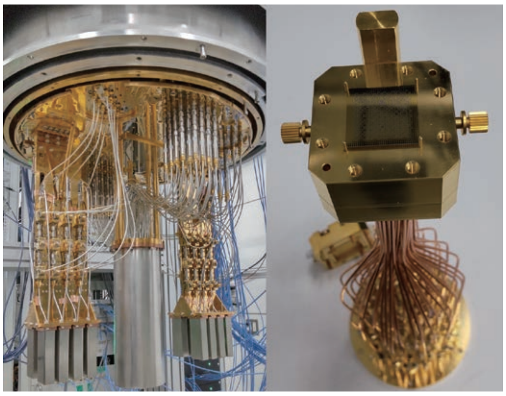
(Special Postdoctoral Researcher) **Hiroto Mukai**

Superconducting Quantum Electronics Joint Research Unit

Keywords: Superconducting quantum circuit, Quantum computing, Quantum technology, Microwave engineering, Quantum entanglement

Research Outline

We develop scalable, multi-qubit quantum computers, in collaboration with the Superconducting Quantum Electronics Research Team. We design a superconducting quantum circuit consisting of Josephson junctions, microwave resonators, transmission lines, filter circuits and so on to implement superconducting qubits and functionalities for coherent controls and non-demolition measurements of their quantum states on a single chip. We integrate a chip, a device package for connecting the chip and coaxial cables, cryogenic microwave components such as Josephson parametric amplifiers, a dilution refrigerator to realize the ultracold environment, and room-temperature electronics for qubit control into a single hardware operating as an intermediate-scale quantum computer with 50 –150 qubits. We evaluate control fidelities for single- and two-qubit gates, initialization, and readout and aim to improve them. At the same time, we explore the potential of the system for NISQ (noisy intermediate-scale quantum) applications. We also work on developing element technologies necessary for further scaling up the number of available qubits, such as packing more microwave cables and components in a limited space, and realizing quantum control across different chips. Ultimately, we aim to pave the way for realizing a system capable of quantum error correction, and to bring a quantum computer that executes computations intractable with classical computers closer to reality.



Left: Wiring of measurement lines inside of a dilution refrigerator

Right: Inside of a dilution refrigerator (left) and a 64-qubit chip mounted on a sample package (right)

Eisuke Abe (D.Sc.), Unit Leader

Selected Publications

1 K. Sasaki, H. Watanabe, H. Sumiya, K. M. Itoh, and E. Abe, “Detection and control of single proton spins in a thin layer of diamond grown by chemical vapor deposition”, Applied Physics Letters 117, 114002 (2020).
2 S. Ishizu, K. Sasaki, D. Misonou, T. Teraji, K. M. Itoh, and E. Abe, “Spin coherence and depths of single nitrogen-vacancy centers created by ion implantation into diamond via screening masks”, Journal of Applied Physics 127, 244502 (2020).
3 D. Misonou, K. Sasaki, S. Ishizu, Y. Monnai, K. M. Itoh, and E. Abe, “Construction and operation of a tabletop system for nanoscale magnetometry with single nitrogen-vacancy centers in diamond”, AIP Advances 10, 025206 (2020).
4 R. Sakano, A. Oguri, Y. Nishikawa, and E. Abe, “Bell-state correlations of quasiparticle pairs in the nonlinear current of a local Fermi liquid”, Physical Review B 99, 155106 (2019).
5 E. Abe and K. Sasaki, “Tutorial: Magnetic resonance with nitrogen-vacancy centers in diamond—microwave engineering, materials science, and magnetometry”, Journal of Applied Physics 123, 161101 (2018).

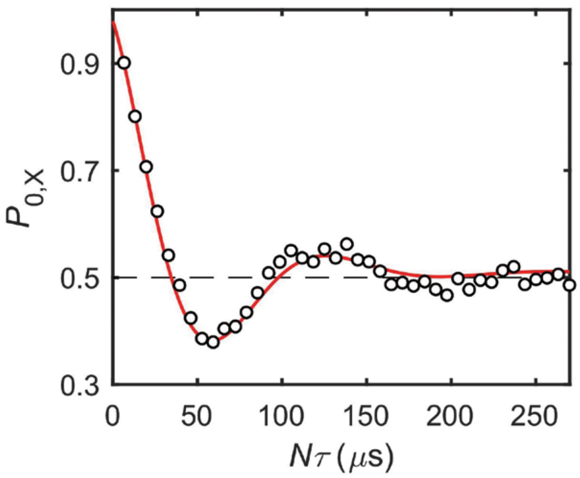
Brief resume

2005 Research Fellow DC2, Japan Society for the Promotion of Science
2006 D. Sci., Keio University
2006 Research Associate, The Institute for Solid State Physics, The University of Tokyo
2010 Postdoctoral Research Assistant, Department of Materials, University of Oxford
2011 Specially-Appointed Researcher, Institute for Nano Quantum Information Electronics, The University of Tokyo
2012 Specially-Appointed Researcher, Principles of Informatics Research Division, National Institute of Informatics
2013 Research Scientist, Center for Emergent Matter Science, RIKEN
2015 Project Lecturer, Faculty of Science and Technology, Keio University
2016 Project Associate Professor, Keio Advanced Research Centers, Keio University
2019 Unit Leader, Center for Emergent Matter Science, RIKEN
2021 Unit Leader, RIKEN Center for Quantum Computing (-present)

Recent Achievements

Detection and control of single proton nuclear spins with a solid-state quantum sensor

Control of solid-state qubits including superconducting qubits often requires high-frequency signals ranging from a few to a few tens of GHz, making microwave engineering a common technology platform. In this study, we apply microwave technologies to a single nitrogen-vacancy (NV) centers, which are solid-state qubits operating at room temperatures and attract attention as quantum sensors, and demonstrate a high-sensitivity detection of a single proton nuclear spin. Proton nuclear spins are the most important detection targets for magnetic resonance imaging (MRI) and molecular structure analysis by nuclear magnetic resonance (NMR). Conventional NMR is limited by the low detection sensitivity. We successfully detected and controlled single proton nuclear spins by using an electronic spin of a single NV center in diamond as a quantum sensor. Furthermore, we obtained the information on the position of the nuclear spin and observed Rabi oscillations and free precessions of the single nuclear spin. These results pave the way for "single molecular structure analysis", in which the individual positions of nuclear spins constituting a single molecule are determined to infer the molecular structure.

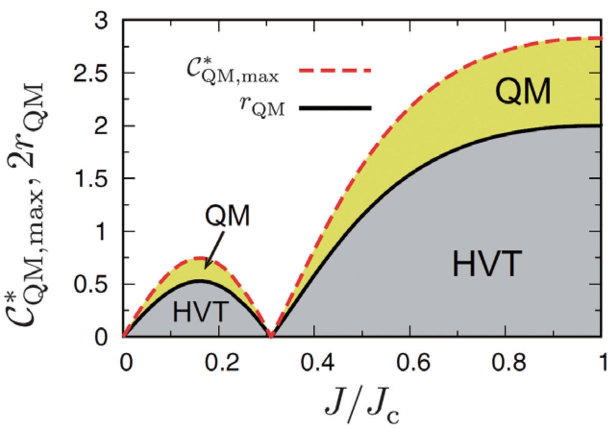


Control of a single proton spin with a quantum sensor. The horizontal axis is the operation time, and the vertical axis is the sensor spin state. The data shows a coherent rotation of a nuclear spin.

https://doi.org/10.1063/5.0016196

Bell-state correlation between quasiparticles excited in solid-state quantum devices

A crucial point that differentiates quantum mechanics from classical mechanics is the existence of quantum entanglement, nonlocal correlation among physical quantities. Entanglement is also thought to play an important role in understanding the origin of computational power of quantum computers. Creation of multi-qubit entanglement in solid-state qubits such as superconducting or spin qubits has thus been an ongoing research theme. Apart from qubits, in solid-state devices, quasiparticles can create nontrivial correlations, with Cooper pairs in superconductors forming spin-singlets as a prime example. In this work, we theoretically studied quantum correlation between quasiparticles excited in quantum dots in the Kondo regime, by deriving a special form of Bell's inequality for current cross correlation. We found that, in specific regimes of interaction parameters, quasiparticles can have correlations beyond the bound defined by the so-called hidden variable theory, thus exhibiting entanglement. This is an interesting result in that the Kondo effect, a central theme in condensed matter physics, is viewed from the perspective of quantum information science.



Relation between the strength of antiferromagnetic interaction and current correlation. The region describable by the hidden variable theory (HVT) and that only describable by quantum mechanics (QM) are shown.

https://doi.org/10.1103/PhysRevB.99.155106

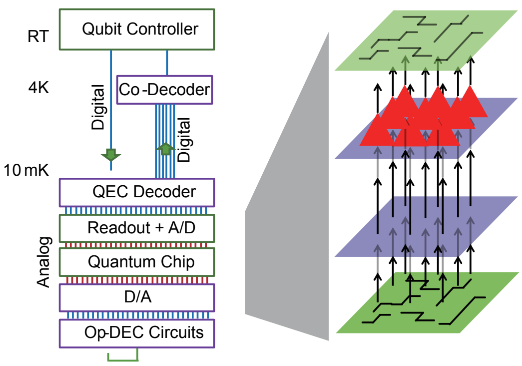
Superconducting Quantum Computing System Research Unit

Keywords: Superconducting quantum computers, System in Package (SIP), Heterogeneous integration

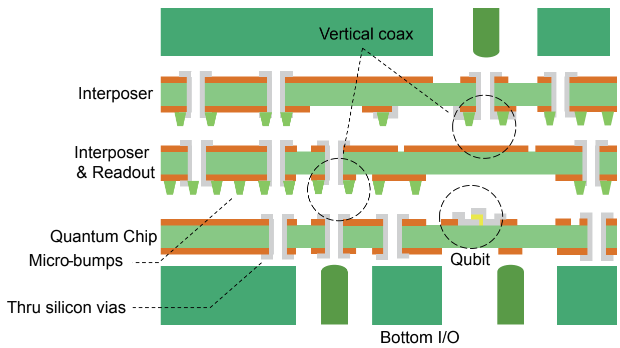
Research Outline

Our unit pursues the realization of practical quantum computers. We study a quantum mechanical system that integrates qubits, readout circuits, wiring, control electronics, cooling units, signal processing circuits, etc., to exploit and maximize a quantum-mechanical feature in superconducting quantum chips. Each component has strengths and weaknesses, and the combination of those gives trade-offs. We establish a design method that harmonizes the elements to expand the performance and scalability of a quantum computing system.

For example, we explore scalable arrangements of qubits, inter-qubit wirings, and control lines in a realistic three-dimensional space as device design. The error-correction mechanism in fault-tolerant quantum computation demands continuous refresh (or update) operation to superconducting qubits, losing room for time division multiplexing to simplify the device structure. Whereas the surface code is extendable in a two-dimensional plane for redundancy and scalability, only one more dimension remains to introduce the control and readout lines to the qubit chip. We seek possibility in stacked module systems that integrate qubits, control, and readout circuitry in a few substrates with essential scalability toward fault-tolerant quantum computation. Furthermore, the structure brings heterogeneous integration where various signal processing circuits, e.g., optical interconnects, single flux quantum circuits, etc., are organized in a single module.



Stacked module systems



Implementation of stacked module systems

Yutaka Tabuchi (Ph.D.), Unit Leader

Selected Publications

1 Y. Ueno, M. Kondo, M. Tanaka, Y. Suzuki, Y. Tabuchi "QULATIS: A Quantum Error Correction Methodology toward Lattice Surgery," *28th IEEE International Symposium on High-Performance Computer Architecture (HPCA)*, pp.274-287 (2022).
2 Y. Ueno, M. Kondo, M. Tanaka, Y. Suzuki, Y. Tabuchi "QECOOL: On-Line Quantum Error Correction with a Superconducting Decoder for Surface Code," *58th IEEE/ACM Design Automation Conference (DAC)*, pp.451-456 (2021).
3 D. Lachance-Quirion, S. Wolski, Y. Tabuchi, S. Kono, K. Usami, Y. Nakamura. "Entanglement-based single-shot detection of a single magnon with a superconducting qubit," *Science*, 367, pp.425-428 (2020).
4 Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, K. Usami, Y. Nakamura. "Coherent coupling between a ferromagnetic magnon and a superconducting qubit," *Science*, 348, pp.405-408 (2015).
5 Y. Tabuchi, S. Ishino, T. Ishikawa, R. Yamazaki, K. Usami, Y. Nakamura. "Hybridizing ferromagnetic magnons and microwave photons in the quantum limit," *Physical Review Letters*, 113, p.083603 (2014).

Brief resume

2012 Postdoctoral Researcher, RCAST, University of Tokyo
2015 JSPS Research Fellowship for Young Scientists
2017 Associate Professor, RCAST, University of Tokyo
2020 Unit Leader, Center for Emergent Matter of Science, Riken
2021 Unit Leader, RIKEN Center for Quantum Computing (-present)

Recent Achievements

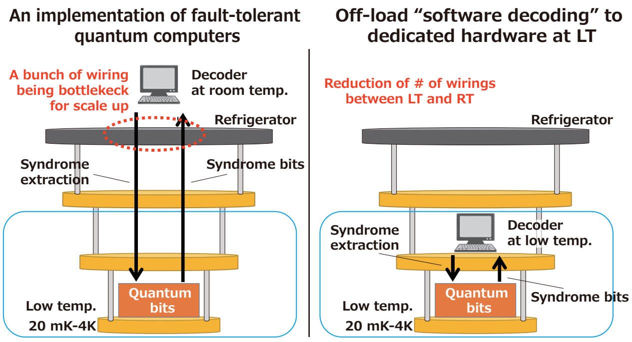
Scalable quantum computers: from control electronics to decoding circuits: Control electronics

Superconducting quantum computers consist of many elements, such as qubits, physical gates, device and device structures (including packaging), refrigerators, analog microwave front-ends, signal processors and controllers, quantum error correction codes, decoders, and logical operations. Each element has to be scalable and integrable to accommodate million of physical qubits for enjoyable application with fault tolerance under an assumption of a code distance and an error per gate of around 30 and 0.1%, respectively.

Here we study analog front-end circuits and back-end controller circuits. In controller circuits, many challenges remain to scale the system toward the goal. For example, the quantum operations to physical qubits demand precise phase synchronization among controller channels since phase coherence of the microwave signals is an inevitable assumption for multi-qubit gates. Here, we have demonstrated in a conference [Takefumi Miyoshi *et al.*, "FPL Demo: A Flexible and Scalable Quantum-Classical Interface based on FPGAs," 22nd International Conference on Field Programmable Logic & Applications (31, Aug, 2022)] the scalable realization of control electronics. For instance, we have shown that a clock synchronization mechanism similar to IEEE1588 guarantees the exact timing alignment in multi-controller operations for phase coherency. Even though we have validated our method with 50-qubit-sized systems, the approach is scalable and can be a concrete path toward the goal.

Scalable quantum computers: from control electronics to decoding circuits: Decoding circuits

In connection with the previous achievement, we study decoding circuits dedicated to ultra-fast operation in cryogenic temperature. Decoding circuits are signal-processing circuits of measurement outcomes for fault-tolerant quantum computation. In a paper [Y. Ueno *et al.*, "QECOOL: On-Line Quantum Error Correction with a Superconducting Decoder for Surface Code," DAC2021], we have organized an "online" decoding circuit and evaluated it in a single flux quantum digital logic platform. The word online means processing faster enough for physical operations, and the measurement outcomes are discardable after the use, leading to drastic wiring reduction from low temperature to room temperature. We have extended the decoder in a paper [Y. Ueno *et al.*, "QULATIS: A Quantum Error Correction Methodology toward Lattice Surgery," HPCA2022] to the one capable of merge-and-split operations in lattice surgery with specialized care at the logical boundary. While this result is a proof-of-principle type of research, concrete evaluation of back-end circuits may recast a different organization of quantum computers having scalability.



Organizations of superconducting quantum computers (left: conventional, right: our proposal)

Core members

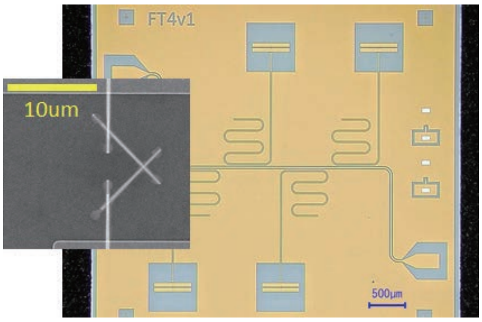
(Technical Staff) **Bunpei Masaoka**
(Technical Staff) **Miyuki Ozawa**

Hybrid Quantum Circuits Research Team

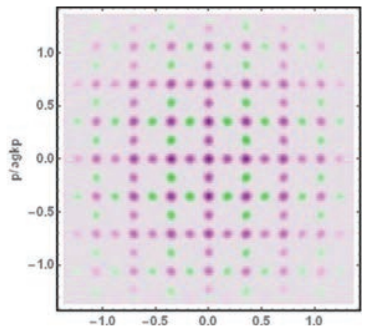
Keywords: Hybrid quantum systems, Microwave quantum optics, Electron trap, Quantum manipulations

Research Outline

A superconducting circuit is not merely a circuit without electrical resistance; with the Josephson junction, various quantum functions such as qubits and parametric circuits can be realized. In particular, our team has recently succeeded in fabricating superconducting qubits with an extremely long lifetime. In addition, taking advantage of the designability of superconducting circuits, we have been investigating of various kinds of quantum gates and their fidelity improvement. Furthermore, we are interested in research and development of hybrid quantum systems that combine such high-performance superconducting circuits with other quantum systems, such as microwave resonators and trapped electrons. They can be ultra-long llifetime quantum systems. By observing and controlling these systems with superconducting circuits, we are trying to establish quantum control technology that greatly surpasses existing performance. The realization of ultimate quantum technologies, such as fault-tolerant quantum computers, will depend on the availability of high-precision quantum control that is far beyond the current state-of-the-art. To address these issues, we aim to realize bosonic quantum error-correcting codes based on superconducting circuits, and quantum manipulations of trapped electron in the vacuum. Furthermore, we aim to develop new quantum fundamental technologies through the coexistence and collaboration of quantum systems.



Transmon qubits made from TiN electrode. We are fabricating the qubit with state-of-the-art.



Wavefunction of the GKP qubit encoded in the Harmonic oscillator. We simulate the stabilizing measurement from the vacuum state.

Atsushi Noguchi (Ph.D.), Team Leader

Selected Publications

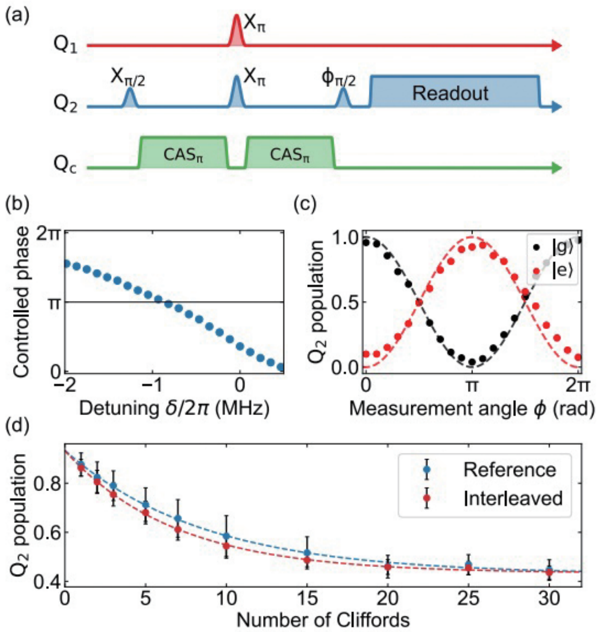
1 S. Shirai, Y. Okubo, K. Matsuura, A. Osada, Y. Nakamura, and A. Noguchi, "All-microwave manipulation of superconducting qubits with a fixed-frequency transmon coupler", arXiv:2302.06930.
2 M. Shigefuji, A. Osada, M. Yabuno, S. Miki, H. Terai, and A. Noguchi, "Efficient low-energy single-electron detection using a large-area superconducting microstrip", arXiv:2301.11212.
3 A. Osada, K. Taniguchi, M. Shigefuji, and A. Noguchi, "Feasibility study on ground-state cooling and single-phonon readout of trapped electrons using hybrid quantum systems", Phys. Rev. Research 4, 033245 (2022).
4 A. Noguchi, A. Osada, S. Masuda, S. Kono, K. Heya, S. Piotr Wolski, H. Takahashi, T. Sugiyama, D. Lachance-Quirion, and Y. Nakamura, "Fast parametric two-qubit gates with suppressed residual interaction using a parity-violated superconducting qubit". Phys. Rev. A 102, 062408 (2020).
5 A. Noguchi, R. Yamazaki, Y. Tabuchi, and Y. Nakamura, "Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator", Nat. Commun. 11, 1183 (2020).

Brief resume

2013 Postdoc researcher, Osaka University
2014 Postdoc researcher, RCAST, The University of Tokyo
2015 Postdoc researcher, RCAST, The University of Tokyo
2015 Project Associate, RCAST, The University of Tokyo (-2018)
2016 Researcher, JST PREST (-2019)
2019 Associate Professor, Graduate School of Arts and Science, The University of Tokyo (-present)
2020 Fellow, Inamori Research Institute for Science (-present)
2020 Team leader, CEMS (-2021)
2021 Team leader, RQC (-present)
2022 Researcher, JST PREST (-present)

Recent Achievements

All-microwave manipulation of superconducting qubits with a fixed-frequency transmon coupler



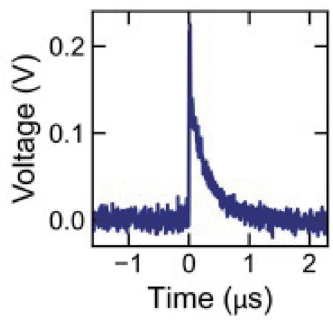
(a) Pulse sequence of the calibration experiment for the gate. (b) The result of the calibration experiment (c) Controlled Z gate. (d) Interleaved randomized benchmarking.

The performance of a quantum computer is strongly dependent on the accuracy of quantum manipulations. Among the circuits used as superconducting qubits, the highest-performance circuit is a fixed-frequency transmon qubit. This circuit does not have an external tuning knob of the frequency, making it robust against noise. However, it is known that the inability to change the frequency limits the accuracy of the quantum gates due to the unwanted residual interactions that occur even when the gate is not active. In this work, we proposed a circuit in which two fixed-frequency qubits are connected through a fixed-frequency qubit coupler, and developed a new quantum gate for this circuit. This method not only reduces the residual interactions, but also has the feature that the residual interactions do not deteriorate the gate accuracy.

S. Shirai, Y. Okubo, K. Matsuura, A. Osada, Y. Nakamura, and A. Noguchi, arXiv:2302.06930.

Efficient low-energy single-electron detection using a large-area superconducting microstrip

Trapped electrons in cryogenic Paul traps are expected to be high fidelity quantum system. However, because of the difficulty of cooling the trapped electrons and the high voltage in the microwave frequency range required for their trapping, electron traps have not been studied extensively. In recent years, there have been reports of electron trap at room temperature, in which captured electrons are emitted from a trap and hit an electrode while being accelerated, which is observed as an amplified electrical signal. However, such electron detectors have been difficult to use in low-temperature environments due to heating problems. In this study, we focused on electron detection with superconducting wires, which are used in superconducting photon detectors (SNSPD). The superconducting electron detector successfully detected electrons of about 15 eV. The electron energy dependence of the detection efficiency suggests that the detection of electrons cab be modeled by the vortex model of SNSPD. A deeper understanding of this mechanism will lead to the development of a device that can lower-energy electrons.



Signal from a single electron

Core members

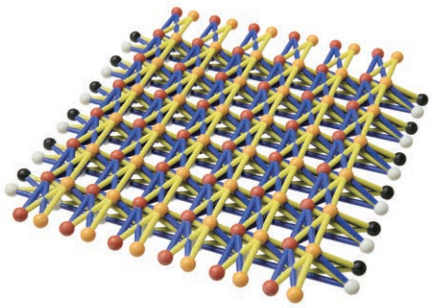
(Special Postdoctoral Researcher) **Ryo Sasaki**
(Postdoctoral Researcher) **Yusuke Tominaga**

Optical Quantum Computing Research Team

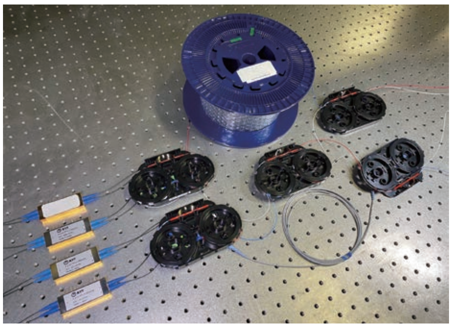
Keywords: Quantum information science, Quantum optics

Research Outline

Quantum computers use interference coming from the wave nature of quantum mechanics to surpass classical computers. There are two types of waves, standing waves and traveling waves, and the feature of our method using light is that it handles traveling waves. Whereas most other methods deal with standing waves, where short decoherence times matter, our method has no decoherence problems because quantum states are generated one after another as traveling light pulses, which are then destroyed by measurement. In our method, quantum teleportation is repeated to pass quantum information to successively generated optical pulses. The huge quantum entanglement for repeated quantum teleportation is called a cluster state, which can be considered as a quantum look-up table containing all input-output relations as a superposition. In our method, this can be created on a large scale in a compact optical system by the time-domain multiplexing technique. The great advantage of our method is high-speed computation. The bandwidth of optical parametric amplifiers that generate quantum light can be as high as 10 THz. Although teleportation is a speed bottleneck, when combined with 5G technology, it is possible to realize quantum computers with very fast clocks of tens of gigahertz. Furthermore, when combined with all-optical teleportation in the future, a super-fast quantum computer that effectively utilizes the bandwidth of 10 THz can be expected.



A model representing the structure of two-dimensional clustered states that can be created in the quantum state of light.



Optical system for generating large cluster states. Interferometers are made using optical fibers.

Akira Furusawa (Ph.D.), RQC Deputy Director, Team Leader

Selected Publications

1 K. Takase, A. Kawasaki, B. K. Jeong, T. Kashiwazaki, T. Kazama, K. Enbutsu, K. Watanabe, T. Umeki, S. Miki, H. Terai, M. Yabuno, F. China, W. Asavanant, M. Endo, J. Yoshikawa, and A. Furusawa "Quantum arbitrary waveform generator", *Science Advances*, 8, eadd4019 (2022).

2 K. Fukui, S. Takeda, M. Endo, W. Asavanant, J. Yoshikawa, P. van Loock, and A. Furusawa "Efficient backcasting search for optical quantum state synthesis", *Phys. Rev. Lett.*, 128, 240503 (2022).

3 K. Takase, A. Kawasaki, B. K. Jeong, M. Endo, T. Kashiwazaki, T. Kazama, K. Enbutsu, K. Watanabe, T. Umeki, S. Miki, H. Terai, M. Yabuno, F. China, W. Asavanant, J. Yoshikawa, and A. Furusawa "Generation of Schrödinger cat states with Wigner negativity using continuous-wave low-loss waveguide optical parametric amplifier", *Optics Express*, 30, 14161-14171 (2022).

4 T. Sonoyama, W. Asavanant, K. Fukui, M. Endo, J. Yoshikawa, and A. Furusawa "Analysis of optical quantum state preparation using photon detectors in the finite-temporal-resolution regime", *Phys. Rev. A*, 105, 043714 (2022).

5 W. Asavanant, Y. Shiozawa, S. Yokoyama, B. Charoensombutamon, H. Emura, R. N. Alexander, S. Takeda, N. C. Menicucci, H. Yonezawa, and A. Furusawa "Generation of time-domain-multiplexed two-dimensional cluster state", *Science*, 366, 373 (2019).

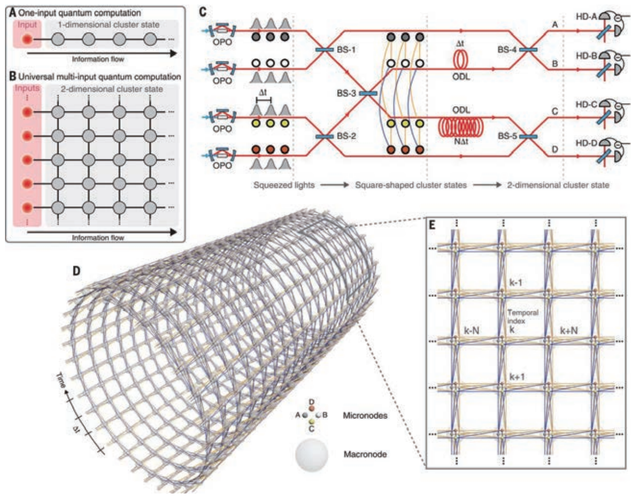
Brief resume

1991 Ph.D. in Physical Chemistry, The University of Tokyo
1986 Research staff member of Nikon Corporation (-2000)
1988 Visiting faculty member at Research Center for Advanced Science and Technology (RCAST), The University of Tokyo
1996 Visiting faculty member at California Institute of Technology
2000 Associate Professor of Applied Physics, The University of Tokyo
2007 Professor of Applied Physics, The University of Tokyo (-present)
2021 Deputy Director of the RIKEN Center for Quantum Computing / Team Leader of the Optical Quantum Computing Research Team (-present)

Recent Achievements

Generation of time-domain-multiplexed two-dimensional cluster state

Cluster states are important entangled states that serve as universal resources in our quantum computers based on quantum teleportation. They contain arbitrary input-output relations as a superposition and can be shrunk to a specific input-output relation by measurement depending on the desired computation. In our previous work, one-dimensional clustered states were generated on a large scale by time-domain multiplexing, which enable a computation on a single input. By using dual time-domain multiplexing, we have succeeded in extending the cluster states to two dimensional structures. This has enabled universal quantum computation that handles multiple inputs.

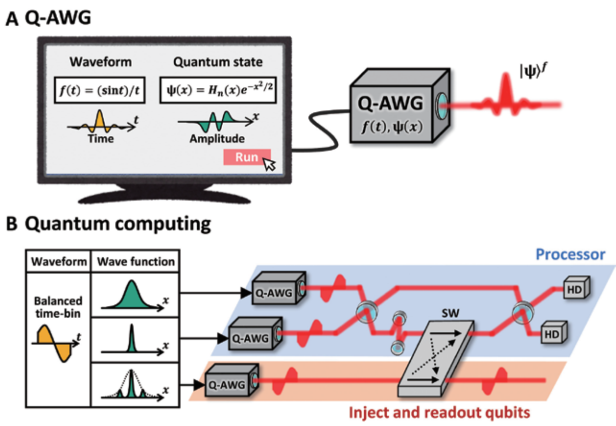


Two-dimensional cluster states by time-domain multiplexing. A, B: Extension from one-dimensional to two-dimensional to accommodate multiple inputs. C: Setup to generate two-dimensional cluster states. D, E: Structure of generated two-dimensional cluster states.

©W. Asavanant *et al.*, Science 366, 373 (2019). DOI: 10.1126/science.aay2645.

Quantum arbitrary waveform generator

Arbitrary waveform generators (AWG), which generate arbitrary waveform optical pulses, have been studied only for classical light. For application to quantum technology, a new light source, quantum arbitrary waveform generator (Q-AWG), which generates arbitrary quantum states with arbitrary waveform optical pulses, will be required in the future. We have proposed a method to achieve this by using quantum entanglement. We have also succeeded in experimentally generating quantum light with a special waveform, which has been difficult. This is an achievement that will lead to a versatile “ultimate quantum light source,” and is expected to contribute to various quantum technologies, including optical quantum computers.



Concept of quantum arbitrary waveform generator. A: Two configuration items of a quantum arbitrary waveform generator, waveform and quantum state. B: Setup where the output of the quantum arbitrary waveform generator is used as input to a quantum computer.

©K. Takase *et al.*, Science Advances 8, eadd4019 (2022). DOI: 10.1126/sciadv.add4019.

Core members

(Research Scientist) **Jun-ichi Yoshikawa**
(Postdoctoral Researcher) **Atsushi Sakaguchi**

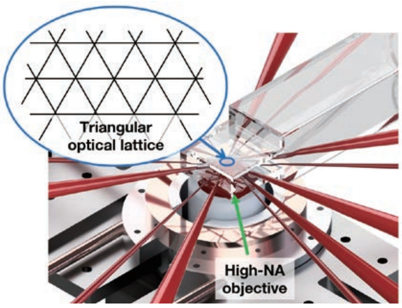
Quantum Many-Body Dynamics Research Team

Keywords: Quantum simulation, Quantum dynamics, Cold atom, Optical lattice

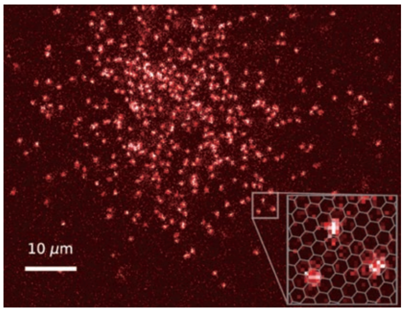
Research Outline

Deepening our knowledge of quantum many-body systems contributes to discover and understand various phenomena and to develop new technologies. Quantum simulation, which experimentally unveil the quantum many-body systems of interest by using other quantum many-body systems with excellent controllability, has been attracting attention. Our team aims to conduct quantum simulation with ultracold atoms in optical lattices. Optical lattice systems provide ideal platforms for studying important issues in condensed matter physics, such as high-temperature superconductivity and quantum frustration. The systems are also suitable for investigating non-equilibrium dynamics in quantum many-body systems due to less dissipation and decoherence.

We especially focus on the physics in frustrated spin systems. Various quantum phases and novel quantum states such as quantum spin liquids emerge in frustrated spin systems, but systematic understanding of these phenomena has not yet been developed. Furthermore, the existence of quantum phases that have not yet been discovered experimentally has been pointed out. As a platform for investigating these issues, we have constructed a geometrically frustrated triangular lattice and loaded a quantum gas into it. We also implemented a quantum gas microscope, which enables us to detect ultracold atoms in optical lattices at the single-atom level, and thus to microscopically observe quantum correlations and dynamics of the system. With this experimental system, we will elucidate frustrated spin systems and explore unknown quantum many-body phenomena and quantum phases.



Schematic of experimental setup. A high-numerical-aperture (NA) objective allows to observe atomic ensembles in triangular optical lattices at the single-atom level.



Single atom detection of ultracold gases in triangular optical lattices

Takeshi Fukuhara (D.Sci.), Team Leader

Selected Publications

1. R. Yamamoto, H. Ozawa, D. C. Nak, I. Nakamura, and T. Fukuhara, “Single-site-resolved imaging of ultracold atoms in a triangular optical lattice”, *New J. Phys.* 22, 123028 (2020).
2. F. Schäfer, T. Fukuhara, S. Sugawa, Y. Takasu, and Y. Takahashi, “Tools for quantum simulation with ultracold atoms in optical lattices”, *Nat. Rev. Phys.*, 2, 411 (2020).
3. D. Yamamoto, T. Fukuhara, and I. Danshita, “Frustrated quantum magnetism with Bose gases in triangular optical lattices at negative absolute temperatures”, *Commun. Phys.*, 3, 56 (2020).
4. I. Nakamura, A. Kanemura, T. Nakaso, R. Yamamoto, and T. Fukuhara, “Non-standard trajectories found by machine learning for evaporative cooling of 87Rb atoms”, *Opt. Express*, 27, 20435 (2019).
5. T. Fukuhara, S. Hild, J. Zeiher, P. Schauß, I. Bloch, M. Endres, and C. Gross, “Spatially Resolved Detection of a Spin-Entanglement Wave in a Bose-Hubbard Chain”, *Phys. Rev. Lett.* 115, 035302 (2015).

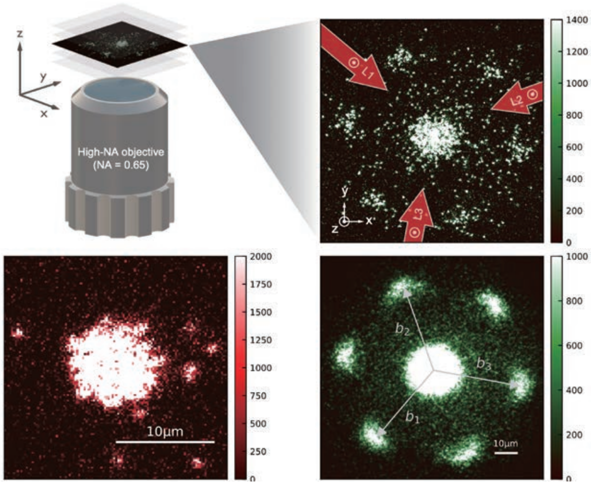
Brief resume

2009 D. Sci., Kyoto University
2009 Researcher, ERATO Ueda Macroscopic Quantum Control Project, Japan Science and Technology Agency
2010 Postdoctoral researcher, Max Planck Institute of Quantum Optics, Germany
2014 Unit Leader, Quantum Many-Body Dynamics Research Unit, Cross-Divisional Materials Research Program, RIKEN Center for Emergent Matter Science
2021 Unit Leader, Quantum Many-Body Dynamics Research Unit, RIKEN Center for Quantum Computing (RQC)
2022 Team Leader, Quantum Many-Body Dynamics Research Team, RIKEN Center for Quantum Computing (RQC) (-present)

Recent Achievements

Quantum gas microscopy of Mott transition in a triangular optical lattice

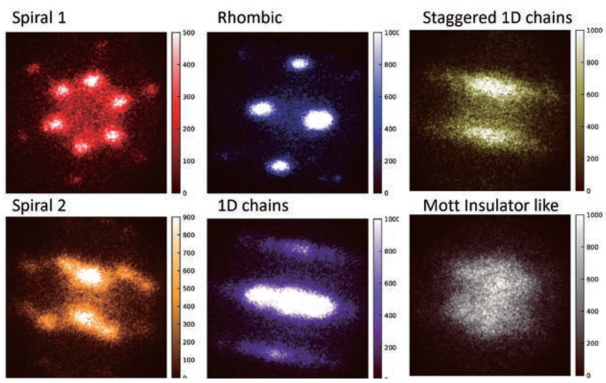
Quantum phase transition from superfluid to Mott insulator occurs when a quantum gas is loaded into a triangular optical lattice and the depth of the optical lattice is increased. Quantum gas microscope allows us to observe real-space distributions of quantum gases at the single-atom level. We observed an increase in the filling at each lattice site as the system goes to the Mott insulating state. In addition, we can obtain information on phase coherence by implementing the time-of-flight method to the quantum gas microscope. The Mott insulating state has been observed also from the disappearance of the phase coherence. The superfluid-Mott insulator quantum phase transition is the most representative phenomenon in the optical lattice systems, and therefore the observation of the transition is an important step towards quantum simulations of strongly correlated quantum many-body systems.



Quantum gas microscope enables us to access both phase coherence (upper right) and real space distributions (lower left) of quantum gas in optical lattices. Lower right image is average data for the phase coherence.

Quantum gas in frustrated triangular optical lattice

By mapping the phase of Bose-Einstein condensates (BECs) in optical lattices as spin, the XY spin model is realized. Since the coupling between spins corresponds to tunneling between lattice sites, ferromagnetic spin-spin coupling is usually realized. By modulating the phase of the optical lattice, we can change the sign and magnitude of the effective tunneling, and thus adjust the spin-spin coupling parameters. We realized XY spin model on the triangular lattice by loading BEC into a triangular optical lattice and confirmed various phases in this spin model by observing measuring interference patterns via time-of-flight measurement. A geometrical frustration induced by the negative tunneling leads to two chiral modes. We also observed that one chiral mode appears randomly in each experiment, due to spontaneous symmetry breaking.

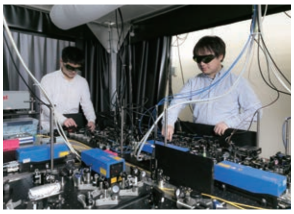


Interference patterns correspond to various phase in the XY spin model on the triangular lattice

H. Ozawa *et al.*, in preparation.

Core members

(Research Scientist) **Ryuta Yamamoto**
(Postdoctoral Researcher) **Hideki Ozawa**



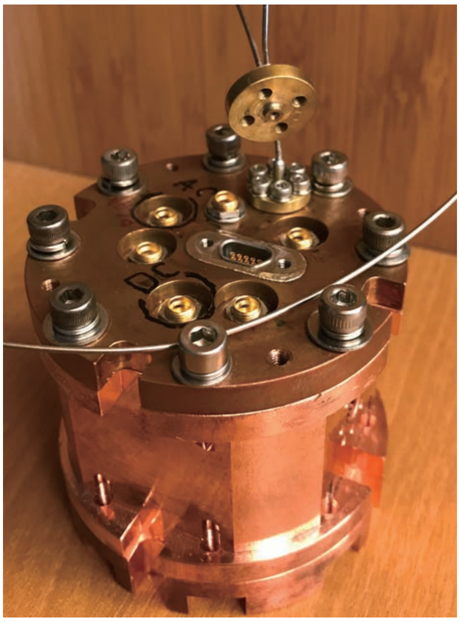
Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team

Keywords: Quantum technology, Quantum computer, Quantum bit, Two-dimensional electron system, Microwave

Research Outline

Our team is working on the application of electrons floating on liquid helium to quantum information. This physical system has a high potential for providing an ideal platform on which to realize a quantum computer, since it is free of impurities and defects. The quantized states normal to the liquid helium surface are called Rydberg states. The Rydberg-ground state and the Rydberg-1st-excited state are located 10 nm and 30 nm away from the liquid helium surface, respectively. The Rydberg state of different electrons can be coupled via the long-range Coulomb interaction, which allows us to place electrons at a moderate distance while keeping a considerable interaction between them to realize a two-qubit gate.

We are also working on the development of cryogenic microwave sources for large-scale quantum computation. In most cases, qubits are placed at low temperature and microwaves are sent to control and read out the qubits' states. For a small-scale quantum computer that is presently existing, we use thick cables that connect microwave generators at room temperature and qubits at low temperature. However, it is difficult to prepare a so high number of such thick cables inside a cryogenic refrigerator as to be required for large-scale quantum computation. In order to overcome this circumstance, we propose to develop small-sized and low-power consumption microwave generators which function at low temperature and place them inside the cryogenic refrigerator.



Experimental apparatus called "cell" to store liquid helium

Erika Kawakami (Ph.D.), Team Leader

Selected Publications

1 E. Kawakami, A. Elarabi, and D. Konstantinov "Relaxation of the excited Rydberg States of Surface Electrons on Liquid Helium", *Phys. Rev. Lett*., 126, 106802 (2021).
2 A. Elarabi, E. Kawakami, and D. Konstantinov "Cryogenic amplification of image-charge detection for readout of quantum states of electrons on liquid helium", J. of Low Temp. Phys. 202, 456 (2021).
3 E. Kawakami, A. Elarabi, and D. Konstantinov "Image-Charge Detection of the Rydberg States of Surface Electrons on Liquid Helium", *Phys. Rev. Lett*., 123 086801 (2019).
4 E. Kawakami, T. Jullien, P. Scarlino, D. R. Ward, D. E. Savage, M. G. Lagally, Viatcheslav Dobrovitski, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, "Gate fidelity and coherence of an electron spin in a Si/SiGe quantum dot with micromagnet", *Proc. Natl. Acad. Sci*., 113, 42, 11738 (2016).
5 E. Kawakami, P. Scarlino, D. R. Ward, F. R. Braakman, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, "Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot", *Nat. Nanotechnol*., 9, 666-670 (2014).

Brief resume

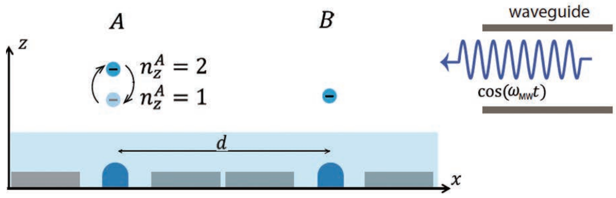
2016 Ph.D., Delft University of Technology, The Netherlands
2016 Postdoctoral researcher, Okinawa Institute of Science and Technology
2017 PRESTO, Japan Science and Technology Agency (-present)
2020 Team Leader, Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team (-present)

Recent Achievements

Hybrid Rydberg-spin qubit of electrons on helium

We propose a new way to realize qubits: a hybrid qubit of the Rydberg state and the spin state of electrons floating on the surface of liquid helium. An artificially introduced interaction between the Rydberg state and the spin state allows us to transfer the qubit state between the Rydberg and spin states. In this way, we can benefit from both the long coherence time of the spin state and the long-range interaction of the Rydberg state in the course of qubit operation.

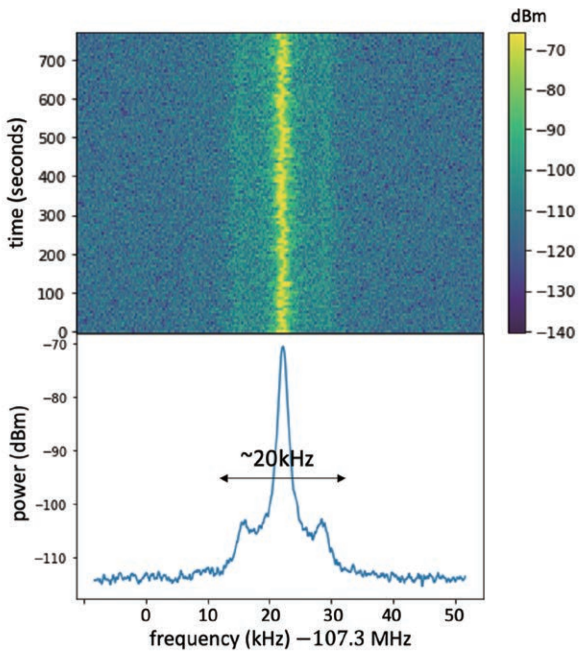
The interaction between the Rydberg state and the spin state is artificially introduced by a ferromagnet which is placed near the electron. We theoretically showed that the introduced magnetic field gradient mixes the spin state and the orbital state and shortens the spin relaxation time to 50 ms but does not degrade the qubit fidelity. We estimated the single-qubit gate and the two-qubit gate fidelities to be > 99.9999% and ~99%, respectively.



A ferromagnetic pillar of which the tip is rounded and of the diameter is 100 nm is shown in blue and the outer electrodes are shown in gray. A single electron is trapped on top of the pillar. The thickness of liquid 4He (light blue) above the center electrode is set to 140 nm. Two neighboring electrons A and B are separated by d = 0.88 μm and are used as qubit A and qubit B, respectively. In the case shown here, electron A's Rydberg transition is on resonance with the MW applied through a waveguide. Electron A goes back and forth between the Rydberg-ground state and the Rydberg-1st-excited state.

Cryogenic microwave source for qubit read-out

One of the key features required to realize a fault-tolerant scalable quantum computer is the integration of reliable and energy-efficient electronics for qubit control and readout. Recently, qubit control electronics have been successfully integrated using cryogenic CMOS technology and superconducting Josephson junctions. Here, we focus on the development of readout electronics using tunnel-diode oscillator circuits. Compared to cryogenic CMOS devices and superconducting Josephson junction circuits, the tunnel-diode circuits have lower power dissipation (~1μW). Furthermore, we propose a new idea to increase the qubit readout fidelity using the synchronization of two oscillator circuits.



Spectrum of the signal generated from the home-made cryogenic microwave source. The signal frequency is around 107.3 MHz.

Core members

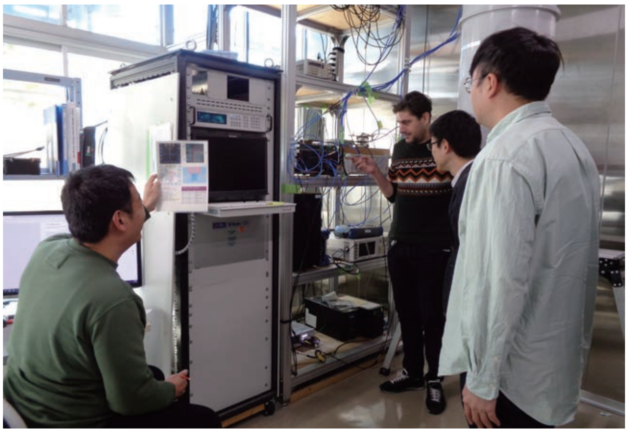
(Technical Scientist) **Ivan Grytsenko**
(Postdoctorial Researcher) **Asher Jennings**
(Technical Staff) **Hiromi Itoh**
(SPDR) **Xianjing Zhou**
(Research Part Timer I) **Mohan Rajesh**
(Research Part Timer I) **Oleksiy Rybalko**

Semiconductor Quantum Information Device Research Team

Keywords: Quantum computer, Semiconductor, Quantum bit, Quantum dot, Electron spin

Research Outline

We perform research and development to apply semiconductor electron (or hole) spins as units (qubits) of quantum information to quantum computing. Studies on semiconductor quantum computing have been motivated by advantages of long coherence time, compatibility with existing semiconductor device integration technology and capability of high-temperature (> 1 Kelvin) operation. To date we have achieved various kinds of major quantum operations, including single qubit and two-qubit gates, initialization and readout with high enough fidelities exceeding fault tolerant thresholds using spin qubits in Si quantum dots. Based on these achievements we are now aiming to build up basic technologies of constructing medium to large scale quantum computers in Si. In this line we will develop relevant quantum logic calculation methods, advanced quantum architectures, qubit devices that have compatibility with semiconductor device integration technology.



Picture of a laboratory

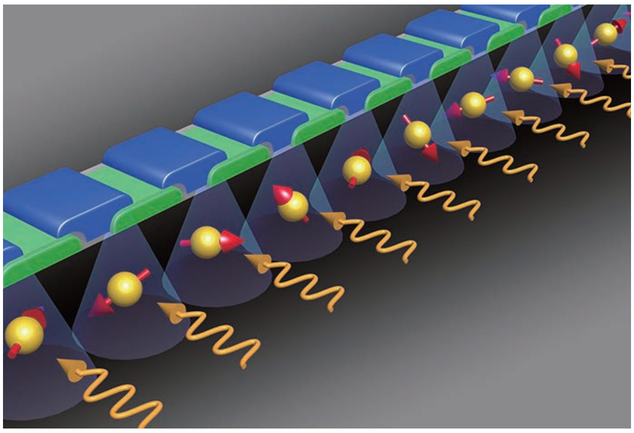


Image of a one-dimensiional spin qubit device

Tarucha Seigo (D.Eng.), Dr.

Selected Publications

1 K. Takeda, A. Noiri, T. Nakajima, T. Kobayashi, and S. Tarucha, “Quantum error correction with silicon spin qubits”, *Nature*, 608, 682-686 (2022).
2 M. Tadokoro, T. Nakajima, T. Kobayashi, K. Takeda, A. Noiri, K. Tomari, J. Yoneda, S. Tarucha, and T. Kodera, “Designs for a two-dimensional Si quantum dot array with spin qubit addressability”, *Sci. Rep.*, 11, 19406 (2021).
3 T. Nakajima, Y. Kojima, Y. Uehara, A. Noiri, K. Takeda, T. Kobayashi, and S. Tarucha, “Real-time feedback control of charge sensing for quantum dot qubits”, *Phys. Rev. Applied*, 15, L031003 (2021).
4 K. Takeda, A. Noiri, J. Yoneda, T. Nakajima, and S. Tarucha, “Resonantly driven singlet-triplet spin qubit in silicon”, *Phys. Rev. Lett.*, 124, 117701-1 – 5 (2020).
5 A.Noiri, K. Takeda, J. Yoneda, T. Nakajima, T. Kodera, and S. Tarucha,” Radio-frequency detected fast charge sensing in undoped silicon quantum dots”, *Nano Lett.*, 20, 947 (2020).

Brief resume

1978 Basic Research Laboratories of Nippon Tel. & Tel. Corp.
1986 Dr of Engineering
1990 Research group leader, NTT Basic Research Laboratory
1998 Professor, Department of Physics, University of Tokyo
2004 Professor, Department of Applied Physics, University of Tokyo
2013 Division Director, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
2013 Group Director, Quantum Functional System Research Group, Division Director, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
2018 Deputy Director, RIKEN Center for Emergent Matter Science
2019 Guest Professor, Department of Physics, Tokyo University of Science (-present)
2020 Team Leader, Semiconductor Quantum Information Device Research Team, RIKEN Center for Emergent Matter Science
(-present)

Recent Achievements

High-fidelity universal quantum gate set using electron spin qubits in silicon

High fidelity (> 99%) quantum gate set is an important ingredient for fault-tolerant quantum computing, but not achieved in silicon (Si) spin qubits until recently. Here we exceed the limit to achieve the fault tolerant condition.

We use a Si quantum dot (QD) device (Fig. 1) made in an isotopically enriched Si/SiGe quantum well and equipped with a micro-magnet which is utilized to speed up the single-qubit rotation. We realize a fast CNOT gate, the most important two-qubit gate with use of the large exchange coupling and fast spin rotation, and obtain the fidelity of 99.8% and 99.5% for the single and two-qubit gate, respectively (Fig. 2).

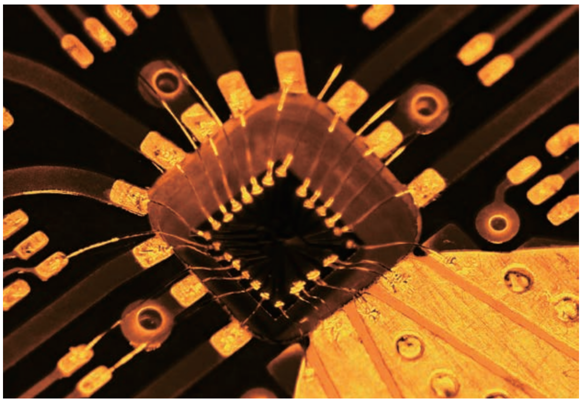


Fig.1 Silicon spin qubit device chip used in this work.

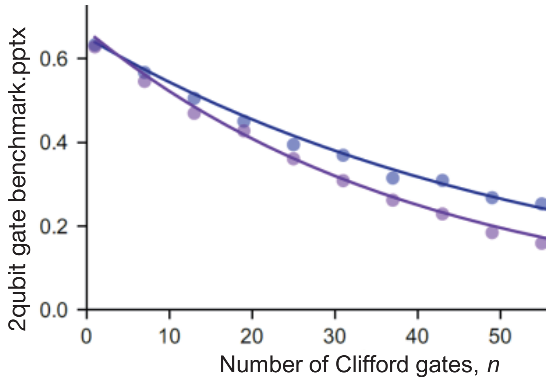


Fig.2 Two-qubit gate fidelity characterization by Clifford-based randomized benchmarking. The gate fidelity is obtained from the decay of the sequence fidelity as a function of number of Clifford gates.

Real-time feedback control of single-electron charge sensor

Readout of spin qubits relies on spin-to-charge conversion followed by charge sensing using a sensor quantum dot (QD). However, a charge sensor is prone to electrical disturbances. We develop a real-time feedback control system that allows for fast and reliable charge sensing.

The feedback controller is implemented on a field-programmable gate array (Fig. 1). The conductance of an on-chip charge sensor placed next to a Si double QD (DQD) is probed by the rf reflectometry and processed in the feedback controller so that the sensor is automatically gate-tuned to keep the conductance constant. A DQD charge stability diagram taken without the feedback reveals only a fraction of the DQD charge transitions because the sensor is occasionally detuned from its sensitive point. This effect is compensated by the feedback and we observe clear charge transitions.

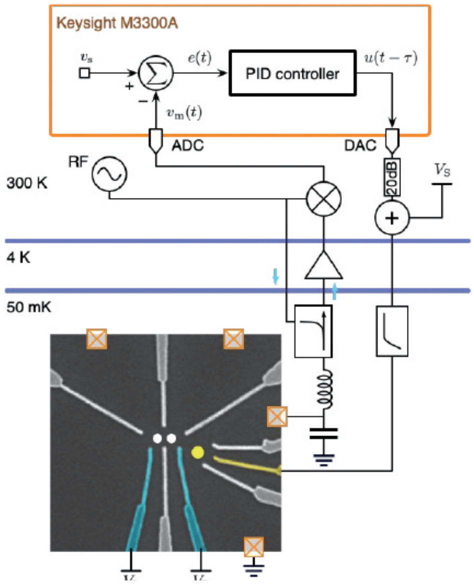


Fig.1 Schematic of the feedback control system for a quantum-dot charge sensor.

Core members

(Research Scientist) **Takashi Kobayashi**

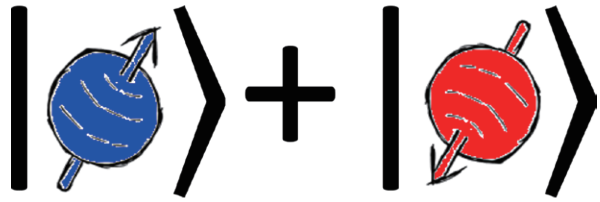
(Postdoctoral Researcher) **Chien-Yuan Chang**

Semiconductor Quantum Information Device Theory Research Team

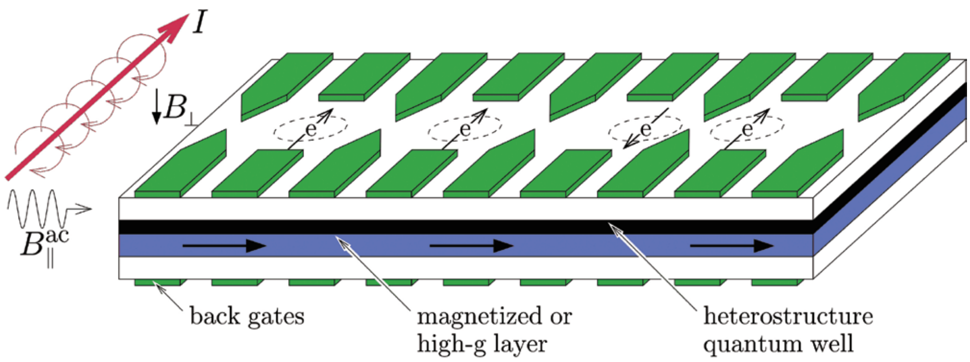
Keywords: Quantum dots, Spin-based quantum information science, Qubit, Spin-orbit interaction, Quantum information processing

Research Outline

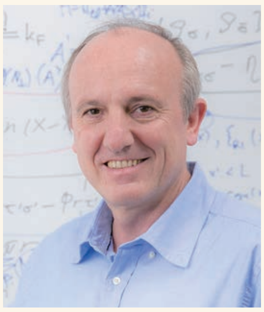
Our team is working on the theory of a spin-based quantum computer. We design its CMOS-compatible components deriving from Si and Ge gated quantum dots. We focus on spin qubits that can be manipulated by electric fields through various spin-orbit interactions. Using advanced band-structure models, we investigate the properties of holes and electrons confined in low-dimensional geometries. We search for optimal setups and ways of protecting the qubits from noise. We analyze perspective qubit interconnects which would allow assembling a large number of qubits into networks. Our ultimate goal is to identify fast, small, and scalable elements of the future quantum computer.



Spin-based quantum computing uses the spin of an electron in a solid to represent a quantum bit.



An array of quantum dots envisioned to realize a quantum processor.



Daniel Loss (Ph.D.), Team Leader

Selected Publications

1 P. Stano and D. Loss, “Review of performance metrics of spin qubits in gated semiconducting nanostructures,”, *Nat. Rev. Phys.* 4, 672 (2022).
2 A. Gutierrez-Rubio, J. S. Rojas-Arias, J. Yoneda, S. Tarucha, D. Loss, and P. Stano, “Bayesian estimation of correlation functions,” *Phys. Rev. Research* 4, 043166 (2022).
3 O. Malkoc, P. Stano, and D. Loss, “Charge-noise induced dephasing in silicon hole-spin qubits”, *Phys. Rev. Lett.* 129, 247701 (2022).
4 T. Nakajima, A. Noiri, J. Yoneda, M. R. Delbecq, P. Stano, T. Otsuka, K. Takeda, S. Amaha, G. Allison, K. Kawasaki, A. Ludwig, A. D. Wieck, D. Loss, S. Tarucha, “Quantum non-demolition measurement of an electron spin qubit”, *Nature Nanotechnology* 14, 555 (2019).
5 D. Loss, D. DiVincenzo, “Quantum computation with quantum dots”, *Phys. Rev.* A 57, 120 (1998).

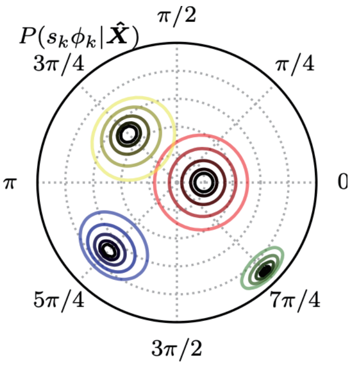
Brief resume

1985 Ph.D. in Theoretical Physics, University of Zurich, Switzerland
1985 Postdoctoral Research Associate, University of Zurich, Switzerland
1989 Postdoctoral Research Fellow, University of Illinois at Urbana-Champaign, USA
1991 Research Scientist, IBM T. J. Watson Research Center, USA
1993 Assistant/Associate Professor, Simon Fraser University, Canada
1996 Professor, Department of Physics, University of Basel, Switzerland (-present)
2012 Team Leader, Emergent Quantum System Research Team, RIKEN
2013 Team Leader, Quantum System Theory Research Team, Quantum Information Electronics Division, RIKEN Center for Emergent Matter Science (-present)
2021 Team Leader, Semiconductor Quantum Information Device Theory Research Team, RIKEN Center for Quantum Computing (-present)

Recent Achievements

Bayesian estimation of correlation functions

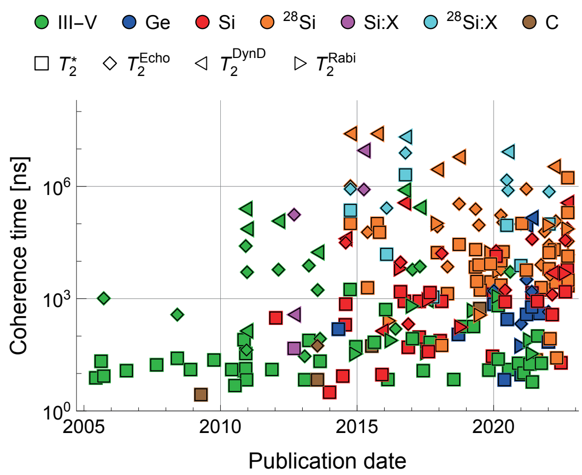
Correlation is intimately related to causality and prediction, and correlation functions are ubiquitous in different theories and formalisms. They also play a major role in the study of noise, which limits current state-of-the-art quantum devices. With the goal of understanding the noise origin and properties, we have constructed a Bayesian theory of estimation of correlations of stochastic variables sampled at regular intervals. Our results allow one to better understand statistical noise fluctuations, assess the correlations between two variables, and postulate parametric models of spectra, which can be further tested. We have also proposed a new method to numerically generate correlated noise with a given spectrum.



Estimated probability distributions of correlations parameters. The plot is in the complex plane, with correlation strength (s_k) as the radial coordinate and correlation phase (φ_k) as the polar angle. The color contours enclose 75, 50, 25, 10, and 5%-probability regions. Different colors correspond to different correlation degree and phase in the signal.
A. Gutierrez-Rubio, J. S. Rojas-Arias, J. Yoneda, S. Tarucha, D. Loss, P. Stano, "Bayesian estimation of correlation functions", Phys. Rev. Research 4, 043166 (2022).

Review of performance metrics of spin qubits in gated semiconducting nanostructures

The field of spin qubits is vast. There is a host of variants on the sample material and structure, device design, or qubit encoding. While this versatility in the qubit types is beneficial for overcoming possible roadblocks, it also makes comparison of different spin qubits difficult. To overcome this difficulty, we have collected values of selected performance characteristics of semiconductor spin qubits defined in electrically controlled nanostructures. The characteristics are envisioned to serve as a community source for the values of figures of merit with agreed-on definitions allowing comparison of different qubit platforms. We include characteristics on the qubit coherence, speed, fidelity, and the qubit-size of multi-qubit devices.



Spin coherence times according to the publication date. The point color shows the device material. The point symbol shows the coherence type as given in the legend.
P. Stano and D. Loss, "Review of performance metrics of spin qubits in gated semiconducting nanostructures", Nature Reviews Physics 4, 672 (2022).

Core members

(Postdoctoral Researcher) **Juan Rojas-Arias**

Quantum Computing Theory Research Team

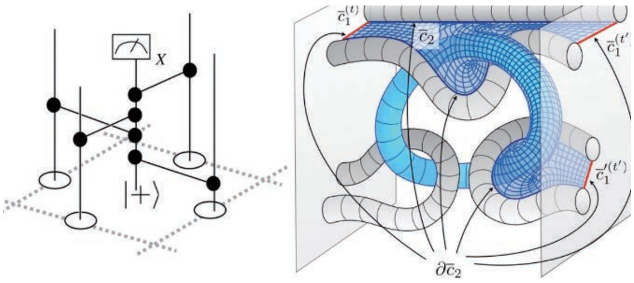
Keywords: Quantum computing, Quantum information science, Quantum machine learning, Quantum error correction

Research Outline

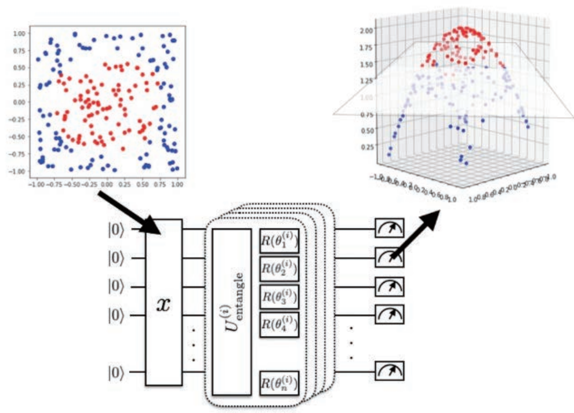
Quantum computing is revolutionizing technology, and Quantum Computing Theory Research team is at the forefront of this transformation. Our focus is on developing quantum computing theory and software essential for realizing quantum computers, designing new quantum algorithms, and analyzing their performance.

Our team is working on near-term technologies to harness the power of quantum computers on scales achievable now and in the near future. We explore applications in fundamental physics, quantum chemistry, and quantum machine learning while addressing quantum computer architectures optimization of quantum circuits. Another target is designing large-scale, fault-tolerant quantum computers being equipped with quantum error correction, which capable of complex calculations with high reliability.

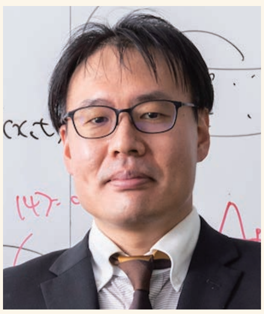
Embracing interdisciplinary research, we foster connections between quantum information science and fields like fundamental physics, quantum chemistry, machine learning, and high-performance computing. We aim to open up new scientific frontiers with quantum computers or through the lens of quantum information science. This collaborative approach drives advancements in quantum computing and its real-world applications, positioning RQC as a key player in shaping the future of quantum technology.



A quantum circuit for quantum error correction (Left), fault-tolerant quantum computing using the surface code (Right).



Quantum Circuit Learning: A supervised machine learning using parameterized quantum circuits.



Keisuke Fujii (Ph.D.), Team Leader

Selected Publications

1 K. Mizuta, Y. O. Nakagawa, K. Mitarai, and K. Fujii, “Local variational quantum compilation of a large-scale Hamiltonian dynamics” PRX Quantum 3, 040302 (2022).

2 K. Fujii, K. Mizuta, H. Ueda, K. Mitarai, W. Mizukami, and Y. O. Nakagawa, “Deep Variational Quantum Eigensolver: a divide-and-conquer method for solving a larger problem with smaller size quantum computers” PRX Quantum 3, 010346 (2021).

3 K. Mitarai, M. Negoro, M. Kitagawa and K. Fujii, “Quantum Circuit Learning”, *Phys. Rev. A*, 98, 032309 (2018).

4 K. Fujii and K. Nakajima, “Harnessing Disordered-Ensemble Quantum Dynamics for Machine Learning”, *Phys. Rev. Applied* 8, 24030 (2017).

5 K. Fujii, M. Negoro, N. Imoto, and M. Kitagawa, “Measurement-Free Topological Protection Using Dissipative Feedback”, *Phys. Rev. X* 4, 041039 (2014).

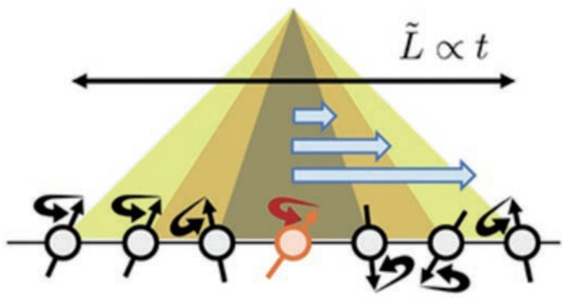
Brief resume

2011 Ph.D. (Engineering), Kyoto University
2011 Postdoc, Osaka University
2013 Program-Specific Assistant Professor, Kyoto University
2016 Assistant Professor, The University of Tokyo
2017 Program-Specific Associate Professor, Kyoto University
2019 Professor, Graduate School of Engineering Science, Osaka University (-present)
2020 Deputy Director, Center for Quantum Information and Quantum Biology, Osaka University(-present)
2020 Team Leader, Quantum Computation Theory Research Team, RIKEN (-present)

Recent Achievements

An efficient compiling of quantum algorithm for large-scale quantum many-body systems

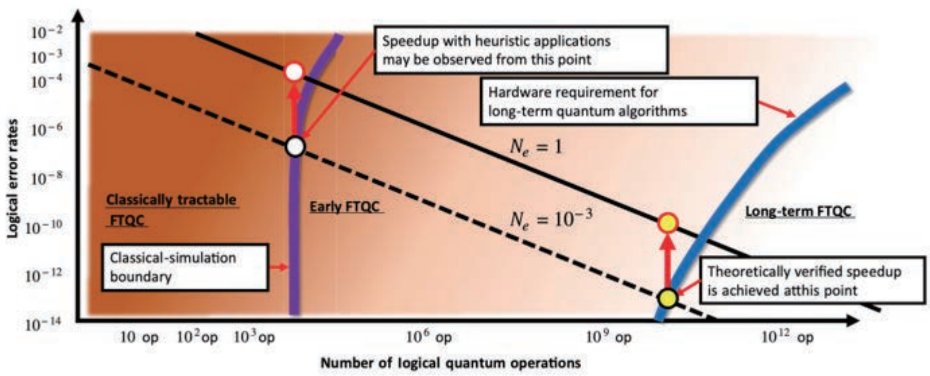
Quantum simulation, crucial for understanding complex quantum systems, relies on implementing time-evolution operators on quantum circuits. The standard method, Trotterization, demands a massive number of gates for accuracy. We have proposed the Local Variational Quantum Compilation (LVQC) algorithm, enabling accurate and efficient compilation of time-evolution operators in large-scale quantum systems through optimization with smaller-sized systems. Utilizing a subsystem cost function and the Lieb-Robinson bound, LVQC can work with limited-size quantum computers or classical simulators. This technique can efficiently construct time-evolution operators for various systems, even with finite-, short-, and long-ranged interactions. By using LVQC, we have successfully compressed the depth of time-evolution operators up to 40 qubits, showcasing its potential for designing large-scale quantum circuits and applications of intermediate-scale quantum devices.



©K. Mizuta *et al.*, "Local variational quantum compilation of a large-scale Hamiltonian dynamics", PRX Quantum 3, 040302 (2022).

Reducing overhead for FTQC by using quantum noise mitigation

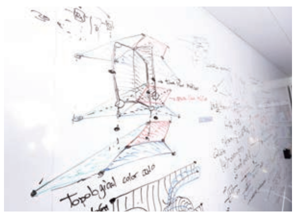
In the early stages of fault-tolerant quantum computing (FTQC), limited scalability of quantum devices and insufficient computational power of classical decoding units create challenges. We have developed an efficient FTQC architecture that integrates quantum error correction and quantum error mitigation to effectively increase the code distance and T-gate count at the cost of constant sampling overheads. This can reduce the required number of physical qubits by 80% to 45% in various quantum computing regimes. When the achievable code distance is up to about 11, the scheme enables executing 10^3 times more logical operations. This breakthrough could significantly reduce computational overheads and accelerate the arrival of the FTQC era.



© Y. Suzuki *et al.*, "Quantum Error Mitigation as a Universal Error Reduction Technique: Applications from the NISQ to the Fault-Tolerant Quantum Computing Eras", PRX Quantum 3, 010345 (2022).

Core members

(Postdoctorial Researcher) **Kaoru Mizuta**
(Postdoctorial Researcher) **Tatsuhiko Ikeda**
(Postdoctorial Researcher) **Koji Inui**



Quantum Information Physics Theory Research Team

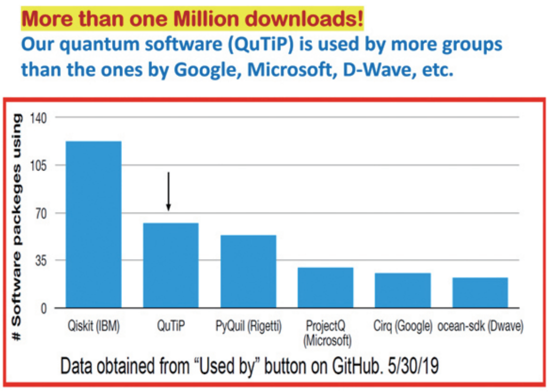
Keywords: Quantum Physics, Quantum optics, Quantum information processing and quantum computing, Artificial Intelligence, Machine learning, Software for quantum physics, Superconducting qubits

Research Outline

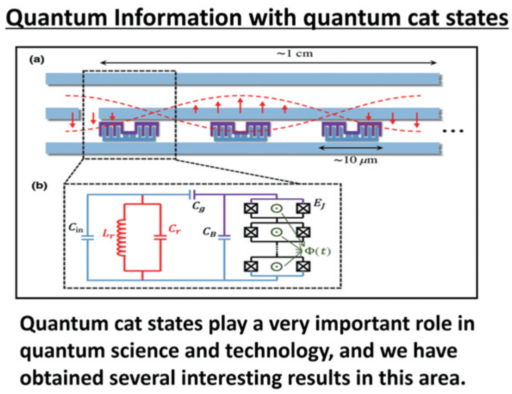
Our research group performs interdisciplinary studies at the interface between quantum computing, quantum information processing, superconducting quantum circuitry for quantum computing, photonics, quantum optics, atomic physics, nano-mechanics, nanoscience, mesoscopics, computational physics, and condensed matter physics.

We developed the QuTiP software used worldwide for quantum information processing, quantum optics, and quantum open systems. We are also using techniques from AI and Machine Learning to solve computationally hard problems. The Web of Science has listed our research work as Highly Cited for the past six years (from 2017 to 2022). Less than 0.1% of researchers reach this milestone.

We have published more than 30 papers in collaboration with various companies (NEC, Hitachi, Toshiba, NTT, IBM, etc.). Currently, we are conducting joint research with NTT Research laboratories with the goal of solving difficult computational problems.



Our software QuTiP is widely used by very many research groups, and it has been downloaded more than one million times.



Quantum cat states play an important role in quantum computing and we have obtained interesting results in this area.

Franco Nori (Ph.D.), Team Leader

Selected Publications

1 W. Qin, A. Miranowicz, F. Nori, "Beating the 3 dB Limit for Intracavity Squeezing and Its Application to Nondemolition Qubit Readout", *Phys. Rev. Lett.* 129, 123602 (2022).
2 W. Qin, A. Miranowicz, H. Jing, F. Nori, "Generating Long-Lived Macroscopically Distinct Superposition States in Atomic Ensembles", *Phys. Rev. Lett.* 127, 093602 (2021).
3 Y. Nomura, N. Yoshioka, F. Nori, "Purifying Deep Boltzmann Machines for Thermal Quantum States", *Phys. Rev. Lett.* 127, 060601 (2021).
4 X. Wang, T. Liu, A.F. Kockum, H.R. Li, F. Nori, "Tunable Chiral Bound States with Giant Atoms", *Phys. Rev. Lett*. 126, 043602 (2021).
5 Y.H. Chen, W. Qin, X. Wang, A. Miranowicz, F. Nori, "Shortcuts to Adiabaticity for the Quantum Rabi Model: Efficient Generation of Giant Entangled Cat States via Parametric Amplification", *Phys. Rev. Lett.* 126, 023602 (2021).

Brief resume

1982 Conicit Fellow and Graduate Research Assistant; Physics Department. Also at the Materials Research Laboratory; University of Illinois, USA
1987 Postdoctoral Research Fellow, Institute for Theoretical Physics, University of California, Santa Barbara, USA
1990 Assistant Professor, Associate Professor, Full Professor and Research Scientist, Department of Physics, University of Michigan, Ann Arbor, USA. (-present)
2002 Team Leader, Frontier Research System and, afterwards, Advanced Science Institute, RIKEN, Saitama, Japan.
2013 Concurrent positions as: Group Director of the Quantum Condensed Matter Research Group, CEMS, and also Team Leader at iTHES (Interdisciplinary Theoretical Sciences). RIKEN
2013 Chief Scientist. Theoretical Quantum Physics Laboratory, Cluster for Pioneering Research, RIKEN, Japan. (-present)
2020 Team Leader for the Quantum Information Physics Theory Research Team, Quantum Computing Center, RIKEN, Japan. (-present)

Recent Achievements

Quantum Information with quantum cat states

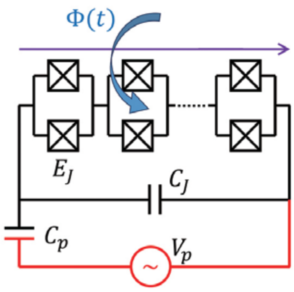
Quantum cat states play a very important role in quantum science and technology, and we have obtained several interesting results in this area. Our recent results in this area can be found in our publications, including these four examples:

Y.H. Kang *et al.*, *Nonadiabatic geometric quantum computation with cat-state qubits via invariant-based reverse engineering*, Phys. Rev. Research 4, 013233 (2022).

Z.Y. Zhou *et al.*, *Enhancing dissipative cat-state generation via nonequilibrium pump fields*, Phys. Rev. A 106, 023714 (2022).

Y.H. Chen *et al.*, *Fault-Tolerant Multiqubit Geometric Entangling Gates Using Photonic Cat-State Qubits*, Phys. Rev. Applied 18, 024076 (2022).

W. Qin, A. Miranowicz, F. Nori, *Beating the 3 dB Limit for Intracavity Squeezing and Its Application to Nondemolition Qubit Readout*, Phys. Rev. Lett. 129, 123602 (2022).



Superconducting quantum circuit for implementing our proposal. The circuit consists of a SQUID array (black), a shunting capacitor (black), a flux bias line (purple), and an ac gate voltage (red).

©APS. Reference: Y.H. Kang *et al.*, *Nonadiabatic geometric quantum computation with cat-state qubits via invariant-based reverse engineering*, Phys. Rev. Research 4, 013233 (2022).

General results in the field of ultrastrong light-matter coupling.

We have obtained several general results in the field of ultrastrong light-matter coupling, including these recent results:

V. Macri *et al.*, *Revealing higher-order light and matter energy exchanges using quantum trajectories in ultrastrong coupling*, Phys. Rev. A 105, 023720 (2022).

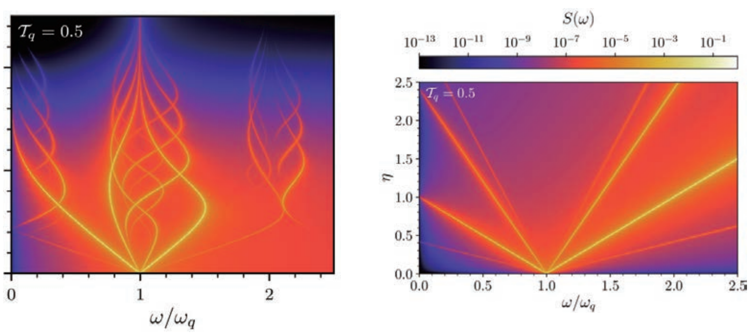
W. Salmon *et al.*, *Gauge-independent emission spectra and quantum correlations in the ultrastrong coupling regime of open system, cavity-QED*, Nanophotonics 11, pp. 1573 (2022).

A. Mercurio *et al.*, *Regimes of cavity QED under incoherent excitation: From weak to deep strong coupling*, Phys. Rev. Research 4, 023048 (2022).

Y.H. Chen *et al.*, *Enhanced-Fidelity Ultrafast Geometric Quantum Computation Using Strong Classical Drives*, Phys. Rev. Applied 18, 064059 (2022).

V. Macri *et al.*, *Spontaneous scattering of Raman photons from cavity-QED systems in the ultrastrong coupling regime*, Phys. Rev. Lett., 129, 273602 (2022).

L.B. Fan *et al.*, *Quantum coherent control of a single molecular-polariton rotation*, Phys. Rev. Lett., 130, 043604 (2023).



Logarithmic 2D plots of the cavity emission spectra Sc(ω) for values of η reaching the Ultra-Strong Coupling and Deep-Strong-Coupling regimes obtained using an effective qubit temperature Tq.

©APS. Reference: A. Mercurio, V. Macri, C. Gustin, S. Hughes, S. Savasta, F. Nori, *Regimes of cavity QED under incoherent excitation: From weak to deep strong coupling*, Phys. Rev. Research 4, 023048 (2022).

Core members

(Research Scientist) **Clemens Gneiting**

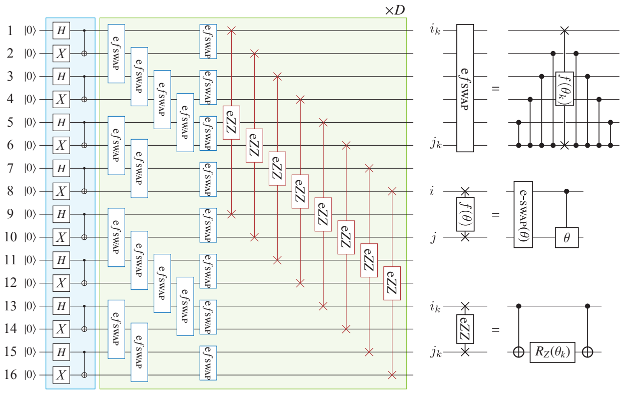
(Postdoctoral Researcher) **Yuran Zhang**

Quantum Computational Science Research Team

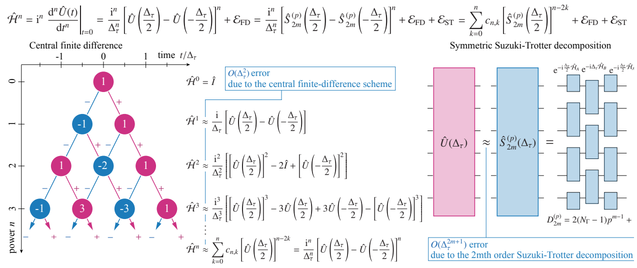
Keywords: Quantum many-body systems, Quantum dynamics, Quantum information physics, Tensor network, High performance computing

Research Outline

Our main interest is to propose quantum-classical hybrid algorithms for simulating quantum many-body systems. We also analyze quantum dynamics of quantum computing based on quantum information. For these purposes, we develop quantum simulations for quantum computing using classical computers. We are also interested in quantum-classical hybrid systems for future high performance computing.



Quantum circuits for VQE calculations of Hubbard model



Schematic figure for quantum power methods

Seiji Yunoki (Ph.D.), Team Leader

Selected Publications

1 Q. Xie, K. Seki, and S. Yunoki, “Variational counterdiabatic driving of the Hubbard model for ground-state preparation”, Phys. Rev. B 106, 155153 (2022).
2 K. Seki and S. Yunoki, “Energy-filtered random-phase states as microcanonical thermal pure quantum states”, Phys. Rev. B 106, 155111 (2022).
3 K. Seki, Y. Otsuka, and S. Yunoki, “Gutzwiller wave function on a quantum computer using a discrete Hubbard-Stratonovich transformation”, Phys. Rev. B 105, 155119 (2022).
4 K. Seki and S. Yunoki, “Spatial, spin, and charge symmetry projections for a Fermi-Hubbard model on a quantum computer”, Phys. Rev. A 105, 032419 (2022).
5 K. Seki and S. Yunoki, “Quantum Power Method by a Superposition of Time-Evolved States”, PRX Quantum 2, 010333 (2021).

Brief resume

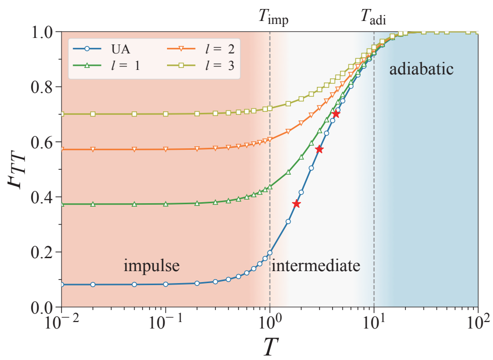
1996 Ph.D. (Engineering), Nagoya University
1996 Postdoc, National High Magnetic Field Laboratory (USA)
1999 Postdoc, Groningen University (The Netherlands)
2001 Postdoc, SISSA (Italy)
2006 Long-Term Visiting Scientist/Research Assistant Professor, Oak Ridge National Laboratory & University of Tennessee
2008 Associate Chief Scientist, Computational Condensed Matter Physics Laboratory, RIKEN
2010 Team Leader, Computational Materials Science Research Team, Advanced Institute of Computational Science, RIKEN
2012 Team Leader, Computational Quantum Matter Research Team, RIKEN Center for Emergent Matter Science
2017 Chief Scientist, Computational Condensed Matter Physics Laboratory, RIKEN
2018 Team Leader, Computational Materials Science Research Team, RIKEN Center for Computational Science
2021 Team Leader, Quantum Computational Science Research Team, Riken Center for Quantum Computing

Recent Achievements

Variational counterdiabatic driving of the Hubbard model for ground-state preparation

Finding the ground state of a quantum many-body system by unitary time evolution is a challenging task and an important application of quantum computation to the study of quantum many-body systems. We apply the variational counterdiabatic driving (CD) protocol to a one-dimensional two-component Fermi-Hubbard model and report the details of obtaining its ground state. The CD protocol introduces an adiabatic gauge potential (AGP) into the driving process, which suppresses the transition to the excited state, thereby enabling fast driving of quantum states. We first show that the set of the optimal variational parameters in an approximate AGP consisting of nested commutators of initial and final Hamiltonians is given as the solution vector of a system of linear equations whose coefficients are given by the square Frobenius norm of these commutators. The variational CD protocol up to the third driving order is then applied to the one-dimensional Fermi-Hubbard model and it is confirmed that the ground-state fidelity is systematically improved with respect to the driving order and the driving duration. Our results demonstrate the usefulness of the variational CD protocol to the Fermi-Hubbard model and permit a possible route towards fast ground-state preparation for many-body systems.

Q. Xie, K. Seki, and S. Yunoki, “Variational counterdiabatic driving of the Hubbard model for ground-state preparation”, Phys. Rev. B 106, 155153 (2022).

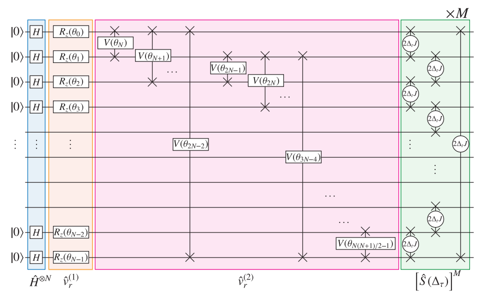


Dependence of the ground-state fidelity (vertical axis) of the Hubbard model on the driving time (horizontal axis). Results are shown for the case without driving assistance (unassisted, UA) and for driving orders l=1,2,3 with variational AGP.

Quantum-classical hybrid computing for microcanonical ensembles

In condensed matter physics, not only the properties of particular states such as the ground state of a quantum many-body system but also the properties of statistical mixture of many quantum states are important. In this study, we propose a quantum-classical hybrid method for microcanonical ensembles. The method is based on the idea that a pure state with a given energy as an approximate expectation value is obtained by the Fourier transform of a time-evolved random state, and the inverse of the time parameter corresponding to the cutoff of the time integration range in the Fourier transform sets the width of the energy shell of the microcanonical ensemble. Thermodynamic quantities such as entropy and temperature are computed from the trace of the time evolution operator through random quantum circuits based on unitary designs and the Fourier representation of the Gaussian. From numerical simulations for the one-dimensional spin-1/2 Heisenberg model, we confirmed that a significant difference in the statistical error appears depending on the order of the unitary design and that the method is most efficient for the target energy around which the dense distribution of energy eigenstates is found.

K. Seki and S. Yunoki, “Energy-filtered random-phase states as microcanonical thermal pure quantum states”, Phys. Rev. B 106, 155111 (2022).



Quantum circuit for preparing a time-evolved random state. The random state is prepared in the first three parts (blue, orange, and red boxes). In the time-evolution operator part (green box), we assume the one-dimensional Heisenberg model under periodic boundary conditions.

Core members

(Research Scientist) **Kazuhiro Seki**

(Postdoctoral Researcher) **Xie Qing**

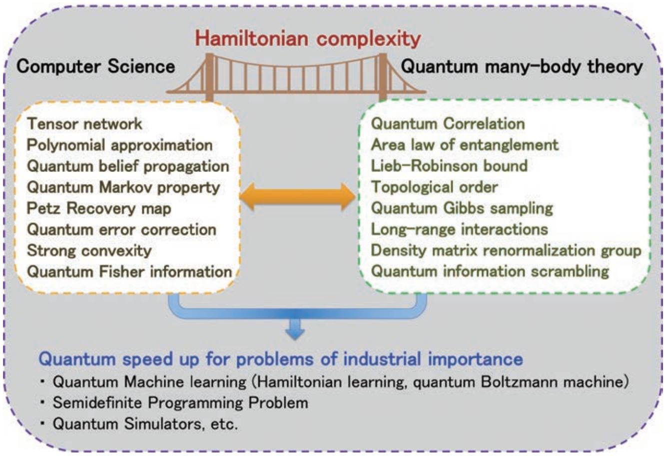
Analytical Quantum Complexity RIKEN Hakubi Research Team

Keywords: Quantum entanglement, Hamiltonian complexity, Quantum many-body systems, Quantum computation, Quantum simulation

Research Outline

The field of revealing the computational complexity of quantum many-body system simulations when using a classical computer (or quantum computer) is called Hamiltonian Complexity. In particular, from the viewpoint of quantum supremacy of quantum computers and quantum algorithms employing NISQ (i.e., a small quantum computer without error correction), Hamiltonian complexity has become one of the most important research topics in the field of quantum information. Our research aims to solve open mathematical problems in Hamiltonian complexity.

The critical concept in the study of Hamiltonian complexity is quantum entanglement, an exotic property arising from the superposition principle of quantum mechanics. The Nobel Prize in Physics for 2022 was awarded to Alain Aspect, John Clauser, and Anton Zeilinger, who experimentally verify the quantum entanglement.



Schematic figure for quantum power methods

Theoretical advances in quantum entanglement have opened up a series of new fields, including the complete classification of quantum phases, the development of classical and quantum algorithms to simulate quantum matter, and fault-torelant quantum computation. Among these, macroscopic length-scale quantum entanglement (long-range entanglement) is a key resource to presenting truly nontrivial quantum effects.

It is generally known that quantum entanglement only survive at ultra-low temperatures close to absolute zero. Since quantum entanglement plays a crucial role in quantum computation, one of the key open problems is to elucidate to what extent quantum entanglement survives in a finite temperature environment. One of the main goals of Hamiltonian complexity is to characterize quantum entanglement quantitatively and qualitatively in quantum many-body systems.

Research Theme

- Entanglement area law
- Lieb-Robinson bound in interacting bosons
- Quantum Markov property at arbitrary temperatures

Tomotaka Kuwahara (Ph.D), RIKEN Hakubi Team Leader

Selected Publications

1 T. Kuwahara, K. Saito, "Exponential Clustering of Bipartite Quantum Entanglement at Arbitrary Temperatures," Physical Review X, 12, 021022 (2022)
2 A. Anshu, S. Arunachalam, T. Kuwahara, M. Soreimanifar (alphabet order), "Sample-efficient learning of quantum many-body systems," Nature Physics, 17, 931–935 (2021), Featured in News&Views
3 T. Kuwahara, A. M. Alhambra, and A. Anshu, "Improved thermal area law and quasi-linear time algorithm for quantum Gibbs states," Physical Review X, 11, 11047 (2021)
4 T. Kuwahara, K. Saito, "Area law of noncritical ground states in 1D long-range interacting systems," Nature Communications, 11 4478 (2020)
5 T. Kuwahara, K. Saito, "Strictly Linear Light Cones in Long-Range Interacting Systems of Arbitrary Dimensions," Physical Review X, 10, 031010 (2020), Featured in Physics

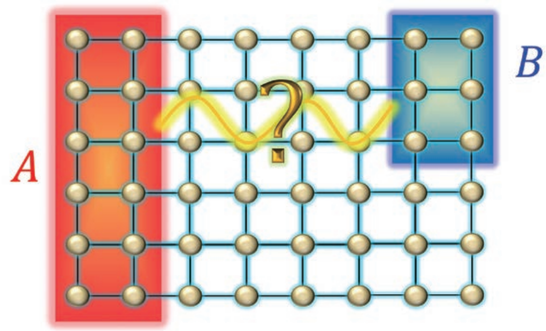
Brief resume

2010 Bachelor in Applied Physics, The Faculty of Engineering, Department of Applied Physics, The University of Tokyo
2012 Master in Physics, Faculty of Science, Department of Physics, The University of Tokyo
2015 Ph.D. in Physics, Faculty of Science, Department of Physics, The University of Tokyo
2015 JSPS Research Fellowship for Young Scientists (JSPS PD), The University of Tokyo
2016 Assistant Professor, Advanced Institute for Materials Research (AIMR), Tohoku University,
2017 Research scientist, Center for Advanced Intelligence Project, RIKEN
2021 Sakigake Researcher, Japan Science and Technology Agency
2022 RIKEN Hakubi team leader, RIKEN Cluster for Pioneering Research / RIKEN Center for Quantum Computing, RIKEN

Recent Achievements

Clustering theorem of quantum entanglement

We have shown that in the thermal equilibrium state of a quantum many-body system, there is generally no "quantum entanglement" over long distances. We proved that beyond a distance of 1/T (T: temperature), the standard "bi-partite" quantum entanglement decays exponentially in distance. This result is quite general in the sense it is applied to all possible quantum many-body systems in any dimension and at any temperature. It shows that long-range entanglement survives only in the form of a special "more than tri-partite" quantum entanglement at finite temperatures. This supports previous observations that long-range entanglement at finite temperatures occurs as a topological order associated with tri-partite quantum entanglement. Our result is expected to provide many clues for quantum computation, including quantum machine learning, and to contribute to the classification of quantum entanglement involved in various quantum phenomena (superconductivity, superfluidity, spin liquid, etc.) observed at finite temperature.



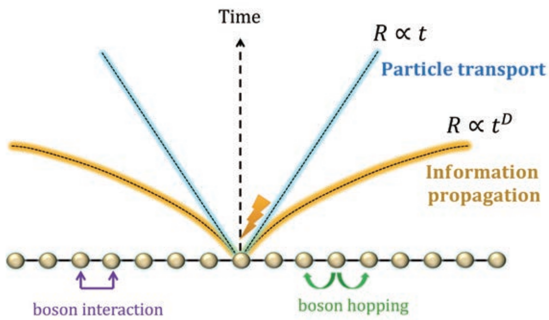
T. Kuwahara and K. Saito, "Exponential clustering of bipartite quantum entanglement at arbitrary temperatures", Physical Review X, 12, 021022 (2022)

Optimal Bosonic Lieb-Robinson bound

We have established the resolution to the Lieb-Robinson bound in interacting boson systems, which has been a long-standing problem in quantum many-body physics and quantum information theory.

A fundamental principle of many-body physics is causality, i.e., a strict prohibition of information propagation outside the light cone. However, in non-relativistic systems, it is often unclear whether such a light cone can be well defined. In the famous work by Lieb and Robinson, the amount of information is proved to be restricted in the effective light cone, which is characterized by the so-called "Lieb-Robinson bound." So far, the Lieb-Robinson bound is a crucial concept in accessing the precision error of various quantum simulation algorithms and mathematical structure of quantum entanglement at low (or zero) temperatures.

Our findings are twofold. As the first main result, we have identified the optimal light cone for interacting bosons and established a gate complexity to simulate the dynamics with an efficiency guarantee. Second, contrary to conventional expectations, our results have unraveled a stark difference between the bosons and fermions regarding information propagation. In detail, we have demonstrated an acceleration of entanglement propagation as a characteristic feature of bosonic systems. A simple protocol should allow the experimental observation for such acceleration.



T. Kuwahara, T. Van Vu and K. Saito, "Optimal light cone and digital quantum simulation of interacting bosons," arXiv:2206.14736

Core members

(Research Scientist) **Yusuke Kimura**
(Postdoctoral Researcher) **Tan Van Vu**
(Part timer) **Hideaki Nishikawa**

RIKEN RQC-FUJITSU Collaboration Center

Keywords: Quantum computer, Superconducting qubit, Error mitigation technology, Error correction technology, Quantum application

Research Outline

Our group, which was established on April 1, 2021, conducts research and development (R&D) to realize quantum computers for practical use. We integrate RIKEN's advanced quantum computer technology using superconducting circuits with FUJITSU's computing technology and knowledge of quantum technology applications based on customer perspectives.

Opening of the "RIKEN RQC-Fujitsu Collaboration Center"

Specifically, we develop hardware and software technologies that will enable large-scale quantum computers with 1,000 qubits. In addition, we develop quantum applications using the quantum computers developed. In terms of research on hardware, we conduct R&D of fundamental technologies, such as the improvement of uniformity in qubit manufacturing, the reduction of the size and noise of peripheral and wiring components, and the development of low-temperature packaging technology. Moreover, we integrate the hardware technologies above and develop a prototype superconducting quantum computer. In terms of software research, we develop middleware and a cloud computing system necessary for operating quantum computers and develop algorithms for quantum applications. We also verify the usefulness of error mitigation technologies in practical applications by executing quantum algorithms that integrate such mitigation technologies with quantum chemistry calculations on a prototype superconducting quantum computer. At the same time, we conduct basic experiments for quantum error detection and correction to identify issues and improve technologies for realizing quantum error correction.

We work together with various research institutions and companies to advance science and technology using quantum computers, and bring about innovations to realize a more sustainable world.

Shintaro Sato (Ph.D.), Deputy Director*

Selected Publications

1 T. Takahashi, N. Kouma, Y. Doi, S. Sato, S Tamate, and Y Nakamura "Uniformity improvement of Josephson-junction resistance by considering sidewall deposition during shadow evaporation for large-scale integration of qubits", *Jpn. J. Appl. Phys.*, 62 SC1002 (2023)

2 T. Kurita, M. Morita, H. Ohshima, and S. Sato "Pauli String Partitioning Algorithm with the Ising Model for Simultaneous Measurements", *J. Phys. Chem. A*, 127, 4, 1068–1080 (2023)

3 J. Fujisaki, H. Oshima, S. Sato, and K. Fujii "Practical and scalable decoder for topological quantum error correction with an Ising machine", *Physical Review Research* 4, 043086 (2022)

4 J. Yamaguchi, H. Hayashi, H. Jippo, A. Shiotari, M. Ohtomo, M. Sakakura, N. Hieda, N.Aratani, M. Ohfuchi, Y. Sugimoto, H. Yamada, and S. Sato "Small bandgap in atomically precise 17-atom-wide armchair-edged graphene nanoribbons." *Commun. Mater.* 1, 36 (2020)

5 H. Hayashi, J. Yamaguchi, H. Jippo, R. Hayashi, N. Aratani, M. Ohfuchi, S. Sato, and H. Yamada "Experimental and Theoretical Investigations of Surface-Assisted Graphene Nanoribbon Synthesis Featuring Carbon–Fluorine Bond Cleavage." *ACS Nano* 11, 6204 (2017)

Brief resume

1990 MS in Science and Engineering (Physics), University of Tsukuba
1990 Ushio Inc. (until 1997)
2001 Ph.D. in Mechanical Engineering, University of Minnesota, USA
2001 Electronic Devices Business Unit, Fujitsu Limited
2002 Researcher, Nanotechnology Research Center, Fujitsu Laboratories Ltd.
2006 Researcher (Senior Researcher from 2007), Semiconductor Leading-Edge Technology Inc. (concurrent position until 2010)
2007 Research Manager, Nanotechnology Research Center, Fujitsu Laboratories Ltd.
2010 Group Leader, Green Nanoelectronics Research Center, The National Institute of Advanced Industrial Science and Technology (AIST) (Sent from Fujitsu until 2014)
2014 Research Manager, Functional Devices Division, Devices and Materials Laboratory, Fujitsu Laboratories Ltd.
2018 Project Director, Next-Generation Materials Project, Devices and Materials Laboratory, Fujitsu Laboratories Ltd.
2018 Fellow, The Japan Society of Applied Physics
2020 Project Director, Quantum Computing Project, ICT Systems Laboratory, Fujitsu Laboratories Ltd.
2021 Head of Quantum Computing Research Center, Fujitsu Research, Fujitsu Limited
2021 Deputy Director, RIKEN RQC-Fujitsu Collaboration Center (-present)
2022 Head of Quantum Laboratory, Fujitsu Research, Fujitsu Limited (-present)

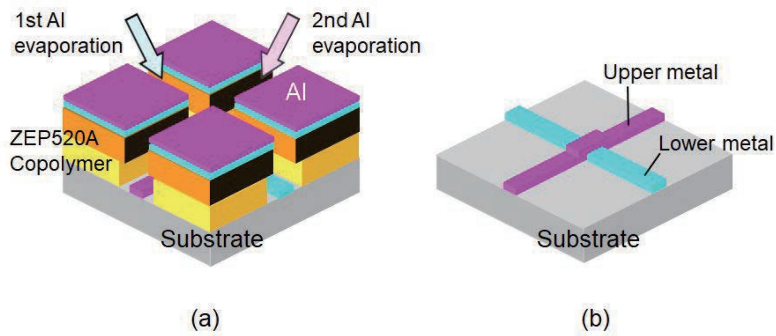
*The current Director is Dr. Yasunobu Nakamura

Recent Achievements

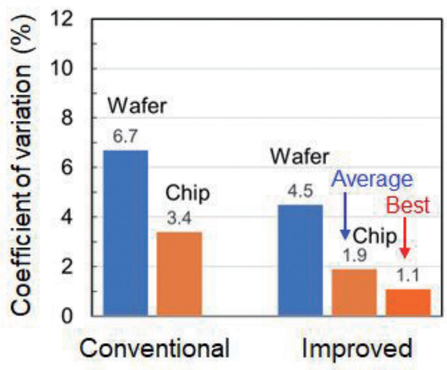
Uniformity improvement of Josephson-junction resistance for large-scale integration of qubits

The uniformity of Josephson-junction (JJ) characteristics is crucial in wafer-scale superconducting qubit integration. However, the JJs with a structure of Al/AlOx/Al have variations in resistance at room temperature. One of the reasons for the variations is that JJs are fabricated by using a method called “angled shadow evaporation”. In this method, a wafer is inclined with respect to the incident axis, casing position-dependent variations of Al deposition. To overcome the issue, our group has clarified the mechanism of the inhomogeneities from a detailed analysis of the evaporation process and introduced a two-step shadow evaporation method to reduce the variations. As a result, the coefficient of variations (CV) across a 3-inch wafer decreases from 6.7% to 4.5%, achieving 1.1% in a chip with an area of 10 mm × 10 mm.

(T. Takahashi *et al.*, Jpn. J. Appl. Phys., 62 SC1002 (2023))



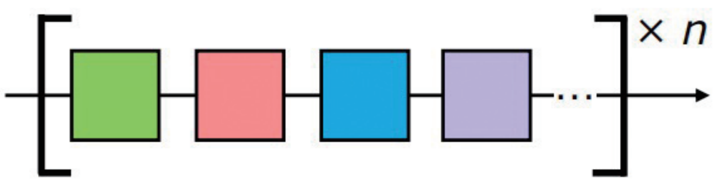
(a) Schematic of the resist pattern and the first and the second metal layers in the Manhattan-style JJ fabrication process (b) Junction structure



Bar chart of the CV values of junction resistances fabricated with the conventional and improved methods

Development of Characterization Methods for Implementation Accuracies of Quantum Operations

Further improvement of implementation accuracies of quantum operations is one of the major challenges for realizing a practical quantum computer. Characterization of implementation accuracies of quantum operations is a fundamental technique for accuracy improvements. Current standard characterization methods have several advantages and disadvantages, and a new method that overcomes the disadvantages is necessary. Our group works on theoretical research toward improving the efficiency and reliability of a characterization method class, called “Quantum Tomography”. Recently, we have developed a new tomographic method for quantum gates, which uses error amplification circuits, and we have theoretically proved that its efficiency at the data-processing part is better than the known method called Gate-Set Tomography.



Conceptual diagram of an error amplification circuit

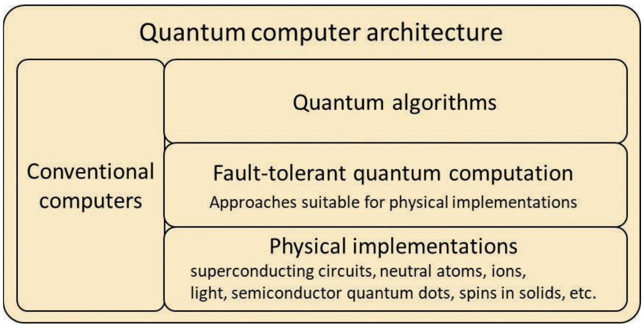
[Est. Apr. 1st 2023]

Quantum Computer Architecture Research Team

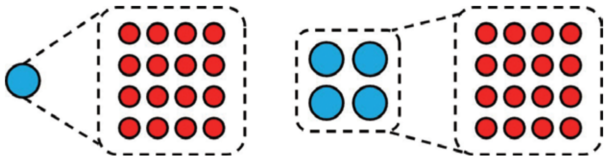
Keywords: Quantum computer, Quantum error correction, Fault-tolerant quantum computation, Physical implementation

Research Outline

We do theoretical research on the total design of quantum computers, from the approaches to fault-tolerant quantum computation (FTQC) to their physical implementations, namely, quantum computer architecture. At present, various physical implementations of quantum computers are under development, such as superconducting circuits, neutral atoms, ions, light, semiconductor quantum dots, and spins in solids. Since different implementations have different types of errors and different connectivity, it is effective to develop an approach to FTQC specialized for each implementation. Also, since early quantum computers will play a role similar to ASIC or an accelerator, they should be designed for specific quantum algorithms. Moreover, since conventional computers play important roles such as control of physical systems, decoding in error correction, and quantum-classical hybrid implementations of algorithms, quantum-classical cooperative system design is required. Thus, the research on quantum computer architecture requires to consider all aspects of quantum computers. The requirement of large resource overheads for FTQC is a central problem at present. To solve this problem, we focus on high-rate codes. Most approaches to FTQC use the encoding of a logical qubit into many physical qubits, which leads to the resource problem. There exist high-rate codes encoding multiple logical qubits at once, but FTQC with them has not been established. We aim at solving the resource problem by developing FTQC with high-rate codes.



Quantum computer architecture



Conventional single-logical-qubit encoding (Left), high-rate code (Right).

Hayato Goto (Ph.D.), Team Leader

Selected Publications

1 H. Goto, “Minimizing resource overheads for fault-tolerant preparation of encoded states of the Steane code”, *Sci. Rep.*, 6, 19578 (2016).
2 H. Goto, “Step-by-step magic state encoding for efficient fault-tolerant quantum computation”, *Sci. Rep.*, 4, 7501 (2014).
3 H. Goto and H. Uchikawa, “Soft-decision decoder for quantum erasure and probabilistic-gate error models”, *Phys. Rev. A*, 89, 022322 (2014).
4 H. Goto and H. Uchikawa, “Fault-tolerant quantum computation with a soft-decision decoder for error correction and detection by teleportation”, *Sci. Rep.*, 3, 2044 (2013).
5 H. Goto and K. Ichimura, “Fault-tolerant quantum computation with probabilistic two-qubit gates”, *Phys. Rev. A*, 80, 040303(R) (2009).

Brief resume

2003 Researcher, Toshiba Corporation
2007 Ph.D. (Science), The University of Tokyo
2016 Senior Research Scientist, Toshiba Corporation
2020 Fellow, Toshiba Corporation (-present)
2023 Team Leader, Quantum Computer Architecture Research Team, RIKEN Center for Quantum Computing (-present)

[Est. Apr. 1st 2023]

Mathematical Quantum Information RIKEN Hakubi Research Team

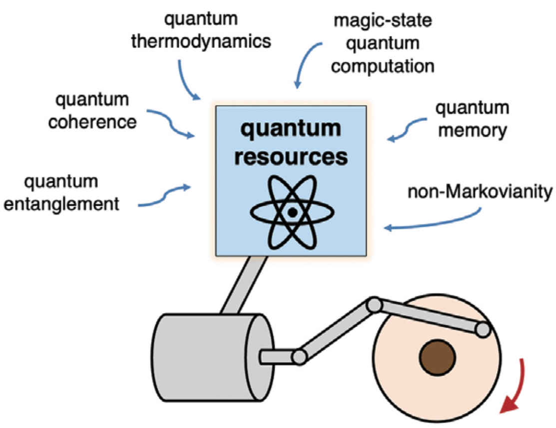
Keywords: Quantum information, Quantum resource theories, Quantum Shannon theory, Mathematical physics

Research Outline

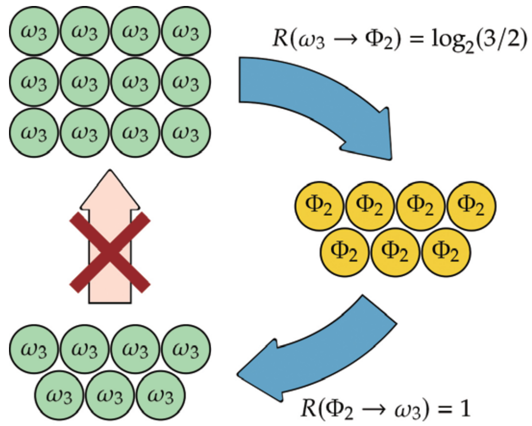
Our group studies the mathematical underpinnings of quantum information theory, with a particular focus on the investigation of the mathematical structure of quantum resources — physical phenomena that underlie practical advantages of quantum technologies in areas such as communication and computation.

We aim to develop technical frameworks that help address the fundamental questions of how to quantify, manipulate, and take advantage of physical resources in quantum information and communication tasks. Our approach is to establish a solid and rigorous mathematical foundation which can be directly used to study a variety of physical settings, allowing for broad applications and generalisations. In addition to advancing the frontiers of knowledge on the fundamental laws governing quantum systems, we hope to provide insight into the physically achievable limits of the advantages of quantum resources, which can then find use in benchmarking practical quantum technologies. We will directly apply our methods to shed light on the properties of resources such as quantum entanglement, quantum coherence, magic-state quantum computation, as well as the dynamical quantum resources of quantum channels.

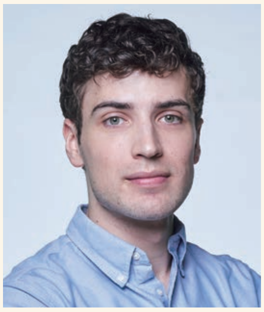
Beyond that, we are broadly interested in the mathematical problems of quantum information theory, e.g. the properties and applications of entropic quantities, the characterisation of operational tasks such as quantum hypothesis testing, and convex optimisation problems, which can be encountered in almost every area of quantum information.



There are many different quantum resources that can fuel the practical applications of quantum technologies. Understanding their properties is thus an important problem, but their complex mathematical structure often makes this very difficult. (Schematic figure adapted from Phys. Rev. X 9, 031053 (2019).)



One of the most significant applications of our general resource-theoretic methods has been the discovery that the theory of entanglement cannot be made reversible, which shows a stark contrast between entanglement manipulation and the theory of thermodynamics. (Figure from Nat. Phys. 19, 184–189 (2023).)



Bartosz Regula (Ph.D.), RIKEN Hakubi Team Leader

Selected Publications

1 L. Lami and B. Regula, “No second law of entanglement manipulation after all”, *Nat. Phys.* 19, 184–189 (2023)
2 B. Regula, “Probabilistic transformations of quantum resources”, *Phys. Rev. Lett.* 128, 110505 (2022)
3 B. Regula and R. Takagi, “Fundamental limitations on distillation of quantum channel resources”, *Nat. Commun.* 12, 4411 (2021)
4 J. R. Seddon, B. Regula, H. Pashayan, Y. Ouyang, and E. T. Campbell, “Quantifying quantum speedups: improved classical simulation from tighter magic monotones”, *PRX Quantum* 2, 010345 (2021)
5 R. Takagi and B. Regula, “General resource theories in quantum mechanics and beyond: operational characterization via discrimination tasks”, *Phys. Rev. X* 9, 031053 (2019)

Brief resume

2018 Ph.D. Mathematics, University of Nottingham, UK
2019 Presidential Postdoctoral Fellow, Nanyang Technological University, Singapore
2021 JSPS Postdoctoral Research Fellow, University of Tokyo, Japan
2023 RIKEN Hakubi Team Leader, Mathematical Quantum Information RIKEN Hakubi Research Team, RIKEN, Japan (-present)

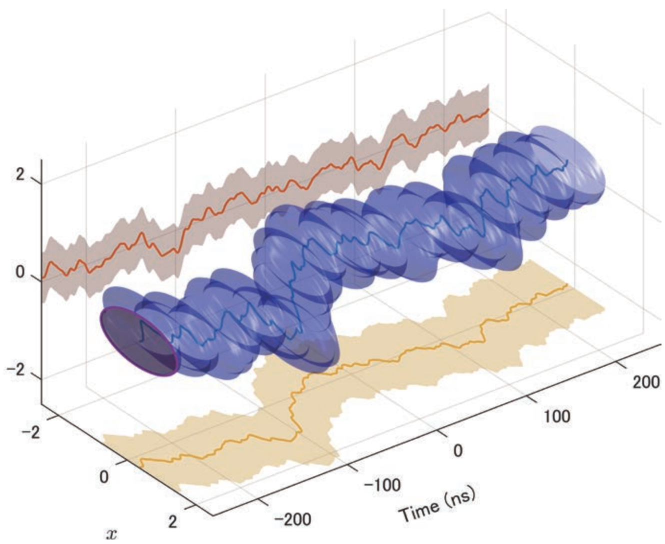
[Est. Jul. 1st 2023]

Optical Quantum Control Research Team

Keywords: Quantum computing, Quantum optics, Quantum control, Optical quantum computing, Quantum estimation

Research Outline

Our team investigates optical quantum control technology with the aim of developing an optical quantum computer. There are many advantages in an optical platform, including compatibility with room temperature, high scalability, and applicability to communication technology. Quantum control is the key technology for quantum applications. Quantum states often fluctuate due to environmental disturbances or measurements. It is critical to develop effective control technology of quantum states, which may involve maintaining or manipulating quantum states in noisy environment, or realising high-performance measurements through control of basic measurement devices. In addition, quantum estimation is also critical because it is the basis for control technology. Our team is investigating high-performance measurement and estimation techniques, control techniques based on them, and related quantum optical technology. Figure 1 shows quantum estimation of the dynamics of quantum states in an optical parametric oscillator. We have achieved high-precision estimation of quantum states using a quantum-state smoothing technique, where both quantum filtering and retro-filtering are used to produce more precise acausal estimation than conventional methods. In addition, we are also investigating coherent control and measurement-based control. Coherent control is a technique that does not involve measurements, leading to a faster and simpler system. Measurement-based control is a technique based on measurement, which allows more complex processing than coherent control. Through these investigations, our team aims to realise and improve optical quantum computers and related quantum information technologies.



Estimation of quantum state of light.

Hidehiro Yonezawa (Ph.D.), Team Leader

Selected Publications

1 S Yokoyama, *et al.*, "Feasibility study of a coherent feedback squeezer," Phys. Rev. A 101, 033802 (2020)
2 S Yokoyama, *et al.*, "Characterization of entangling properties of quantum measurement via two-mode quantum detector tomography using coherent state probes," Opt. Express 27, 34416 (2019)
3 W. Asavanant, *et al.*, "Generation of time-domain-multiplexed two-dimensional cluster state," Science 366, 373 (2019).
4 S. Yokoyama, *et al.*, "Ultra-large-scale continuous-variable cluster states multiplexed in the time domain," Nature Photon. 7, 982 (2013).
5 H. Yonezawa, *et al.*, "Quantum-Enhanced Optical-Phase Tracking," Science 337, 1514 (2012).

Brief resume

2007 Ph.D. in Engineering, The University of Tokyo
2007 Research associate, The University of Tokyo
2009 Project Assistant Professor, The University of Tokyo
2013 Senior lecturer, University of New South Wales (-present)

Office of the Center Director

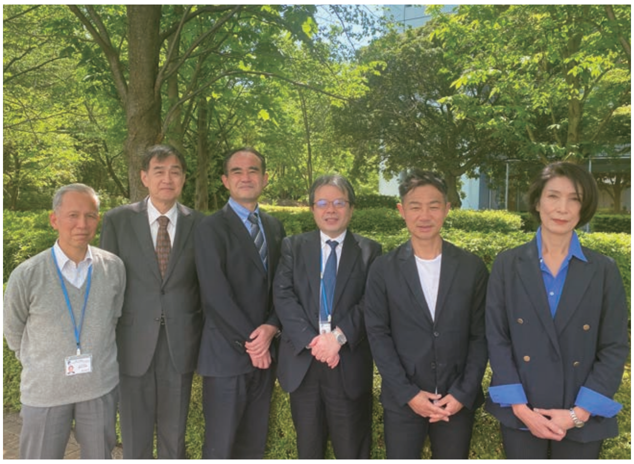
Keywords: Management of RQC, Head quarter of Quantum technology innovation hubs

Outline

The Office of the Center Director performs management tasks related to the overall operation of the Center, including budget management, research space management, surveys on technology trends, intellectual property and standardization trends, information dissemination, and the organization of events.

Based on the government's Quantum Technology Innovation Strategy, RIKEN has been positioned as a core organization that coordinates the 10 quantum technology innovation hubs. We are responsible for the management of this core organization. In addition, we are engaged in managing and promoting MEXT Q-LEAP project (Quantum information technology) as the head quarter.

I am also working on research and development of superconducting integrated systems for fault tolerant quantum computers as one of the project performers of the Moonshot Research and Development Program of the Cabinet Office.



Members of Office of the Center Director

Core members

(Coordinator) **Toshio Tonouchi**
(Research Administrator) **Koji Ikado**
(Research Administrative Support Staff) **Kimiko Kowashi**
(Temporary Employee) **Masanobu Arai**
(Temporary Employee) **Haruyuki Iwabuchi**

Shinichi Yorozu (Ph.D.), RQC Deputy Director, Director of Office of the Center Director

Selected Publications

1 Y. Iwasaki, R. Sawada, V. Stanev, M. Ishida, A. Kirihara, Y. Omori, H. Someya, I. Takeuchi, E. Saitoh, S. Yorozu, Identification of advanced spin-driven thermoelectric materials via interpretable machine learning, npj Computational Materials volume 5, Article number: 103 (2019)
2 A. Kirihara, M. Ishida, R. Yuge, K. Ihara, Y. Iwasaki, R. Sawada, H. Someya, R. Iguchi, K. Uchida, E. Saitoh, S. Yorozu, Annealing-temperature-dependent voltage-sign reversal in all-oxide spin Seebeck devices using RuO2, 2018 J. Phys. D: Appl. Phys. 51 154002
3 K. Uchida, H. Adachi, T. Kikkawa, A. Kirihara, M. Ishida, S. Yorozu, S. Maekawa, E. Saitoh, Thermoelectric Generation Based on Spin Seebeck Effects, Proceedings of the IEEE (Volume: 104, Issue: 10, Oct. 2016) 1946 – 1973
4 K. Takemoto, Y. Nambu, T. Miyazawa, Y. Sakuma, T. Yamamoto, S. Yorozu, Y. Arakawa, Quantum key distribution over 120 km using ultrahigh purity single-photon source and superconducting single-photon detectors, Scientific Reports 5, Article number: 14383 (2015)
5 A. Kirihara, K. Uchida, Y. Kajiwara, M. Ishida, Y. Nakamura, T. Manako, E. Saitoh, S. Yorozu, Spin-current-driven thermoelectric coating, Nature Materials, Vol. 11, pp. 686–689 (2012)

Brief resume

1993 Ph.D. in Applied Physics, The University Tokyo
1993 Researcher, Fundamental Research Laboratories, NEC Corporation
1997 Visiting Researcher, State University of New York at Stony Brook
2005 Senior Manager, Fundamental and Environmental Research Laboratories, NEC Corporation
2015 Deputy General Manager, Smart Energy Research Laboratories, NEC Corporation
2018 Executive Chief Engineer, System Platform Research Laboratories, NEC Corporation
2019 Coordinator, RIKEN Center for Emergent Matter Science
2021 Deputy Director, RIKEN Center for Quantum Computing (-present)

Realizing fault-tolerant quantum computers

A proposal to use cat states promises to make more quantum computers less prone to errors

Category: Applied Physical Sciences **Field:** Quantum computing

Error correction in quantum computers could be simplified by a new protocol proposed by an all-RIKEN team based on 'cat states'[1]. It could cut the computing resources needed to fix errors to the same level as conventional computers, making quantum computers cheaper and more compact.

Quantum computers are looming ever larger on the horizon of computing. They have already demonstrated the ability to outperform traditional computers for certain kinds of calculations. But they are more prone to errors than conventional computers.

Since traditional computers are based on bits that are either 0 or 1, the only error they are susceptible to is when a bit accidentally flips from 0 to 1 or vice versa.

But quantum computers use qubits, which can be in a superposition of two states. When the states are depicted on a sphere, the angle between the two states is known as the qubit's phase. This phase can also be flipped in quantum computers. They thus need more computing resources to correct for this additional source of error.

An attractive way to sidestep this problem is to use qubits based on so-called cat states. These states are named after Schrödinger's hypothetical cat, which is simultaneously dead and alive until observed. By analogy, cat states are superpositions of two states with opposite phase.

Unlike other qubits, cat-state qubits cannot undergo phase flips, so that engineers making quantum computers based on them need only worry about bit flips—just like in conventional computers. Researchers are now exploring how to use these cat-state qubits to perform computations.

Now, Ye-Hong Chen and four co-workers, all at the RIKEN Center for Quantum Computing, have theoretically demonstrated a way to use cat states to realize fault-tolerant gates for connecting multiple qubits in a process known as entanglement.

"Conventional computers can only process data one bit at a time, but entanglement allows quantum computers to process a lot of data simultaneously," explains Chen. "The gates can rapidly generate entangled cat states with high accuracy."

The team showed that such fault-tolerant quantum gates could be used to implement a quantum search algorithm with a high efficiency. The algorithm will allow databases to be searched faster than is currently possible using conventional computers.

"Let us assume that you are searching for one key that will open a box among 100 keys. On average, you would need to try 50 keys using a conventional search algorithm to identify the one key that opens that box," says Chen. "But with the quantum search algorithm the average is only 10 attempts," says Chen.

The team is now exploring how to develop other useful quantum algorithms based on fault-tolerant quantum codes.

In a thought experiment, Schrödinger conjectured a cat could be both alive and dead until observed if a quantum event such as the decay of a radioactive particle (right) would trigger an event that will kill the cat. Now, by using cat states, RIKEN researchers have proposed a scheme for realizing fault-tolerant gates to entangle multiple qubits.

Reference

1. Chen, Y.-H., Stassi, R., Qin, W., Miranowicz, A. & Nori, F. Fault-tolerant multiqubit geometric entangling gates using photonic cat-state qubits. *Physical Review Applied* 18, 024076 (2022).

RIKEN Research Spring 2023

These articles are edited versions of RIKEN Research Highlights.

Nanoscale heat engines

A nanoscale device offers insights into how single electrons interact with vibrations in the presence of a temperature gradient

Category: Applied Physical Sciences **Field:** Quantum heat engines

RIKEN physicists have fabricated a nanoscale 'heat engine' that uses a property of electrons known as spin as the effective working medium[1]. It is promising for exploring the development of spintronic heat engines capable of harvesting waste heat from devices.

Heat engines convert a heat difference into more useful forms of energy as heat flows from warmer to cooler regions of electronic devices. Reducing them to the nanoscale would enable waste heat generated to be converted back into electrical energy and thus improve efficiency.

One way to create nanoscale heat engines is to use tiny crystals of semiconductors known as quantum dots (Fig. 1). Somewhere in the range of 10 to 100 nanometers in diameter, a quantum dot can trap one or a few electrons.

All heat engines are driven by a difference in temperature—one end of the heat engine needs to be hotter than the other for the heat engine to work. In quantum systems, there are two different temperatures: the temperature of the atoms (or lattice temperature) and that of the electrons.

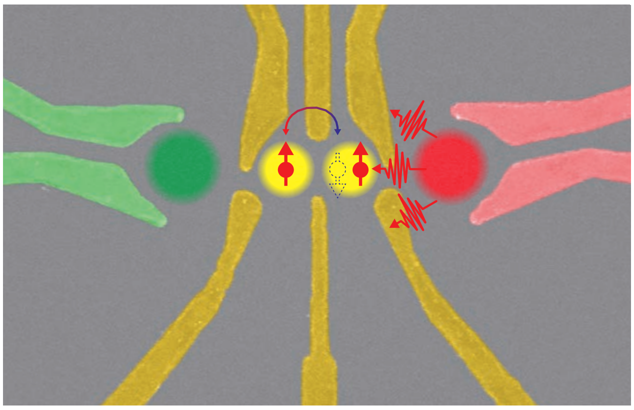
Previous heat engines based on quantum dots have used reservoirs of electrons at different temperatures. However, to gain a better understanding of the underlying thermodynamics it is desirable to create a heat engine that operates on lattice temperature. But generating a lattice temperature gradient across a few hundred nanometers is technically challenging.

Now, Seigo Tarucha at the RIKEN Center for Emergent Materials Science and his colleagues have succeeded in doing this in their quantum-dot heat engine.

In their device, electrons are confined using electric fields generated at surface metal electrodes on a gallium arsenide surface. The device had two interlinked quantum dots and a built-in charge sensor to passively monitor what was going on within the double quantum dot (Fig. 1). A third quantum dot was used to control the double quantum dot's thermal environment; effectively, it acted as a local heater.

The researchers anticipate the device will greatly contribute to our understanding of the fundamental physics of thermoelectric devices. "The results give valuable insights into developing spintronic heat engines," says Tarucha. "In particular, this setup will provide an experimental platform for studying the thermodynamics of cooperative spin–charge systems."

The next challenge will be to introduce on-demand control of heat flow in the spin–charge cooperative system. "We're now developing a technique to rapidly switch the heat flow," explains Tarucha. "This will provide a new platform to study the physics and apply for development of spintronic heat engines."



A double quantum dot device enables the study of how the spin and charge of an electron influences thermodynamic action in the presence of a lattice temperature gradient. Lattice vibrations known as phonons (three red squiggles) come from the red quantum dot on the right, which acts as a local heater. They can cause the spin on of the two electrons (yellow dots) to flip, which is detected by the green quantum dot, which acts as a charge sensor.

Reference

1. Kuroyama, K., Matsuo, S., Muramoto, J., Yabunaka, S., Valentin, S. R., Ludwig, A., Wieck, A. D., Tokura, Y. & Tarucha, S. Real-time observation of charge-spin cooperative dynamics driven by a nonequilibrium phonon environment. *Physical Review Letters* 129, 095901 (2022). (doi: 10.1103/PhysRevLett.129.095901)

RIKEN Research Spring 2023

These articles are edited versions of RIKEN Research Highlights.

Observing field-theory physics in the bathtub

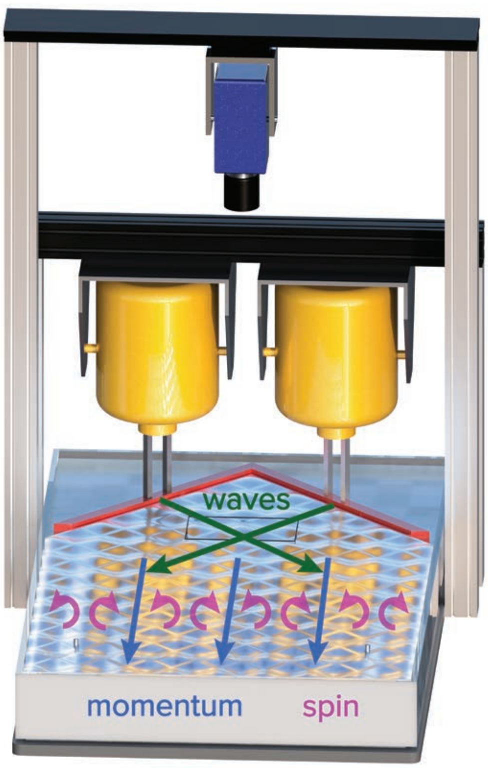
An important concept in quantum physics known as spin can be seen in water waves

Category: Exploratory Physical Sciences **Field**: Wave physics

Water waves can be used to visualize fundamental concepts, such as spin angular momentum, that arise in relativistic field theory, RIKEN physicists have shown[1]. This will help to provide new insights into very different wave systems.

First introduced nearly a century ago, the concept of spin angular momentum, or spin, is critically important in quantum physics and underpins the emerging fields of spintronics and quantum computing. In high school physics, the spin of an electron is usually described as the electron spinning on its axis, similar to a spinning top. But a fuller description of spin is more abstract and doesn't yield itself to simple pictures.

Now, Konstantin Bliokh of the RIKEN Theoretical Quantum Physics Laboratory and his co-workers have shown that spin can appear as small circular motions of water particles in water waves (Fig.).



Researchers at RIKEN have used water waves to generate small circulations of water particles (pink arrows) that generate spin angular momentum of water waves, a classical counterpart of the spin of quantum wave fields.

"We were surprised that our collaborators from the Australian National University were able to observe this effect in experiments so readily," says Bliokh. "Similar phenomena in optics and acoustics tend to be too tiny to observe, but with water waves, everything is a few millimeters in size and you can observe it with your eyes. That's the beauty of this experiment."

It was also unexpected because the concept of spin comes from the mathematics that describes relativistic field theory, and does not apply directly to water waves. But the researchers were able to show that there is a mathematical connection between water waves and formal theory for spin angular momentum. As is often the case in physics, diverse phenomena that appear to be totally unrelated can be connected by common mathematics.

"It's nice to gain a unified picture of different wave systems and see the parallels between them," says Bliokh. "This approach illuminates the physics behind different phenomena and could be very fruitful for the future development of different fields." He notes that insights could flow both ways and that we could learn more about fluid dynamics from the connection.

Bliokh also considers that the demonstration could be helpful for teaching quantum field theory. "Quantities like spin density are derived in a very abstract way. It appears in some equations, but you observe totally different things in experiments," says Bliokh. "For the first time, we have directly observed spin density in water waves. So it's really a platform for visualizing properties that are hidden in quantum field theory."

The team is now exploring how field theory can be used to gain new insights into other types of classical waves.

Reference

1. Bliokh, K. Y., Punzmann, H., Xia, H., Nori, F. & Shats, M. Field theory spin and momentum in water waves. *Science Advances* 8, eabm1295 (2022). (doi: 10.1126/sciadv.abm1295)

RIKEN Web Research News Apr.18, 2022

These articles are edited versions of RIKEN Research Highlights.

Applying the latest computing technologies to quantum gravity

Emerging technologies are promising for helping physicists develop a theory that unites quantum physics and gravity

Category: Exploratory Physical Sciences **Field:** Quantum gravity

RIKEN physicists have put quantum computing and deep learning through their paces and found that they are powerful tools for gleaning insights into new theories of quantum gravity[1]. They could thus help solve one of the most formidable challenges in modern physics—developing a theory of gravity that jives with quantum physics.

When Einstein nutted out his theory of general relativity in 1915, his only tools were pen and paper. The same was true of the pioneers of quantum theory. But the next major breakthrough in theoretical physics could be made with help from emerging technologies such as quantum computers and machine learning, Enrico Rinaldi of RIKEN Theoretical Quantum Physics Laboratory thinks. “I believe these technologies are poised to transform the way we do theoretical physics,” he says.

Both general relativity and quantum physics are incredibly successful at describing different aspects of physical reality. The only snag is that they are incompatible with each other. This keeps theoretical physicists up at night because it means that our understanding of reality is incomplete, and there is a more comprehensive theory waiting to be discovered.

There has been a sustained push to derive a quantum theory of gravity. But while many theories have been proposed, it is notoriously difficult to perform even the simplest calculations based on them.

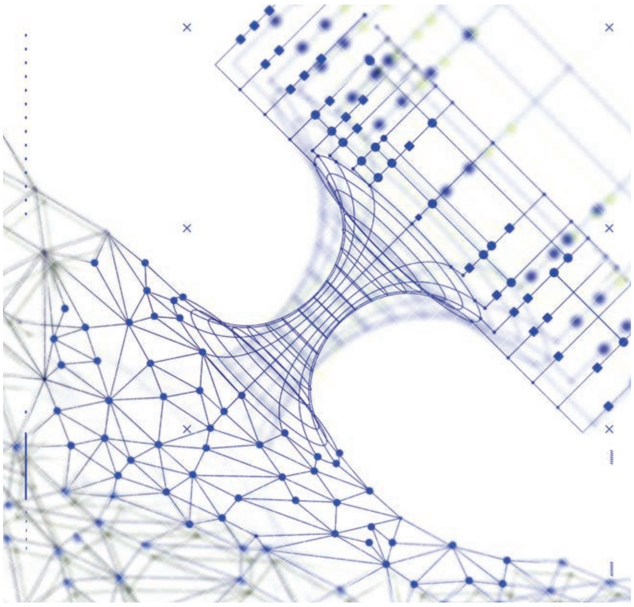
Now, Rinaldi and his co-workers have explored whether quantum computing and deep learning could aid theoretical physicists with these calculations.

They applied the two techniques to problems in holographic duality—theories that relate particles in one system to gravity in a system that has an additional dimension, much like a two-dimensional hologram can create a three-dimensional image. For the purposes of the trial, they picked problems that could be solved by conventional techniques so they could assess the accuracy of the methods.

Both techniques performed well. Of the two, deep learning had the upper hand. “The deep-learning method had the best scaling with resources,” notes Rinaldi.

But quantum computing also showed impressive performance. “The biggest surprise was how well the quantum-computing algorithm performed. We just took what was available—so we didn’t know if it would work,” says Rinaldi. “We were surprised how accurate the answers it gave were.”

The team didn’t use a real quantum computer since the technology is still in its infancy; instead they simulated a quantum computer on a conventional computer.



RIKEN researchers have used quantum computing (represented by lines, squares and circles in the top right of the image) and deep learning (depicted by graph points in the bottom left of the image) to perform calculations using quantum gravity theories.

Rinaldi is encouraged by the recent progress being made in developing theories of quantum gravity. “I really think we’re getting closer,” he says. “There has been a lot of progress in the past two years.”

Reference

1. Rinaldi, E., Han, X., Hassan, M., Feng, Y., Nori, F., McGuigan, M. & Hanada, M. Matrix-model simulations using quantum computing, deep learning, and lattice Monte Carlo. *PRX Quantum* 3, 010324 (2022). (doi: 10.1103/PRXQuantum.3.010324)

RIKEN Web Research News Apr.11, 2022

These articles are edited versions of RIKEN Research Highlights.

Protecting quantum matter with light

Quantum light can help create longer lasting quantum states useful for information processing

Category: Exploratory Physical Sciences **Field:** Quantum materials

Quantum optics might offer a way to make a class of exotic materials known as topological materials even more robust against defects, theoretical physicists at RIKEN have shown[1]. This finding could benefit the development of quantum computers and other emerging quantum technologies.

Topological materials are exciting because local defects and imperfections in them don't affect their properties. But they are not immune to larger-scale, non-local disorder within the material.

Quantum optics is the study of how individual 'particles' of light, or photons, interact with matter. Its theory tells us that this interaction can be altered by controlling the electromagnetic properties of the matter's environment.

Coupling between light and matter has been employed to detect and manipulate topological matter. However, it is an open question how topological matter is modified by quantum light.

Now, in a theoretical study, Wei Nie and Franco Nori from the RIKEN Theoretical Quantum Physics Laboratory and their colleagues from France and China have discovered that the topology can be protected in vacuum electromagnetic fields.

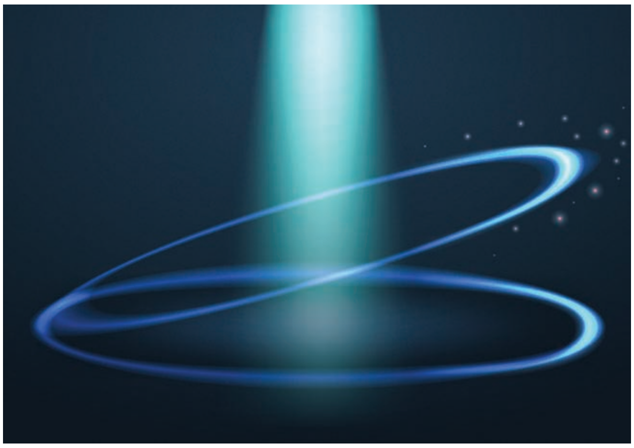
"Our work pinpoints the novel properties of topological light–matter coupling," says Nori. "This may allow us to manipulate topological matter with quantum light."

By combining ideas from both condensed-matter physics and quantum optics, the researchers found that light emission from the topological electronic states changes with the strength of the light–matter coupling in a counterintuitive way. Light can be emitted in a weak-coupling regime, whereas strong light–matter coupling inhibits emission. It also increases the quantum coherence—the length of time the light can maintain its quantum state.

This is counterintuitive because stronger coupling to the environment usually reduces coherence: the symmetries protecting topological matter are supposed to be broken by the electromagnetic environment. "Instead, our work shows that for a topological emitter array coupling to a one-dimensional electromagnetic environment, the chiral symmetry that protects the system can be preserved," explains Nori.

This suggests an approach to tune quantum coherence without fiddling with the coupling between the system and the environment. Topological matter's robustness to local disorder makes it of great interest for quantum computation. However, non-local disorder remains a problem and limits the quantum coherence that is vital for all quantum technologies. The improved coherence offered by taking advantage of strong coupling can therefore be employed for better quantum information storage.

"Our work shows that topological light–matter coupling is an important resource for quantum optics and condensed-matter physics," says Nie. "The topological features of matter give rise to novel quantum optical phenomena, which are useful for quantum computation and quantum technologies."



Background vector created by macrovector - www.freepik.com [https://www.freepik.com/vectors/background].

Chiral-symmetry protected topological states can be preserved through strong coupling to its electromagnetic environment.

Reference

1. Nie, W., Antezza, M., Liu, Y.-X. & Nori, F. Dissipative topological phase transition with strong system-environment coupling. *Physical Review Letters* 127, 250402 (2021). (doi: 10.1103/PhysRevLett.127.250402)

RIKEN Research Fall 2022 (p23)

Quantum reboot gets a speed boost

Simulations suggest a new technique for resetting ‘qubits’ in a quantum computer without harming them

Category: Applied Physical Sciences **Field:** Quantum heat engines

Rebooting a quantum computer is a tricky process that can damage its parts, but now two RIKEN physicists have proposed a fast and controllable way to hit reset[1].

Conventional computers process information stored as bits that take a value of zero or one. The potential power of quantum computers lies in their ability to process ‘qubits’ that can take a value of zero or one—or be some fuzzy mix of both simultaneously.

“However, to reuse the same circuit for multiple operations, you have to force the qubits back to zero fast,” says Jaw Shen Tsai, a quantum physicist at the RIKEN Center for Quantum Computing. But that is easier said than done.

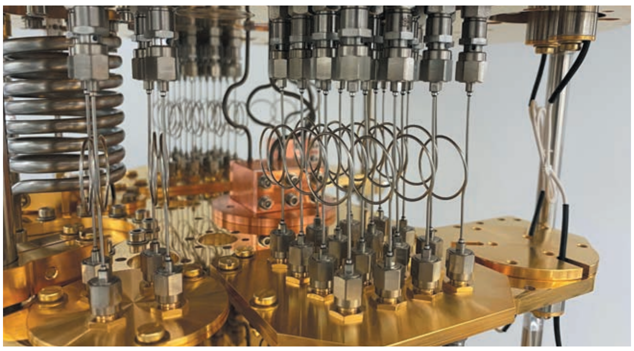
One of the best current ways to hit reset for qubits built from tiny superconductors is to link the qubit to a photon—a particle of light—in a tiny device called a resonator. The qubit transfers its energy to the resonator, after which the photon in the resonator decays, releasing its energy to the environment. This process causes the qubit state to drop back to the ground state (zero). The trouble with this method is that permanent entanglement to a decaying photon rapidly degrades the qubit’s quality, so that it rapidly ceases to be useful for future operations. “It’s bad for the qubit, whose lifetime becomes short,” says Tsai.

Now, Tsai and his RIKEN colleague Teruaki Yoshioka have devised a simulation to help find a better way of resetting the qubit, without harming it.

Based on their calculations, the pair proposed building a resonator that can be controlled using an additional junction made by sandwiching a superconducting material with an insulator, a normal metal, another insulator and another superconductor. This layered junction is controlled by applying a voltage. While the qubit operation is being carried out, the set-up is tuned so that the photon cannot decay. Only when the operation has been completed do the physicists change the voltage, allowing the photon to release energy. “This adjustable resonator is the key to our proposal,” says Tsai.

The best current lab record for resetting a qubit is 280 nanoseconds, with 99.0% fidelity. “Our simulations suggest we could reset the qubit in 80 nanoseconds, with 99.0% fidelity,” says Yoshioka.

The team is now testing this set-up, which is held at low temperatures using a dilution refrigerator (Fig.), with promising results. “This device should be very useful if we can implement it in a quantum circuit,” Tsai says.



A photograph of a dilution refrigerator that houses qubits.

Reference

1. Yoshioka, T. & Tsai, J. S. Fast unconditional initialization for superconducting qubit and resonator using quantum-circuit refrigerator. *Applied Physics* Letters 119, 124003 (2021). (doi: 10.1063/5.0057894)

RIKEN Research Summer 2022 (p8)

These articles are edited versions of RIKEN Research Highlights.

Looking for rules within quantum complexity

Tomotaka Kuwahara
Team Leader, Analytical Quantum Complexity RIKEN
Hakubi Research Team, RIKEN Center for Quantum Computing

Please briefly describe your current research.

My team aims to solve the most important unsolved problems in the field of quantum information.

To do this, I look at Hamiltonian complexity. The Hamilton of a system is the sum of its kinetic energy (energy of motion) and its potential energy (energy of position). Hamiltonian complexity is the study of the universal structural constraints of a system of many interacting quantum particles—quantum many-body systems—due to these energies.

Currently, my aim is to characterize via an information-theoretic lens the intrinsic complexity of quantum many-body systems and apply these understandings to the quantification, storage and communication of digital information.

What excites you the most about your current research?

Well, statements on Hamiltonian complexity are universal and can be written in mathematically precise ways. These laws may resolve great mysteries about how the world works.

Physicists are also very keen to figure out how to solve quantum many-body problems using quantum/classical hybrid computers. However, understanding the computational complexity of a quantum many-body system is equivalent to completely clarifying the information-theoretic structure of the quantum many-body system.

How did you become interested in your current field of research?

I was initially puzzled about why our living world is so complicated despite having such simple fundamental laws. This, I discovered, may boil down to the essential difference between one-body and many-body problems. However, realistic quantum many-body systems are thought to be 'not too complicated'. That is, realistic many-body systems are much simpler than typical theoretical ones. So I became interested in why our world has a moderate level of complexity in terms of physics.

What do you think has been the most interesting discovery in the last few years?

Recently, the 'no low energy trivial state conjecture', a previously unproven idea posed in 2014, has been solved. It had been a fundamental unresolved obstacle to applying a theorem, called the PCP theorem, to the quantum realm. The PCP theorem is a cornerstone of conventional computing, helping us to understand algorithmic complexity and the conditions of near-optimal solutions for optimization. This finding inspired me to work towards solving famous unsolved conjectures.

What other goals do you have at RIKEN and in your life?

I aim to lead a team that will increase the presence of Japanese researchers at the world's most prestigious international conferences on quantum physics, such as the Quantum Information Processing conference and the Theory of Quantum Computation, Communication and Cryptography conference. Since I am a Christian, my ultimate goal is to follow in the footsteps of great Christian physicist predecessors like Isaac Newton, Michael Faraday, and Blaise Pascal. This always encourages me: "For I can do everything through Christ, who gives me strength" (Philippians 4:13).

These articles are edited versions of RIKEN Research Highlights.

Modeling quantum environments

Neill Lambert

Senior Research Scientist, Theoretical Quantum Physics Laboratory, RIKEN Cluster for Pioneering Research

How and when did you join RIKEN?

I joined RIKEN in 2008 after spending several years at the University of Tokyo as a Japan Society for the Promotion of Science fellow. Initially I came to give a seminar in RIKEN, and then applied for a postdoc position after enjoying the interactions I had with Dr. Franco Nori's group (the Theoretical Quantum Physics Laboratory within the RIKEN Cluster for Pioneering Research).

Please describe your role.

I study open quantum systems, or how a large environment affects the behavior of small quantum systems, particularly in situations where parts of the environment itself must be modelled quantum mechanically. This research could be important to understanding how to control noise within quantum computers or how thermodynamics behave in quantum regimes. Day to day, I mainly work on developing new methodologies for this field, conduct numerical simulations, and assist with developing and administering a popular open-source software package for simulating the dynamics of open quantum systems created by our group – QuTiP (the Quantum Toolbox in Python).

What are some of the technologies that you use?

Recently, because of several numerically demanding projects, I have been using the excellent computing resources available in RIKEN, in particular the Hokusai BigWaterFall supercomputer.

What excites you the most about your current research?

The question of whether quantum effects can be observed with large objects is fascinating. Some of my recent work helps us to unravel part of this issue, like how large collections of small quantum systems might start to appear classical, which also helps make practical simulation methods and tools more efficient.

What do you think has been the most interesting recent discovery in your field?

The development of small-scale quantum computers by the likes of IBM and Google has truly changed the field I work in. As a theorist, it is exciting that I can access real devices, through a cloud computing service, and conduct my own experiments.

How did you become interested in your current research field?

As an undergraduate student, I did an exciting quantum physics course taught by Professor Tobias Brandes at UMIST (now The University of Manchester) in the UK. He would eventually become my Ph.D. supervisor.

What has been your most memorable experience at RIKEN?

I have very much enjoyed the opportunity to supervise and train international students. One student recently contacted me and told me he had found a tenured university position in his home country, which made me very happy.

These articles are edited versions of RIKEN Research Highlights.

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