2024

RIKEN Center for Quantum Computing

Annual Report

RIKEN QUANTUM COMPUTING

RIKEN

Contents

Director's Greetings

The RIKEN Center for Quantum Computing (RQC) was established in April 2021. Our mission is to develop quantum computers and pioneer the frontier of quantum information science. We engage in full-stack research and development encompassing layers of science and technology from hardware to software and basic science to applications.

Quantum mechanics is the most fundamental theory of physics, which has evolved through the collective efforts of numerous researchers. It has contributed widely to the development of science and technology in general. Quantum information science, which emerged in the late 20th century, has also attracted attention for exploiting new possibilities by applying the principles of quantum mechanics to information science.

In recognition that this year, 2025, marks the centennial of the theory of quantum mechanics, UNESCO has declared it the "International Year of Quantum Science and Technology." In light of that, various quantum-related events and symposiums will be held. Additionally, a new permanent exhibition about quantum computers has opened at the National Museum of Emerging Science and Innovation (Miraikan), and RQC is providing a 144-qubit integrated circuit chip for the exhibition.

The global research and development of quantum computers are rapidly gaining momentum, with new ideas and technologies constantly emerging. At RQC, we are at the forefront of this dynamic landscape, conducting research on various quantum computing platforms, such as superconducting, optical, and semiconducting. In FY2024, we established two new research teams on cold-atom platforms and are accelerating our research and development. We foster a culture of mutual discovery and learning, generating new ideas through synergy by pursuing multiple approaches simultaneously. RQC also houses other experimental research teams developing basic technology for quantum information processing through novel techniques and several theoretical teams covering quantum information theory, quantum computing theory, quantum algorithms, quantum architecture, quantum software, etc. Our diverse teams collaborate on various topics, from basic science to applications and from experiments to theories, striving for breakthrough research every day.

Last year, we succeeded in developing a new optical quantum computer. It is the world's first platform for general-purpose optical quantum computers. This has made RQC an internationally unique research organization that develops and owns actual quantum computers based on different approaches, such as the superconducting quantum computer, including the first domestic quantum computer "A," and the world's first general-purpose optical quantum computing platform.

Furthermore, RQC plays a pivotal role as the headquarters and the quantum computer development hub at the core of all twelve Quantum Technology Innovation Hubs under the Quantum Technology and Innovation Strategy promoted by the Government of Japan. We spearhead advancements and collaborations in Japanese quantum technology research and development. Through activities connecting participants in academia, industry, and the government, as well as by sharing knowledge across diverse subfields and tightening lateral collaborations, we accelerate innovation cycles, promote the development of science and technology, and contribute value to society.

The fusion of quantum information science with rapidly evolving cutting-edge technologies, such as artificial intelligence, high-performance computers, semiconductors, and optical communication, is also emerging as an essential topic. We will further strengthen collaborations among researchers inside and outside RIKEN, encourage interdisciplinary discussions among researchers with diverse backgrounds and expertise, and foster future leaders who will shape the next generation of quantum science and technology, while continuing our persistent research and development efforts towards realizing quantum computers.

June 30, 2025

Overview of RIKEN Center for Quantum Computing

The RIKEN Center for Quantum Computing (RQC) launched two new teams in FY2024, giving it a lineup of 20 research laboratories in total. It is developing quantum computers with various physics-related teams that cover the superconducting method, the optical method, the semiconductor method, cold-atom platforms, and so on, and promoting research and development by theoretical teams that cover quantum algorithms, quantum computation theory, and other fields.

RQC adopts various approaches to develop quantum computers, enhance their functions, and combine them with computational science and electronics technologies, while striving to expand their computable capabilities toward resolving social challenges, as well as promoting basic research in order to establish the next generation of quantum computer technology, with the aim of realizing quantum computers as innovative information processing units based on the principles of quantum mechanics.

RIKEN Center for Quantum Computing

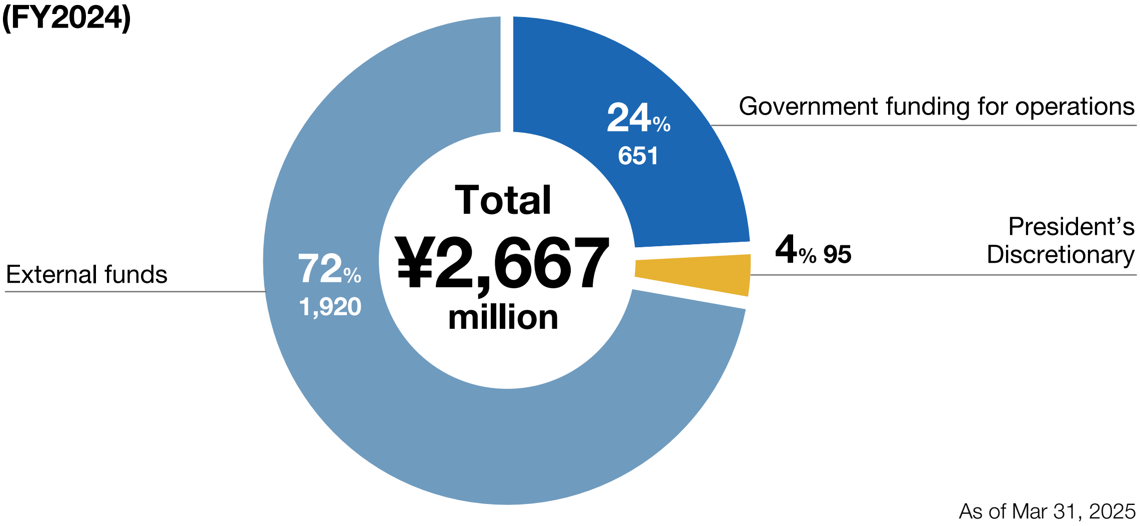
Director: Yasunobu Nakamura
Deputy director: Akira Furusawa, Shinichi Yorozu

- **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
- **Nanophotonic Cavity Quantum Electrodynamics Research Team:** Takao Aoki
- **Quantum Many-Body Dynamics Research Team:** Takeshi Fukuhara
- **Cold-Atom Quantum System Research Team:** Sylvain de Léséleuc
- **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
- **Analytical Quantum Complexity RIKEN Hakubi Research Team:** Tomotaka Kuwahara
- **Mathematical Quantum Information RIKEN Hakubi Research Team:** Bartosz Regula
- **RIKEN RQC-FUJITSU Collaboration Center:** Yasunobu Nakamura
- **Office of the Center Director:** Shinichi Yorozu

Superconductivity · Optics · Atoms · Electrons · Semiconductor · Theory · Administration

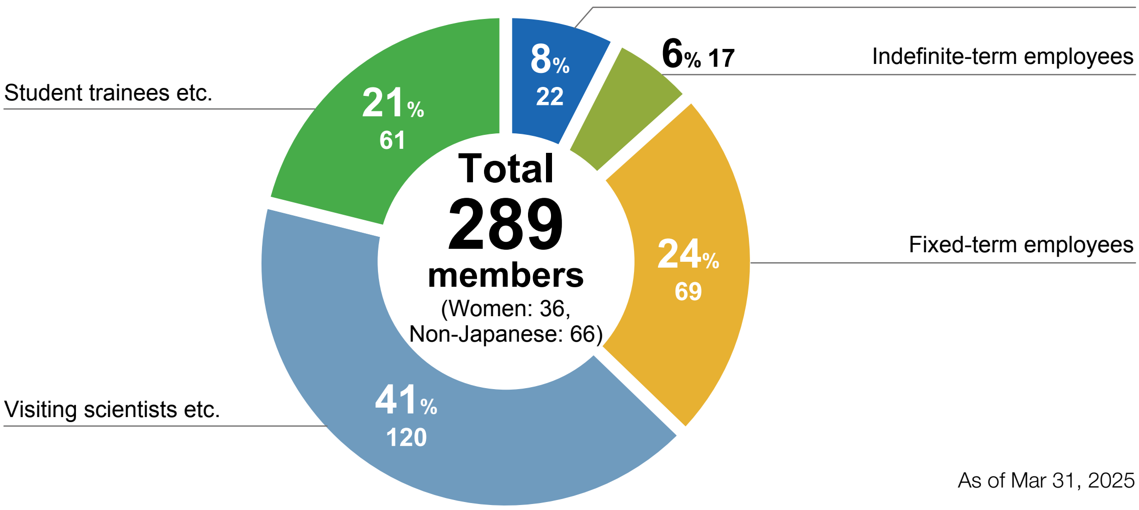
Overview of RIKEN Center for Quantum Computing (Continued)

Budget (FY2024)



As of Mar 31, 2025

Members (FY2024)



As of Mar 31, 2025

RQC Colloquiums and RQC Seminars

FY2024 RQC Colloquiums

At the RQC, we regularly invite renowned researchers and hold RQC Colloquiums. RQC Colloquiums were held 10 times in FY2024, 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
23	April 24, 2024 (online)	Prof. John J.L. Morton	UCL, Quantum Motion, Phasecraft, UK	The role of silicon in quantum computing
24	June 3, 2024	Prof. Andreas Wallraff	Department of Physics, ETH Zurich	Quantum Science and Technology with Superconducting Circuits
25	June 17, 2024	Prof. Dafei Jin	University of Notre Dame, USA	Single electrons on solid neon – a long-coherence high-fidelity qubit platform
26	July 9, 2024	Prof. Nicolas C Menicucci	RMIT University, Australia	Quantum computing with continuous-variable optical systems: recent breakthroughs in scalability and fault tolerance
27	September 24, 2024	Prof. David Elkouss	Okinawa Institute of Science and Technology, Japan	Exploiting near-term quantum networks
28	November 6, 2024	Prof. Dan Stamper-Kurn	University of California, Berkeley, USA	Quantum systems and devices built of ultracold atoms and light
29	December 10, 2024	Dr. Emmanuel Flurin	CEA-Saclay, French	Single Atom Magnetic Resonance by Microwave Photon Counting
30	January 6, 2025 (online)	Prof. Dorit Aharonov	Hebrew University, Israel	The search for evidence of quantum advantage
31	February 26, 2025 (online)	Dr. Bharti Kishor	Agency for Science, Technology and Research (A*STAR), Singapore	What is Quantum Contextuality and Why Should You Care?
32	March 13, 2025	Prof. Oliver Benson	Humboldt-Universität zu Berlin, Germany	Experimental Resources for Quantum Information Processing via Quantum Networks

FY2024 RQC Seminars

Additionally, at the RQC we also hold RQC Seminars, which each PI organizes independently. RQC Seminars were held 80 times in FY2024, and vigorous discussions were held that went beyond the team framework with the aim of making breakthroughs related to the research and development of quantum computers.

No.	Date	Speaker	Affiliation
109	April 5, 2024	Mr. Boxi Li	Forschungszentrum Jülich, Germany
110	April 17, 2024	Dr. Hidehiro Yonezawa	RQC, Optical Quantum Control Research Team, Japan
111	April 10, 2024	Dr. Rui Li	RQC, Superconducting Quantum Electronics Research Team, Japan
112	April 25, 2024	Prof. Alireza Marandi	California Institute of Technology, USA
113	April 22, 2024	Mr. Jonah Peter	Harvard University, USA
114	April 23, 2024	Dr. Tomasz Linowski	University of Gdansk, Poland
115	April 24, 2024	Mr. Enze Li	University of science and technology of China
116	May 21, 2024	Dr. Nicolò D'Anna	The University of California San Diego (UCSD), USA
117	May 23, 2024	Prof. Yuri Kivshar	Australian National University, Australia
118	July 22, 2024	Prof. Konstantinos Makris	Department of Physics, University of Crete, Greece
119	June 14, 2024	Dr. Stefano Carrazza	Department of Physics, University of Milan, Italy
120	June 10, 2024	Dr. Alexander Tzalenchuk	National Physical Laboratory, Teddington UK Royal Holloway, University of London, Egham, UK
121	June 3, 2024	Mr. Trip Thripsuwan	Chiang Mai University, Thailand
122	June 11, 2024	Dr. Lara Faoro	Google Quantum AI, USA
123	June 12, 2024	Dr. Lev Ioffe	Google Quantum AI, USA
124	June 28, 2024	Dr. Patryk Gumann	IBM Quantum, USA
125	July 29, 2024	Dr. Stephen Jordan	Google Quantum AI, USA
126	July 8, 2024	Dr. Sylvain de Léséleuc	RQC, Cold-Atom Quantum System Research Team, Japan
127	July 19, 2024	Dr. Erkka Haapasalo	National University of Singapore
128	August 21, 2024	Mr. András Márton Gunyhó	Department of Applied Physics, Aalto University, Finland
129	August 22, 2024	Prof. Xing Fan	Northwestern University, USA
130	September 13, 2024	Dr. Youngkyu Sung	Atlantic Quantum, USA
131	July 30, 2024	Prof. Alexandre Zagoskin	Department of Physics Loughborough University, UK
132	July 31, 2024	Dr. Po-Chen Kuo	Department of Physics, National Cheng Kung University, Taiwan

No.	Date	Speaker	Affiliation
133	August 2, 2024	Prof. Hossein Sadeghpour	ITAMP- Harvard University, USA
134	August 5, 2024	Dr. Zhengyang Zhou	Zhejiang Sci-Tech University, China
135	August 7, 2024	Prof. Chia-Yi Ju	Department of Physics, National Sun Yat-Sen University, Taiwan
136	August 8, 2024	Prof. Tao Liu	South China University of Technology, School of Physics and Optoelectronics, China
137	August 9, 2024	Prof. Guang-Yin Chen	Dept. of Physics, National Chung Hsing University, Taiwan
138	August 6, 2024	Prof. Keyu Xia	Nanjing University, China
139	August 13, 2024	Prof. Yuran Zhang	School of Physics and Optoelectronics, South China University of Technology, China
140	August 20, 2024	Prof. IoChun Hoi	Department of Physics City University of Hong Kong, China
141	August 14, 2024	Dr. Masanori Hanada	School of Mathematical Sciences, Queen Mary University of London, UK
142	August 15, 2024	Prof. Valentin Freilikher	Bar-Ilan University, Israel
143	August 16, 2024	Prof. Adam Miranowicz	Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poland
144	August 19, 2024	Prof. Ravindra Chhajlany	Solid State Theory Division, Faculty of Physics, Adam Mickiewicz University, Poland
145	August 21, 2024	Prof. Karol Bartkiewicz	Nonlinear Optics Division, Faculty of Physics, Adam Mickiewicz University in Poznań, Poland
146	August 22, 2024	Prof. Peng-Bo Li	School of Physics, Xi'an Jiaotong University, China
147	August 23, 2024	Prof. Lin Zhirong	Shanghai Institute of Microsystem and Information Technology, China
148	August 26, 2024	Prof. Roberto Stassi	University of Messina, Italy
149	August 28, 2024	Prof. Yuxi Liu	Institute of Integrated Nanoelectronics Science, Tsinghua University, China
150	September 4, 2024	Prof. Michał Oszmaniec	Center for Theoretical Physics, Polish Academy of Sciences, Poland

No.	Date	Speaker	Affiliation
151	September 27, 2024	Prof. Eduardo Fradkin	Director, Anthony J. Leggett Institute for Condensed Matter Theory Department of Physics University of Illinois, USA
152	August 27, 2024	Mr. Gerardo Suarez	Director, Anthony J. Leggett Institute for Condensed Matter Theory Department of Physics University of Illinois, USA
153	September 5, 2024	Mr. Riya Baruah	Department of Applied Physics Aalto University, Finland
154	September 17, 2024	Dr. Lirandë Pira	Centre for Quantum Technologies, the National University of Singapore
155	September 18, 2024	Mr. Alberto Del Ángel Medina	Chalmers University of Technology, Sweden
156	September 25, 2024	Prof. Dario Poletti	Chalmers University of Technology, Sweden
157	September 13, 2024	Prof. Roee Ozeri	The Weizmann Institute of Science, Israel
158	September 18, 2024	Mr. Francesco Anna Mele	Scuola Normale Superiore di Pisa, Italy
159	October 10, 2024	Prof. Lincoln Carr	Quantum Engineering Program, Department of Physics, Colorado School of Mines, USA
160	October 11, 2024	Dr. Katiuscia Cassemiro	American Physical Society, USA
161	October 15, 2024	Mr. Kumar Saurav	University of Southern California, USA
162	October 17, 2024	Mr. Maximilian Meyer-Mölleringhof	Uppsala University, Sweden
163	October 31, 2024	Ms. Aziza Almanakly	Massachusetts Institute of Technology, USA
164	November 1, 2024	Mr. Gavin Barclay Crowder	Massachusetts Institute of Technology, USA
165	November 5, 2024	Ms. Sofia Arranz Regidor	Queen’s University, Canada
166	October 23, 2024	Prof. Masaya Nakagawa	The University of Tokyo, Japan
167	October 25, 2024	Prof. Stephen Hughes	The Department of Physics, Engineering Physics & Astronomy, Queen's University, Canada
168	November 19, 2024	Dr. Ulysse Reglade	Alice & Bob, French
169	October 18, 2024	Dr. Kushal Das	Quantum Nanoscience Laboratory School of Physics, Faculty of Science, The University of Sydney, Australia
170	October 30, 2024	Mr. Artem Ryzhov	B. Verkin ILTPE of NASU, Kharkiv, Ukraine

No.	Date	Speaker	Affiliation
171	November 25, 2024	Dr. Sebastian de Graaf	National Physical Laboratory, UK
172	December 6, 2024	Dr. Patrice Bertet	Quantronics Group SPEC/CEA Saclay, French
173	December 6, 2024	Prof. Yangsen Ye	Department of Hefei National Research Center for Physical Sciences at the Microscale and School of Physical Sciences, University of Science and Technology of China
174	November 21, 2024	Mr. Finn Schmolke	Institute for Theoretical Physics I, University of Stuttgart, Germany
175	November 28, 2024	Dr. Kasra Nowrouzi	Advanced Quantum Testbed, Lawrence Berkeley National Laboratory, USA
176	December 24, 2024	Dr. Nana Shumiya	Department of Electrical and Computer Engineering, Princeton University, USA
177	December 9, 2024	Mr. Linus Ekstrom	Honda Research Institute EU, Germany
178	December 27, 2024	Dr. Anton Frisk Kockum	Chalmers University of Technology, Sweden
179	January 17, 2025	Prof. Gabriel Aeppli	ETH Zurich, the Department of Physics, Switzerland
180	February 7, 2025	Dr. Alberto Mercurio	École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
181	January 24, 2025	Prof. Hui Jing	Hunan Normal University, China
182	January 29, 2025	Prof. Lewis Antill	Institute of Quantum Biophysics, Department of Biophysics, Sungkyukwan University, South Korea
183	January 27, 2025	Mr. Alex Chapple	Département de physique, Faculté des sciences, Université de Sherbrooke, Canada
184	January 31, 2025	Dr. Ben Criger	Quantinuum Ltd., USA
185	February 5, 2025	Prof. Mackillo Kira	University of Michigan, USA
186	February 4, 2025	Prof. Steven T. Cundiff	Department of Physics and Quantum Research Institute, University of Michigan, USA
187	March 27, 2024	Prof. Andrei Faraon	William L Valentine Professor of Applied Physics and Electrical Engineering, California Institute of Technology, USA
188	March 31, 2025	Dr. Marcello Dalmonte	International Centre for Theoretical Physics (ICTP), Italy

Collaborations

International

[Europe]

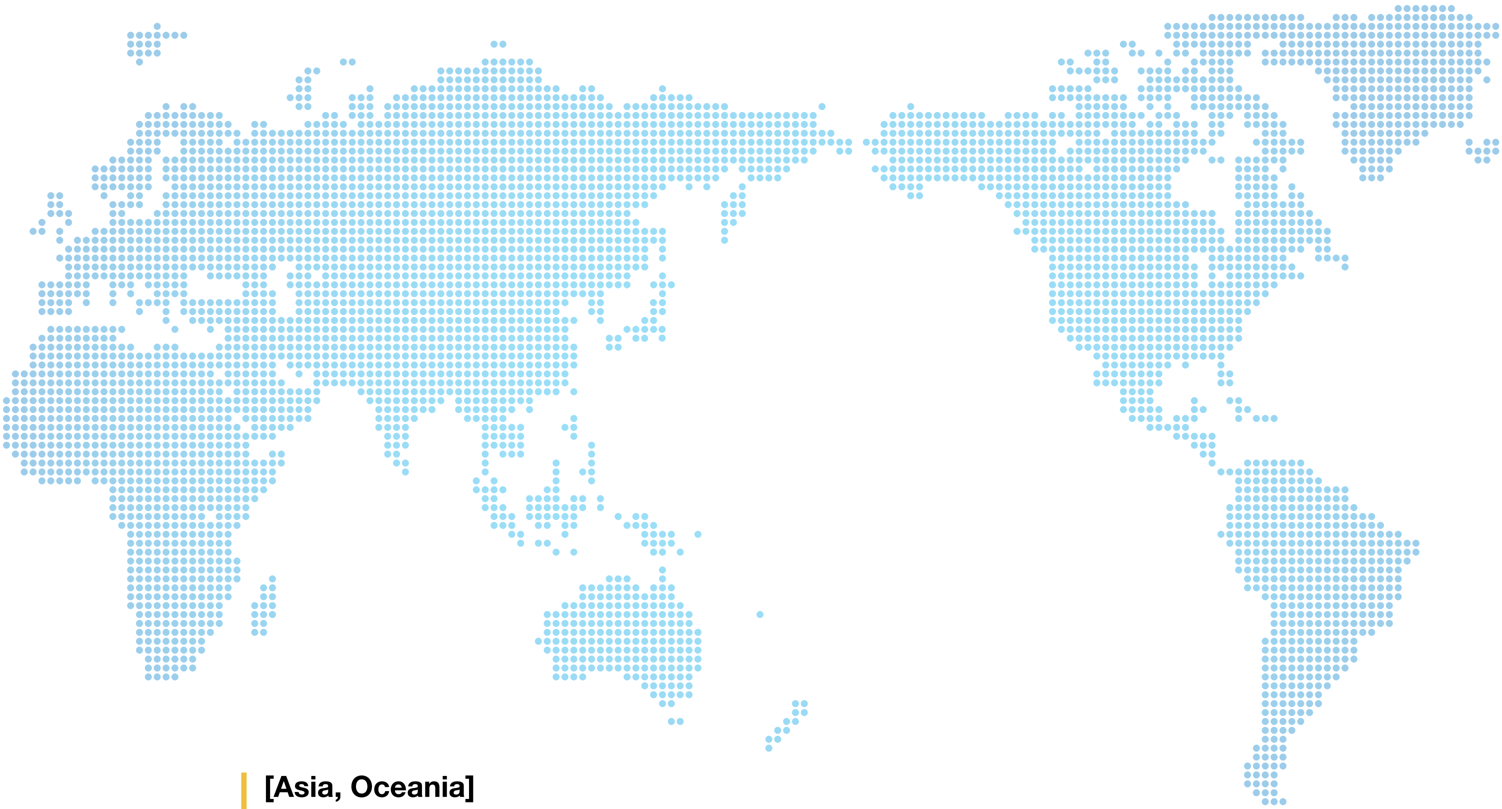
- Aalto University
- B. Verkin ILTPE of NASU
- Chalmers University of Technology
- Delft University of Technology (TU Delft)
- Interuniversity Microelectronics Centre (IMEC)
- Johannes Gutenberg University Mainz
- Kazan Federal University
- Max Planck Institute of Quantum Optics
- Moscow Institute of Physics and Technology (MIPT)
- Palacky University
- Paris-Saclay University
- Stefan Meyer Institute
- Swiss Federal Institute of Technology in Lausanne (EPFL)
- University of Basel
- University of Hamburg
- University of Oxford
- University of Stuttgart
- University of Tübingen
- Walther Meissner Institute (WMI)

etc.

[North America]

- Harvard University
- Intel Corporation
- McGill University
- Massachusetts Institute of Technology (MIT)
- Nord Quantique
- University of California, Berkeley

etc.



[Asia, Oceania]

- Australian National University
- Center for Axion and Precision Physics Research, Institute for Basic Science
- Griffith University
- Hunan Normal University
- Indian Institute of Technology (BHU) Varanasi
- National Chiao Tung University
- National Tsing Hua University (NTHU)
- The University of New South Wales (UNSW)
- University of Technology Sydney (UTS)

etc.

National

[Research Institute]

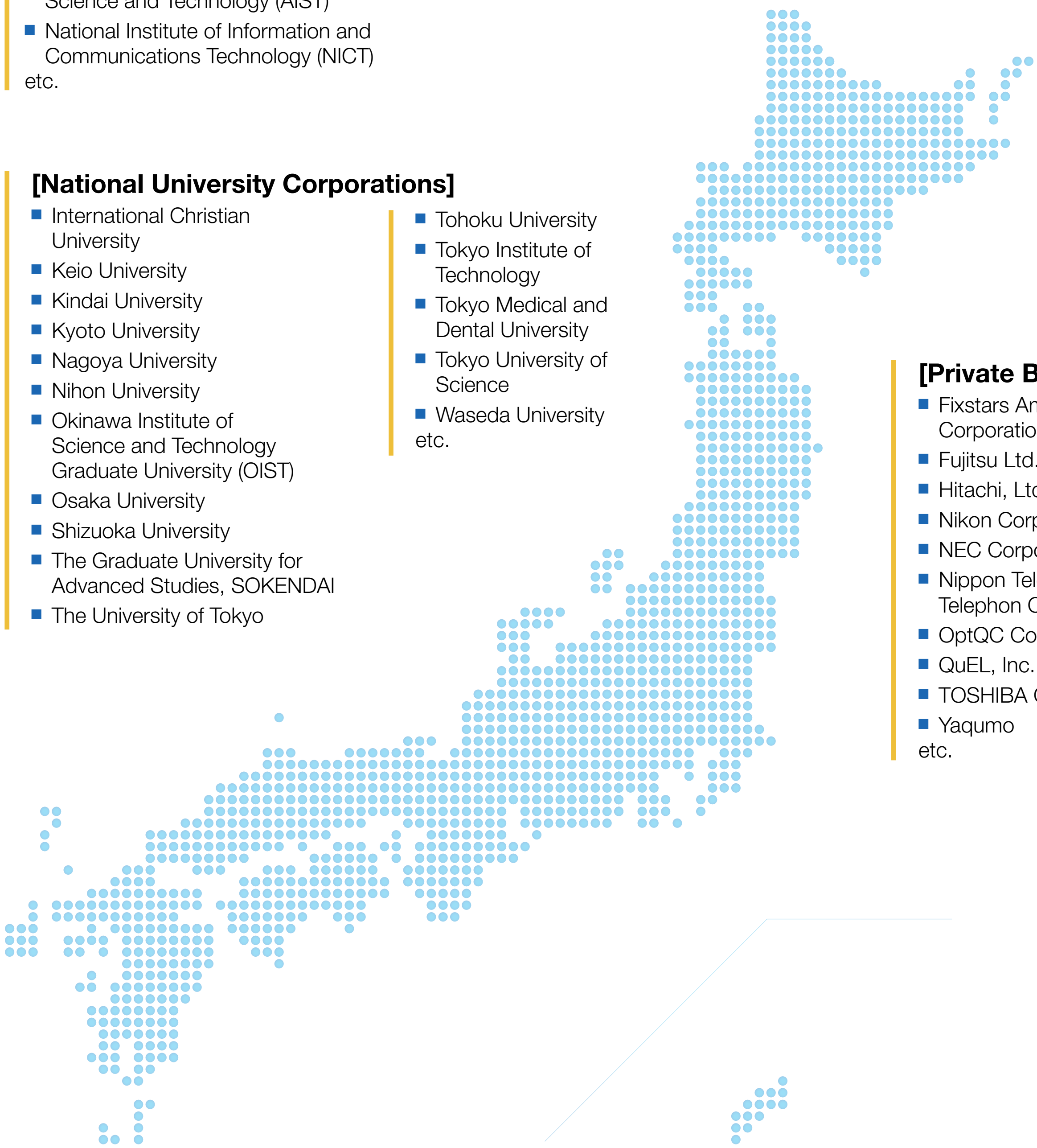
- Institute for Molecular Science (IMS)
- National Institute of Advanced Industrial Science and Technology (AIST)
- National Institute of Information and Communications Technology (NICT)

etc.

[National University Corporations]

- International Christian University
- Keio University
- Kindai University
- Kyoto University
- Nagoya University
- Nihon University
- Okinawa Institute of Science and Technology Graduate University (OIST)
- Osaka University
- Shizuoka University
- The Graduate University for Advanced Studies, SOKENDAI
- The University of Tokyo
- Tohoku University
- Tokyo Institute of Technology
- Tokyo Medical and Dental University
- Tokyo University of Science
- Waseda University

etc.



[Private Business]

- Fixstars Amplify Corporation
- Fujitsu Ltd.
- Hitachi, Ltd.
- Nikon Corporation
- NEC Corporation
- Nippon Telegraph and Telephon Corporation
- OptQC Corp.
- QuEL, Inc.
- TOSHIBA CORPORATION
- Yaqumo

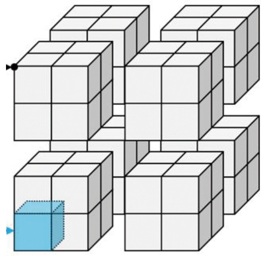
etc.

Press Releases

September 5, 2024

Powerful quantum error correction with a beautiful geometry

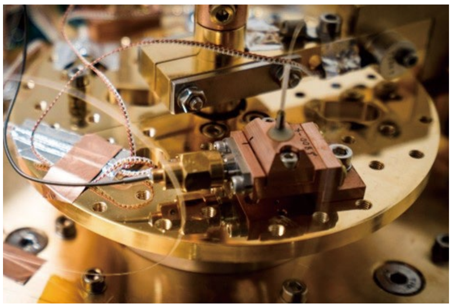
Quantum Computer Architecture Research Team



November 5, 2024

High-speed generation of optical quantum state: Acceleration of optical quantum computers via optical communication technology

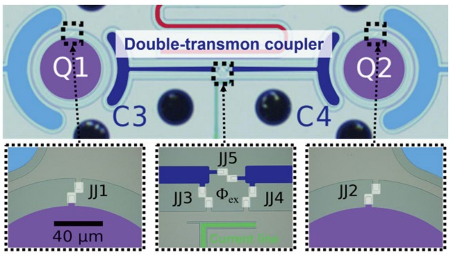
Optical Quantum Computing Research Team



November 22, 2024

Scientists develop novel high-fidelity quantum computing gate

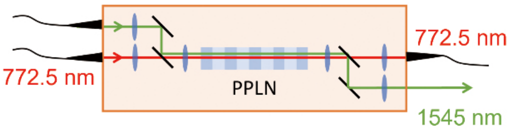
Superconducting Quantum Electronics Research Team



January 30, 2025

Ultra-fast real-time observation of optical quantum entanglement: Pioneering a new era with 1000 times faster quantum entanglement

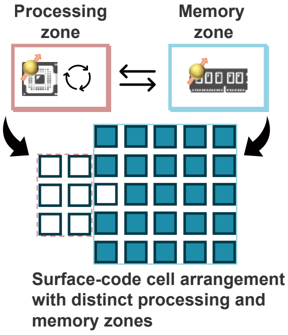
Optical Quantum Computing Research Team



March 4, 2025

New quantum computer architecture with separate memory and processor: Portable memory-efficient design paves the way to practical quantum computation

Superconducting Quantum Computing System Research Unit

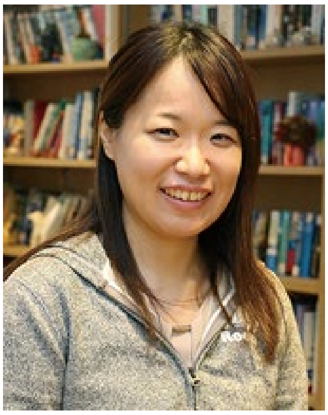


Awards

May 18, 2024

Dr. Erika Kawakami awarded Funai Foundation for Information Technology's Funai Information Technology Award

Dr. Erika Kawakami, RIKEN Hakubi Team Leader of Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team, has been awarded the Funai Foundation for Information Technology's Funai Information Technology Award. This award is presented to young researchers who have achieved outstanding research results in the broad field of science and engineering, centering on the fields of information science and information technology. Dr. Kawakami received the award for her results relating to discerning the quantum state of electrons floating in a vacuum and advancing the realization of quantum computers.



November 19, 2024

Dr. Franco Nori selected as Clarivate Highly Cited Researcher 2024

Dr. Franco Nori, Team Leader of the Quantum Information Physics Theory Research Team, has been selected as a Clarivate Highly Cited Researcher 2024. Clarivate Highly Cited Researchers are selected in each field of research, as the authors of papers that rank in the top 1% based on the number of citations in Clarivate Analytics' Essential Science Indicators database.

March 26, 2025

Special Postdoctoral Researcher Yasushi Yoneta selected for the JSTAT Scientific Directors for the Highlights collection

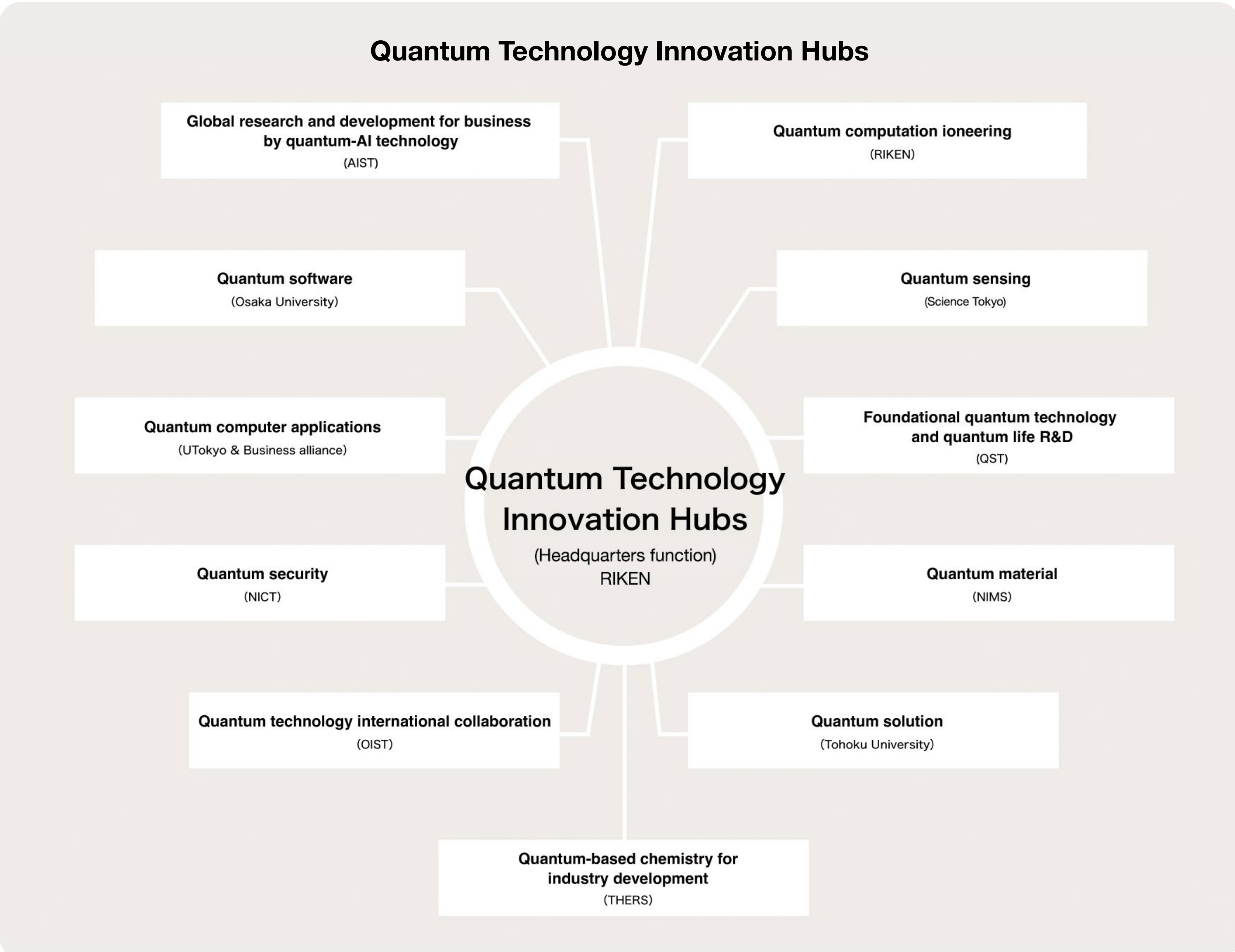
Special Postdoctoral Researcher Yasushi Yoneta of the Quantum Computing Theory Research Team has been selected for the JSTAT Scientific Directors for the Highlights collection. This honor is presented to those whose papers are recognized as particularly insightful and highly useful among research results announced in the field of statistical physics. The title of the paper selected for the collection was "Statistical ensembles for phase coexistence states specified by noncommutative additive observables."

Overview of Quantum Technology Innovation Hubs

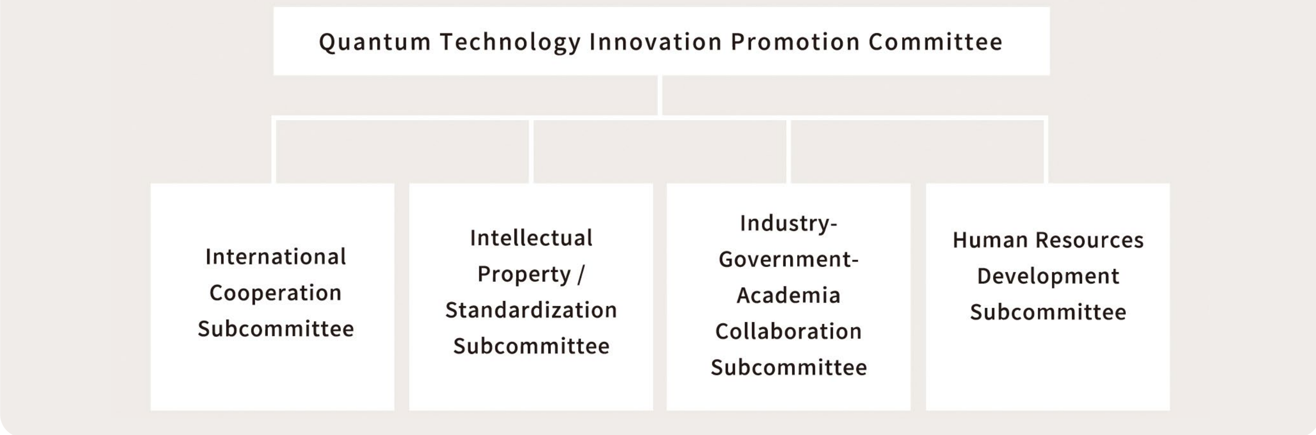
The eleven Quantum Innovation Hubs (QIH), with RIKEN serving as the headquarters, are accelerating the social implementation of quantum technology.

Quantum Innovation Hubs (hereinafter QIH) were established with the aim of strengthening international competitiveness in quantum technology based on government strategies known as the Quantum Technology and Innovation Strategy (January 2020), the Vision of Quantum Future Society (April 2022) and the Strategy of Quantum Future Industry Development (April 2023). They collaborate with academia, industry, and government to engage in activities ranging from basic research on quantum technology to technology verification, intellectual property management, and human resources development.

As the core organization of the QIH, RIKEN performs a headquarters function that strives for coordination among the eleven hubs. At the same time, RIKEN is one of the eleven hubs, and it operates as a quantum computation pioneering hub that carries out research and development of quantum computer systems.



Activities



Subcommittees of the QIH

The QIH established and operate the Quantum Technology Innovation Promotion Committee, which promotes the social implementation of quantum technology and makes proposals for the implementation. It has four subcommittees where the hubs discuss themes of each subcommittee field and share strategies in the field.

- 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: Promotes an increase in the number of young researchers in the quantum field and the strengthening of human resources development across institutions and research fields.

Pick-up Activities in FY2024

Quantum Innovation 2024, an international symposium concerning quantum science and technology innovation, was held in Tokyo from October 21 (Mon.) to 23 (Wed.). During the three-day period, it featured 82 lectures, two panel discussions, and 160 poster presentations. Government officials from nine countries, including Japan, introduced their quantum strategies. 714 people from 23 countries attended the symposium. The symposium provided an opportunity to share a lot of valuable information, and the reception held during the symposium also promoted international exchange. In the poster session, 18 excellent poster presentations won the poster awards for young researchers. The award encourages young researchers.

From Quantum Innovation 2024

The QIH are also focusing on outreach activities, such as summer vacation science events, in order to promote the training and retention of personnel who will lead future quantum technology. Furthermore, the QIH operate the Q-Portal[1], which is a portal site for quantum technology. April 2025 marked two years since the launch of the Q-Portal, and its X[2] account has attracted approximately 2,000 followers.

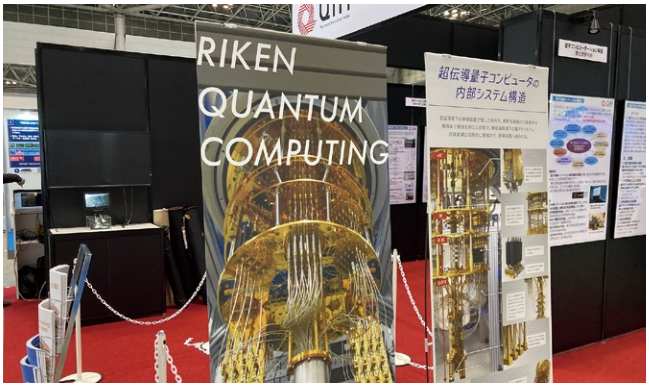
[1] Q-Portal https://q-portal.riken.jp/
[2] Q-Portal's X account https://x.com/Q_Portal_

Overview of Quantum Technology Innovation Hubs (Continued)

Outreach activities in FY2024

Summer vacation event “Explore Quantum Computers through Quizzes and Games!” was held (August 3-5, at Miraikan)

A quantum computer VR was exhibited in Science Agora (October 26-27, at the Telecom Center Building)



Exhibited at nano tech 2025 (January 29-31, at Tokyo Big Sight)

Exhibited at pre-event held for Expo 2025 Osaka, Kansai, Japan (March 23, in Shibuya)

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

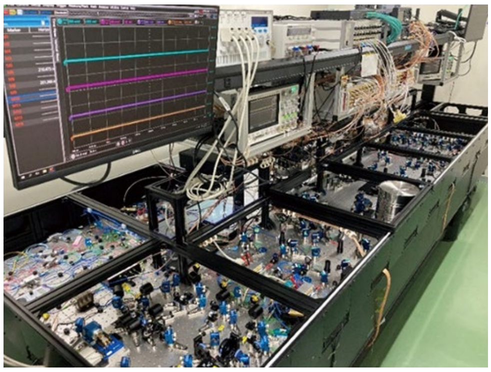
1990 B.S. in Information Science, The University of Tokyo
1992 M.S. in Information Science, The University of Tokyo
1992 Researcher, C&C Systems Research Laboratories, NEC Corporation
1999 Visiting Researcher, Imperial College
2004 Principal Researcher, Internet System Research Laboratories, NEC Corporation
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 engaged in work of the headquarters of QIH as a coordinator.

RQC FY2024 Pick-up Topics

New type of quantum computer realized
–World’s first platform for general-purpose optical quantum computer begins operating–

On November 8, 2024 a joint research group comprising the Optical Quantum Computing Research Team, the Optical Quantum Control Research Team, Nippon Telegraph and Telephone Corporation, and Fixstars Amplify Corporation succeeded in developing a new type of quantum computer. The optical quantum computer developed by the group adopts a cloud-based system, allowing it to be accessed and used via the Internet. For the time being, use of the computer will be through a joint research agreement, but going forward it is anticipated that it will contribute to expanding the use of domestic quantum computing platforms, creating use cases (utilization methods) for quantum computers, and advancing the domestic quantum industry as well as enhancing its international competitiveness.

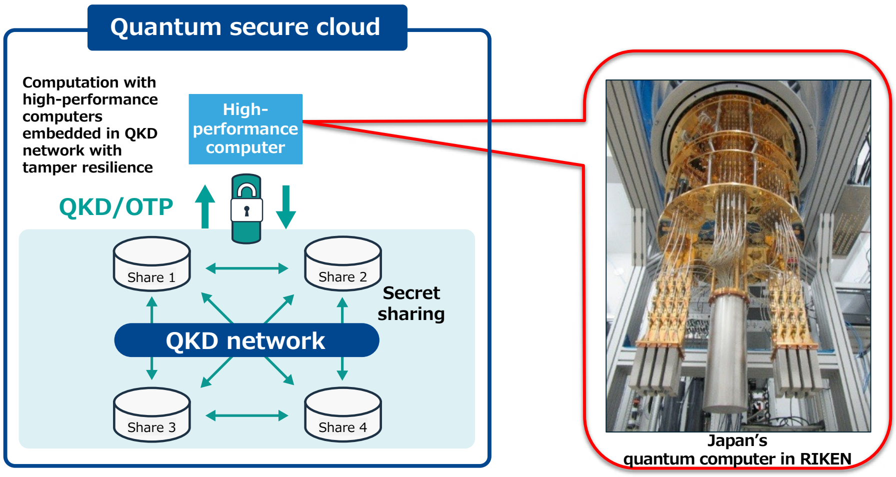


Optical quantum computer (actual machine)

Integration of quantum secure cloud and quantum computer successfully verified
–Safe transmission and storage of high-value-added information generated by quantum computer verified–

On March 13, 2025 the quantum secure cloud that the National Institute of Information and Communications Technology (NICT) has put in place and is moving ahead with researching, developing, and operating was connected to a domestic gate-type quantum computer that RQC had a central role in developing, thus constructing an interconnected environment enabling the safe utilization of the domestic gate-type quantum computer. The quantum cloud users were able to use and apply the domestic quantum computer’s functions, and the ability to safely transmit and store the generated data was verified.

RQC’s superconducting quantum computer being operated from Tokyo QKD Network at NICT, where a quantum secure cloud has been built



Integration of NICT’s quantum secure cloud (left) and RIKEN’s quantum computer (right)

Technology transfer of a superconducting quantum computer achieved

The RIKEN RQC-FUJITSU Collaboration Center was established in April 2021 and has been undertaking joint research aimed at scaling-up superconducting quantum computers. A computer system that Fujitsu has put into practical use by utilizing technology cultivated by the Collaboration Center is scheduled to be operated by the Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT) of the National Institute of Advanced Industrial Science and Technology (AIST) in early 2025. This is the first time that a domestic vendor has received an order for a commercial quantum computer system, indicating that the technology transfer of a superconducting quantum computer has been achieved.

Superconducting Quantum Electronics Research Team

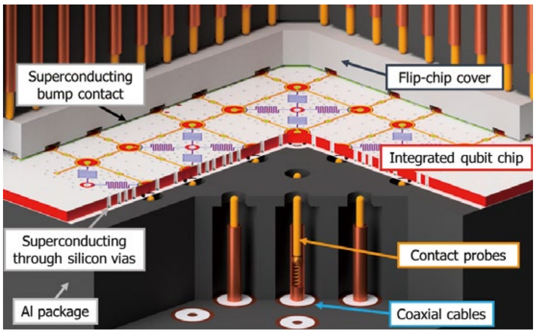
Keywords: Quantum computing, Superconducting circuits, Josephson junction, Microwave quantum optics, Circuit quantum electrodynamics

Research Outline

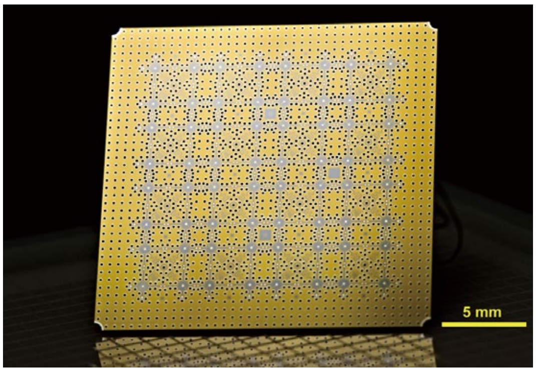
Our team, in collaboration with other teams in RQC as well as collaborators outside RIKEN, is conducting research and development on superconducting quantum circuits for quantum computing and other quantum technologies. Currently, our focus is on the development of a superconducting quantum computing platform with integrated qubits. As a scalable implementation of qubits on a chip, we propose architecture that implements fixed-frequency transmon qubits in a two-dimensional array on a Si wafer with superconducting through silicon vias where the microwave control signal is introduced from the backside of the chip. We are developing the superconducting quantum computer with more than 100 qubits and setting up dilution refrigerators and software for the control electronics. The automation of the measurements and benchmarking is also part of the focus of our research.

We are also developing underlying technologies to improve the quality of qubit operations. Our research focus is on the gate and readout schemes that are compatible with the qubit integration, including two-qubit gates with small residual coupling and high-speed multiplexed readout. We are also developing quantum-limited amplifiers, especially traveling wave Josephson parametric amplifiers, which are essential for multiplex readout of superconducting qubits.

Through those activities, we deepen our understanding of quantum computers further and master superconducting quantum electronics, which we believe leads us to the 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 Director

Selected Publications

1 R. Li, K. Kubo, Y. Ho, Z. Yan, Y. Nakamura, and H. Goto, “Realization of high-fidelity CZ gate based on a double-transmon coupler”, *Phys. Rev. X* 14, 041050 (2024).
2 Y. Sunada, K. Yuki, Z. Wang, T. Miyamura, J. Ilves, K. Matsuura, P. A. Spring, S. Tamate, S. Kono, and Y. Nakamura, “Photon-noise-tolerant dispersive readout of a superconducting qubit using a nonlinear Purcell filter”, *PRX Quantum* 5, 010307 (2024).
3 Y. Sunada, S. Kono, J. Ilves, S. Tamate, T. Sugiyama, Y. Tabuchi, and Y. Nakamura, “Fast readout and reset of a superconducting qubit coupled to a resonator with an intrinsic Purcell filter”, *Phys. Rev. Applied* 17, 044016 (2022). Editors’ Suggestion
4 N. Gheeraert, S. Kono, and Y. Nakamura, “Programmable directional emitter and receiver of itinerant microwave photons in a waveguide”, *Phys. Rev. A* 102, 053720 (2020).
5 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).

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)
2007 Research Fellow, Nanoelectronics Research Laboratories, NEC Corporation
2010 Research Fellow, Green Innovation 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

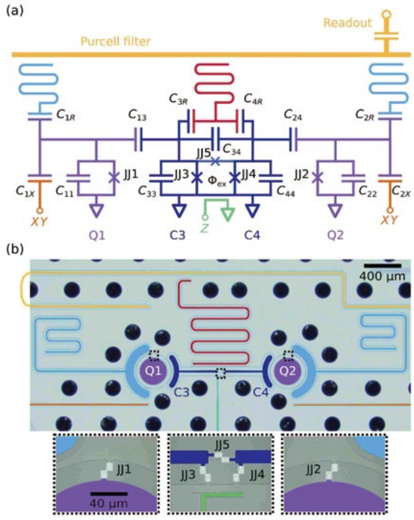
Realization of high-fidelity two-qubit gate based on a double-transmon tunable coupler

A superconducting quantum computer is implemented by multiple qubits being connected in a two-dimensional lattice. One of the important challenges is to implement a high-fidelity two-qubit gate while suppressing the residual interaction when the operation is not performed. In other words, it is essential to implement a high on-off ratio interaction with minimal circuit elements toward the integration of the qubits.

We realized a ZZ interaction with more than 10^4 on-off ratio between the fixed frequency qubits by introducing a double-transmon coupler, which is composed of coupled frequency-tunable qubits. We also implemented a two-qubit gate by using the ZZ interaction and achieved 99.9% fidelity after optimizing the pulse shape based on reinforcement learning.

By using the proposed method, we can adopt fixed-frequency qubits that have relatively longer coherence time as data qubits. The requirement for the frequency detuning between the data qubits can also be relaxed, which is favorable for the large-scale integration.

R. Li *et al.*, "Realization of high-fidelity CZ gate based on a double-transmon coupler", Phys. Rev. X 14, 041050 (2024).



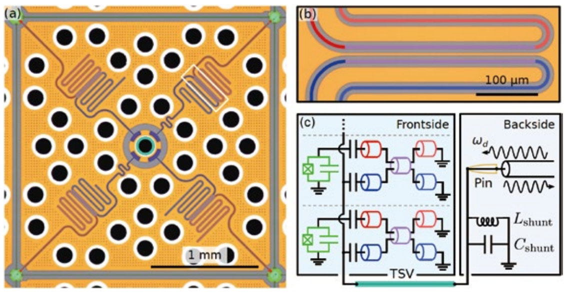
(a) Schematic circuit diagram of the double-transmon-coupler scheme. (b) False-color picture of the device. The colors correspond to the circuit elements in (a).

Fast, high-fidelity frequency-multiplexed readout of superconducting qubits

Fast and high-fidelity readout of superconducting qubits is one of the important challenges toward realization of fault-tolerant quantum computers. To achieve the fast dispersive readout of superconducting qubits, we need to increase the coupling between the qubit and the readout resonator as well as the coupling between the readout resonator and the readout line. On the other hand, the increased coupling to the external readout line induces decoherence of the qubits. To protect the qubit from decoherence, the so-called Purcell filter is essential to prevent the microwave signal of the qubit frequency leaking out to the readout line. As implementation of high-performance Purcell filter requires relatively larger circuit footprint, it is difficult to make it compatible with the integration of qubits.

We proposed the implementation of the intrinsic Purcell filter by utilizing the coupling circuitry between readout and filter coplanar resonators as an additional notch filter circuit. The implementation provides high enough suppression of qubit decay with minimal circuit footprint. As a result, we achieved the multiplex readout of four superconducting qubits with the low average error rate of 0.23% in a short integration time of 56 ns.

P.A. Spring *et al.*, "Fast multiplexed superconducting-qubit readout with intrinsic Purcell filtering using a multiconductor transmission line", PRX Quantum 6, 020347 (2025).



(a) False-color picture of the device for 4-qubit multiplexed readout (b) Intrinsic filter structure between readout and filter resonators (c) Circuit schematic of the multiplexed readout. The frontside filter resonators are connected to the backside coaxial cable by the through-silicon via placed at the center of the figure (a).

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**
(Postdoctoral Researcher) **Peter Anthony Spring**
(Postdoctoral Researcher) **Arvind Mamgain**
(Senior Technical Staff) **Koichi Kusuyama**
(Senior Technical Staff) **Hikota Akimoto**
(Technical Staff I) **Laszlo Szikszai**
(Technical Staff I) **Harumi Hayakawa**
(Technical Staff I) **Yuji Sakoda**
(Technical Staff I) **Machie Kaito**
(Technical Staff I) **Koki Muto**

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.

Bosonic code, which is relatively easy to correct errors in quantum computers, protects quantum information from errors by taking advantage of the infinite number of degrees of freedom of the resonator. We are conducting research on Cat Qubit, which realizes Cat code, which is one of the practical bosonic codes, using a car parametric oscillator (KPO) using superconducting circuits. By generating a cat state with a two-dimensional KPO circuit (Fig 1 and 2) and evaluating the fidelity using a quantum tomography method, we succeeded in realizing a universal quantum gate that can operate 1-bit and 2-bit gates.

In the 2-bit circuit, we used the unique properties of KPO to generate an entangled cat state in two ways. The first method is to convert the entangled state (bell state) based on the Fock state to the entangled cat state. In the second method, a $\sqrt{\text{iSWAP}}$ gate is added to two independent cat states to create an entangled cat state.

These results indicate that the planar superconducting KPO circuit successfully developed in this study has the potential to become a new platform of scalable quantum information processing.

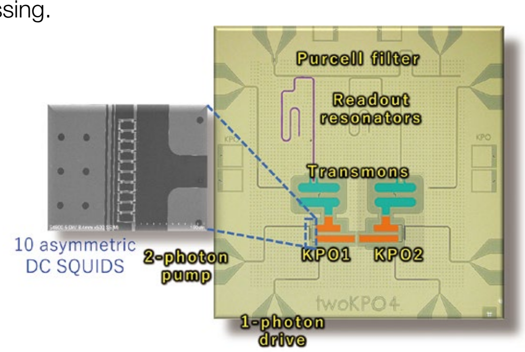


Fig 1. Chip photo of 2D KPO circuit. It contains two coupled KPOs.

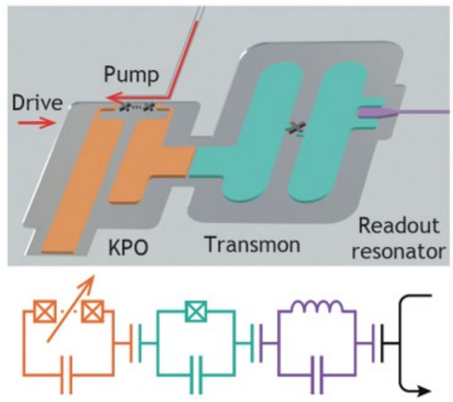
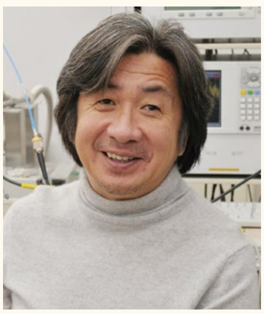


Fig 2. Schematic diagram and equivalent circuit of a 1-bit KPO. Ancilla transmon was used for readout.



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

Selected Publications

1 D. Hoshi, T. Nagase, S. Kwon, D. Iyama, T. Kamiya, S. Fujii, H. Mukai, S. Ahmed, A. F. Kockum, S. Watabe, F. Yoshihara and J. S. Tsai, "Entangling Schrödinger's cat states by bridging discrete- and continuous-variable encoding", *Nature Communications*, 16, 1309 (2025).
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).

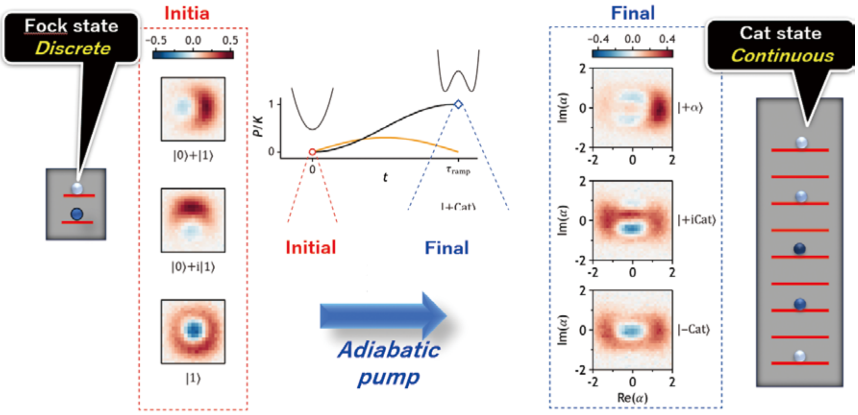
Brief resume

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 (-present)
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

Conversion from a discrete variable quantum state (Fock state) to a continuous variable quantum state (Cat state)

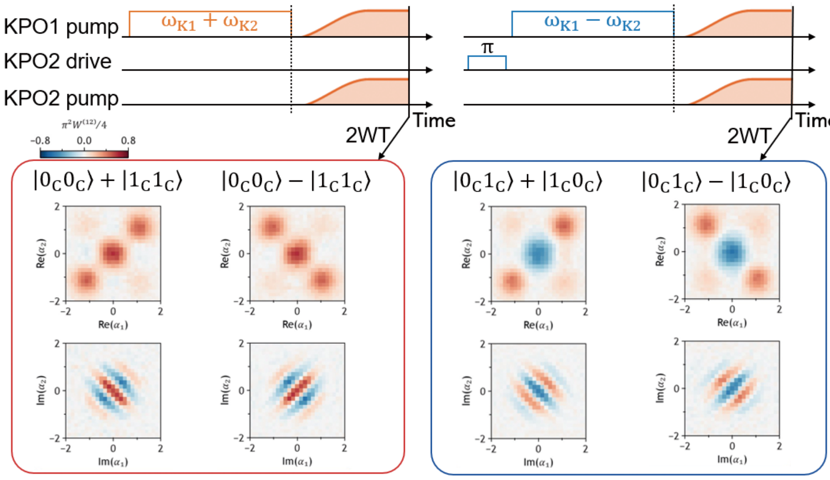
By adiabatic two-photon pumping of superconducting KPO qubits, it is possible to freely convert from the Fock state, which is an arbitrary discrete variable quantum state, to the Cat state, which is a continuous variable quantum state. By pumping discrete variable quantum states, many microwave photons are injected into the KPO qubits, causing them to interfere and create the Cat state. In the figure below, the experimental results of the Cat state obtained as a result of pumping three types of Fock states are shown as a typical example. The quantum state is the result of Wigner tomography. From top to bottom: The state of |+a>, which is a continuous variable quantum state, is created by adiabatic pumping the Fock state of |0> +|1>. Adiabatic pumping of Fock state |0> + i|1> creates the |+iCat> state, which is a continuous variable quantum state. By adiabatic pumping the Fock state of |1>, the continuous variable quantum state |-Cat> state is created. The estimate of the fidelity of the final state was generally around 0.8.



Converting a Fock State to a Cat State

2-KPO gate: Bell-Cat state generation

Two coupled superconducting KPO qubits can be controlled using the sum frequency pulse and the difference frequency pulse of the two KPOs to create an arbitrarily entangled Bell-Fock state. By adiabatic two-photon pumping of this Bell-Fock state, we succeeded in generating various entangled Bell-Cat states corresponding to it. The figure shows the results of joint Wigner tomography of the pulse sequence used in the experiment and the final entangled Bell-Cat state. This experiment shows that all combinations of Bell-Cat states were generated. The interference fringes in imaginary space of the joint Wigner tomography in the lower row indicate that the two KPOs are entangled. The estimate of the fidelity of the final state of this 2-bit KPO operation was approximately 0.6.



Pulse sequence of Bell-Cat state generation and joint Wigner tomography results.

Core members

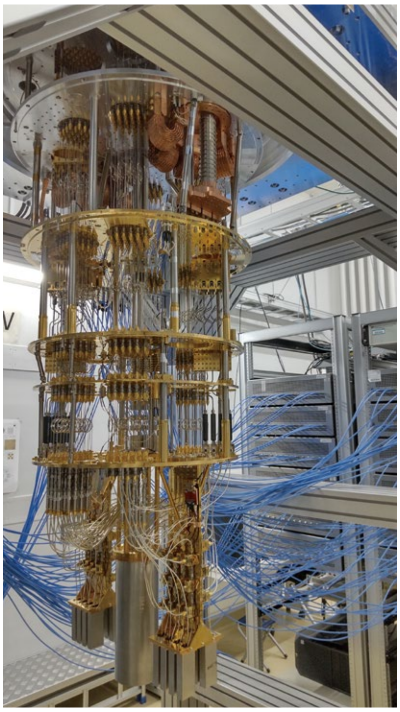
(Postdoctoral Researcher) **Hang Xue**

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 have built a 64-qubit superconducting quantum computer named “A,” and started testing a 144-qubit system. We aim to improve the fabrication yield and uniformity of qubit chips as well as extending the coherence times of the qubits. We also 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, implement a proof-of-principle experiment of quantum error correction, and simulate many-body quantum systems, using our quantum computer. 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 large-scale quantum error correction, and to bring a quantum computer that executes computations intractable with classical computers closer to reality.



64-qubit superconducting quantum computer “A”

Eisuke Abe (D.Sci.), Unit Leader

Selected Publications

1 K. Ishibashi *et al.*, “Research on Quantum Materials and Quantum Technology at RIKEN”, *ACS Nano* 19, 12427 (2025).
2 K. Sasaki and E. Abe, “Suppression of Pulsed Dynamic Nuclear Polarization by Many-Body Spin Dynamics”, *Physical Review Letters* 132, 106904 (2024).
3 E. Abe, “Superconducting route to quantum computing”, Proceeding of 2023 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), P.1–4 (2023).
4 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).
5 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).

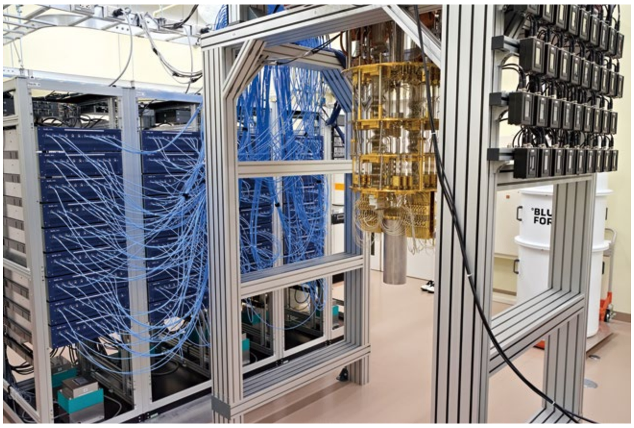
Brief resume

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)

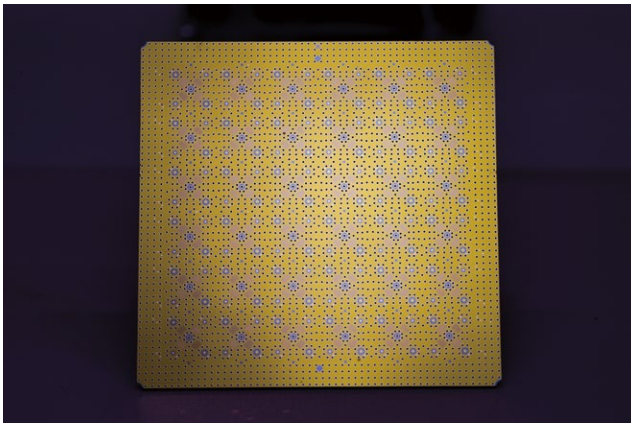
Recent Achievements

Development of a 144-qubit superconducting quantum computing system

A salient feature of the tileable square-lattice qubit design with coaxial cables for qubit control and readout addressing the backside of the chip from the vertical direction, which has been adopted in the 64-qubit superconducting quantum computer “A,” is its natural extendibility to larger systems. We have developed a new system consisting of 144 qubits in the form of a 12-by-12 square lattice. Key differences from the previous system are that (1) qubit frequencies have been lowered from the 8-GHz range to the 5-GHz range, (2) adoption of high-density coaxial wiring technology to accommodate the required number of cables while still keeping the fridge size, and (3) development of Josephson traveling wave parametric amplifiers with over 20 dB gain and over 5-GHz bandwidth for the first-stage output signal amplification. We have finished the construction of the hardware and started testing the performance of the qubit chip.



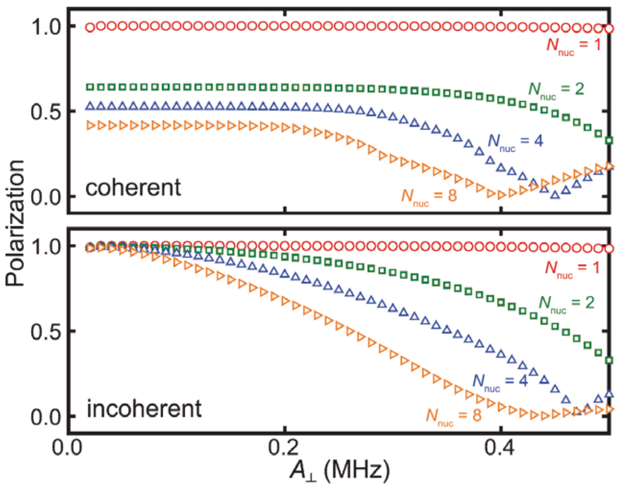
144-qubit superconducting quantum computing system



144-qubit chip

Suppression of pulsed dynamic nuclear polarization by many-body spin dynamics

The initialization of qubits is the first step of quantum control in any physical system. Nuclear spin systems, with weak interactions with their environments and small Zeeman splitting under the magnetic fields, exhibit notoriously small initialization fidelities (spin polarization). Recently, pulsed dynamic nuclear polarization (DNP) methods, in which the electron-nuclear spin interaction is engineered via a microwave pulse sequence to improve the nuclear polarization, has attracted attention. In this work, we reveal that, in a system with multiple nuclear spins with negligible spin-spin interactions and longitudinal relaxation, there exists a mechanism that suppresses the polarization achievable by pulsed DNP via higher-order nuclear spin dynamics mediated by an electron spin, using analytical and numerical calculations. The formation of a dark state is a well-known phenomenon whereby nuclear polarization is suppressed by a many-body effect, but we discuss under a certain condition higher-order effect cooperatively suppress the polarization. This work highlights the importance of taking the higher-order many-body effect into account when designing control sequences of nuclear spin systems.



Numerical simulation of nuclear spin polarization as a function of the hyperfine interaction strength ($A_\perp$) and the number of nuclear spins (N_{nuc}). The increase in both the hyperfine interaction strength and the number of nuclear spins results in suppressed polarization. The upper (lower) figure takes (does not take) into account the formation of the nuclear spin dark state.

https://doi.org/10.1103/PhysRevLett.132.106904

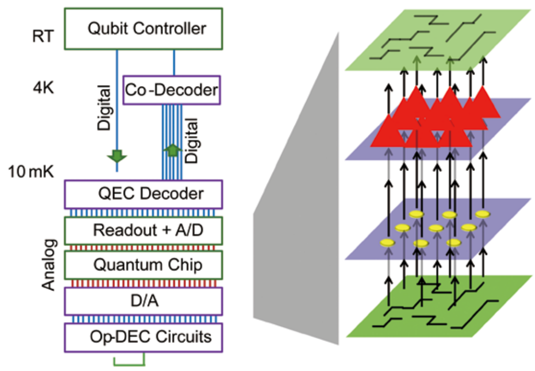
Superconducting Quantum Computing System Research Unit

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

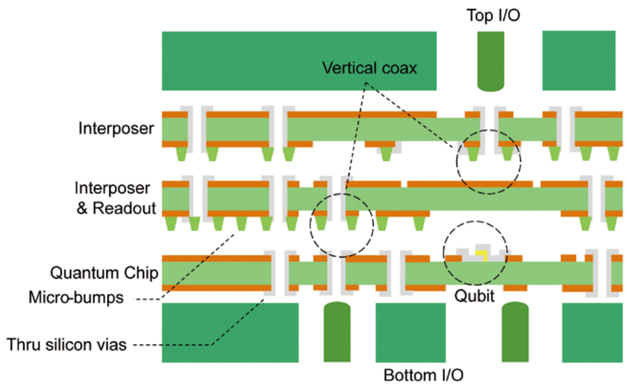
Research Outline

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 possibilities 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, S. Imamura, Y. Tomida, T. Tanimoto, M. Tanaka, Y. Tabuchi, K. Inoue, H. Nakamura, C3-VQA: Cryogenic counter-based co-processor for variational quantum algorithms, *IEEE Transactions on Quantum Engineering* 6, 1-17 (2025).
2 T. Kobori, Y. Suzuki, Y. Ueno, T. Tanimoto, S. Todo, Y. Tokunaga, LSQCA: Resource-efficient load/store architecture for limited-scale fault-tolerant quantum computing, 2025 IEEE International Symposium on High Performance Computer Architecture (HPCA), 304-320 (2025).
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).

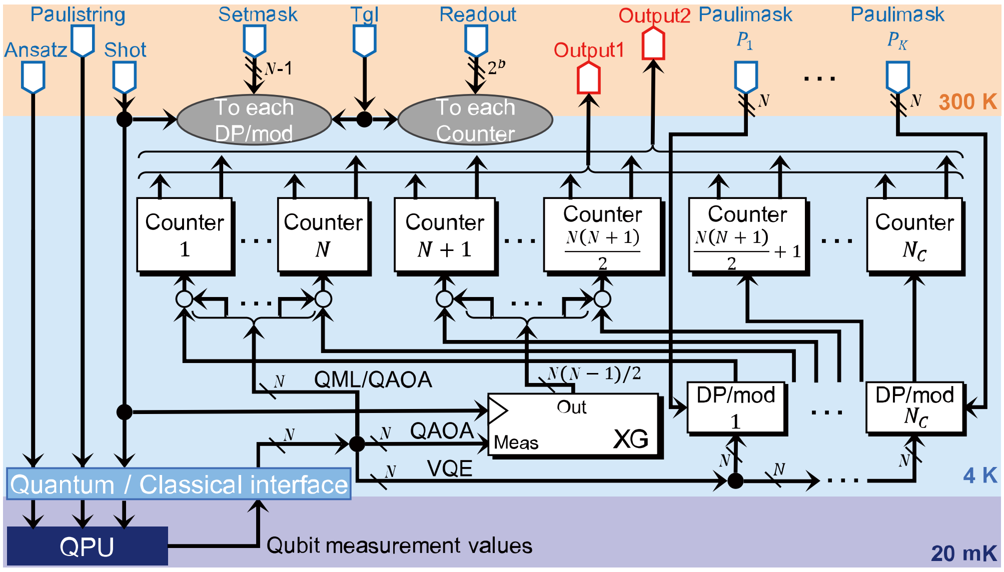
Brief resume

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

C3-VQA: Cryogenic counter-based co-processor for variational quantum algorithms

Cryogenic quantum computers, crucial for demonstrating quantum advantage, face scalability challenges due to cooling limitations. Heat from wires and component power in the cryostat demands the number of wires and inter-temperature signal bandwidth without raising internal power consumption. We demonstrate near-data processing with ultra-low-power logic within the cryostat. The cryogenic counter-based co-processor for variational quantum algorithms (C3-VQA) utilizes single-flux-quantum logic circuits located at 4 Kelvin to pre-calculate expectation values and buffer intermediate data, significantly lowering inter-temperature bandwidth with minimal added power. Evaluations show C3-VQA reduces heat dissipation at 4 K by 30% (sequential) and 81% (parallel). This paper was published in IEEE Transactions on Quantum Engineering.



Counter circuit composed of single-flux-quantum circuits plated at the 4 Kelvin stage.

System improvement of fixed-frequency transmon superconducting quantum computers

In the system improvement towards the practical application of superconducting quantum computers, noise associated with quantum gates poses a significant challenge. Achieving the error rate of 10^{-3} or less while maintaining scalability, which is necessary for quantum error correction, requires further research of system design. The challenge with parametrically activated two-qubit gates is the increased error rate caused by unwanted Floquet sidebands generated by microwave drive acting on neighboring qubits. This issue is particularly significant for fixed-frequency qubits where we are faced with taking fabrication variation of qubit resonance frequency into account.

This research focuses on the unwanted sidebands specific to parametrically driven quantum gates and precisely simulates their frequencies. Furthermore, it investigates the optimal frequency configuration to address the frequency variations among qubits. By leveraging the arbitrariness of the driving frequency inherent in microwave-induced ZZ interaction, we demonstrate that selecting the optimal frequency can suppress non-adiabatic transitions such as incoherent leakage. Moreover, a high yield is anticipated in a 100-qubit scale quantum computer. These research findings were reported at the March Meeting of the American Physical Society in 2025.

Core members

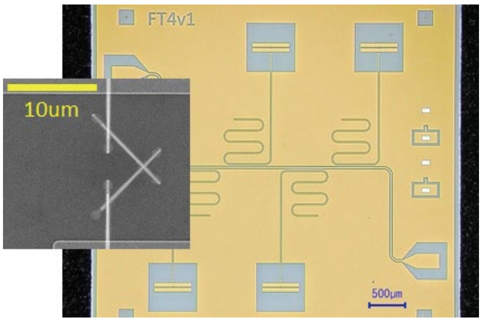
(Special Postdoctoral Researchers) **Yosuke Ueno**
(Technical Staff) **Bunpei Masaoka**
(Technical Staff) **Miyuki Ozawa**

Hybrid Quantum Circuits Research Team

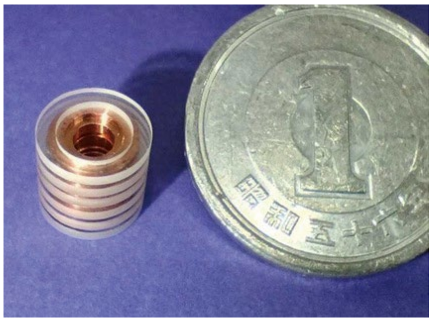
Keywords: Hybrid quantum systems, Microwave quantum optics, Electron trap, Quantum manipulations

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.



Compact electron trap electrode for realization of qubits

Atsushi Noguchi (Ph.D.), Team Director

Selected Publications

1 Y. Tsuchimoto, I. Nakamura, S. Shirai, and A. Noguchi, “Superconducting surface trap chips for microwave-driven trapped ions”, *EPJ Quantum Technology* 11, 56 (2024).
2 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”, *Phys. Rev. Lett*. 130, 260601 (2023).
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

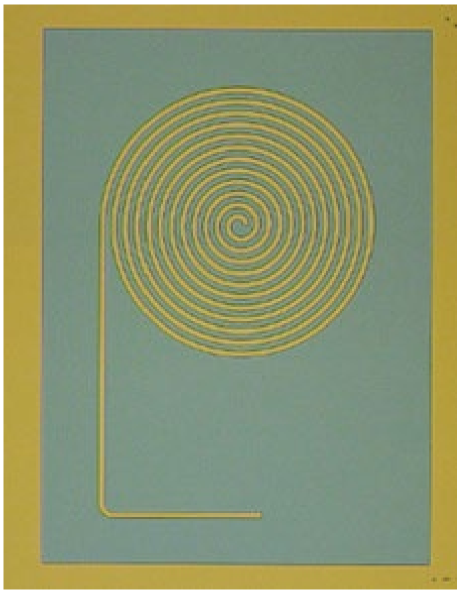
2013 Postdoc researcher, Osaka University
2014 Postdoc researcher, RCAST, The University of Tokyo
2015 Postdoc researcher, RCAST, The University of Tokyo
2015 Project Associate, RCAST, The University of Tokyo (-2018)
2016 Researcher, JST PREST (-2019)
2019 Associate Professor, Graduate School of Arts 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

Enhancing intrinsic quality factors approaching 10 million in superconducting planar resonators via spiral geometry

Superconducting resonators are used to read out superconducting qubits and as host quantum systems in the bosonic coding. They are also utilized as circuits for controlling and reading out other physical systems such as trapped ions and trapped electrons. The performance of the quantum functionalities of these superconducting resonators is limited by the Q factor of the resonator. Two-dimensional superconducting circuits with coplanar waveguide structures have been mainly utilized so far. These studies have pointed out that losses are concentrated at the interface between superconducting film, substrate, and other. In this study, we focused on a new superconducting resonator with a spiral structure and found that this structure reduces the concentration of the electric field at the interface. We were fabricating samples using titanium nitride thin films on the silicon substrates and found that spiral resonators have a higher Q factor compared to coplanar resonators. The Q factor in single-photon intensity reached 10,000,000, the highest Q-value in the world for a two-dimensional integrated circuit.

[1] Yusuke Tominaga, Shotaro Shirai, Yuji Hishida, Hirotaka Terai, and Atsushi Noguchi, arXiv:2502.17901 (2025).

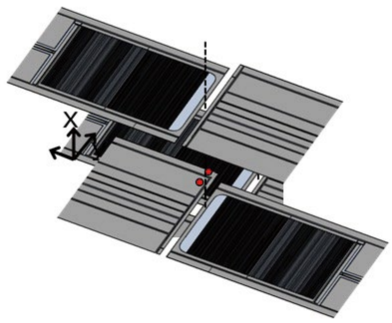


Microscope image of the superconducting spiral resonator.

Superconducting surface trap chips for microwave-driven trapped ions

Ion trap quantum computers have attracted much attention due to high-fidelity quantum gate using lasers. Toward even higher fidelity, oscillating magnetic field gradients instead of lasers have recently been investigated for the control of ions. Currently, the world's highest performance two-qubit gate in ion trapping is based on RF magnetic field gradients. On the other hand, this gate method requires a very large RF intensity, which poses a challenge to scalability. Also, it is known that even higher accuracy requires a larger magnetic field gradient, which causes thermal problems. We have succeeded in fabricating a microwave resonator with a Q factor of about 100,000, which generates the same magnetic field gradient as for the previous quantum gate with 1,000 times smaller RF input power.

[1] Yuta Tsuchimoto, Ippei Nakamura, Shotaro Shirai, and Atsushi Noguchi, EPJ Quantum Technology 11, 56 (2024).



Ion trap electrode with integrated superconducting microwave resonators. A microwave magnetic field gradient amplified by a pair of superconducting microwave resonators is irradiated to the ions.

Core members

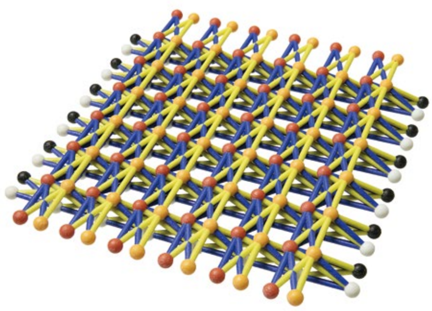
(Special Postdoctoral Researcher) **Ryo Sasaki**
(Postdoctoral Researcher) **Yusuke Tominaga**
(Postdoctoral Researcher) **Shotaro Shirai**
(Postdoctoral Researcher) **Markus Fleck**

Optical Quantum Computing Research Team

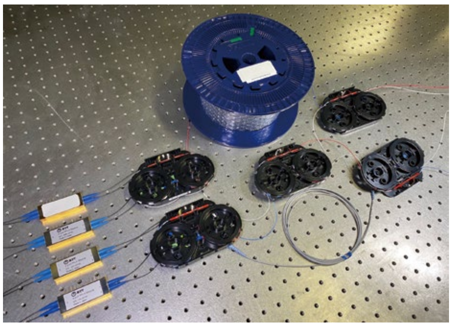
Keywords: Quantum information science, Quantum optics

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.



Graph of large-scale entangled states for quantum computation



Simplified optical setup to create large-scale entangled states

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

Selected Publications

1. A. Kawasaki, H. Brunel, R. Ide, T. Suzuki, T. Kashiwazaki, A. Inoue, T. Umeki, T. Yamashima, A. Sakaguchi, K. Takase, M. Endo, W. Asavanant, and A. Furusawa, “Real-time observation of picosecond-timescale optical quantum entanglement toward ultrafast quantum information processing”, *Nature Photonics* 19, 271–276 (2025).
2. A. Kawasaki, R. Ide, H. Brunel, T. Suzuki, R. Nehra, K. Nakashima, T. Kashiwazaki, A. Inoue, T. Umeki, F. China, M. Yabuno, S. Miki, H. Terai, T. Yamashima, A. Sakaguchi, K. Takase, M. Endo, W. Asavanant, and A. Furusawa, “Broadband generation and tomography of non-Gaussian states for ultra-fast optical quantum processors”, *Nature Communications* 15, 9075 (2024).
3. S. Konno, W. Asavanant, F. Hanamura, H. Nagayoshi, K. Fukui, A. Sakaguchi, R. Ide, F. China, M. Yabuno, S. Miki, H. Terai, K. Takase, M. Endo, P. Marek, R. Filip, P. van Loock, and A. Furusawa, “Logical states for fault-tolerant quantum computation with propagating light”, *Science* 383, 6680 (2024).
4. A. Sakaguchi, S. Konno, F. Hanamura, W. Asavanant, K. Takase, H. Ogawa, P. Marek, R. Filip, J. Yoshikawa, E. Huntington, H. Yonezawa, and A. Furusawa, “Nonlinear feedforward enabling quantum computation”, *Nature Communications* 14, 3817 (2023).
5. 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).

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
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)
2024 Director of OptQC

Recent Achievements

Launch of a general-purpose optical quantum computing platform

The platform for general-purpose optical quantum computation has been successfully developed. Optical quantum computers are advantageous in speed and large scale. Our optical quantum computer is a measurement-based continuous-variable quantum computer employing the time-domain multiplexing technique. The devices to generate broadband quantum light were provided by NTT Device Technology Laboratories, and the cloud system was developed in cooperation with Fixstars Amplify Corp. The actual optical quantum computer located in RIKEN is connected to the cloud. The user sends his/her quantum circuit design and receives the execution results via the cloud.

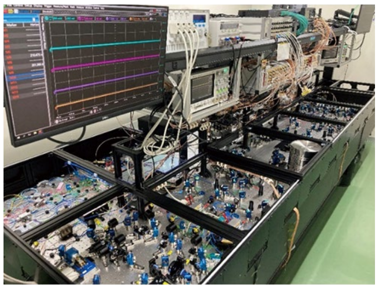
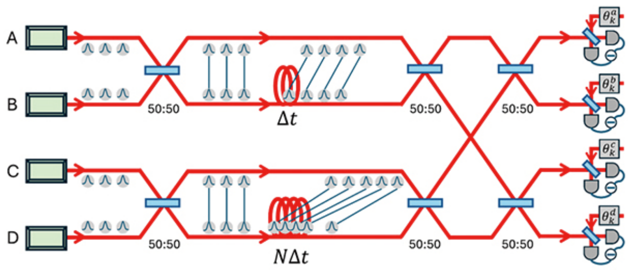


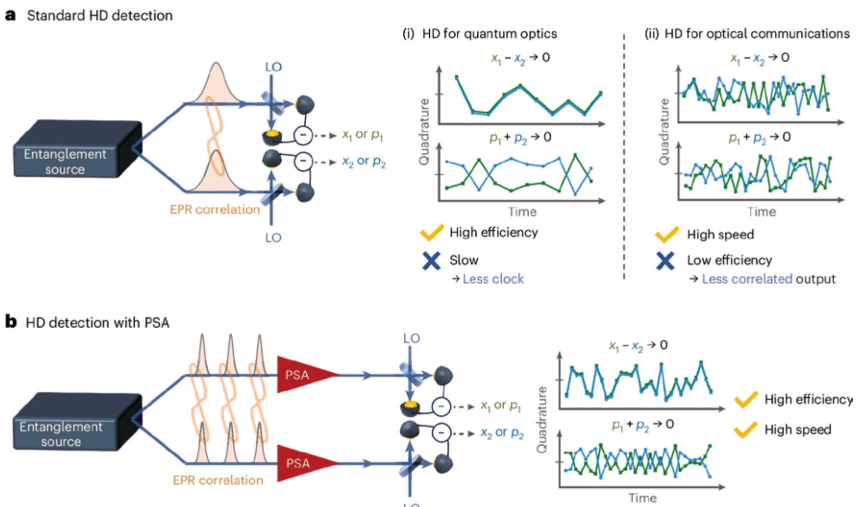
Photo of optical quantum computer



Schematic of optical quantum computer

Real-time observation of picosecond-timescale optical quantum entanglement

Quantum entanglement of light is a resource for various quantum information processing applications. For high-speed quantum information processing, it is necessary to handle quantum entanglement among short wave packets. However, in conventional methods, there is a trade-off between accuracy and high speed in homodyne measurements. Here, the loss of measurement accuracy is due to the low quantum efficiency of the measuring instrument. We solved this trade-off by inserting a broadband waveguide optical parametric amplifier for phase-sensitive amplification before the homodyne measurement, which effectively suppresses the quantum inefficiency of a fast homodyne detector. We succeeded in measuring 4.5 dB-squeezed quantum correlations between optical wave packets as short as 40 picoseconds. 40 picoseconds correspond to a repetition rate of 2.5 GHz, which is 1000 times faster than previous demonstrations.



Top: Trade-off between accuracy and speed in conventional quantum correlation measurements.
Bottom: Fast and accurate quantum correlation measurements we realized.

©A. Kawasaki *et al.*, Nature Photonics 19 271-276 (2025).

Core members

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

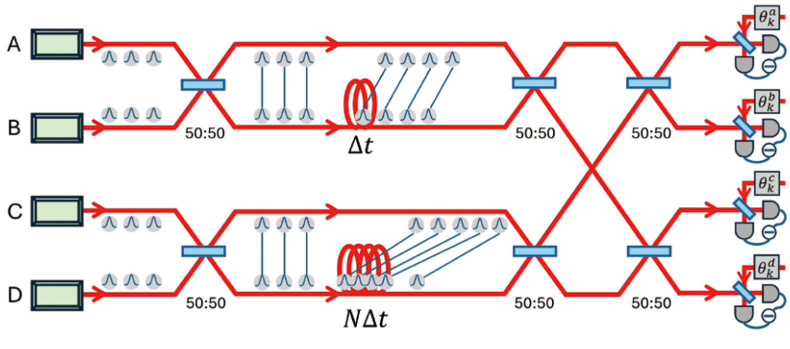
Optical Quantum Control Research Team

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

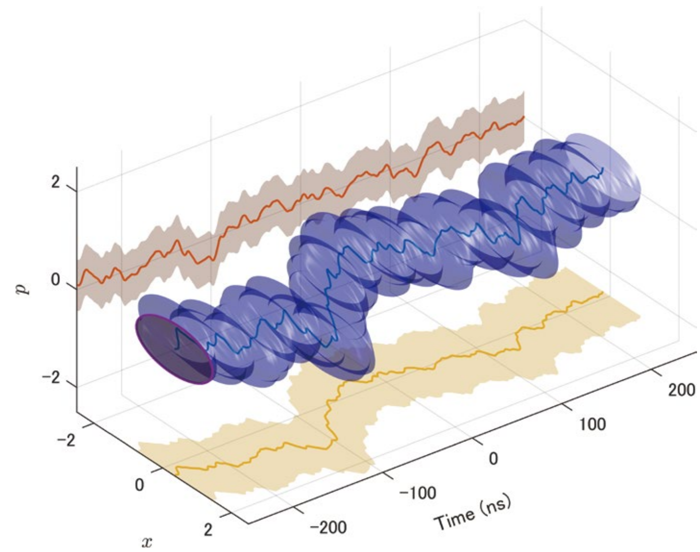
Research Outline

The goal of our team is to develop an optical quantum computer. In particular, we investigate optical quantum control technology and measurement-based optical quantum computation. There are many advantages in an optical platform, including compatibility with room temperature, high scalability, and applicability to communication technology. The key technology for optical quantum information processing is quantum control. 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 a core technique because it is the basis for quantum control technology.

To build a scalable measurement-based optical quantum computer, we employ time-domain multiplexing technique. We generate large-scale entanglement in the time domain and sequentially measure it using various measurement bases to perform quantum operations. We are also developing a cloud-based system to enhance usability, with the aim of exploring applications of optical quantum computing and promoting its practical use.



Measurement-based optical quantum computer



Estimation of optical quantum state

Hidehiro Yonezawa (Ph.D.), Team Director

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).

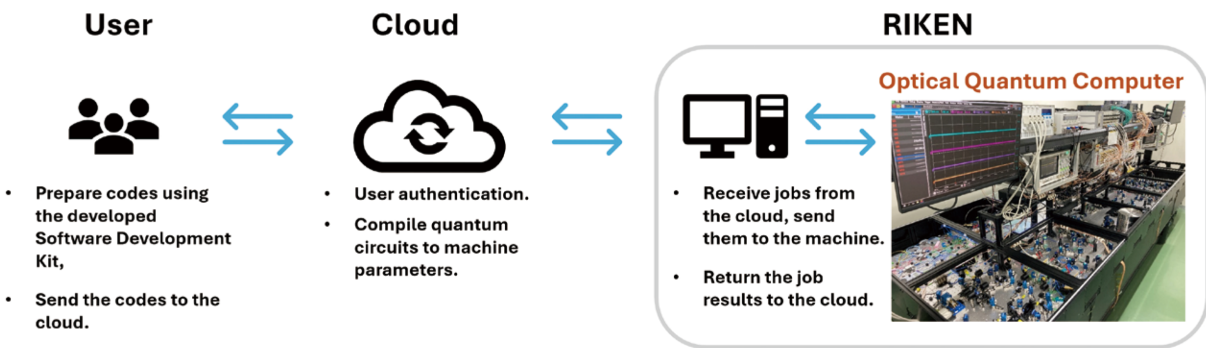
Brief resume

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
2023 Team Director, Optical Quantum Control Research Team, RIKEN Center for Quantum Computing, RIKEN (-present)

Recent Achievements

Development of optical quantum computer cloud system

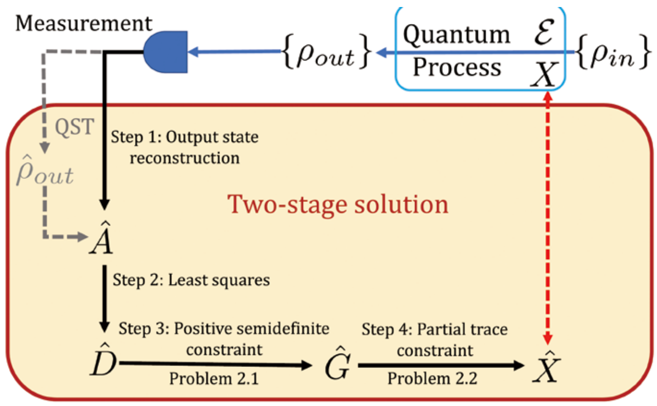
Our team is developing an optical quantum computer cloud system in collaboration with the Optical Quantum Computing Research Team. Our optical computer is a measurement-based analog optical quantum computer that utilizes time-domain multiplexing techniques. It consists of four NTT-made squeezers, an optical interferometer with delay lines, and four homodyne detection systems. The interferometer employs two optical delay lines of different lengths, generating ultra-large-scale quantum entanglement in the time domain. This entanglement is measured in various measurement bases to realize quantum operations. The system works at 100 MHz clock frequency and is capable of performing linear transformation on 101 quantum input modes using continuous variables. The optical quantum computer is cloud-connected and accessible via the internet. Users can design quantum circuits using a dedicated software development kit (SDK), which automatically compiles the circuit to the machine-executable parameters and send them to the optical quantum computer for execution. This cloud-based optical quantum computer system is expected to accelerate application research in areas such as continuous-variable optimisation problems and neural networks.



Optical quantum computer cloud system

Two-stage solution to quantum process tomography

In the field of quantum information technology, it is critical to accurately characterize and precisely control quantum states, processes, and measurements. Quantum process tomography is a method for characterizing quantum processes using known quantum states and measurement settings. We have developed a two-stage solution for quantum process tomography that applies to both trace-preserving and non-trace-preserving processes. We have demonstrated the computational complexity of our algorithm as a function of tomographic resources, established analytical error upper bound, and designed optimal input states and measurement settings. The effectiveness and validity of the proposed algorithm have been demonstrated through numerical simulations.



Procedure for the two-stage quantum process tomography

©S. Xiao, Y. Wang, J. Zhang, D. Dong, G. J. Mooney, I. R. Petersen, H. Yonezawa, "A Two-Stage Solution to Quantum Process Tomography: Error Analysis and Optimal Design," IEEE Trans. Inf. Theory 71, 1803-1823 (2025).

Core members

(Senior Research Scientist) **Shota Yokoyama**

Nanophotonic Cavity Quantum Electrodynamics Research Team

Keywords: Nanophotonics, Cavity QED, Quantum optics, Quantum computing, Quantum network

Research Outline

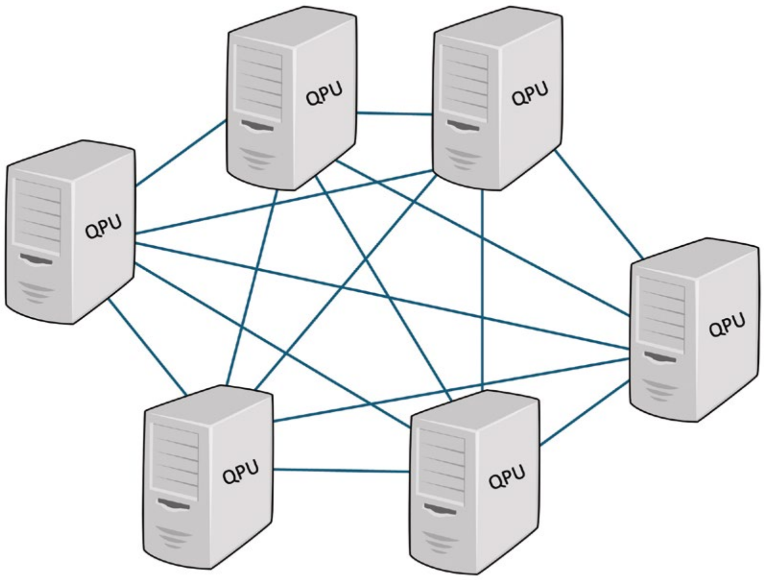
Our team is advancing experimental studies in cavity quantum electrodynamics (QED) using nanophotonic devices. A cavity QED system is a hybrid platform consisting of photons confined in an optical cavity and atoms, and it serves as an ideal quantum interface between atomic and photonic qubits.

In conventional cavity QED experiments, systems based on free-space optical cavities using bulk mirrors have enabled the deterministic generation of non-classical states of light, such as single photons and Schrödinger cat states, as well as quantum non-demolition measurements of photons.

However, such free-space optical cavities suffer from poor compatibility with fiber optics and require extremely complex and precise alignment and control. As a result, it has been difficult to connect multiple cavity QED systems while maintaining low loss.

To address these issues of connectivity and integrability, our team is developing a novel cavity QED system based on nanophotonic devices, aiming to realize scalable quantum technologies.

Specifically, we are developing nanophotonic devices with strong light confinement capabilities, leveraging state-of-the-art nanofabrication techniques, to achieve strong coupling with laser-cooled and trapped atoms. Furthermore, we aim to realize key technologies for distributed quantum computing and quantum networks with high efficiency and high fidelity, and to build an integrated photonic quantum system.



Schematic of distributed quantum computing / quantum network system based on nanophotonic cavity QED.

Takao Aoki (Ph.D.), Team Director

Selected Publications

1 S. K. Ruddell, K. E. Webb, M. Takahata, S. Kato, and T. Aoki, “Ultra-low-loss nanofiber Fabry–Perot cavities optimized for cavity quantum electrodynamics”, *Opt. Lett.* 45, 4875 (2020).

2 D. H. White, S. Kato, N. Német, S. Parkins, and T. Aoki, “Cavity Dark Mode of Distant Coupled Atom-Cavity Systems”, *Phys. Rev. Lett.* 122, 253603 (2019).

3 S. Kato, N. Német, K. Senga, S. Mizukami, X. Huang, S. Parkins, and T. Aoki, “Observation of dressed states of distant atoms with delocalized photons in coupled-cavities quantum electrodynamics”, *Nature Communications* 10, 1160 (2019).

4 S. Kato and T. Aoki, “Strong Coupling between a Trapped Single Atom and an All-Fiber Cavity”, *Phys. Rev. Lett.* 115, 093603 (2015).

5 R. Nagai and T. Aoki, “Ultra-low-loss tapered optical fibers with minimal lengths”, *Opt. Express* 23, 28427-28436 (2014)

Brief resume

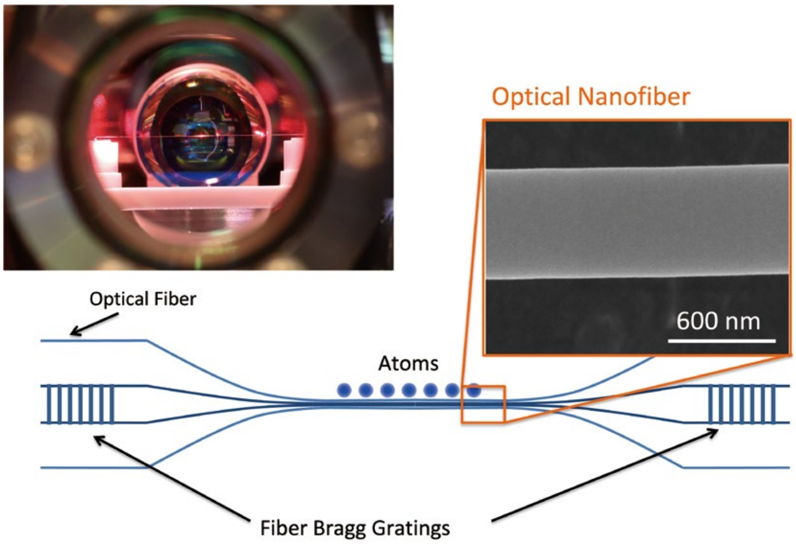
2001 Ph. D. in Engineering, The University of Tokyo
2001 Research Associate, The University of Tokyo
2006 PRESTO Researcher, JST
2008 Program-Specific Associate Professor, Kyoto University
2011 Associate Professor, Waseda University
2014 Professor, Waseda University (-present)
2024 Team Leader, RIKEN (-present)

Recent Achievements

Realization of nanofiber cavity QED system

We have realized a cavity QED system in the strong coupling regime between a trapped single atom and a nanofiber cavity, using a nanofiber cavity developed based on our original ideas and technologies [S. Kato and T. Aoki, Phys. Rev. Lett. 115, 093603 (2015)]. This achievement marks the first realization of a cavity QED system using an all-fiber optical cavity.

Furthermore, we have constructed, for the first time, a "coupled cavity QED system" in which two nanofiber cavity QED systems are coherently connected entirely via fiber. We successfully observed all five eigenmodes of this system [S. Kato *et al.*, Nature Communications 10, 1160 (2019); D. White et al., Phys. Rev. Lett. 122, 253603 (2019)]. These results represent a significant step toward the realization of high-efficiency distributed quantum computing and quantum networks.



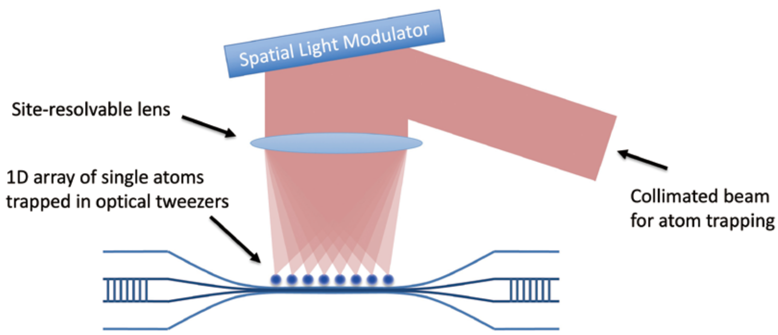
Schematic of nanofiber cavity QED system.

Coupling of individually addressable atoms to an optical nanofiber cavity

In the nanofiber cavity QED system realized above, atoms were trapped by the evanescent field of the guided mode of the nanofiber. This approach has a limitation: when multiple atoms are coupled to the cavity, it is not possible to individually address each atom.

To overcome this challenge, we developed a new technique in which a one-dimensional array of single-atom optical tweezers is formed on the surface of the nanofiber, enabling optical access to individually addressable atoms coupled to the nanofiber.

Specifically, we applied spatial phase modulation to a collimated trapping beam using a spatial light modulator (SLM), and formed a one-dimensional array of optical tweezers capable of trapping single atoms on the surface of the nanofiber inside a vacuum chamber, using a high-NA, long-working-distance objective lens.



Formation of a one-dimensional optical tweezer array on a nanofiber cavity using a spatial light modulator and a single-site-resolved optical system

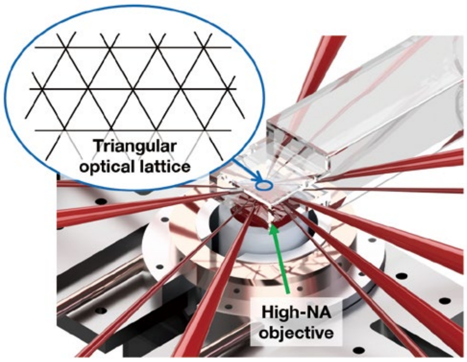
Quantum Many-Body Dynamics Research Team

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.

Takeshi Fukuhara (D.Sci.), Team Director

Selected Publications

1 H. Ozawa, R. Yamamoto, and T. Fukuhara, "Observation of chiral-mode domains in a frustrated XY model on optical triangular lattices", *Phys. Rev. Res*. 5, L042026 (2023).
2 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).
3 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).
4 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).
5 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).

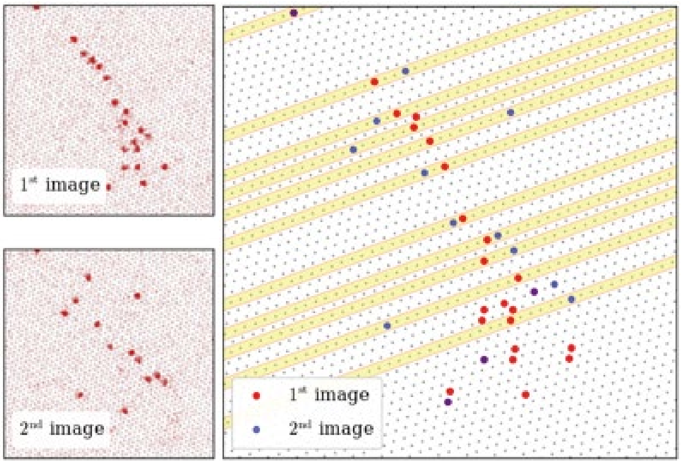
Brief resume

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)
2024 Professor (non-tenure-track), Waseda University (-present)

Recent Achievements

Cooling of atoms after single-atom detection

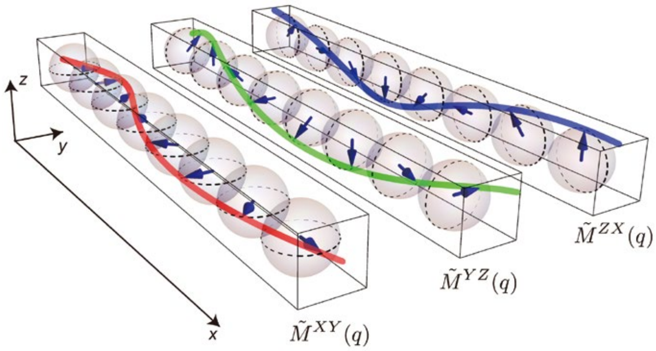
Quantum gas microscopy enables us to observe atomic distributions in optical lattices at the single-atom and single-site level. However, the observed atoms are usually heated during the measurement process, resulting in vibrational excitations. To address this problem, we aimed to cool the atoms to the vibrational ground state by applying Raman sideband cooling after the measurement. By optimizing the parameters of several lasers used for Raman sideband cooling, we succeeded in cooling most of the atoms to their vibrational ground state after the measurement. Furthermore, by reducing the lattice depth after the measurement, quantum walks of the atoms in the optical lattice have been observed, which confirmed that most of the atoms were cooled down to their vibrational ground state. The method can be applied to faster data acquisition in quantum dynamics and to feedback control of quantum systems based on measurements.



Initial atom distribution (top left) and atom distribution after observation, cooling and 1.75-ms quantum dynamics in the optical lattice (bottom left). By comparing the two measured images, quantum walks of each atom can be observed.

Proposal for entanglement measurement in optical lattice experiment

Density matrices, which describe quantum states, can be reconstructed by quantum state tomography. Usually, quantum state tomography requires local operations for preparing measurement basis and a large number of measurements on the basis. However, both are difficult to realize in optical-lattice experiments and require a lot of effort. To solve this problem, we proposed a method of quantum state tomography with a spin-spiral-structured measurement basis, which does not require local manipulation. Using a simple model, we demonstrated that this method can also be utilized to evaluate the entanglement entropy from the density matrix of the subsystem.

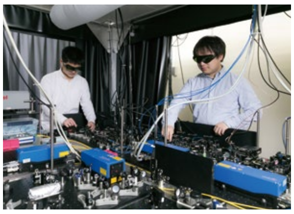


Spin-spiral structure for measurement.

©Giacomo Marmorini, Takeshi Fukuhara, and Daisuke Yamamoto, "Measuring entanglement without local addressing via spiral quantum state tomography", arXiv: 2411.16603

Core members

(Research Scientist) **Ryuta Yamamoto**
(Research Scientist) **Hideki Ozawa**
(Technical Staff I) **Yoichiro Otsuka**



Cold-Atom Quantum System Research Team

Keywords: Cold atoms, Quantum physics, Quantum optics, Quantum computer, Photonics

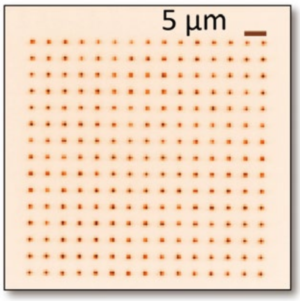
Research Outline

We invent quantum technologies based on individual atoms manipulated with laser beams. For example, lasers can cool atoms to absolute zero temperature, trap and move them with optical tweezers, and excite their electrons to the giant Rydberg orbitals. This allows us to exploit the quantum nature of atoms and to build quantum systems atom-by-atom for both fundamental research as well as practical applications.

Working towards such a practical, long-term outcome, our team is part of the Japan-wide Moonshot Goal 6 “Neutral-Atom Quantum Computer” program targeting the realization of a fault-tolerant quantum computer based on neutral atoms. In particular, we are joining the development of a first machine located at the Institute for Molecular Science (Okazaki). We are also participating in an ASPIRE program connecting the Japanese and German community researching neutral-atom quantum computers and simulators.

A more fundamental research direction is the study of collective light-matter emission, where an assembly of atoms emits spontaneous photons in a collaborative manner, rather than individually. Reaching this fascinating regime in free-space, i.e. in absence of any confinement of the light, puts stringent requirements on the control of the atoms’ positions. We are developing a completely new approach based on flying atoms.

The collaboration team for the first neutral-atom quantum computer of the Moonshot Goal 6 program in front of the Quantum Processing Unit (QPU). The QPU consists of an array of atoms which will be manipulated by a myriad of precisely-positioned laser beams, and will start operating from mid-2025. The members are from the Institute for Molecular Science (Okazaki, JP), the company Infleqtion (Boulder, USA), and the “Cold-Atom Quantum System” team director.



An array of single Rubidium atoms trapped in optical tweezers. The atoms are made to fluoresce with a resonant laser beam, and their light is collected on a sensitive camera, giving the image shown here. Each optical tweezer has a diameter of around 1 micrometer and a separation of 5 micrometers in this example, but they can be shaped and organized arbitrarily using holography techniques. Such arrays are the core of our neutral-atom-based quantum technologies.

Sylvain de Léséleuc (Ph.D.), Team Director

Selected Publications

1 T. Denecker, Y.T. Chew, O. Guillemant, G. Watanabe, T. Tomita, K. Ohmori, and S. de Léséleuc, “Measurement and feedforward correction of the fast phase noise of lasers”, *Phys. Rev. A* 111 (4), 042614 (2025).
2 Y.T. Chew, M. Poitrinal, T. Tomita, S. Kitade, J. Mauricio, K. Ohmori, and S. de Léséleuc, “Ultraprecise holographic optical tweezer array”, *Phys. Rev. A* 110 (5), 053518 (2024).
3 Y.T. Chew, T. Tomita, T.P. Mahesh, S. Sugawa, S. de Léséleuc, K. Ohmori, “Ultrafast energy exchange between two single Rydberg atoms on a nanosecond timescale”, *Nat. Photonics* 16 (10), 724 (2022).
4 S. de Léséleuc, V. Lienhard, P. Scholl, D. Barredo, S. Weber, N. Lang, H.P. Buchler, T. Lahaye, and A. Browaeys, “Observation of a symmetry protected topological phase of interacting bosons with Rydberg atoms”, *Science* 365, 775 (2019).
5 D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, and A. Browaeys, “An atom-by-atom assembler of defect-free arbitrary 2d atomic arrays”, *Science* 354, 1021 (2016).

Brief resume

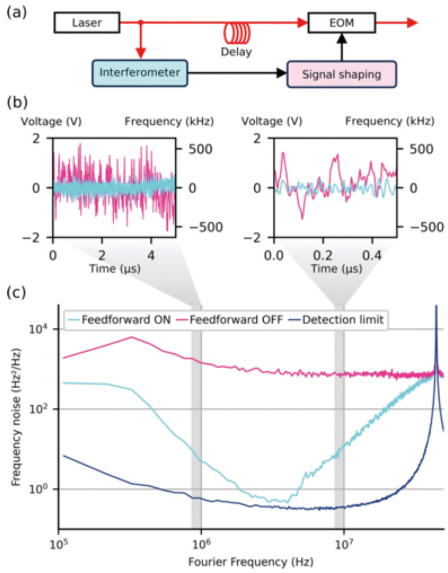
2010 Engineer Degree at Ecole Polytechnique (Palaiseau, France) (-2013)
2013 Master of Science at ETH Zurich (Master Thesis at U. Tokyo as an exchange student) (-2015)
2015 PhD at University Paris-Saclay, Institut d’Optique (Palaiseau, France) on “Quantum simulation of spin models with assembled arrays of Rydberg atoms” (-2018)
2018 Post-doctoral researcher at Institut d’Optique (-2019)
2019 Assistant Professor at Institute for Molecular Science, National Institutes of Natural Sciences (Okazaki, Japan) (-2023)
2023 Project Associate Professor at IMS, NINS (-present)
2024 Team Director at RIKEN, Center for Quantum Computing (-present)

Recent Achievements

Measurement and feedforward correction of the fast phase noise of lasers

As part of our quantum computing effort, we have investigated the phase noise of lasers. For entangling two atoms separated by a micrometer distance, it is required to excite the atoms' outermost electron to a giant Rydberg orbital. To realize this operation with the outstanding precision required to make a quantum computer, it is crucial to use lasers with very low noise of their phase in the micro and sub-microsecond timescale. We have developed a fully-fiberized instrument that can detect and even correct such fast phase fluctuations of lasers. We demonstrated a measurement noise floor of less than 0.1 Hz^2/Hz, and a noise suppression of more than 20 dB for Fourier frequencies in the 1 to 10 MHz region (reaching up to 30 dB at 3 MHz).

Published as *Phys. Rev.* A 111 (4), 042614 (2025).

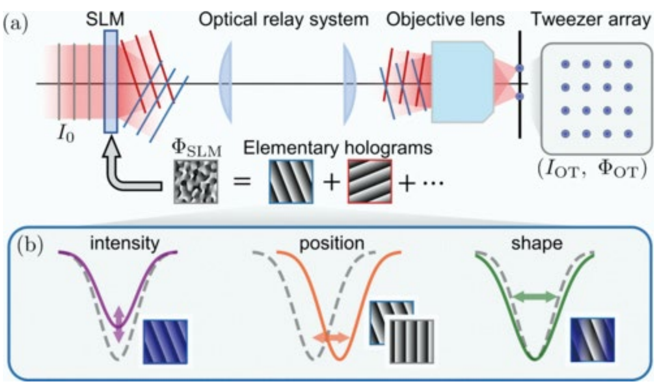


Measurement and correction of fast phase noise. (a) Schematic of the phase noise eater. (b) Time traces of the measured frequency noise with (in blue) and without (in pink) the feedforward correction. (c) Frequency noise PSD with and without the correction. The dark blue curve is the noise floor. A cancellation of more than 30 dB is achieved at a Fourier frequency of 3 MHz, where the noise is suppressed down to 0.5 Hz^2/Hz.

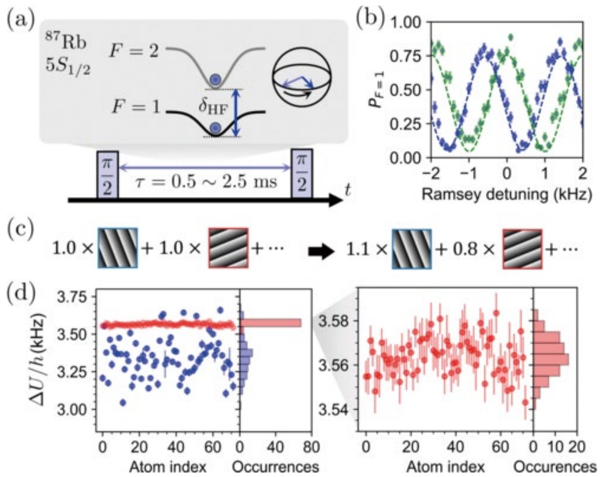
Ultra-precise holographic optical tweezers

Neutral atoms trapped in microscopic optical tweezers have emerged as a growing platform for quantum science. Achieving homogeneity over the tweezers array is an important technical requirement, and our research focuses on improving it for holographic arrays generated with a Spatial Light Modulator (SLM). We present a series of optimization methods to calculate better holograms, fueled by precise measurement schemes. These innovations enable to achieve intensity homogeneity with a relative standard deviation of 0.3%, shape variations below 0.5%, and positioning errors within 70 nm. Such ultra-precise holographic optical tweezers arrays allow for the most demanding applications in quantum science with atomic arrays.

Published as *Phys. Rev. A* 110 (5), 053518 (2024).



Generation of optical tweezers arrays using an SLM. (a) An SLM is employed to modulate spatially the incoming laser beam and create an array of optical tweezers. The phase of the SLM can be reduced to a superposition of elementary holograms for our specific array. (b) Imperfections lead to intensity, position, and shape inhomogeneity between tweezers. Specific modifications of the elementary holograms in the SLM phase calculation can correct these inhomogeneities.



Intensity homogenization with Ramsey interferometry. (a) The tweezers' intensity at a given site induces a differential light-shift on the clock transition of the trapped 87Rb atom. The latter is measured by Ramsey interferometry. (b) Ramsey fringes for two different atoms. The shift is caused by a different tweezer intensity. (c) Schematic showing the amplitude adjustment of each elementary hologram. (d) Differential light shift of the individual atom before (left) and after (right) homogenization, together with histograms. After the homogenization procedure, the intensity inhomogeneity decreased from 4 % to 0.3 %.

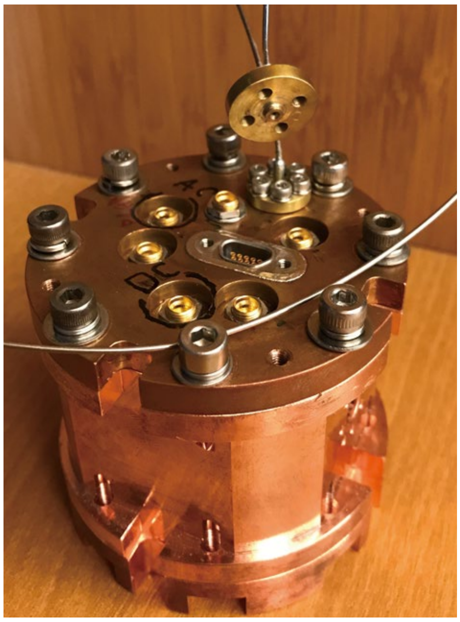
Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team

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.), RIKEN Hakubi Team Leader

Selected Publications

1 I. Grytsenko, S. van Haagen, O. Rybalko, A. Jennings, R. Mohan, Y. Tian, E. Kawakam, "Characterization of Tunnel Diode Oscillator for Qubit Readout Applications", *J. Low Temp. Phys.* (2025). https://doi.org/10.1007/s10909-025-03293-4
2 A. Jennings, X. Zhou, I. Grytsenko, E. Kawakami, "Quantum computing using floating electrons on cryogenic substrates: Potential And Challenges", *Appl. Phys. Lett.* 124, 120501 (2024).
3 E. Kawakami, J. Chen, M. Benito, D. Konstantinov, "Blueprint for quantum computing using electrons on helium", *Phys. Rev. Appl.* 20, 054022 (2023).
4 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).
5 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).

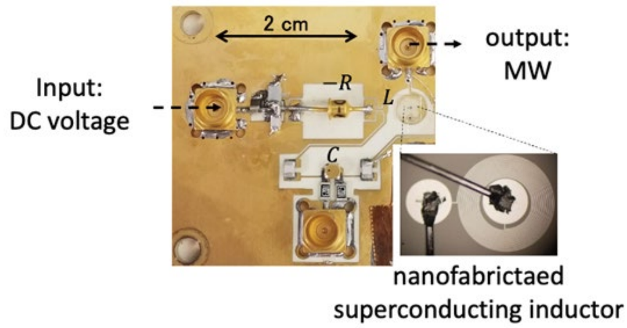
Brief resume

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
2020 RIKEN Hakubi Team Leader, Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team (-present)

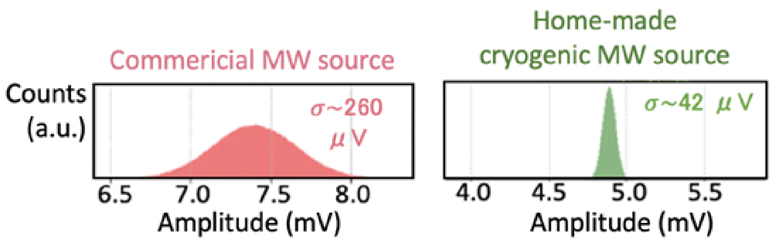
Recent Achievements

Development of cryogenic microwave sources for scalable quantum computing

To realize a large-scale quantum computer, it is necessary to connect qubits operating at cryogenic temperatures with room-temperature instruments via coaxial cables. However, the number of such cables is physically constrained, making it essential to develop measurement devices that function at low temperatures. Since qubits are controlled by microwaves, we developed a compact microwave oscillator based on a tunnel diode that operates reliably under cryogenic conditions. By connecting a tunnel diode, which exhibits negative resistance, to an LC resonator and applying a DC voltage, microwave signals are generated. The oscillator is compact (2×2 cm), operates stably at low temperatures, and exhibits smaller amplitude fluctuations than commercial microwave sources. Because amplitude stability directly impacts qubit readout fidelity, this oscillator enables more precise quantum state measurements.



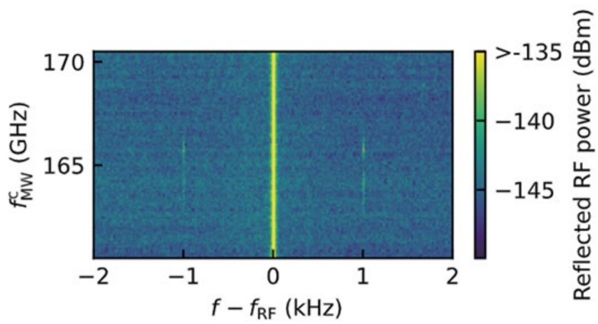
The developed microwave oscillator successfully operates at cryogenic temperatures (10 mK). In the circuit diagram, –*R* represents the tunnel diode. The capacitor (*C*) is a varactor diode used to tune the frequency in the range of 10 MHz, and the inductor (*L*) is a microfabricated superconducting inductor to minimize resistive losses.



Comparison of amplitude stability between a commercial microwave oscillator and the cryogenic microwave oscillator developed in this work.

RF reflectometry of the Rydberg states of electrons on helium

Electrons on liquid helium offer a clean platform for quantum computing, with spin states expected to have long coherence times. However, spin-state detection remains challenging. A promising approach maps the spin state onto a Rydberg state, detectable via an LC tank circuit with high sensitivity and small footprint. As a proof of concept, we detect Rydberg transitions of an electron ensemble using frequency-modulated microwaves. Adiabatic transitions induce measurable quantum capacitance. The achieved sensitivity allows resolving the Rydberg transition of a single electron, paving the way for scalable spin-state readout and helium-based quantum technologies.



Reflected RF power measured with a spectrum analyzer as a function of the microwave (MW) carrier frequency f_{MW}. The frequency modulation (FM) parameters are f_{mf} = 1 kHz and f_{ma} = 768 MHz. Sideband signals appear at $f = f_{RF} \pm f_{mf}$ around f_{MW} = 165 GHz, corresponding to the Rydberg transition.

Core members

(Technical Scientist) **Ivan Grytsenko**
(Postdoctorial Researcher) **Asher Jennings**
(Postdoctoral Researcher) **Jun Wang**
(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.

Inside the laboratory

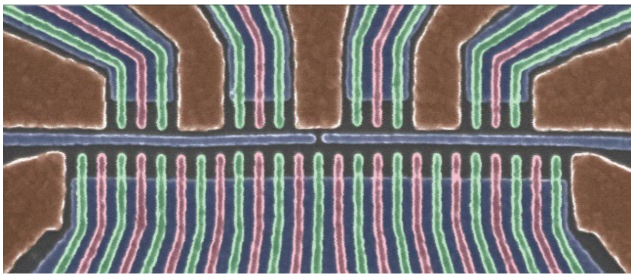
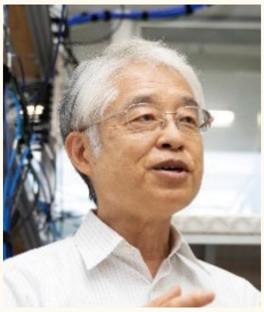


Photo of 12-qubit device currently in production



Seigo Tarucha (D.Eng.), Team Director

Selected Publications

1 K. Takeda, A. Noiri, T. Nakajima, L. C. Camenzind, T. Kobayashi, A. Sammak, G. Scappucci, and S. Tarucha, “Rapid single-shot parity spin readout in a silicon double quantum dot with fidelity exceeding 99 %”, *npj Quantum Info*. 10, 22 (2024).
2 T. Kobayashi, T. Nakajima, K. Takeda, A. Noiri, J. Yoneda, and S. Tarucha, “Feedback-based active reset of a spin qubit in silicon”, *npj Quantum Information* 9, 52 (2023).
3 J.S. Rojas-Arias, A. Noiri, P. Stano, P (Stano, P.), T. Nakajima, J. Yoneda, K. Takeda, T. Kobayashi, A. Sammak, G. Scappucci, D. Loss, and S. Tarucha, “Spatial noise correlations beyond nearest neighbors in 28Si/Si-Ge spin qubits”, *Phys. Rev. Appl.* 20, 5 (2023).
4 K. Takeda, A. Noiri, T. Nakajima, T. Kobayashi, and S. Tarucha, “Quantum error correction with silicon spin qubits”, *Nature*, 608, 682-686 (2022).
5 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).

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 Director, Semiconductor Quantum Information Device Research Team, RIKEN Center for Quantum Computing (-present)

Recent Achievements

High-fidelity spin readout in silicon qubits

It is difficult to directly detect spin orientation in a single shot measurement. Therefore, a combined method of spin to charge information conversion and charge sensing is employed. For the spin-charge conversion spin dependent tunneling is often utilized. However, this method is slow and not so accurate. Here we use spin blockade effect instead to significantly improve the speed and accuracy of spin readout in silicon (Si) qubit devices.

We fabricate a Si quadruple quantum dot (QD) device made in Si/SiGe and use a double QD having two electron spins for the spin readout experiment (Fig.1). When the two spins are antiparallel, either electron can move between the two dots, generating double occupation (2,0) while when they are parallel, the double occupancy does not appear, according to Pauli exclusion. We improve the charge sensor design for detecting the electron occupancy either (2,0) or (1,1) (Fig.2), and in addition the sensitivity of the charge sensor and have finally raised visibility of the charge sensor signal for distinguishing the spin state up to 99.6% (highest in the world), and shortened the measurement time as well.

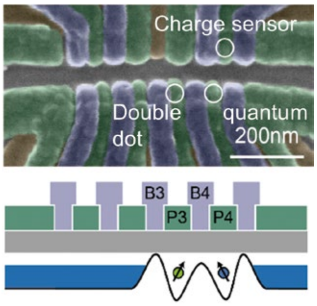


Fig.1 Two qubit device

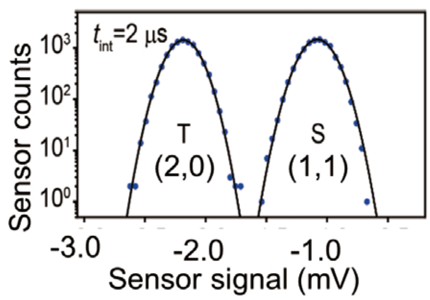


Fig. 2 Spin readout

Feedback-based active reset of a spin qubit in silicon

Feedback preparation of qubits is a sought-after technique for important quantum information protocols such as fault-tolerant quantum error correction. Such a preparation scheme is implemented for silicon spin qubits recently, but the preparation fidelity is limited by the qubit readout fidelity. We have developed an advanced feedback protocol to improve the preparation fidelity.

We incorporate a cumulative readout technique consisting of multiple quantum non-demolition (QND) measurements of a qubit to a feedback control system (Fig.1). The control pulse is conditioned according to the cumulative readout result, which enables the preparation fidelity to exceed the readout fidelity of the single measurement. We have achieved the preparation fidelity higher than 98% and expected further improvements with higher readout fidelity and short measurement time.

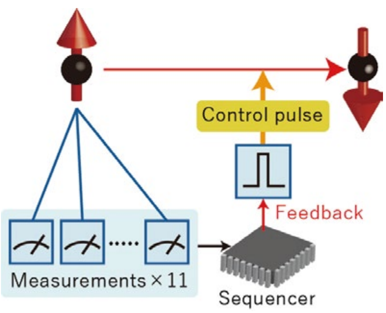


Fig.1 Schematic of the feedback quantum control based on multiple measurement results.

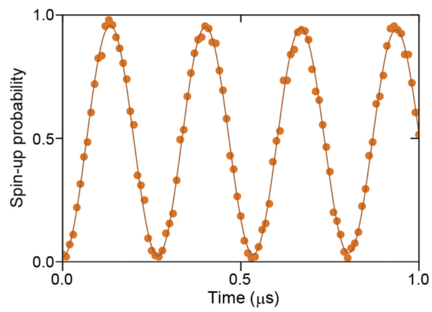


Fig.2 An example of qubit operation after the active reset. The preparation fidelity can be estimated from the visibility of the oscillations.

Core members

(Research Scientist) **Takashi Kobayashi**

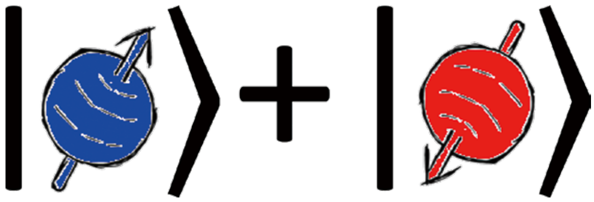
(Technical staff I) **Reiko Kuroda**

Semiconductor Quantum Information Device Theory Research Team

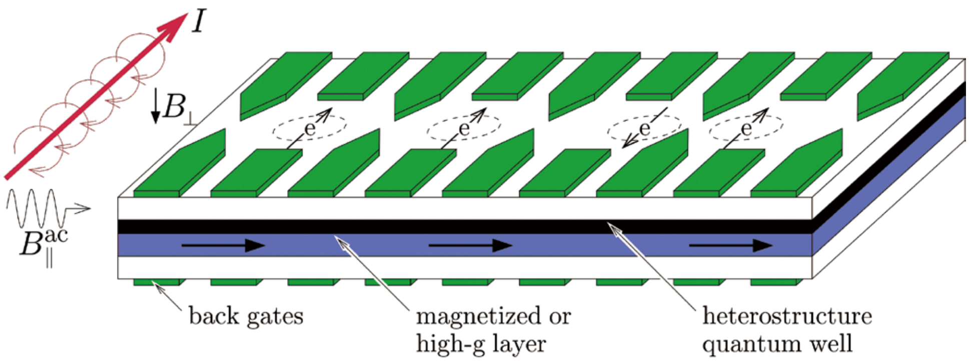
Keywords: Quantum dots, Spin-based quantum information science, Qubit, Spin-orbit interaction, Quantum information processing

Research Outline

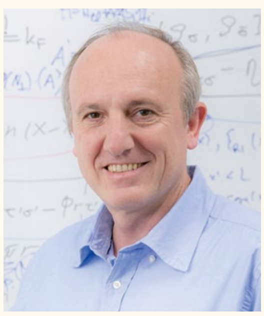
Our team is working on the theory of a spin-based quantum computer. We design its CMOS-compatible components deriving from Si and Ge gated quantum dots. We focus on spin qubits that can be manipulated by electric fields through various spin-orbit interactions. Using advanced band-structure models, we 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 Director

Selected Publications

1. J. S. Rojas-Arias, A. Noiri, P. Stano, T. Nakajima, J. Yoneda, K. Takeda, T. Kobayashi, A. Sammak, G. Scappucci, D. Loss, and S. Tarucha, "Spatial noise correlations beyond nearest neighbors in ^{28}Si/Si-Ge spin qubits", *Phys. Rev. Appl.* 20, 054024 (2023).
2. J. Yoneda, J. S. Rojas-Arias, P. Stano, K. Takeda, A. Noiri, T. Nakajima, D. Loss, and S. Tarucha, "Noise-correlation spectrum for a pair of spin qubits in silicon", *Nat. Phys.* 19, 1793 (2023).
3. P. Stano and D. Loss, "Review of performance metrics of spin qubits in gated semiconducting nanostructures,", *Nat. Rev. Phys.* 4, 672 (2022).
4. 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).
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

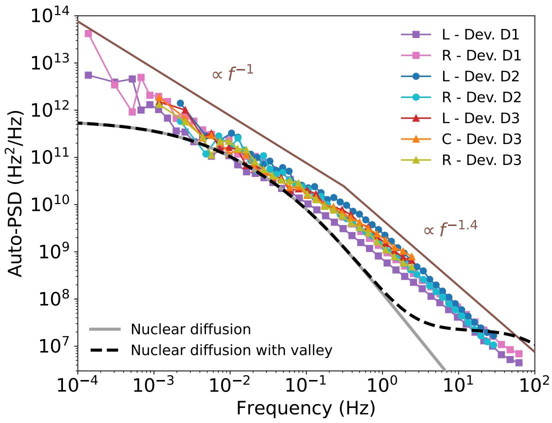
Origin of noise affecting spin qubits in natural silicon

To improve the performance of spin qubits, it is essential to understand the limitations they currently face. One major limitation is noise. In collaboration with experimentalists, we investigated the physical mechanisms responsible for fluctuations in the Zeeman splitting of spin qubits hosted in natural-silicon quantum dots. To this end, we employed a combination of techniques to probe the qubit noise power spectral density, including Ramsey interferometry and CPMG dynamical decoupling. In addition, we adapted and implemented—for the first time—a novel spectroscopy protocol based on correlations of single-shot measurements. Together, these methods allowed us to reconstruct the qubit noise spectral density over nine orders of magnitude in frequency, with no gaps.

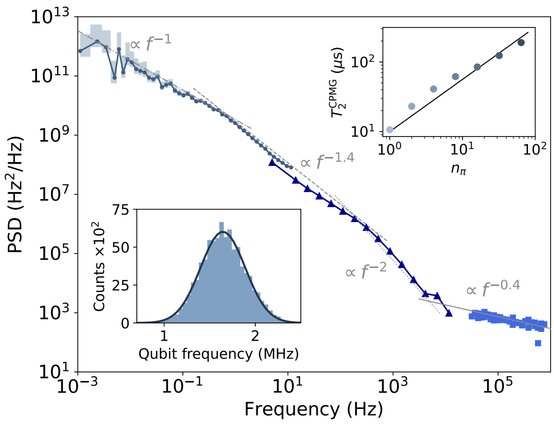
At low frequencies, we observed a universal noise spectrum across seven qubits in three different devices. This noise is attributed to hyperfine coupling to residual ^{29}Si nuclear spins in the material. Supporting this interpretation, we found that increasing the external magnetic field—which enhances the micromagnet-induced magnetic field gradient—led to improved qubit coherence. This behavior is consistent with the suppression of nuclear spin diffusion, as larger gradients inhibit energy-conserving flip-flop processes among nuclear spins.

In contrast, charge noise exhibited distinct characteristics on each device and lacked the universal behavior of the nuclear-spin-induced fluctuations. Cross-correlation measurements between qubits further support the presence of these two separate noise mechanisms. At higher frequencies, charge noise dominates and shows a strongly qubit-dependent spectrum.

These findings provide a detailed characterization of noise in natural-silicon spin qubits and clarify the distinct roles of magnetic and electric noise sources in driving qubit energy fluctuations.



Noise auto-correlation spectra of qubit energies for seven qubits across three devices (as labeled). The brown lines indicate reference slopes proportional to f^{-1} and $f^{-1.4}$. The gray solid lines represent theoretical predictions based on nuclear spin diffusion. The black dashed lines include the effect of valley oscillations in the electron wavefunction, as described by the extended diffusion model.



Qubit noise auto-power spectral density (PSD) measured over nine orders of magnitude in frequency. The spectrum is reconstructed by combining three complementary techniques: Bayesian estimation of qubit energy correlations (connected dots), a novel single-shot time-correlation method (connected triangles), and CPMG dynamical decoupling spectroscopy (squares). The shaded regions indicate 90% confidence intervals for the Bayesian method. *Upper right inset*: coherence time as a function of the number of CPMG pulses, showing improved coherence with pulse number. *Lower left inset*: histogram of qubit energy fluctuations, with a Gaussian fit (solid line), illustrating the distribution of extracted energy values.

Core members

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

Quantum Computing Theory Research Team

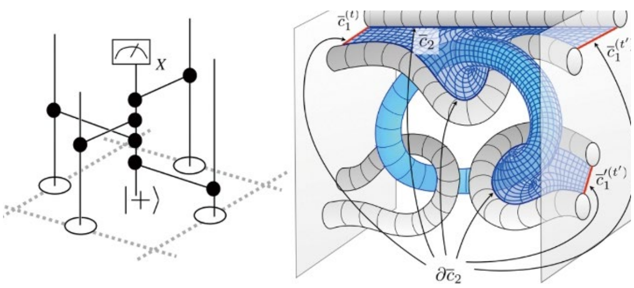
Keywords: Quantum computing, Quantum information science, Quantum machine learning, Quantum error correction

Research Outline

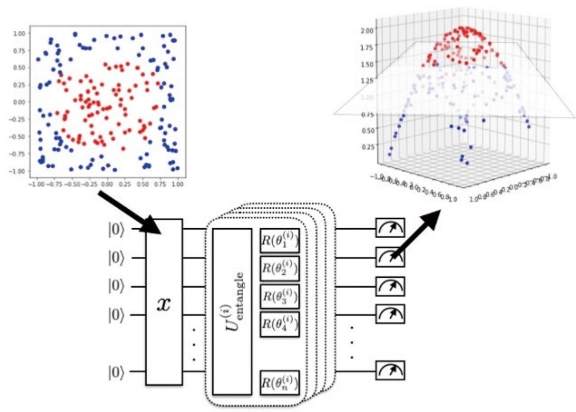
Quantum computing is revolutionizing technology, and Quantum Computing Theory Research team is at the forefront of this transformation. Our focus is on developing quantum computing theory and software essential for realizing quantum computers, designing new quantum algorithms, and analyzing their performance.

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.

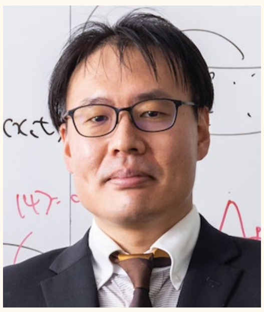
Embracing interdisciplinary research, we foster connections between quantum information science and fields like fundamental physics, quantum chemistry, machine learning, and high-performance computing. We aim to open up new scientific frontiers with quantum computers or through the lens of quantum information 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 Director

Selected Publications

1. Y. Akahoshi, K. Maruyama, H. Oshima, S. Sato, and K. Fujii, “Partially fault-tolerant quantum computing architecture with error-corrected clifford gates and space-time efficient analog rotations”, *PRX Quantum* 5, 010337 (2024).
2. 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).
3. 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).
4. K. Mitarai, M. Negoro, M. Kitagawa and K. Fujii, “Quantum Circuit Learning”, *Phys. Rev. A*, 98, 032309 (2018).
5. K. Fujii and K. Nakajima, “Harnessing Disordered-Ensemble Quantum Dynamics for Machine Learning”, *Phys. Rev. Applied* 8, 24030 (2017).

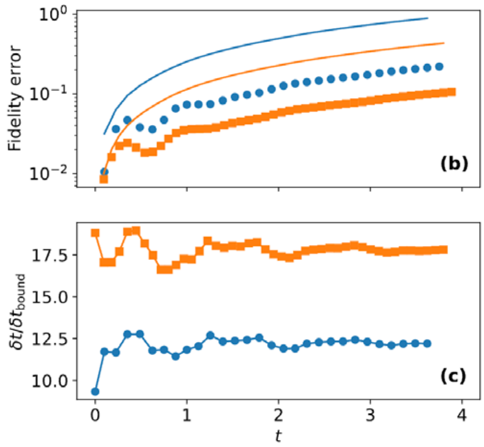
Brief resume

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
2024 Team Director, Quantum Computation Theory Research Team, RIKEN (-present)

Recent Achievements

Measuring Trotter error and its application to precision-guaranteed Hamiltonian simulations

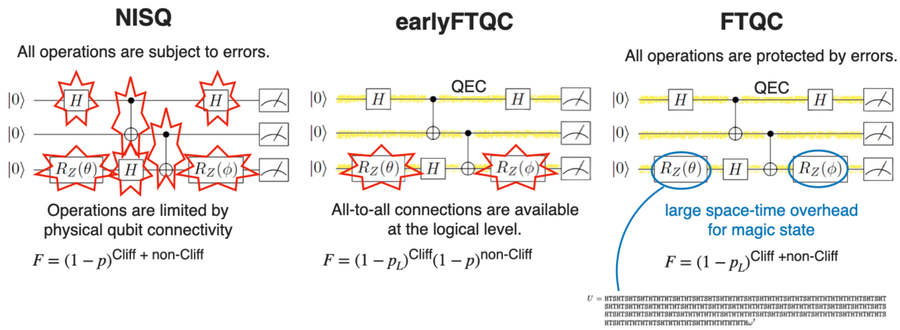
This study proposes the "Trotter24" algorithm, which directly measures the error of the widely used Trotter decomposition on quantum circuits and keeps circuit depth low while maintaining a target accuracy. By coupling second- and fourth-order Trotterizations to estimate the error, it eliminates the need for ancillary qubits and automatically chooses, at each step, the largest time slice that remains within a preset tolerance. Traditional methods adopt conservative step sizes based on worst-case theoretical bounds, leading to unnecessarily deep circuits; in contrast, Trotter24 treats the higher-order formula as an "error meter" and adaptively sets the step width. Applicable to both time-dependent and time-independent Hamiltonians, the algorithm was validated on spin chains, where it preserved accuracy with step sizes roughly ten times larger than those dictated by theoretical error bounds, cutting gate counts dramatically. The work advances accuracy-guaranteed Hamiltonian simulation from the NISQ era into early fault-tolerant quantum computing.



(Top panel) Comparison between the errors produced by the proposed method (blue: low target accuracy; orange: high target accuracy) and the curve given by the theoretical upper bound. (Bottom panel) Ratio of the Trotter step size prescribed by the proposed method to the step size prescribed by the theoretical upper bound.

Practical quantum advantage on partially fault-tolerant quantum computer

We propose a framework for achieving practical quantum advantage on early fault-tolerant quantum computing (FTQC) devices, bridging the gap between NISQ machines and fully fault-tolerant architectures. By adopting partially fault-tolerant operations at the logical level, we develop a space-efficient protocol that generates auxiliary states for small-angle non-Clifford rotations, eliminating the need for costly T-gate distillation and attaining logical error rates proportional to the rotation angle θ. As proof-of-concept applications, we consider Trotterized time evolution and quantum phase estimation (QPE); for an 8 × 8 Hubbard model, our analysis shows that QPE can be performed at a physical error rate of 10^{-4} with 4.9 × 10^4 qubits in nine days, or in just twelve minutes under full parallelization. This outperforms state-of-the-art tensor-network simulations and points the way to materials calculations on the order of sixty-thousand qubits. By sidestepping the heavy cost of distillation and dramatically cutting space-time overhead, the method offers clear guidance for implementing practical quantum algorithms in the early-FTQC era.



Comparison of the partially fault-tolerant approach envisioned for early FTQC with both NISQ and fully fault-tolerant regimes. By sidestepping the magic-state distillation normally needed for non-Clifford operations, quantum advantage can be achieved with a smaller number of physical qubits.

Core members

(Special Postdoctoral Researcher) **Yasushi Yoneta**
(Research Scientist) **Tatsuhiko Ikeda**
(Postdoctoral Researcher) **Takaya Matsuura**

Quantum Information Physics Theory Research Team

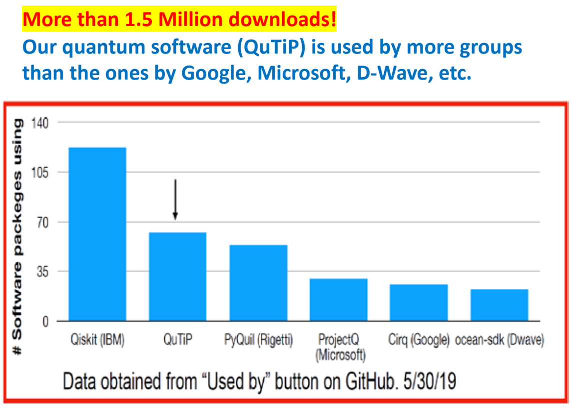
Keywords: Quantum physics, Quantum optics, Quantum information processing and quantum computing, Artificial intelligence, Machine learning, Software for quantum physics, Superconducting qubits

Research Outline

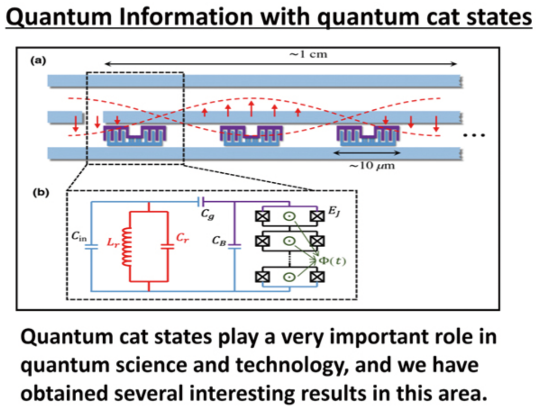
Our research group performs interdisciplinary studies at the interface between quantum computing, quantum information processing, superconducting quantum circuitry for quantum computing, photonics, quantum optics, atomic physics, nano-mechanics, nanoscience, mesoscopics, computational physics, and condensed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

We developed the QuTiP software used worldwide for quantum information processing, quantum optics, and quantum open systems. QuTiP has been downloaded more than two million times. 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 eight years (from 2017 to 2024). 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.).



Our software QuTiP is widely used by many research groups, and it has been downloaded more than 1.5 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 Director

Selected Publications

1 Y. Zeng, W. Qin, Y.H. Chen, C. Gneiting, F. Nori, "Neural-Network-Based Design of Approximate Gottesman-Kitaev-Preskill Code", *Phys. Rev.* Lett. 134, 060601 (2025).
2 W. Qin, A. Miranowicz, F. Nori, "Exponentially Improved Dispersive Qubit Readout with Squeezed Light", *Phys. Rev.* Lett. 133, 233605 (2024).
3 Y. Zeng, Z.Y. Zhou, E. Rinaldi, C. Gneiting, F. Nori, "Approximate Autonomous Quantum Error Correction with Reinforcement Learning", *Phys. Rev.* Lett. 131, 050601 (2023).
4 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).
5 W. Qin, A. Miranowicz, H. Jing, F. Nori, "Generating Long-Lived Macroscopically Distinct Superposition States in Atomic Ensembles", *Phys. Rev.* Lett. 127, 093602 (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 and afterwards Team Director for the Quantum Information Physics Theory Research Team, Quantum Computing Center, RIKEN, Japan. (-present)

Recent Achievements

Neural network design of quantum error correction codes

GKP encoding holds promise for continuous-variable fault-tolerant quantum computing. While an ideal GKP encoding is abstract and impractical due to its nonphysical nature, approximate versions provide viable alternatives. Conventional approximate GKP codewords are superpositions of multiple large-amplitude squeezed coherent states. This feature ensures correctability against single-photon loss and dephasing at short times, but also increases the difficulty of preparing the codewords. To minimize this tradeoff, we utilize a neural network to generate optimal approximate GKP states, allowing effective error correction with just a few squeezed coherent states. We find that such optimized GKP codes outperform the best conventional ones, requiring fewer squeezed coherent states, while maintaining simple and generalized stabilizer operators. Specifically, the former outperform the latter with just one-third of the number of squeezed coherent states at a squeezing level of 9.55 dB. This optimization drastically decreases the complexity of codewords while improving error correctability.

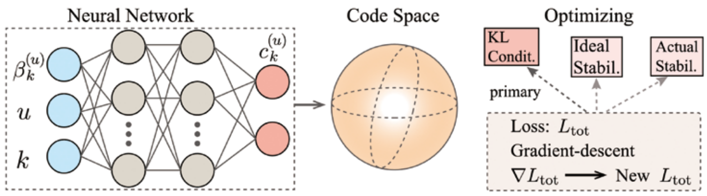
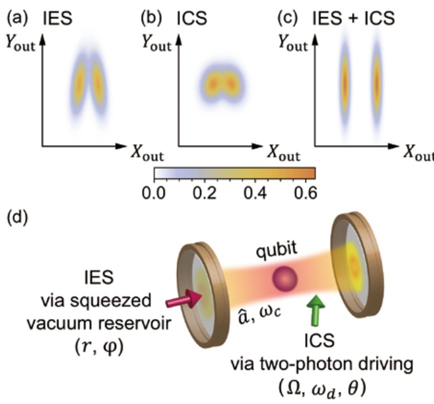


Diagram of the code optimization process. The input of the neural network is shown in blue, and the output in light red. The gradient-based optimization of the loss function L_{tot} determines the coefficients of the output of the neural network.

©Y. Zeng, W. Qin, Y.H. Chen, C. Gneiting, F. Nori, *Neural-Network-Based Design of Approximate Gottesman-Kitaev-Preskill* Code, Phys. Rev. Lett. 134, 060601 (2025).

Exponentially improved dispersive qubit readout with squeezed light

It has been a long-standing goal to improve dispersive qubit readout with squeezed light. However, injected external squeezing (IES) cannot enable a practically interesting increase in the signal-to-noise ratio (SNR), and simultaneously, the increase of the SNR due to the use of intracavity squeezing (ICS) is even negligible. Here, we counterintuitively demonstrate that using IES and ICS together can lead to an exponential improvement of the SNR for any measurement time, corresponding to a measurement error reduced typically by many orders of magnitude. More remarkably, we find that in a short-time measurement, the SNR is even improved exponentially with twice the squeezing parameter. As a result, we predict a fast and high-fidelity readout. This work offers a promising path toward exploring squeezed light for dispersive qubit readout, with immediate applications in quantum error correction and fault-tolerant quantum computation.



(a)–(c) Phase-space representation of dispersive qubit readout (DQR) with injected internal squeezing (IES), intracavity squeezing (ICS), and these two simultaneously. The separate use of IES and ICS cannot enable a significant improvement of practical interest in the SNR, but their simultaneous use can. (d) Schematic of DQR with both IES and ICS. The qubit is dispersively coupled to the cavity mode "a" of frequency ω_c. A squeezed vacuum reservoir (squeezing parameter r, reference phase ϕ) provides IES for the cavity, while a two-photon driving (amplitude Ω, frequency ω_d, phase θ) is used to generate ICS.

©W. Qin, A. Miranowicz, F. Nori, *Exponentially Improved Dispersive Qubit Readout with Squeezed Light*, Phys. Rev. Lett. 133, 233605 (2024).

Core members

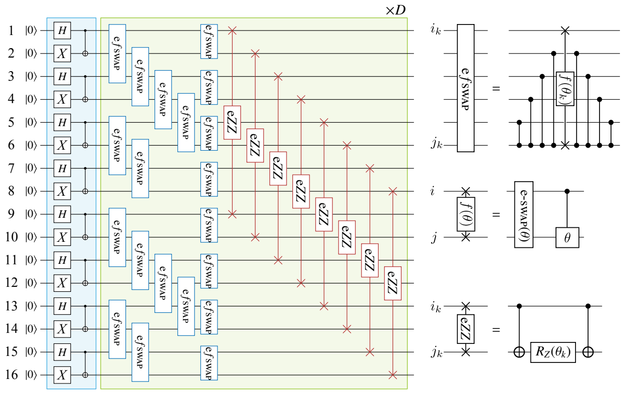
(Research Scientist) **Clemens GNEITING**
(JSPS Postdoctoral Researcher) **Paul Menczel**
(JSPS Postdoctoral Researcher) **Therese Karmstrand**
(RIKEN SPDR) **Ran Huang**

Quantum Computational Science Research Team

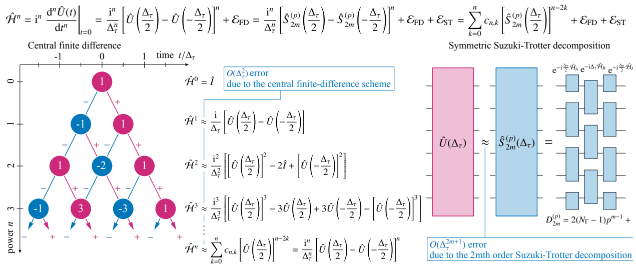
Keywords: Quantum many-body systems, Quantum dynamics, Quantum information physics, Tensor network, High performance computing

Research Outline

Our main interest lies in developing quantum-classical hybrid algorithms for simulating quantum many-body systems. We also study quantum dynamics in quantum computing from the perspective of quantum information theory. To this end, we design and implement quantum simulations on classical computers. In addition, we are exploring quantum-classical hybrid systems as a foundation for future high-performance computing.



Quantum circuits for VQE calculations of Hubbard model



Schematic figure for quantum power methods

Seiji Yunoki (Ph.D.), Team Director

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).

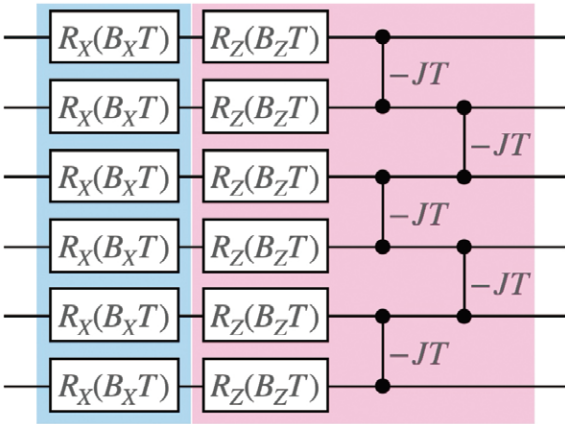
Brief resume

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 (-present)
2017 Chief Scientist, Computational Condensed Matter Physics Laboratory, RIKEN (-present)
2018 Team Leader, Computational Materials Science Research Team, RIKEN Center for Computational Science (-present)
2021 Team Leader, Quantum Computational Science Research Team, Riken Center for Quantum Computing (-present)

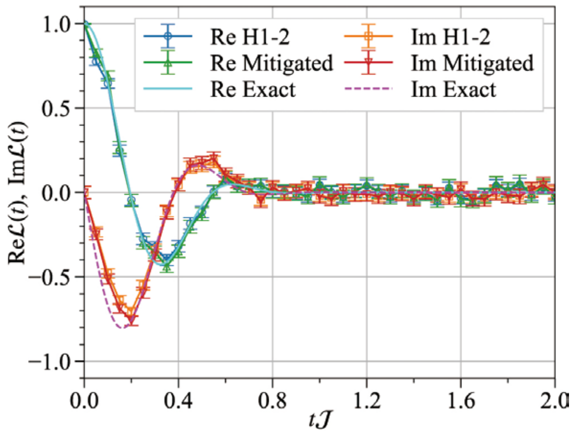
Recent Achievements

Simulating Floquet scrambling circuits on trapped-ion quantum computers

Complex quantum many-body dynamics spread initially localized quantum information across the entire system. Information scrambling refers to such a process whose simulation is one of the promising applications of quantum computing. We demonstrate the Hayden-Preskill recovery protocol and the interferometric protocol for calculating out-of-time-ordered correlators to study the scrambling property of a one-dimensional kicked-Ising model on 20-qubit trapped-ion quantum processors. The simulated quantum circuits have a geometrically local structure that exhibits the ballistic growth of entanglement, resulting in the circuit depth being linear in the number of qubits for the entire state to be scrambled. We experimentally confirm the growth of signals in the Hayden-Preskill recovery protocol and the decay of out-of-time-ordered correlators at late times. As an application of the created scrambling circuits, we also experimentally demonstrate the calculation of the microcanonical expectation values of local operators adopting the idea of thermal pure quantum states.



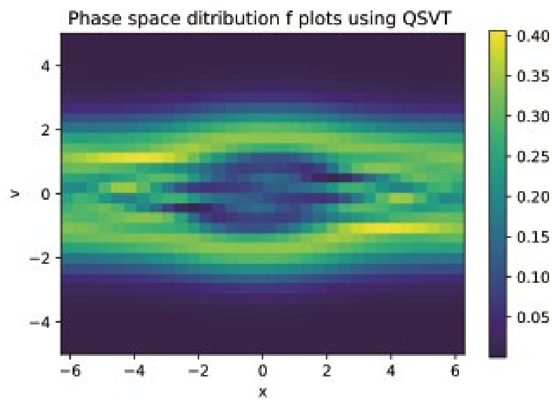
Schematic figure of Floquet quantum circuit based on one-dimensional kicked Ising model. A single period of the Floquet circuit consists of X-rotation gates, Z-rotation gates, and ZZ-rotation gates.



Real and Imaginary parts (cool and warm colors) of the Loschmidt amplitude of a one-dimensional 16-site Heisenberg model as a function of time. Squares represent hardware results, triangles represent error-mitigated results based on a global depolarizing noise model, and lines represent noiseless simulation results.

Efficient Hamiltonian simulation of nonlinear differential equations based on quantum singular value transformation

The Vlasov-Maxwell equations provide kinetic simulations of collisionless plasmas, but numerically solving them on classical computers is often impractical. This is due to the computational resource constraints imposed by the time evolution in the 6-dimensional phase space, which requires broad spatial and temporal scales. In this study, we develop a quantum-classical hybrid Vlasov-Maxwell solver. Specifically, the Vlasov solver implements the Hamiltonian simulation based on Quantum Singular Value Transformation (QSVT), coupled with a classical Maxwell solver. We perform numerical simulation of a 1D advection test and a one coordinate in space and one coordinate in velocity (1D1V) two-stream instability test on the Qiskit-Aer-GPU quantum circuit emulator with an A100 GPU. It was also confirmed that, compared to conventional classical methods for solving nonlinear differential equations, the quantum algorithm-based approach offers a partial exponential speedup in computational complexity.



The quantum computational numerical results of the QSVT-based Hamiltonian simulation scheme for the 1D1V Vlasov-Maxwell equations under the two-stream instability conditions. The distribution function in the x-v phase space is shown at real time T = 53, with the vertical axis representing the velocity space and the horizontal axis representing the physical space.

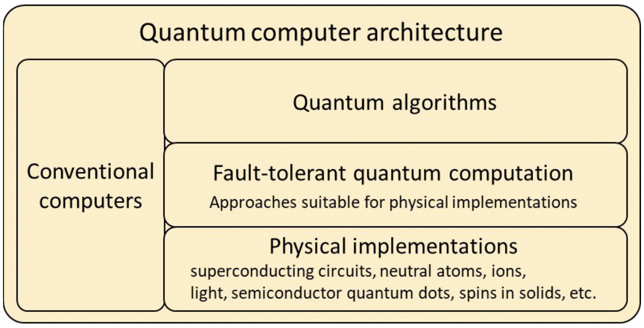
Quantum Computer Architecture Research Team

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

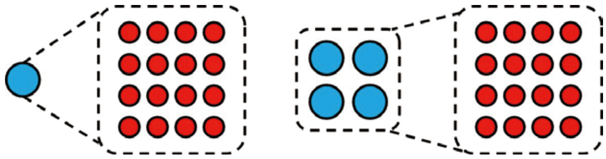
Research Outline

We are theoretically studying 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, such as superconducting circuits, neutral atoms, ions, light, semiconductor quantum dots, and spins in solids, are under development. Since different implementations have different types of errors and different connectivity, it is effective to develop an approach to FTQC dedicated to each implementation. Also, since early quantum computers will be small, they should be designed for desirable 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. Conventional approaches to FTQC use the encoding of a single logical qubit into many physical qubits, leading to the resource problem. Thus high-rate codes encoding many logical qubits at once have recently attracted much attention. However, 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) and high-rate code (right).

Hayato Goto (Ph.D.), Team Director

Selected Publications

1 H. Goto, “High-performance fault-tolerant quantum computing with many-hypercube codes”, *Sci. Adv.* 10, eadp6388 (2024).
2 H. Goto, Y. Ho, and T. Kanao, “Measurement-free fault-tolerant logical-zero-state encoding of the distance-three nine-qubit surface code in a one-dimensional qubit array”, *Phys. Rev.* Research, 5, 043137 (2023).
3 H. Goto, “Minimizing resource overheads for fault-tolerant preparation of encoded states of the Steane code”, *Sci. Rep.*, 6, 19578 (2016).
4 H. Goto, “Step-by-step magic state encoding for efficient fault-tolerant quantum computation”, *Sci. Rep.*, 4, 7501 (2014).
5 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).

Brief resume

2003 Researcher, Toshiba Corporation
2007 Ph.D. (Science), The University of Tokyo
2016 Senior Research Scientist, Toshiba Corporation
2020 Fellow, Toshiba Corporation
2023 Senior Fellow, Toshiba Corporation (-present)
2023 Team Leader, Quantum Computer Architecture Research Team, RIKEN Center for Quantum Computing
2025 Team Director, Quantum Computer Architecture Research Team, RIKEN Center for Quantum Computing (-present)

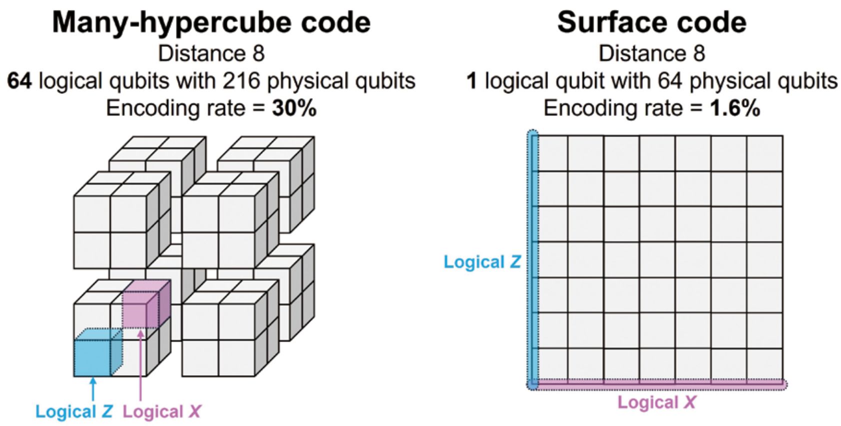
Recent Achievements

High-performance fault-tolerant quantum computing with the proposed high-rate codes named “many-hypercube codes”

In conventional fault-tolerant quantum computation (FTQC), a single logical qubit is encoded into many physical qubits. For instance, the distance-d surface code encodes a logical qubit into d^2 physical qubits, where the distance represents the code size and distance-d codes can correct, in principle, qubit errors less than $d/2$. In the case of the surface code, the encoding rate r is $1/d^2$, which asymptotically becomes zero as the code size increases. This is the major reason for huge resource overhead in FTQC. Thus recently, high-rate codes with constant rates, such as quantum LDPC (low-density parity check) codes, have attracted attention. For example, 4%-rate quantum LDPC codes have been well studied for FTQC. However, the quantum LDPC codes have the issues that their rates are still low and moreover it is relatively difficult for them to perform logical gates in parallel. Hence, the “high-performance FTQC” realizing both high encoding rates and parallelizability of logical gates has been difficult so far.

We propose the $[[6^L,4^L,2^L]]$ quantum code obtained by concatenating the [[6,4,2]] code (distance-two quantum error-detecting code encoding 4 logical qubits into 6 physical qubits), which is one of the simplest quantum codes. The structure of this code can be expressed by 4^L hypercubes. Therefore we call it “many-hypercube code.” The encoding rate of this code is $(4/6)^L$, which asymptotically approaches zero, but as high as 30% and 20% for the distance 8 and 16 (L=3, 4), respectively. We have developed a high-performance decoder for the high-rate quantum code. Moreover, developing fault-tolerant encoders dedicated to this code, we have shown by numerical simulation that the error threshold for logical controlled-NOT gates is as high as 1%. Also, we have proposed the methods to perform logical gates necessary for universal quantum computation in parallel. Thus, our proposed many-hypercube code will allow us to realize the high-performance FTQC.

H. Goto, “High-performance fault-tolerant quantum computing with many-hypercube codes”, Sci. Adv. 10, eadp6388 (2024).



Comparison between many-hypercube code and surface code (code distance is 8)

Core members

(Research Scientist) **Ryota Nakai**

(Postdoctoral Researcher) **Naoyuki Kanomata**

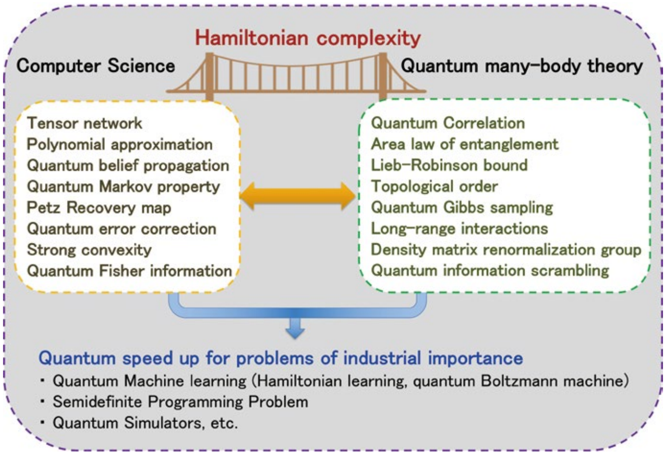
Analytical Quantum Complexity RIKEN Hakubi Research Team

Keywords: Quantum Computing, Quantum Entanglement, Hamiltonian Complexity, Quantum many-body physics, Quantum Algorithm

Research Outline

Over the past two decades, quantum computation within the realm of quantum information theory remained largely theoretical, with doubts cast on its practical applicability. This changed recently, especially in 2019, when Google's 53-qubit "Sycamore" quantum computer demonstrated "quantum supremacy" by performing specific calculations much faster than conventional computers. However, many issues still need resolution for practical use.

To meet these challenges, researchers worldwide are working on developing more useful algorithms, particularly in quantum many-body theory. In the realm of quantum physics, invisible particles like electrons and atoms play the main roles. Their interactions determine the properties of matter. These collections of particles, known as "quantum many-body systems," are central to understanding phenomena from electron movement to superconductivity and the development of quantum computers. This theory, which deals with the interactions of numerous quantum particles, can lead to unexpected phenomena, making it difficult to calculate. This area of study is known as Hamiltonian complexity.



Schematic figure for quantum Hamiltonian

Hamiltonian complexity research focuses on when and how quantum Hamiltonians can be efficiently simulated. Significantly, many problems in quantum computing belong to a class known as QMA (the quantum version of NP), which can be reduced to quantum many-body problems. Therefore, developing algorithms to solve quantum many-body problems is key to addressing all problems in the QMA class.

Hamiltonian complexity is a research area between computer science and physics with many mathematically defined unsolved problems. Our laboratory explores solutions to these mathematical challenges, having already achieved partial or complete solutions to significant issues such as the quantum entanglement boundary law conjecture, the quantum Markov conjecture, the line-ar-light-cone problem in the Lieb-Robinson bounds, quantum Hamiltonian learning, and long-range quantum entanglement at finite temperatures. Our goal is to further develop our research findings and tackle new unsolved problems.

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

Selected Publications

1 R. Achutha, D. Kim, Y. Kimura, T. Kuwahara, "Efficient Simulation of 1D Long-Range Interacting Systems at Any Temperature," *Physical Review Letters* 134 (19), 190404 (2025).
2 Z-G. Lu, G. Tian, X-Y. Lü, C. Shang, "Topological quantum batteries," *Physical Review Letters* 134 (18), 180401 (2025).
3 D. Kim, T. Kuwahara, K. Saito, "Thermal Area Law in Long-Range Interacting Systems," *Physical Review Letters* 134 (2), 020402 (2025).
4. Y. Kimura, T. Kuwahara, "Clustering theorem in 1D long-range interacting systems at arbitrary temperatures," *Communications in Mathematical Physics* 406 (3), 1-43 (2025).
5 T. V. Vu, T. Kuwahara, K. Saito, "Optimal light cone for macroscopic particle transport in long-range systems: A quantum speed limit approach," *Quantum* 8 1483 (2024).

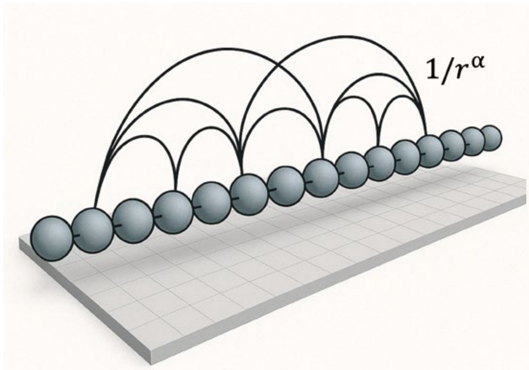
Brief resume

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 (-present)
2022 RIKEN Hakubi team leader, RIKEN Cluster for Pioneering Research / RIKEN Center for Quantum Computing, RIKEN (-present)

Recent Achievements

Resolution of the entanglement area law conjecture in bosonic systems

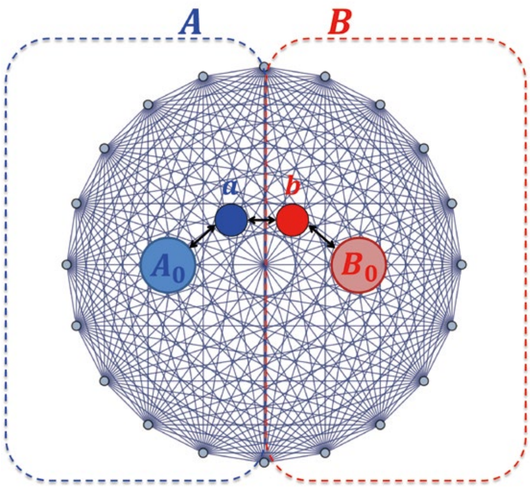
The entanglement area law states that the amount of quantum entanglement between two subsystems, when a global system is bipartitioned, is proportional to the size of the boundary between them. The area law conjecture posits that this behavior holds universally in any non-critical ground state. This conjecture forms the foundational assumption behind a range of tensor network-based algorithms, such as the density matrix renormalization group (DMRG). A breakdown of the area law would imply a fundamental failure of these computational methods. Furthermore, the area law plays a central role in the classification of quantum phases, making its rigorous proof one of the most important unresolved problems spanning quantum information science and quantum many-body theory. While proofs in one-dimensional systems have been well established, they have relied on the assumption of finite and short-range interactions. Previous work extended the area law to long-range systems; however, the case where interaction strengths diverge, such as in interacting bosonic systems, has remained largely unexplored. In this study, we have succeeded in proving the most general form of the area law in one-dimensional systems, removing both constraints: bosonic statistics and long-range interaction. This result constitutes a complete proof of the area law conjecture in one dimension.



Interacting bosonic systems are known to lack an upper bound on energy, and this study considers systems with long-range interactions decaying as 1/r^α. This result establishes the most general proof of the entanglement area law in one-dimensional systems, removing fundamental assumptions such as short-range interactions and bounded energy.

Generalized entanglement area law on fully connected graphs

Significant progress has also been made on the area law conjecture in higher-dimensional systems. Prior to this work, no unconditional proof had been established for the area law in dimensions beyond one. All known results required strong assumptions, such as locality constraints or specific decay properties of correlations, making general conclusions elusive. In this study, we successfully proved the entanglement area law unconditionally on a fully connected graph, which corresponds to the infinite-dimensional limit. In this setting, the boundary size is quantified in terms of the Schmidt rank between subsystems. This result is particularly noteworthy because it had long been believed that the area law fails in infinite-dimensional graphs; explicit counterexamples had been known, and it was widely assumed that such structures violate the area law due to their nonlocal nature. Contrary to this belief, our findings demonstrate that even in these extreme cases, the area law can hold, establishing a new direction in the study of entanglement structure in complex quantum systems. In addition, we developed a novel method to efficiently simulate ground states on infinite-dimensional graphs based on our proof. This framework opens the door to a new class of efficient algorithms applicable to highly connected quantum many-body systems. This work has been presented at Quantum Information Processing 2025 (QIP'25).



Schematic illustration of the generalized area law on a fully connected graph. The system is partitioned into two subsystems, A and B. When the interaction between A and B has a low Schmidt rank, the entanglement across the boundary is effectively governed by a limited number of degrees of freedom, denoted as a and b in the figure. This reflects the generalized area law, which states that the entanglement entropy between A and B is bounded by a constant, up to poly-logarithmic corrections. This work proves that such a bound on entanglement can be guaranteed with only a poly-logarithmic overhead.

Core members

(Research Scientist) **Yusuke Kimura**
(Postdoctoral Researcher) **Donghoon Kim**
(Postdoctoral Researcher) **Shang Cheng**
(RIKEN JRA student) **Ayumi Ukai**
(Part Timer) **Hideaki Nishikawa**

Mathematical Quantum Information RIKEN Hakubi Research Team

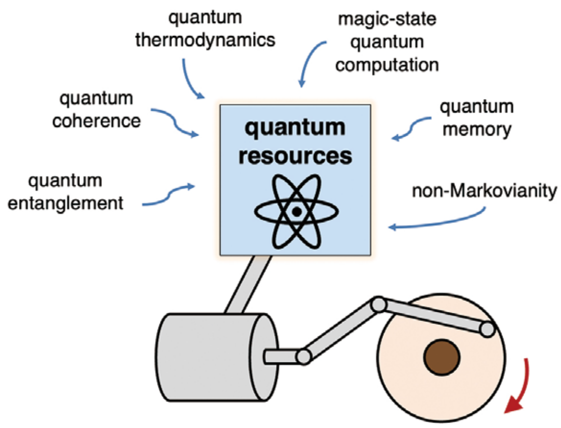
Keywords: Quantum information, Quantum resource theories, Quantum Shannon theory, Mathematical physics

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.



Many different resources underlie the power of quantum information. We aim to develop tools to understand them better through general, mathematical approaches.

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

Selected Publications

1 B. Regula and L. Lami, “Reversibility of quantum resources through probabilistic protocols”, *Nat. Commun*. 15, 3096 (2024).
2 L. Lami and B. Regula, “No second law of entanglement manipulation after all”, *Nat. Phys.* 19, 184–189 (2023).
3 B. Regula, “Probabilistic transformations of quantum resources”, *Phys. Rev. Lett.* 128, 110505 (2022).
4 B. Regula and R. Takagi, “Fundamental limitations on distillation of quantum channel resources”, *Nat. Commun.* 12, 4411 (2021).
5 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).

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)

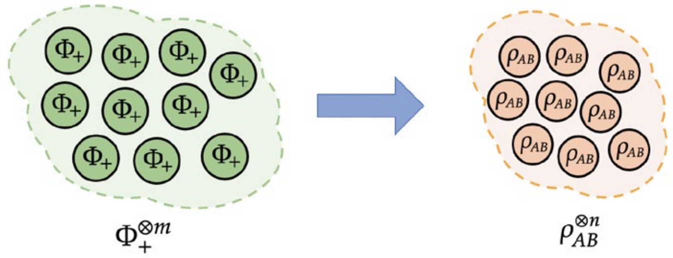
Recent Achievements

Efficiently computing the cost of entanglement

How “expensive” is a quantum state to prepare? Since quantum entanglement is one of the most precious resources in quantum information, it is natural to ask about the entanglement cost, that is, how costly a given quantum state is in terms of the required entanglement. To realize the best possible protocols for this problem, one needs to manipulate many copies of quantum states, and the lowest entanglement cost is then computed by evaluating the asymptotic limit where the number of copies can be arbitrarily high. However, such asymptotic problems are typically extremely hard to compute exactly.

Here we show that, surprisingly, the exact entanglement cost can be computed efficiently through an accessible optimization method known as semidefinite programming. We define a hierarchy of semidefinite programs and show that it captures exactly the properties of entanglement cost, allowing for the first time for its computation for any quantum state.

L. Lami, F. A. Mele, and B. Regula, “Computable entanglement cost under positive partial transpose operations”, Physical Review Letters 134, 090202 (2025)



$$E_N = E_{\chi,0} \leq E_{\chi,1} \leq E_{\chi,2} \leq \ldots \leq E_{c,\mathrm{PPT}}^{\mathrm{exact}} \leq \ \ldots \leq E_{\kappa,3} \leq E_{\kappa,2} \leq E_\kappa$$

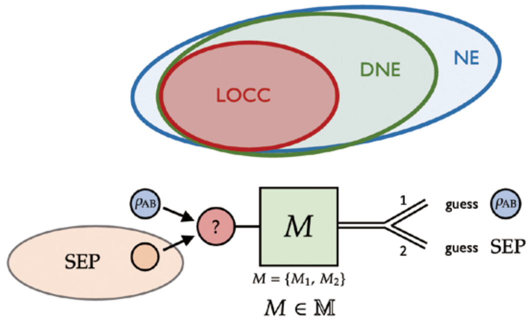
We establish methods for the efficient computation of the entanglement cost, that is, the amount of entanglement (here visualised as the green maximally entangled states Φ_+) that is needed to produce a desired many copies of a desired quantum state ρ_{AB}. Our method uses a hierarchy of semidefinite programs, each of which can be computed efficiently, to give an arbitrarily close approximation of the entanglement cost.

A formula for distillable entanglement

Quantum entanglement is a key resource behind the advantages of quantum technologies. Many applications require pure “entanglement bits” (maximally entangled pure states) but real-world quantum states are often noisy. This makes extracting useful entanglement from noisy states — entanglement distillation — essential. Despite attention since the early days of quantum information, the protocol remains poorly understood, and basic questions, like how many entanglement bits can be distilled, are still open.

Here we give one of the very first exact solutions for the problem of distillation by establishing a precise formula for the number of bits that can be extracted asymptotically, connecting the rate of distillation with the task of quantum state discrimination and with an entropic quantity based on the quantum relative entropy of entanglement.

L. Lami and B. Regula, “Distillable entanglement under dually non-entangling operations”, Nature Communications 15, 10120 (2024)



We compute the rate of entanglement distillation under dually non-entangling (DNE) operation, which provides an approximation to the operations that can be efficiently realized in a laboratory (denoted LOCC). Our technique is to connect the task of distillation with a quantum state discrimination problem where the measurements are suitably constrained (bottom part of the figure). This leads to an exact formula for the rate of distillation, which we expressed using a variant of quantum relative entropy.

Core members

(Postdoctoral Researcher) **Hayato Arai**

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.

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.

Opening of the "RIKEN RQC-Fujitsu Collaboration Center"

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

Selected Publications

1 R. Toshio, Y. Akahoshi, J. Fujisaki, H. Oshima, S. Sato, K. Fujii, "Practical quantum advantage on partially fault-tolerant quantum computer," *Phys. Rev. X* 15, 021057 (2025).
2 Y. Akahoshi, K. Maruyama, H. Oshima, S. Sato, K. Fujii, "Partially Fault-tolerant Quantum Computing Architecture with Error-corrected Clifford Gates and Space-time Efficient Analog Rotations," *PRX Quantum* 5, 010337 (2024).
3 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).
4 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).
5 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).

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
2023 Fellow, Head of Quantum Laboratory, Fujitsu Research, Fujitsu Limited (-present)

*Director is Dr. Yasunobu Nakamura

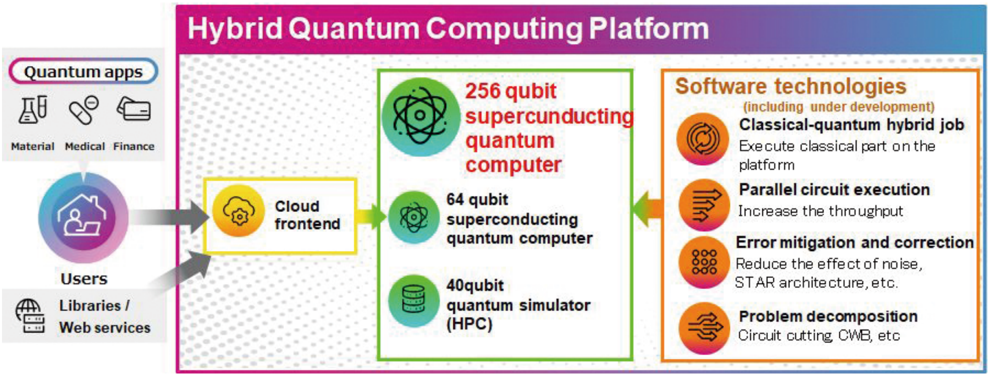
Recent Achievements

Development of world-leading 256-qubit superconducting quantum computer

Our group developed a world-leading 256-qubit superconducting quantum computer, which is based on the advanced technology of the 64-qubit superconducting quantum computer launched in October 2023 and newly developed high-density integration technology.

In the 256-qubit computer, it is demonstrated that the unit cell design established in the 64-qubit computer can be scaled up to 256-qubit. In addition, it was possible to achieve four times higher density while using the same dilution refrigerator as the 64-qubit computer by implementing a housing design to improve cooling efficiency. The 256-qubit superconducting quantum computer will be integrated into Fujitsu's platform for hybrid quantum computing lineup and offered to companies and research institutions globally starting in the first quarter of FY2025.

256-qubit quantum computer

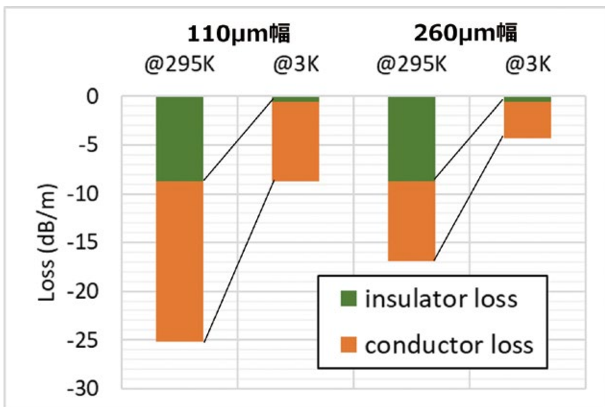


Overview of the new platform for hybrid quantum computing

Development of material parameter extraction method at low temperature

High-density wiring at low temperature has become increasingly important for increasing the number of qubits. However, while there are reports regarding PCB material parameters using resonators at around room temperature, the parameters at low temperatures (less than several K) are not well understood. We proposed a novel method to extract the material parameters, which consists of simple wiring measurement and 3D electromagnetic analysis. This method involves preparing two or more wiring cross-sectional shapes and two or more wiring lengths, and separating dielectric loss, conductor loss, and other losses.

By using the method, we demonstrated that both dielectric loss and conductor loss decrease at low temperatures, with conductor loss becoming dominant, which is the key factor for increasing wiring density and the number of wires.



Example of breakdown of printed circuit board wiring loss at 10 GHz at low temperatures

Office of the Center Director

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

Outline

We are responsible for the management of the Quantum Computing Research Center's overall operations, including research on technology, intellectual property, and standardization trends, information dissemination, and the organization of events.

Based on the government's Quantum Technology Innovation Strategy, RIKEN is positioned as the core organization that coordinates the 11 domestic quantum technology innovation centers and their activities from basic research to social implementation of quantum technology. We are responsible for the management of this core organization. Furthermore, as the head quarter of Flagship Program for the Q-LEAP by MEXT, we are engaged in promotion activities for the quantum technology. We are also in charge of the operation and management of the superconducting quantum computer "A," which has been opened to the public in March 2023.

I am also involved in the following research and development.

- A project leader of "Building and operation of a domestically developed quantum computer testbed environment" on CSTI-SIP program "Promoting the application of advanced quantum technology platforms to social issues".
- A project leader of "Design and fabrication of hybrid chips of qubits and peripheral electronics" on "Development of Integration Technologies for Superconducting Quantum Circuits" of Moonshot Goal6 projects.

Members of Office of the Center Director

Core members

(Coordinator) **Toshio Tonouchi**
(Research Administrator) **Koji Ikado**
(Research Administrator) **Satoshi Tomita**
(Research Administrator) **Hideaki Oba**
(Research Administrative Support Staff) **Kimiko Kowashi**
(Temporary Employee) **Masanobu Arai**
(Temporary Employee) **Haruyuki Iwabuchi**
(Administrative Part-time Worker I) **Minako Yamaguchi**

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
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)

Tracing the main source of noise in silicon quantum computers

Measurements of the noise experienced by two neighboring quantum dots will aid the design of silicon quantum computers

Category: Applied Physical Sciences **Field**: Physics/Astronomy

The noise in silicon-based quantum computers is mainly electrical in origin, a RIKEN team has found[1]. This finding will help to suppress noise in future quantum computers.

Quantum computers are set to revolutionize computing since they harness the quantum properties of tiny objects to perform calculations that are not possible using conventional computers.

Like most people, however, quantum computers struggle to perform calculations in noisy environments. In the case of quantum computers, the noise is not audible, but rather it comes from a variety of sources and can be electrical or magnetic. It has the effect of degrading the 'quantumness' of qubits—the quantum equivalent of bits—which can introduce errors in calculations.

One of the most promising platforms being pursued for quantum computers involves tiny silicon structures known as quantum dots. One big advantage they have is that many quantum dots can be squeezed into a small area, which will help to scale up to the larger quantum computers needed to tackle practical problems. However, cramming a lot of qubits close together will increase the likelihood that they will be affected by noise.

But little has been known about the main sources of noise for qubits made from silicon quantum dots.

Now, a team led by Seigo Tarucha of the RIKEN Center for Emergent Matter Science has measured the noise between two silicon qubits that were 100 nanometers apart.

To their surprise, they found that the noise the two qubits experienced displayed similar patterns over time. This similarity points to a common source of noise, which the team found is electrical in origin.

This finding was not what the researchers had anticipated. "We initially thought that the metal gates in our device would largely shield the qubits from charge noise," says Tarucha. "But the screening turned out to be smaller than we had expected."

This finding has important ramifications for the design of future quantum computers based on silicon qubits. "It will be important to modify device geometry to suppress this noise that affects multiple qubits simultaneously," says Tarucha. "We believe this can be done."

In addition, the nanoscopic approach adopted in this study provides a powerful tool for investigating noise correlation between silicon qubits. "Noise correlation significantly influences the fault tolerance of quantum computers, error-correction protocols and the design of multi-qubit devices," says Tarucha. "However, there has been no accurate way to measure it until now."

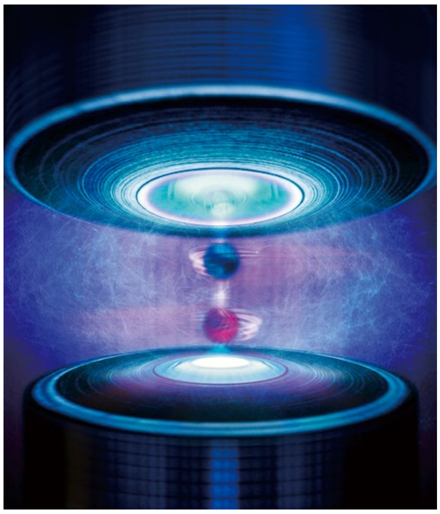


Figure: An artist's impression of the quantum property known as spin. A RIKEN team has measured the noise experienced by two spin qubits in silicon that are 100 nanometers apart and found a high degree of correlation between them.

"We plan to analyze the correlation-noise characteristics more accurately and to optimize device design so as to minimize noise correlation," adds Tarucha. "We eventually want to apply the concept to implement devices with large numbers of qubits."

Related content:

Quantum computers start to measure up [https://www.riken.jp/en/news_pubs/research_news/rr/20231221_1/index.html]

Researchers demonstrate error correction in a silicon qubit system [https://www.riken.jp/en/news_pubs/research_news/pr/2022/20220825_1/]

Scientists achieve key elements for fault-tolerant quantum computation in silicon spin qubits [https://www.riken.jp/en/news_pubs/research_news/pr/2022/20220120_1/index.html]

Reference

1. Yoneda, J., Rojas-Arias, J. S., Stano, P., Takeda, K., Noiri, A., Nakajima, T., Loss, D. & Tarucha, S. Noise-correlation spectrum for a pair of spin qubits in silicon. *Nature Physics* 19, 1793–1798 (2023). (doi.org/10.1038/s41567-023-02238-6)

RIKEN Research Spring 2024
These articles are edited versions of RIKEN Research Highlights.

Fast and faithful quantum measurements of electron spin qubits

A method for rapidly and precisely measuring the quantum state of electrons in a silicon device could help scale up quantum computers

Category: Applied Physical Sciences **Field:** Physics/Astronomy

Measuring a quantum system quickly and accurately is crucial for realizing reliable quantum computers. Physicists at RIKEN have developed a method that achieves both these requirements in a silicon-based device[1].

Most practical quantum technologies harness the weirdness of quantum mechanics in a basic element known as a qubit—the quantum equivalent of a bit in conventional computers. Qubits hold and maintain a quantum state.

They can be realized in various systems, including superconducting circuits, isolated atoms and laser beams. Another option is silicon devices that use the quantum state of a trapped electron—specifically, an electron property known as spin. These qubits have a real advantage over other qubits in that they are compatible with existing semiconductor-based computer components and fabrication technologies.

Practical applications of qubits, such as in fault-tolerant quantum computers, require a way to measure the quantum state accurately and quickly—before the quantum state degrades or collapses in a process referred to as decoherence.

Now, Kenta Takeda and Seigo Tarucha from the RIKEN Center for Emergent Matter Science and their co-workers have demonstrated a method for measuring spin in a silicon device with an accuracy of more than 99% and in just a few microseconds—hundreds of times faster than typical decoherence times.

Measuring the spin of a single electron directly is massively challenging because it involves detecting tiny magnetic fields. This limits the measurement accuracy, or fidelity.

To overcome this problem, Takeda and his team adopted a different approach—they converted the spin into an electrical charge.

To test this approach, they built a silicon device that trapped two electrons (Fig. 1). Owing to a fundamental principle of quantum physics that states that no two electrons can occupy the same quantum state, the team was able to infer the quantum state by monitoring current flowing through the device. In this so-called Pauli spin blockade effect, the measurement signal results from the difference in the charge states, which is easier to measure than magnetic fields.

"Spin measurement in silicon-based spin qubits has previously been slow, and its fidelity wasn't high enough," explains Takeda. "We improved the Pauli spin blockade by optimizing the structure of our device to enhance the sensitivity of the charge sensor. We also improved the spin-to-charge conversion technique so that the spin state was well preserved during the process."

"This achievement paves the way for realizing fault-tolerant quantum computing in this platform," he adds.

Related content:

Tracing the main source of noise in silicon quantum computers [https://www.riken.jp/en/news_pubs/research_news/rr/20240404_2/index.html]

Researchers demonstrate error correction in a silicon qubit system [https://www.riken.jp/en/news_pubs/research_news/pr/2022/20220825_1/]

Connecting distant silicon qubits for scaling up quantum computers [https://www.riken.jp/en/news_pubs/research_news/rr/20230331_1/index.html]

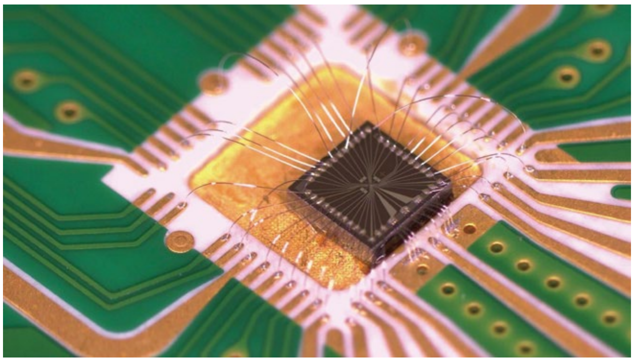


Figure: A silicon-based device that captures two electrons enables quick and accurate quantum-state measurement for quantum information processing.

Reference

1. Takeda, K., Noiri, A., Nakajima, T., Camenzind, L. C., Kobayashi, T., Sammak, A., Scappucci, G. & Tarucha, S. Rapid single-shot parity spin readout in a silicon double quantum dot with fidelity exceeding 99%. *npj Quantum Information* 10, 22 (2024). doi: 10.1038/s41534-024-00813-0

These articles are edited versions of RIKEN Research Highlights.

Boson systems break the finite speed limit

Information can travel faster than individual particles in systems made up of interacting bosons

Category: Exploratory Physical Sciences **Field**: Physics/Astronomy

The propagation of information can speed up over time in systems of certain quantum particles, a theoretical analysis by RIKEN physicists has revealed[1].

Having a Zoom call with someone on Mars would be challenging because of the 3-to-20-minute delay involved, but the delay would balloon to nearly 3 hours for Uranus. Switching to a better internet provider wouldn't help—these time lags are unavoidable since, according to Einstein, nothing can outpace light.

The two delays represent two points on a 'light cone' that spreads out from a source of electromagnetic radiation such as light.

But what about systems made up of quantum particles that travel much slower than light? Are there similar limitations on how fast information can propagate in them?

Two physicists explored that question in the early 1970s and came up with the concept of an 'effective light cone' for such systems. They also derived a speed limit for the propagation of information in them, which is known as the Lieb–Robinson velocity.

"Essentially, the Lieb–Robinson bound indicates that the impact of local changes within a quantum system cannot spread instantly everywhere; rather, these effects are limited to an effective light cone determined by this maximum speed," explains Tomotaka Kuwahara of the RIKEN Center for Quantum Computing. "The bound sets a universal speed limit for how quickly information can travel in these systems."

Scientists have measured the shapes of effective light cones in many different systems. But so far no one has determined it for a system made up of 'bosons' that interact with each other. Bosons are quantum particles that have a spin that is a whole number; examples include photons, gluons and the Higgs boson.

Now, Kuwahara and two co-workers have conducted a theoretical analysis for interacting bosons and found a surprise—information can travel much faster than the particles in certain cases.

This contrasts with the other type of quantum particles, fermions, which have half integer values of spin (e.g., 1/2 and 3/2) and which include electrons, protons and neutrinos.

"Previous studies had suggested that bosons and fermions behave the same in terms of information propagation," says Kuwahara. "We clarified that this intuition isn't correct and that significant differences exist between bosons and fermions."

The analysis, which involved a 115-page proof, revealed that bosons can send information much faster than fermions can, especially as time goes on. "For fermions, there's a fixed speed limit for how fast information can propagate," says Kuwahara. "But the picture is very different for systems of bosons—information can travel faster over time."

This finding could help to discover new quantum phases, Kuwahara says.

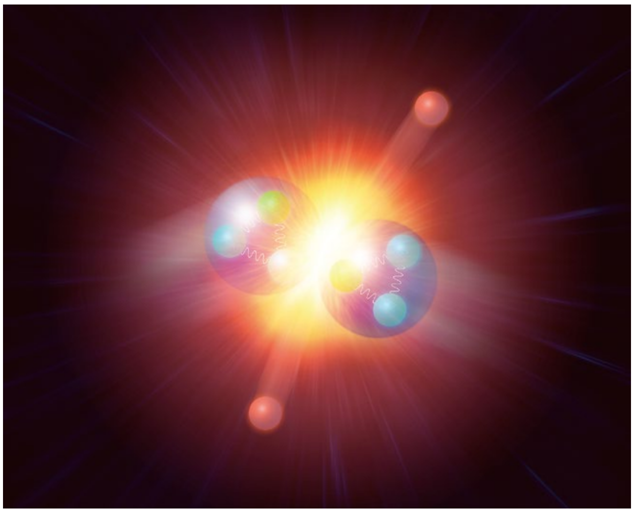


Figure: Conceptual illustration of the Higgs boson (orange, top and bottom) being produced by colliding two protons. RIKEN researchers have found that the propagation of information in systems of interacting bosons can accelerate over time.

[https://www.sciencephoto.com/media/1158510/view]

Related content:

Long-range quantum interactions limit the speed of information [https://www.riken.jp/en/news_pubs/research_news/rr/20201002_1/index.html]

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RIKEN Research Summer 2024

These articles are edited versions of RIKEN Research Highlights.

Unentangling entropy in the quantum realm

The classical thermodynamic concept of entropy is also applicable to the phenomenon of quantum entanglement

RIKEN researchers have shown that a rule of 'entropy', or disorder, applies to the phenomenon of quantum entanglement—a finding that could help to develop future quantum computers[1].

One of the most fundamental laws of nature, the second law of thermodynamics states that the entropy of an isolated system will always increase with time. It creates the so-called 'arrow of time'.

However, while the principle of entropy is known to apply to all classical systems, researchers are increasingly exploring the quantum world.

Quantum entanglement is a fascinating phenomenon whereby two or more quantum particles become connected in such a way that a change to one particle affects the other particles, even if they are separated by large distances—Einstein's famous "spooky action at a distance".

Quantum entanglement is highly useful for communication, computation and cryptography, but is difficult to analyze.

To demonstrate a 'second law' for quantum entanglement, physicists have to show that entanglement transformations are reversible, just as work and heat can be interconverted in thermodynamics.

But so far, all attempts to establish a reversible theory of entanglement have failed. Some physicists even suspected that entanglement may be irreversible, making the quest impossible.

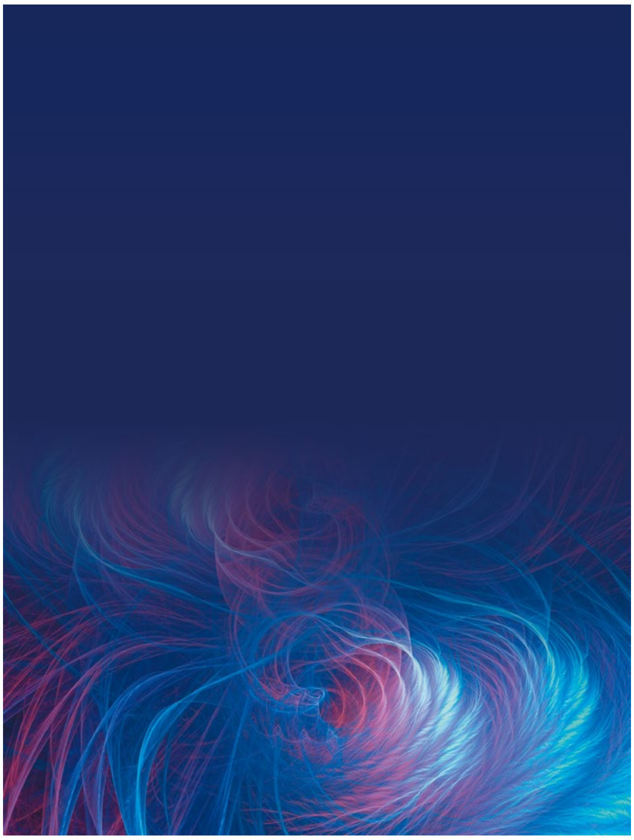
Now, a team led by Bartosz Regula of the RIKEN Center for Quantum Computing has solved this long-standing conjecture by using 'probabilistic' entanglement transformations. While these transformations are only guaranteed to be successful some of the time, they are more effective than non-probabilistic ones in converting quantum systems.

Under such transformations, the researchers showed that it is indeed possible to establish a reversible framework for entanglement manipulation. They thus identified a setting in which a unique 'entropy of entanglement' emerges.

"Our findings mark significant progress in understanding the basic properties of entanglement," says Regula. "They reveal fundamental connections between entanglement and thermodynamics, and crucially, provide a major simplification in the understanding of entanglement conversion processes."

The demonstration has practical implications. "This not only has immediate and direct applications in the foundations of quantum theory, but it will also help with understanding the ultimate limitations on our ability to efficiently manipulate entanglement in practice," says Regula.

While the finding is a major step forward, it raises new questions. "Our work serves as the very first evidence that reversibility is an achievable phenomenon in entanglement theory," says Regula. "However, even stronger forms of reversibility have been conjectured. Understanding the precise requirements for reversibility to hold thus remains a fascinating open problem."



RIKEN researchers have shown that the classical physics concept of entropy also applies to quantum entanglement, depicted artistically here.

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RIKEN Research Fall 2024 (p.21)

These articles are edited versions of RIKEN Research Highlights.

A beautiful approach to correcting quantum errors

A method for correcting errors in quantum computers based on geometric structures shows promise

A new approach for correcting errors in quantum computing has been proposed by a RIKEN researcher[1]. It could contribute to highly parallel methods that will allow fault-tolerant quantum computing, the next stage in the evolution of quantum computers.

Quantum computers promise to revolutionize computing in coming decades. In particular, quantum computers that are tolerant to faults because they can correct errors have the potential to surpass the performance of conventional computers on certain calculations.

"Thanks to recent experimental progress, there is now great hope that we will be able to build fault-tolerant quantum computers," says Hayato Goto of the RIKEN Center for Quantum Computing. "To achieve this, however, it is important to develop efficient quantum error correction."

Many error-correction methods have been proposed. A conventional one is based on encoding a single logical qubit (a qubit is the equivalent of a bit in a conventional computer) onto many entangled physical ones, and then using a decoder to retrieve the logical qubit from the physical ones.

But this is difficult to scale up since the number of physical qubits required goes up enormously, resulting in huge resource overheads.

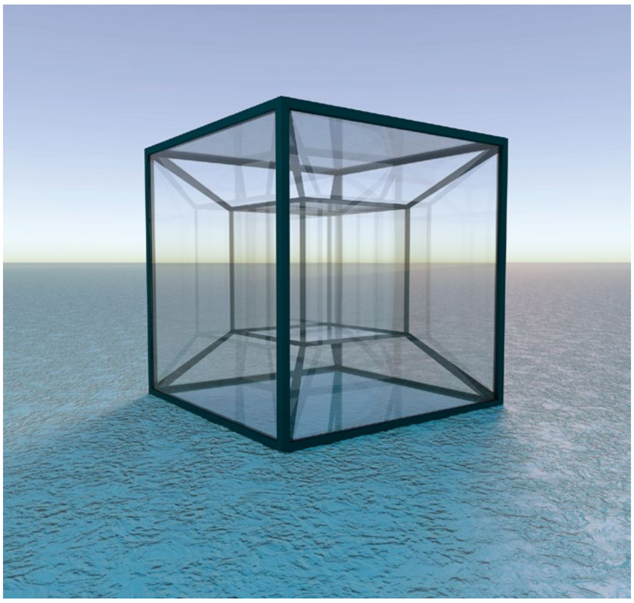
To overcome this problem, high-rate quantum codes have been proposed. But they require setting up logic gates mostly sequentially rather than fully parallel, slowing computing down.

To remedy this, Goto has proposed an approach he calls many-hypercube codes. In this approach, the logical qubits can be visualized mathematically as forming a hypercube—a class of shapes that includes squares and cubes as well as higher-order shapes such as the tesseract. In contrast to other high-rate quantum codes, many-hypercube codes have remarkably beautiful mathematical and geometric structures.

For these new codes to improve performance, Goto needed to develop a novel dedicated decoder that can interpret the result from the physical qubits.

His innovative technique is based on level-by-level minimum distance decoding, which allows for high performance. Unlike similar methods, it also allows for logical gates to be arranged in parallel rather than in series, which makes the system analogous to parallel processing in conventional computers.

The codes developed by Goto realized one of the highest encoding rates—the ratio between logical and physical qubits—among codes used for fault-tolerant quantum computing. Even with this high encoding rate, the codes had performances comparable to those of conventional codes with low encoding rates.



A model of a hypercube known as a tesseract. A RIKEN researcher has developed a method for correcting errors in quantum computers that is based on hypercubes.

Goto believes that the code could be implemented in practical quantum computing systems that use neutral atoms trapped in laser beams as qubits.

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RIKEN Research Winter 2024 (p.17)

These articles are edited versions of RIKEN Research Highlights.

A high-fidelity gate for quantum computers

A new kind of coupler could enable more accurate quantum computation

RIKEN physicists have realized a novel coupling scheme that achieved high-fidelity gate operations between qubits for quantum computers[1]. This development promises to both boost the performance of existing superconducting quantum computers and pave the way for realizing future fault-tolerant quantum computing.

Because they are based on qubits rather than bits, quantum computers have the potential to revolutionize computing by being able to solve problems that are extremely difficult or intractable using conventional computers.

Unleashing the full potential of quantum computing requires developing quantum gates—operations on qubits—with much higher fidelities than are currently achievable. This is important because realizing high gate fidelities is essential for minimizing errors and thereby enhancing the reliability of quantum computation and reducing overheads for error correction.

Now, a team led by Yasunobu Nakamura of the RIKEN Center for Quantum Computing and Hayato Goto of Toshiba Corporation has demonstrated high-fidelity gates between two qubits by using a special coupler.

"By reducing the error rates in quantum gates, we have made more reliable and accurate quantum computation possible," says Nakamura. "This is particularly important for developing fault-tolerant quantum computers, which are the future of quantum computing."

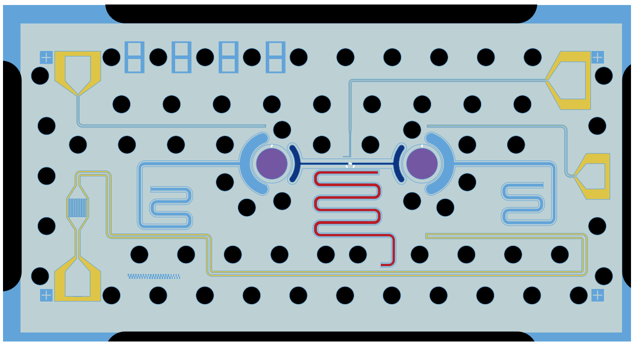
The team used a new kind of tunable coupler composed of two fixed-frequency transmons—a type of qubit that is relatively insensitive to charge noise. This coupler both suppressed residual interaction and realized fast high-fidelity two-qubit gate operations, even for highly detuned qubits.

Using the coupler, the team realized a two-qubit gate with an impressive fidelity of 99.9% within a gate time shorter than 50 nanoseconds. This is a big advance as no two-qubit gate has been demonstrated at the level of the fidelity and speed between two fixed-frequency qubits.

The two keys to this demonstration were constructing precisely designed qubits using state-of-the-art fabrication techniques and optimizing the gate using machine learning. This allowed the researchers to translate the theoretical potential of the double-transmon coupler, proposed by Goto in 2022, into practical application.

The team used these approaches to balance two remaining types of errors—leakage error and decoherence error—that remained within the system. They minimized these two error sources by optimizing the pulse length and shape. Thanks to this, they achieved among the highest fidelities reported in the field.

"This device's ability to realize quantum gates effectively with long-coherence fixed-frequency qubits makes it a versatile and competitive building block for various quantum computing architectures," says Nakamura. "It can be integrated into existing and future superconducting quantum processors, enhancing their overall performance and scalability.



The development of a two-qubit gate (shown here) with a very high fidelity could help improve the performance of superconducting quantum computers.

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