2023

RIKEN Center for Quantum Computing

Annual Report

RIKEN
QUANTUM
COMPUTING

RIKEN

Contents

Team Outlines and Achievements

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.

Next year, in 2025, we will mark the centennial of the theory of quantum mechanics, a milestone in the history of science. Quantum mechanics, which has evolved over a century through the collective efforts of numerous researchers, is the most fundamental theory of physics and 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.

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 are set to establish two new research teams on cold-atom platforms, a testament to our commitment to accelerate 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 talents cooperate on various topics, from basic science to applications and from experiments to theories, striving for breakthrough research every day.

Following the release of “RQC-A,” the first Japan-built superconducting quantum computer, RQC started operating a cloud service in FY2023. In addition, a second unit was unveiled at the RIKEN RQC-FUJITSU Collaboration Center. We also collaborated on releasing a third machine at the Center for Quantum Information and Quantum Biology at Osaka University. While technology is still evolving, we hope to amass the wisdom of many people through open innovation for future development.

Furthermore, RQC plays a pivotal role as the headquarters and the quantum computer development hub, at the core of all eleven 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 the activities connecting participants in academia, industry, and the government, as well as by sharing knowledge across diverse subfields and tightening lateral collaborations, we accelerate the innovation cycles, promote the development of science and technology, and contribute to social values.

In FY2023, we launched three new research teams in RQC as a part of our growth plan to establish a critical mass. 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 nurture talents to lead the next generation of quantum science and technology, along with our persistent research and development towards realizing quantum computers.

Overview of RIKEN Center for Quantum Computing

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

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

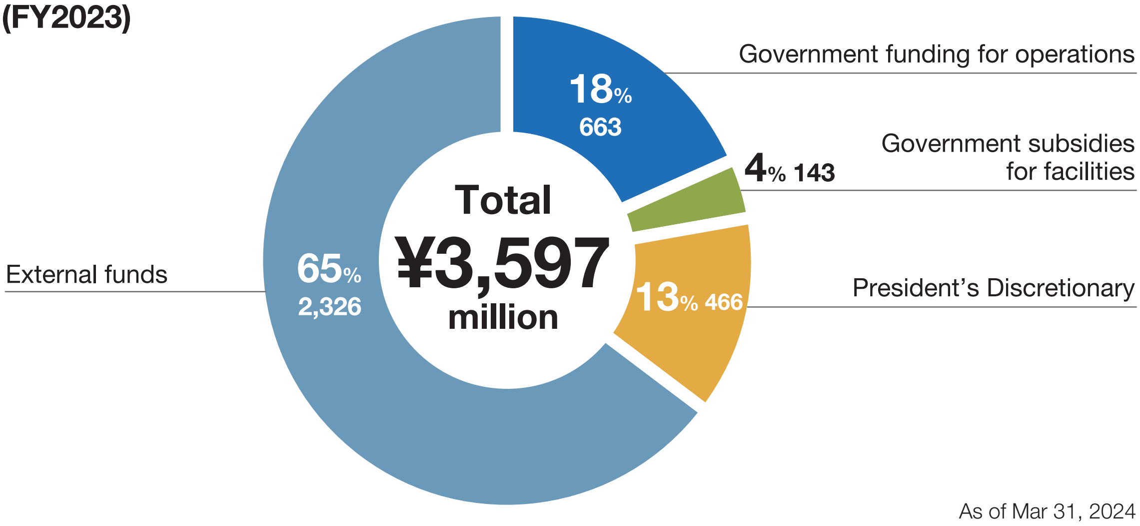
RIKEN Center for Quantum Computing

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

- **RQC Advisory Council**
- **Superconducting Quantum Electronics Research Team:** Yasunobu Nakamura
- **Superconducting Quantum Simulation Research Team:** Jaw-Shen Tsai
- **Superconducting Quantum Electronics Joint Research Unit:** Eisuke Abe
- **Superconducting Quantum Computing System Research Unit:** Yutaka Tabuchi
- **Hybrid Quantum Circuits Research Team:** Atsushi Noguchi
- **Optical Quantum Computing Research Team:** Akira Furusawa
- **Optical Quantum Control Research Team:** Hidehiro Yonezawa
- **Quantum Many-Body Dynamics Research Team:** Takeshi Fukuhara
- **Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team:** Erika Kawakami
- **Semiconductor Quantum Information Device Research Team:** Seigo Tarucha
- **Semiconductor Quantum Information Device Theory Research Team:** Daniel Loss
- **Quantum Computing Theory Research Team:** Keisuke Fujii
- **Quantum Information Physics Theory Research Team:** Franco Nori
- **Quantum Computational Science Research Team:** Seiji Yunoki
- **Quantum Computer Architecture Research Team:** Hayato Goto
- **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

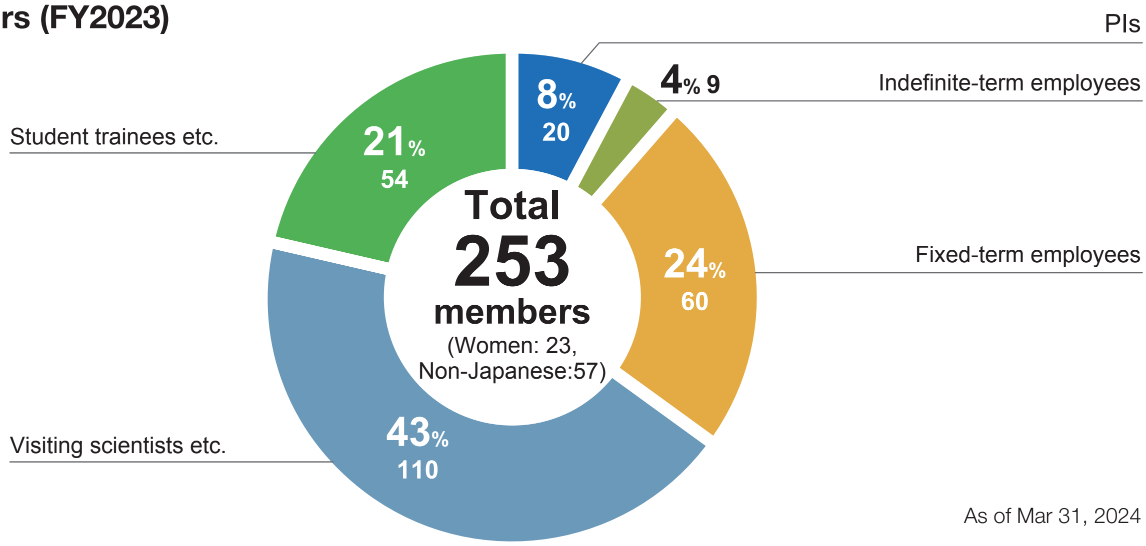
Overview of RIKEN Center for Quantum Computing (Continued)

Budget (FY2023)



As of Mar 31, 2024

Members (FY2023)



As of Mar 31, 2024

RQC Colloquiums and RQC Seminars

FY2023 RQC Colloquium

At the RQC, we regularly invite renowned researchers and hold RQC Colloquiums. RQC Colloquiums were held 12 times in fiscal 2023, 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
11	April 19, 2023 (online)	Prof. Michel Devoret	Yale University	Error correction of a logical quantum bit
12	May 17, 2023 (online)	Prof. Scott Aaronson	University of Texas at Austin	How much information is in a quantum state?
13	June 21, 2023	Prof. Kenji Ohmori	Institute for Molecular Science	Ultrafast quantum simulation and quantum computing with ultracold atom arrays at quantum speed limit
14	July 7, 2023	Prof. Jacob Taylor	National Institute of Standards and Technology	Exploring fundamental physics with quantum information science
15	July 21, 2023	Prof. Ulrik Lund Andersen	Technical University of Denmark	Advancements in continuous variable quantum information technology
16	September 13, 2023	Prof. Takao Aoki	Waseda University	Nanofiber cavity quantum electrodynamics systems for distributed quantum computing
17	October 25, 2023	Prof. Mio Murao	The University of Tokyo	Fully-quantum learning: Higher-order quantum algorithms for comparison and inversion of unknown unitary operations
18	November 21, 2023 (online)	Prof. Charles Marcus	University of Washington	New views of a classic (but not classical) system the Josephson Junction Array
19	December 27, 2023	Prof. Kihwan Kim	Tsinghua University	Scalable and programmable phononic network using vibrational modes of trapped ions
20	January 31, 2024	Prof. Seth Lloyd	Massachusetts Institute of Technology	Quantum machine learning
21	February 14, 2024	Prof. Hidetoshi Nishimori	Tokyo Institute of Technology	Quantum simulations of problems in statistical physics
22	March 19, 2024	Prof. Eric Lutz	University of Stuttgart	Converting quantum statistics into work

FY2023 RQC Seminar

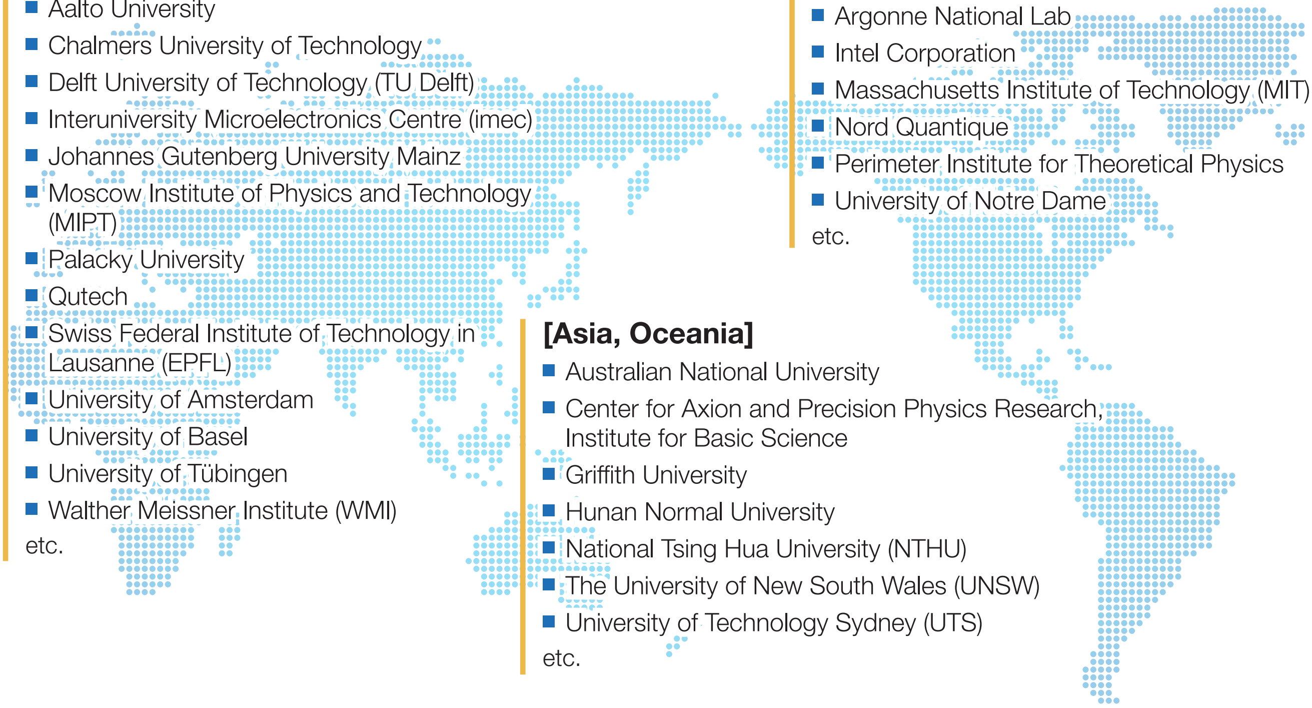
Additionally, at the RQC we also hold RQC Seminars, which each PI organizes independently. RQC Seminars were held 72 times in fiscal 2023, and vigorous discussions that went beyond the team framework were held, with the aim of making breakthroughs related to the research and development of quantum computers.

No.	Date	Speaker	Affiliation
37	April 3, 2023	Prof. Mauro Antezza	University of Montpellier
38	April 10, 2023	Dr. Fabrizio Minganti	Ecole Polytechnique Fédérale de Lausanne
39	April 12, 2023	Mr. Yi-Te Huang	National Cheng Kung University
40	April 14, 2023	Dr. Onur Oktay	University of Surrey
41	April 17, 2023	Dr. Carlos Sánchez Muñoz	Autonomous University of Madrid
42	April 20, 2023	Prof. Kyungwon An	Seoul National University
43	May 1, 2023	Prof. Wolfgang Lorenzon	University of Michigan
44	May 9, 2023	Prof. Xuedong Hu	University of Buffalo
45	May 11, 2023	Prof. Oleksandr Dobrovolskiy	University of Vienna
46	May 15, 2023	Dr. Daria Smirnova	Australian National University
47	May 19, 2023	Ms. Therese Karmstrand	Chalmers University of Technology
48	May 25, 2023	Dr. Bartosz Regula	RIKEN RQC
49	May 26, 2023	Dr. Takuya Okuda	The University of Tokyo
50	June 2, 2023	Mr. Yuma Kawaguchi	The City College of New York
51	June 5, 2023	Dr. Josephine Dias	Okinawa Institute of Science and Technology Graduate University
52	June 14, 2023	Dr. Hayato Goto	RIKEN RQC
53	June 16, 2023	Mr.Vaibhav Gautam	University of Surrey
54	June 23, 2023	Dr. Fredrik Brange	Aalto University
55	June 27, 2023	Prof. Chia-Yi Ju	National Sun Yat-Sen University
56	June 28, 2023	Dr. Yosuke Ueno	RIKEN RQC
57	June 30, 2023	Prof. Guang-Yin Chen	National Chung Hsing University
58	July 11, 2023	Prof. Rainer Dumke	Nanyang Technological University, National University of Singapore
59	July 12, 2023	Prof. Omar Di Stefano	Università degli Studi di Messina
60	July 14, 2023	Prof. Salvatore Savasta	Università degli Studi di Messina
61	July 18, 2023	Dr. Steve Brierley	Riverlane
62	July 20, 2023	Mr. Daniele Lamberto	Università degli Studi di Messina
63	July 21, 2023	Prof. Britton Plourde	Syracuse University
64	July 24, 2023	Mr. Po-Rong Lai	National Cheng Kung University
65	July 13, 2023	Prof. Hou Ian	University of Macau
66	July 27, 2023	Dr. Hirofumi Yanagisawa	Shizuoka University
67	July 28, 2023	Dr. Antoine Reserbat-Plantey	CNRS, CRHEA, Université Nice Côte d'Azur
68	July 28, 2023	Dr. Reiko Yamada	The Institute of Photonic Sciences
69	July 31, 2023	Dr. Martin Rodriguez-Vega	Physical Review Letters
70	August 4, 2023	Prof. Adam Miranowicz	Adam Mickiewicz University
71	August 7, 2023	Prof. Enectali Figueroa-Feliciano	Northwestern University
72	August 8, 2023	Ms. Zara Yu	Massachusetts Institute of Technology
73	August 9, 2023	Prof. Xin Wang	Xi'an Jiaotong University
74	August 10, 2023	Mr. Harvey Cao	Imperial College London
75	August 18, 2023	Prof. Masaki Tezuka	Kyoto University
76	August 14, 2023	Dr. Vanja Maric	Université Paris-Saclay
77	August 21, 2023	Prof. Mark Mitchison	Trinity College Dublin
78	August 22, 2023	Mr. Isaac Layton	University of College Longon
79	August 29, 2023	Mr. Donghoon Kim	KAIST
80	August 31, 2023	Prof. Hong-Bin Chen	National Cheng Kung University
81	September 4, 2023	Dr. Roberto Stassi	Messina University
82	September 7, 2023	Prof. Valentin Freilikher	Bar-Ilan University
83	September 12, 2023	Dr. Éric Giguère	ISC Applied Systems
84	September 14, 2023	Prof. Martin Kliesch	Hamburg University of Technology
85	September 15, 2023	Prof. Mauricio Gutiérrez	University of Costa Rica
86	October 12, 2023	Dr. Gustav Andersson	The University of Chicago

No.	Date	Speaker	Affiliation
87	October 24, 2023	Prof. Hideo Kosaka, Dr. Hodaka Kurokawa	Yokohama National University
88	October 26, 2023	Prof. Igor Aronson	The Pennsylvania State University
89	October 27, 2023	Dr. Huan-Yu Ku	National Cheng Kung University
90	October 30, 2023	Priv.-Doz. Dr. Hans Huebl	Bavarian Academy of Sciences and Humanities
91	October 30, 2023	Prof. Stephen A. Lyon	Princeton University and EeroQ Corp
92	October 31, 2023	Mr. Feng-Jui Chan	National Cheng Kung University
93	November 1, 2023	Prof. Yueh-Nan Chen	National Cheng Kung University
94	November 9, 2023	Dr. Takahiro Tsunoda	Yale University
95	November 13, 2023	Mr. Zhiyu Jiang	Hokkaido University
96	November 17, 2023	Mr. Juan Román Roche	University of Zaragoza
97	November 20, 2023	Prof. Simone De Liberato	University of Southampton
98	November 22, 2023	Dr. Suguru Endo	NTT
99	December 4, 2023	Dr. Edwin Ng	NTT
100	December 14, 2023	Dr. Maja Cassidy	University of New South Wales
101	December 15, 2023	Mr. Dolev Bluvstein, Mr. Marcin Kalinowski$6	Harvard University
102	December 15, 2023	Dr. Emanuele Mendicelli	York University
103	December 28, 2023	Dr. Anton Frisk Kockum	Chalmers University of Technology
104	January 9, 2024	Dr. Shingo Kono	Ecole Polytechnique Fédérale de Lausanne
105	January 24, 2024	Dr. Satoya Imai	QSTAR, INO-CNR, and LENS
106	February 2, 2024	Mr. Siddhant Singh	Delft University of Technology
107	March 18, 2024	Prof. Ludovico Lami	QuSoft / University of Amsterdam
108	March 21, 2024	Prof. Mario Berta	RWTH Aachen University

Collaborations

International



[Europe]

- Aalto University
- Chalmers University of Technology
- Delft University of Technology (TU Delft)
- Interuniversity Microelectronics Centre (imec)
- Johannes Gutenberg University Mainz
- Moscow Institute of Physics and Technology (MIPT)
- Palacky University
- Qutech
- Swiss Federal Institute of Technology in Lausanne (EPFL)
- University of Amsterdam
- University of Basel
- University of Tübingen
- Walther Meissner Institute (WMI)

etc.

[North America]

- Argonne National Lab
- Intel Corporation
- Massachusetts Institute of Technology (MIT)
- Nord Quantique
- Perimeter Institute for Theoretical Physics
- University of Notre Dame

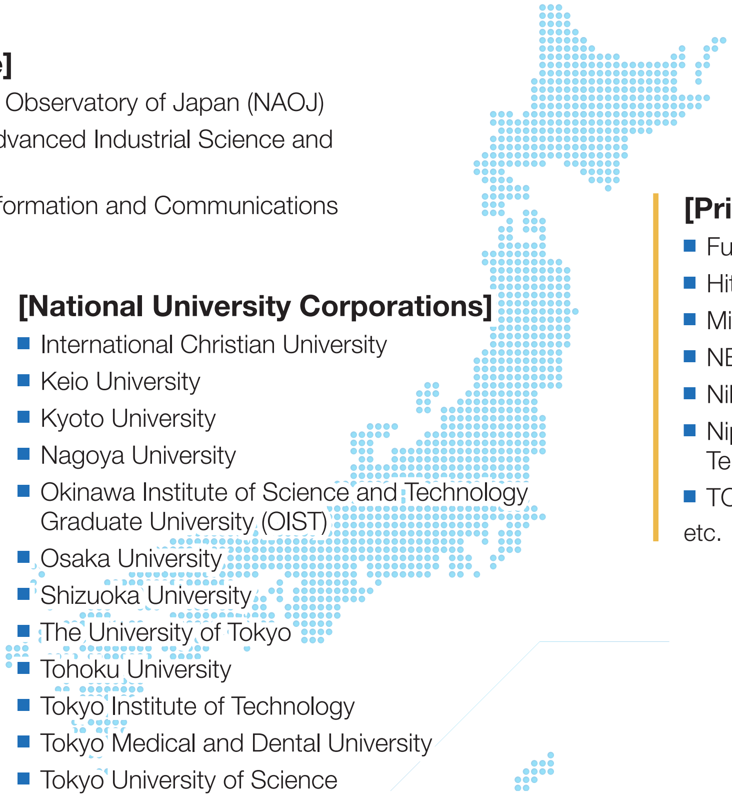
etc.

[Asia, Oceania]

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

etc.

National



[Research Institute]

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

etc.

[National University Corporations]

- International Christian University
- Keio University
- Kyoto University
- Nagoya University
- Okinawa Institute of Science and Technology Graduate University (OIST)
- Osaka University
- Shizuoka University
- The University of Tokyo
- Tohoku University
- Tokyo Institute of Technology
- Tokyo Medical and Dental University
- Tokyo University of Science

etc.

[Private business]

- Fujitsu Ltd.
- Hitachi, Ltd.
- Mitsubishi Electric Corporation
- NEC Corporation
- Nikon Corporation
- Nippon Telegraph and Telephon Corporation (NTT)
- TOSHIBA CORPORATION

etc.

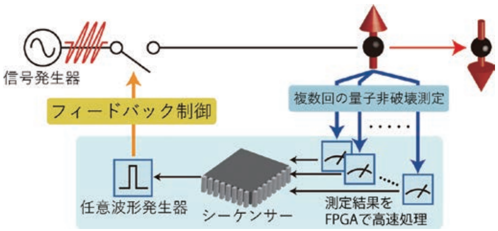
Press Releases

June 1, 2023

Feedback system could help to correct errors in quantum computers

-Quantum circuit can reset quantum bits carried by electron spins in silicon-

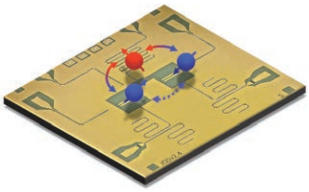
Semiconductor Quantum Information Device Research Team



June 30, 2023

Invention of the small cross-talk quantum gate for superconducting quantum computer

Hybrid Quantum Circuits Research Team



July 12, 2023

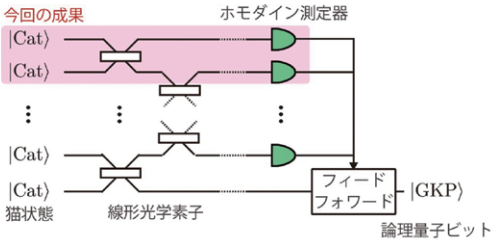
Nonlinear feedforward enabling quantum computation

Optical Quantum Computing Research Team

January 19, 2024

Logical states for fault-tolerant quantum computation with propagating light

Optical Quantum Computing Research Team

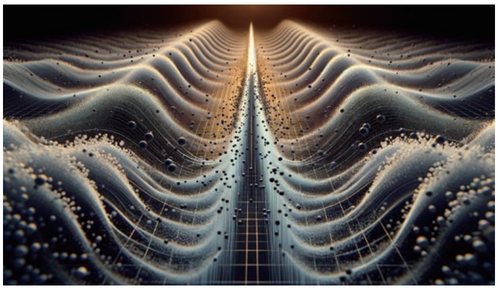


March 29, 2024

Speed limit of quantum information propagation

-theoretical discovery in interacting boson systems and applications to quantum computation-

Analytical Quantum Complexity RIKEN Hakubi Research Team



Awards

April 7, 2023

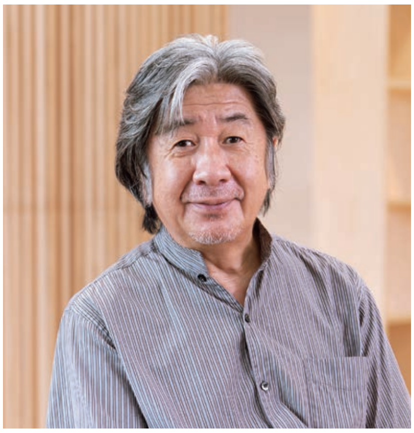
Researcher Tatsuhiko Ikeda awarded Commendation by Minister of Education, Culture, Sports, Science and Technology

Researcher Tatsuhiko Ikeda of the Quantum Computing Theory Research Team received the Minister of Education, Culture, Sports, Science and Technology (MEXT) Prize for Young Scientists in the field of science and technology for the fiscal year 2023. This prize is awarded to honor individuals who have achieved outstanding results in research and development, promotion of understanding, and other areas related to science and technology. Mr. Ikeda was awarded the prize for his work: "Analysis of Optical Phenomena using Floquet Theory and Research on New Phenomena Exploration."

September 5, 2023

Dr. Yasunobu Nakamura and Dr. Jaw-Shen Tsai awarded Hattori Hokokai Foundation's Hattori Hoko Award

Dr. Yasunobu Nakamura, Director of RQC, and Dr. Jaw-Shen Tsai, Team Leader, Superconducting Quantum Simulation Research Team, have been awarded the 2023 (93rd) Hattori Hokokai Foundation's Hattori Hoko Award. This award is presented to researchers who have achieved outstanding research results in the field of engineering, and Dr. Nakamura and Dr. Tsai received the award for their work: "Pioneering Research on Superconducting Qubit Circuits toward realizing Quantum Computers."



July 18, 2023

Dr. Franco Nori selected for Academia Europaea

Dr. Franco Nori, Team Leader, Quantum Information Physics Theory Research Team, has been selected for Academia Europaea. Academia Europaea members are selected once a year as a result of recommendations and screening by members. Dr. Nori was selected based on his influential research achievements and large amount of important joint research with researchers in Europe.

October 10, 2023

Dr. Yasunobu Nakamura and Dr. Jaw-Shen Tsai awarded C&C Prize

Dr. Yasunobu Nakamura, Director of RQC, and Dr. Jaw-Shen Tsai, Team Leader, Superconducting Quantum Simulation Research Team, have been awarded the 2023 C&C Prize. This prize is awarded to individuals who have undertaken pioneering work and/or research in the fields of information processing technology, communications technology, electronic devices technology, and technological fields that integrate those technologies and have made remarkable contributions to social-scientific research activities that bring about progress in those fields. Dr. Nakamura and Dr. Tsai received the prize for their work: "Contributing to the Field of Quantum Information Technology, including the Development of Superconducting Qubits and Quantum Computers."

October 19, 2023

RIKEN JRA student Shang Cheng awarded the Beijing Academy of Quantum Information Sciences' Best Poster Award

RIKEN JRA student Shang Cheng of the Analytical Quantum Complexity RIKEN Hakubi Research Team has been awarded the Beijing Academy of Quantum Information Sciences' Best Poster Award. Mr. Shang was presented with the award at the 5th International Symposium on Quantum Physics and Quantum Information Sciences (QPQIS-2023) for his poster entitled "Equivalence between operator spreading and information propagation."

November 15, 2023

Dr. Franco Nori selected as Clarivate Highly Cited Researcher 2023

Dr. Franco Nori, Team Leader, Quantum Information Physics Theory Research Team, has been selected as a Clarivate Highly Cited Researcher 2023. Clarivate Highly Cited Researchers are selected in each field of research, as the authors of papers that rank in the top 1% based on number of citations in Clarivate Analytics' Essential Science Indicators database.

March 8, 2024

Dr. Franco Nori selected as the 2024 recipient of the Charles Hard Townes Medal (Optica)

Dr. Franco Nori, Team Leader, Quantum Information Physics Theory Research Team, has been selected as the 2024 recipient of the Charles Hard Townes Medal (Optica). Dr. Nori received the medal for his many fundamental contributions to quantum optics, quantum information processing, and quantum circuits, and for his track record of developing key quantum software tools.

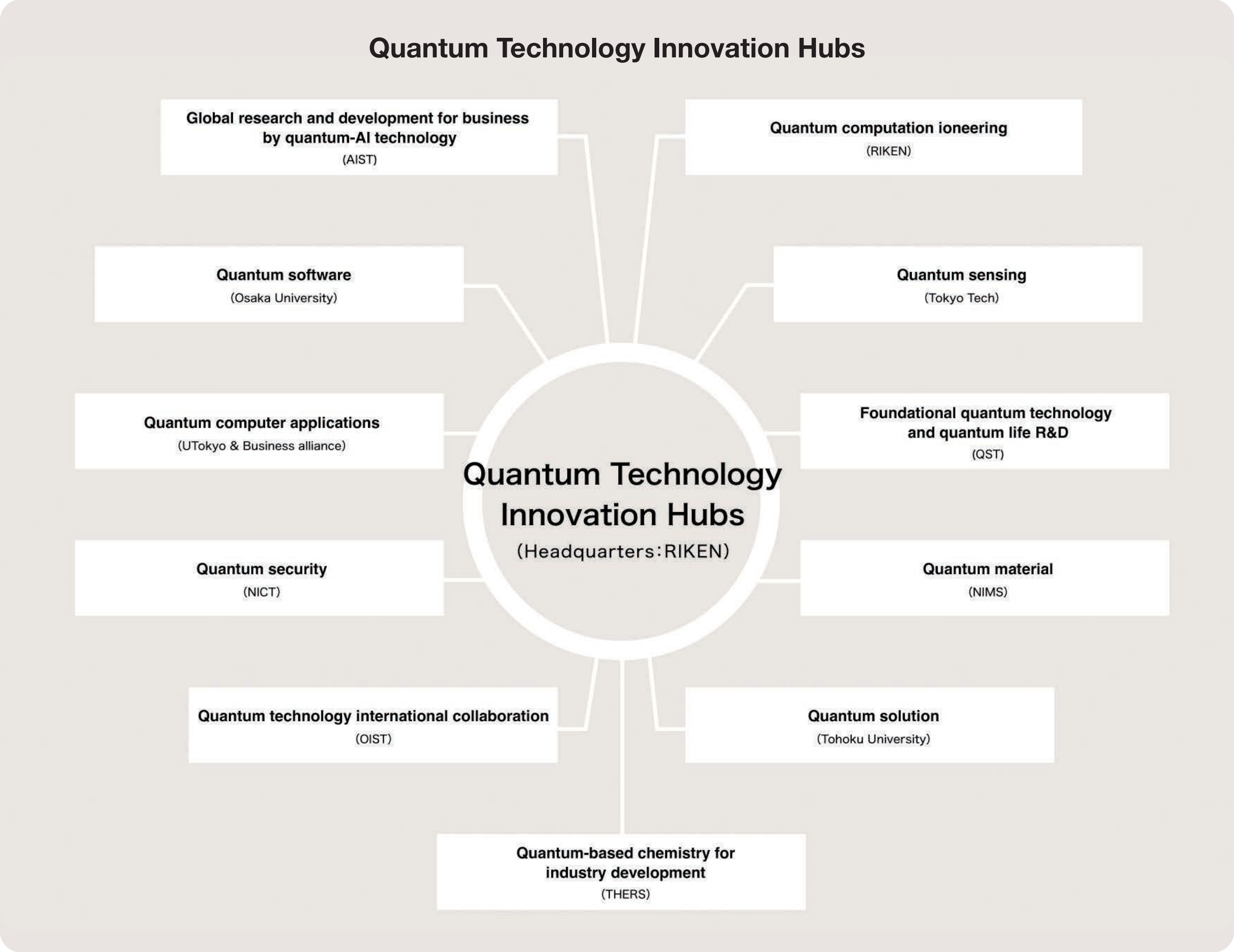
Overview of Quantum Technology Innovation Hubs

QIH
Quantum Innovation Hubs

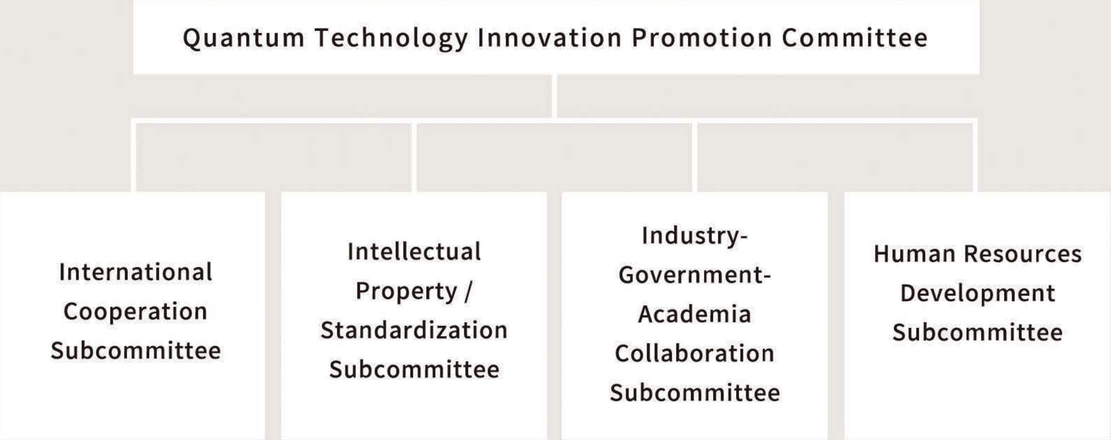
As the core organization of the eleven Quantum Innovation Hubs (QIH), RIKEN brings all the hubs together as one to accelerate the social implementation of quantum technology.

Quantum Innovation Hubs (hereinafter QIH) were established as hubs for industry, government and academia to engage in a streamlined manner in everything from basic research on quantum technology through to technology verification, intellectual property management and human resources development. They are securing and strengthening Japan's international competitiveness, on the basis of 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).

As the core organization of the QIH, RIKEN performs a headquarters function that strives for coordination among the eleven hubs. At the same time, as one of the eleven hubs RIKEN is a quantum computation pioneering hub that aims to realize and establish quantum computer systems.



Activities



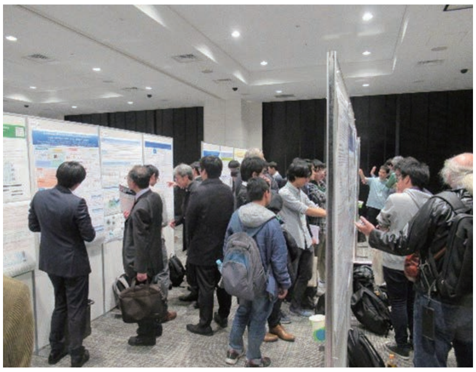
The positioning of the respective subcommittees

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

- International Cooperation Subcommittee: Holds international symposiums, and promotes international collaborations such as international joint research.
- Intellectual Property / Standardization Subcommittee: Shares strategies between the hubs on intellectual property and international standardization.
- Industry-Government-Academia Collaboration Subcommittee: Promotes industry-government-academia collaborations aimed at the social implementation of quantum technology.
- Human Resources Development Subcommittee: Promotes an increase in the number of young researchers in the quantum field and strengthens human resource development across institutions and research fields.

Pick up Activities

Quantum Innovation 2023, an international symposium concerning quantum science and technology innovation, was held in Tokyo on November 15-17, 2023 as one part of the QIH activities. With things returning to normal following the COVID-19 pandemic, this time the symposium was held in a face-to-face format for the first time. Over the three-day period it featured 132 lectures, three panel discussions and 140 poster presentations. More than 600 people from 14 participating countries registered to take part, and 543 people attended. Along with serving as a valuable forum for disseminating information, the symposium included a reception that also served as an opportunity for international exchange. In addition, of the poster presentations that were given by students, outstanding poster awards were presented for 15 presentations with the goal of nurturing young talent.



Overview of Quantum Technology Innovation Hubs (Continued)

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

Summer vacation science event “What are Quantum Computers?” held at the Science Museum from August 11 (Fri.) to 13 (Sun.), 2023

nano tech 2024 exhibition at Tokyo Big Sight from January 31 to February 2, 2024

Toshio Tonouchi (Ph.D.), Coordinator

Selected Publications

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

Brief resume

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

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

RQC FY2023 Pick Up Topics

“Call for quantum computer development supporters – RIKEN RQC” crowdfunding held

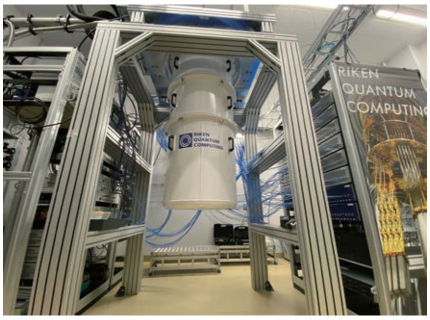
Crowdfunding was carried out at RQC from April 7, 2023 to May 31, 2023. We were able to reach our monetary target thanks to the support of a large number of individuals, and the contributions are being utilized to strengthen our quantum-related human resources development and outreach activities (for making our research results known).

Examples of thank you gifts: Left: Acrylic stand commemorating the launch of Japan’s first quantum computing cloud service   Right: Replica of a superconducting qubit chip

Nickname and logo decided for Japan’s first homemade quantum computer

Following an open call for suggestions for a nickname for the first Japanese built quantum computer available through the cloud, on 27 March, 2023 we settled on “A” (in Japanese “EI”) as the nickname. Furthermore, with the aim of making “A” feel more familiar to a larger number of people, we came up with a logo expressing the notable characteristics that “A” possesses.

Logo for “A”



Superconducting quantum computer “A”

Unveiling and press conference for Japan-made quantum computer available through the cloud held at the RIKEN RQC-FUJITSU Collaboration Center

A new superconducting quantum computer was developed based on the development expertise accumulated with “A”, Japan’s first homemade quantum computer, and it began being operated on Fujitsu’s hybrid quantum computing platform on 5 October, 2023 at the RIKEN RQC-FUJITSU Collaboration Center. In addition, a press conference was held on the same day and the event was covered by a wide range of media, including newspapers and TV broadcasters.

Commemorative Photo at the Press Conference

Commemorative Photo at the Tour of the Quantum Computer

Awarded the Prime Minister Award, the highest honor, at the 53rd Japan Industrial Technology Awards

On March 15, 2024 a joint research group that included RIKEN, Fujitsu and others won the Prime Minister Award, the highest honor, at the 53rd Japan Industrial Technology Awards, which was hosted by Nikkan Kogyo Shimbun, Ltd., for a high-performance computing platform that utilizes a superconducting quantum computer.

Commemorative Photo at the Award Ceremony

Receiving the Award

Superconducting Quantum Electronics Research Team

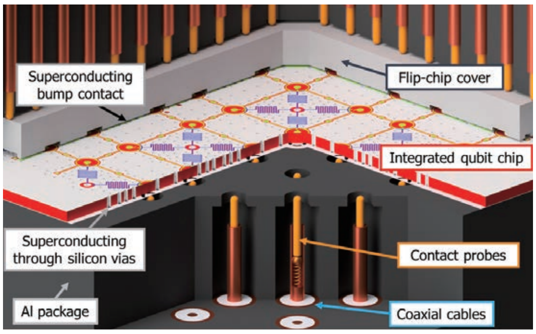
Keywords: Quantum computing, Superconducting circuits, Josephson junction, Microwave quantum optics, Circuit quantum electrodynamics

Research Outline

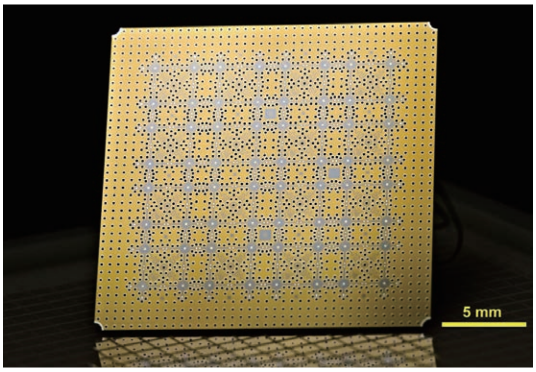
Our team, in collaboration with other teams in RQC as well as collaborators outside RIKEN, is conducting research and development on superconducting quantum circuits for quantum computing and other quantum technologies. Currently, our focus is on the development of a superconducting quantum computing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

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

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



Schematics of the package for an integrated superconducting-qubit circuit



Photograph of a 64-qubit chip

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

Selected Publications

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

Brief resume

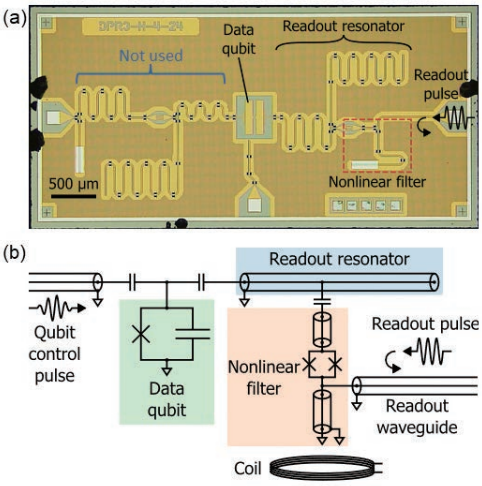
1992	Researcher, Fundamental Research Laboratories, NEC Corporation
1997	Senior Researcher, Fundamental Research Laboratories, NEC Corporation
2001	Principal Researcher, Fundamental Research Laboratories, NEC Corporation (-2005)
2001	Visiting Researcher, Department of Applied Physics, Delft University of Technology (-2002)
2002	Researcher, Frontier Research System, RIKEN (-2013)
2005	Research Fellow, Fundamental and Environmental Research Laboratories, NEC Corporation (-2012)
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

Dispersive readout of a superconducting qubit using a nonlinear Purcell filter

Residual noise photons in a readout resonator become a major source of dephasing for a superconducting qubit when the resonator is optimized for a fast, high-fidelity dispersive readout. Here, we propose and demonstrate a nonlinear Purcell filter that suppresses such an undesirable dephasing process without sacrificing the readout performance. When a readout pulse is applied, the filter automatically reduces the effective linewidth of the readout resonator, increasing the sensitivity of the qubit to the input field. The noise tolerance of the device we have fabricated is shown to be enhanced by a factor of 3 relative to a device with a linear filter. A readout fidelity of 99.4% is achieved using a 40-ns readout pulse.

Y. Sunada *et al.*, "Photon-noise-tolerant dispersive readout of a superconducting qubit using a nonlinear Purcell filter", PRX Quantum 5, 010307 (2024).

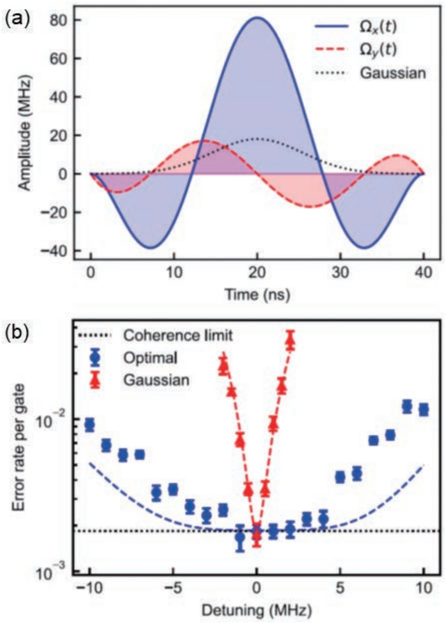


Qubit readout circuit containing a nonlinear Purcell filter. (a) Photograph of the entire chip. (b) Distributed-element circuit model.

Single-qubit-gate robustness optimization against residual ZZ interactions between superconducting qubits

Overcoming the issue of qubit-frequency fluctuations is essential to realizing stable and practical quantum computing with solid-state qubits. Static ZZ interaction, which causes a frequency shift of a qubit depending on the state of neighboring qubits, is one of the major obstacles to integrating fixed-frequency transmon qubits. Here we propose and experimentally demonstrate ZZ-interaction-free single-qubit-gate operations on a superconducting transmon qubit by utilizing a semi-analytically optimized pulse based on a perturbative analysis. The gate is designed to be robust against slow qubit-frequency fluctuations. Our result paves the way for an efficient approach to overcoming the issue of ZZ interaction without any additional hardware overhead.

S. Watanabe *et al.*, "ZZ-interaction-free single-qubit-gate optimization in superconducting qubits", Phys. Rev. A 109, 012616 (2024).



(a) Optimized single-qubit-gate drive waveform.
(b) Error rate per gate versus drive detuning.

Core members

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

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.

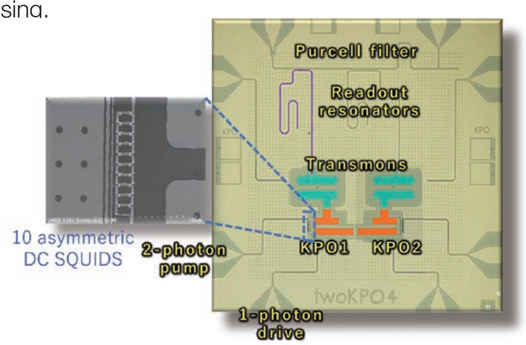


Fig 1. Chip photo of 2D KPO circuit. It contains two coupled KPOs.

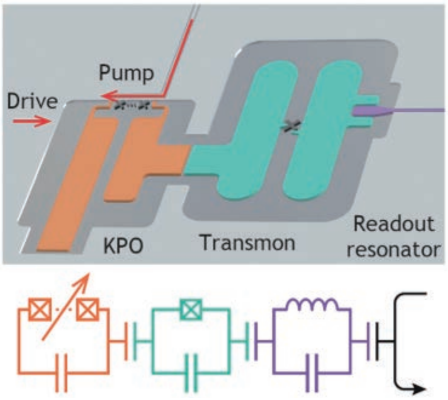
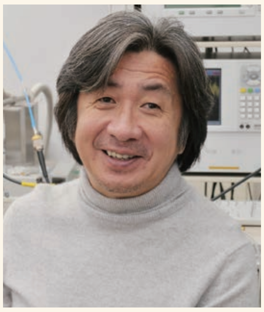


Fig 2. Schematic diagram and equivalent circuit of a 1-bit KPO. Ancilla transmon was used for readout.



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

Selected Publications

1 Daisuke Iyama, Takahiko Kamiya, Shiori Fujii, Hiroto Mukai, Yu Zhou, Toshiaki Nagase, Akiyoshi Tomonaga, Rui Wang, Jiao-Jiao Xue, Shohei Watabe, Sangil Kwon & Jaw-Shen Tsai, "Observation and manipulation of quantum interference in a superconducting Kerr parametric oscillator", *Nature Communications*, 15:86 (2024), doi.org/10.1038/s41467-023-44496-1

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

Realization of the cat state in superconducting KPO and its one-qubit manipulation

We have fabricated KPO consisting of 10 DC SQUIDs. After a Fock state was prepared, the intensity of the two-photon pump was slowly increased from 0 to generate cat states, and the quantum interference of KPO was confirmed by Wigner tomography.

We performed quantum gate operations in the cat state. The X/2 gate was embodied by applying a single quantum drive, and the Z/2 gate was embodied by modulating the frequency of the pump. In the case of the KPO cat state, the pump is the reference phase, so when observing the Rabi oscillation by the X-gate, the phase (φ_d) and frequency detuning (Δ_d) of the drive must be matched. Quantum process tomography was used to determine the fidelity after performing X/2 and Z/2, which were 0.844 and 0.794, respectively (Fig 3).

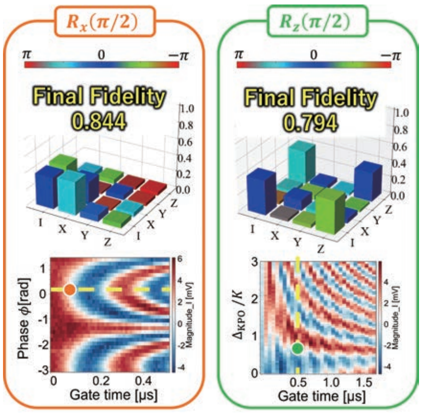


Fig 3. X Gate and Y Gate process topographies of superconducting KPO cat qubit and their Rabi oscillation

Entanglement generation and 2-qubit gate operation with superconducting KPO qubit

Using two KPOs, we showed that the entangled Bell-Fock state is converted one-to-one to the entangled cat state (Bell-Cat state). In a 2-mode Wigner tomography, the interference pattern was observed. It indicates that the two cat states are entangled rather than simply correlated.

In addition, we succeeded in directly entangling two cat states by iSWAP gate operation (Fig 4). This research achievement is significant for it realizes a universal gate set of gate operation with planar KPO circuits, and it indicates that it is a new scalable quantum information processing platform.

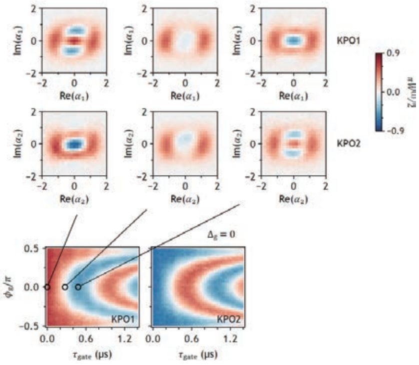


Fig 4. Rabi oscillation caused by the energy exchange of the two cat states. The gate time of $\sqrt{iSWAP}$ is 275 ns.

Integration of 5 qubit using resonator-network

Our team has integrated qubits based on the proposed pseudo-two-dimensional architecture. As a demonstration, we have integrated five transmon superconducting qubits using resonator-network coupling. In the pseudo-two-dimensional architecture, all the control wiring of the qubits can be arranged in a planar form. This requires the use of a crossed resonator network with air bridges (Fig 5).

Characterization of this chip showed a lifetime of about 40 us. We will continue to improve the performance of the integrated qubit chip. Since a single qubit chip for testing has a lifetime of over 100 us using essentially the same fabrication process, the lifetime of the integrated chip will be improved by clarifying the difference between the two.

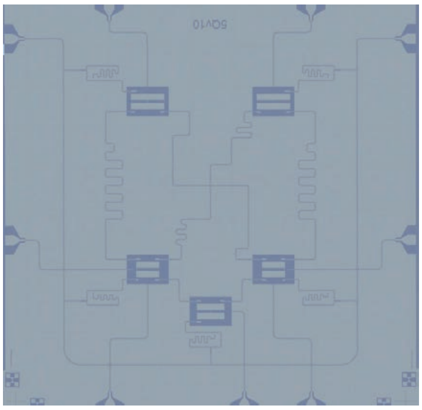


Fig 5. The chip is 10 mm square. The two resonators in the center intersect using air bridges.

Core members

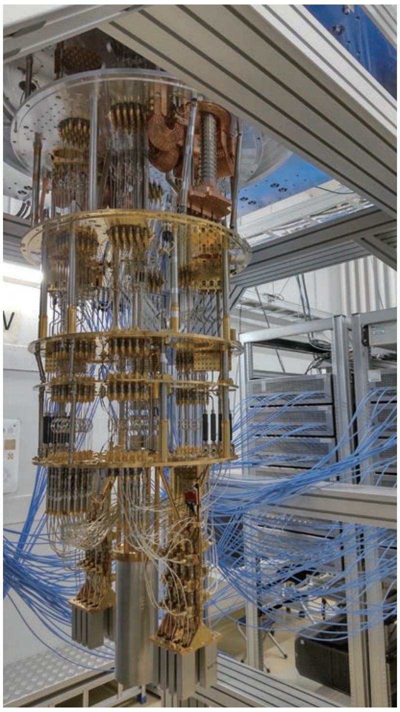
(Special Postdoctoral Researcher) **Hiroto Mukai**
(Postdoctoral Researcher) **Hang Xue**

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 are currently setting up a system with more than 100 qubits. 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.Sc.), Unit Leader

Selected Publications

1 K. Sasaki and E. Abe, “Suppression of Pulsed Dynamic Nuclear Polarization by Many-Body Spin Dynamics”, Physical Review Letters 132, 106904 (2024).
2 E. Abe, “Superconducting route to quantum computing”, Proceeding of 2023 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), P.1–4 (2023).
3 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).
4 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).
5 D. Misonou, K. Sasaki, S. Ishizu, Y. Monnai, K. M. Itoh, and E. Abe, “Construction and operation of a tabletop system for nanoscale magnetometry with single nitrogen-vacancy centers in diamond”, AIP Advances 10, 025206 (2020).

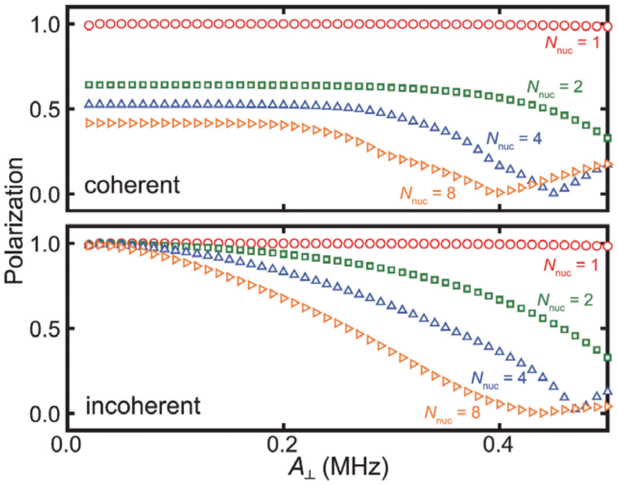
Brief resume

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

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.

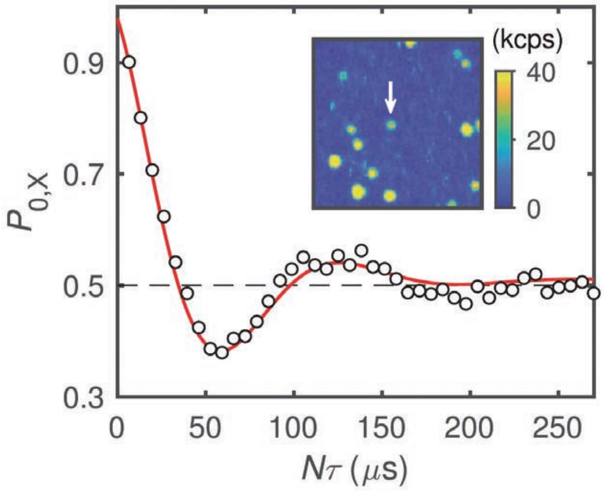


Numerical simulation of nuclear spin polarization as a function of the hyperfine interaction strength ($A_\perp$) and the number of nuclear spins (N_{nuc}). The increase in both the hyperfine interaction strength and the number of nuclear spins results in suppressed polarization. The upper (lower) figure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

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

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

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



Control of a single proton spin with a quantum sensor. The horizontal axis is the operation time, and the vertical axis is the sensor spin state. The data shows a coherent rotation of a nuclear spin. The inset is a confocal microscope image of the sample, with the arrow indicating the emission of the quantum sensor used for the measurement.

https://doi.org/10.1063/5.0016196

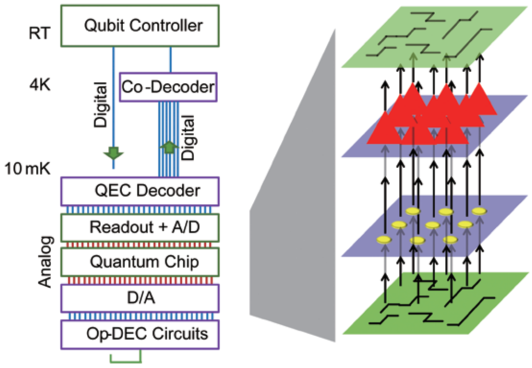
Superconducting Quantum Computing System Research Unit

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

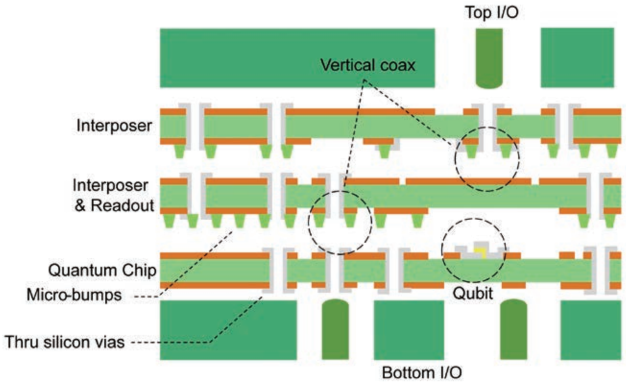
Research Outline

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

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



Stacked module systems



Implementation of stacked module systems

Yutaka Tabuchi (Ph.D.), Unit Leader

Selected Publications

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

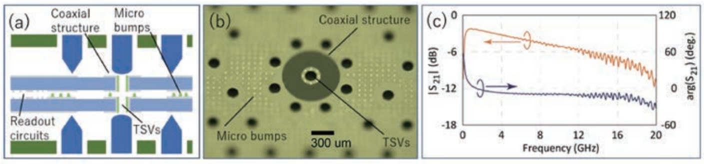
Brief resume

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

Recent Achievements

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

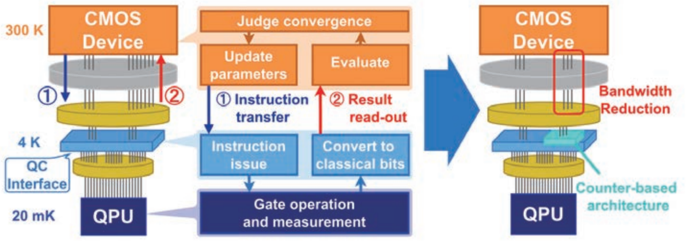
We study chip stacking techniques for superconducting circuits to improve the scalability of qubit devices. The chip-stacking method secures the available footprint area for the circuits, enabling us to integrate devices with a higher density. We have demonstrated a vertical signal waveguide as an analog interface between substrates [Bunpei Masaoka *et al.*, "Vertical signal transmission in stacked substrates for superconducting quantum circuits," The 36th International Symposium on superconductivity (2023)]. We have designed the vertical waveguide through the substrate using a pseudo-coaxial structure consisting of a center- and ground-electrode vias and demonstrated a broadband signal transmission from 2-10 GHz with an insertion loss of less than 2 dB. The established technology makes it possible to integrate superconducting devices by connecting inner-layer circuits to the through-substrate waveguide.



(a) A schematic illustration of vertical coax structure. (b) A photograph of the device structure. (c) Transmission coefficient obtained through the stacked chips.

Scalable quantum computers: from control electronics to decoding circuits: Signal processing circuits and architecture

The bandwidth restriction between cryogenic and room-temperature electronics is one of the critical bottlenecks in superconducting noisy intermediate-scale quantum computers. We have demonstrated an algorithm-aware system-level optimization to address the bottleneck issue [Yosuke Ueno *et al*., Inter-Temperature Bandwidth Reduction in Cryogenic QAOA Machines, IEEE Computer Architecture Letters 23, 6-9 (2023)]. We focus on the quantum approximate optimization algorithm as a target algorithm. We design digital circuits that count the coincidence of the qubit outcome using single-flux quantum logic operated at cryogenic temperature. We show in our detailed analysis of the circuit exponential bandwidth reduction and suppressions of heat inflow and peripheral power consumption of inter-temperature cables, highlighting the scalability of superconducting quantum computers.



Baseline system design of a superconducting quantum computer (left) and proposed system design (right).

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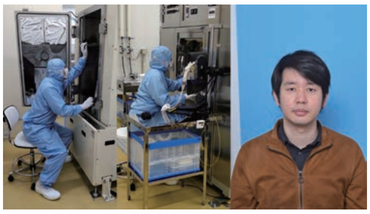
Core members

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

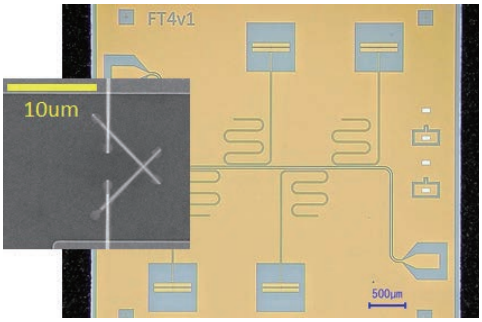


Hybrid Quantum Circuits Research Team

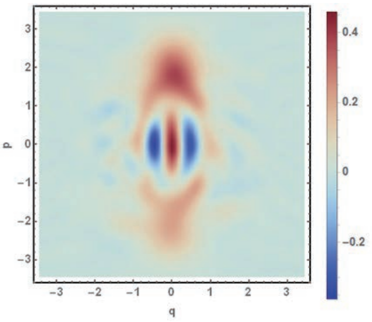
Keywords: Hybrid quantum systems, Microwave quantum optics, Electron trap, Quantum manipulations

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.



The Schrödinger's cat state generated by the backaction of the quantum measurement.

Atsushi Noguchi (Ph.D.), Team Leader

Selected Publications

1 S. Shirai, Y. Okubo, K. Matsuura, A. Osada, Y. Nakamura, and A. Noguchi, "All-microwave manipulation of superconducting qubits with a fixed-frequency transmon coupler", Phys. Rev. Lett. 130, 260601 (2023).
2 M. Shigefuji, A. Osada, M. Yabuno, S. Miki, H. Terai, and A. Noguchi, "Efficient low-energy single-electron detection using a large-area superconducting microstrip", arXiv:2301.11212.
3 A. Osada, K. Taniguchi, M. Shigefuji, and A. Noguchi, "Feasibility study on ground-state cooling and single-phonon readout of trapped electrons using hybrid quantum systems", Phys. Rev. Research 4, 033245 (2022).
4 A. Noguchi, A. Osada, S. Masuda, S. Kono, K. Heya, S. Piotr Wolski, H. Takahashi, T. Sugiyama, D. Lachance-Quirion, and Y. Nakamura, "Fast parametric two-qubit gates with suppressed residual interaction using a parity-violated superconducting qubit". Phys. Rev. A 102, 062408 (2020).
5 A. Noguchi, R. Yamazaki, Y. Tabuchi, and Y. Nakamura, "Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator", Nat. Commun. 11, 1183 (2020).

Brief resume

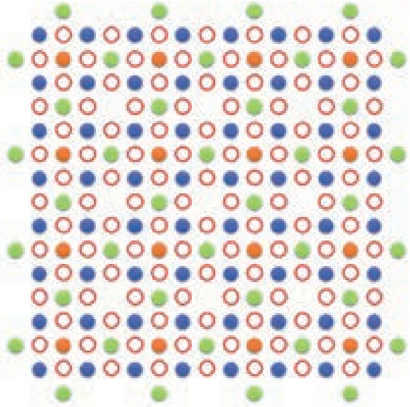
2013	Postdoc researcher, Osaka University
2014	Postdoc researcher, RCAST, The University of Tokyo
2015	Postdoc researcher, RCAST, The University of Tokyo
2015	Project Associate, RCAST, The University of Tokyo (-2018)
2016	Researcher, JST PREST (-2019)
2019	Associate Professor, Graduate School of Arts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

Recent Achievements

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

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

S. Shirai, Y. Okubo, K. Matsuura, A. Osada, Y. Nakamura, and A. Noguchi, Phys. Rev. Lett. 130, 260601 (2023).

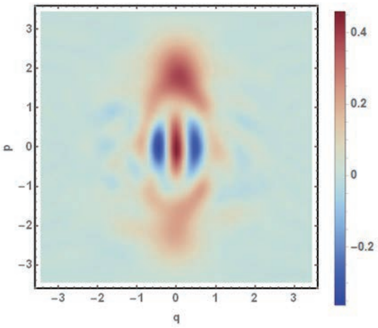


Integrated-circuit architecture with frequency-fixed couplers and multiplexed wirings.

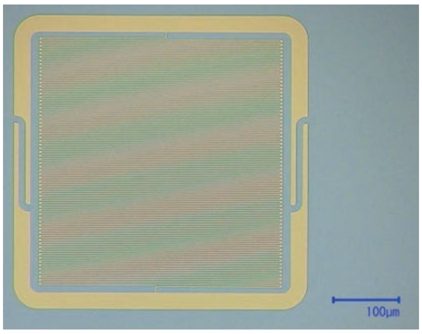
Quantum manipulation of the microwave photon and its back action

The operation of correcting errors in quantum circuits and extending the lifetime of quantum states is called the quantum error correction. In particular, by using microwave photons in a resonator, which has a larger degree of freedom than a qubit, quantum error correction can be realized with less overhead, leading to higher-performance quantum chips. Such research has been conducted using 3D microwave resonators due to their long lifetime, but from the viewpoint of scalability, it is desirable to realize such research in 2D circuits. Our team aims to improve the performance of 2D resonators to realize quantum microwave photon systems with both high integration and high performance.

In this fiscal year, we fabricated a lumped element microwave resonator with a high-performance titanium nitride superconducting film and developed a two-dimensional resonator with a Q-value exceeding 1,000,000. We have succeeded in developing a quantum chip by coupling this microwave resonator and the cubic transmon developed by our team. Using this chip, we realized a quantum measurement called modular measurement, which is important for quantum error correction using microwave photons. Furthermore, we succeeded in generating a macroscopic quantum state called Schrödinger's cat state in the resonator by controlling the quantum state of microwave photons through the reaction of the measurement.



We have demonstrated a modular measurement of the resonator with the superconducting qubit and manipulated it by the back action of the measurement.



High-Q microwave resonator with lumped-element circuits.

Core members

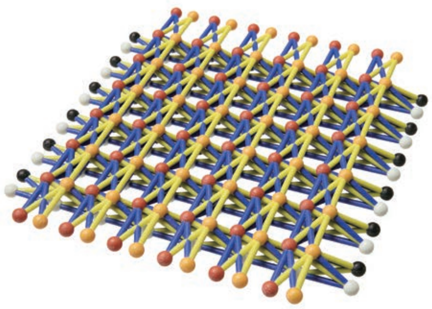
(Special Postdoctoral Researcher) **Ryo Sasaki**
(Postdoctoral Researcher) **Yusuke Tominaga**

Optical Quantum Computing Research Team

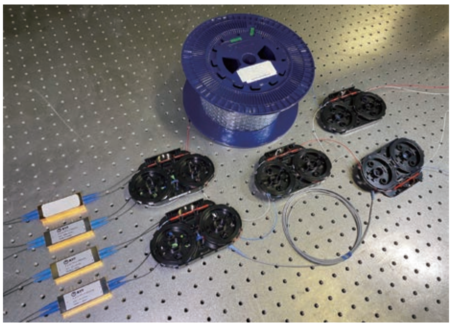
Keywords: Quantum information science, Quantum optics

Research Outline

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



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



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

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

Selected Publications

1 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).
2 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).
3 F. Hanamura, W. Asavanant, S. Kikura, M. Mishima, S. Miki, H. Terai, M. Yabuno, F. China, K. Fukui, M. Endo, and A. Furusawa, “Single-shot single-mode optical two-parameter displacement estimation beyond classical limit”, Phys. Rev. Lett. 131, 230801 (2023).
4 A. Inoue, T. Kashiwazaki, T. Yamashima, N. Takanashi, T. Kazama, K. Enbutsu, K. Watanabe, T. Umeki, M. Endo, and A. Furusawa, “Toward a multi-core ultra-fast optical quantum processor: 43-GHz bandwidth real-time amplitude measurement of 5-dB squeezed light using modularized optical parametric amplifier with 5G technology”, Appl. Phys. Lett. 122, 104001 (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
2000	Associate Professor of Applied Physics, The University of Tokyo
2007	Professor of Applied Physics, The University of Tokyo (-present)
2021	Deputy Director of the RIKEN Center for Quantum Computing / Team Leader of the Optical Quantum Computing Research Team (-present)

Recent Achievements

Nonlinear feedforward enabling quantum computation

Measurement-based quantum computer using time-domain multiplexing of propagating light is promising from the viewpoint of scalability. In this approach, fault-tolerance and universality of quantum computation are achieved via appropriate quantum state preparation and electro-optic feedforward of measurement results. Linear feedforward is an established technology, and various Gaussian operations have been realized using it. On the other hand, nonlinear feedforward, which enables deterministic non-Gaussian operations, had not been realized. We realized for the first time a fast and flexible nonlinear feedforward and further demonstrated non-Gaussian measurements by combining it with non-Gaussian ancillary states. This achievement will lead to high-speed and universal quantum computation using propagating light.

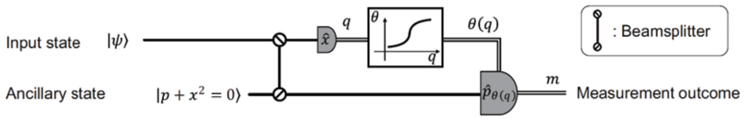
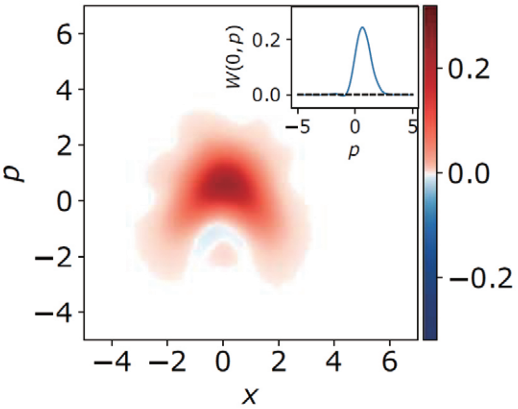


Diagram of nonlinear measurement using nonlinear feedforward. The measurement at the bottom is adaptively changed, according to nonlinear calculations on measurement results at the top.

©A. Sakaguchi *et al*. Nat. Commun. 14, 3817 (2023).



Virtual quantum state expressing nonlinear measurement. Parabolic structure indicates quadratic nonlinearity, and interference structure shows nonclassicality.

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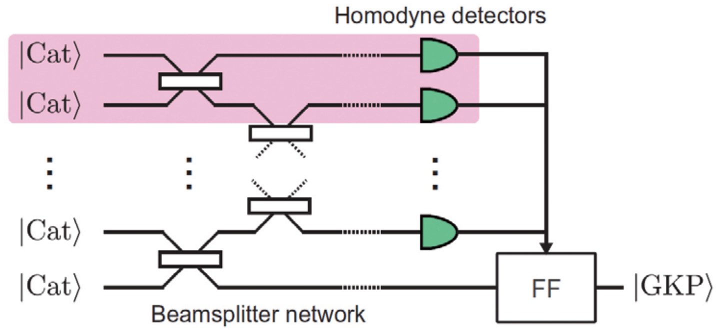
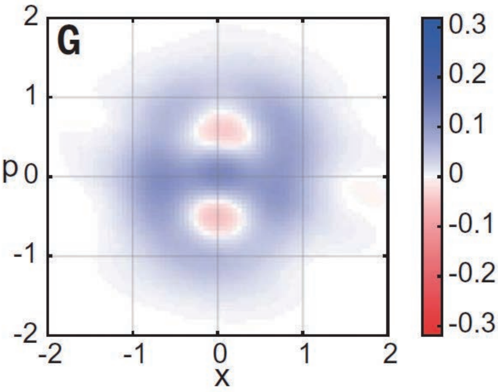
Logical states for fault-tolerant quantum computation with propagating light

A promising approach to realize fault-tolerant quantum computer in bosonic quantum system such as light is to utilize Gottesman-Kitaev-Preskill (GKP) qubits. GKP qubits are quantum states with a lattice-like distribution embedded in continuous-variable state space of bosonic quantum system. Although it is very hard to generate GKP qubits in propagating light, it is known that approximate ones can be generated by interference of multiple Schrödinger cat states followed by homodyne measurements. We for the first time succeeded in generating such approximate GKP qubits from interference of two Schrödinger cat states. We expect improvement of quality by increasing the number of Schrödinger cat states in the future.



Setup to generate optical GKP qubits from Schrödinger cat states.

©S. Konno *et al.*, Science 383, 289 (2023).



Approximate GKP qubit state generated from interference of two Schrödinger cat states and homodyne measurement.

©S. Konno *et al.*, Science 383, 289 (2023).

Core members

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

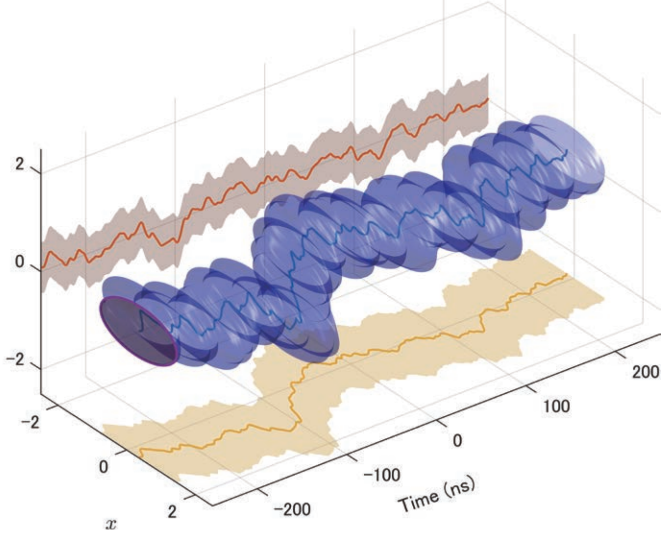
Optical Quantum Control Research Team

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.

We are investigating high-performance measurement and estimation techniques, control techniques based on them, measurement-based optical quantum computation, and related quantum optical technology. Figure shows quantum estimation of the dynamics of quantum states in an optical parametric oscillator. We have achieved high-precision estimation of quantum states using a quantum-state smoothing technique, where both quantum filtering and retro-filtering are used to produce more precise acausal estimation than conventional methods. In addition, we are also investigating coherent control and measurement-based control. Coherent control is a technique that does not involve measurements, leading to a faster and simpler system. Measurement-based control is a technique based on measurement, which allows more complex processing than coherent control. Through these investigations, our team aims to realise and improve optical quantum computers and related quantum information technologies.



Estimation of quantum state of light

Hidehiro Yonezawa (Ph.D.), Team Leader

Selected Publications

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

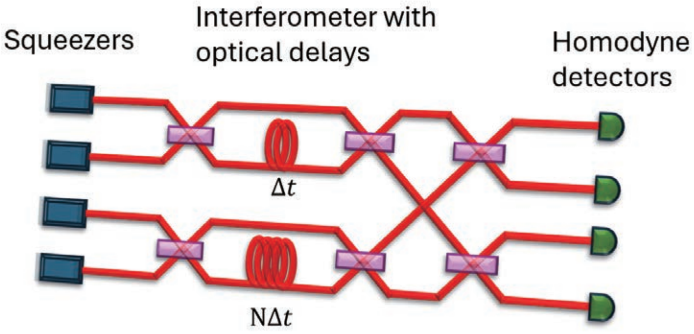
Brief resume

2007	Ph.D. in Engineering, The University of Tokyo
2007	Research associate, The University of Tokyo
2009	Project Assistant Professor, The University of Tokyo
2013	Senior lecturer, University of New South Wales
2023	Team leader, Optical Quantum Control Research Team, RIKEN Center for Quantum Computing, RIKEN (-present)

Recent Achievements

Development of measurement-based optical quantum computer

Our team is developing a measurement-based optical quantum computer in collaboration with optical quantum computation research team. Our optical quantum computer consists of four squeezers, an optical interferometer with delay lines, and four homodyne detection systems. The squeezers are NTT-made LN waveguide modules with 6 THz bandwidth, which enables ultra-fast quantum computation in future. The optical interferometer utilises two different length optical delay lines, creating ultra-large-scale quantum entanglement with time multiplexing. The number of inputs of our current quantum computer, which are determined by the length of the optical delay lines, is 102, while there is no limitation for computational steps. In the four homodyne detector systems, we measure the entanglement and perform quantum computation by changing the measurement bases. We have developed optical quantum computer hardware and verify the correlation in the ultra-large-scale quantum entanglement.



Schematic of optical quantum computer

Research on quantum state smoothing

Quantum smoothing is a method used in quantum estimation, where the estimate is calculated as a weighted average of the forward and backward estimations. While real-time estimation is not possible with this method, it can achieve higher accuracy estimation in problems where post-processing is allowed. So far, quantum smoothing has mainly been applied to parameter estimation, where classical smoothing techniques are almost directly applicable. In recent years, quantum smoothing technique has been extended for quantum state estimation with quantum mechanically valid formulation, revealing that it is possible to estimate quantum states more accurately through smoothing. Our team is conducting research with quantum optical techniques to apply quantum smoothing to the estimation of quantum states inside an optical cavity. As an optical cavity interacts with environment, the internal state of the cavity undergoes decoherence. By measuring the leakage from the optical cavity and applying quantum smoothing, accurate estimation is achieved. This leads to purer quantum state inside the optical cavity by suppression of the decoherence. In this research we investigate the effectiveness of quantum smoothing in detail.

Core members

(Senior Research Scientist) **Shota Yokoyama**

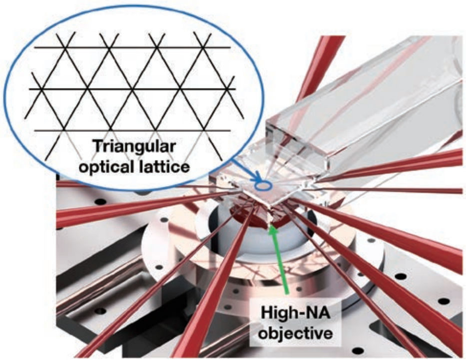
Quantum Many-Body Dynamics Research Team

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 Leader

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).

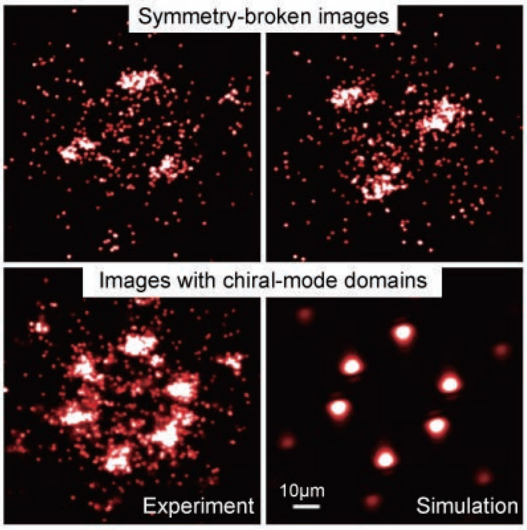
Brief resume

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)

Recent Achievements

Observation of chiral-mode domains

By mapping the phase of a Bose-Einstein condensate (BEC) in an optical lattice as a spin, the XY spin model is realized. For the BEC in a triangular optical lattice, the sign of the spin-spin coupling can be altered by modulating the phase of the optical lattice, which enables us to change the system from non-frustrated to frustrated. If the change is performed slowly enough, the system can be transferred to the ground state of the frustrated spin system, which has two degenerate chiral modes. We observed that one chiral mode appears randomly in each experiment, due to spontaneous symmetry breaking. Further, we investigated nonequilibrium dynamics (relaxation and excitation) after the change. We observed that chiral mode domain structures were formed when the system is changed relatively quickly.

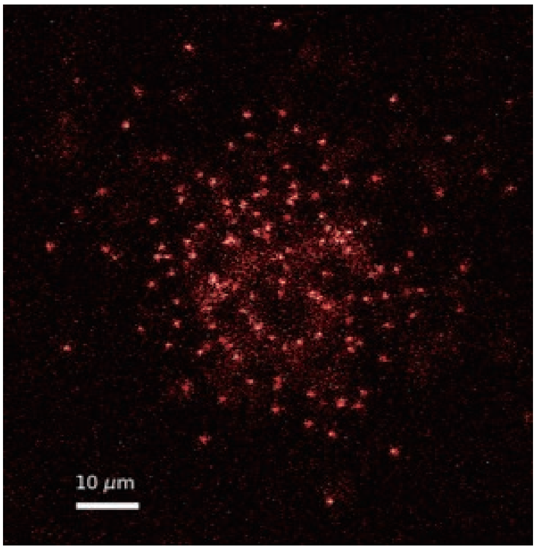


(Upper) Images with two chiral modes steaming from spontaneous symmetry breaking. (Lower) Images with chiral-mode domains. Experimental data (left) and numerical simulation (right).

©Hideki Ozawa, Ryuta Yamamoto, and Takeshi Fukuhara, "Observation of chiral-mode domains in a frustrated XY model on optical triangular lattices", Physical Review Research 5, L042026 (2023).

Observation of single atoms in an ultracold ^{85}Rb gas

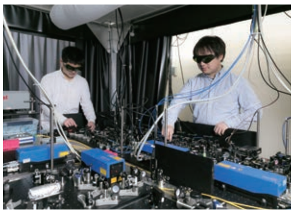
By loading bosonic atoms into an optical lattice and preparing a Mott insulating state with unity filling, we can realize a quantum spin system that is governed by spin-1/2 Heisenberg model if we consider two internal atomic states as pseudospin. In this mapping, the anisotropy of the spin-spin interaction can be controlled by changing the interatomic interaction via a Feshbach resonance. Although, for quantum gas microscope experiments, rubidium-87 atoms have been utilized, in this study we performed experiments using rubidium-85 atoms which have a Feshbach resonance at a magnetic field of B ~ 155 Gauss. We cooled rubidium-85 atoms down to a temperature of the order of micro Kelvin, and, for the first time in the world, succeeded in observing the atoms in a triangular lattice at the single-atom level. This system is expected to be used for a quantum simulation of frustrated magnets that follow the spin-1/2 triangular-lattice antiferromagnetic Heisenberg model.



Single atom detection of ultracold ^{85}Rb gases

Core members

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



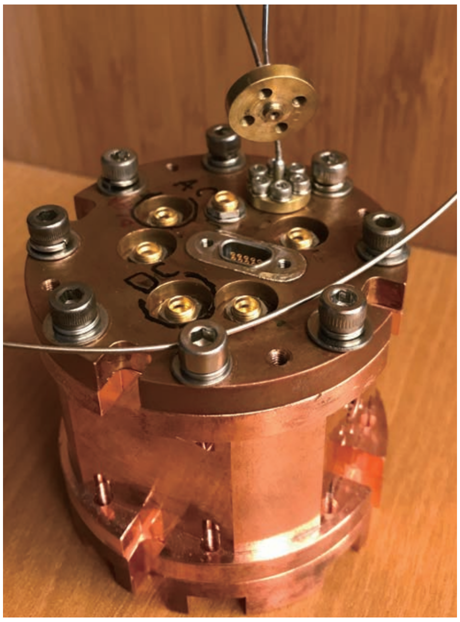
Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team

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

Brief resume

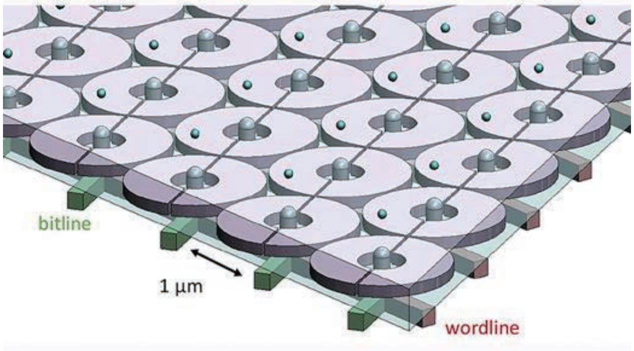
2016	Ph.D., Delft University of Technology, The Netherlands
2016	Postdoctoral researcher, Okinawa Institute of Science and Technology
2017	PRESTO, Japan Science and Technology Agency
2020	RIKEN Hakubi Team Leader, Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team (-present)

Recent Achievements

Blueprint for quantum computing using electrons on helium

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

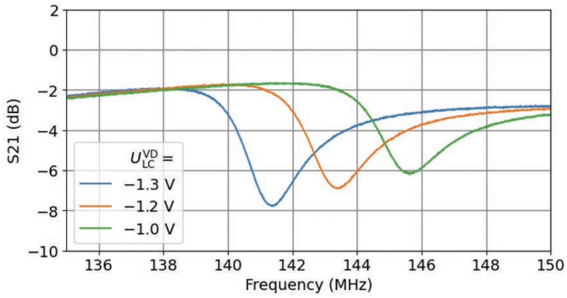
The interaction between the Rydberg state and the spin state is artificially introduced by a ferromagnet which is placed near the electron. We theoretically showed that the introduced magnetic field gradient mixes the spin state and the orbital state and shortens the spin relaxation time to 50 ms but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

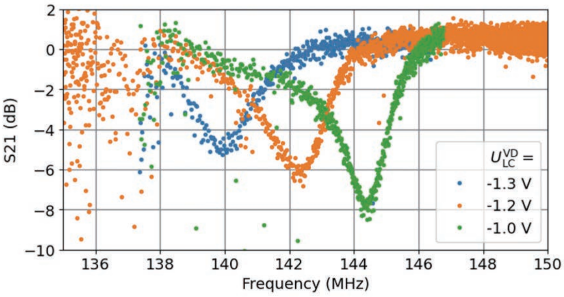


Electrons (blue circles) are arranged in a two-dimensional array to facilitate a scalable quantum computer. Our goal is to integrate quantum bits at bitline and wordline intersections, echoing the DRAM method of classical computers.

Cryogenic microwave source for qubit read-out

One of the key features required to realize a fault-tolerant scalable quantum computer is the integration of reliable and energy-efficient electronics for qubit control and readout. Recently, qubit control electronics have been successfully integrated using cryogenic CMOS technology and superconducting Josephson junctions. Here, we focus on the development of readout electronics using tunnel-diode oscillator circuits. Compared to cryogenic CMOS devices and superconducting Josephson junction circuits, the tunnel-diode circuits have lower power dissipation (~1µW). Recently, we successfully measured the characteristics of a resonator placed at ultra-low temperatures using a tunnel diode oscillator that also operates under ultra-low temperatures.





The upper figure shows the measurement results of a resonator placed in an ultra-low temperature environment using a microwave oscillator also set at ultra-low temperatures. The lower figure presents the results of measuring the resonator at ultra-low temperatures using a microwave oscillator placed at room temperature, for comparison

Core members

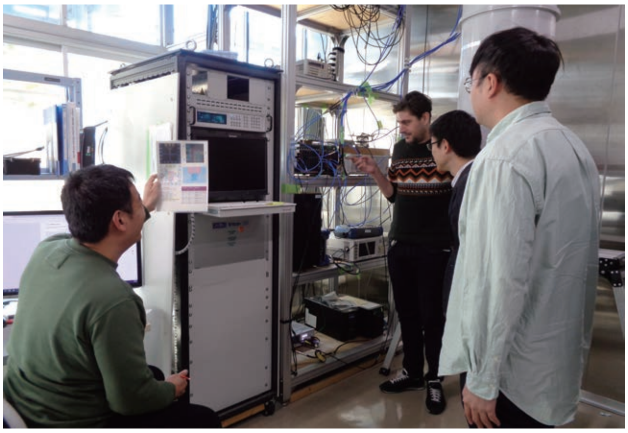
(Technical Scientist) **Ivan Grytsenko**
(Postdoctorial Researcher) **Asher Jennings**
(Research Part Timer I) **Oleksiy Rybalko**

Semiconductor Quantum Information Device Research Team

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

Research Outline

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



Picture of a laboratory

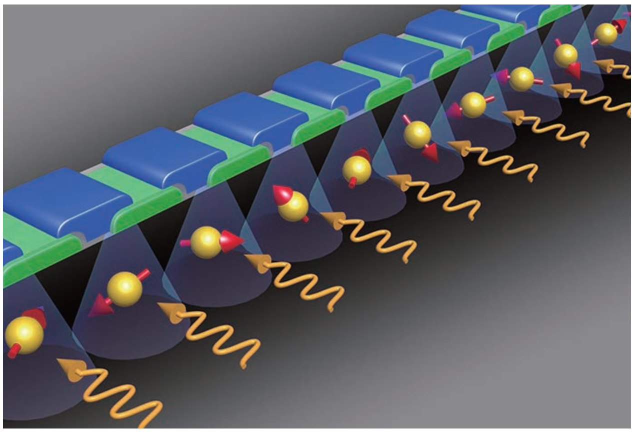


Image of a one-dimensiional spin qubit device

Seigo Tarucha (D.Eng.), Team Leader

Selected Publications

1 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).

2 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).

3 K. Takeda, A. Noiri, T. Nakajima, T. Kobayashi, and S. Tarucha, “Quantum error correction with silicon spin qubits”, *Nature*, 608, 682-686 (2022).

4 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).

5 T. Nakajima, Y. Kojima, Y. Uehara, A. Noiri, K. Takeda, T. Kobayashi, and S. Tarucha, “Real-time feedback control of charge sensing for quantum dot qubits”, *Phys. Rev. Applied*, 15, L031003 (2021).

Brief resume

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

Recent Achievements

High-fidelity 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.

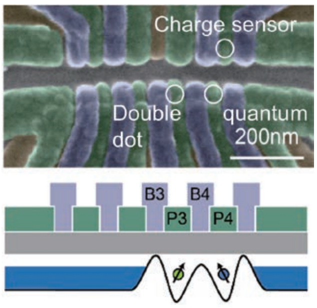


Fig.1 Two qubit device

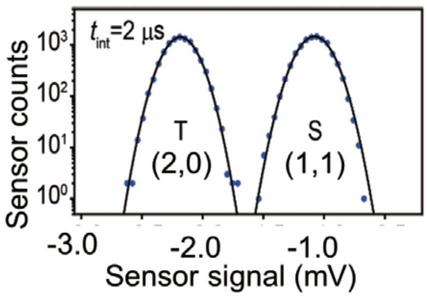


Fig. 2 Spin readout

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.

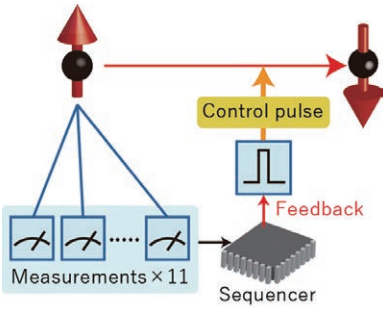


Fig.1 Schematic of the feedback quantum control based on multiple measurement results.

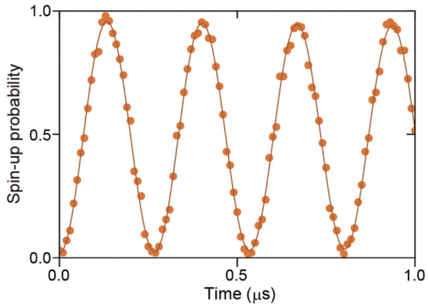


Fig.2 An example of qubit operation after the active reset. The preparation fidelity can be estimated from the visibility of the oscillations.

Core members

(Research Scientist) **Takashi Kobayashi**

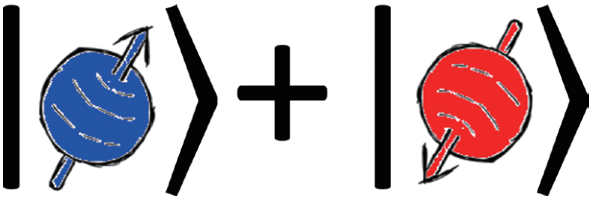
(Technical staff I) **Reiko Kuroda**

Semiconductor Quantum Information Device Theory Research Team

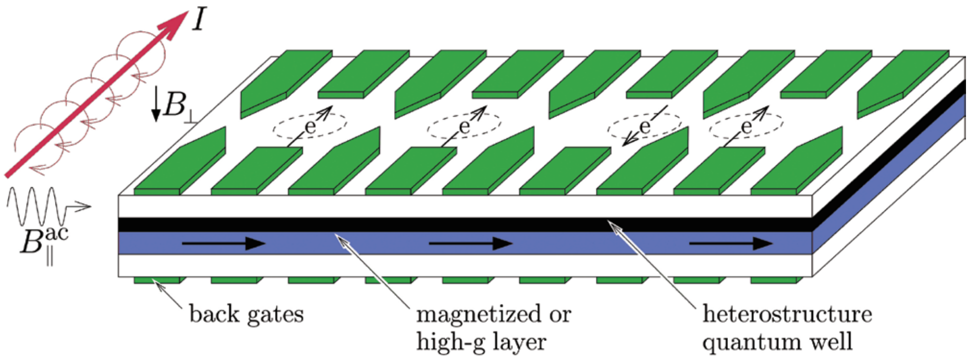
Keywords: Quantum dots, Spin-based quantum information science, Qubit, Spin-orbit interaction, Quantum information processing

Research Outline

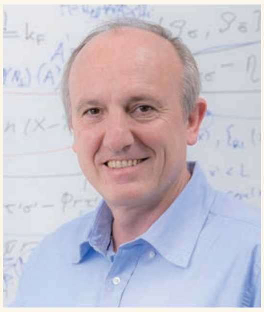
Our team is working on the theory of a spin-based quantum computer. We design its CMOS-compatible components deriving from Si and Ge gated quantum dots. We focus on spin qubits that can be manipulated by electric fields through various spin-orbit interactions. Using advanced band-structure models, we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

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).

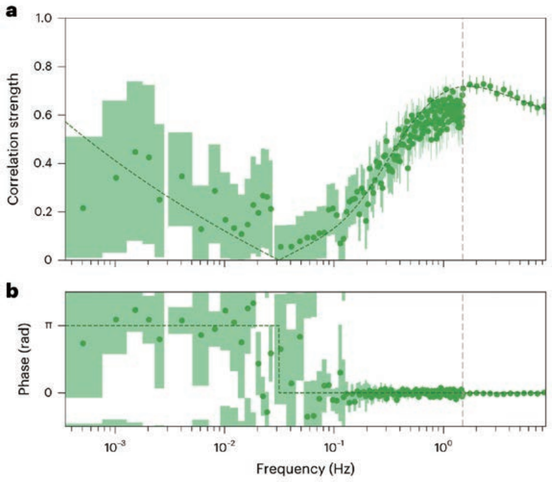
Brief resume

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

Noise-correlation spectrum for a pair of spin qubits in silicon

One of the main advantages of spin qubits is their reduced size, in the order of tens of nanometers, a great feature for scalability. However, at the same time, the compactness of the system implies that the qubits share the same local environment and could be subject to correlated noise, which could be a big obstacle in the implementation of an error-corrected quantum computer. In collaboration with experimentalists, we quantified for the first time the noise correlations between two neighboring spin qubits and found that, indeed, the noise can be strongly correlated between qubits and with exchange interaction. We devised a simple theoretical model for the effect of charge noise on the qubits and reached quantitative agreement with the measurements without any fitting parameters, proving that the model encapsulates the main physics behind decoherence in the device and that we understand the origin of the noise correlations.

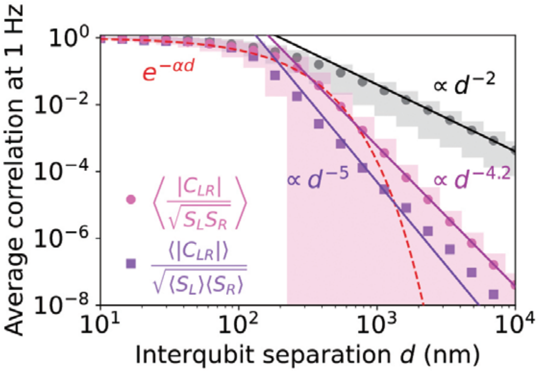


Normalized noise cross-correlation amplitude (a) and phase (b) for a pair of neighboring spin qubits. Two regimes are found: one with completely out-of-phase correlations at low frequencies, and another one with fully in-phase correlations at higher frequencies. This is the first quantification of qubit-noise correlations in spin qubits.

©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).

Scaling of charge noise correlations with interqubit distance

Knowing that noise in spin qubits is correlated, the natural question that arises is: "What is the range of the noise correlations?". The question is not trivial and is of the outmost importance for quantum error correction. To answer it, we modeled charge noise as the effect of charge two-level fluctuators that act on the qubits via Coulomb interaction. With the model we fitted the noise cross-spectra of real devices reaching quantitative agreement. Finally, we performed Monte-Carlo simulations to quantify the average correlation amplitude dependence on interqubit separation. We found a power-law decay which is steeper in the presence of screening from the metallic gates on the surface of the device. Our work suggests that it is preferable to fabricate devices with a high density of metallic gates to suppress noise correlations and provides an expectation on their range.



Average noise cross-correlation amplitude as a function of interqubit distance. Pink (gray) shows the results in the presence (absence) of screening from the metallic gates. Circles and squares show two different types of averaging.

©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).

Core members

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

Quantum Computing Theory Research Team

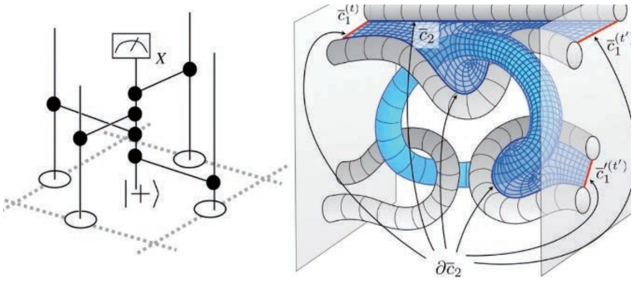
Keywords: Quantum computing, Quantum information science, Quantum machine learning, Quantum error correction

Research Outline

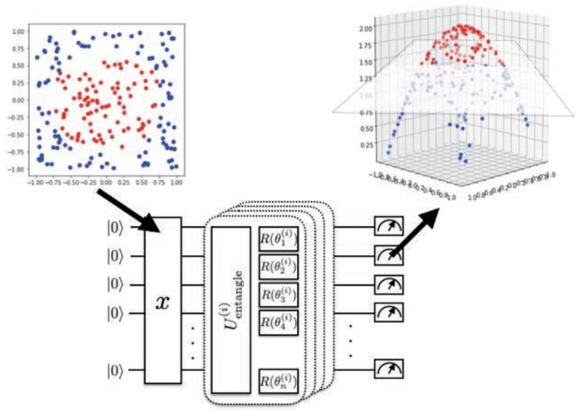
Quantum computing is revolutionizing technology, and Quantum Computing Theory Research team is at the forefront of this transformation. Our focus is on developing quantum computing theory and software essential for realizing quantum computers, designing new quantum algorithms, and analyzing their performance.

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

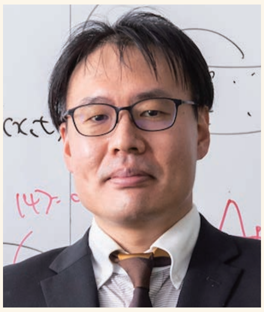
Embracing interdisciplinary research, we foster connections between quantum information science and fields like fundamental physics, quantum chemistry, machine learning, and high-performance computing. We aim to open up new scientific frontiers with quantum computers or through the lens of quantum information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



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



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



Keisuke Fujii (Ph.D.), Team Leader

Selected Publications

1 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).

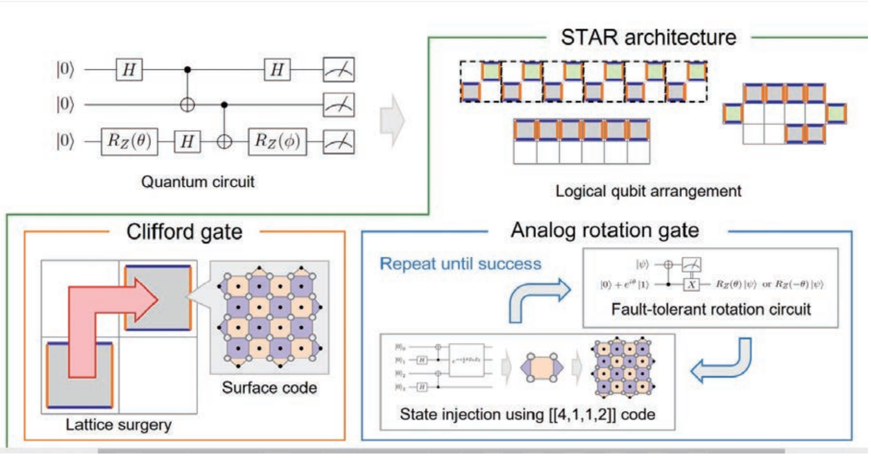
Brief resume

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 (-present)

Recent Achievements

A new concept quantum computer architecture using partial quantum error correction

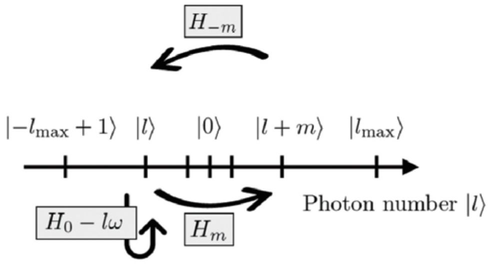
Computational power of the current quantum computers with tens to hundreds qubits is limited by the problem of noise. Therefore, the realization of a fault-tolerant quantum computer (FTQC) with quantum error correction is necessary to execute complex quantum algorithms with theoretically proven quantum speedup. It is estimated that a fault-tolerant quantum computer requires the order of one million qubits, a gap of four orders of magnitude between NISQ and FTQC. In this study, we propose a new architecture for early fault-tolerant quantum computation (earlyFTQC), in which Clifford operations, which are frequently required in quantum algorithms, are protected by quantum error correction, while continuous rotation gates, which usually require much overhead for quantum error correction, are executed with error detection. With an error probability of 10^{-4}, even 10,000 qubits can perform tasks that are difficult to simulate even on a supercomputer with guaranteed accuracy. This architecture is a new milestone for the evolution of quantum computers from the NISQ era to FTQC in a sustainable manner, and also enables early application of quantum computers to real-world problems.



A conceptual design of a new quantum computer architecture for early FTQC.

Optimal quantum algorithm for simulating time-dependent Hamiltonian dynamics

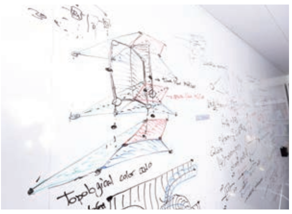
Since Richard Feynman proposed the concept of a quantum computer by saying, “if you want to make a simulation of nature, you’d better make it (computer) quantum mechanical,” the simulation of quantum many-body systems has been one of the most promising applications of quantum computers. In particular, a new type of algorithm called the quantum singular value transformation algorithm has recently emerged, which is the optimal quantum algorithm for the time-independent simulation of Hamiltonian dynamics. In this study, by applying Floquet theory to time-dependent Hamiltonians, we construct a quantum algorithm that optimally simulates the time evolution under a time-dependent Hamiltonian. The results enable faster and more accurate simulations of complex phenomena such as nonequilibrium phenomena and chemical reactions.



Conceptual diagram of the effective Hamiltonian when the time-dependent Hamiltonian is described in a Floquet-Hilbert space

Core members

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



Quantum Information Physics Theory Research Team

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

Research Outline

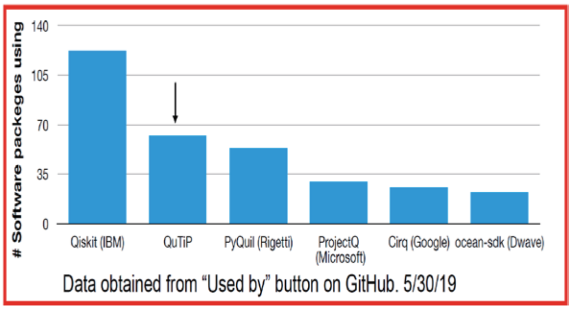
Our research group performs interdisciplinary studies at the interface between quantum computing, quantum information processing, superconducting quantum circuitry for quantum computing, photonics, quantum optics, atomic physics, nano-mechanics, nanoscience, mesoscopics, computational physics, and condensed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

We developed the QuTiP software used worldwide for quantum information processing, quantum optics, and quantum open systems. We are also using techniques from AI and Machine Learning to solve computationally hard problems. The Web of Science has listed our research work as Highly Cited for the past seven years (from 2017 to 2023). Less than 0.1% of researchers reach this milestone.

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

More than 1.5 Million downloads!

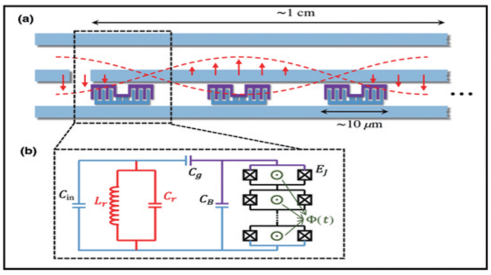
Our quantum software (QuTiP) is used by more groups than the ones by Google, Microsoft, D-Wave, etc.



Data obtained from "Used by" button on GitHub. 5/30/19

Our software QuTiP is widely used by very many research groups, and it has been downloaded more than 1.5 million times.

Quantum Information with quantum cat states



Quantum cat states play a very important role in quantum science and technology, and we have obtained several interesting results in this area.

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

Franco Nori (Ph.D.), Team Leader

Selected Publications

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

2 W. Qin, A. Miranowicz, H. Jing, F. Nori, "Generating Long-Lived Macroscopically Distinct Superposition States in Atomic Ensembles", *Phys. Rev. Lett.* 127, 093602 (2021).

3 Y. Nomura, N. Yoshioka, F. Nori, "Purifying Deep Boltzmann Machines for Thermal Quantum States", *Phys. Rev. Lett.* 127, 060601 (2021).

4 X. Wang, T. Liu, A.F. Kockum, H.R. Li, F. Nori, "Tunable Chiral Bound States with Giant Atoms", *Phys. Rev. Lett*. 126, 043602 (2021).

5 Y.H. Chen, W. Qin, X. Wang, A. Miranowicz, F. Nori, "Shortcuts to Adiabaticity for the Quantum Rabi Model: Efficient Generation of Giant Entangled Cat States via Parametric Amplification", *Phys. Rev. Lett.* 126, 023602 (2021).

Brief resume

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

Recent Achievements

Quantum Information with quantum cat states

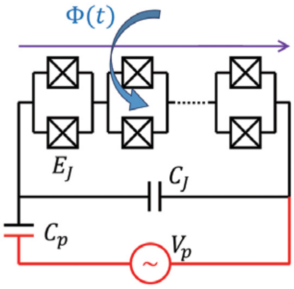
Quantum cat states play a very important role in quantum science and technology, and we have obtained several interesting results in this area. Our recent results in this area can be found in our publications, including these four examples:

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

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

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

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



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

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

General results in the field of ultrastrong light-matter coupling

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

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

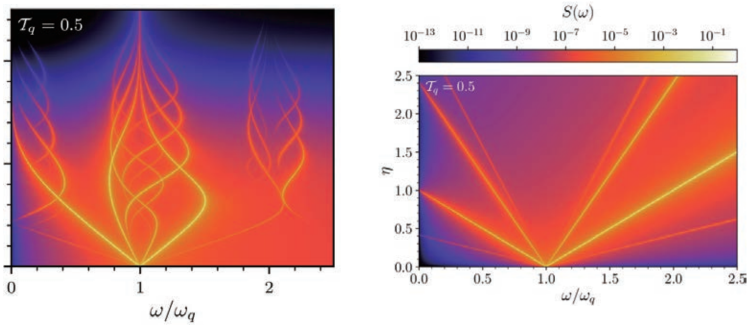
W. Salmon *et al.*, *Gauge-independent emission spectra and quantum correlations in the ultrastrong coupling regime of open system, cavity-QED*, Nanophotonics 11, pp. 1573 (2022).

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

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

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

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



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

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

Core members

(Research Scientist) **Clemens Gneiting**

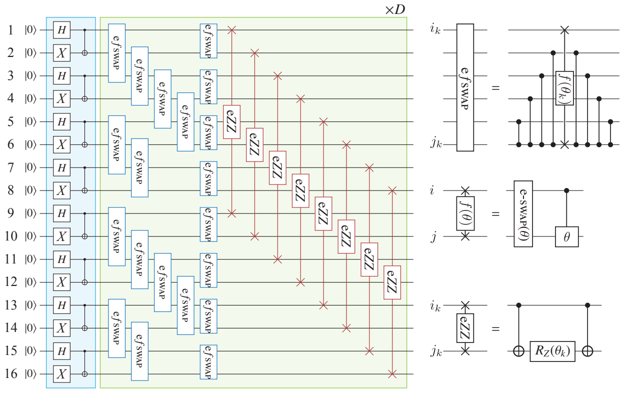
(JSPS Postdoctoral Researcher) **Paul MENCZEL**

Quantum Computational Science Research Team

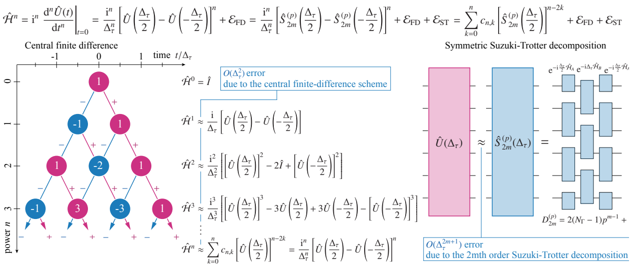
Keywords: Quantum many-body systems, Quantum dynamics, Quantum information physics, Tensor network, High performance computing

Research Outline

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



Quantum circuits for VQE calculations of Hubbard model



Schematic figure for quantum power methods

Seiji Yunoki (Ph.D.), Team Leader

Selected Publications

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

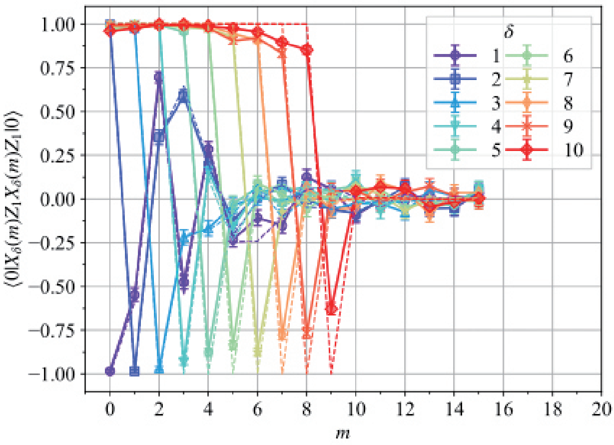
Brief resume

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

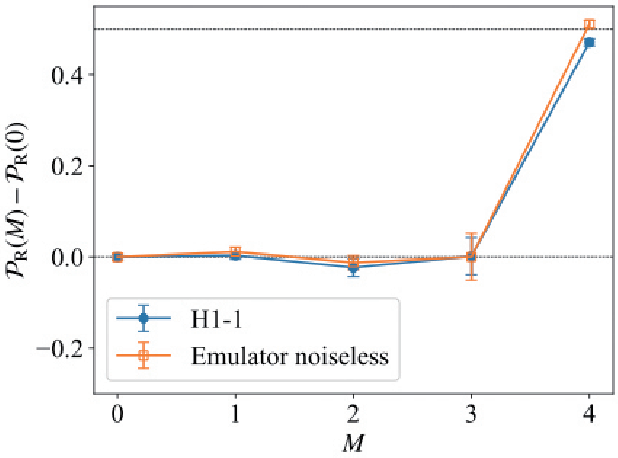
Complex quantum many-body dynamics spread initially localized quantum information across the entire system. Information scrambling refers to such a process, whose simulation is one of the promising applications of quantum computing. We demonstrate the Hayden-Preskill recovery protocol and the interferometric protocol for calculating out-of-time-ordered correlators to study the scrambling property of a Floquet dynamics based on a one-dimensional kicked-Ising model on a 20-qubit trapped-ion quantum processor. 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. These results imply that the Floquet quantum circuit indeed exhibits information scrambling.



The figure shows the out-of-time-ordered correlators for various positions δ (figure legends) of butterfly operators as a function of Floquet cycles.

Topologically distinct ground states of a Su-Schrieffer-Heeger model described by parametrized quantum circuits

The Su-Schrieffer-Heeger (SSH) model exhibits two topologically distinct ground states depending on the relative magnitude of hopping parameters within and between unit cells. We conducted a classical simulation of the ground state of the SSH model using a variational quantum circuit in the form of the Quantum Alternating Operator Ansatz (QAOA) to investigate the quantum resources required to prepare topologically trivial or non-trivial ground states. The results revealed the following: (i) When the initial state and final state belong to the same topological phase, the variational energy approaches the exact ground state energy exponentially with respect to circuit depth. (ii) When the initial state and final state belong to different topological phases, a circuit depth equal to a quarter of the system size is always required. Furthermore, we calculated the topological order parameter using an ion trap quantum computer for an 18-site system and exper-imentally validated the topological phase transition.



The figure shows the dependence of the polarization P_R on the depth of the variational quantum circuit M for an 18-qubit system. It demonstrates the transition from a topologically trivial initial state (M=0) to a nontrivial final state (M=4).

Core members

(Research Scientist) **Kazuhiro Seki**

(Postdoctoral Researcher) **Qing Xie**

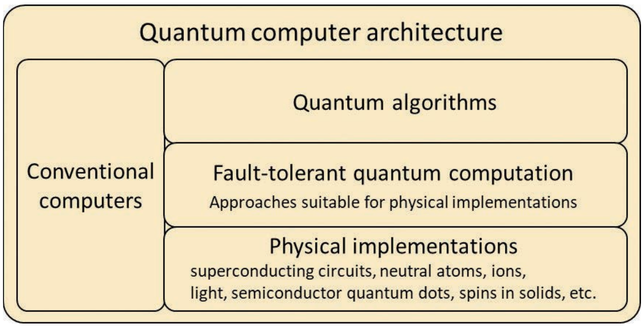
Quantum Computer Architecture Research Team

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

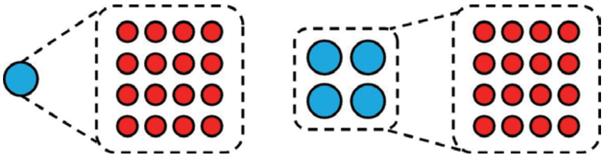
Research Outline

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 play a role similar to ASIC or an accelerator, they should be designed for specific quantum algorithms. Moreover, since conventional computers play important roles such as control of physical systems, decoding in error correction, and quantum-classical hybrid implementations of algorithms, quantum-classical cooperative system design is required. Thus, the research on quantum computer architecture requires to consider all aspects of quantum computers.

The requirement of large resource overheads for FTQC is a central problem at present. To solve this problem, we focus on high-rate codes. 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 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), high-rate code (Right).

Hayato Goto (Ph.D.), Team Leader

Selected Publications

1 H. Goto, “Many-hypercube codes: High-rate quantum error-correcting codes for high-performance fault-tolerant quantum computation”, arXiv:2403.16054 (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 (-present)

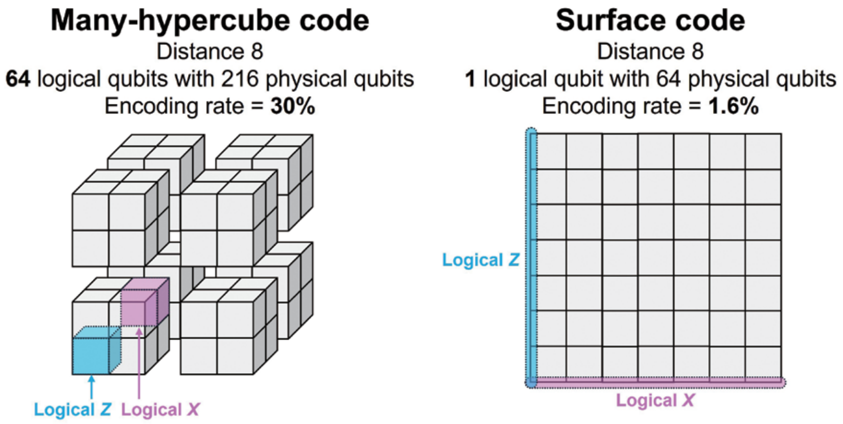
Recent Achievements

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 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 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, “Many-hypercube codes: High-rate quantum error-correcting codes for high-performance fault-tolerant quantum computation”, arXiv:2403.16054 (2024).



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

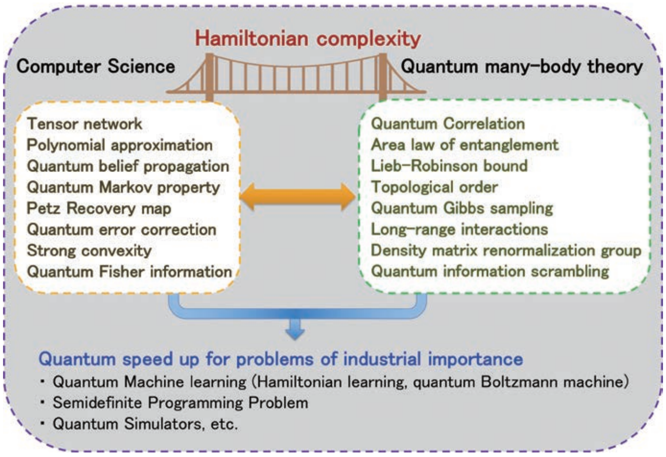
Core members

(Research Scientist) **Ryota Nakai**

Analytical Quantum Complexity RIKEN Hakubi Research Team

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

Research Outline



Schematic figure for quantum Hamiltonian

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.

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 Tomotaka Kuwahara, Tan Van Vu, Keiji Saito, "Effective light cone and digital quantum simulation of interacting bosons" Nature Communications 15(1) 2520 (2024).
2 T. Kuwahara, K. Saito, "Exponential Clustering of Bipartite Quantum Entanglement at Arbitrary Temperatures," Physical Review X, 12, 021022 (2022).
3 A. Anshu, S. Arunachalam, T. Kuwahara, M. Soreimanifar (alphabet order), "Sample-efficient learning of quantum many-body systems," Nature Physics, 17, 931–935 (2021), Featured in News&Views.
4 T. Kuwahara, A. M. Alhambra, and A. Anshu, "Improved thermal area law and quasi-linear time algorithm for quantum Gibbs states," Physical Review X, 11, 11047 (2021).
5 T. Kuwahara, K. Saito, "Area law of noncritical ground states in 1D long-range interacting systems," Nature Communications, 11 4478 (2020).

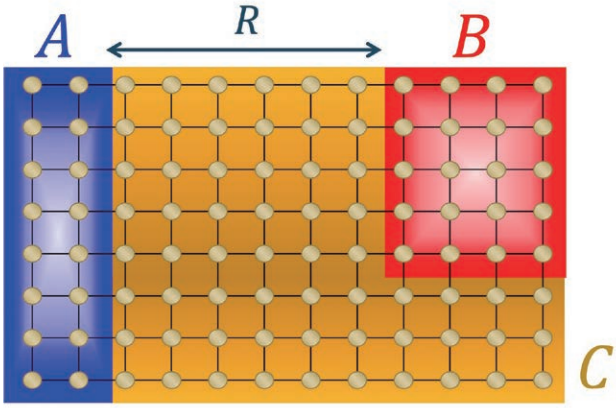
Brief resume

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

Partial resolution of quantum Markov expectation in quantum many-body systems.

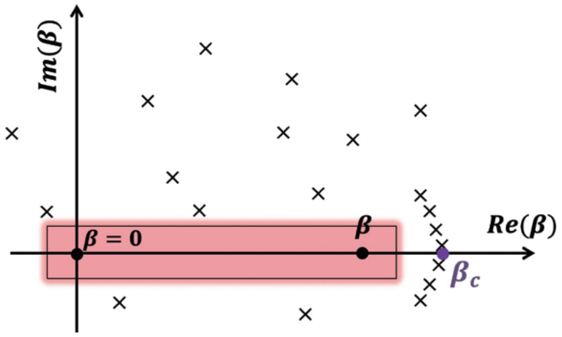
One of the most fundamental properties of classical probability theory is Markovianity, which prescribes conditional independence between the random variables. A multivariate probability distribution satisfying Markov property is called the Markov network. The celebrated Hammersley-Clifford theorem connects the classical Markovianity to the many-body physics, which guarantees the equivalence of Markov networks and Gibbs distributions. Whether a quantum version of this holds is called the quantum Markov conjecture, which is mathematically described as “the exponential decay of the conditional mutual information in an arbitrary quantum Gibbs state.” In this study, we provide proof of the exponential decay of the mutual information content among small subsystems. This result shows in general that all quantum Gibbs states are at least Pairwise Markov networks. This result was accepted for a Long Plenary Talk at Quantum Information Processing 2024 (QIP2024). Only 4 submissions are chosen from over 1000 submissions (<0.4%).



We prove that quantum states at finite temperature generally satisfy quantum Markov property. In other words, we show that the conditional mutual information decays exponentially with the distance. Previous results only prove this for high temperature regimes above a temperature threshold, and we aim to extend this to all temperature regimes.

Clustering theorem in 1D long-range interacting systems at arbitrary tempera

One of the most fundamental theorems in statistical mechanics is the absence of phase transitions in one-dimensional systems. The extension to quantum systems was achieved in a famous 1969 paper by Hujihiro Araki, but this result imposes the condition that the interaction length is finite. Recently, an extension of this result to long-range interacting systems was discussed, but it became clear that there exists an essential problem of divergence of the complex Lieb-Robinson bound. The absence of phase transitions in long-range interacting systems has been a fundamental open question. In collaboration with Yusuke Kimura of our team, we tackled this problem and succeeded for the first time in extending the decay theorem (Clustering theorem) for two-body correlations. On the other hand, to solve the non-existence of phase transitions in long-range interacting systems, it is necessary to investigate the zero point of the partition function, and we plan to continue our analysis in the next fiscal year and beyond. This work was selected as an Outstanding poster at Theory of Quantum Computation, Communication and Cryptography 2024 (TQC2024).



The zero point of the partition function characterises quantum many-body systems with finite temperatures. The complex zero points means that the partition function becomes zero when the inverse temperature is extended to complex planes, and it is known that the zero-free region has smaller complexity in the computer science sense. We aim to establish a universal theorem on the distribution structure of zero points, in particular, the non-existence of phase transitions in one-dimensional long-range interacting systems.

Core members

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

Mathematical Quantum Information RIKEN Hakubi Research Team

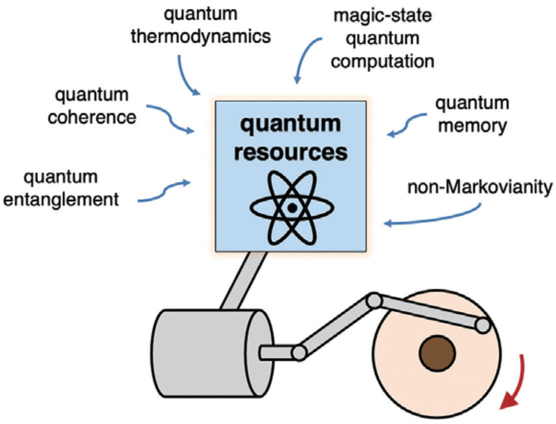
Keywords: Quantum information, Quantum resource theories, Quantum Shannon theory, Mathematical physics

Research Outline

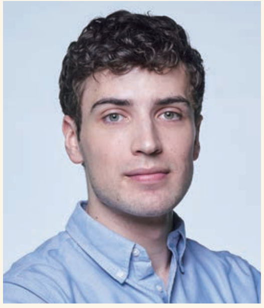
Our group studies the mathematical underpinnings of quantum information theory, with a particular focus on the investigation of the mathematical structure of quantum resources — physical phenomena that underlie practical advantages of quantum technologies in areas such as communication and computation.

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.



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



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

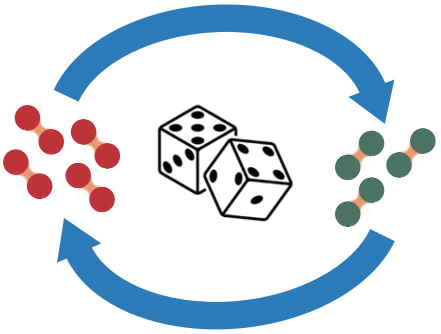
2018	Ph.D. Mathematics, University of Nottingham, UK
2019	Presidential Postdoctoral Fellow, Nanyang Technological University, Singapore
2021	JSPS Postdoctoral Research Fellow, University of Tokyo, Japan
2023	RIKEN Hakubi Team Leader, Mathematical Quantum Information RIKEN Hakubi Research Team, RIKEN,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

Recent Achievements

A probabilistic “second law” of quantum resources

The second law of thermodynamics is a fundamental law of physics. It tells us that the thermodynamic transformations of physical systems are governed by a single function: the entropy. We show that a similar result can be obtained not only in thermodynamics, but also for general quantum phenomena that find use as resources in physical settings — in particular, for quantum entanglement, whose dynamics are notoriously hard to characterise exactly.

We showed that the transformations of quantum systems can be described by a single entropic measure of resources, and all transformations can be made asymptotically reversible in a suitable probabilistic setting. The result simplifies the characterisation of the transformations of quantum resources and the understanding of their limitations. The price to pay in our approach is that reversibility, and thus the second law, is only achievable with some probability.



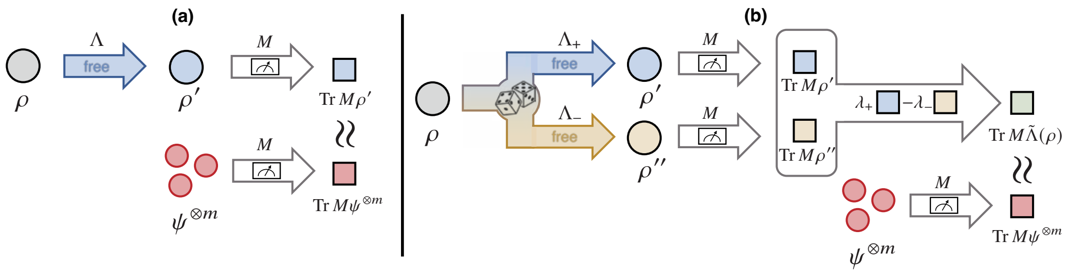
Schematic illustration of probabilistic reversibility of quantum entanglement. Transformations between many copies of entangled quantum states (here represented by red and green shapes) are made reversible by using probabilistic protocols, with the transformation rate given by the regularised relative entropy of entanglement. This leads to a consistent and unique notion of an entropic measure of entanglement.

©B. Regula and L. Lami, “Reversibility of quantum resources through probabilistic protocols”, Nature Communications 15, 3096 (2024)

Virtual distillation of quantum resources

Distillation (purification) is central to the practical use of quantum resources in noisy settings often encountered in quantum communication and computation. Conventionally, distillation requires using some restricted 'free' operations to convert a noisy state into one that approximates a desired pure state. We propose to relax this setting by only requiring the approximation of the measurement statistics of a target pure state. This allows us to integrate the power of classical postprocessing to enhance the capabilities of free quantum operations.

We show that this extended scenario of virtual resource distillation provides considerable advantages over standard approaches, allowing for the purification of noisy states from which no resources can be distilled conventionally. Our methods can be applied to various settings such as the theories of entanglement, coherence, or non-stabiliser quantum computation.



Comparison of conventional and virtual resource distillation. (a) Conventional resource distillation employs a free operation Λ to map a noisy state ρ into a state that approximates (many copies of) the target state ψ. (b) Virtual distillation approximates the measurement outcomes of copies of ψ by using a virtual operation, that is, a linear combination of free operations.

©X. Yuan, B. Regula, R. Takagi, and M. Gu, “Virtual quantum resource distillation”, Physical Review Letters 132, 050203 (2024)

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

Opening of the “RIKEN RQC-Fujitsu Collaboration Center”

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.

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

Selected Publications

1 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)
2 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)
3 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)
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Brief resume

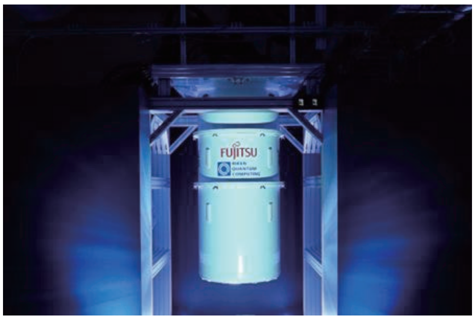
1990	MS in Science and Engineering (Physics), University of Tsukuba
1990	Ushio Inc. (until 1997)
2001	Ph.D. in Mechanical Engineering, University of Minnesota, USA
2001	Electronic Devices Business Unit, Fujitsu Limited
2002	Researcher, Nanotechnology Research Center, Fujitsu Laboratories Ltd.
2006	Researcher (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

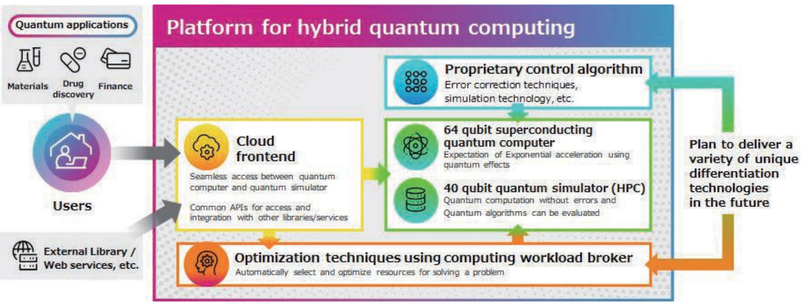
Recent Achievements

Development of superconducting quantum computer, paving the way for platform for hybrid quantum computing

Our group developed a new 64 qubit superconducting quantum computer at the RIKEN RQC-Fujitsu Collaboration Center. The new quantum computer leverages the technology developed by RIKEN and a consortium of joint research partners including Fujitsu for Japan's first superconducting quantum computer, which was first revealed to the public in March 2023. Accompanying this announcement, we further revealed the launch of a platform for hybrid quantum computing, which combines the computing power of the newly developed 64 qubit superconducting quantum computer with one of the world's largest 40 qubit quantum computer simulators developed by Fujitsu. Fujitsu and RIKEN provided the new platform to companies and research institutions that are conducting joint research with Fujitsu and RIKEN from October 5, 2023. The new hybrid platform enables easy comparison of calculation results of noisy intermediate-scale quantum (NISQ) computers against error-free results from quantum simulators, contributing to accelerated research in areas including performance evaluation of error mitigation algorithms in quantum applications.



Quantum computer developed at the RIKEN RQC-Fujitsu Collaboration Center

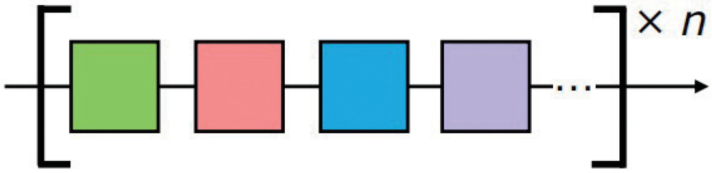


Overview of the new platform for hybrid quantum computing

Improvement of Characterization Method toward Achievement of Quantum Operations with Higher Accuracy

Further improvement of implementation accuracies of quantum operations is one of the major challenges for realizing a practical quantum computer. Characterization of implementation accuracies of quantum operations is a fundamental technique for accuracy improvements. Current standard characterization methods have several advantages and disadvantages, and a new method that overcomes the disadvantages is necessary. Our group works on research toward improving the efficiency and reliability of a characterization method class, called "Quantum Tomography". Specifically, we focus on reduction of experimental and numerical costs of a method called "Gate-Set Tomography" (GST).

Analytical method of error amplification circuits plays an important role at cost reduction of GST. We developed a new tomographic method for quantum gates, which is a cost reduction of GST, but it had a problem that it was not applicable to an important class of quantum gates, 180-degree-rotation gates. Recently, we have improved the analytical method of error amplification, and the cost-reduced method has become applicable to 180-degree-rotation gates.



Conceptual diagram of an error amplification quantum circuit

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 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

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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)
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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)

Simplifying quantum computation

A novel protocol for quantum computers could reproduce the complex dynamics of quantum materials

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

A quantum-computational algorithm that could be used to efficiently and accurately calculate atomic-level interactions in complex materials has been developed by RIKEN researchers[1]. It has the potential to bring an unprecedented level of understanding to condensed-matter physics and quantum chemistry—an application of quantum computers first proposed by brilliant physicist Richard Feynman in 1981.

Quantum computers bring the promise of enhanced number-crunching power and the ability to crack problems that are out of the reach of conventional computers.

Qubits, the building blocks of quantum computers, are essentially tiny systems—nanocrystals or superconducting circuits, for example—governed by the laws of quantum physics. Unlike bits used in conventional computers, which can be either one or zero, qubits can have multiple values simultaneously. It is this property of qubits that gives quantum computers their advantage in terms of speed.

An unconventional way of computation also requires a new perspective on how to efficiently process data in order to tackle problems too difficult for conventional computers.

One notable example of this is the so-called time-evolution operator. “Time-evolution operators are huge grids of numbers that describe the complex behaviors of quantum materials,” explains Kaoru Mizuta of the RIKEN Center for Quantum Computing. “They’re of great importance because they give quantum computers a very practical application—better understanding quantum chemistry and the physics of solids.”

The prototype quantum computers demonstrated to date have achieved time-evolution operators using a relatively simple technique called Trotterization. But Trotterization is thought to be unsuitable for the quantum computers of the future because it requires a huge number of quantum gates and thus a lot of computational time. Consequently, researchers have been striving to create quantum algorithms for accurate quantum simulations that use fewer quantum gates.

Now, Mizuta, working with colleagues from across Japan, has proposed a much more efficient and practical algorithm. A hybrid of quantum and classical methods, it can compile time-evolution operators at a lower computational cost, enabling it to be executed on small quantum computers, or even conventional ones.

“We have established a new protocol for constructing quantum circuits that efficiently and accurately reproduce time-evolution operators on quantum computers,” explains Mizuta. “By combining small quantum algorithms with the fundamental laws of quantum dynamics, our protocol succeeds in designing quantum circuits for replicating large-scale quantum materials, but with simpler quantum computers.”

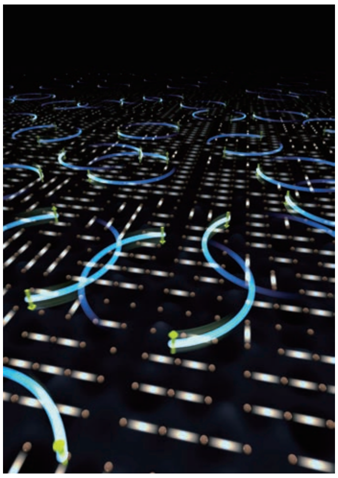

Figure: An illustration showing the two states of a cuprate high-temperature superconductor. A new protocol for constructing quantum circuits could help with calculations on quantum materials such as superconductors.
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Mizuta and his team next intend to clarify how the time-evolution operators optimized by their method can be applied to various quantum algorithms that can compute the properties of quantum materials. “We anticipate that this work will demonstrate the potential of using smaller quantum computers to study physics and chemistry.”

Related content:

Quantum computing and deep learning could help solve the mysteries of quantum gravity
[https://www.riken.jp/en/news_pubs/research_news/rr/20220411_1/index.html]

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]

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Reference

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RIKEN Research Summer 2023 (p.21)

Feedback system could fix quantum-computing errors

Quantum circuit can reset quantum bits carried by electron spins in silicon

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

A method to reset the data held in silicon-based, quantum-computing devices has been developed by RIKEN researchers[1]. This could help to enhance the reliability of quantum computers by forming a crucial part of an error-correction system.

Quantum computers promise to dramatically increase our computing power, but these highly sensitive devices are prone to errors.

Data in quantum computers is encoded by the quantum states of particles, such as the spin of an electron. These quantum bits (qubits) can be linked together through a phenomenon called entanglement, and then process information through a combination, or superposition, of their quantum states. This enables quantum computers to perform certain complex calculations much more rapidly than conventional computers.

Electrical confinement in silicon formed by metallic electrodes, known as quantum dots, is a promising candidate to host an electron-spin qubit. But quantum states can be delicate, and the qubits often acquire errors that need to be corrected.

To help address this problem, RIKEN researchers have devised a way to rapidly and accurately read a spin qubit, and then reset it. This kind of control system will be essential to build fault-tolerant quantum computers based on silicon quantum dots.

One challenge the team faced is that a qubit loses correlation between the readout result and the qubit state after reading. To overcome this, the team used a pair of silicon quantum dots to accommodate two entangled qubits. While one qubit carried data, the other served as an auxiliary. By using a charge sensor to read the auxiliary qubit, the researchers could estimate the state of the data qubit without destroying its information—a method known as a quantum non-demolition (QND) measurement. Depending on the outcome of the measurement, the system could then deliver a microwave pulse that resets the data qubit.

The team constructed a quantum circuit to repeatedly perform the QND measurements, producing a single microwave pulse to reset the data qubit with cumulatively improved reliability. “Since the quantity measured by a quantum non-demolition measurement is not disturbed by the measurement, it can be measured again and again to estimate the data-qubit state more accurately,” says Takashi Kobayashi of the RIKEN Center for Quantum Computing.

The whole reset process currently takes about 60 microseconds at least, which might be too slow for a practical quantum computer. To shorten this time, the researchers suggest adding a second auxiliary qubit, which would allow them to use a faster measurement method.

“The time for the protocol might be reduced to a few microseconds,” says Kobayashi. “This would pave the way to feedback-based quantum error correction.”

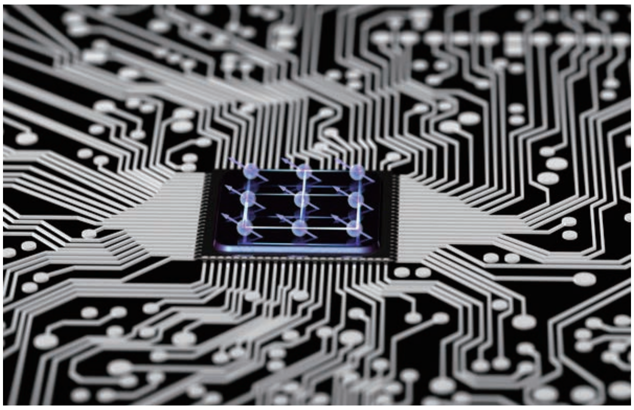
Related content:

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

Two-electron qubit points the way to scaling up quantum computers
https://www.riken.jp/en/news_pubs/research_news/rr/20200619_1/

Scientists succeed in measuring electron spin qubit without demolishing it
https://www.riken.jp/en/news_pubs/research_news/pr/2020/20200303_2/

Faster technique for resetting quantum circuits proposed
https://www.riken.jp/en/news_pubs/research_news/rr/20220121_1/index.html



Conceptual illustration of a computer microchip with a grid of quantum spin states. RIKEN researchers have shown how a quantum circuit can reset quantum bits carried by electron spins in silicon.
https://www.sciencephoto.com/media/948603/view
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RIKEN Research Winter 2023 (p.11)

These articles are edited versions of RIKEN Research Highlights.

Machine learning realizes better quantum error correction

Harnessing machine learning helps to correct errors that develop in quantum computers

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

In a step toward realizing practical quantum computers, RIKEN researchers have demonstrated that machine learning can be used to perform error correction for quantum computers[1].

Classical computers perform operations using bits, which can take the values 0 and 1. In contrast, quantum computers use qubits, which can assume any superposition of these two states. When combined with quantum entanglement—a quantum way of linking distant objects—qubits enable quantum computers to perform entirely new operations. This gives them a potential advantage over conventional computers for some tasks, such as large-scale searches, optimization and cryptography.

The main hurdle to realizing quantum computers for practical applications is the extremely fragile nature of quantum superpositions. Tiny perturbations from the environment can generate errors that rapidly destroy quantum superpositions.

To tackle this problem, sophisticated methods for quantum error correction have been developed. While they can, in theory, neutralize the effect of errors, they often greatly increase device complexity, which itself is error prone and thus potentially even increases exposure to errors. Consequently, full-fledged error correction has remained elusive.

Now, a team led by Franco Nori of the RIKEN Center for Quantum Computing (RQC) has leveraged machine learning in a search for error-correction schemes that minimize the device overhead while maintaining good error-correction performance.

The team adopted an autonomous approach to quantum error correction, where a cleverly designed, artificial environment replaces the need to perform frequent measurements to detect errors.

They also looked at ‘bosonic qubit encodings’, which are, for instance, available and utilized in some of the currently most promising and widespread quantum-computing machines based on superconducting circuits.

Finding high-performing candidates in the vast search space of bosonic qubit encodings was a complex optimization task. The team addressed this problem by using reinforcement learning, an advanced machine learning method in which an agent explores a possibly abstract environment to learn and optimize its action policy.

Using this approach, the team found a surprisingly simple, approximate qubit encoding that could not only greatly reduce the device complexity compared to other proposed encodings, but that also outperformed its competitors in terms of its ability to correct errors.

“Our work not only demonstrates the potential for deploying machine learning towards quantum error correction, but it may also bring us a step closer to the successful implementation of quantum error correction in experiments,” says Yexiong Zeng, also of the RQC.

“Machine learning can play a pivotal role in addressing large-scale quantum computation and optimization challenges,” says Nori. “Currently, we are actively involved in a number of projects that integrate machine learning, artificial neural networks, quantum error correction, and quantum fault tolerance.”

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RIKEN Research Winter 2023 (p.19)

These articles are edited versions of RIKEN Research Highlights.

Quantum computers start to measure up

An alternative approach to quantum computers that stores and processes information as light could enable reprogrammable systems.

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

The race to develop quantum computers has really heated up over the past few years. State-of-the-art systems can now run simple algorithms using dozens of qubits—or quantum bits—which are the building blocks of quantum computers.

Much of this success has been achieved in so-called gate-based quantum computers. These computers use physical components, most notably superconducting circuits, to host and control the qubits. This approach is quite similar to conventional, device-based classical computers. The two computing architectures are thus relatively compatible and could be used together. Furthermore, future quantum computers could be fabricated by harnessing the technologies used to fabricate conventional computers.

But the Optical Quantum Computing Research Team at the RIKEN Center for Quantum Computing has been taking a very different approach. Instead of optimizing gate-based quantum computers, Atsushi Sakaguchi, Jun-ichi Yoshikawa and Team Leader Akira Furusawa have been developing measurement-based quantum computing.

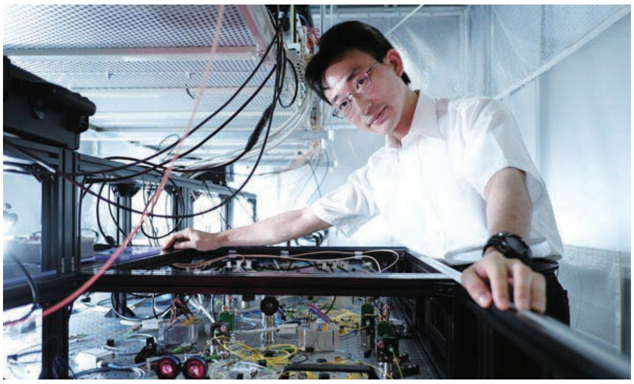
MEASUREMENT-BASED COMPUTING

Measurement-based quantum computers process information in a complex quantum state known as a cluster state, which consists of three (or more) qubits linked together by a non-classical phenomenon called entanglement. Entanglement is when the properties of two or more quantum particles remain linked, even when separated by vast distances.

Measurement-based quantum computers work by making a measurement on the first qubit in the cluster state. The outcome of this measurement determines what measurement to perform on the second entangled qubit, a process called feedforward. This then determines how to measure the third. In this way, any quantum gate or circuit can be implemented through the appropriate choice of the series of measurements.

Measurement-based schemes are very efficient when used on optical quantum computers, since it's easy to entangle a large number of quantum states in an optical system. This makes a measurement-based quantum computer potentially more scalable than a gate-based quantum computer. For the latter, qubits need to be precisely fabricated and tuned for uniformity and physically connected to each other. These issues are automatically solved by using a measurement-based optical quantum computer.

Importantly, measurement-based quantum computation offers programmability in optical systems. "We can change the operation by just changing the measurement," says Sakaguchi. "This is much easier than changing the hardware, as gated-based systems require in optical systems."



Atsushi Sakaguchi and his team are exploring the possibility of using light to produce quantum computers that are measurement based rather than gate based.

Gate-based quantum computers are becoming more common. But the Optical Quantum Computing Research Team at the RIKEN Center for Quantum Computing has been developing measurementbased quantum computing, with digital circuitry for electrical-optical control (pictured). Measurementbased systems are potentially more scaleable than gatebased quantum computing.

But feedforward is essential. "Feedforward is a control methodology in which we feed the measurement results to a different part of the system as a form of control," explains Sakaguchi. "In measurement-based quantum computation, feedforward is used to compensate for the inherent randomness in quantum measurements. Without feedforward operations, measurement-based quantum computation becomes probabilistic, while practical quantum computing will need to be deterministic."

The Optical Quantum Computing Research Team and their co-workers—from The University of Tokyo, Palacký University in the Czech Republic, the Australian National University and the University of New South Wales, Australia—have now demonstrated a more advanced form of feedforward: nonlinear feedforward. Nonlinear feedforward is required to implement the full range of potential gates in optics-based quantum computers.

“We’ve now experimentally demonstrated nonlinear quadrature measurement using a new nonlinear feedforward technology,” explains Sakaguchi. “This type of measurement had previously been a barrier to realizing universal quantum operations in optical measurement-based quantum computation.”

OPTICAL COMPUTERS

Optical quantum computers use qubits made of wave packets of light. At another institution, some of the current RIKEN team had previously constructed the large optical cluster states needed for measurement-based quantum computation. Linear feedforward has also been achieved to construct simple gate operations, but more advanced gates need nonlinear feedforward.

A theory for practical implementation of nonlinear quadrature measurement was proposed in 2016. But this approach presented two major practical difficulties: generating a special ancillary state (which the team achieved in 2021) and performing a nonlinear feedforward operation.

The team overcame the latter challenge with complex optics, special electro-optic materials and ultrafast electronics. To do this they exploited digital memories, in which the desired nonlinear functions were precomputed and recorded in the memory. “After the measurement, we transformed the optical signal into an electrical one,” explains Sakaguchi. “In linear feedforward, we just amplify or attenuate that signal, but we needed to do much more complex processing for nonlinear feedforward.”

The key advantages of this nonlinear feedforward technique are its speed and flexibility. The process needs to be fast enough that the output can be synchronized with the optical quantum state.

“Now that we have shown that we can perform nonlinear feedforward, we want to apply it to actual measurement-based quantum computation and quantum error correction using our previously developed system,” says Sakaguchi. “And we hope to be able to increase the higher speed of our nonlinear feedforward for high-speed optical quantum computation.”

“But the key message is that, although superconducting circuit-based approaches may be more popular, optical systems are a promising candidate for quantum-computer hardware,” he adds.

Reference

For a full list of references, check the online version of this article: www.riken.jp/en/news_pubs/research_news/

RIKEN Research Winter 2023 (p.26)

This feature looks at the work of ATSUSHI SAKAGUCHI

Atsushi Sakaguchi completed his PhD under the supervision of Akira Furusawa at the University of Tokyo in 2021. He then joined his current team, the Optical Quantum Computing Research Team at the RIKEN Center for Quantum Computing. Here he works on experimental quantum optics and quantum information research. He is currently collaborating on research into classical operations for quantum computing.

These articles are edited versions of RIKEN Research Highlights.

Publication List

Data for FY2023

Title	Authors	Article
Black hole graviton and quantum gravity	Y. Kimura	Physica Scripta 99, 045024 (2024).
Effective light cone and digital quantum simulation of interacting bosons	T. Kuwahara, T. V. Vu, and K. Saito	Nature Communications 15, 2520 (2024).
Kekule valence bond order in the Hubbard model on the honeycomb lattice with possible lattice distortions for graphene	Y. Otsuka and S. Yunoki	Physical Review B 109, 115131 (2024).
Quantum computing using floating electrons on cryogenic substrates: Potential And Challenges	A. Jennings, I. Grytsenko, and E. Kawakami	Applied Physics Letters Perspective 124, 120501 (2024).
Realizing quantum optics in structured environments with giant atoms	X. Wang, H. B. Zhu, T. Liu, and F. Nori	Physical Review Research 6, 013279 (2024).
Emergent parallel transport and curvature in Hermitian and non-Hermitian quantum mechanics	C. Y. Ju, A. Miranowicz, Y. N. Chen, G. Y. Chen, and F. Nori	Quantum 8, 1277 (2024).
Passive magnetic-free broadband optical isolator based on unidirectional self-induced transparency	H. Wu, J. Tang, M. Chen, M. Xiao, Y. Lu, K. Xia, and F. Nori	Optics Express 32, 11010 (2024).
Proposal of ensemble qubits with two-atom decay	W. Qin, A. Miranowicz, and F. Nori	New Journal of Physics 26, 033006 (2024).
Suppression of pulsed dynamic nuclear polarization by many-body spin dynamics	K. Sasaki and E. Abe	Physical Review Letters 132, 106904 (2024).
Partially fault-tolerant quantum computing architecture with error-corrected Clifford gates and space-time efficient analog rotations	Y. Akahoshi, K. Maruyama, H. Oshima, S. Sato, and K. Fujii	PRX Quantum 5, 010337 (2024).
Control and readout of a transmon using a compact superconducting resonator	J. Zotova, S. Sanduleanu, G. Fedorov, R. Wang, J. S. Tsai, and O. Astafiev	Applied Physics Letters 124, 102601 (2024).
Experimental demonstration of a high-fidelity virtual two-qubit gate	A. P. Singh, K. Mitarai, Y. Suzuki, K. Heya, Y. Tabuchi, K. Fujii, and Y. Nakamura	Physical Review Research 6, 013235 (2024).
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Topological temporally mode-locked laser	C. R. Leefmans, M. Parto, J. Williams, G. H. Y. Li, A. Dutt, F. Nori, and A. Marandi	Nature Physics 20, 852 (2024).
Rapid single-shot parity spin readout in a silicon double quantum dot with fidelity exceeding 99%	K. Takeda, A. Noiri, T. Nakajima, L. C. Camenzind, T. Kobayashi, A. Sammak, G. Scappucci, and S. Tarucha	npj Quantum Information 10, 22 (2024).
Tuning the initial phase to control the final state of a driven qubit	P. O. Kofman, S. N. Shevchenko, and F. Nori	Physical Review A 109, 022409 (2024).
Virtual quantum resource distillation	X. Yuan, B. Regula, R. Takagi, and M. Gu	Physical Review Letters 132, 050203 (2024).
Tunable compact on-chip superconducting switch	J. Zotova, A. Semenov, R. Wang, Y. Zhou, O. Astafiev, and J. S. Tsai	Physical Review Applied 21, 024059 (2024).
Virtual quantum resource distillation: General framework and applications	R. Takagi, X. Yuan, B. Regula, and M. Gu	Physical Review A 109, 022403 (2024).
Water-wave vortices and skyrmions	D. A. Smirnova, F. Nori, and K. Y. Bliokh	Physical Review Letters 132, 054003 (2024).
Quantum phase transitions in optomechanical systems	B. Wang, F. Nori, and Z. L. Xiang	Physical Review Letters 132, 053601 (2024).
Identifying topology of leaky photonic lattices with machine learning	E. Smolina, L. Smirnov, D. Leykam, F. Nori, and D. Smirnova	Nanophotonics 13, 271 (2024).
Photon-noise-tolerant dispersive readout of a superconducting qubit using a nonlinear Purcell filter	Y. Sunada, K. Yuki, Z. Wang, T. Miyamura, J. Ilves, K. Matsuura, P. A. Spring, S. Tamate, S. Kono, and Y. Nakamura	PRX Quantum 5, 010307 (2024).
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