FY2023 Annual Report

Quantum Information Science and Technology Unit

Professor Kae Nemoto

Abstract

In Quantum Information Science and Technology (QIST) unit, we have several directions of research. Our research has expanded in several directions: quantum machine learning, quantum networks, quantum communications, quantum hybrid systems, quantum error correction and quantum computer architecture/middleware. QIST has established a research network though our several national projects: the Moonshot projects, Q-LEAP fundamental research project, the COI-NEXT (SQAI), and SIP.

1. Staff

- Kae Nemoto, Professor
- Nicolo Lo Piparo, Staff Scientist
- Josephine Dias, Postdoctoral Scholar

- Thomas Scruby, Postdoctoral Scholar
- Akitada Sakurai, Postdoctoral Scholar
- Henry Nourse, Postdoctoral Scholar
- Hon Wai Lau, Postdoctoral Scholar
- Nicholas Connolly, Postdoctoral Scholar
- Chaimae El bouazizi, Technician
- Peizhe Li, Special Research Student
- Shin Nishio, Special Research Student
- Aoi Hayashi, Special Research Student

Thesis Supervising

- Sougato Chowdhury

Hosting Rotation Students

- Ka Wing Yip
- Sougato Chowdhury
- Jiajun Che
- Salome Catherine Hayes-Shuptar
- Tuan Duc Hoang
- Llia Ryzov

Research Intern

- Andreas Raikos
- Thep Ananh Virathavone

Mentoring

- Javier Pagan Lacambra

2. Collaborations

2.1 Architecture and applications for small to large scale quantum computation [MEXT, Quantum Leap Flagship Program] (Principal Investigator: Kae Nemoto)

- Type of collaboration: Joint project
- Researchers:
    - Prof. Mio Murao, University of Tokyo
    - Dr. William J. Munro and Dr Victor M. Bastidas, NTT
    - Prof. Takeaki Uno, National Institute of Informatics

2.2 Large-scale distributed quantum computer architecture [JSPS, Grant-in-Aid for Scientific Research(A)] (Principal Investigator: Kae Nemoto)

- Type of collaboration: Joint research
- Researchers:
  - Dr. William J. Munro, NTT, OIST

2.3 Research and Development of Theory and Software for Fault-tolerant Quantum Computers [Cabinet Office, Moonshot Research and Development Program] (Project Manager: Masato Koashi)

- Type of collaboration: Joint project
- Researchers:
  - Dr. Thomas Scruby, OIST

2.4 Scalable and Robust Integrated Quantum Communication System [Cabinet Office, Moonshot Research and Development Program] (Project Manager: Shota Nagayama)

- Type of collaboration: Joint project
- Researchers:
  - Prof. David Elkouss, OIST
  - Dr. Maity Ananda, OIST
  - Mr. Casapao Joshua Carlo Aparicio, OIST

2.5 Center of Innovation for Sustainable Quantum AI [JST, Program on Open Innovation Platforms for Industry-academia Co-creation (COI-NEXT)] (Project Leader: Shinji Todo)

- Type of collaboration: Joint project
- Researchers:
  - Prof. Thomas Busch, OIST
  - Dr. Thomás Fogarty, OIST
  - Chaimae El bouazizi, Technician, OIST

2.6 Promoting the application of advanced quantum technology platforms to social issues [The Cross-ministerial Strategic Innovation Promotion Program（SIP）, Promoting the application of advanced quantum technology platforms to social issues] (Principal Investigator: Kae Nemoto)

- Type of collaboration: Joint project (See OCQT website)

2.7 Quantum reservoir computing, [Collaborative research with DENSO Corporation] (Principal Investigator: Kae Nemoto)

- Type of collaboration: Joint research

3. Activities and Findings

3.1 Quantum neuronal sensing of quantum many-body states on a 61-qubit programmable superconducting processor

Classifying many-body quantum states with distinct properties and phases of matter is one of the most fundamental tasks in quantum many-body physics. However, due to the exponential complexity that emerges from the enormous numbers of interacting particles, classifying large-scale quantum states has been extremely challenging for classical approaches. Here, we propose a new approach called quantum neuronal sensing. Utilizing a 61-qubit superconducting quantum processor, we show that our scheme can efficiently classify two different types of many-body phenomena: namely the ergodic and localized phases of matter. Our quantum neuronal sensing process allows us to extract the necessary information coming from the statistical characteristics of the eigenspectrum to distinguish these phases of matter by measuring only one qubit and offers better phase resolution than conventional methods, such as measuring the imbalance. Our work demonstrates the feasibility and scalability of quantum neuronal sensing for near-term quantum processors and opens new avenues for exploring quantum manybody phenomena in larger-scale system

3.2 Chimera patterns in conservative Hamiltonian systems and Bose–Einstein condensates of ultracold atoms

Experimental realizations of chimera patterns, characterized by coexisting regions of phase coherence and incoherence, have so far been achieved for non-conservative systems with dissipation and exclusively in classical settings. The possibility of observing chimera patterns in quantum systems has rarely been studied and it remains an open question if chimera patterns can exist in closed, or conservative quantum systems. Here, we tackle these challenges by first proposing a conservative Hamiltonian system with nonlocal hopping, where the energy is well-defined and conserved. We show explicitly that such a system can exhibit chimera patterns. Then we propose a physical mechanism for the nonlocal hopping by using an additional mediating channel. This leads us to propose a possible experimentally realizable quantum system based on a two-component Bose–Einstein condensate (BEC) with a spin-dependent optical lattice, where an untrapped component serves as the matterwave mediating field. In this BEC system, nonlocal spatial hopping over tens of lattice sites can be achieved and simulations suggest that chimera patterns should be observable in certain parameter regimes.

3.3 Memoryless Quantum Repeaters Based on Cavity-QED and Coherent States

A quantum repeater scheme based on cavity-quantum electrodynamics (QED) and quantum error correction of channel loss via rotation-symmetric bosonic codes (RSBCs) is proposed to distribute atomic entangled states over long distances without memories and at high clock rates. In this scheme, controlled rotation gates, i.e., phase shifts of the propagating light modes conditioned upon the state of an atom placed in a cavity, provide a mechanism both for the entangled-state preparations and for the error syndrome identifications. In order to assess the performance of this repeater protocol, an explicit instance of RSBCs—multicomponent cat codes—are studied quantitatively. It is found that the total fidelity and the success probability for quantum communication over a long distance (such as 1000 km) both can almost approach unity provided a small enough elementary distance between stations (smaller than 0.1 or 0.01 km) and rather low local losses (up to 0.1%) are considered. In a quantum key distribution application, secret key rates can become correspondingly high, both per channel use, beating the repeaterless bound, and per second thanks to the relatively high clock rates of the memoryless scheme. Based upon the cavity-QED setting, this scheme can be realized at room temperature and at optical frequencies.

3.4 Local Probabilistic Decoding of a Quantum Code

flip is an extremely simple and maximally local classical decoder which has been used to great effect in certain classes of classical codes. When applied to quantum codes there exist constant-weight errors (such as half of a stabiliser) which are uncorrectable for this decoder, so previous studies have considered modified versions of flip, sometimes in conjunction with other decoders. We argue that this may not always be necessary, and present numerical evidence for the existence of a threshold for flip when applied to the looplike syndromes of a three-dimensional toric code on a cubic lattice. This result can be attributed to the fact that the lowest-weight uncorrectable errors for this decoder are closer (in terms of Hamming distance) to correctable errors than to other uncorrectable errors, and so they are likely to become correctable in future code cycles after transformation by additional noise. Introducing randomness into the decoder can allow it to correct these “uncorrectable” errors with finite probability, and for a decoding strategy that uses a combination of belief propagation and probabilistic flip we observe a threshold of ~ 5.5% under phenomenological noise. This is comparable to the best known threshold for this code (~ 7.1%) which was achieved using belief propagation and ordered statistics decoding [Higgott and Breuckmann, 2022], a strategy with a runtime of $O(n^3)$ as opposed to the $O(n)$ ($O(1)$ when parallelised) runtime of our local decoder. We expect that this strategy could be generalised to work well in other low-density parity check codes, and hope that these results will prompt investigation of other previously overlooked decoders.

3.5 Room-temperature addressing of single rare-earth atoms in optical fiber

Rare-earth (RE) atoms in solid-state materials are attractive components for photonic quantum information systems because of their coherence properties even in high-temperature environments. We have experimentally performed the single-site optical spectroscopy and optical addressing of a single RE atom in an amorphous silica optical fiber at room temperature. The single-site optical spectroscopy of the tapered RE-doped fiber shows nonresonant emission lines similar to those seen in the case of an unstructured fiber and the autocorrelation function of photons emitted from the fiber shows the antibunching effect due to the spatial isolation given by the tapered fiber structure. The ability to address single RE atoms at room temperature provides a very stable and cost-effective technical platform for the realization of a solid-state system for a large-scale quantum optical network and other quantum technologies based on a large number of spectral channels from visible to midinfrared wavelengths.

3.6 Impact of the form of weighted networks on the quantum extreme reservoir computation

The quantum extreme reservoir computation (QERC) is a versatile quantum neural network model that combines the concepts of extreme machine learning with quantum reservoir computation. Key to QERC is the generation of a complex quantum reservoir (feature space) that does not need to be optimized for different problem instances. Originally, a periodically driven system Hamiltonian dynamics was employed as the quantum feature map. In this work we capture how the quantum feature map is generated as the number of time-steps of the dynamics increases by a method to characterize unitary matrices in the form of weighted networks. Furthermore, to identify the key properties of the feature map that has sufficiently grown, we evaluate it with various weighted network models that could be used for the quantum reservoir in image classification situations. At last, we show how a simple Hamiltonian model based on a disordered discrete time crystal with its simple implementation route provides nearly optimal performance while removing the necessity of programming of the quantum processor gate by gate.

3.7 Entanglement generation between distant spins via quasilocal reservoir engineering

The generation and preservation of entanglement is a central goal in quantum technology. Traditionally, dissipation in quantum systems is thought to be detrimental to entanglement, however dissipation can also be utilized as a means of generating entanglement between quantum spins that are not directly interacting. In particular, entanglement can be generated between two qubits, or multiqubit systems via a collective coupling to a reservoir. In this work, we explore multiple spin domains pairwise coupled to different reservoirs and show that entanglement can be generated between spins which are not coupled to each other, or even coupled to the same reservoir.

4. Publications

4.1 Journals

1. Ming Gong, He-Liang Huang, Shiyu Wang, Chu Guo, Shaowei Li, Yulin Wu, Qingling Zhu, Youwei Zhao, Shaojun Guo, Haoran Qian, Yangsen Ye, Chen Zha, Fusheng Chen, Chong Ying, Jiale Yu, Daojin Fan, Dachao Wu, Hong Su, Hui Deng, Hao Rong, Kaili Zhang, Sirui Cao, Jin Lin, Yu Xu, Lihua Sun, Cheng Guo, Na Li, Futian Liang, Akitada Sakurai, Kae Nemoto, W. J. Munro, Yong-Heng Huo, Chao-Yang Lu, Cheng-Zhi Peng, Xiaobo Zhu, Jian-Wei Pan, *Quantum neuronal sensing of quantum many-body states on a 61-qubit programmable superconducting processor*, Science Bulletin, 68(9) 906-912, https://doi.org/10.1016/j.scib.2023.04.003 (2023)
2. Hon Wai Hana Lau, Jörn Davidsen and Christoph Simon, *Chimera patterns in conservative Hamiltonian systems and Bose–Einstein condensates of ultracold atoms,* Scientific Reports 13, 8590, https://doi.org/10.1038/s41598-023-35061-3 (2023)
3. Pei-Zhe Li, Peter van Loock, *Memoryless Quantum Repeaters Based on Cavity-QED and Coherent States,* Advanced Quantum Technologies 6(8), 2200151, https://10.1002/qute.202200151 (2023)

4. T. R. Scruby, K. Nemoto, *Local Probabilistic Decoding of a Quantum Code,* Quantum 7, 1093, https://doi.org/10.22331/q-2023-08-29-1093 (2023)
5. Mikio Takezawa, Ryota Suzuki, Junichi Takahashi, Kaito Shimizu, Ayumu Naruki, Kazutaka Katsumata, Kae Nemoto, Mark Sadgrove, and Kaoru Sanaka, *Room-temperature addressing of single rare-earth atoms in optical fiber*, Physical Review Applied 20(4), 044038, http://dx.doi.org/10.1103/PhysRevApplied.20.044038 (2023)
6. Aoi Hayashi, Akitada Sakurai, Shin Nishio, William J. Munro, Kae Nemoto, *Impact of the form of weighted networks on the quantum extreme reservoir computation*, Physical Review A 108(4), 042609, https://doi.org/10.1103/PhysRevA.108.042609 (2023)
7. Josephine Dias, Christopher W. Wächtler, Kae Nemoto, William J. Munro, *Entanglement generation between distant spins via quasilocal reservoir engineering*, Physical Review Research 5(4), 043295, https://doi.org/10.1103/PhysRevResearch.5.043295 (2023)

4.2 Proceedings

1. W. J. Munro, K. Nemoto, *Quantum fog computing,* Proceedings 'Quantum Communications and Quantum Imaging XXI', vol. PC12692, PC1269201, https://doi.org/10.1117/12.2675678 (2023)
2. William J. Munro, Nicoló Lo Piparo, Kae Nemoto, *Quantum multiplexing for quantum networking and distributed quantum computation*, Proceedings Volume PC12911, Quantum Computing, Communication, and Simulation IV; PC1291119, SPIE Quantum West, 2024, San Francisco, California, United States https://doi.org/10.1117/12.3001202 (2024)

4.3 Other publications

1. 根本 香絵, *2022 年ノーベル物理学賞に量子もつれと量子情報科学*, 情報処理 64(7) 320 - 325, https://doi/10.20729/00226341 (2023)
2. Kae Nemoto, *Our future with quantum computers*, JSAP Review 2023, ID:230212, https://doi.org/10.11470/jsaprev.230212 (2023)

4.4 Oral and Poster Presentations

Invited Oral Presentation

1. Josephine Dias, *Reservoir-assisted energy migration in hybrid quantum systems*, 51st RQC Seminar, Riken, Saitama, Japan (2023/6/5)
2. Kae Nemoto, *Classification problems for quantum machine learning: How should we ask questions to quantum computers?*, International Network on Quantum Annealing Conference(INQA), Innsbruck, Vienna (2023/11/8)
3. Kae Nemoto, *Science and technology of quantum complex dynamics*, EQUS Annual Workshop 2023 Freemantle, Australia (2023/11/22)
4. Kae Nemoto, *Designing quantum transport with environment*, The Feedback in Quantum Machines 2023 (FQM2023) Okinawa, Japan (2023/11/27)
5. Kae Nemoto, *Hybrid Sensing*, International Advanced Research Workshop, Pursuing Quantum Sensing for Reliable Roadmaps, Rome, Italy (2023/12/5)

6. Nicolo Lo Piparo, *Towards a more feasible implementation of quantum networks*, 2023 International Workshop on Frontiers in Quantum Information, Hainan, China, (2023/12/13)
7. Kae Nemoto, *Quantum Dynamics and Machine Learning*, The 6th R-CCS International Symposium, Kobe, Japan (2024/1/29)
8. Kae Nemoto, *What can 10 qubits do to solve classification problems*?, APS March Meeting 2024, Minneapolis, USA (2024/3/7)
9. Shin Nishio, *Quantum Error Correction and Quantum Multiplexing*, Yukawa Institute for Theoretical Physics Quantum Error Correction Workshop, Kyoto, Japan (2024/3/18)
10. Thomas Scruby, *Quantum Rainbow Codes: Constructing Triorthogonal Codes from Hypergraph Product*, Yukawa Institute for Theoretical Physics Quantum Error Correction Workshop Kyoto, Japan (2024/3/26)

Oral Presentation

1. W. J. Munro, *Designing large scale quantum networks*, CLEO: Fundamental Science 2023, FF3A.6, San Diego, USA (2023/5/12)
2. 西尾真, *量子計算機システム分野の概況,* 新奇アーキテクチャ×アルゴリズムの会 (第 3 回), Tokyo, Japan (2023/7/3)
3. Aoi Hayashi, *Impact of the form of weighted networks on the quantum extreme reservoir computation*, JFQI2023 Workshop (Japanese-French Quantum Information 2023 workshop), Tokyo, Japan (2023/12/15)
4. Akitada Sakurai, *Utilizing the non-interacting bionic particle sampling to solve image classification tasks*, APS March Meeting 2024, Minneapolis, USA (2024/3/8)
5. 櫻井彰忠, *Boson Sampling で手書き数字分類を解く,* 第 71 回応用物理学会春季学術講演会, Tokyo, Japan (2024/3/22)
6. 林碧惟, *量子機械学習における量子ビットの相互作用ネットワークが形成する量子特徴マップの解析,* 第 71 回応用物理学会春季学術講演会, Tokyo, Japan (2024/3/22)

Poster Presentations

1. Nicolo Lo Piparo, *Resource reduction in an error correction code using quantum multiplexing*, AQIS2023(23rd Asian Quantum Information Science Conference), Seoul, Korea, (2023/8/29)
2. Nicolo Lo Piparo, *Resource reduction in an error correction code using quantum multiplexing,* 1st International Workshop on Quantum Information Engineering (QIE2023) Okinawa, Japan (2023/10/11)
3. Thomas Scruby, *Local Probabilistic Decoding of a Quantum Code,* 1st International Workshop on Quantum Information Engineering (QIE2023), Okinawa, Japan (2023/10/11)
4. Aoi Hayashi*, Impact of the form of weighted networks on the quantum extreme reservoir computation,* 1st International Workshop on Quantum Information Engineering (QIE2023), Okinawa, Japan (2023/10/11)
5. Thomas Scruby, *Local Probabilistic Decoding of a Quantum Code*, 6th International Conference on Quantum Error Correction (QEC 2023) Sydney, USA (2023/10/31)
6. Thomas Scruby, *Single-Shot Decoding of Small Quantum LDPC Codes*, 6th International Conference on Quantum Error Correction (QEC 2023) Sydney, USA (2023/10/31)

7. Shin Nishio, *Surface Code Communication with Quantum Multiplexing,* 6th International Conference on Quantum Error Correction (QEC 2023) Sydney, USA (2023/10/31)
8. Akitada Sakurai, *A new approach of quantum linear optics to solve classification tasks,* International Network on Quantum Annealing Conference (INQA 2023), Innsbruck, Vienna (2023/11/7)
9. Aoi Hayashi, *Impact of the form of weighted networks on the quantum extreme reservoir computation*, International Network on Quantum Annealing Conference (INQA 2023), Innsbruck, Vienna (2023/11/7)
10. Peizhe Li, *Performance of rotation-symmetric bosonic codes in a quantum repeater*, Quantum Innovation 2023, Tokyo, Japan (2023/11/16)
11. Nicolò Lo Piparo, *Advantages of using quantum multiplexing for quantum error correction*, Quantum Innovation 2023, Tokyo, Japan (2023/11/16)
12. Shin Nishio, *Operations on graph states and flows,* The International Conference on Quantum Information Processing 2024 (QIP2024), Taipei, Taiwan (2024/1/16)
13. Peizhe Li, *Towards More Feasible Quantum Networks Based on Cavity-QED and Continuous-variable Codes*, APS March Meeting 2024, Minneapolis, USA (2024/3/5)

Other Invited Lectures

1. 根本香絵, *機械学習と量子ダイナミクス*, 第 3 回量子ソフトウェアワークショップ:量子 AI の可能性と実現への道のり, 東京大学大学院理学系研究科「量子ソフトウェア」寄付講座(COI-NEXT「量子ソフトウェアと HPC・シミュレーション技術の共創によるサスティナブル AI 研究拠点」), オンライン, (2023/8/3)
2. Kae Nemoto, *Quantum Science and Machine Learning*,OIST-KEIO Showcase Talk Series 5 -Science Meets Society: Exploring the Nexus of Planetary Well-being for a Sustainable Future, Okinawa Japan (2023/11/16)
3. 根本香絵, *Quantum technology development and education*, 先導的人材育成フェローシップ量子分野会議, 量子フェローシップ 活動報告会＋コンソーシアム会議講演会, Kyushu University, Japan (2024/2/20)

4.5 Program

Thomas Scruby, *"Qesee"*, Website: https://trowans.github.io/qesee/ (2023)

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report

6. Meetings and Events

6.1 Symposiums and Workshops

1st International Workshop on Quantum Information Engineering (QIE2023)

- Date: October 11-13, 2023
- Venue: OIST Seaside House
- Organizer: Quantum Information Engineering Research Group in The Japanese Society of Applied Physics (JSAP)
- Co-organizer: Okinawa Institute of Science and Technology (OIST)
- Invited Speakers

Max Hays (MIT)

Ryoichi Ishihara (Qutech, TU Delft)

Junko Ishi-Hayase (Keio University)

Tetsuo Kodera (Tokyo Tech)

Kazuki Koshino (Tokyo Medial and Dental University)

Roy Li (imec)

Chao-Yang Lu (University of Science and Technology of China)

Chithrabhanu Perumangatt (Toshiba Research Europe Ltd)

Michael Trupke (University of Vienna)

Tsuyoshi Yamamoto (NEC)

6.2 Seminars

6.2.1 Fast erasure decoder for a class of quantum LDPC codes

- Date: April 19, 2023
- Venue: OIST Campus LabC
- Speaker: Dr. Nicholas Connolly (INRIA Paris)

6.2.2 Optimizing space and time overhead for fault-tolerant error correction

- Date: July 10, 2023
- Venue: OIST Campus Lab5
- Speaker: Dr. Theerapat Tansuwannont (Duke University)

6.2.3 Magnetic Raman spectra of quasi-one-dimensional frustrated antiferromagnets

- Date: November 21, 2023
- Venue: OIST Campus Lab5
- Speaker: Dr. Oliver Bellwood (University of Queensland)

6.2.4 Europe’s Roadmap to a Quantum Workforce

- Date: December 19, 2023

- Venue: OIST Campus Lab5
- Speaker: Mr. Simon Goorney (European Quantum Readiness Center, Aarhus University)

7. Other

External Grants

1. Ministry of Education, Culture, Sports, Science and Technology (MEXT), MEXT - Quantum Leap Flagship Program (MEXT Q-LEAP), Architecture and applications for small to large scale quantum computation (2018-2027) Principal Investigator

2. The Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research(A) , Large-scale distributed quantum computer architecture (2021-2025) , Principal Investigator

3. Cabinet Office, Government of Japan, Moonshot Research and Development Program (Project Manager: Masato Koashi) Research and Development of Theory and Software for Fault-tolerant Quantum Computers (2021-2025), Co-Investigator

4. Cabinet Office, Government of Japan, Moonshot Research and Development Program (Project Manager: Shota Nagayama), Scalable and Robust Integrated Quantum Communication System (2022-2025), Co-Investigator

5. Japan Science and Technology Agency(JST), Program on Open Innovation Platforms for Industry-academia Co-creation (COI-NEXT), (Project Leader: Shinji Todo) Center of Innovation for Sustainable Quantum AI (2022-2031), Co-Investigator

6. Cabinet Office, Government of Japan, The Cross-ministerial Strategic Innovation Promotion Program（SIP）, Promoting the application of advanced quantum technology platforms to social issues(2023-2027), Principal Investigator

7. Collaborative research, DENSO Corporation, Quantum reservoir computing (2023), Co-Investigator