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QIS 3.0: Entanglement Distribution among Six Remote Quantum Nodes through Cold Atomic Ensembles and Photon Polarizations

**SHENGWANG DU
UNIVERSITY OF TEXAS AT DALLAS
800 WEST CAMPBELL RD.
SP2.25
RICHARDSON, TX, 75080
USA**

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14. ABSTRACT Computation and communication are two major foundations of modern information science and technology. While classical information technology has dramatically reshaped our society, the emerging quantum information technology could further revolutionize computing, communication, security, and sensing by utilizing the unique and powerful capabilities of quantum mechanics. In quantum information technology, entanglements distributed over multiple remote quantum nodes are crucial resources for quantum network, computation and sensing, but their implementation in realistic experimental environment has been extremely challenging. Despite significant experimental efforts, only a three-node quantum network of remote solid-state qubits based on entanglements among spin qubits and flying photons has been reported in 2021. The experimental difficulty roots in the drawbacks of current singlephoton presence-absence protocol, which prevent its use in scalable entanglement generation and distribution in a large quantum network. In this project, we propose a new approach to overcome these drawbacks based on cold atomic ensembles and their interaction with singlephoton polarization qubits and experimentally realize distributing quantum entanglement across a six-node quantum network. The proposed projects include the experimental realization of atom-photon and atom-atom entanglement, 3-6 nodes Greenberger-Horne-Zeilinger states, distributed quantum memory for multi-party entanglement, remote quantum gates, programmable any-to-any entanglement routing, as well as theoretical analysis of quantum advantages and limitations of such quantum networks. The realization of six interconnected remote quantum nodes not only provides a scalable platform for studying entanglement generation and control for quantum networks, but also opens the pathway for designing cloud quantum technologies with tailored applications in metrology, communications, computations, and imaging.			
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Technical Report

Project Title: Entanglement Distribution among Six Remote Quantum Nodes through Cold Atomic Ensembles and Photon Polarizations

Report Period: 12/01/2021 – 11/30/2023

PI: Shengwang Du

Accomplishments

1. Research Objectives: Please list the main research objectives of this project.

The research objectives of this project are to build a fully functional entanglement distributed quantum network with six remotely connected quantum nodes. We will

1) Create entanglement between cold atomic nodes and photonic polarization qubits. By controlling laser-atom interactions, we will create entanglement between collective atomic spin wave spatial modes and single-photon polarizations. We will realize single node manipulation (e.g., writing, reading, rotation).

2) Generate Greenberger–Horne–Zeilinger (GHZ) states of 3~6 remote atomic nodes. We will propose and demonstrate a few schemes for realizing GHZ state of three to six remote atomic nodes.

3) Realize entanglement distribution networks and remote quantum gate operations. We will realize certain entanglement resource states distributed in the quantum network and associated remote quantum gate operations.

4) Demonstrate efficient distributed quantum memory network for multi-party entanglement. We will extend our developed quantum memory technique to demonstrate efficient cloud quantum memory for multiphoton or multi-atomic-node entanglement distributed in the quantum network.

5) Develop protocols for programmable any-to-any entanglement routing and teleportation. We will demonstrate atom-atom entanglement based on Bell State Measurement (BSM) entanglement swapping. We will realize entanglement routing and teleportation between any two nodes through entanglement swapping.

6) Investigate quantum advantages and limitations of six-node quantum networks and beyond. We will theoretically analyze quantum advantages and limitations of the network with realistic experimental conditions and develop new quantum technologies such as nonlocal quantum sensing based on such quantum networks.

2. Please provide details of accomplishments during this reporting period.

1) Atomic ensemble quantum nodes development

During the current reporting period, notable advancements were achieved in the development of atomic ensemble quantum nodes, marking a significant milestone for our project aligned with Objectives 1-6. We successfully developed a total of six atomic ensemble quantum nodes, each constituting a critical component of our quantum network infrastructure. In these nodes, we meticulously trapped approximately 10^9 laser-cooled ^{87}Rb atoms with a temperature of 10-20 μK in an ultra-high vacuum cell (10^{-11} Torr). This trapping was accomplished using a two-

dimensional (2D) magneto-optical trap (MOT) configuration, which is renowned for its precision and efficiency in cooling and trapping atoms. Figure 1(a) provides a detailed illustration of the optical setup utilized in one of these quantum nodes, showcasing the meticulous design and engineering that went into its development. Complementing this, Figure 1(b) presents the MOT fluorescence image, vividly depicting the successful trapping and cooling of the atoms. The establishment of these six atomic ensemble quantum nodes constitutes a foundational step in the project, laying down a robust hardware base that is crucial for the realization of the envisioned quantum network.

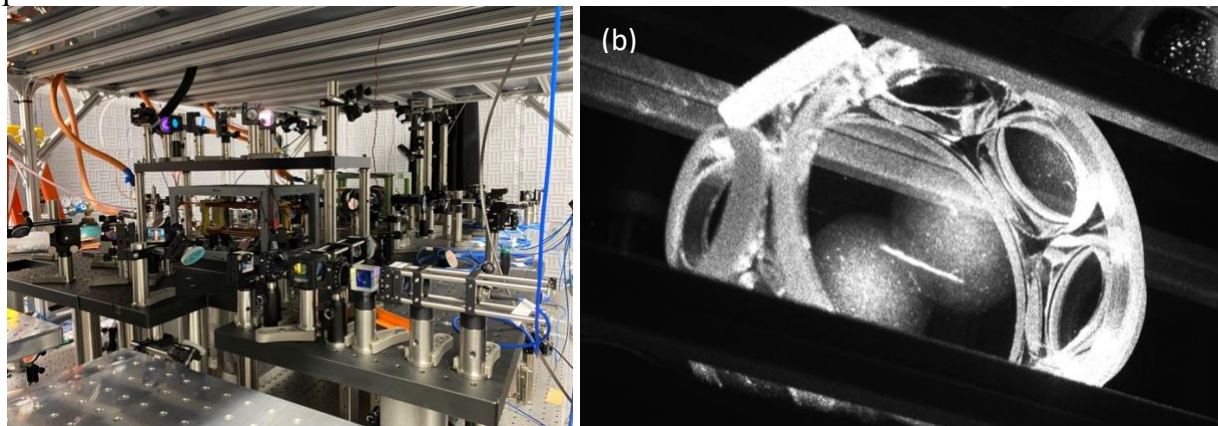


Fig. 1: Quantum node. (a) Optical setup. (b) Fluorescence image of the 2D MOT.

2) Quantum squeezing and sensing with pseudo-anti-parity-time symmetric optical four-wave mixing in cold atoms

Within the scope of our project, one of our primary objectives was to generate advantageous photonic quantum states to facilitate connections between nodes in the quantum network. In pursuit of this goal, we have conducted extensive research on the quantum states of photons emanating from the optical four-wave mixing process within an atomic ensemble quantum node. This investigation led us to a groundbreaking discovery: for the first time, we observed a phase transition in the quantum squeezing of two-mode continuous quadrature variables, a phenomenon induced by pseudo anti-parity-time (APT) symmetry. Our approach leverages the process of four-wave mixing with intentional phase mismatching as a novel method to engineer a quantum pseudo-APT symmetry within a two-mode bosonic system, notably without the need to account for Langevin noise contributions. This innovative strategy has unveiled that the spontaneous breaking of pseudo-APT symmetry ushers in an exceptional point, delineating a boundary between distinct regimes of quantum squeezing dynamics. This significant breakthrough not only provides a novel physical platform for delving into the intriguing domain of APT symmetry physics within the quantum landscape but also opens up new avenues for the application of these principles in precision quantum sensing. The fruits of this research have been recognized and published in *Physical Review Letters* **128**, 173602 (2022), providing a testament to the novelty and significance of our work. By addressing Objective 6, this result not only contributes to our understanding of quantum physics but also lays the groundwork for advancements in quantum technology and network connectivity.

Publication:

Xi-Wang Luo, Chuanwei Zhang*, and Shengwang Du*, “Quantum squeezing and sensing with pseudo-anti-parity-time symmetry,” *Physical Review Letters* **128**, 173602 (2022).

3) Quantum Langevin theory for two coupled phase-conjugated electromagnetic waves

We find a general macroscopic phenomenological formula of quantum Langevin equations for two coupled phase-conjugated electromagnetic fields with linear loss (gain) and complex nonlinear coupling coefficient. The macroscopic phenomenological formula is obtained from the coupling matrix to preserve the field commutation relations and correlations, which does not require knowing the microscopic details of light-matter interaction and internal atomic structures. To validate this phenomenological formula, we take spontaneous four-wave mixing in a double- Λ four-level atomic system as an example to numerically confirm that our macroscopic phenomenological result is consistent with that obtained from the microscopic Heisenberg-Langevin theory. We show that a complex-valued nonlinear coupling coefficient can lead to noises even without linear gain or loss. Finally, we apply the quantum Langevin equations to study the effects of linear gain and loss, complex phase mismatching, as well as complex nonlinear coupling coefficient in entangled photon pair (biphoton) generation, particularly to their temporal quantum correlations. This work lays down the theoretical foundation for studying nonlinear four-wave mixing quantum signal processing in neutral atoms. Objective 6 was addressed.

Publication:

Yue Jiang*, Yefeng Mei*, and Shengwang Du*, “Quantum Langevin theory for two coupled phase-conjugated electromagnetic waves,” *Phys. Rev. A* **107**, 053703 (2023).

4) Atom-photon quantum network simulator

One fundamental goal of quantum networks is to provide node-to-node entanglement distribution. In this project, we developed a computer software simulator, called A2Tango, for entanglement generation between two remote atom-ensemble nodes in a quantum network following Briegel, Dur, Cirac and Zoller (BDCZ) protocol. We encode quantum information to the two spatial modes of local atomic-ensemble spin waves and polarization states of single photons. The basic operations include atom-photon entanglement generation, quantum memory write-read operations, two-photon Bell-state measurement, and quantum state tomography. We model multi-photon events during the local excitation and propagation to account for their induced error in entanglement generation and distribution. We investigate the entanglement generation rate and fidelity as functions of the parameters which are realizable in experiments. Our work improves the open-sourced SeQUeNCe simulator and inspires the development of future quantum networks. Objectives 1, 3, 4, 5, and 6 were addressed.

Publication:

Ruilin Zhou, Xuanying Lai, Yuhang Gan, Katia Obraczka, Shengwang Du, and Chen Qian, “A Simulator of Atom-Atom Entanglement with Atomic Ensembles and Quantum Optics,” 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 1271-1277, Bellevue, Washington, September 17-22, 2023. (doi: 10.1109/QCE57702.2023.00143)

5) Hybrid photon-atom two-qubit controlled gates

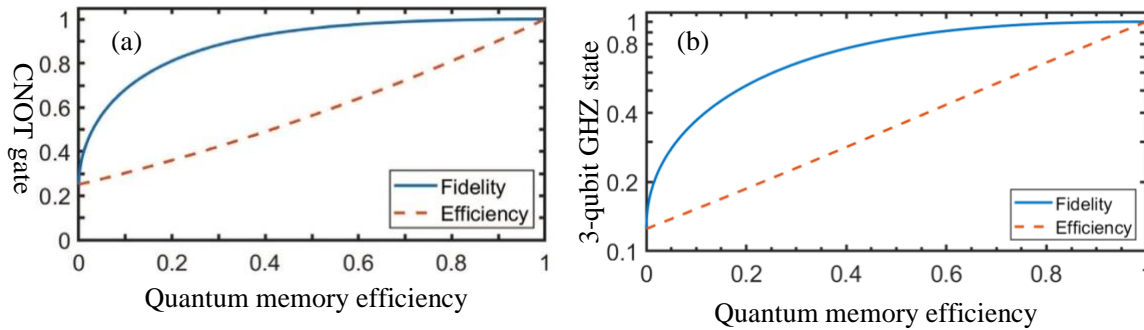


Fig. 2: Fidelity and efficiency of (a) hybrid CNOT gate and (b) remote 3-qubit GHZ state as functions of quantum memory efficiency.

To mediate remote controlled gate operation, we proposed and evaluated a new scheme of hybrid photon-atom two-qubit gate module, making use of quantum memories and Rydberg blockade effect. We demonstrated that two of these hybrid CNOT gates can be used to generate a 3-qubit GHZ state. Figure 2 shows fidelity and efficiency of hybrid CNOT gate and remote 3-qubit GHZ state as functions of quantum memory efficiency. We further demonstrate spatial and temporal scalability of this scheme. Our results show this photon-atom network hybrid approach can be an alternative solution to universal distributed quantum computing in a quantum network. This work has been published in *Advanced Quantum Technologies* 6, 2300007 (2023) and selected as its Back Cover in Volume 6 Issue 6 June 2023 [see Fig. 3]. A patent application (No.: PCT/US23/69089) has been filed. Objectives 1-5 were addressed.

Publications:

- [1] Eun Oh, Xuanying Lai, Jianming Wen, and Shengwang Du, “Distributed quantum computing with photons and atomic memories,” *Advanced Quantum Technologies* 6, 2300007 (2023); Selected as its Back Cover in Volume 6 Issue 6 June 2023.
- [2] Shengwang Du, Xuanying Lai, Eun Oh, and Jianming Wen, “Quantum computing apparatus with photons and atomic memories,” US PCT/US23/69089 (filed on 06/26/2023).

6) Distributed quantum computing (DQC) with shared quantum gate processing unit (S-QGPU) in a photon-atom quantum network

We introduce an innovative DQC architecture leveraging a Shared Quantum Gate Processing Unit (S-QGPU, as shown in Fig. 4), which centralizes hybrid two-qubit gate modules to facilitate remote gate operations. This configuration contrasts with the traditional DQC architectures, streamlining resource allocation by consolidating communication qubits, which results in a marked reduction in both local and total system costs. Our analysis and simulations indicate that the S-QGPU enables more efficient resource utilization, particularly when concurrent remote

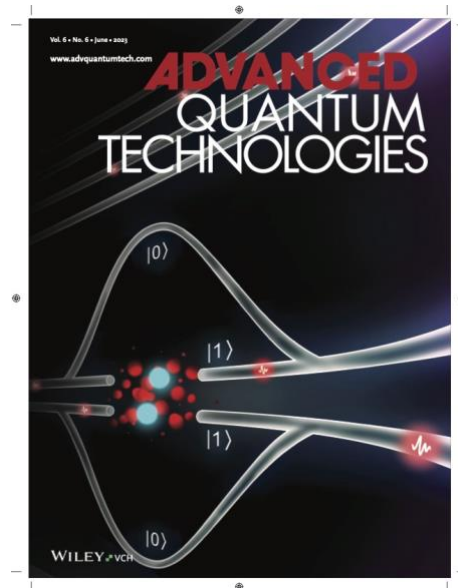


Figure 3: Our work of distributed quantum computing with photons and neutral atoms is selected as the back cover page of *Advanced Quantum Technologies* (Issue 6).

gate operations are not required across all data qubits, thus minimizing the need for communication qubits. Moreover, our S-QGPU-centric DQC model offers a deterministic approach, enhancing operational efficiency. Objectives 3, 4, and 6 were addressed.

Publications:

[1] Shengwang Du*, Yufei Ding*, and Chunming Qiao*, “S-QGPU: Shared Quantum Gate Processing Unit for distributed quantum computing,” arXiv:2309.08736 [quant-ph].

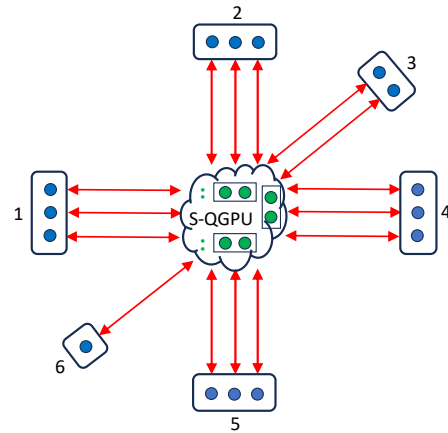


Fig. 4: DQC architecture with a Shared Quantum Gate Processing Unit (S-QGPU).

3. How were the results disseminated to communities of interest? If there is nothing significant to report during this reporting period, state “Nothing to Report.”

The results have been disseminated to communities of interest through the following publications, preprints, and presentations:

- [1] Shengwang Du*, Yufei Ding*, and Chunming Qiao*, “S-QGPU: Shared Quantum Gate Processing Unit for distributed quantum computing,” arXiv:2309.08736 [quant-ph].
- [2] Eun Oh, Xuanying Lai, Jianming Wen, and Shengwang Du, “Distributed quantum computing with photons and atomic memories,” *Advanced Quantum Technologies* **6**, 2300007 (2023); Selected as its Back Cover in Volume 6 Issue 6 June 2023.
- [3] Yue Jiang*, Yefeng Mei*, and Shengwang Du*, “Quantum Langevin theory for two coupled phase-conjugated electromagnetic waves,” *Phys. Rev. A* **107**, 053703 (2023).
- [4] Ruilin Zhou, Xuanying Lai, Yuhang Gan, Katia Obraczka, Shengwang Du, and Chen Qian, “A Simulator of Atom-Atom Entanglement with Atomic Ensembles and Quantum Optics,” 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 1271-1277, Bellevue, Washington, September 17-22, 2023. (doi: 10.1109/QCE57702.2023.00143)
- [5] Xi-Wang Luo, Chuanwei Zhang, and Shengwang Du, “Quantum squeezing and sensing with pseudo-anti-parity-time symmetry,” *Phys. Rev. Lett.* **128**, 173602 (2022); arXiv:2108.12873 [quant-ph].
- [6] Shengwang Du and Chuanwei Zhang, “Quantum squeezing and sensing with anti-parity-time symmetric quantum optics,” SPIE Photonics West, Conference 12447 – Session 15 Enabling Technologies for Precision Sensing III, Paper 12447-73, San Francisco, California, January 28 – February 02, 2023. **(Invited)**
- [7] Shengwang Du, “Quantum Langevin noises of two coupled phase-conjugated electromagnetic waves,” Workshop on Quantum Mechanics: Foundations and Applications, Texas A&M University, College Station, Texas, January 17-18, 2023. **(Invited)**

- [8] Shengwang Du, “Distributed quantum computing and quantum networks with photons and atoms,” Purdue Quantum Science and Engineering Institute (PQSEI), Purdue University, May 19, 2023. **(Invited)**
- [9] Shengwang Du, “Quantum networks and distributed quantum computing with photons and atoms,” CM-AMO Seminar, Department of Physics, University of Michigan, Ann Arbor, Michigan, November 08, 2022. **(Invited)**
- [10] Shengwang Du, “Distributed quantum computing and quantum networks with photons and atoms,” Q4I Quantum Information Science 4th Annual International Workshop, Rome, New York, USA, July 12-14, 2022. **(Invited)**
- [11] Shengwang Du, “Energy-time entangled narrowband photon pairs,” The 15th Asia Pacific Physics Conference (ACCP15), **Online**, Association of Asia Physical Societies (AAPPS) and Korean Physical Society, August 21-26, 2022. **(Invited)**

4. (Interim Reports Only) What do you plan to do during the next reporting period to accomplish the goals and objectives? If there are no changes to the agency-approved application or plan for this project or if this is the final report, state “Nothing to Report.”

Nothing to Report. This is the project final report.

Impacts

1. Development of the principal discipline(s) of the project

- 1) Advancements in Pseudo Anti-Parity-Time (APT) Symmetry within Quantum Optics. Symmetry plays a pivotal role across various domains of physics, with the emergence of parity-time (PT) symmetry marking a significant evolution in our understanding of non-Hermitian physics. However, the quest to actualize quantum PT symmetry is hampered by the intrinsic challenge posed by unavoidable Langevin noises, which disrupt the PT symmetry. Our project made a groundbreaking discovery by identifying quantum squeezing associated with pseudo APT symmetry during the nonlinear four-wave mixing process. This achievement marks the first instance of a quantum system designed to exhibit pseudo APT symmetry, cleverly circumventing the limitations imposed by Langevin noises. We have unearthed a phase transition in quantum squeezing at the APT-induced exceptional point, unveiling new possibilities for ultra-precision quantum sensing. This pioneering work not only provides a valuable framework for exploring APT symmetry physics in the quantum domain but also sets the stage for further investigations into fundamental non-Hermitian quantum effects and their potential applications in quantum technology.
- 2) Innovations in Distributed Quantum Computing (DQC) and Quantum Networks. Our project introduces an innovative photon-atom hybrid architecture that seamlessly integrates established techniques of photonic linear manipulation with the dynamic, nonlinear interactions of neutral atom Rydberg states. This architecture lays the foundational elements for both quantum computing and the broader spectrum of quantum networks. A notable aspect of our approach is the facilitation of spatially and temporally

distributed quantum computing units, a concept that remains largely unexplored in the current landscape of quantum computing and networks. This is primarily due to the existing gap in protocols for networking distributed multi-qubit quantum computers. Our methodology proposes a natural quantum network interface that bridges flying photons with stationary atomic quantum nodes, potentially enabling the construction of distributed quantum computers or the realization of cloud-based quantum computing frameworks. The introduction of a shared quantum gate processing unit (S-QGPU) within our cost-effective architecture represents the first deterministic solution for DQC, promising to revolutionize the field by offering practical and scalable quantum computing and networking solutions.

2. Other disciplines:

Nothing to Report.

3. Describe the impact in this reporting period on the development of human resources

The experimental and theoretical studies in this project provide training and professional development opportunities to graduate students.

4. Describe the impact on teaching and educational experiences

Nothing to Report.

5. Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

Nothing to Report.

6. Impact on society beyond science and technology:

Nothing to Report.

Changes

1. Changes in approach

Nothing to Report.

2. Problems or delays

Because of the global supply chain difficulty during the COVID-19 pandemic, the delivery of equipment and parts has been significantly delayed.

- 1) We ordered three customized ultra-high vacuum cells in 2021, but have not received them by now. Fortunately we eventually received them in Spring 2023 so that the entire project could be completed in time.
- 2) We ordered a Toptica laser in September 2022, and the delivery time is 8-9 months which is unexpected longer than before. The laser was received in May 2023 and did not cause the delay of the entire project.

3. Expenditure Impacts

Nothing to Report.

4. Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards

Nothing to Report.

5. Changes to the primary place of performance from that originally proposed

Nothing to Report.