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# Randomly Disordered-Topological Edge-State of Rydberg Atom Array

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Rydberg atoms would be essential ingredients in the N-qubit operation. However, we need to control and identify the N-Rydberg system efficiently. For control, we demonstrated a fast-image processing technique applied to atom array. To remove ambiguity, we theoretically demonstrated how to identify the base states of the Rydberg-atoms inversely via machine learning (ML). Due to the UM institutional policy and PI’s personal situation, the project could not be completed, and the remaining budget had been returned to AOARD. However, this final report includes an update of the PI’s academic activities supported by the grant.

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Final Report for AOARD Grant FA2386-20-1- 4068

# “Randomly Disordered-topological Edge-state Of Rydberg Atom Array”

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## Abstract:

Rydberg atoms would be essential ingredients in the N-qubit operation. However, we need to control and identify the N-Rydberg system efficiently. For control, we demonstrated a fast-image processing technique applied to atom array. To remove ambiguity, we theoretically demonstrated how to identify the base states of the Rydberg-atoms inversely via machine learning (ML). Due to the UM institutional policy and PI’s personal situation, the project could not be completed, and the remaining budget had been returned to AOARD. However, this final report includes an update of the PI’s academic activities supported by the grant.

## Introduction:

Our research aims at the most robust Rydberg-atom quantum system via both topological properties and machine learning. At the beginning of the project, we demonstrated the fast imaging of a three-dimensional atom array [1] for the multi-qubit Rydberg system. We also proposed machine learning classification of the Rydberg Hamiltonian [2] by collaborating with the KAIST QCL (quantum computing lab). Our research will apply to the fast and robust quantum simulation/computation [3].

## Experiment:

Ref [1]: For N-qubit scalability, the Rydberg-atom needs a three-dimensional array. The atomic position can be checked via 4-f imaging techniques, and another dimension (z-axis) costs additional processing time. A holographically programmed phase-mask (Fresnel lenslets) was implemented to collect all 3D locations at once for speedy processing. PI participated in the work done by collaboration with KAIST QCL.

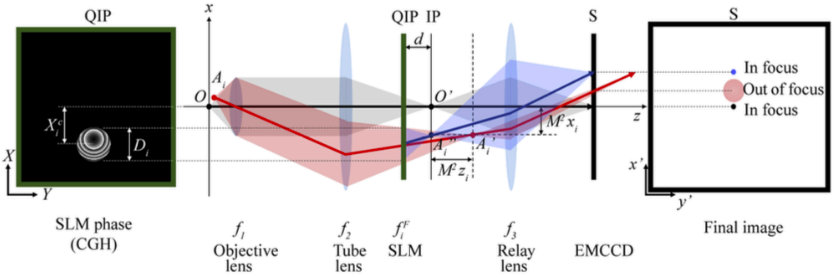
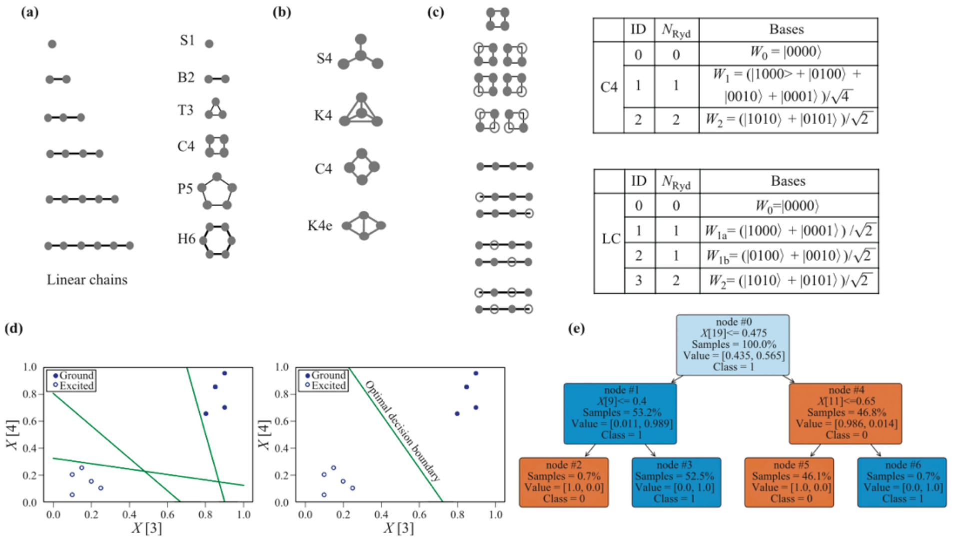


**Fig. 2.** Optical layout of the 3D holographic imaging microscope, which consists of an objective lens (of focal length $f_1$), a tube lens ($f_2$), an SLM at the quasi-image plane (QIP), and a relay lens ($f_3$) to the final image screen (S). The red line indicates the chief ray of a point source $A_i = (x_i, y_i, z_i)$ to the original, unshaped image $A_i' = (-Mx_i, -My_i, 2L + M^2 z_i)$ on the intermediate image plane (IP), which results in an out-of-focus screen image. With a Fresnel lenslet programmed on the QIP, which is separated by $d$ from the IP, the redirected ray (blue line) is focused on to IP. The left-hand side figure shows the CGH pattern $\Phi_{\mathrm{SLM}}(X, Y)$ of the Fresnel lenslet and the right-hand side figure compares the original and as-focused images on the screen.

Fig.1. The schematic diagram of the Fresnel lenslets. Figure courtesy of Ref [1].

Ref [2]: Temporal excitation probability data of Rydberg atoms represent each base state of the Rydberg ground state or excitation. However, as the number of atoms increase, the profile shows ambiguity among bases. We've inversely identified the base states from their temporal probability data by implementing two machine learning classification methods (SVM and RFC). We took 300 experimental-like data sets for each base state by collaboration with the KAIST QCL (quantum computing lab.).



| | ID | $N_{\mathrm{Ryd}}$ | Bases |
|---|---|---|---|
| C4 | 0 | 0 | $W_0 = \vert 0000\rangle$ |
| | 1 | 1 | $W_1 = (\vert 1000> + \vert 0100\rangle + \vert 0010\rangle + \vert 0001\rangle)/\sqrt{4}$ |
| | 2 | 2 | $W_2 = (\vert 1010\rangle + \vert 0101\rangle)/\sqrt{2}$ |

| | ID | $N_{\mathrm{Ryd}}$ | Bases |
|---|---|---|---|
| LC | 0 | 0 | $W_0 = \vert 0000\rangle$ |
| | 1 | 1 | $W_{1a} = (\vert 1000\rangle + \vert 0001\rangle)/\sqrt{2}$ |
| | 2 | 1 | $W_{1b} = (\vert 0100\rangle + \vert 0010\rangle)/\sqrt{2}$ |
| | 3 | 2 | $W_2 = (\vert 1010\rangle + \vert 0101\rangle)/\sqrt{2}$ |

**Fig. 1** Schematics of considered Rydberg-atom configurations. Classification by **(a)** the number of atoms from one to six, **(b)** various connected graphs of 4 atoms, and **(c)** Rydberg excitation. **(d)** Illustration of the possible decision boundaries to classify the ground state and excited single atoms and SVM's optimal decision boundary. **(e)** A decision tree from the random forest classifier used to classify the ground state and excited single atoms generated with **plot_tree()**, as explained in Section 3.2.

Fig.2. The schematic diagram of machine learning identification. Figure courtesy of Ref [2].

## Results, Discussion:

Ref [1]: The performance of the Fresnel-lenslet image shows uniformity in terms of the width with sufficient intensities. Demonstrated methodologies enable simultaneous imaging of $N_{\max} = 200$ atoms in a volume of $V_{\max} = 1.2 \times 10^7$ μm$^3$. If we consider currently available fabrication technologies, the possible number of imaging points increases to $N = 10^3$.

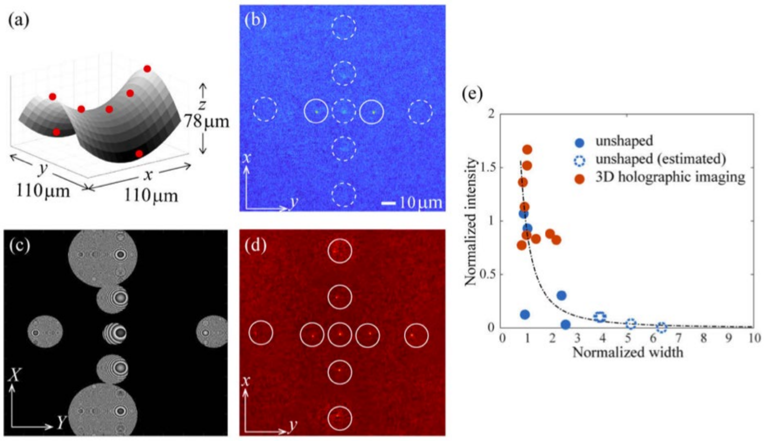


**Fig. 4.** (a) Nine atoms are placed on the surface of a hyperbolic paraboloid (a saddle-shape), on five different axial layers, respectively, at $z/z_{\mathrm{DOF}} = -15.3, 0.0, 2.6, 5.3,$ and $10.2$. (b) Conventional images of the atoms without the Fresnel lenslet programming. (c) The CGH $\Phi_{\mathrm{SLM}}(X, Y)$ of Fresnel lenslets for the seven atoms on the $z \neq 0$ planes. (d) The resulting 3D holographic image. (e) The peak intensities and widths of conventional (blue) and 3D holographic (red) images (normalized with the $z = 0$ plane values).

Fig.3. The main achievement from Ref [1]. 3D array all at once with uniformity.

Ref [2]: We found the relationship between the identification accuracy dependence on the system noise or shapes of an array. Compared to the linear chains, the closed form (square, pentagon, and hexagon) does not affect the ML-ID accuracy under various noise levels.

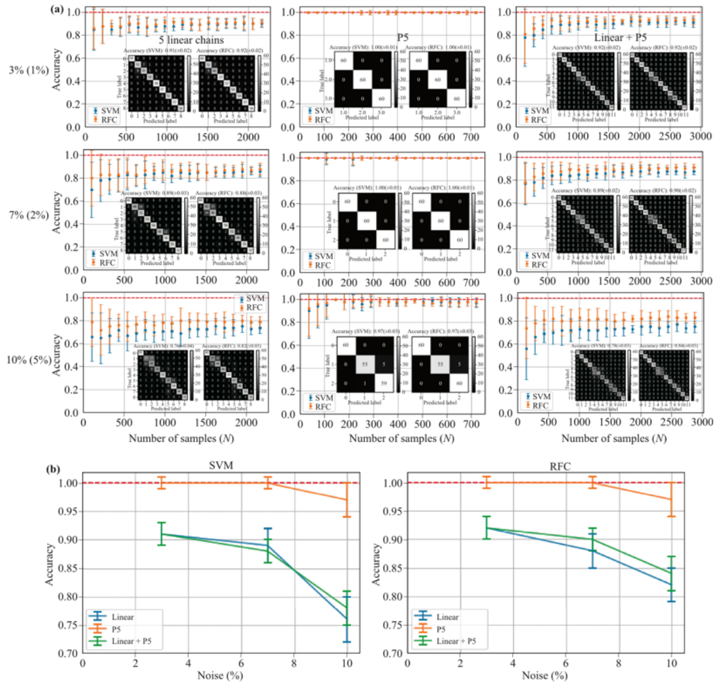


**Fig. 15** Accuracy dependence on laser noise intensity for five atoms. **(a)** Accuracy as a function of sample size $N$ for various laser noise intensity fluctuations. **(b)** Accuracy as a function of fluctuation level (standard deviation). The fluctuation of 3% (1%) and 7% (2%) represent practical experimental situations in the lab. For comparison, we considered the significant fluctuation level of 10% (5%), which rarely occurs.

Fig.4. The main achievement from Ref [2]. Accuracy dependence on the system noise levels or shapes of an array.

**Others (Journal Publication):**

While collaborating with KAIST Quantum Computing Lab, we were invited to review Rydberg quantum computing from KPS [3]. It was timely because 2022 was remarkable for the Rydberg community, which paved the way toward universal quantum gate operation by two research groups. One of the co-authors performed the research therein.

**Reason for Termination:**

During the project, I moved to another institute, SKKU (S. Korea), and planned to continue the intended project. Unexpectedly, relocating the grant from the U. of Malaya was not smooth. Instead, we agreed to terminate the project and return the remaining budget to AOARD. Then, I proposed a new one and waited for the AOARD opinion for the next step. I continued my collaboration research on the project as I added updates.

**List of Publications:**

a) papers published in peer-reviewed journals:
[1] H. Sun, Y. Song, A. Byun, H. Jeong, and J. Ahn, "Imaging three-dimensional single-atom arrays all at once," Optics Express, 29, 4082-4090 (2021)
[2] D. R. Chong, M. Kim, J. Ahn, H. Jeong, "Machine learning identification of symmetrized base states of Rydberg atoms," Front. Phys. 17(1), 12504 (2021)
[3] M. Kim, J. Ahn, Y. Song, J. Moon, **H. Jeong**, "*Quantum computing with Rydberg atom graphs,*" J. Kor. Phys. Soc, https://rdcu.be/c7ycA (2023)

d) conference presentations without papers:
[4] H. Jeong, 'Atomic & Molecular Optics (AMO) based Quantum Information Technology' UM Computational Science and Engineering (CSE) Symposium, University Malaya, 19th Feb. 2021
[5] H. Jeong, 'Rydberg atom array for Quantum Simulation', 2021 KPS Fall Meeting (Virtual), Tutorial talk, 20th Oct. 2021

**Attachments:** Publications a) listed above are attached.