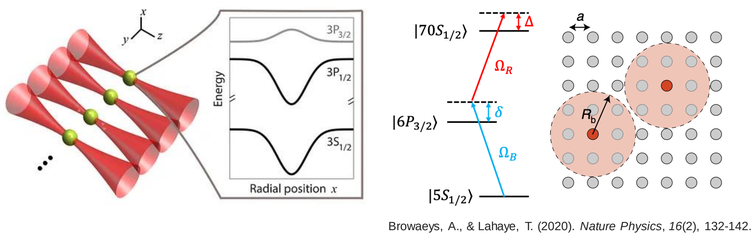
Geometrically frustrated Rb atom arrays in Rydberg states for quantum many-body simulation

Weikun Tian[1], Fan Jia[1], Wen Jun Wee[1], An Qu[1], Luheng Zhao[1], Datla Prithvi Raj[2], Jiacheng You[1], Mohammad Mujahid Aliyu[1], Huanqian Loh [1,2]

[1]Centre for Quantum Technologies, National University of Singapore, Singapore, 117543

[2]Department of Physics, National University of Singapore, Singapore 117542

Introduction



Browaeys, A., & Lahaye, T. (2020). *Nature Physics*, *16*(2), 132-142.

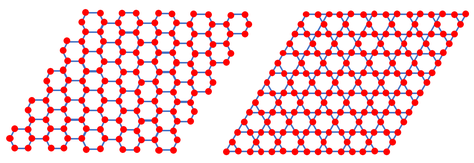
Challenge: To generate arbitrary, large-scale and defect-free 2D atom arrays

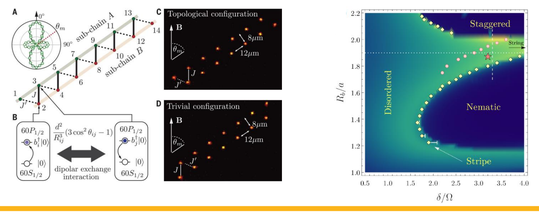
Neutral Rydberg atom array

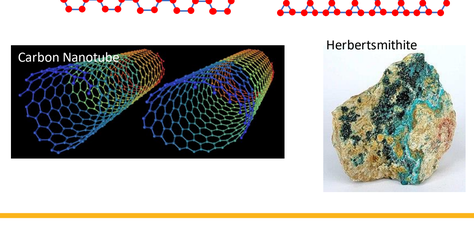
- Programmability: With optical tweezers, we can access various geometries with different topological structure.
- Scalability: 2D atom arrays scaling up to hundreds of atoms can be generated with SLM or AODs.
- Long-range interactions with Rydberg excitation: Different Hamiltonian can be engineered.

Our setup

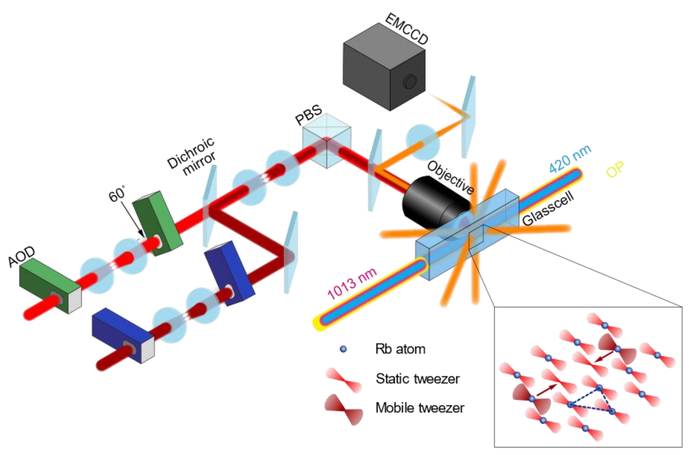
- AODs in 60-degree configuration → Talbot-free triangle tweezer array → Spin frustration phenomenon
- Novel multi-tweezer moving algorithm → Efficient parallel rearrangement & arbitrary geometries
- Rydberg excitation with a two-photon process → Long-range interaction → Many-body physics simulation

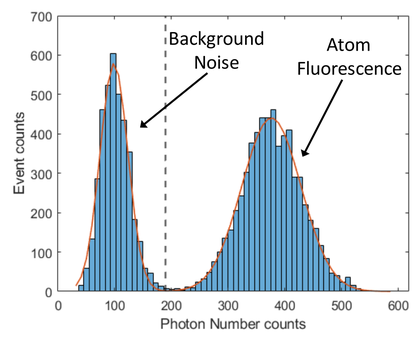


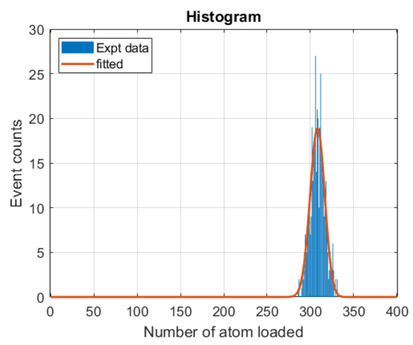




Apparatus



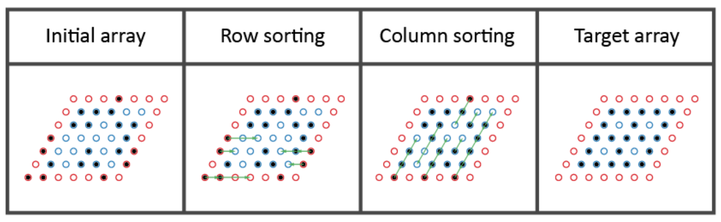


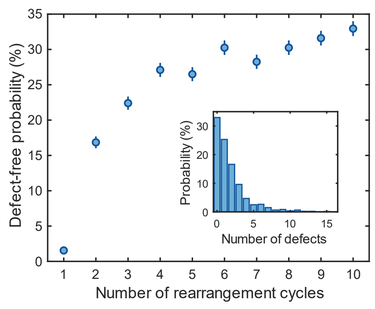


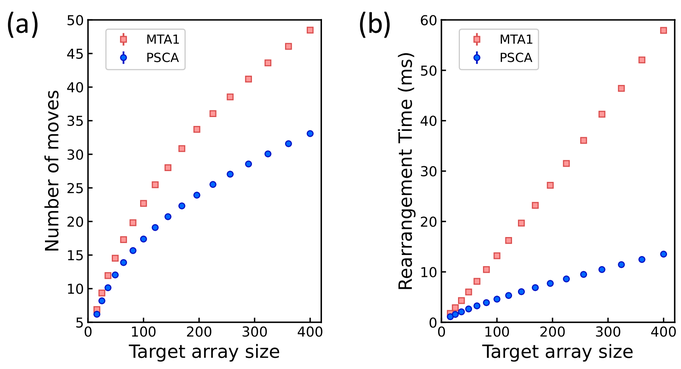
- We generated 400 optical traps in a triangular configuration with average trap depth = 300 μK.
- With D1 gray molasses loading, the filling fraction of the array reaches 78%.
- Single atom detection fidelity exceeds 99.9%
- 225-atom defect-free triangle array generation with 33(1)% success probability using our novel parallel rearrangement algorithm

Parallel atom rearrangement

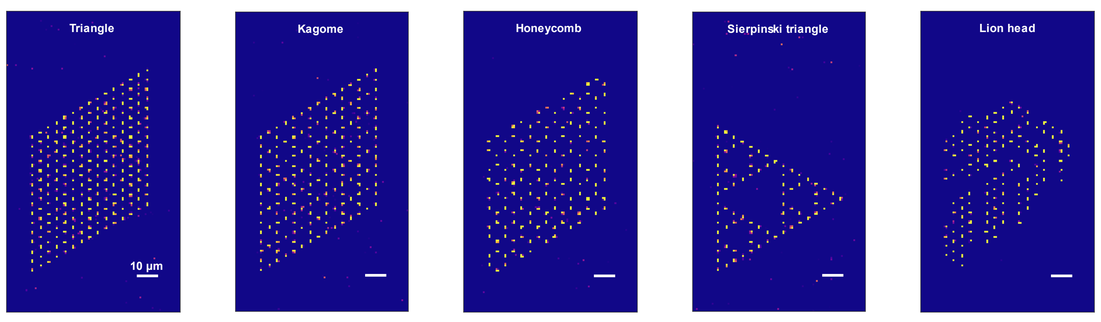
Parallel sort-and-compression algorithm (PSCA)



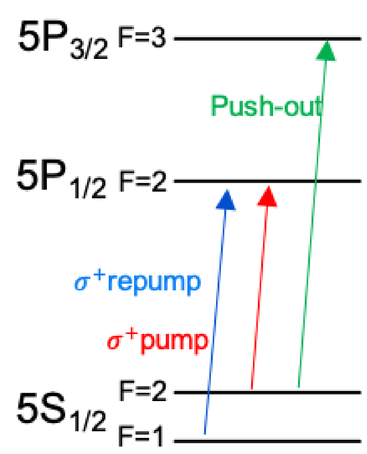




- PSCA gives a higher efficiency in defect-free array generation compared to existing rearrangement methods based on single and multiple tweezers
- With PSCA, we can generate 225-atom defect-free arrays in < 65 ms for the 1st rearrangement and < 35 ms for the 2nd rearrangement, including all hardware delays.
- Multi-cycle rearrangement brings the success probability of generating 225-atom defect-free arrays up to 33(1)%.

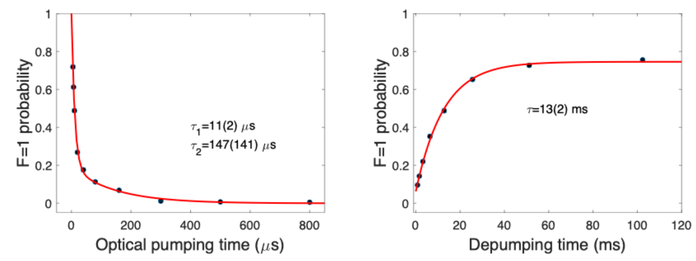


Optical pumping



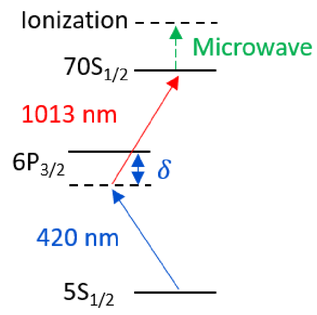
We first prepare atoms in $|g\rangle = |5S_{1/2}, F=2, m_F=+2\rangle$ with D1 σ^+ optical pumping. The hyperfine-state-selective readout is performed by removing the F=2 states with a D2 resonant σ^+ push-out beam before imaging.

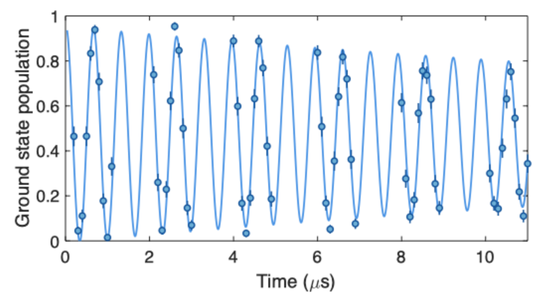
Comparing the Optical pumping time and depumping time, we yield a discrepancy over 1000 times.

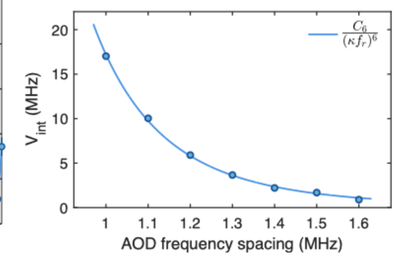


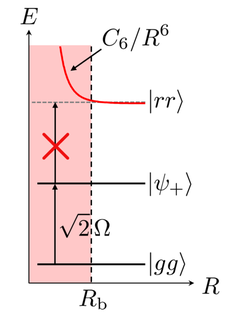
Rydberg state excitation

- Atoms are excited into $|r\rangle = |70S_{1/2}, m_J = +1/2\rangle$ via a two-photon process.
- Counter-propagating Rydberg lasers to reduce the decoherence caused by Doppler effect.
- Rydberg excitation lasers are shaped into highly-elliptical profile in order to yield high Rabi frequency while preserving the intensity homogeneity across the array.
- Rydberg atoms are detected as a vacancy in the array. An ionization microwave is applied after the Rydberg excitation to enhance the Rydberg detection fidelity to ~ 97%.



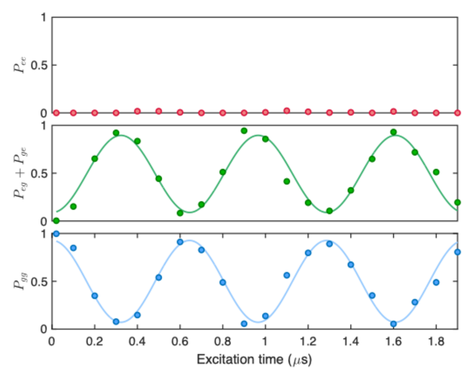






- An average Rabi oscillation frequency of $2\pi \times 1.518(1)$ MHz is achieved.
- **State-of-art** Rabi oscillation 1/e time up to 27(6) μs.
- Measured Rydberg state lifetime is 36(5) μs.

- Rydberg-Rydberg interactions are characterized via the van der Waals relation $V_{int} = C_6/r^6$.
- 1 MHz AOD frequency spacing corresponds to 6.08(1) μm in atomic spacing.



- Rabi oscillations are observed between the ground state and W state in a pair of atoms when they are put within the blockage radius, while doubly excited states are prohibited.
- Blockade induced oscillation enhancement are observed. Two atoms excitation frequency = 1.55 MHz is approximately $\sqrt{2}$*single atom Rabi frequency (1.115 MHz).

Summary and outlook

- We developed a novel rearrangement protocol for defect-free array generation and it is more efficient than the existing rearrangement methods.
- We realized defect-free neutral atom arrays scaling up to 225 atoms embedded in triangular Bravais lattice, which allows us to explore spin-frustrated phenomenon and simulate topological properties of 2D lattices related to triangular geometries.
- We managed to drive the Rydberg transition of Rb atoms with an inhomogeneity less than 2% in Rabi frequency and a detection fidelity ~97%.
- By reducing the phase noise of Rydberg lasers, the Rabi oscillation 1/e time is extended to 27(6) μs .
- Rydberg-Rydberg interactions are characterized and W state excitation is observed when putting an atom pair within blockage radius.
- Combining large-scale triangle-based defect-free atom array and a higher-quality Rydberg state excitation, we would be able to explore the many-body phases and dynamics on these lattices.

References & Acknowledgements

[1] Aliyu, M. M., Zhao, L., Quek, X. Q., Yellapragada, K. C., & Loh, H. (2021). *PR Research*, *3(4)*, 043059.
[2] Samajdar, R., Ho, W. W., Pichler, H., Lukin, M. D., & Sachdev, S. (2021). *PNAS*, 118(4), e2015785118.
[3] Sylvain de Léséleuc, et al. *Science*, 365.6455 (2019): 775-780.
[4] Zhang, J. T., Picard, L. R., Cairncross, W. B., Wang, K., Yu, Y., Fang, F., & Ni, K. K. (2022). *Quantum Science and Technology*, *7*(3), 035006.
[5] Browaeys, A., & Lahaye, T. (2020). *Nature Physics*, *16*(2), 132-142.
[6] Schlosser, M., Tichelmann, S., Schäffner, D., de Mello, D. O., Hambach, M., & Birkl, G. (2019). *arXiv:1902.05424*.
[7] De Mello, D. O., Schäffner, D., Werkmann, J., Preuschoff, T., Kohfahl, L., Schlosser, M., & Birkl, G. (2019). *PRL*, *122*(20), 203601.
[8] Graham, T. M., Kwon, M., Grinkemeyer, B., Marra, Z., Jiang, X., Lichtman, M. T., Sun Y., Ebert M., & Saffman, M. (2019). *PRL*, *123*(23), 230501.
[9] Brown, M. O., Thiele, T., Kiehl, C., Hsu, T. W., & Regal, C. A. (2019). *PRX*, *9*(1), 011057.
[10] Jackson Ang'ong'a, Huang, C., Covey, J. P., & Gadway, B. (2022). *PR Research*, *4*(1), 013240.
[11] Tian, W., Wee, W. J., Qu, A., Lim, B. J. M., Datla, P. R., Koh, V. P. W., & Loh, H. (2023). *PR Applied*, 19(3), 034048.
[12] Endres, Manuel, et al. *Science* 354.6315 (2016): 1024-1027.
[13] Ebadi, Sepehr, et al. *Nature* 595.7866 (2021): 227-232.
[14] Miles, Cole, et al. *arXiv:2112.10789* (2021).
[15] Barredo, D., De Léséleuc, S., Lienhard, V., Lahaye, T., & Browaeys, A. (2016). *Science*, *354*(6315), 1021-1023.
[16] Schymik, K. N., Lienhard, V., Barredo, D., Scholl, P., Williams, H., Browaeys, A., & Lahaye, T. (2020). *PRA*, *102*(6), 063107.
[17] Sheng, C., Hou, J., He, X., Xu, P., Wang, K., Zhuang, J., Li, X., Liu, M., Wang, J., & Zhan, M. (2021). *PR Research*, *3*(2), 023008.
[18] Jenkins, A., Lis, J. W., Senoo, A., McGrew, W. F., & Kaufman, A. M. (2022). *PRX*, *12*(2), 021027.
[19] Yan, Z., Spar, B. M., Prichard, M. L., Chi, S., Wei, H. T., Ibarra-García-Padilla, E., Hazzard, K.R., & Bakr, W. S. (2022). *arXiv:2203.15023*.
[20] Singh, K., Bradley, C. E., Anand, S., Ramesh, V., White, R., & Bernien, H. (2023). *Science*, 380(6647)
[21] Semeghini, Giulia, et al. *Science* 374.6572 (2021): 1242-1247.

Agency for Science, Technology and Research SINGAPORE

National Research Foundation Prime Minister's Office Singapore