Netural Atom Quantum Computation introduction

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why Netural Atom?

1). Naturally identical and stable

2). Large qubit count

3). Wireless gates and position control

4). Strong interactions available for multi-qubit gates

Outline

1. **principle**
2. **experiment**
3. **discussion**

main reference

1). Henriet, Loic, Lucas Beguin, Adrien Signoles, Thierry Lahaye, Antoine Browaeys, Georges-Olivier Reymond, and Christophe Jurczak. **Quantum Computing with Neutral Atoms**. Quantum 4 (21 September 2020): 327. `https://doi.org/10.22331/q-2020-09-21-327`.

Outline

1. **principle**
   - control
   - operation
2. **experiment**
   - scalability
   - error correction
3. **discussion**

optical tweezers[1]

1. the diameter of a trapped particle $\gg$ the wavelength of light

2. the diameter of a trapped particle $\ll$ the wavelength of light

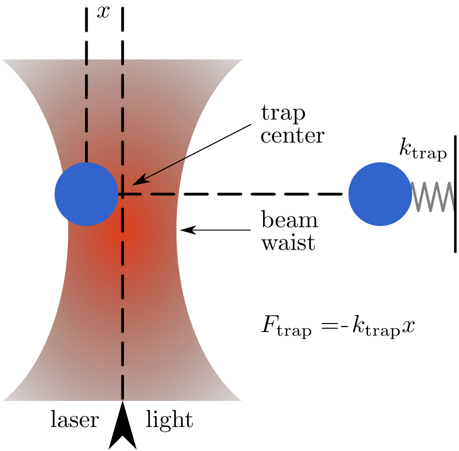

Figure: Dielectric objects are attracted to the center of the beam, slightly above the beam waist

[1] `https://en.wikipedia.org/wiki/Optical_tweezers`

Electric dipole approximation

1). Induction by light (assume the dielectric particle is linear):

$$p = \alpha \cdot E_{light}$$

p is the induced dipole moment, E_{light} is the electric field of the light, and α is the polarizability of the atom

2). Gradient Force:

$$F_{gradient} = \nabla(p \cdot E_{light})$$

develop histroy

1). Endres, Manuel, Hannes Bernien, Alexander Keesling, Harry Levine, Eric R. Anschuetz, Alexandre Krajenbrink, Crystal Senko, Vladan Vuletic, Markus Greiner, and Mikhail D. Lukin. "Atom-by-atom assembly of defect-free one-dimensional cold atom arrays." Science 354, no. 6315 (2016): 1024-1027. https://www.science.org/doi/abs/10.1126/science.aah3752.

2). Barredo, Daniel, Sylvain de Léséleuc, Vincent Lienhard, Thierry Lahaye, and Antoine Browaeys. "An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays." Science 354, no. 6315 (2016): 1021-1023. https://www.science.org/doi/abs/10.1126/science.aah3778.

optical lattice / optical tweezers array[2]

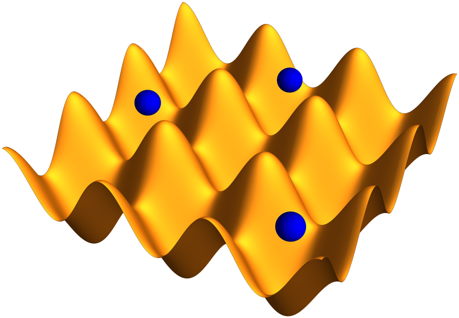

Figure: Atoms (represented as blue spheres) pictured in a 2D-optical lattice potential (represented as the yellow surface)

[2] `https://en.wikipedia.org/wiki/Optical_lattice`

AOD VS. SLM

1). **Acousto-optic deflector (AOD):**

- *Operating Principle:* Uses acoustic waves to diffract and control light's amplitude.
- *Advantages:* Features high-speed modulation and scanning capabilities, low power consumption, and robustness for long-term use.
- *Limitations:* Restricted to amplitude modulation without phase control, possible noise from acoustic wave generation, and efficiency dependent on material properties.

2). **Spatial Light Modulator (SLM):**

- *Operating Principle:* Modulates light's amplitude, phase, or polarization through an array of individually adjustable pixels, enabling complex light pattern generation.
- *Advantages:* Capable of intricate wavefront shaping and modulation across amplitude, phase, and polarization.
- *Limitations:* Higher complexity and cost, potential diffraction artifacts due to its pixelated nature, and limited refresh rate for dynamic applications.

work flow

1). metal

2). atomic beam

3). cooling

   1). zeeman slower

   2). MOT cooling

4). optical lattice

5). rearrange

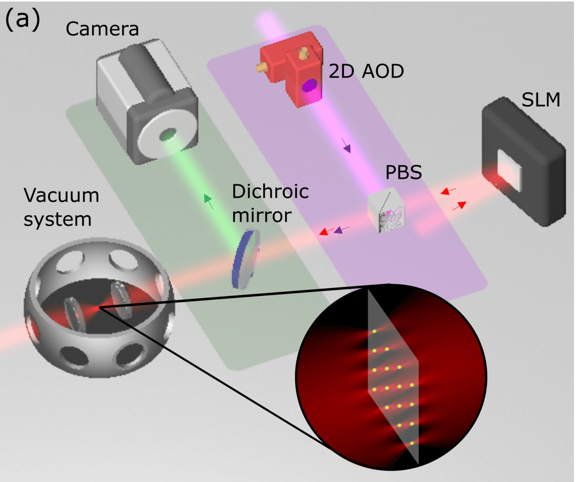

Figure: Overview of the main hardware components constituting a quantum processor

rearrange

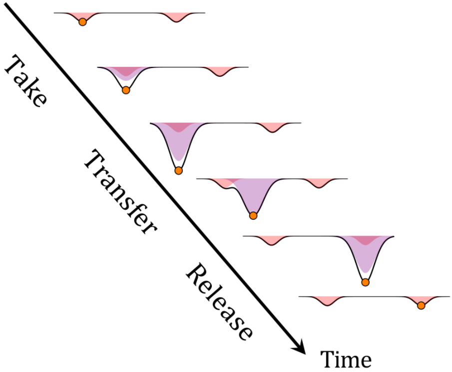

Figure: Moving a single atom from one site to another (both in red) in the register

some confused words

1). qubit sites

2). a mean number of loading individual atoms

3). defect-free atomic qubit clusters

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single-qubit gate

1). *principle:* an optical laser field driving Raman transitions through an intermediate atomic state.

2). The atom-laser interaction is characterized by:

- the Rabi frequency Ω(its strength, proportional to the amplitude of the laser field)
- the detuning δ (the difference between the qubit resonance and the field frequencies)
- the relative phase φ
- the duration τ

3). induces rotations around the (x, y, z) axes with angles $(\Omega\tau\cos\varphi, \Omega\tau\sin\varphi, \delta\tau)$

Rydberg blockade[3]

1). Van der Waals force, $\propto R^{-6}$

2). dipole-dipole interaction, $\propto R^{-3}\left(\vec{p}_1 \cdot \vec{p}_2 - 3(\vec{p}_1 \cdot \hat{R})(\vec{p}_2 \cdot \hat{R})\right)$, while $\vec{p} = q \cdot \vec{d}$

3). $d \propto n^2$, while rydberg atoms in experiment $50 \leq n \leq 70$

4). two closed atoms can't be $|rr\rangle$

[3] https://en.wikipedia.org/wiki/Rydberg_atom

how to choose atomic?

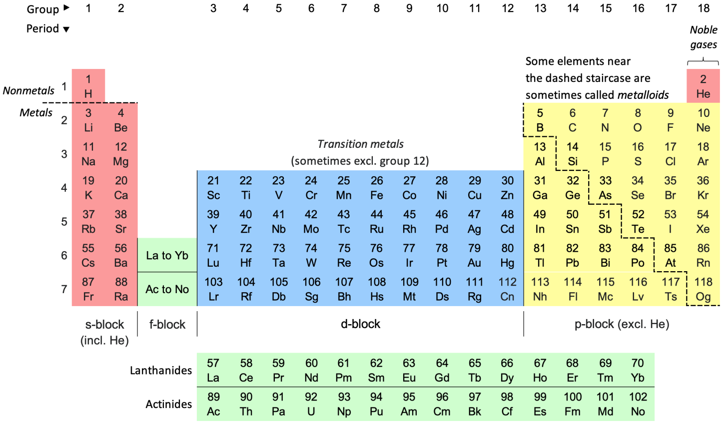

Figure: A periodic table from [5]. Usually, people use alkaline erath elements for naturely stable qubits, like Rubidium (Rb).

[4] https://en.wikipedia.org/wiki/Periodic_table

[5] https://en.wikipedia.org/wiki/Periodic_table

multi-qubit gate

realize: $2|gg\rangle\langle gg| - \mathbb{I}$

1). $|gg\rangle \xrightarrow{\pi_1} |gg\rangle \xrightarrow{2\pi_2} |gg\rangle \xrightarrow{\pi_1} |gg\rangle$

2). $|eg\rangle \xrightarrow{\pi_1} |rg\rangle \xrightarrow{2\pi_2} |rg\rangle \xrightarrow{\pi_1} -|eg\rangle$

3). $|ge\rangle \xrightarrow{\pi_1} |ge\rangle \xrightarrow{2\pi_2} -|ge\rangle \xrightarrow{\pi_1} -|ge\rangle$

4). $|ee\rangle \xrightarrow{\pi_1} |re\rangle \xrightarrow{2\pi_2} |re\rangle \xrightarrow{\pi_1} -|ee\rangle$

Or: $|ee\rangle \xrightarrow{\pi_{1,2}} \frac{|er\rangle+|re\rangle}{\sqrt{2}} \xrightarrow{\pi_{1,2}} -|ee\rangle$

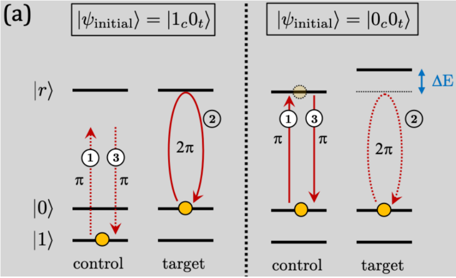

Figure: Principle of the controlled-Z gate based on dipolar Rydberg interaction. First a π pulse is applied on the control atom, then a 2π pulse on the target atom, and finally another π pulse on the control one.As a result, those pluses apply a gate $e^{i\pi}Z$.

noise sources

1). Thermal Noise, Quantum Decoherence, Imperfections in the implementation of quantum gates, Measurement Errors

2). Atom loss
- Residual Pressure
- Photon Scattering and Atom Heating during detection

3). Transient non-zero population of Rydberg states

potential developments

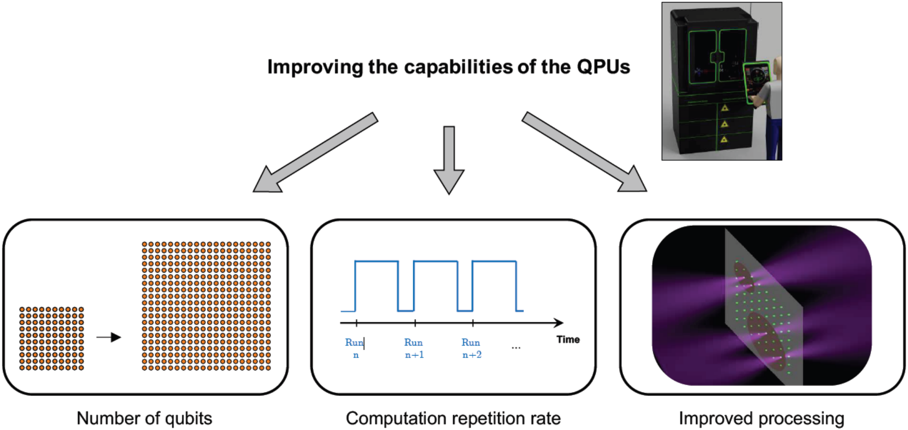

Figure: The three main axes of hardware developments to improve the performances of the QPUs

technological enhancements

1). Higher optical power lasers for more optical tweezers.

2). Advanced imaging systems for larger qubit registers.

3). Overcoming Residual Pressure Limitations

4). Enhanced atomic sources for quicker register loading.

5). High-bandwidth electronics for precise operation control.

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breakthrough

1). Pause, Lars, Lukas Sturm, Marcel Mittenbühler, Stephan Amann, Tilman Preuschoff, Dominik Schäffner, Malte Schlosser, and Gerhard Birkl. **Supercharged Two-Dimensional Tweezer Array with More than 1000 Atomic Qubits**. Optica 11, no. 2 (7 February 2024): 222. `https://doi.org/10.1364/OPTICA.513551`.

2). Norcia, M. A., H. Kim, W. B. Cairncross, M. Stone, A. Ryou, M. Jaffe, M. O. Brown, et al. **Iterative Assembly of ^{171}Yb Atom Arrays in Cavity-Enhanced Optical Lattices**. arXiv, 9 February 2024. `http://arxiv.org/abs/2401.16177`.

3). Gyger, Flavien, Maximilian Ammenwerth, Renhao Tao, Hendrik Timme, Stepan Snigirev, Immanuel Bloch, and Johannes Zeiher. **Continuous Operation of Large-Scale Atom Arrays in Optical Lattices**. arXiv, 10 February 2024. `http://arxiv.org/abs/2402.04994`.

supercharged

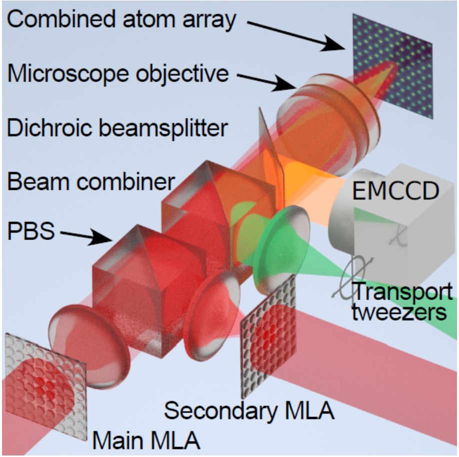

Figure: In the experimental setup described in the paper titled *Supercharged*, the implementation encompasses 3000 qubit sites, including 441 qubits, utilizing Rubidium (Rb) as the core element.

cavity

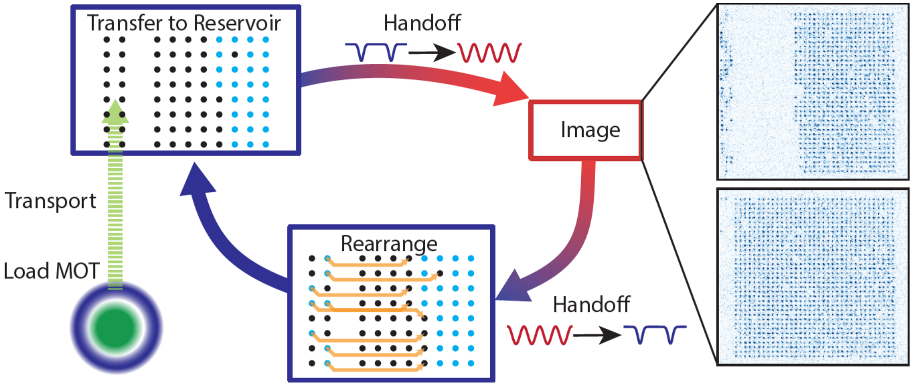

Figure: The paper titled *Cavity* introduces a groundbreaking approach for assembling large atom arrays with up to 1225 sites, achieving a remarkable 99% per-site occupancy rate using Ytterbium (Yb) atoms, through an iterative loading sequence enabled by the synergistic use of optical tweezers and cavity-enhanced optical lattices.

continuous

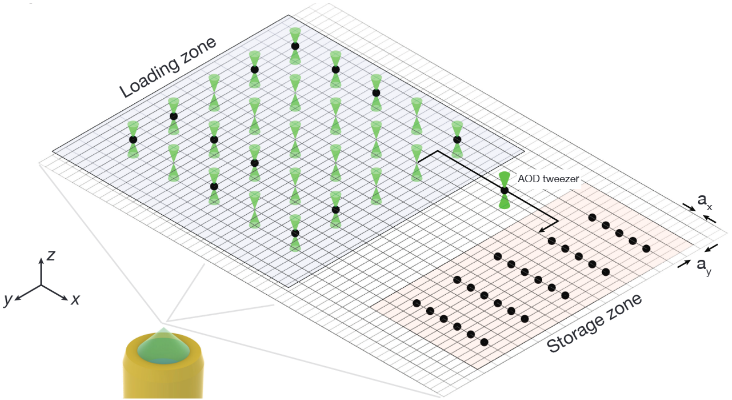

Figure: The paper titled *Continuous* introduces a novel approach for the uninterrupted operation of extensive atom arrays within optical lattices. This method involves subdividing the accessible area to support the assembly and maintenance of the array, realizing a continuously refilled system with a net 2.5 seconds cycle time for over 1000 Strontium atoms.

summarize

1). the power of laser systems

- optimize experiment setup
- use other element

2). computation repetition

- subdivide the accessible area
- high-fidelity and low-loss detection of single atoms

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main reference

1). Bluvstein, Dolev, Simon J. Evered, Alexandra A. Geim, Sophie H. Li, Hengyun Zhou, Tom Manovitz, Sepehr Ebadi, et al. **Logical Quantum Processor Based on Reconfigurable Atom Arrays**. Nature 626, no. 7997 (1 February 2024): 58–65. `https://doi.org/10.1038/s41586-023-06927-3`.

experiment set up

D-dimensional color code:

1). the graph is a homogeneous simplicial D-complex obtained as a triangulation of the interior of a D-simplex.

2). the graph is D+1-colorable.

transversal gates: inherently fault-tolerant.

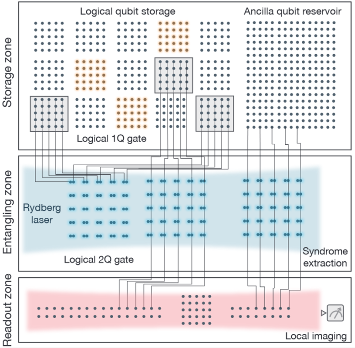

Figure: Schematic of the logical processor, segmented into three zones: storage, entangling, and readout.

reconfigurable atom arrays

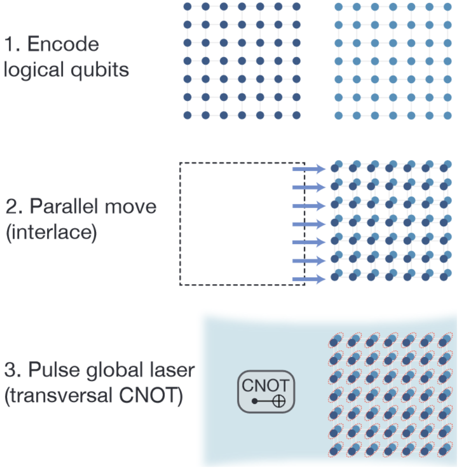

Figure: Illustration of two qubit gate on parallel atom transport.

GHZ experiment

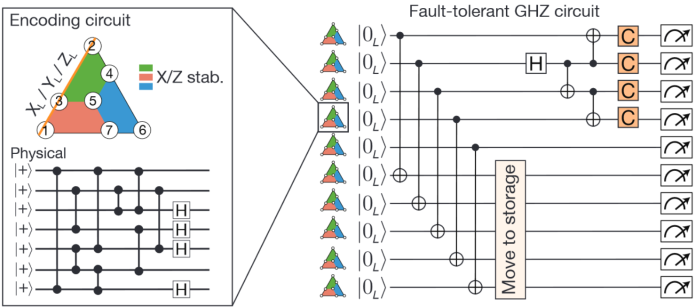

Figure: Circuit for preparation of logical GHZ state. Ten color codes are encoded non-fault-tolerantly (nFT), and then parallel transversal CNOTs between computation and ancilla logical qubits perform FT initialization. In this experiment, pyhsocal qubit initialization is 99.32%, physical two-qubit gate fidelity is 99.5%. Using the fault-tolerant, the $|0\rangle_L$ initialization fidelity is 99.91%. The GHZ state fidelity is 72%. Using postselect, the fidelity increase 99.85%.

non-Clifford gate

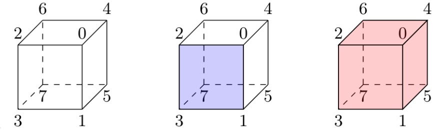

Figure: Geometric representation of the [[8,3,2]] code. The physical qubits reside at the vertices of the cube.

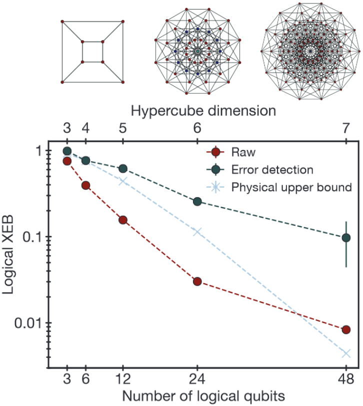

Figure: Physical upper-bound fidelity (blue) is calculated using best measured physical gate fidelities. Diagrams show physical connectivity.

Outline

discussion

- Entering the initial phase of fault-tolerant quantum computing, the strategy of carefully selecting both the algorithm and the qubit encoding to match the hardware's capabilities offers significant potential. This approach can efficiently address new types of problems.
- Benefits of Atomic Computation:
  1). Expands the spectrum of gate operations to include advanced options like non-Clifford CCZ and nonlinear CZ gates.
  2). Streamlines the integration of parallel processing and the execution of non-local operations.
- Future choice:
  - multi-element atom array
  - trad off between stationery with dynamic