Netural Atom Quantum Computation introduction

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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.

2). 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.

Outline

Outline

1. **principle**
    - control
    - operation
2. **device**
    - scalability
    - error correction
3. **synthess**

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

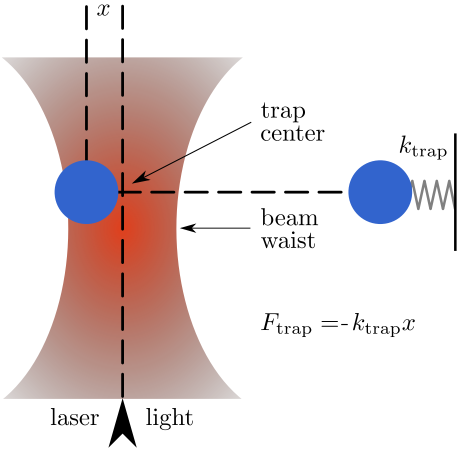

Figure: Dielectric objects are attracted to the center of the beam, slightly above the beam waist

[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:

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

optical lattice / optical tweezers array[2]

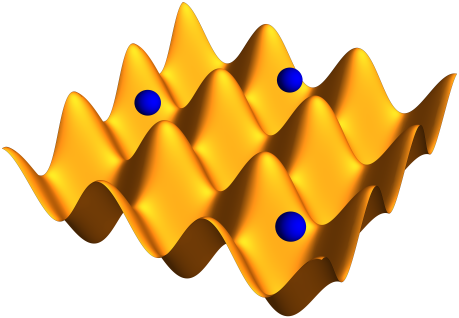

Figure: Atoms (represented as blue spheres) pictured in a 2D-optical lattice potential (represented as the yellow surface)

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

AOD VS. SLM

1). **Amplitude Object Design (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.

develop histroy

1). Bose-Einstein condensate

2). 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`.

3). 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`.

work flow

1). metal

2). atomic beam

3). cooling

    1). zeeman slower

    2). 2D MOT

    3). 3D MOT

4). optical lattice

5). rearrange

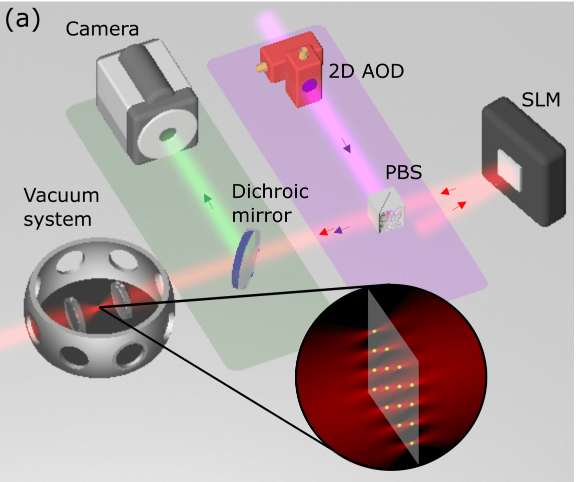

Figure: Overview of the main hardware components constituting a quantum processor

rearrange

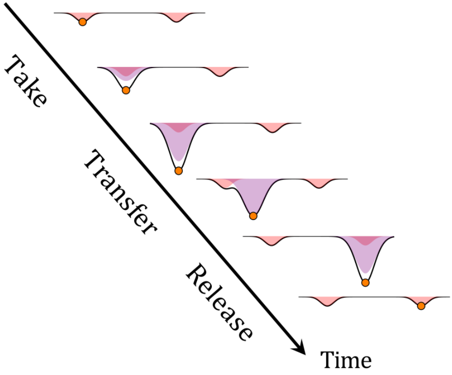

Figure: Moving a single atom from one site to another (both in red) in the register

some confused words

1). qubit sites

2). a mean number of loading individual atoms

3). defect-free atomic qubit clusters

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readout

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). $r = \frac{n^2 \hbar^2}{ke^2 m}$, 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?

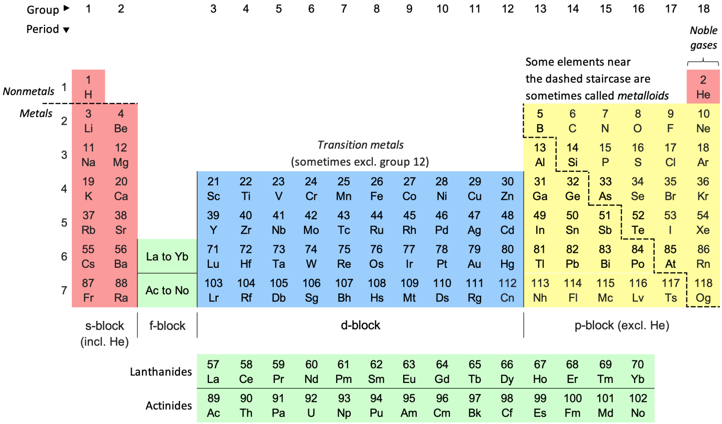

Figure: Periodic table[4]

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

multi-qubit gate

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

1). $|gg\rangle \rightarrow |gg\rangle$

2). $|eg\rangle \rightarrow |rg\rangle \rightarrow -|eg\rangle$

3). $|ge\rangle \rightarrow |gr\rangle \rightarrow -|ge\rangle$

4). $|ee\rangle \rightarrow |re\rangle \rightarrow -|ee\rangle$

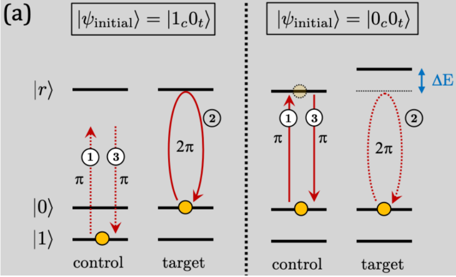

Figure: Principle of the controlled-Z gate based on dipolar Rydberg interaction. First a π pulse is applied on the control atom, then a 2π pulse on the target atom, and finally another π pulse on the control one.

summarize

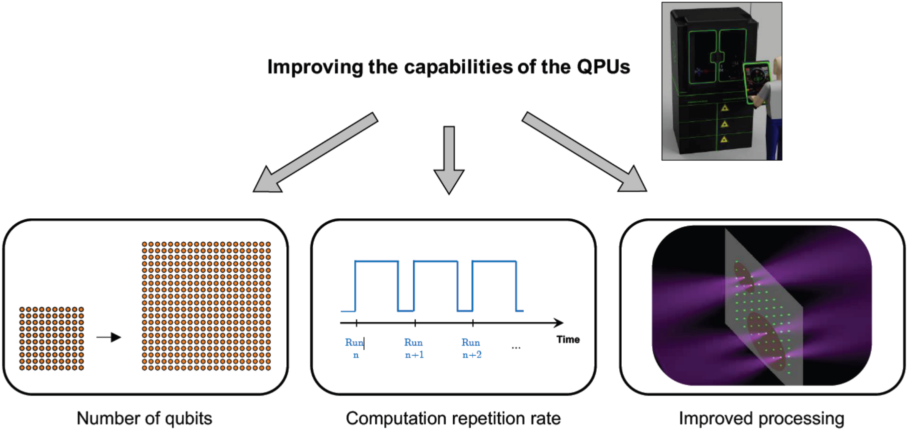

Figure: The three main axes of hardware developments to improve the performances of the QPUs

Limitations and Solutions

1). **Qubit Scaling and Laser Systems**

- Higher optical power lasers for more optical tweezers.
- Advanced imaging systems for larger qubit registers.
- Tackling atom lifetime limitations in vacuum chambers.

2). **Overcoming Residual Pressure Limitations**

- Compact cryogenic QPUs for extended atom lifetimes.
- Faster operation cycles to outpace decoherence.

Technological Enhancements

1). **Hardware and Atomic Source Flux**
   - Enhanced atomic sources for quicker register loading.
   - Improved repetition rate for high-frequency experiments.

2). **Qubit Manipulation and Error Reduction**
   - Reducing decoherence through environmental control.
   - 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.

Technische Universität

Atom Computing

Max-Planck-Institut

summarize

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set up

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discussion