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.

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

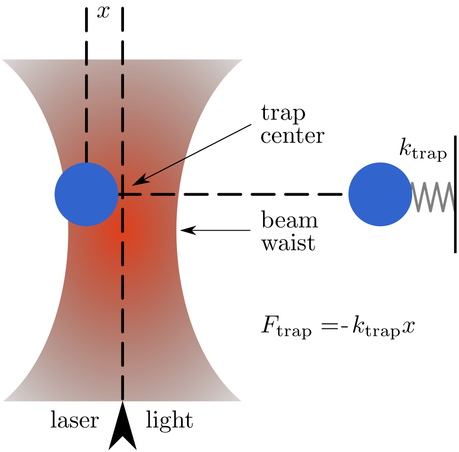

Figure: Dielectric objects are attracted to the center of the beam, slightly above the beam waist

[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]

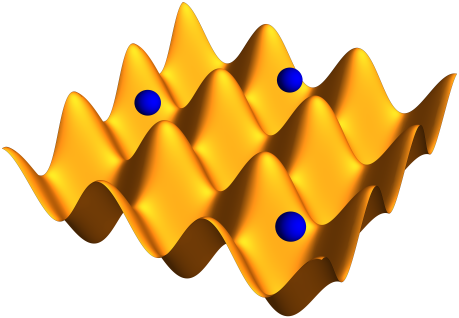

Figure: Atoms (represented as blue spheres) pictured in a 2D-optical lattice potential (represented as the yellow surface)

[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

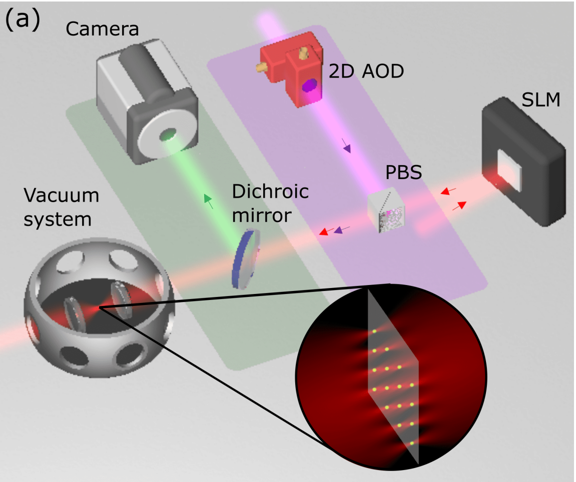

Figure: Overview of the main hardware components constituting a quantum processor

rearrange

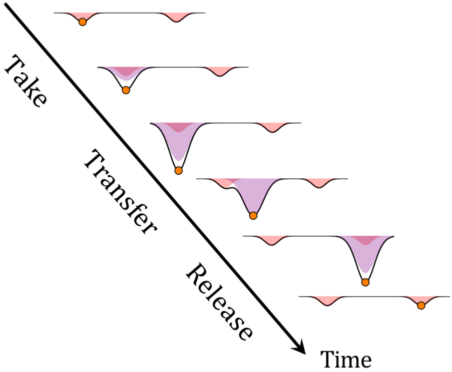

Figure: Moving a single atom from one site to another (both in red) in the register

some confused words

1). qubit sites

2). a mean number of loading individual atoms

3). defect-free atomic qubit clusters

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?

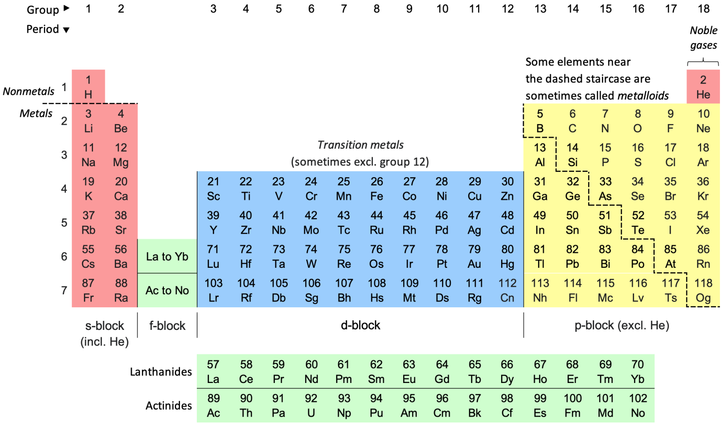

Figure: Periodic table[4]

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

multi-qubit gate

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

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

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

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

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

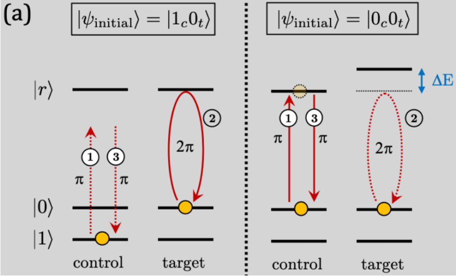

Figure: Principle of the controlled-Z gate based on dipolar Rydberg interaction. First a π pulse is applied on the control atom, then a 2π pulse on the target atom, and finally another π pulse on the control one.

potential developments

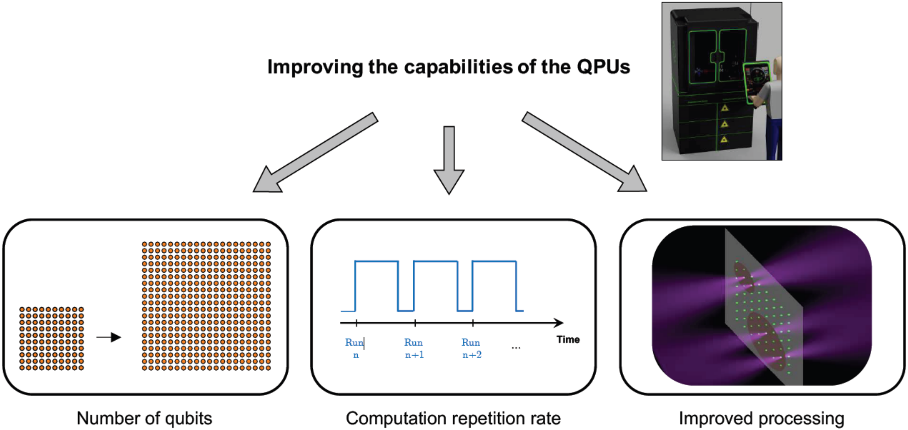

Figure: The three main axes of hardware developments to improve the performances of the QPUs

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.

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`.

Atom Computing

Max-Planck-Institut

summarize

set up

discussion