Laser cooling and trapping of atoms for neutral atom computing

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Abstract

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1 Introduction

The study of ultracold atoms and molecules is an emerging field of interest. It has a potential of addressing variety of problem across different branches of quantum science. To create ultracold atoms or molecules we use laser cooling and trapping techniques to cool these atoms at temperatures near absolute zero. At such low temperatures, the quantum mechanical properties of the cooled matter become significant. This enables researchers to manipulate their quantum states, frame Hamiltonians for many body problems and even implement quantum computing.

Over the past few years, a new physical implementation of quantum computing called neutral atom computing has received widespread attention in the quantum computing community. Ultracold atoms of alkali metals such as rubidium are used in the preparation of qubits which can be arranged into well-defined structures with the help of optical tweezers. Compare to other physical implementations, trapped neutral atoms are quite robust and weakly interact with the environment, this allows the qubits to have longer coherence time. However, this is only the case when we are dealing with a few hundreds of qubits. The real challenge is maintaining a long coherence time when scaling to many thousands of qubits. In this paper, we will discuss different laser cooling and trapping techniques and explore some possible ideas which can improve the scalability and error tolerance of qubits.

2 Laser cooling and trapping techniques

2.1 Magneto Optical Trapping (MOT)

This is the most widely used technique to cool and trap atoms due to its long trapping range and containment volume. Let us take the case of a one-dimensional trap in a $J_g = 0 \rightarrow J_e = 1$ transition.

In this configuration, we use two red detuned counter-propagating circular polarized laser beams in the presence of a magnetic field gradient generated by two circular coils in the anti-Helmholtz configuration. This magnetic field gradient splits the $J=1$ level into three magnetic sublevels(weak field Zeeman splitting) whose energies vary linearly with respect to the position($z$). The $\sigma^+$ polarized light beam drives $\Delta m = +1$ transitions and $\sigma^-$ drives $\Delta m = -1$ transitions. If an atom is towards the left of the center (point of zero magnetic field), its m=1 transition frequency approaches the laser frequency. Hence the atom absorbs $\sigma^+$ polarized photons, which directs the atom towards the center. The same case applies to atoms towards the right.

The lowest temperatures achieved by MOTs are in the order of hundreds of microkelvins to a few tens of microkelvins. It is important to note that before we perform quantum information-related
experiments, the laser beams must be turned off to avoid decoherence. Generally, these ultracold atoms are loaded into optical tweezer traps which generate a weak optical potential to protect the quantum states of atoms from environmental disturbances.

2.2 Sisyphus cooling

Sisyphus cooling is a sub-Doppler laser cooling technique through which atoms can be cooled in the order of a few microkelvins. In this technique, the atoms are cooled through multiple cycles of optical pumping. We will take the case of a one-dimensional system in a $J_g = 1/2 \rightarrow J_e = 3/2$ transition. In this configuration, two linear orthogonal polarised counter-propagating laser beams interfere with each other to form standing waves with polarizations varying from $\sigma^+$ to $\sigma^-$. The ground state energy sublevels of the atoms experience position-dependent light shifts which can be visualized as a series of potential hills along the z-axis. Let us take an atom starting from $z=0$ and moving along the positive z-axis. The atom climbs the potential hill of $g_{+1/2}$ sublevel and just when it reaches the top of the hill at $z=3\lambda/8$, it is optical pumped to the lower energy level $g_{-1/2}$ sublevel. In this process, the atom has lost its potential energy in the form of the photon emitted during optical pumping. This cycle can be repeated multiple times to convert the atom’s kinetic energy to potential energy which is lost during optical pumping.

It must be noted that Sisyphus cooling is not a trapping technique, hence it must be integrated with a MOT to trap the cooled atoms. Researchers are working on a new cooling and trapping technique.
2.3 Blue-Detuned MOT

Conventional MOTs use red-detuned laser beams where the laser frequency is set lower than the transition frequency. Researchers from the Imperial College of London demonstrated that by implementing Blue Detuned MOT, they were able to cool and trap rubidium atoms at temperatures a thousand times lesser than what’s achieved by red MOTs, and also achieving higher atomic densities. The reasons for these extraordinary results are largely determined by the Doppler and Sisyphus forces involved. In red MOT, Sisyphus heating dominates at low atomic speeds and Doppler cooling dominates at higher speeds. This prevents cooling to lower temperatures. But in blue MOT the Sisyphus cooling force dominates over the Doppler heating force for a range of atomic speeds.

3 Optical Tweezer Traps

As discussed previously, to perform any quantum information experiment we need to transfer the ultracold atoms or molecules from the MOT to Optical Tweezer Traps. A single optical tweezer uses a highly focused red-detuned laser beam to trap the atoms or molecules and move them from one point to another. The electric field distribution in the laser beam is Gaussian in nature, due to which the atoms or molecules are pulled towards the center of the beam where the intensity is maximum. The outer electrons in the atoms experience an attractive force towards the center of the field, however, the protons experience a repulsive force. Ultimately, in this tug of war, the force...
on electrons dominates; pulling the entire atom toward the center. Using spatial modulators or AOD (acoustic-optic deflector), the laser beam can be divided into Optical Tweezer arrays that trap individual atoms or molecules and arrange them into well-defined 2D or 3D structures.

Figure 3: Working principle of Optical Tweezer arrays. The AOD splits the laser beam into many beams which are then focused through a series of lenses, and directed to the vacuum chamber to trap the atoms.

4 Challenges in neutral atom computing

4.1 Scalability

While there is no issue in creating thousands of ultracold atoms or molecules, scaling quantum hardware to such a large number of qubits is a challenge. The current optical tweezer technology relies on spatial modulators to divide the laser beam, but this means that the more we divide the beam, the lesser the intensity of each beam. Hence, there will be a point where each beam cannot trap any atom or molecule. An obvious solution to this problem would be to just use more laser sources, but that would significantly increase the volume of our hardware. A potential research solution could be to integrate pulsed lasers in optical tweezer technology which at present mostly relies on continuous wave lasers. Pulsed lasers have demonstrated better trapping ability and could also provide more precise control of the qubits. However, they might reduce the coherence time of the qubits. To solve this issue we can look into hybrid solutions where we integrate both continuous wave lasers and pulsed lasers.
4.2 Decoherence

There are many factors that could decohere the cold atom qubits such as electromagnetic fields caused by lab equipment, collisions with residual atoms or molecules in the vacuum chamber, and fluctuations in the laser fields that trap the atoms. Therefore, we must explore new laser cooling and trapping technologies such as the blue-detuned MOT, which has achieved higher atomic cloud density and lower temperatures compared to conventional red-detuned MOT. This can help reduce thermal noise and increase the qubit’s coherence time. Another area to focus on is the development of fault-tolerant codes for our neutral atom computer. It is important to understand the nature of errors specific to neutral atom computing hardware and build appropriate noise models using techniques such as quantum tomography. Once we have created the noise models, we can develop error correction codes.

5 Conclusion

In this paper, I have talked about laser cooling and trapping techniques to create ultracold atoms and discussed possible ideas to minimize decoherence and improve the scalability of quantum hardware. Neutral atom computing is a fast-moving field thanks to the rapid ongoing development of laser technologies over the past few decades. It still has a lot of ground to cover in order to achieve quantum supremacy, but it’s quickly catching up with the leading competitors of quantum computing i.e. trapped ions and superconducting qubits.

6 References

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