New frontiers in quantum information with atoms and ions

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INTRODUCTION

The success story of quantum optics during the last ten years is largely based on progress in gaining quantum control on the single quantum level while suppressing unwanted interactions with the environment causing decoherence. These achievements are illustrated by storage and laser cooling of single trapped ions and atoms, and the manipulation of single photons in Cavity QED, opening the field of engineering interesting and useful quantum states. In the mean time the frontier has moved towards building larger composite systems of a few atoms and photons, while still allowing complete quantum control of the individual particles. The new physics to be studied in these systems is based on entangled states, both from a fundamental point of testing quantum mechanics for larger and larger systems, but also in the light of possible new applications like quantum information processing or precision measurements [1, 2]

The last two years were characterized by extraordinary progress in experimental AMO physics. Below, we will discuss two highlights of these developments: laser cooled trapped ions[3–8]. and cold atoms in optical lattices[9–13] These two examples also serve to illustrate the different perspectives and strength of AMO systems. Systems of a few trapped ions have demonstrated quantum entanglement engineering with high fidelity in the laboratory, and these systems are well on their way towards scalable quantum computing[1, 2] with – at least from our present understanding – no fundamental obstacles in sight. Atoms in optical lattices, on the other hand, can be loaded from a Bose Einstein condensate via a Mott insulator quantum phase transition into an optical lattice, providing a huge number of qubits, which can be entangled in massively parallel operations. This holds the promise to develop a quantum simulator with the hope of gaining insight into other fields of physics, such as condensed matter physics.

This paper summarizes some of the accomplishments with trapped ions and neutral atoms in optical lattices in the context of quantum information processing during the last few years. We also discuss the perspectives of these systems to build medium scale quantum computers and quantum simulators. First, we will discuss the essential ingredients needed to build a quantum computer with trapped ions, and we will explain why this system is almost ideal for this purpose. Then, we will review how neutral atoms can be stored at the potential wells of an optical lattice, and how their internal states can be manipulated to perform quantum gates and quantum simulations.

COLD TRAPPED IONS

Right after the discovery of Shor's factoring algorithm in 1994 [1], trapped ions interacting with laser light were identified [3] as one of the most promising candidates to build a small–scale quantum computer. The reason is that, for many years, the technology to control and manipulate single (or few) ions had been very strongly developed in the fields of ultrahigh precision spectroscopy and atomic clocks [14]. In particular, ions can be trapped and cooled such that they remain practically frozen in a specific region of space; their internal states can be precisely manipulated using lasers, and one can perform measurements with practically 100% efficiency; they also interact with each other very strongly due to the Coulomb repulsion, and they can, at the same time, be decoupled from the environment very efficiently.

The ions stored and laser cooled in an electromagnetic trap (see Fig. 1) can be described in terms of a set of external and internal degrees of freedom. The first ones are closely related to the center of mass motion of each ion, whereas the second ones are related to the motion of electrons within each atom, as well as to the presence of electronic and nuclear spins, and are responsible for the existence of a discrete energy level structure in each ion. Each qubit can be stored in two of those internal levels, which we will denote by $|0\rangle$ and $|1\rangle$. These levels have to be very long–lived, such that they are not disturbed during the computation. This can be achieved, for example, by choosing them as ground hyperfine or metastable Zeeman levels, where spontaneous emission is either not present or inhibited.

To start the computation, one can prepare all the qubits in state $|0\rangle$ by using optical pumping techniques, in which whenever the ion is in a state different to $|0\rangle$ it absorbs a photon and decays into another state until it finally reaches the desired state. After the computation, one can read out the state of the ions by performing measurements based on the quantum jumps technique[14]. The idea is to illuminate the ions with a laser light with the appropriate frequency and polarization so that if an ion is in the state $|0\rangle$ it does not absorb photons, whereas if it is in $|1\rangle$ it absorbs and emits photons. Whenever flu-

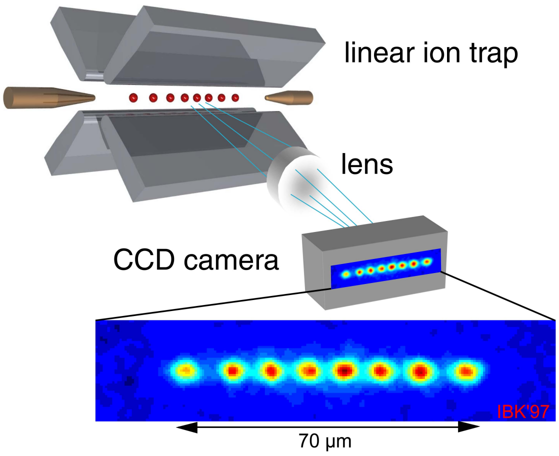

FIG. 1: String of ions in a linear trap (upper part) and a CCD image (lower part) (courtesy of R. Blatt at the University of Innsbruck).

orescence is detected or not, this indicates that the atom has been measured in state $|1\rangle$ and $|0\rangle$, respectively.

The computation itself requires the implementation of single– and a particular two–qubit gates (see Box 1). The first ones can be carried out on each atom independently by coupling their internal states $|0\rangle$ and $|1\rangle$ with a laser (or two, in Raman configuration). By adjusting the frequency and intensity of the laser, one can carry out general single–qubit gates. For the two–qubit gates, controlled interactions are always required. In the case of the trapped ions, the interaction is provided by the Coulomb repulsion [3]. This force, however, does not depend on the internal states, and thus it is not sufficient to produce the gate by its own. The main idea introduced in Ref. [3] is to use a laser to couple the internal state of the ions to the external ones, which are in turn affected by the Coulomb force, and in this way one produces the desired effect in the internal levels of the ions. The way in which the gate takes place can be explained schematically as follows:

$$\begin{aligned} |\epsilon_1\rangle_i \otimes |\epsilon_2\rangle_j \otimes |\Psi\rangle &\to |\epsilon_1'\rangle_i \otimes |\epsilon_2'\rangle_j \otimes |\Psi'_{\epsilon_1,\epsilon_2}\rangle \\ &\to -(-1)^{\epsilon_1\epsilon_2} |\epsilon_1'\rangle_i \otimes |\epsilon_2'\rangle_j \otimes |\Psi'_{\epsilon_1,\epsilon_2}\rangle \\ &\to -(-1)^{\epsilon_1\epsilon_2} |\epsilon_1\rangle_i \otimes |\epsilon_2\rangle_j \otimes |\Psi\rangle \qquad (1) \end{aligned}$$

Here, $|\epsilon\rangle_{i,j}$, with $\epsilon = 0, 1$, denote the two internal states of ions i and j on which the gate is applied, and $|\Psi\rangle$ denotes the motional state (external degrees of freedom). Another way of interpreting the way in which this gate proceeds is by noting that the motional states are somehow shared by all the atoms (i.e., if we move an atom then the others will move as well). Thus, the laser couples the internal state of each of the ions to the common motional state and then another laser interaction couples the modes back. The fact that the laser couples the internal and external degrees of freedom of the ions is a simple consequence of the fact that each time an ion absorbs or emits a photon, not only the internal but also the motional state is changed due to the photon recoil.

The specific way in which the two–qubit gate was implemented in the proposal [3] required that the ions be at zero temperature and that they can be singly addressed by the laser beam without affecting the rest. In recent years, various ingenious ways of simplifying these requirements have been proposed by various groups, in particular also Mlmer and Srensen, Milburn and Plenio and collaborators [2, 14].

The experimental verification of these ideas started in 1995 [6] with a proof of principle experiment in which a two–qubit quantum gate was realized. Since then on, several milestones have been achieved, especially in the laboratories led by David Wineland at NIST and Rainer Blatt in Innsbruck. Several versions of two–qubit gates have been carried out leading to very high efficiencies [7, 8], the so–called Deutsch–Jozsa algorithm[1] with a single ion has been implemented in Innsbruck, and even three and four particle entangled state have been prepared by performing small quantum computations in these labs.

The main obstacle to scale–up the current set–ups is based on the fact that as the number of ions in the trap is increased, it becomes harder to only affect the desired ions with the laser, without affecting the rest, something which spoils the computation. About three years ago, new proposals to overcome this obstacle emerged [4, 5]. The idea proposed in [4] is to separate the region where the ions are stored from the one in which the gates take place (See Fig. 2). In order to perform a gate, the ion (or ions) are moved from the storage region to the gate region, something which does not disturb their internal state (since, as mentioned above, the Coulomb interaction is independent of that unless we couple them with a laser). There, they are driven by lasers to perform the gate, and then they are moved back to the storage region. The additional heating of the ions motion due to this transfer can be removed by cooling an ion of a different species which, on the one hand cools the other sympathetically and, on the other, does not disturb their internal states. Preliminary experiments demonstrating all the basic elements of this proposal have been successfully carried out at NIST. In view of this experiments, we see at present no fundamental obstacle to achieve scalable quantum computation in these systems.

For the near future, we expect a very crucial experimental progress with trapped ions. Very likely, proof of principle experiments demonstrating teleportation, quantum error correction [1], and other intriguing properties of Quantum Mechanics will take place with 3 to 6 ions. When the technology allows to reach 30 ions (e.g. using the scalable proposals) a new avenue of experiments will open up. In that case, one could start performing computations which would compete with the most powerful classical computers that we have nowadays (See Box

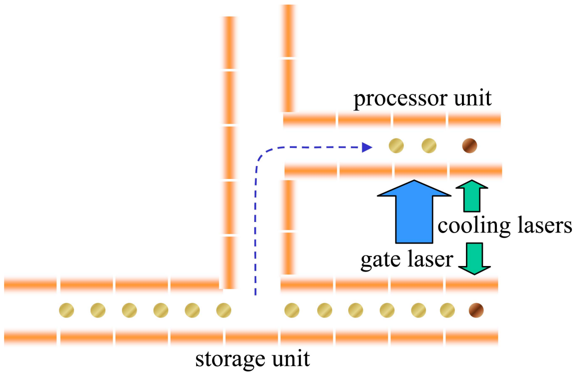

FIG. 2: Scalable scheme for quantum computing with trapped ions as proposed in [4]. Internal states of ions serve as quantum memory. To perform one- or two-qubit gate operations ions are moved from the storage to a processing area. Heating due to transport can be suppressed by sympathetic cooling with laser-cooled ions. (Redrawn from Ref.**??**)

2). Whether it will be possible to scale–up the present setups up to several hundred thousands of ions or not, something which is required to factor 200 digit numbers using Shor's algorithm and which requires fault–tolerant error correction [1], is still an open question. What we know by now is that there is no fundamental obstacle to achieve this goal, but it does only depend on the capability to develop the appropriate technologies. We would like to emphasize that trapped ions are the only system where this strong statement can be made nowadays.

COLD ATOMS IN OPTICAL LATTICES

Bose Einstein condensates (BEC) provide a source of a large number of ultracold cold atoms. In a condensate, due to the weak interactions, all atoms occupy the single particle ground state of the trapping potential, corresponding to a product state of the wave function. As first proposed in Refs. [9, 10], arrays of a large numbers of identifiable qubits are obtained in a Mott insulator phase of cold atoms, which is obtained by loading an atomic BEC in an optical lattice [9]. These qubits can be entangled in massively parallel operation with spin-dependent lattices [10] (see also [15]). This scenario has recently been realized in the laboratory in a series of remarkable experiments in Munich [11, 12].

Optical lattices are periodic arrays of microtraps for cold atoms generated by standing wave laser fields. Atoms loaded in an optical lattice will only occupy the lowest Bloch band due to the low temperatures. The physics of these atoms can be understood in terms of a Hubbard model with Hamiltonian [9]

$$H = -\sum_{\langle i,j\rangle} J_{ij} b_i^\dagger b_j + \frac{1}{2} U \sum_i b_i^\dagger b_i^\dagger b_i b_i$$

with b_i and $b_i^\dagger$ bosonic destruction operators for atoms at each lattice site, J_{ij} is hopping matrix element connecting two lattice sites via tunneling, and U the onsite interaction of atoms resulting from the collisional interactions. The distinguishing feature of this system is the time dependent control of the hopping matrix elements J_{ij} (kinetic energy) and onsite interaction U (potential energy) by the intensity of the lattice laser. Increasing the intensity deepens the lattice potential, and suppresses the hopping while at the same time increasing the atomic density at each lattice site and thus the onsite interaction. Increasing the intensity will, therefore, decrease the ratio the ratio of kinetic to potential energy, J_{ij}/U, and the system becomes strongly interacting. In the case of bosonic atoms, the system will undergo a quantum phase transition from the superfluid state (the condensate in the optical lattice) to a Mott insulator state[9]. In this Mott insulator regime we achieve a situation where exactly one atom is loaded per lattice site, thus providing a *very large* number of identifiable atoms whose internal hyperfine or spin states can serve as qubits. This Mott insulator quantum phase transition was first realized in a remarkable experiment in Munich[11].

Entanglement of these atomic qubits is obtained by combing the collisional interactions with a *spin-dependent* optical lattice [10], where by an appropriate choice of atomic states and laser configurations the qubit in state $|0\rangle$ sees a different laser lattice potential than the atom in state $|1\rangle$. This allows us to move atoms conditional to the state of the qubit. In particular, we can collide two atoms "by hand" , as illustrated in Fig. 3, so that the component of the wave function with the first atom in $|1\rangle$ and the second atom in $|0\rangle$ will pick up a collisional phase ϕ, which entangles the atoms. For atoms prepared in an equal superposition of the two internal states, we have again a phase gate between adjacent atoms $|\epsilon_1\rangle_i|\epsilon_2\rangle_{i+1} \longrightarrow e^{i\phi}|\epsilon_1\rangle_i|\epsilon_2\rangle$. In Fig. 4 we illustrate a Ramsey type experiment to generate and detect a Bell state via these collisional interactions. Again this idea has been realized recently in a seminal experiment in the Munich group[12]

In a lattice loaded with many atom a single movement will entangle in parallel all qubits. For three atoms this produces a maximally entangled GHZ-state, and for $2D$ lattices this allows the generation of a cluster state, which is the basic resource for universal quantum computing in Briegel *et al.*'s one way quantum computer[16].

The parallelism inherent in the lattice movements makes "atoms in optical lattices" an ideal candidate for a Feynman-type quantum simulator for bosonic, fermionic and spin many body systems, allowing simulation of various types and strengths of particle interactions, and $1, 2$ or $3D$ lattice configurations in a regime of many atoms, clearly unaccessible to any classical computer. By a stroboscopic switching of laser pulses and lattice movements combined with collisional interactions one can im-

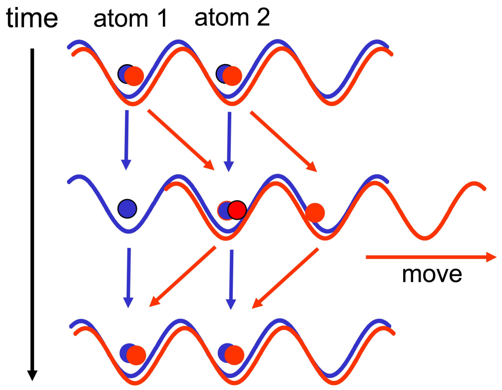

FIG. 3: Controlled collisions of two atoms with internal states $|0\rangle$ and $|1\rangle$ (red and blue circles) in a moveable state-dependent optical lattice (red and blue lattice) to entangle two atoms[10, 12]. This scheme unterlies the quantum simulator on the optical lattice.

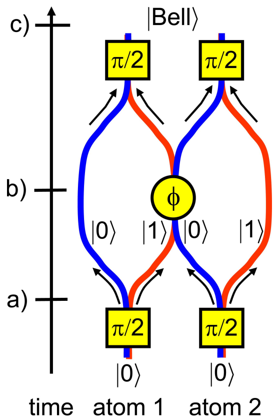

FIG. 4: Ramsey experiment with two atoms colliding in a lattice to generate a Bell state following Ref. [10, 12]. Time evolution is from bottom to top. The two atoms are initially prepared in the product state $|0\rangle|0\rangle$. A $\pi/2$ pulse generates the (unnormalized) superposition state $(|0\rangle+|1\rangle)((|0\rangle+|1\rangle))$ (a). A coherent collision provides a phase shift ϕ conditional to the first atom being in state $|1\rangle$ and the second atom being in state $|0\rangle$, i.e. $|0\rangle|0\rangle+e^{i\phi}|0\rangle|1\rangle+|1\rangle|0\rangle+|1\rangle|1\rangle$ (b). A final $\pi/2$-pulse closes the Ramsey interferometer resulting in the state $(1-e^{i\phi})|\text{Bell}\rangle+(1+e^{i\phi}|1\rangle|1\rangle$, which for $\phi=\pi$ is a Bell state. (Redrawn from Ref. [12])

plement sequences of 1 and 2-qubit operations to simulate the time evolution operator of a many body system [17] (see Box 2). For translationally invariant systems, there is no need to address individual lattice sites, which makes the requirements quite realistic in the light of the present experimental developments. On the other hand, as noted above, Hubbard Hamiltonians with interactions controlled by lasers can also be realized directly with cold bosonic or fermionic atoms in optical lattices. This "analogue" quantum simulation provides a direct way of studying properties of strongly correlated systems in cold atom labs, which in the future may develop into a novel tool of condensed matter physics.

While most of the above discussion has focused on optical lattices, new designs of arrays of microtraps e.g. based on nano-optics or magnetic microtraps will be one way to allow individual addressing of atomic qubits and entanglement operations. The ideas reviewed above about how to implement quantum gates with atoms in optical lattices can be easily extended to these systems, and we expect that in the near future will be implemented experimentally. The main advantage of these systems is that once they operate correctly, they can be relatively easily scaled-up.

For the near future, we expect that atoms in optical lattices will be used to simulate a variety of other physical systems like, for example, interacting Fermions in 2 Dimensions using different lattice geometries. We also expect an important progress towards loading single (neutral) atoms in different types of potentials (optical, magnetic, etc), and the performance of quantum gates with few of these systems. This would allow to create few atom entangled states which may be used to observe violations of Bell inequalities, or to observe interesting phenomena like teleportation or error correction. As opposed to the trapped ions, at the moment it is hard to predict if scalable quantum computation will be possible with neutral atoms in optical lattices with the present experimental set–ups. In any case, due to the high parallelism of these systems, we can clearly foresee that they will allow us to obtain a very deep insight in condensed matter physics via quantum simulations.

CONCLUSIONS

During the last few years the fields of atomic physics and quantum optics have experienced an enormous progress in controlling and manipulating atoms with lasers. This has immediate implications for quantum information processing, since this progress allows atomic systems to fulfill the basic requirements to implement the basic building blocks of a quantum computer[2]. In this article we have illustrated these statements with two particular systems: trapped ions and neutral atoms in optical lattices.

The physics of trapped ions is very well understood. In fact, with the recent experimental results we can foresee no fundamental obstacle to build a scalable quantum computer with trapped ions. Of course, technical development may impose severe restrictions to the time scale in which this is achieved. On the other hand, neutral atoms in optical lattices seem to be ideal candidates to study a variety of physical phenomena by using them to simulate other physical systems. This quantum simulation may turn out to be the first real application of quantum information processing.

There are other quantum optical systems that have experienced a very remarkable progress during the last years, and which may equally important in the context of quantum information. Just to mention some examples, in the context of cavity QED groups at Caltech, Georgia Tech, Innsbruck, and Munich have trapped single atoms and ions inside cavities, and let them interact with the cavity field, which can be used as single (or entangled) photon(s) generators as well as to build quantum repeaters for quantum communication. Atoms have been trapped in several kinds of optical and magnetic traps, and they have been moved very precisely to different locations in space. Distant ensembles of atoms have been entangled using laser fields, and the quantum state of light has been recorded in the ensembles and read out.

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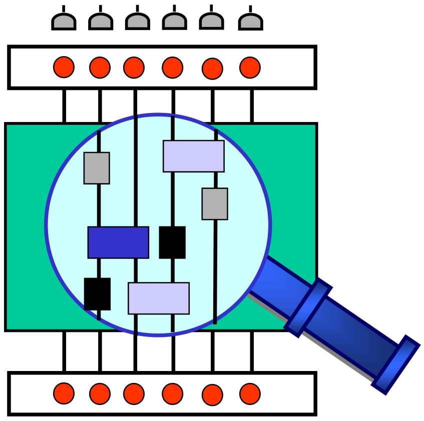

FIG. 5: Quantum computer. Qubits are prepared in the initial state (lower circles), then processed using a universal set of quantum gates (center), and their final state is detected (upper circles).

Box1: Quantum Computing

The basic element of quantum computing is the qubit, i.e. a two-level or spin-1/2 system $|0\rangle$,$|1\rangle$. A string of N qubits provides a quantum register. The general quantum state of the register is an entangled state

$$|\Psi\rangle = \sum_{\{x_i=0,1\}} c_{x_{N-1}x_{N-2}\ldots x_0}|x_{N-1}x_{N-2}\ldots x_0\rangle$$

in the 2^N-dimensional product Hilbert space of the qubits.

Quantum computing corresponds to unitary operations $\hat{U}$ on the state of the quantum register, $|\psi\rangle \longrightarrow \hat{U}|\psi\rangle$. These unitary operations $\hat{U}$ can be decomposed into a sequence of single and a two qubit quantum gates. A single qubit gate corresponds to the general rotation of the spin-1/2 representing the qubit, while a two qubit gate is a nontrivial entanglement operation of a pair of qubits, for example in form of a Controlled-NOT $|x_1\rangle|x_2\rangle \longrightarrow |x_1\rangle|x_1 \oplus x_2\rangle$ where $\oplus$ denotes addition modulo 2, or a phase gate $|x_1\rangle|x_2\rangle \longrightarrow (-1)^{x_1x_2}|x_1\rangle|x_2\rangle$. The final step is a read out of the state of the qubits.

The physical requirements for implementing a quantum computer are summarized in the *DiVincenzo criteria* [2].

Box2: Quantum Simulations

Let us consider a quantum system composed of N qubits all initially in state $|0\rangle$ [1]. We apply a two–qubit gate (specified by a 4×4 unitary matrix) to the first and second qubit, another one to the second and the third, and so on until we have performed $N-1$ such gates. Now, we measure the last qubit in the basis $|0\rangle,|1\rangle$. Let us denote by p_0 and p_1 the probability of obtaining 0 and 1 in this measurement. Our goal is to determine such probabilities with a prescribed precision (for example, of 1%). A way to determine the probabilities using a classical computer is to simulate the whole process: we

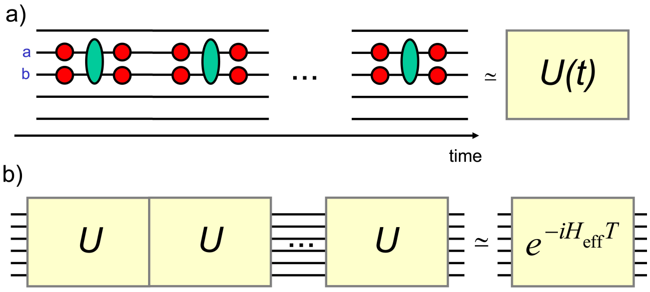

FIG. 6: Quantum simulator: a) Time evolution for a single time step $U(t)$ is built up from a sequence of single and two-qubit gates (red and green circles) operating on qubits (denoted by a and b). b) The effective time evolution operator $\exp -iH_{\rm eff}t$ is built from a sequence of operators $U(t)$.

take a vector which has 2^N components and multiply it by a $2^N \times 2^N$ matrix every time we simulate the action of a gate. At the end we can calculate the desired probabilities using the standard rules of Quantum Mechanics. However, as soon as N is of the order of 30, we will not be able to store the vector and the matrices in any existing computer. Moreover, the time required to simulate the action of the gates will increase exponentially with the number of qubits. However, with a quantum computer this simulation will required to repeat the same computation of the order of 100 times, and each computation requires only $N-1$ gates. Thus, we see that the quantum computer itself is much more efficient to simulate quantum systems, something that Feynman already pointed out in 1982 [1, 17]. Of course, this particular example is artificial, and it is not related to a real problem. However, there exist physical systems which cannot be simulated with classical computers but in which a quantum computer could offer an important insight on some physical phenomena which are not yet understood [17]. For example, one could use a quantum computer to simulate spin systems or Hubbard models, and extract some information about open questions in condensed matter physics. Another possibility is to use an "analogue" quantum computer to do the job, i.e. to choose a system which is described by the same Hamiltonian which one wants to simulate, but that can be very well controlled and measured.