Quantum information processing with trapped ions

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Abstract

Strings of atomic ions confined in an electromagnetic field configuration, so-called ion traps, serve as carriers of quantum information. With the use of lasers and optical control techniques, quantum information processing with trapped ions was demonstrated during the

last few years. The technology is inherently scalable to larger devices and appears very promising for an implementation of quantum processors.

Introduction

The use of strings of trapped ions in electromagnetic traps, so-called Paul traps, provides a very promising route towards scalable quantum information processing. There are ongoing investigations in several laboratories whose direction is towards implementing a quantum computer based on this technique. In the following, the methods will be briefly described and the state-of-the-art will be highlighted with some of the latest experimental results.

Ion trapping

Trapping configurations for ions using ac voltages are known since 1958 and are named after their inventor, Wolfgang Paul (University of Bonn, Nobel prize 1989). Paul traps are frequently used in mass spectrometry. However, only since the early 80s has it become possible to store and optically detect individual ions in Paul traps. This is due to the fact that the confined ions usually move quickly inside the trap, so that they exhibit a large Doppler effect which broadens the emitted spectrum and makes them difficult to detect spectroscopically. With the advent of the optical cooling techniques, originally proposed by Hänsch and Schawlow for free atoms and by Wineland and Dehmelt for trapped particles, then first realized by Neuhauser, Toschek and Dehmelt (Univ. Heidelberg) and Wineland (NBS Boulder, Co) with a single trapped ion, the motion of ions could be reduced such that they move only within a region smaller than the wavelength of the incident radiation. In this regime the Doppler effect essentially disappears, making precise control and detection of the ions possible. A single trapped ion can scatter light sufficiently strongly that it can even be observed with the naked eye. These experiments laid the foundation of experimenting with single atoms and their manipulation using laser light.

One of the unique features of experiments with single trapped ions is that each ion is available over and over again for repeated measurements. In the middle of the 80s single ions in Paul traps allowed the observation for the first time of the long-postulated phenomenon of *quantum jumps*. In such an experiment, one exploits the fact that during the scattering of fluorescent photons the ion must jump back and forth between a pair of its electronic states. If during this process the ion gets excited to a different (third) electronic state it is no longer available to generate fluorescence and thus it ceases to radiate. Thus as the ion moves to and from the third state, sometimes called a 'shelf' state, the relatively strong fluorescence disappears and reappears again. These characteristic jumps in the observed fluorescence indicate the fundamental quantum process of a single quantum system, here the ion, being forced by observation to choose between possible states. Furthermore, the quantum state it chooses is indicated by the detected fluorescence with close to 100% reliability. This technique, known as the *electron shelving* or the *quantum jump* method results from experimenting with a single particle and provides an important asset for the realization of a quantum information processor. It provides a fast and very reliable way to measure the quantum bits: this is both crucial for reading out the final result of a computation, and also very useful for correcting errors as the computation proceeds.

Quantum information processing

Qubits are implemented using two energy levels of a single trapped ion. Quantum registers need rows of such ions which are interacting in a controlled way. This can be realized using so-called linear Paul traps (see **Figure 1**). Such a trap device is derived from the Paul mass filter which employs four hyperbolic electrodes and rf-voltages to transmit an ion beam in a mass selective way. For a trap, the basic structure is an arrangement of four rods (rf-voltages) and two ring electrodes (dc-voltages) for axial confinement, but many variations on this structure are possible, including for example flat electrodes constructed on the surface of a substrate by microfabrication techniques. Ions are confined along the longitudinal axis in the centre of the four rods. Under the action of laser cooling, the ions form a string as shown in **Figure 2**. The distance between neighbouring ions slightly varies along the string because the ions all lie in a parabolic well and also repel one another. The result is that the repulsive forces from the outer ions squeeze the inner ones closer together. Such an ion string provides a register with the quantum information stored in the electronic states of the individual ions.

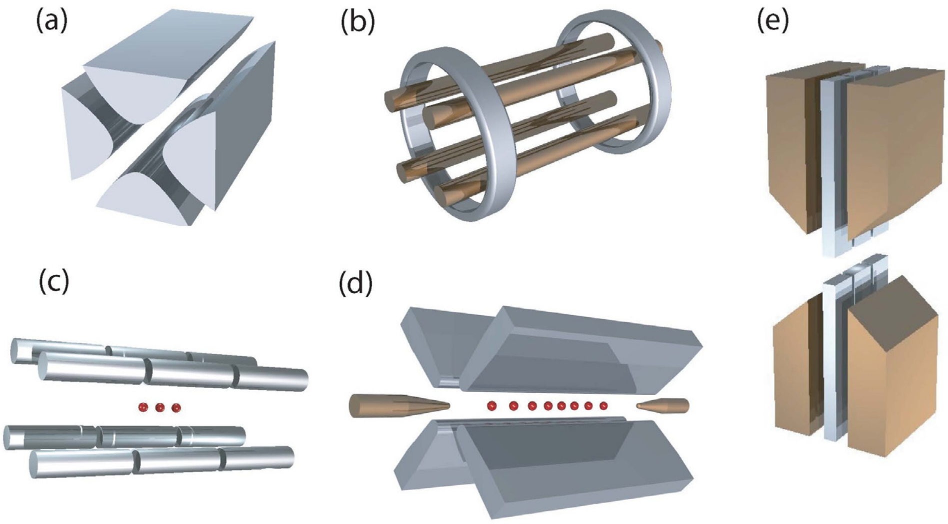

Figure 1

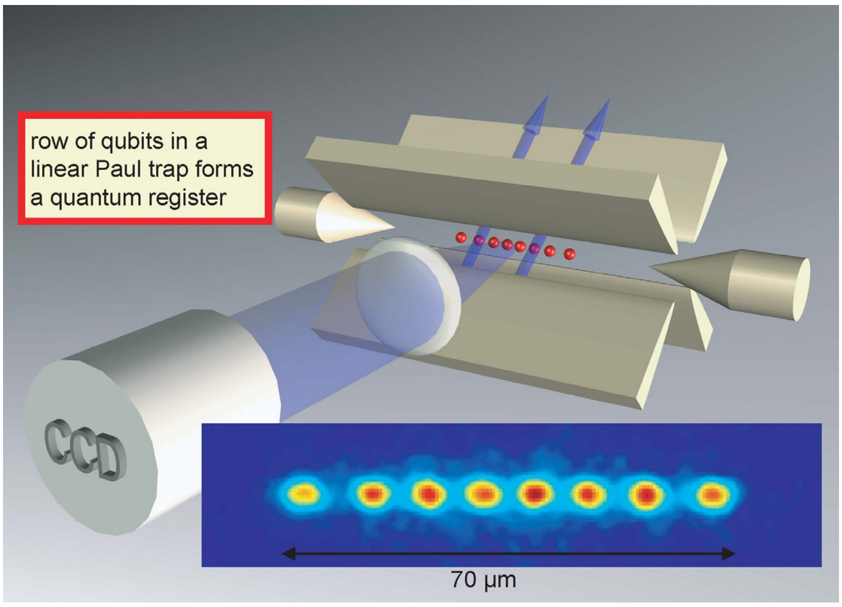

Figure 2

The distance between neighbouring ions can be adjusted by means of the dc voltages. Each ion can be manipulated individually with a focussed laser beam, i.e. single-qubit operations are possible. In addition to single qubit operations, CNOT-gate operations between any two qubits are necessary to build a universal quantum computer. Ignacio Cirac and Peter Zoller (Univ. Innsbruck) proposed a procedure for this in 1995. The important idea was that the ion *motion* provides an additional degree of freedom which can be used to carry and convey information. It is significant that the strong repulsive Coulomb forces imply that the ions are interacting, and indeed they tend to move as a single body. Using methods first developed for laser cooling, Cirac and Zoller showed how to link the internal electronic state of any given ion, i.e. any qubit in the register, to the quantum state of motion of the whole string of ions. The Cirac-Zoller proposal is, in short, to use a sequence of such links to achieve a state change of a target qubit conditional to the state of a controlling qubit.

For this purpose, they suggest that one starts with the quantum register at complete rest, i.e. initially the motion of the string of ions needs to be completely frozen, or in quantum mechanical terms, it is considered to be in the ground state of the corresponding harmonic oscillator. With a laser pulse directed to the controlling qubit, the internal excited state information of that particular qubit (which could be any ion of the quantum register, depending on the algorithm in question) is then mapped onto the centre-of-mass motion, i.e. in case there was a (non-zero) excited state amplitude, that is now written into an excited state amplitude of the motion, whereas the controlling ion's internal state is put in its ground state. Due to the Coulomb interaction this quantum of centre-of-mass motion describes the movement of the entire ion string and is, of course, shared by all ions. Thus, the new quantum state of the register is an entangled state of the internal (electronic) and the external (vibronic or motional) states. With a laser directed subsequently to any other ion (serving as the target ion, depending on the algorithm) it is then possible to manipulate the internal state of that target ion if and only if there is motion in the ion string. Finally, taking the motion out of the string by undoing the first step to the controlling ion, and thus restoring the controlling qubit, makes it possible to realize the truth table of the CNOT-gate operation completely and coherently.

This 1995 proposal launched the interest in ion trap quantum computing, because all the essential ingredients of a computer were shown to be available using experimental techniques which were already either realised or very close to realisation in the laboratory. We will discuss below the subsequent experimental implementations of this and related ideas.

As a carrier for the quantum information, long-lived atomic states are required. Since 1995 a variety of ions has been investigated as candidates for quantum information processing. The qubits can be encoded either by using narrow optical transitions (so-called ‘forbidden’ transitions), or by using radio-frequency transitions between levels split by an applied magnetic field (Zeeman effect) or by the internal hyperfine interaction of the ion. The latter is most promising because it is highly stable, it is used for example in atomic clocks. While the actual technical implementation varies strongly depending on the ions used, the Cirac-Zoller concept can be realized in any type of configuration. Three teams have up till now realised a controlled quantum gate such as CNOT between trapped ions: the Boulder group (D. Wineland et al. at NIST, Boulder, Co., USA), the Innsbruck group (R. Blatt et al. at Univ. Innsbruck, Austria) and the Oxford group (A. Steane and D. Lucas et al. at University of Oxford, England). The Michigan group (C. Monroe et al at University of Michigan, USA) have demonstrated entanglement of an ion and an emitted photon.

During the last few years, in particular the experiments of the Boulder and Innsbruck groups have proved the feasibility of quantum information processing using different approaches. While the Innsbruck experiments follow closely the original Cirac-Zoller proposal and use optical transitions with individual addressing in Ca^+ ions, the Boulder experiments use Be^+ ions where the qubits are encoded in hyperfine states and coherent manipulation is achieved by using further gate proposals implemented by Raman-transitions. In the Boulder experiments individual addressing is achieved by separating off ions from the string using control voltages. Although quite different experimentally, both experiments have implemented quantum information processing quite successfully and very similar conceptually. Below, we will present some examples based on the Innsbruck Ca^+ experiment, however, the Boulder results are very similar and at this time it is by no means obvious which element will actually be best suited for a scaled implementation using trapped ions. **Figure 2** shows the Ca^+ setup schematically and a string of ions representing a quantum register.

Fundamental 2-ion logic gate

A universal quantum information processor requires the implementation of a CNOT-gate operation, i.e. a conditional operation between any two qubits of a quantum register. Following closely the proposal by Cirac and Zoller, two ions were loaded where the first one serves as the control qubit and the second one represents the target qubit. With a laser pulse directed towards ion 1, its excited state amplitude was written to the motion using a sideband pulse, i.e. a laser pulse exciting the internal and the external degrees of freedom of the controlling qubit. Then a series of pulses was applied to the target ion in such a way that the amplitude of the wave function is changed if and only if there was any motion in the two-ion string. Finally, a laser pulse applied to the controlling ion again remaps the motional state to the excited state of the first ion and the string is at rest as it was before the entire operation started. **Figure 3** shows the schematically the sequence of laser pulses and the realized truthtable of the operation.

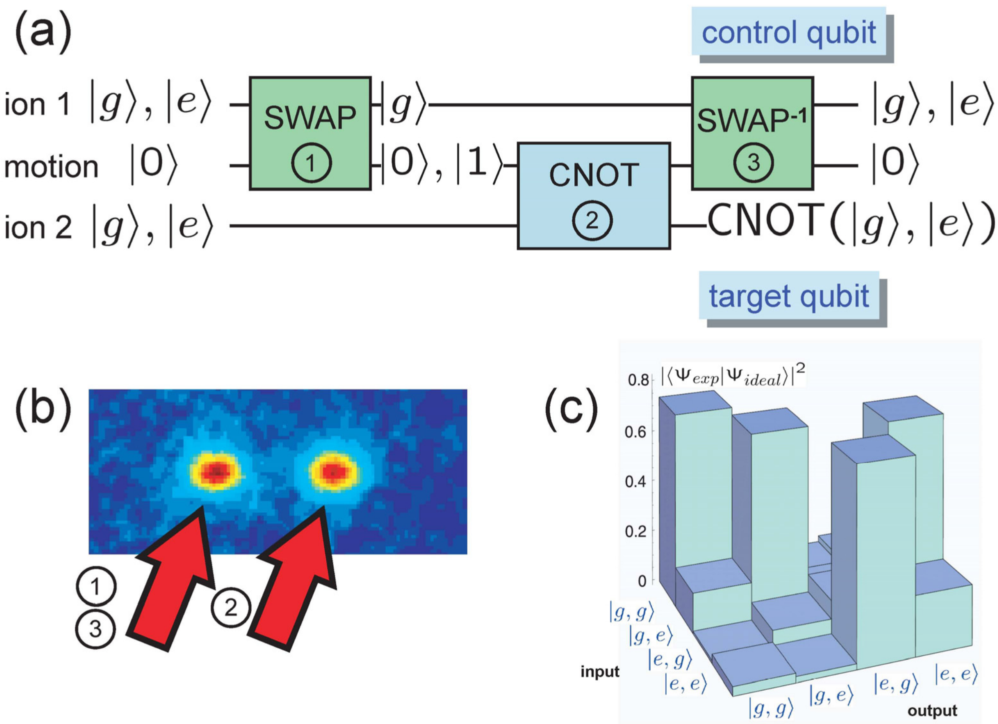

Figure 3

In the experiments in Boulder, a laser pulse illuminated two ions together, in such a way that they experienced an oscillating force which depended on their internal qubit states. The ions experienced a driven oscillation which returned them to their initial motional state after an integer number of periods, while causing the joint qubit state to undergo a net rotation which is equivalent to the CNOT gate.

Algorithms with trapped ions

The simplest quantum algorithms can be demonstrated using just two qubits.

Consider the following, quite classical, problem: Throwing coins usually is a fair game since on the average the outcome has a 50% probability showing either side. On the other hand, if someone tries to cheat and uses a (fake) coin with two equal sides, such bets become extremely unfair. Therefore, prior to betting a measurement is in order to ensure fair play. However, answering the question whether a coin is fair (head on one side, tail on the other) or fake (heads or tails on both sides) requires two examinations, i.e. a look on each side. In a quantum world this is not the case due to the fact that superpositions are completely acceptable. Therefore, if a coin were represented in a quantum way (say a “quantum coin”), the information concerning whether both sides are equal or different is clearly available in the quantum description. Accordingly, an appropriately taken quantum measurement on such a quantum coin would certainly be able to tell the difference since it could check for the superposition in question. Therefore, using a quantum processor and an appropriately written algorithm allows one to obtain the required information (fair or fake) in a *single* step. The associated quantum program is known as the Deutsch-Josza algorithm and it requires for a coin a two-valued function. A quantum advantage is truly present here, because one may imagine a case where evaluating the function is a long and complicated process: the quantum computer only needs to run the evaluating logic once, not twice as would be required by traditional computing methods. For a minimal demonstration, two qubits are needed. Clearly, an implementation of such a rudimentary example does not solve an advanced problem. However, it is able to demonstrate quantum information processing and its advantages compared to classical computing.

The two quantum bits can be provided with a single ion. This is because even with a single ion the internal electronic state can be used to carry one qubit and the external (centre-of-mass) motion is able to carry another qubit.

This quantum algorithm was demonstrated by the Innsbruck group using the internal and external (motional) excitations as qubits. The entire procedure requires several manipulations which are realized with a sequence of laser pulses. The outcome of the procedure is either “0” (encoded in the excited state population of the ion) if the “quantum coin” was false (i.e. two equal sides) or it is “1” if the quantum coin was fair (i.e. two different sides of the coin). The procedure was completely general and proves that quantum information processing is faster, i.e. it requires less steps, than classical computing. The reason for this is of course, that in quantum mechanics a superposition is available whereas classically only two discrete states are available.

Quantum state computation

While the use of superposition states already demonstrates some of the computational power of quantum information processing, for example with the Deutsch-Jozsa algorithm, the ultimate potential of quantum state manipulation becomes visible only by including non-local operations. Superpositions of quantum systems at different positions are outside the realm of classical experience and therefore such 'entangled' states really demonstrate the quantum nature of information processing systems. Non-local operations can be realized in a computational way by making use of the Cirac-Zoller CNOT-gate operation. Consider for example the result of such a computation step if the controlling ion carries a superposition as an input, clearly an operation which cannot be done classically. Producing such states makes it impossible to describe the state in terms of individual independent particles at different locations. In fact, from a mathematical viewpoint it becomes impossible to consider the particles as independent: they are 'inextricably interwoven' and the quantum state of the system is highly non-local, in that it cannot be described as a sum or product of its parts.

Such states are also called EPR states (after Einstein, Podolski and Rosen, who first envisioned such nonlocal quantum states in 1935) and are nowadays usually called Bell states (after John Bell who used them to distinguish between the quantum and classical world). Such states are of a peculiar nature and they cannot be produced by any classical means: they require non-local quantum operations. With an ion trap quantum information processor, however, such Bell states can simply be created at the push of a button. Moreover, these states are then available as a resource for further quantum information processing, unlike the correlated pairs of photons or decaying particles, where such states are only probabilistically available and are usually destroyed when detected.

Adding another ion to the quantum register allows us to process quantum information with three qubits. Aside from the larger computational space this makes it possible for the first time to investigate entanglement for three particles at the push of a button. Tri-partite entangled states have become important for experiments exploring the fundamentals of quantum mechanics, for quantum communication purposes and they provide the first step towards studying multi-particle entanglement.

The maximally entangled state $|\Psi\rangle=1/\sqrt{2}(|ggg\rangle+|eee\rangle$ (i.e. in a measurement one observes either all ions in state $|g\rangle$ or in state $|e\rangle$ and no other combinations) is known as the Greenberger-Horne-Zeilinger (GHZ) state. Its importance is due to the fact that entangling more than two particles leads to a conflict with local realism for non-statistical predictions of quantum mechanics. This is in contrast to experiments with two entangled particles testing Bell's inequalities, which observe conflicts only with statistical predictions. With the three-qubit quantum processor it is now possible for the first time to actually “quantum compute” these states at the push of a button and to investigate, for example, their decoherence and their dynamical behaviour under the influence of a measurement.

Teleportation

In addition to “computing states”, with the availability of even a small quantum information processor, a variety of quantum protocols can now be run and tested. One of the most important and most striking way to convey quantum information is the teleportation protocol by Bennett et al.. Teleportation is concerned with the complete transfer of information from one particle to another.

Specifying a quantum state completely generally requires an infinite amount of information, even for qubits. Moreover, measuring a system would immediately alter its state, therefore transferring quantum information is hard. However, as shown by Bennett et al., entanglement can be used together with classical communication to achieve the complete transfer of quantum information, a process coined teleportation. Teleportation using pairs of photons has been demonstrated, however, the techniques employed are probabilistic and they require post-selection of measured photons. That is, the success of the protocol is rare, perhaps once in 10000 attempts, and these good events are only identified after the fact. In contrast, a fully controlled process such as is possible in trapped ions can succeed on most attempts.

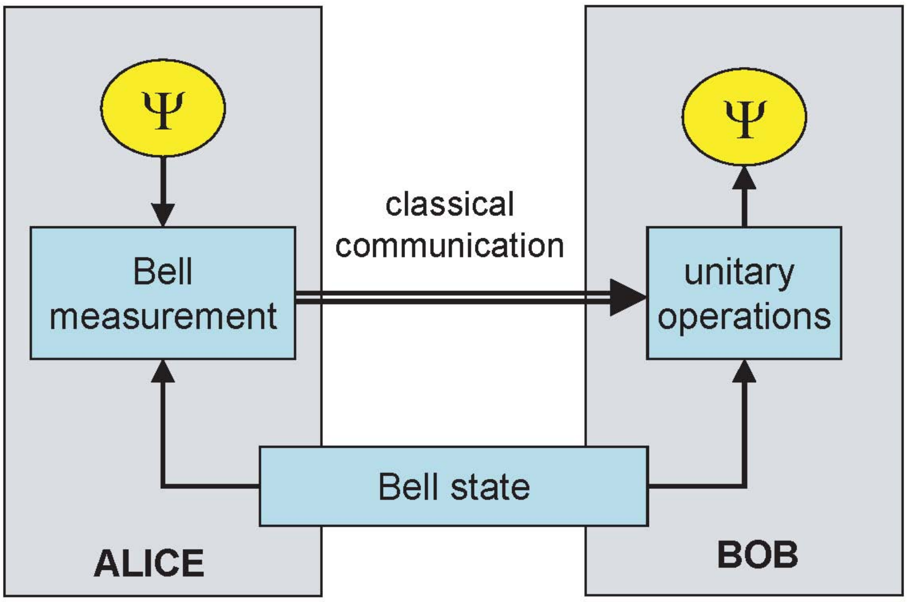

Figure 4

The teleportation protocol works as follows (see **Figure 4**): In order to transfer the quantum information Alice and Bob establish two channels, a classical channel and a quantum channel. On the latter they share a Bell state as a resource required for the protocol. Sender Alice manipulates the unknown input two-qubit state |Ψ> coherently by a CNOT-gate operation and a single qubit rotation. Then Alice measures the respective states of the ions and gets as a result the information on which Bell state she now has. Clearly, during this measurement the quantum information at Alice's location (and thus the original state |Ψ>) is destroyed. The outcome of Alice's measurement is then classically communicated to Bob who subsequently manipulates (using laser pulses) his part of the originally shared Bell state depending on the measured result. In this way, Bob exactly retrieves the initially given state |Ψ> and teleportation is achieved.

Such fully controlled or deterministic teleportation was achieved for the first time in 2004 by the teams at Innsbruck and, independently, Boulder.

Teleportation is highly significant, not only as a communication protocol, but also because it is a central ingredient of fault-tolerant methods. These are required to implement operations and corrections within the registers of a quantum computer, when the computer is stabilised by quantum error correction.

Scalability and error correction

One of the major advantages of the ion trap quantum computer is its scalability. This is achieved, for example, by simply adding another ion to the string confined in the trap. Loading an additional ion to the register does not change the basic frequency of the vibrating string, the lowest frequency of its common motion is always the same. Thus, by adding ions to the register the Cirac-Zoller approach works in exactly the same way as with fewer ions. The drawback, however, is that by adding ions the entire register becomes "heavier", and therefore influencing the ion motion becomes slower, and of course, putting everything into the ground state to begin with becomes more and more difficult. But, more importantly, all entangling excitations become slower since they include the excitation or de-excitation of a vibrational quantum. Eventually, with very many ions such a system becomes sluggish and hard to handle. It will become technically very difficult to operate. Therefore, this may actually limit direct scaling to tens of ions in a single string.

Consequently, it would be much better to keep single or few ions stored in individual sites and then try to interconnect between them. In this way the ions are well confined, isolated from each other and can be individually controlled and accessed. Quantum information processing then requires a quantum channel to convey the quantum information between the different sites. One way to achieve this, is to write the static information contained in the atomic qubits to a photon which then could be transmitted via an optical fibre and finally coupled again to another ion. For this, a full transmission protocol (photonic channel) was proposed by Cirac, Zoller, Kimble and Mabuchi and a corresponding experiment is currently under way in Innsbruck. For this, the single ions are trapped inside an arrangement of two opposing mirrors called an optical cavity which forces the atom to emit or absorb into the cavity axis. With appropriate reflection and transmission properties of the mirrors and an optimized timing, quantum information can be reliably transferred. Although the linking protocol and the physics of the interface provide a beautiful method, the cavity technology requires advanced hardware and thus poses severe experimental problems.

For this reason and in order to build up a larger-scale quantum processor, the Boulder group proposed a "quantum-charged-coupled-device" (QCCD or "ion-chip") which consists of many interconnected segmented ion traps. The idea is to shuttle ions between different locations to carry the quantum information. This would allow communication between sets of ions. In such a structure one could distinguish between a loading area, a cooling and logic region. It is conceivable that shuttling the ions back and forth between different areas of such a segmented trap structure would allow one to interconnect different groups of ions serving as memory and the auxiliary ions which would be required to implement error corrections.. Currently, several groups are pursuing this approach with the goal to build and operate a small ion chip. With this technique, in fact, scaling the ion-trap quantum information processor seems feasible after all.

A major ingredient for further scaling of any quantum information processor is the implementation of error correction. Whereas in classical information processing error correction is very well known and implemented, it was not clear for some time whether error correction would actually work with quantum processes. The reason for this is simply that quantum information cannot be copied like classical information and therefore, classical error correction protocols which usually rely on redundant encoding do not work Fortunately and surprisingly, it is known now for several years that with the use of entangling operations, quantum error correction protocols can actually work and first experiments towards their implementation have already been carried with NMR-based systems and very recently even with trapped ions by the Boulder group.

For a reliable operation of extended quantum information processing it will be indispensable to implement error correction protocols routinely. It appears that the information of a single two-level system needs to be encoded into five or even seven physical qubits and a certain number of quantum gate operations and measurements will be necessary to keep that information stored and "alive" as a logical qubit. Scaling a quantum information processor will then require the coupling of logical qubits and subsequently gate operations between them.

Conclusions

While quantum information processors with trapped ions seems bulky and often balky at present, they offer a viable route towards larger devices. An outline of a design for an ion chip computer allowing a billion operations on 300 logical qubits has been set out by one of us. This is not feasible yet but such a document acts as a guide to the next stage of development. In the nearer term, ion traps will provide us with the playground on which we can try out and invent more algorithms, better quantum processing and even do new physics. Using quantum coherences and their possibly uninterrupted, protected or corrected, dynamical evolution will lead to new schemes for precision measurements and offer new ways of bringing the quantum world to a larger scale.

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QUEST
Quantum entangled states of trapped particles
Start date: 01/05/2000
End date: 31/04/2004

Project web site: http://www.iota.u-psud.fr/~quest/index.html
Contact Person: Philippe Grangier, IOTA, Orsay, France, philippe.grangier@iota.u-psud.fr

CONQUEST
Controlled quantum coherence and entanglement in sets of trapped particles
Start date: 01/03/2004
End date: 28/02/2008
Project web site: http://www.quniverse.sk/conquest/
Contact Person: Vladimir Buzek, Bratislava, Slovakia, buzek@savba.sk

QGATES
Quantum Gates and Elementary Scalable Processors Using Deterministically Addressed Atoms
Start date: 01/01/2003
End date: 31/12/2005
Project web site: http://www.ph.imperial.ac.uk/qgates/
Contact person: Peter Knight, Imperial College of Science, technology and Medecine, p.knight@ic.ac.uk

QUBITS
Quantum Based Information Processing and Transfer with Single Atoms and Photons
Start date: 01/01/2000
End date: 31/12/2002
Project web site: http://www.imperial.ac.uk/physics/qubits/
Contact Person: Peter Knight, Imperial College, London, UK, p.knight@ic.ac.uk

SCALA : FP6 project under negotiation
Scalable Quantum computing with Light and Atoms
Contact person: Philippe Grangier, CNRS, philippe.grangier@iota.u.psud.fr

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