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Preface

Quantum information processing using selectively addressed atoms

This special issue of the *Journal of Modern Optics* draws heavily on the work of a recent European Union Project entitled 'Quantum Gates and Elementary Scalable Processors Using Deterministically Addressed Atoms' (QGATES). A more comprehensive overview article (with a more complete list of references) which accompanies the papers published here will appear in a future issue of the *Journal of Modern Optics*. In that article we will put this work into context with the worldwide state of the art in this important area of Quantum Information Processing (QIP). (See [1] for a readable overview which covers the wider field of QIP in general.)

Broadly speaking it is possible to split experimental approaches to QIP into two categories: those based on the methods of atomic physics and atom-optical interfaces and those based on solid state or condensed matter physics. A more complete overview of the field of quantum information processing as a whole can be gained by studying the EU and US roadmaps for QIP [2, 3]. The QGATES project encompassed both theoretical and experimental work in the general areas of trapped neutral atoms, cavity QED and trapped ions.

Neutral atoms may be trapped using light and the interference between two or more laser beams can be employed to create 1-, 2- and even 3-D arrays of traps into which individual atoms can be loaded (optical lattices). For applications to quantum information processing the vision is of an array with a single atom at each trapping site and the ability to generate entanglement between nearest neighbours in the array. Read-out is then accomplished using the well-known techniques already employed with trapped ions. The ability to load individual atoms into trapping sites is clearly a key requirement and this has been facilitated for individual traps by the discovery of a process dubbed 'collisional blockade' [4] and for optical lattices by the demonstration of the Mott insulator transition [5]. Collisional blockade ensures that tight optical traps favour holding either a single atom or no atom at all. If a second atom attempts to join a single atom already located in the trap both atoms are immediately ejected from the trap. The Mott insulator transition is a collective effect which drives a superfluid state in a Bose-Einstein condensate into a state in which the atoms arrange themselves with a single atom at each lattice site. Another key step is the ability to generate entanglement between atoms held in dipole traps. One way this can be done is

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through 'controlled collisions' between atoms – the positions of the atoms are manipulated by varying the parameters of the laser beams that generate the traps and atoms are brought close to each other for a short period of time and then separated again. During the process a phase is accrued by the atoms and entanglement can be generated. A number of groups are working on these ideas both theoretically and experimentally.

Great strides have been made worldwide by the optical lattices community in the last three years. Within the QGATES consortium the coherent control of individual atoms in 1-D lattices has been demonstrated. The group at the University of Bonn have recently created strings of up to 7 equally spaced atoms under exquisite control [6]. The atom chip community have also made great progress with the integration of a variety of optical components, including high-finesse cavities, onto their chips which has led to recent reports of atom detection at the single particle level in systems [7, 8].

In the early days of cavity QED the goals were to test QED revealing, with ever increasing clarity, the quantum nature of the electromagnetic field and the role of decoherence. For practical reasons many of these experiments were done in the microwave region of the spectrum using Rydberg atoms. The ENS group used these techniques to great effect to perform a range of pioneering experiments including the first generation of three-qubit entanglement using one- and two-qubit gates [9]. *Optical* cavity QED really began to make headway with the development in the early 1990s of extremely high reflectivity mirrors. A new impetus to this work was provided by theoretical work on linear-optical quantum computing. The techniques of optical cavity QED hold great promise for providing experimentalists with the tools necessary to make this approach work. Until recently most cavity QED experiments were performed with essentially free atoms interacting briefly with the cavity mode as they pass through. The recent ability to trap atoms and hold them at a well defined position within the cavity mode looks set to revolutionize this field. Theoretical efforts in this area, particularly in the field of cavity-mediated cooling forces, are now being tested in more recent cavity QED experiments [10]. The interconnectivity of our community is perfectly demonstrated by a pair of European groups working on cavity QED experiments using trapped ions. One of these experiments has already generated a single photon source with some unique properties [11] and collectively these systems hold great promise as testing grounds for cavity mediated entanglement and interconnects in quantum networks.

The blueprint for a quantum computer based on trapped ions was laid out in the seminal paper of Cirac and Zoller [12]. They envisaged a quantum computer whose qubits were the internal states of individual trapped ions. Entanglement could be produced using the collective motion of a chain of ions in a linear rf trap as a 'bus' qubit. This paper stimulated an enormous amount of activity and many elements of their approach have been realised. This has led to the experimental demonstration of quantum gates, algorithms and multi-atom entanglement with as many as eight ions [13]. However, it has been accepted for some time now that the scheme as originally laid out is not scalable to large numbers of qubits.

For large numbers of ions the spectrum of motional frequencies becomes far too congested and keeping calculations isolated to the computational basis becomes progressively more difficult. The issue of scalability in this system was carefully addressed in a paper by Kielpinski *et al.* [14]. In this paper they envisage a quantum computer based on trapped ions held in multiple miniature rf ion traps. Two ions may be loaded into a single trap where gate operations may be performed. Individual ions are then shuttled into different miniature traps for storage. These ions may be retrieved at a later time to continue with the calculation. In the last few years a number of key parts of this approach have been demonstrated.

Theoretical Quantum Information Processing is now a major field attracting theorists from a remarkably wide range of backgrounds. In this context, theorists with a background in Quantum Optics continue to play a key role with regard to atomic and optical realisations of QIP and beyond: whilst they have, in many cases, contributed to the more abstract areas of the subject, they have the necessary background to be able to make direct contact with experimentalists and have thus pioneered a range of techniques that have fed directly into the experimental programmes. To take a single example the subject of decoherence-free subspaces has gone from a theoretical idea to an experimental tool in a few short years. Ideas concerning other uses for entanglement have come forward, in part because of the close contact between quantum optics based theorists and experimentalists, many of whom have their roots in national standards laboratories. Entanglement has been shown to be a means of producing improved frequency stability in atomic clocks and standards laboratories around the world are now taking these ideas very seriously.

For experimental groups that have generated entanglement, being able to demonstrate unambiguously what has been achieved turns out to be a thorny problem. A great deal of work on 'quantum process reconstruction' has been done in recent years. Process reconstruction using finite ensembles of identically prepared test states can sometimes fail, i.e. the estimated map does not correspond to a physical transformation. A range of strategies for dealing with situations like this have been suggested and some of these have already been adopted in the latest experiments on multi-particle entanglement.

In summary, a much clearer picture is now emerging regarding the various atomic and optical approaches. These approaches have gone from strength to strength and repeatedly research across the full array of atomic and optical approaches has shown its worth. We would like to take this opportunity to stress the interconnectivity of our community. Visiting laboratories or attending conferences one is struck by the mobility of workers in our field. What may appear from the outside to be dividing lines (e.g. between people working on trapped ions and those working with neutral atoms) are nothing of the sort. It is clear that workers in this field share so much in common that they will, in time, coalesce around the most favourable approaches to QIP with minimum need for external intervention.

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