1. Introduction

Quantum Information (QI) uses the laws of quantum mechanics for the efficient processing of certain computational tasks that are intractable by classical physics. In the implementation of QI processing, both bottom up and top-down approaches are being currently explored. Although no fundamental physical obstacles seem to stand in the way of a scalable quantum computer, no single technology currently satisfies all the so-called DiVincenzo criteria necessary for the realisation of the basic building blocks of a quantum computer.

The trend toward successful implementations of QI Technologies imposes several crucial challenges, which call for smart strategies that avoid very large complexities. For example within the effort to miniaturize quantum information processors and to scale them beyond the present small-scale devices, a main difficulty is that single-site addressability and scaling may be hard to reconcile. Quantum Communication (also among parts of a processor) demands the realization of functional networks. Key goals here are the achievement of quantum control, of parallel quantum processing, of broadband quantum communication. The variety of the Quantum Information Processing and Communication (QIPC) targets requires an interdisciplinary effort.

Within the different schemes devised so far, the combined use of light and matter plays a decisive role in addressing the above issues. Light should play the main role as the carrier of information over large distances and between logic elements within a processor. On the other hand, matter degrees of freedom experiencing weak decoherence process should be the tools were information can be stored and processed. In this scheme the light-matter interface plays a crucial role in the development of quantum information tools.

Many systems have been promoted for the implementation of quantum computing, as outlined in the EU roadmap for quantum computing [1,2]. In this context, atomic/molecular optical (AMO) technologies in general are amongst the most promising. For instance, quantum computing with trapped ions achieves a precise control of the individual qubits...
and targets to realise a scalable system. Arrays of qubits such as neutral atoms in an optical lattice, on the other hand, offer the possibility of a massive parallelism, with many pairs of qubits interacting at once. Photon flying qubits have been widely tested for quantum communication between atomic qubits. While there is a clear need to further refine current emerging AMO technologies, there is also a distinct need for radically new ideas to realise the next-generation of AMO-based technology for quantum computing and quantum simulations.

The entanglement, defined as the quintessential of the quantum mechanics, has been identified since a long time as an essential resource for QI Technologies. In fact all present demonstrations of these technologies were based on the entanglement between a limited number of objects. However, the standard approach of quantum photon/atom optics that deals with simple systems, involving a limited number of photons or particles, turns out to be inadequate to tackle the problems posed by a practical implementation of quantum technologies. Here the imperative is towards faster processing of ever increasing quantities of data, which creates an arrow in the direction of multi-dimensional, multi-modal and multi-particle quantum entanglement. Some progress was recent achieved by the combination of different photon–quantum matter approaches in the path towards the solution of these problems. Even with the outstanding recent progress, major research challenges will be faced within the effort of expanding to a larger number of entangled qubits, that effort requiring both basic research and new technologies.

In recent years the links and interconnections between the physics of condensed matter and AMO physics have become solid and well established. One of the most challenging aspects of modern quantum physics lies in the understanding of interacting many-body systems. These systems have shown striking macroscopic quantum effects in solid-state physics such as superconductivity or the quantum Hall effect. On the practical side, the development of nanotechnologies requires a more refined knowledge of the behaviour of interacting quantum many-body systems. Even if over the last decades significant progress has been made towards understanding these systems, our knowledge still remains limited. Interacting quantum systems remain difficult to analyse and to simulate due to their strongly correlated nature, which means that the particles cannot be treated independently, but interactions between them dominate their quantum states and phases as well as their dynamics. Paradigmatic examples of such systems can be realised by loading ultracold atomic Bose or Fermi gases or their mixtures into optical lattices [3,4]. In these systems the values of practically all the relevant parameters can be controlled both statically and dynamically in experiments. Such a degree of control, in particular regarding the range and strength of interactions, is impossible to achieve in solid-state systems. Take, for example, a high-temperature superconductor, containing planes of copper and oxygen ions arranged in a square pattern. This system could be modelled through a two-dimensional Fermi-Hubbard model, but nobody can prove that the model produces superconductivity. The Fermi-Hubbard model, which can be realised by loading ultracold atoms into a two-dimensional optical lattice, would simulate the copper-and-oxygen planes. Powerful analogue quantum simulators, where a Hamiltonian for another system is directly engineered, and the time evolution of the system under this Hamiltonian observed, may be realized using AMO tools.

The main focus of the FET11 Session presented here was to outline future AMO scenarios aimed to address the problems in play, and to outline the large progress achieved so far in their solution. In addition, because the next lap in the QIPC technologies will reply on the heavy hybridization of the quantum matter objects mentioned above, the Session target was to open interactive perspectives for future developments within interdisciplinary efforts. The present text concentrates on three different themes representing main directions of the AMO effort in quantum entanglement and quantum simulation, and covers a variety of experimental and theoretical features. Sec. II outlines the status of the art in the use of trapped ions for quantum computation and quantum simulation. Sec. III outlines recent experiments of quantum simulations with neutral atoms. Sec. IV outlines the status of the art in the realization of quantum interfaces and quantum memories. A conclusion completes the present work.

2. Open-system quantum simulations

Every quantum system is inevitably coupled to its surrounding environment. Tremendous efforts have then been invested in isolating these systems from their environment in order to achieve a precise control of the dynamics of several qubits. These efforts have lead to the realization of high-fidelity quantum gates and the implementation of small-scale quantum computing and communication devices, as well as the measurement-based probabilistic preparation of entangled states in atomic, photonic, NMR and solid-state systems. In particular, successful demonstrations of quantum simulators, which allow one to mimic and study the dynamics of complex quantum systems, have been reported. Using
trapped ions, such simulations include Ising spins exhibiting frustration effects, the Dirac equation and Klein paradox as well as quantum walks.

In contrast to such closed systems, the control of the more general dynamics of open systems amounts to engineering both the coherent time evolution of the system as well as its coupling to the environment. This ability to design dissipation is a useful resource, as in the context of the preparation and preservation of a desired entangled state from an arbitrary initial state as well as in the closely related fields of dissipative quantum computation and quantum memories. Recently, using a quantum computing architecture with trapped ions, an experiment demonstrated a toolbox of coherent and dissipative multi-qubit manipulations to control the dynamics of open systems [5]. These toolbox enabled the dissipative preparation of entangled states, coherent multi-body interactions and the quantum nondemolition measurement of multi-qubit operators. These experiments open the door to the realization of open-system simulation of spin models, including lattice gauge theories, realized with Rydberg atoms in optical lattices [6], as well as in diverse fields including condensed-matter physics [7] and quantum chemistry, possibly in modelling quantum effects in biology, and in quantum computation driven by dissipation. These open-system simulations can also be readily adapted to other physical platforms, ranging from AMO systems to solid-state devices.

3. Quantum simulation with neutral atoms

Current methods of quantum computation/simulation based on neutral atoms can be roughly divided into two classes: The top-down approach begins with the preparation of a large ensemble of ultracold atoms, e.g. a Bose-Einstein condensate. The condensate is then transferred to an optical lattice, where within the Mott insulator phase in each lattice site a single atom acts as a qu-bit. In contrast, the bottom-up approach seeks to directly prepare individual atoms in an optical lattice and construct many body systems step by step. In both cases the important target is the creation, the investigation and the application of many body quantum correlations [4].

Tools for preparing, trapping, selectively addressing and transporting individual atoms, for storing information in and retrieving information from the atomic qubits have been already been well established [8]. A remarkable recent achievement is the single site optical detection of atoms in optical lattices [9–11] by a combination of high resolution microscope objectives and image processing schemes, which lends great potential to the merger of the bottom-up and top-down approaches mentioned above. Application of this methodological breakthrough has resulted in the direct observation of discrete quantum walks [12] with cold atoms. The quantum walk, the quantum analog of the well-known random walk, has properties markedly different from the classical counterpart and might lead to extensive applications in quantum information science. The experiment implemented a quantum walk in one dimension with single neutral atoms by deterministically delocalizing them over the sites of a one-dimensional spin-dependent optical lattice. This experiment as well as the single-site observation of the Mott insulator quantum-phase transition in refs. [10,11] evidences that the route towards the implementation of quantum simulators for many body quantum systems with sensitivity to all constituents seems be open.

4. Quantum interfaces and quantum memories: present and future

Quantum interfaces capable of transferring quantum states and generating entanglement between electro-magnetic fields and matter play a crucial role in the development of QI science and technology. Electro-magnetic fields ranging from optical to microwave to radio-frequency domains are natural resources for quantum control and quantum information carrier, whereas atomic and solid state devices are natural platforms for processing information and for measurement and sensing fields and forces.

In the past few years quantum interfaces between atomic ensembles and optical photons have been extensively developed by several European collaborations. Quantum state transfer from light to matter, including quantum memory for multi-dimensional quantum states [13] and quantum teleportation, entanglement of massive objects, measurements and sensing at and beyond quantum limits have been demonstrated [14]. Measurements of fields [15] and of time beyond the standard quantum limits of precision set by the quantum fluctuations of particles have been recently reported.

Near future goals towards developing practical quantum interfaces include i) extending the benchmark achievements in interfacing atomic ensembles, solid state quantum memories and light onto interfacing multiple integrated devices; ii) developing a new frontier - hybrid quantum interfaces, which will bridge atomic spin ensembles, optical photons, electronic circuits, and solid state devices. Such ambitious, but realistic, goals include the development of fiber-coupled
integrated quantum atomic sensors and solid state memories for light, the laser cooling and readout of electronic circuits and nuclear spins in solids for ultrasensitive quantum-limited magnetic field measurements and nuclear magnetic resonance. An additional goal is the quantum teleportation of states across the full range of carriers from atoms and solid state memories to light, to radio-frequency electronics, and to nuclear spins.

5. Conclusion

This FET11 Session has presented the state-of-the-art in the applications of AMO tools to the areas of quantum information and quantum communication. AMO qubits and quantum memories are based on ions or neutral atoms, and photon flying qubits are the key elements for the quantum interfaces. These systems have provided the experimental tools used to realize qubit gate operations and quantum simulators. The realization and application of many body quantum systems made up from trapped neutral atoms or ions is an active and challenging topic of the current research in AMO physics.

Novel prospective research targets are represented by the request to expand the present quantum control level to a larger number of entangled qubits. A specific grand challenge is the development of hybrid systems, based on the combination of ultracold atoms/ions and solid-state nanodevices, with photons representing the quantum interface elements. This merging of the strong quantum control features of two research areas will lead to major advances in the realization of large scale quantum information/communication devices and to implement further processes in QI science.

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