QUROPE Research Agenda

Quantum Information Foundations and Technologies

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Motivation

The novel combination of quantum physics with information science has opened the way to exploring the use of quantum degrees of freedom to perform calculations and tasks of a complexity unattainable by systems behaving classically. Significant research efforts have established, over the last ten years, the most secure methods of communication as well as the basic building blocks of quantum computation on a range of hardware platforms.

This is to a significant extent an outcome of previous European Commission initiatives on Quantum Information Processing and Communication (QIPC) in the two past Framework Programmes, which have set quite ambitious objectives for a first exploratory stage. The quantum information community has delivered the expected results with a series of very successful projects, putting Europe at the forefront of the international competition.

As a consequence, it is now appropriate to develop a new conceptual platform for a family of potentially disruptive technologies, adding a new stage and new perspectives to the already staggering impact of conventional ITs.

The proposed strategic area on Quantum Information Foundations and Technologies (QIFT) will focus on these technologies with the purpose of significantly advancing their scope and breadth, while at the same time speeding up the process of bringing them from the lab to the real world. It will ensure a constant progress in the whole quantum information processing area through the integration of the scientific base built up to now, in order to conceive theoretically and develop experimentally novel and powerful technological applications of quantum coherence and entanglement.

Challenges

The latest developments of the field are pointing to several future fundamental challenges that need to be thoroughly addressed:

- **Quantum simulators.** The approach to scalability characterizing special purpose quantum computers - quantum simulators - will be the first one in delivering a device capable to operate on quantum many-particle systems, and to extract useful numbers out of them [1]. The challenge in this case will be to improve the simulation capabilities of such devices, moving from condensed-matter theoretical models towards the simulation of materials and/or chemical compounds.

- **Hybrid systems.** Currently we are witnessing the birth of a new quantum paradigm that unifies atomic, molecular, optical (AMO) and condensed matter physics. It combines the advantages of different specific realizations of quantum bit systems to realize essential building blocks such as memories, repeaters, and interconnects [2]. There is therefore a clear need to bring hybrid technologies past the proof-of-principle stage, by bridging AMO systems with condensed matter systems in order to
  - Develop devices interconnecting different qubit 'memories' and quantum information carriers, in order to develop quantum networks composed of many nodes and channels;
  - Develop a working quantum repeater for bringing quantum communications to a global scale (the "quantum internet" [3]).
- **Coherent operations with multiple qubits.** High qubits densities entail a new set of problems with respect to those encountered in single and two-qubit operations (e.g., a more complex and noisier environment for carrying out quantum operations, which includes cross-talk from nearby qubits and their control, coupling, and readout systems). These problems (which can be specific to a particular qubit implementation or common to several of them) have to be identified, explored, and solved, possibly implementing demonstration algorithms [4].
- **Quantum technologies.** Novel practical devices exploiting entanglement as a resource [5], such as quantum sensing, imaging, measurement, and communication technologies, need to be investigated, in view of expanding their field of applicability towards new unprecedented directions (see examples in the next section).
- **Improvement and optimization of existing platforms.** A major goal of the field will be finally to improve and push the limits of the existing platforms and technologies [6]. The most promising systems need to be identified and reliable fault-tolerant gates and architectures proving their scalability to tens/hundreds of qubits developed.

The challenges outlined above are to be considered both experimental and theoretical: Theory, besides finding and investigating fundamentally new techniques (e.g., quantum feedback and quantum optimal control) algorithms and protocols for computing and communicating, and opening new multidisciplinary research directions (such as the recent studies on the potential exploitation of quantum effects in biological systems), must in fact guide and support experimental developments, covering the whole range of physical systems and technologies.

Impact

The results obtained within the field of Quantum Information Foundations and Technologies are constantly changing our way to look at physical processes, continuously pushing forward the boundaries of our knowledge; while this, per se, is of paramount importance, there will be significant technological achievements that one can realistically expect to positively impact the Information and Communication society in the short- to mid-term:

- **Quantum communication technologies** embedded in the current telecom fiber infrastructure will allow transforming present-day point-to-point (classical) communication networks into absolutely secure quantum ones, without the need of changing the existing architecture;
- **Entanglement assisted sensors and metrology** will have a strong impact on various fields, e.g. by enabling sub-micron imaging, sub-shot noise measurements and single-spin sensing, or the development of ultra-precise clocks;
- **Quantum simulators** will help us in the understanding and designing of novel artificial quantum materials with tailored properties and enable a better comprehension of the dynamic of complex systems and phenomena;
- **Quantum computers** will open up a viable route to provide the next generation of scalable processors beyond micro and nano electronics, thus avoiding the known roadblocks on the

route towards higher and more energy efficient computing power;
- **Hybrid systems** implementing quantum interconnects between quantum processors and quantum links will provide the technology that finally lead to the quantum repeater. Hence they will extend the distance of local quantum links to a truly global scale paving the way towards the advent of the quantum internet.

In the long run there are strong reasons to believe that these efforts will result in a new wealth of quantum technologies capable of unprecedented tasks being thought, developed and finally commercialized for the benefit and welfare of the whole European society. Entanglement assisted sensors and metrology are expected to positively affect various fields ranging from biomedical imaging for early detection and diagnostic, to the exploration of environmental hazards, to the search for mineral resources. The accurate description of chemical compounds and reactions made possible by quantum simulators could hopefully lead to the design, testing and commercialization of fundamentally new drugs, and allow the design of new energy efficient materials, accelerating the transition towards renewable energy sources. And finally, quantum computers are expected to boost our understanding of the dynamics of complex problems such as, climate models and protein folding, eventually leading to fundamental advances in this and correlated fields.

Thus, the potential long-term impact of Quantum Information Foundations and Technologies on the strategic priorities of the European Commission (coping with ageing society, ensuring sustainable energy supply and maintaining a clean environment) can be hardly overestimated.

Disciplines involved

The QIFT field is strongly multidisciplinary by nature, since the consolidation of already-conceived technological applications and the development of yet unthought-of ones, requires exposing physicists, mathematicians, engineers, computer and material scientists to all aspects of quantum mechanics. It is quite remarkable that along the past ten years a common “qubits” language has emerged, revealing the deep unity of quantum concepts, ranging from quantum chemistry to computer science, through physics and engineering based on quantum optics, condensed matter, and superconducting devices.

Level of maturity

As the nature of the research activities will be quite different depending on the technological maturity of the subfield, a two-tier approach might be best suited.

- The challenges involving still significant activities at the level of foundational research shall be tackled in an open approach allowing for several competing strands of research (e.g., towards a usable quantum simulator). These activities are mainly driven by scientists from universities and research institutes. While interest of industry will be solicited as early as possible, active involvement is expected to happen later in the process of R&D generation.
- For other aspects of the area which are closer to a technology deployable in real world application (e.g., quantum key distribution based on quantum repeaters for distances up to 600 km) a focused effort will be made to facilitate the transition from scientific results to technologies that can be commercialized. For these aspects scientists will actively seek the involvement of industry in order to make the advent of quantum technologies happen.

Stackeholders

While commercial exploitation has already begun for quantum communications (e.g., quantum key distribution systems), other quantum technologies are currently at the pre-application stage. The latter however possess a novelty and a richness that suggests an equal or even greater impact than the one of the transistor and the laser. Thus, in addition to Universities and Government labs, there is an initial industrial support, in particular by the companies listed below, that is expected to significantly grow in the short- to mid-term.

An up-to-date list of industrial stakeholders is available here.

References

[1] I. Bloch, J. Dalibard and W. Zwerger, Many-Body Physics with Ultracold Gases, Rev. Mod. Phys. 80, 885 (2008)
[2] M. Wallquist, K. Hammerer, P. Rabl, M. Lukin and P. Zoller, Hybrid quantum devices and quantum engineering, Phys. Scripta (to appear)
[3] H. J. Kimble, The Quantum Internet, Nature 453, 1023 (2008)
[4] For an US initiative on similar topics see http://www.iarpa.gov/solicitations_mqco.html
[5] See Quantum Information Processing and Communication: Strategic report on current status, visions and goals for research in Europe
[6] P. Zoller et al., Quantum Information Processing and Communication, Eur. Phys. J. D36, 203 (2005)