QSTAR
Quantum Science and Technology in ARcetri

Joint Research Centre MPQ-UNIFI-IIT-LENS
Activity Report 2013

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Introduction

Quantum Technology is a highly interdisciplinary area of research that brings together the most diverse fields of physics, information technology and chemistry. Over the last few decades, this technology has undergone an extremely broad and rapid development at global scale, in terms of both the conceptual scope of the methodology – which is yielding ever greater insights into quantum mechanics, in other words the physical rules that govern the Universe we live in – and of the remarkable technological spin-offs in the fields of atomic physics, engineering, chemistry, biology and medicine.

The dream of succeeding in developing authentic “quantum machines” which can fully exploit the properties of both macroscopic and microscopic quantum states is the bedrock of what is called the “second quantum revolution” and promises to have an even greater impact on human life than the first, which led to the invention of the transistor, the PC and the laser.

This is a completely new way of transforming and transmitting information, leading directly to the technology of tomorrow, when the performance of industrial applications will be defined by the limitations of quantum phenomena.

Thanks to the vision of Massimo Inguscio and Theodor Hänsch, the University of Florence, the Max Planck Gesellschaft (MPG) and the European Laboratory for Nonlinear Spectroscopy (LENS) where brought together on 7 April 2010 by a memorandum of intent, valid for five years and tacitly renewable for another five, to foster cooperation between the three institutions within the area of Quantum Science and Technology.

On 21 November 2012 an operational agreement was then reached between the MPQ Max Planck Institute for Quantum Optics (part of the MPG), the Italian Institute of Technology, the University of Florence and LENS. The National Institute of Optics (INO) of the Italian National Research Council, which has its premises on the hill of Arcetri, immediately joined forces with the Centre.

The scientific objective of the Centre is the exploration of the frontiers of quantum science, combining the methods and strategies developed in atomic, molecular and optical physics and in nanoscience. The participating institutes complement each other: for example the IIT brings with it significant experience in the sphere of biophysics, which dovetails with the expertise acquired over the years by the LENS, and the spearheading proposals of the Nobel prize-winner Theodor Hänsch, who is one of the founders of the Centre.

QSTAR benefits from the unique environment offered by the location on the hill of Arcetri in Firenze. This special location has a great potential in attracting world leaders. We are located in the place, where modern science started with Galileo and where during the last century scientists like Enrico Fermi and Bruno Rossi actively worked.

Mission

The aim of QSTAR is the exploration of the frontiers of quantum science, by combining methods and strategies developed in different areas of physics, including AMO physics and nano-sciences. We envision a parallel investigation of fundamental phenomena in different physical systems, including photons, atoms and artificial materials like metamaterials photonic, photonic crystals, semiconductor heterostructures and atomic lattice gases.
The coordinated, interdisciplinary attack of challenging frontier themes of quantum science will allow to overcome present roadblocks in the various subfields and to rapidly develop a novel understanding of fundamental quantum phenomena and their possible exploitation to realize new quantum devices. They will become increasingly important in the next 10-20 years, as the ability to perform control of quantum properties will continue to evolve.

Research

QSTAR main research effort is currently a theoretical one, but the close proximity to LENS and INO has allowed to jump-start some experimental activities.

Theory

Under the direction of Theory Coordinator Augusto Smerzi already eight theoretical lines have begun to flourish.

Quantum Interferometry

Luca Pezzé, Michele De Regis, Marco Gabbrielli, Safoura Mirkhalaf, Sophie Pelisson, <u>Augusto Smerzi</u>
Entanglement, the most puzzling feature of quantum theory, is at the heart of the speedup promised by quantum technologies. Quantum interferometry exploits the engineering of particle-entangled states to estimate time, forces, accelerations and lengths with a sensitivity exceeding — in principle by several orders of magnitude — the bound of classical interferometers. Our research focuses on the deep implications of entanglement and its realistic implementation for precision measurements with light and matter.

Quantum Dynamics and Thermodynamics in Optical Lattices

Pierfrancesco Buonsante, Roberto Franzosi, Marco Moratti, Luca Pezzé, <u>Augusto Smerzi</u>
This line of research focuses on the dynamic and thermodynamic properties of strongly correlated quantum lattice systems. We aim at linking the dynamic properties to the thermodynamic quantum phases characterizing the system, in a variety of experimentally

relevant conditions. Also, we are interested in the quest for possible dynamical generalizations of such thermodynamic phases, as well as to the dynamic production of topological defects as the system is driven through the boundaries between phases of either kind. Our goals include a systematic study of thermalization of dynamic states, also focuing on the pathways to negative-temperature states.

Josephson Effects with Ultracold Atoms in Double-Wells

Tommaso Macrì, Augusto Smerzi

The Josephson effect is a well known macroscopic quantum phenomenon which has been discovered in the context of superconductivity and has prompted multiple technological applications. In ultracold atomic setups novel Josephson effects were predicted 15 years ago and recently observed in bosonic systems trapped in double well geometries. The recent realization and control of interacting ultracold fermionic systems constitutes a new platform where the effects of quantum coherence can be tested on a wide range of interaction strengths, along the so-called BCS-BEC crossover. Our research focus on the theoretical investigation of the Josephson effects with ultracold Bose and strongly interacting Fermi gases in connection with experiments that are conducted at LENS and MPQ.

Nanoscale Optics and Spectroscopy

Diego Martin Cano, Mario Agio

We investigate the properties of light beyond the diffraction limit and study its interaction with nanoscale matter. We are particularly interested in interrogating single quantum systems and in exploring quantum phenomena that occur at the subwavelength scale. Although we primarily address fundamental questions related to light, matter and their interaction, our efforts may also make their way into practical devices, such as a new class of light-sources, sensors and functional materials.

Many body systems, decoherence, quantum control, quantum information

Karim Murr, Giulia Gualdi

The quest for a deeper understanding of decoherence is of both practical and of fundamental relevance. This phenomenon lies at the heart of the loss of quantum behaviour and the emergence of classicality and therefore represents the major obstacle towards the implementation of quantum technologies and of quantum information processing in particular. The focus of our research is the investigation of decoherence mechanisms arising in complex many body systems and the ensuing development of strategies to control the dynamics of a quantum system undergoing dissipation.

Quantum Emitters and Cavity QED

Giulia Gualdi, Karim Murr

The modern physics of quantum emitters illuminates the most fundamental aspects of coherence and decoherence in quantum physics, where very rich theoretical models guide experiments to reveal intriguing aspects of reversible and dissipative quantum dynamics. It is remarkable that many avenues share the same concepts, whereas they explore different regimes with essentially different techniques. For instance, the recent years have brought the demonstration that the dynamics of single atoms strongly coupled to a quantized field can be well studied in a solid-state architecture, where now artificial atoms made of Josephson junctions are coupled to on-chip superconducting resonators. As a rule, quantum bits can consist of atoms, ions, electron spins in quantum dots, N-V centres in diamond, or any elementary system to be conceived in the future that couples to electromagnetic fields in the optical or microwave regime. In years to come, the importance of quantum emitters will grow as researchers build on a rich infrastructure to tackle open questions in micro- and mesoscopic physics. For instance, after a work started at the MPQ on the squeezing of single atoms coupled to an optical cavity, we studied the squeezing generated by a single atom coupled to a nanostructure in collaboration with the nano-optics group of Dr Mario Agio at Q*. Other research is concerned with the analysis of the mechanism of Rydberg Blockade under the strong coupling between 2 (and more) atoms and single photons in a cavity quantum electrodynamics setup.

Search for an Extension of Quantum Mechanics

Giulia Gualdi, <u>Karim Murr</u>

What we mean by extension of quantum mechanics is a new theory, not an interpretation of it. The current status of experimental and theoretical physics is that quantum mechanics "works", and as Steven Weinberg (Nobel Prize 1979) puts it, working in such a field of research is such that "very often you do not know what is the right problem until you are close to solving it." We are working on changing the algebraic structure of the quantum theory prior to changing the dynamics. The first route is to enlarge the notion of a group in the sense of Évariste Galois. Instead of working with binary operations, which enter a Galois group and derivatives such as rings and fields etc, one can construct n-ary algebraic structures to represent complex quantum correlations. Another research line is to view the wavefunction, and more generally a given complex number as composed of more abstract numbers. These numbers cannot be complex numbers, otherwise we end up in a tautological argument. Due to physical constraints, we found that these numbers will most likely belong to a new algebra, different from hypercomplex numbers for instance.

Quantum Transport in Noisy Systems and Biological Light-Harvesting Nanostructures

<u>Filippo Caruso</u>

In this research activity we investigate theoretically and experimentally the role of quantum effects in biology, especially in natural photosynthesis, by studying theoretical models of energy transport in quantum complex networks and testing them by means of designed experiments based on quantum optics, atomic physics, and also ultra-fast laser spectroscopy on natural and artificial light-harvesting complexes. This will allow us to have a deeper understanding of how Nature exploits quantum coherence and environmental noise to get very efficient and robust energy transfer, and to pave the way for the realization of a new generation of more powerful solar energy technologies based on quantum phenomena.

Philosophy of Science and Aesthetics

Natalia Baeza

The central topic of this research line is the relationship that science and art have to truth, and therefore to knowledge. Up to the late 18th century, philosophical knowledge is generally taken to be more encompassing than both natural science and aesthetic experience, but all are seen as harmonious. In the 19th and 20th centuries, many important thinkers begin to argue that philosophy has to follow either the model of modern science or that of aesthetic experience, and that the two models are opposed. Continental European philosophers have tended to argue that art has a privileged relation to truth, while the scientific model of reason is only a matter of technique, whose primacy actually occludes the possibility of truth. Philosophers associated with the Anglo-American tradition, on the other hand, have usually argued that science is the paradigm of knowledge and art has only emotive value. Our aim is to clarify the central issue at the heart of this dispute. We propose that it lies in two different conceptions of truth: a notion of the correspondence between mind and reality (adequatio rei et intellectus) for the anglo-American tradition, and a dynamic model of the revelation of Being as disclosure (Unverborgenheit) for the continental tradition. By tracing the debate over the value of science and art back to its roots in divergent conceptions of truth, we aim to offer a diagnosis of the antagonism between science and aesthetics that characterizes contemporary thought, and to suggest new ways to think of the relation between art, science, and knowledge.

Experiments

Experimental efforts require, by their very nature, an infrastucture that cannot be realized overnight. The initial efforts of QSTAR have been realized in LENS laboratories coordinated by the Experimental Coordinator Francesco Cataliotti. New directions connected to bio-physics and nano-optics are soon to be added once the recruitment of personnel by IIT will be completed.

Atom Chip and Quantum Interfaces

Filippo Caruso, Augusto Smerzi, Francesco S. Cataliotti

One of the primary tools for handling ultra-cold atoms is the magnetic trap, which is needed both during cooling than during the experiment. In addition to macroscopic coils, it can be also possible to produce the necessary magnetic fields using the current circulating in a suitable gold and silicon chip a few inches from the side: an AtomChip. The benefits are higher frequencies of the trap at least an order of magnitude, lower evaporative time and a less stringent vacuum.

Currently we study the behavior of the cloud of cold atoms, the goal is to make the best use of AtomChips in full quantum simulation experiments and in technological applications as quantum memories.

Organic Molecules for Quantum Optics

Francesco S. Cataliotti, Costanza Toninelli

The focus of our activity on molecules for quantum optics is the combination of advanced photonic materials with organic molecules, with the idea of developing novel light-matter interfaces for quantum technologies. Single-molecule-based photon sources can be selectively coupled to the evanescent electromagnetic field of plasmonic excitations, graphene, or complex dielectric media. The system hence represents a valuable testbed for applications ranging from microscale opto-electronics, to fluorescence-based sensing and solid-state protocols for quantum communication. The group is also working on the coupling of single molecule to the Atom-Chip condensate.

Events

A cooperative effort by its very definition, QSTAR has immediately been very active to collaborate in the organization of conferences and events, taking full advantage of the attractiveness of Firenze and the hill of Arcetri. Two symposia, two workshops and the 2013 Quantum Information Processing and Communication Conference, together with numerous seminars in just 15 months represent a huge organizational effort that QSTAR has been able to afford through the work of Roberta Carnevale, Scientific Secretary of the Centre.

QSTAR meets LKB and MPL
Workshop
January 21-22, 2013

New Research Horizon in Arcetri
QSTAR Workshop
March 12, 2013

Quantum Information Processing and Communication Conference – QIPC2013
June 30 - July 5 2013
Chairs: Marco Bellini, Francesco S. Cataliotti, Augusto Smerzi

Il Futuro è Quantum
In occasione dei 100 anni dell'atomo di Bohr e dei primi 80 anni di Tito Fortunato Arecchi
December 11, 2013

Frontiers in the Quantum World
A Symposium in honour of Ennio Arimondo on the occasion of his retirement
March 10, 2014

The Location

Thanks to the generosity of Ente Cassa di Risparmio di Firenze which has financed the restoration of office spaces, QSTAR is located in the headquarters of the old Institute of Physics, which hosts nowadays the Department of Physics and Astronomy of the University of Florence.

This building was finished in 1921 thanks to Antonio Garbasso. A group of brilliant physicists such as Gilberto Bernardini, Enrico Fermi, Joseph Loupe, Giulio Racah, Franco Rasetti and Bruno Rossi worked there and it was in that place that Enrico Fermi wrote his fundamental work on the statistics of the electrons in 1926.

Enrico Fermi with Rita Brunetti, Nello Carrara and Franco Rasetti in the courtyard of "Garbasso"

The "Garbasso" building, is one of the main structures on the hill of Arcetri, which has recently been celebrated as a historic site by the European Physical Society (EPS), as it is rich in historical and scientific interest. Going up the hill you will see also the National Institute of Optics, founded in 1927 by Vasco Ronchi, protagonist of the rebirth of optics in Italy, and the Arcetri Astrophysical Observatory, built in 1872 on the initiative of Giovan Battista Amici and Giovan Battista Donati. Higher up, on the edge of the area, there is "The Jewel", a Villa where Galileo spent the last years of his life (1631-1642). There Galileo completed the writing of the fundamental work "Dialogues of the New Sciences" (1638).

Publications

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Dissemination

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