GDR 3322

⟨IQ|FA⟩

CNRS

7th *Colloquium* of the CNRS GDR № 3322 on Q. Engineering, Foundations & Applications

Ingénierie Quantique, des aspects Fondamentaux aux Applications – IQFA

Télécom ParisTech

November 16-18 2016

Book of Abstracts

LAB. TRAITEMENT ET COMMUNICATION DE L'INFORMATION — LTCI

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1 What is IQFA ?

1.1 A CNRS "Groupement de Recherche" (Research Network)

The **GDR IQFA, "Ingénierie Quantique, des aspects Fondamentaux aux Applications"**, GDR № 3322 of the Centre National de la Recherche Scientifique (CNRS[1]), is a Research Network supported by the CNRS Institutes of Physics (INP[2]) and of Systems & Engineering Sciences (INSIS[3]), with which the quantum information community is mostly associated. This GDR gathers more than 50 French laboratories through which more than 90 teams are involved.

The goal of the GDR "Quantum Engineering, Foundations & Applications" (IQFA[4]) is two-fold: first, to establish a common base of knowledge, and second, to use this platform to emulate new knowledge.

IQFA's main road-map can be summarized as follows:

- a willingness to shape the discipline in order to create stronger bridges between the various thematics;
- establishment of a shared basis of knowledge through specific lecturing activities when the colloquiums of the GDR occur;
- promotion of foundations & applications of Quantum Information in a "bound-free laboratory" to facilitate the emergence of new projects which meet the current and future challenges of the field.

IQFA is organized along the 4 newly identified thematics - ART[5] - that are currently highly investigated all around the world, and particularly with the next European Flaghsip project:

- Quantum Communication & Cryptography – Qcom,
- Quantum Sensing & Metrology – Qmet,
- Quantum Processing, Algorithms, & Computation – Qpac,
- Quantum Simulation – Qsim,

all surrounded by transverse Fundamental Quantum Aspects – Fqa.

For more details on those thematics, e.g. scope and perspectives, please visit IQFA webpage: http://gdriqfa.unice.fr/.

1.2 Scientific Committee of the GDR IQFA

Members: Alexia Auffèves (CNRS, Uni. Grenoble Alpes),
Antoine Browaeys (CNRS, Inst. d'Optique Graduate School, Uni. Paris Saclay),
Thierry Chanelière (CNRS, Uni. Paris Saclay),
Eleni Diamanti (CNRS, Uni. Pierre & Marie Curie - Paris 6),
Pascal Degiovanni (CNRS, ENS Lyon),
Iordanis Kerenidis (CNRS, Uni. Paris Diderot - Paris 7),
Tristan Meunier (CNRS, Uni. Grenoble Alpes),
Pérola Milman (CNRS, Uni. Paris Diderot - Paris 7),
Simon Perdrix (CNRS, Uni. de Lorraine Metz-Nancy),
Sébastien Tanzilli (Head, CNRS, Uni. Côte d'Azur - Nice),
Nicolas Treps (Secretary, ENS Paris, Uni. Pierre & Marie Curie - Paris 6),

Administration manager: Nathalie Koulechoff (CNRS, Uni. Côte d'Azur - Nice).

[1] http://www.cnrs.fr/
[2] http://www.cnrs.fr/inp/
[3] http://www.cnrs.fr/insis/
[4] French acronym for "Ingénierie Quantique, des aspects Fondamentaux aux Applications.
[5] In French: Axes de Réflexion Thématiques.

2 IQFA's 7th Colloquium – Scientific Information

2.1 Welcome !

IQFA's 7th colloquium is mainly organized by the Laboratoire de Traitement et Communication de l'Information (LTCI) at Télécom ParisTech[6].

From the scientific side, the main goal of this colloquium is to gather all the various communities working in Quantum Information, and to permit, along 3 days, to exchange on the recent advances in the field. The colloquium will be outlined along 3 communication modes:

- 7 tutorial talks, having a clear pedagogical purpose, on the very foundations and most advanced applications of the field;
- 15 contributed/invited talks on the current hot topics within the strategic thematics (ARTs) identified by the GDR IQFA (see online the ARTs[7] for more details);
- and 2 poster session gathering more than 100 posters, again within IQFA's strategic thematics (ARTs).

In total this year, **IQFA's Scientific Committee (see Sec. 1.2) has received 110 scientific contributions**.

You will find in this book of abstracts an overview of all the contributions, *i.e.* including the tutorial lectures and contributed talks, as well as the poster contributions.

We wish all the participants a fruitful colloquium.

Eleni Diamanti (IQFA's Scientific Committee member, President of the 7th colloquium),
& **Sébastien Tanzilli** (IQFA's Director),

On behalf of IQFA*'s Scientific Committee.*

[6]https://www.telecom-paristech.fr
[7]http://gdriqfa.unice.fr/spip.php?rubrique2

2.2 Program of the colloquium

Wednesday, November 16, 2016

TIME	EVENT
8:30 am - 9:00 am	Opening Session (Amphitheater) - Eleni Diamanti (CNRS, UPMC) & Sébastien Tanzilli (CNRS, UCA)
9:00 am - 10:30 am	Quantum Communication & Cryptography (QCOM) (Amphitheater) - Eleni Diamanti (CNRS & UPMC)
09:00 - 10:00	› Quantum Key Distribution : From the concept to a commercial application - *Hugo Zbinden, Uni. Geneva (CH)*
10:00 - 10:30	› Trust, Security and Quantumness - *Damian Markham, CNRS & Uni. Pierre et Marie Curie (France)*
10:30 am - 11:00 am	Coffee break (Hall)
11:00 am - 12:30 pm	European Flagship Round Table (Amphitheater) - Eleni Diamanti (CNRS, UPMC) & Sébastien Tanzilli (CNRS, UCA)
12:30 pm - 2:00 pm	Lunch (Hall)
2:00 pm - 3:30 pm	Quantum Processing, Algorithm, & Computing (QPAC) (Amphitheater) - Iordanis Kerenidis (CNRS, Uni. Paris Diderot)
14:00 - 15:00	› Quantum optimal control for quantum technologies - *Tommaso Calarco, Uni. Ulm (Germany)*
15:00 - 15:30	› Quantum information processing in phase space: A modular variables approach - *Andreas Ketterer, Uni. Paris Diderot (France)*
3:30 pm - 4:00 pm	Coffee break (Hall)
4:00 pm - 5:00 pm	Quantum Communication & Cryptography (QCOM) (Amphitheater) - Thierry Chanelière (CNRS, Uni. Psud)
16:00 - 16:30	› Recent results in experimental satellite quantum communication - *Daniele Dequal, Uni. Padova (Italy)*
16:30 - 17:00	› Generation of temporally multiplexed pairs of photons with controllable delay in a crystal - *Jean Etesse, Uni. Geneva (CH)*
5:00 pm - 7:00 pm	Poster Session 1 (Hall) - Thematics QCOM & QMET

Thursday, November 17, 2016

TIME	EVENT
9:00 am - 10:30 am	Fundamental Quantum Aspects (FQA) (Amphitheater) - Pérola Milman (CNRS, Uni. Paris Diderot)
09:00 - 10:00	› An introduction to quantum thermodynamics - *Stephanie Wehner, Delft University of Technology*
10:00 - 10:30	› Bell inequalities for maximally entangled states - *Alexia Salavrakos, ICFO (Spain)*
10:30 am - 11:00 am	Coffee break (Hall)
11:00 am - 12:00 pm	Fundamental Quantum Aspects (FQA) (Amphitheater) - Sébastien Tanzilli (CNRS, UCA)
11:00 - 11:30	› Light-matter interfacing with quantum dots : a polarization tomography approach - *Paul Hilaire, C2N-CNRS (France)*
11:30 - 12:00	› Dipolar quantum droplets, a liquid from quantum correlations - *Igor Ferrier-Barbut, Uni. Stuttgart (Germany)*
12:00 pm - 12:30 pm	Quantum Communication & Cryptography (QCOM) (Amphitheater) - Eleni Diamanti (CNRS & UPMC)
12:00 - 12:30	› Tunable single photon source with carbon nanotubes - *Yannick Chassagneux, ENS Paris (France)*
12:30 pm - 2:00 pm	Lunch (Hall)
2:00 pm - 3:30 pm	Quantum Sensing & Metrology (QMET) (Amphitheater) - Nicolas Treps (UPMC)
14:00 - 15:00	› New Frontiers in Quantum Optomechanics - *Markus Aspelmeyer, Uni. Vienna (Austria)*
15:00 - 15:30	› Magnetic resonance with squeezed microwaves - *Patrice Bertet, CEA Saclay (France)*
3:30 pm - 4:00 pm	Break (Hall)
4:00 pm - 5:00 pm	Quantum Processing, Algorithm, & Computing (QPAC) (Amphitheater) - Iordanis Kerenidis (CNRS, Uni. Paris Diderot)
16:00 - 16:30	› Quantum walking in (3 + 1)-dimensional curved spacetime - *Marcelo Forets, Uni. Grenoble Alpes (France)*
16:30 - 17:00	› Tomography of mode-tunable coherent single-photon subtractor - *Young-Sik Ra, Uni. Pierre et Marie Curie (France)*
5:00 pm - 7:00 pm	Poster Session 2 (Hall) - Thematics FQA, QPAC, & QSIM
7:00 pm - 10:00 pm	Banquet (Hall)

Friday, November 18, 2016

TIME	EVENT
9:00 am - 10:30 am	Quantum Simulation (QSIM) (Amphitheater) - Pascal Degiovanni (CNRS, ENS Lyon)
09:00 - 10:00	› Spin qubits in semiconductors: an overview and outlook - *Daniel Loss, University of Basel (CH)*
10:00 - 10:30	› Multimode circuit QED : Towards many-body physics - *Nicolas Roch, Institut Néel CNRS, Uni. Grenoble Alpes (France)*
10:30 am - 11:00 am	Coffee break (Hall)
11:00 am - 12:30 pm	Quantum Sensing & Metrology (QMET) (Amphitheater) - Thierry Chanelière (CNRS, Uni. Psud)
11:00 - 12:00	› Quantum sensors with matter waves - *Philippe Bouyer, CNRS & Institut d'Optique Graduate School (Bordeaux, France)*
12:00 - 12:30	› State-of-the-art cold atom gyroscope without dead time - *Remi Geiger, SYRTE (France)*
12:30 pm - 2:00 pm	Lunch (Hall)
2:00 pm - 3:00 pm	Quantum Simulation (QSIM) (Amphitheater) - Pascal Degiovanni (CNRS, ENS Lyon)
14:00 - 14:30	› Spreading of Quantum Correlations in Short- and Long-Range Interacting Systems - *Laurent Sanchez-Palencia, CNRS & Institut d'Optique Graduate School (France)*
14:30 - 15:00	› Measurements of spectral function of ultra-cold atoms in disordered potentials - *Musawwadah Mukhtar, Institut d'Optique Graduate School (France)*
3:00 pm - 3:30 pm	Quantum Sensing & Metrology (QMET) (Amphitheater) - Thierry Chanelière (CNRS, Uni. Psud)
15:00 - 15:30	› Electron spin resonance from NV centers in diamonds levitating in an ion trap - *Gabriel Hétet, ENS Paris (France)*
3:30 pm - 4:00 pm	Closing Session (Amphitheater) - Sébastien Tanzilli (CNRS, UCA)

2.3 Télécom ParisTech, the LTCI, and their scientific environment

Télécom ParisTech[8] (also known as ENST or Télécom or École nationale supérieure des télécommunications) is one of the top French public institutions for higher education and research (Grandes Écoles) of engineering in France. Located in Paris, it is also a member of the ParisTech Group and the Institut Telecom. In 1991, Télécom ParisTech and the EPFL in Lausanne (CH) collaborated and established a school named Institut Eurécom located in Sophia-Antipolis. Students can now be admitted in two different curriculums, located either in the Paris or the Sophia-Antipolis campus.

Télécom ParisTech is also one of the approved application schools for the École Polytechnique, making it possible for fourth-year students to complete their studies with a one-year specialization at Télécom ParisTech. Télécom ParisTech also provides education for the Corps des télécommunications.

Around 250 engineers graduate each year from Télécom ParisTech. Thirty to thirty-five percent of the graduates are foreign students coming from all over the world. Specialization courses cover all aspects of computer science and communication engineering: Electronics, Signal processing, Software engineering, Networking, Economics, Finance, etc.

Research at Télécom ParisTech consists of:

- Optimization and transmission of information;
- Improvements in data processing;
- Microelectronics, such as FPGA and DSP systems;
- Image and signal processing, wavelets;
- and Artificial intelligence, data mining, distributed and real-time systems.

Télécom ParisTech has 4 research departments:

- Electronics and Communications;
- Computer Science and Networking;
- Signal and Image Processing;
- Economic and Social Sciences.

Those are within the **Laboratoire Traitement & Communication de l'Information (LTCI)**.

Within the context of supporting scientific research & colloquiums, Télécom ParisTech and the LTCI support and welcome IQFA*'s 7th colloquium.*

3 IQFA's 7th Colloquium – Practical Information

3.1 Registration

The participants' registration will be made available from Wednesday the 16th of November at 7:30 am, in the Hall of Télécom ParisTech's amphitheater where the colloquium takes place.

3.2 Internet Connection

A Wi-Fi connection will be available inside the building, with dedicated network and password for each registered participant. Otherwise, the EDUROAM network will also be available for those of the participants who have already made the necessary application with their respective universities.

[8]https://www.telecom-paristech.fr

3.3 Coffee breaks, lunches & buffet

All the coffee breaks during the colloquium will be taken on site, namely in the Hall. The lunches will be taken in the Hall of Télécom ParisTech's amphitheater. Coffee breaks and lunches are free of charge for all registered participants.

The banquet of the colloquium will be organized on Thursday the 17^{th} and will be taken on site. It will start around 7:00 pm, right after Thursday's poster session (see the program in Sec. 2.2) and is free of charge for people who have mentioned their participation at the early registration stage.

3.4 Venue

IQFA's 7^{th} colloquium will take place at **Télécom ParisTech in Paris**, 46 rue Barrault 75013 Paris. **All the tutorial and contributed talks will be given in the "Amphitheater" inside Télécom ParisTech's building**. Télécom ParisTech is accessible using public transportation, as shown by the Localization Maps in Sec. 3.5. Also note that the poster sessions will be organized in the Hall next to the amphitheater, in the same building.

3.5 Localization map

Localization map of Télécom ParisTech and surrounding area.

Access to Télécom ParisTech in Paris:
You can join us using the following means:

- *By public transportation*:
  Subway: Take the line 6 and stop at Corvisart station;
  RER: Take the RER B up to Denfert-Rochereau station. Connection in Denfert Rochereau and take the subway line 6;

Bus: Line 62 (Vergniaud), 21 (Daviel), or 67 (Bobillot).
The Paris public transportation website can be reached online at RATP[9].

- *Using Vélib'*:
  Stations 13022 (27 & 36, rue de la Butte aux Cailles), 13048 (20, rue Wurtz) or 13024 (81, rue Bobillot).

For more details on how to reach the place of the colloquium, please refer to its webpage at: How to reach the Colloquium[10], or refer to the Telecom ParisTech website[11].

3.6 Organization & financial supports

This colloquium is organized by: the GDR IQFA,

at, and with the help of: Télécom ParisTech and the LTCI,

and with the financial supports of: the CNRS, through the Institutes INP and INSIS,
Télécom ParisTech,
the IFRAF (Région Ile-de-France),
ID QUANTIQUE,
that are warmly acknowledged.

3.7 Local organization committee for this colloquium

President: Eleni Diamanti (CNRS, UPMC, Paris),

Members: Isabelle Zaquine (Télécom ParisTech),
the Q. Information group at the LTCI,

with the remote help of: Sébastien Tanzilli, Nathalie Koulechoff,
& Bernard Gay-Para (CNRS, UCA, Nice).

[9] http://www.ratp.fr
[10] https://iqfacolloq2016.sciencesconf.org/resource/acces
[11] https://www.telecom-paristech.fr/telecom-paristech/adresses-acces-contacts.html

4 Abstracts of the contributions

In the following, you can find, after the tutorial lectures, all the contributions given per ART. The first abstracts of each ART correspond to contributed talks (see the Program in Sec. 2.2), and all the following abstracts correspond to poster contributions.

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Tutorial Talks

An introduction to quantum thermodynamics

Stephanie Wehner*
Delft University of Technology

Quantum information provides a powerful tool to analyse thermodynamics in small (quantum) systems beyond the reach of statistical methods. Here, we will explore an introduction to the quantum information approach to thermodynamics.

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New Frontiers in Quantum Optomechanics

Markus Aspelmeyer[1*]
[1] *Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria*

The quantum optical control of solid-state mechanical devices, quantum optomechanics, has emerged as a new frontier of light-matter interactions. Devices currently under investigation cover a mass range of more than 17 orders of magnitude - from nanomechanical waveguides of some picograms to macroscopic, kilogram-weight mirrors of gravitational wave detectors. This development has been enabled by the insight that quantum optics provides a powerful toolbox to generate, manipulate and detect quantum states of mechanical motion, in particular by coupling the mechanics to an optical or microwave cavity field. Originally, such cavity optomechanical systems have been studied from the early 1970s on in the context of gravitational wave antennas. Advancements in micro-fabrication and micro-cavities, however, have resulted in the development of a completely new generation of nano- and micro-optomechanical devices. Today, 10 years after the first demonstrations of laser cooling of micromechanical resonators, the quantum regime of nano- and micromechanical motion is firmly established. Recent experimental achievements include the generation of genuinely non-classical states of micromechanical motion such as quantum squeezing and entanglement. This level of control over solid-state mechanical degrees of freedom is now also being utilized in diverse application domains ranging from classical sensing, to low-noise optical coatings for precision interferometry, and also to photon-phonon quantum interfaces.

From the fundamental physics point of view, one of the fascinating prospects of quantum optomechanics is to coherently control the motional degree of freedom of a massive object in an unprecedented parameter regime of large mass and long coherence time, hence opening up a new avenue for macroscopic quantum experiments. The availability of quantum superposition states involving increasingly massive objects could enable a completely new class of experiments, in which the source mass character of the quantum system starts to play a role. This addresses directly one of the outstanding questions at the interface between quantum physics and gravity, namely “how does a quantum system gravitate ?”.

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Quantum Key Distribution : From the concept to a commercial application

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In this tutorial, I will first explain the concepts of QKD [1]. Then, I will explain some experimental realisations and discuss some limits and challenges. Finally, I will briefly present the Geneva spin-off id Quantique [2], who is commercializing QKD systems, Quantum Random Generators, and instruments for quantum optical laboratories.

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Quantum optimal control for quantum technologies

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Quantum mechanics is at the basis of all present-day information and communication technologies : to name just two examples, transistors and lasers would be impossible to build without understanding the quantum behaviour of matter and light. But the control of individual quantum systems has long been considered only a "thought experiment", something only possible in theory. However, today this is routinely achieved in labs around the world, and it is the basis of quantum technologies. The exquisite level of control needed for quantum technologies to outperform present-day technologies can be achieved by quantum optimal control theory (QOCT). After reviewing the main applications of quantum technologies, ranging from secure communications to ultra-high precision sensing and metrology, and from extremely powerful computers to the simulation of complex materials, I will explain how QOCT can be applied to a few of these fields and present the experimental results obtained with the CRAB (Chopped Random Basis) optimisation algorithm that I proposed and developed in recent years.

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Quantum sensors with matter waves

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The past decades has seen dramatic progress in our ability to manipulate and coherently control the motion of atoms. Although the duality between wave and particle has been well tested since de Broglie introduced the matter-wave analog of the optical wavelength in 1924, manipulating atoms at a level of coherence allowing for precision measurement has only become possible thanks with our ability to produce atomic samples of few microdegrees above absolute zero. Since the initial experiments many decades ago, the field of coherent atom optics has grown in many directions. This progress has both fundamental and applied significance. The exquisite control of matter waves offers the prospect of a new generation of force sensors[1] of unprecedented sensitivity and accuracy, from applications in navigation and geophysics, to tests of general relativity or study of highly-entangled quantum states.

The spectacular sensitivity or matter-wave interferometers can be used for very precise measurements. It is for example possible to measure the acceleration of gravity[2] with an accuracy of 1 part per billion, the rotation of the Earth[3] with an accuracy better than 1 millidegree per hour and detect minute changes in gravity caused by mass displacements. These devices are so precise that they are used today as reference for fundamental constants (mass, gravity), and are powerful candidates to test general relativity on ground, underground[4] or in space[5]. Projects are currently ongoing to verify the universality of free fall[6, 7] or to detect gravitational waves in a frequency range yet unreachable with current detectors[8].

Nevertheless the future of matter-wave inertial sensors goes far beyond lab-based inertial sensors. While these experiments are typically quite large, require a dedicated laboratory, and are designed to operate well only in environments where the temperature, humidity, acoustic noise is tightly constrained, many efforts have been put in designing compact, robust and mobile sensors[9]. The development of this technology lead to a new generation of atomic sensors that have been operated in airplanes [10] and soon in rockets, that are commercially available and could be the next generation of navigation unit[11].

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SPIN QUBITS IN SEMICONDUCTORS: AN OVERVIEW AND OUTLOOK

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I will present a tutorial overview of spin qubits in semiconducting nanostructures such as quantum dots and nanowires for electron and hole spins [1] from a theorist's point of view. Despite enormous experimental efforts in many labs worldwide over the last twenty years or so, progress has been slow due to many challenges posed by complex material issues and the related many-body physics (due to e.g. nuclear spins and phonons) limiting the coherence of spin qubits. Nevertheless, the field has evolved steadily, in theory and experiment, and there are good reasons to believe that the ultimate goal of building a powerful quantum computer most likely will be reached with spin qubits in semiconductor material which have the advantage of being inherently small and fast: In principle, it is possible to fit a billion spin qubits on a square centimeter and have them operate at a clock speed of GHz. Recently, hole spins in InAs and in Si/Ge material have emerged as strong candidates for spin qubits due to their strong built-in spin orbit interaction which allows a high electrical control and coupling to microwave cavities [2], which can be used for a 2D surface code architecture.
If time permits, I will touch on some recent theoretical ideas on hybrid qubit systems which aim to combine topological qubits, such as Majorana fermions and parafermions, with spin qubits [3]. Promising platforms for such topological hybrids are nanowires such as InAs or InSb with strong Rashba spin orbit interaction, which can support both, quantum dots and topological superconductivity.

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Trust, Security and Quantumness

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We study the relationship between trust, security and different quantum features in various quantum cryptography settings. In recent work we understand that steering plays a key role in a family of protocols whose aim is to verify quantum computation, whereas other families rely on non-locality. In this way we observe a broad link between the assumptions made in a physical theory (contextuality e.t.c.), and the assumptions made in security analysis (trust of devices, parties e.t.c.). We will discuss the practical implications of these and various tradeoffs which arise.

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Fundamental Quantum Aspects (FQA)

1D Discrete-Time Quantum Walk - IQFA Quantum Abstract

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Quantum random walks have been much studied due to the nonclassical behavior of the walker. We study one possible route to classical behavior for the discrete quantum random walk in changing, at each step of the walk, the bias of the quantum coin.

An 1D discrete-time quantum walk is described by the entanglement of a two dimensional system, the coin, with an 1D lattice space, the walker. More formally, the Hilbert space is given by $\mathcal{H} = \mathcal{H}_c \otimes \mathcal{H}_w$ where $\mathcal{H}_c = \text{span}\{|\uparrow\rangle, |\downarrow\rangle\}$ is the coin's Hilbert space, and $\mathcal{H}_w = \text{span}\{|x\rangle, x \in \mathbb{Z}\}$ is the walker's Hilbert space. At each step, we apply two operators, one which will correspond to the coin, and another to the displacement of the walker. The coin flip operator $\hat{\mathbf{C}}$ is the quantum equivalent of the randomness tied to the classical coin, it is a unitary operator acting on the coin space $\mathcal{H}_c$. Then, the walker moves according to the displacement operator $\hat{\mathbf{D}} = \sum_x |\uparrow\rangle\langle\uparrow| \otimes |x+1\rangle\langle x| + |\downarrow\rangle\langle\downarrow| \otimes |x-1\rangle\langle x|$. Just as the final position depends on the output of the coin, the walker's position becomes entangled with the coin.

The evolution of the system for one toss of coin is governed by the operator $\hat{\mathbf{U}} = \hat{\mathbf{D}}(\hat{\mathbf{C}} \otimes \hat{\mathbf{1}}_w)$ where $\hat{\mathbf{1}}_w$ is the identity operator acting on the walker space $\mathcal{H}_w$. At step t, the state is given by $|\psi(t)\rangle = \hat{\mathbf{U}}^t |\psi_0\rangle$, where $|\psi_0\rangle$ is the initial state of the lattice.

As the initial state, we take $|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_c + \mathrm{i}\,|\downarrow\rangle_c) \otimes |0\rangle_w$ in order to have a symmetric walk. Indeed, the real and imaginary parts of the state will take opposite directions and they will not interact because our coin operator is real. This way, we can focus on the walker spreading into the quantum walk, namely its variance.

The variance, which here reduces to $\langle x^2 \rangle_t$, shows a complicated behaviour: in a classical random walk $\langle x^2 \rangle_t \propto t$, while in the quantum walk $\langle x^2 \rangle_t \propto t^2$. This behaviour is more diverse if we play with the coin operator. Instead of applying the same coin operator $\hat{\mathbf{C}}$, we apply a different coin $\hat{\mathbf{C}}_{(j)}$ depending on the step on the walk. The final state becomes $|\psi(t)\rangle = \hat{\mathbf{U}}_{(t-1)} \dots \hat{\mathbf{U}}_{(0)} |\psi_0\rangle$, where $\hat{\mathbf{U}}_{(j)} = \hat{\mathbf{D}}(\hat{\mathbf{C}}_{(j)} \otimes \hat{\mathbf{1}}_w)$. Some of these sequences of coin operators were investigated numericaly [1].

In this work, I study these properties with analytical methods [2]. I clarify the link between a sequence of coins and the variance of the walker in order to study the feasibility of quantum computation in this specific quantum walk.

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Adiabatic elimination preserving the quantum structure for composite quantum systems

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When studying interacting quantum systems, the complexity of the dynamics grows quickly with the number of connected systems. Frequently we are mainly interested in one of the systems while the others are present merely for technical or experimental purposes (e.g. ancilla). From the complete dynamics, it is possible to derive a reduced dynamics concerning only the system of interest in several situations.For instance, often the evolution of the system we are interested into is much slower than the one of the ancilla; in these situations, adiabatic elimination allows to eliminate the fast dynamics and directly include their effect on the slow dynamics of interest. This allows to study e.g. the effect of small perturbations on stabilized decoherence-free subspaces or to include more accurately the effects of a fast bath on a target system.

For closed systems described by Hamiltonian dynamics, adiabatic elimination is standard [10]. However for open quantum systems described by a Lindblad master equation, the problem is more complicated. Several particular examples have been successfully treated ([1],[3],[8],[9],[5]). Treating the master equation as a linear system or applying the generalized Schrieffer-Wolff formalism [7] implies the inversion of super-operators, losing physical meaning in the reduced model. In [2], they derive a reduced quantum stochastic equation model, which converges to the full dynamics as the speed of the fast dynamics goes to infinity.

The aim of our work is to provide a more precise reduced model in quantum master equation form. We give not only the explicit Lindblad form of the reduced dynamics, but also the Kraus form (completely positive and trace preserving map) describing the hybridization between target and fast systems. Furthermore, by treating the slow dynamics as a perturbation of the fast system, we provide an asymptotic expansion along the lines of center manifold techniques [4] and geometric singular perturbation theory [6], but constrained to have the Lindblad/Kraus structure. This expansion can, in principle, be solved to arbitrary order depending on the effective time scale separation and desired precision.

Here we consider two interacting quantum systems of finite dimension. One of the systems is assumed highly dissipative (i.e. on a fast time scale) and converges towards a unique equilibrium (possibly mixed) state. The other system has slow Hamiltonian dynamics, including a weak coupling to the fast system. We give explicit formulas for the Lindblad and Kraus form associate to the reduced system up to second order. The first order dynamics correspond to the well known Zeno effect while the second order expansion introduces decoherence operators. This also gives structural results on the (maximum) number of decoherence channels in the reduced model, depending on the structure of the interaction. The key element of the computations is a proper inversion of the fast dynamics on a particular subspace. Finally, we apply our method to a qubit coupled to a driven and highly dissipative quantum harmonic oscillator subject to thermal noise.

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Anomalous broadening in driven–dissipative Rydberg systems

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Due to their strong, long-range, coherently-controllable interactions, Rydberg atoms have been proposed as a basis for quantum information processing and simulation of many-body physics. Many proposals require fine control over the preparation and manipulation of such high energy states. Rydberg dressing schemes in particular promise, through the use of non-resonant excitation, long-lived and highly interacting states. The power of such proposals arise from the possibility to control the interaction strength.

Using the coherent dynamics of such highly excited atomic states, however, requires addressing challenges posed by the dense spectrum of Rydberg levels, the detrimental effects of spontaneous emission, and strong interactions.

We report the observation of interaction-induced broadening of the two-photon $5s - 18s$ Rydberg transition in ultra-cold $87Rb$ atoms, trapped in a 3D optical lattice. The measured linewidth increases by nearly two orders of magnitude with increasing atomic density and excitation strength, with corresponding suppression of resonant scattering and enhancement of off-resonant scattering. We attribute the increased linewidth to resonant dipole-dipole interactions of 18s atoms with spontaneously created populations of nearby Rydberg p-states.

This dephasing mechanism implies that the timescales available for coherent addressing of such systems are dramatically shortened by this effect. Additionally, the pollutant states arising rapidly and in an uncontrolled way, this mechanism is expected happen quite generally in many-body systems in the regime where dissipation plays a role. This has the potential to hamper many recent proposals to use Rydberg-dressed atoms for quantum simulation.

Our results were published in PRL [1] and are available as well in the arXiv [arXiv:1510.08710] .

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Antibunched photons emitted by voltage biased Josephson junction

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Microwave radiation is most simply generated by alternating currents driven through a classical conductor, but can also be emitted by dc biased quantum conductors. This stems from the quantum fluctuations of the current reflecting the probabilistic transfer of granular charges through the conductor. Can one take advantage of these peculiar properties of quantum electrical transport to produce radiative states with strong non-classical properties such as, e.g., single photons ? I will show that indeed the photons emitted by a dc biased junction coupled to a high impedance mode are strongly antibunched. This reflects the fact that in such a strange regime, the presence of a photon in the resonator inhibits the tunneling of a Cooper pair.

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Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry

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Reducing the size of a conductor usually decreases its conductivity because of the enhanced effect of disorder in low dimensions, leading to diffusive transport and to weak, or even strong localization. Notable exceptions are the ballistic chiral one-dimensional edge states of the quantum Hall effect, or the recently discovered spin-polarized, counter-propagating edge states of the quantum spin Hall effect found in 2D topological insulators, that are protected from scattering by spin-momentum locking. By measuring the CPR of a micrometer-long oriented single crystal bismuth nanowire connected to superconducting electrodes, we demonstrate that transport occurs ballistically along two extremely narrow edges along topological facets. In addition, we show that a magnetic field can induce to 0-ïĄř transitions and ϕ_0-junction behavior, thanks to the extraordinarily high g-factor and spin orbit coupling in this system, providing a way to manipulate the phase of the supercurrent-carrying edge states and generate spin supercurrents.

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Bell inequalities for maximally entangled states

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Measurements on separated subsystems in a joint entangled state may display correlations that cannot be mimicked by local hidden variable models [1]. These correlations are known as nonlocal, and they are detected by violating the so-called Bell inequalities. In recent years, however, it has become clear that non-locality is interesting not only for fundamental reasons, but also as a resource for many device-independent (DI) quantum information tasks [2], such as quantum key distribution [3, 4] or random number generation [5, 6]. From this new point of view, the violations of Bell inequalities are not merely indicators of non-locality, but can be used to infer qualitative and quantitative statements about operationally relevant quantum properties.

Traditionally, the construction of Bell inequalities has been addressed from the point of view of deriving constraints satisfied by local models. Following this standard approach, the inequalities are constructed using well-known techniques in convex geometry, since the set of correlations admitting a local hidden variable model corresponds to a polytope. The facets of this polytope are the desired Bell inequalities, and they are optimal detectors of non-locality in the sense that they provide necessary and sufficient criteria to detect the non-locality of given correlations. The CHSH [7] and CGLMP [8] inequalities are examples of such facet inequalities.

However, these facet Bell inequalities are not necessarily optimal for inferring specific quantum properties in the device-independent setting. In our work, we consider the problem of constructing Bell inequalities whose maximal quantum violation is attained for maximally entangled states of two qudits. This is a desirable property since these states have particular features and therefore many quantum information protocols rely on them. The facet CGLMP inequalities, however, were found not to be maximally violated by maximally entangled states [10, 11], which may not be that surprising given that no quantum property was used for their construction.

Our approach does not follow the traditional one : we start from quantum theory and exploit the symmetries and perfect correlations of maximally entangled states to derive a family of Bell inequalities. Our method is also closely linked to sum of squares decompositions of the Bell operator, which allows us to determine their maximal quantum violation, also called Tsirelson bound [9], in a completely analytical way. Thus, we present a method for generating new Bell inequalities in which quantum theory becomes a key ingredient.

The Bell inequalities that we obtain, as well as their properties, are valid for any number of measurements and outcomes. They are the first known in this scenario to be maximally violated by the maximally entangled states. Our inequalities also have the potential to be used in DI quantum information protocols, as they are good candidates for improved DI random number generation or quantum key distribution protocols or to self-test [12] maximally entangled states of high dimension. Interestingly, they also give further insight into the structure of the set of quantum correlations.

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Bose-Einstein condensation of semiconductor excitons in a trap

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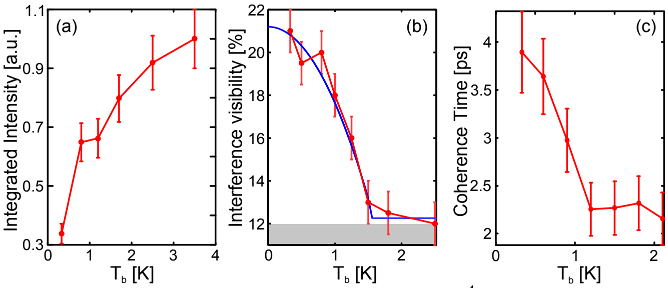
Semiconductor excitons, i.e. electron-hole pairs bound by Coulomb attraction, have been studied for long in the quest for Bose-Einstein condensation. This situation is somewhat surprising : compared to alkali atoms, excitons are very light composite bosons such that the quantum phase transition is accessible below a few Kelvin.

Recently, M. Combescot and co-workers have brought forward one direct reason to explain the absence of signatures for excitons condensation [1] : they showed that the ground excitonic state is always optically dark so that Bose-Einstein statistics hides the condensate in a macroscopic population of dark excitons. In fact, quantum signatures can only be detected directly above a density threshold, experimentally accessible, when fermion exchanges between excitons can introduce coherently a small fraction of bright excitons to the dark condensate [2]. The latter then becomes "grey" and is possibly studied through a very weak and coherent optical signal.



***(a)** Fraction of bright excitons for about 10^4 excitons confined in a 10μm trap vs. T_b. **(b)** Threshold for the spatial coherence with a critical temperature $T_c \sim 1K$. The solid blue line shows the model for a 2D gas of trapped non-interacting bosons. **(c)** Threshold of excitonic temporal coherence across Bose-Einstein condensation.*

Here we report model experiments to demonstrate these predictions for Bose-Einstein condensation of excitons : We confine long-lived excitons in a trap where we probe an homogeneously broadened gas at controlled density and temperature. Thus, we show that the photoluminescence emitted from the trap anomalously decreases while excitons are cooled to the sub-Kelvin regime (see Fig.a). The darkening violates classical expectations and in fact marks the quantum condensation in the lowest energy dark states. Our measurements then reveal that the weak photoluminescence radiated from the trap exhibits both quantum spatial coherence (Fig.b) and increased temporal coherence (Fig.c) below a threshold temperature of about 1K. These observations combine the signatures expected for a "grey" condensate of excitons. We then discuss the perspectives of our findings in the context of ultra-cold gases with strong dipolar interactions.

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Bright and dark modes in quantum optics in nano-structured media

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We will discuss the construction of the quantum theory of electromagnetic fields in a structured medium that can have metallic and dielectric elements, and their interaction with atoms, molecules and other quantum emitters, like quantum dots. We introduce the concept of bright and dark plasmon-polariton modes and their use in the construction of effective models.

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Cavities and Quantum Memories for engineering of non-classical states of light

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The production of non-classical states of light is the central issue of quantum optics. Schrödinger cat states (SCSs), superpositions of two coherent states $|\alpha\rangle$ in phase opposition ($|\phi_{\mathrm{cat}}\rangle = |\alpha\rangle \pm |-\alpha\rangle$), constitute an important member of this family since they work as qubits in hybrid quantum information processing. Such states have found promising applications in testing fundamental concepts, in quantum cryptography, and in quantum information, making them highly popular in the quantum optics domain [1, 2]. The SCSs produced so far had small amplitudes α, thus limiting their applicability. Increasing α is possible with iterative protocols [3] however with some precautions to maintain a high success probability as α is grown.

In order to produce such highly non-classical states of light at a high repetition rate, we start by preparing a first building block, namely a single-photon generator. Pulses from a mode-locked Ti:sapphire laser (central wavelength $\sim$ 850 nm, pulse duration $\sim$ 3 ps, repetition rate $\sim$ 76 MHz) are frequency-doubled in a synchronous bow-tie cavity via intra-cavity second-harmonic generation with a BiB_3O_6 crystal [4]. Using such a cavity, conversion efficiencies as high as 70% have been reached. Photon pairs at 850 nm are then produced using the frequency-doubled beam to pump an optical parametric amplifier placed in a second bow-tie cavity.

The photon pairs being produced with a poissonian probability, one photon of the pair is used to herald the other one which is subsequently used in the rest of the experiment. As the number of single photons required increases with the size of the SCS to be produced, the probability of generating such a state would drop significantly. We thus seek to implement quantum memories to store the states that have been successfully generated while the other resources are being prepared. Such quantum memories would consist in a cavity combined with a Pockels cell allowing the non-classical states to be extracted once they are required in the rest of the protocol.

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Classical hidden Markov chains pertaining in asymptotics of quantum evolutions

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We study the asymptotic behaviour of quantum irreversible evolutions within a general framework able to describe sharp or unsharp repeated measurements on a quantum system. In this framework, the evolution becomes a **classical** Markov process whose state space is the set of quantum states **S**, i.e. either the space of density operators on a Hilbert space or the set of states of a von Neumann algebra ot type II_1. Since we are interested in the asymptotic properties of the evolution, we can limit ourselves merely on discrete-time evolution ; in that case, the Markov process becomes a classical hidden Markov chain with state space **S**.

In the Hilbert space formulation of quantum mechanics, the set **S** is the set of density operators on a Hilbert space. When the system is subject to an unsharp measurement, described by a family of $(E[a])_{a\in\mathbb{A}}$ of unsharp effects (i.e. a resolution of the identity in terms of positve operators) indexed by a denumerable family $\mathbb{A}$, its density operator $\rho \in \mathbf{S}$ undergoes an irreversible transformation $\rho \mapsto T_a(\rho) = \frac{Z[a]\rho Z[a]^*}{\mathsf{tr}(Z[a]\rho Z[a]^*)}$, where $E[a] = Z[a]^* Z[a]$. The operators are known as Kraus operators of the transformation. When the results of the measurement are not filtered, the evolution induces a transformation $\rho \mapsto \Phi(\rho) = \sum_{a\in\mathbb{A}} p_a(\rho) T_a(\rho)$, where $p_a(\rho) = \mathsf{tr}(Z[a]\rho Z[a]^*)$. Repeated measurements of this type produce a classical hidden Markov chain on the space **S**.

Such type of chains have been studied in the literature under different names and in different contexts (both classical and quantum) and instances (see [1] for a recent review). As evolutions of quantum states, they have been studied (in some particular instances) in [2, 3]. In [4], a connection between the asymptotic behavriour of the Markov chain and its Poisson boundary has been established ; this connection is further exploited here.

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Coherent internal state manipulation by a three-photon STIRAP-like scheme

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A STIRAP-like scheme is proposed to exploit a three-photon dark resonance taking place in alkaline-earth-metal ions. A three photon coherent population trapping in calcium like ions has been identified [1] and could be used in a STIRAP-like process to coherently transfer the population from one metastable state to the other one. This scheme is designed for state transfer between the two fine structure components of the metastable D-state which are two excited states that can serve as optical or THz qu-bit. The advantage of a coherent three-photon process compared to two-photon STIRAP lies in the possibility of exact cancellation of the first order Doppler shift which opens the way for an application to a sample composed of many ions. The use of a large atomic sample to store an information in its internal state allows a large signal to noise ratio to be reached in a shorter time than when chains of ions are used. The transfer efficiency and its dependence with experimental parameters are analysed by numerical simulations [2]. This efficiency is shown to reach a fidelity as high as $(1 - 8.10^{-5})$ with realistic parameters.

The experimental observation of a three-photon dark line in an ion cloud is in progress and its building blocks are also presented on the poster. The setup relies on a linear radio-frequency trap where up to 10^6 laser cooled ions can be trapped and on three phase coherent lasers (397 nm, 729 nm, 866 nm). This phase coherence will be reached by their simultaneous lock on a frequency comb. The 729nm-laser is an ultra-narrow and very stable Ti :Sa laser, locked on an ULE cavity, and the frequency comb is expected to transfer its high quality to the two other involved lasers [3].

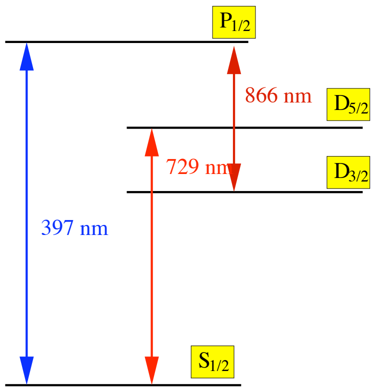

FIGURE 1. Transitions involved in the three-photon coherent population trapping in Ca^+ ions

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Dipolar quantum droplets, a liquid formed from quantum correlations

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In a Bose-Einstein condensate, quantum correlation impose an increase in energy with respect to a mean-field estimate. Effectively, this acts as a repulsion between the atoms when the density is increased. We report on the experimental observation of a phase transition between a gas and liquid state, which is formed from the balance of this repulsion and an attraction due to magnetic interactions. These observations are obtained in a very dilute atomic Bose-Einstein condensate of dysprosium.

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Your GDR - IQFA Quantum Abstract

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Recently, a tensor representation of spin systems was introduced that generalizes the spin-1/2 Bloch sphere picture to larger spins [1]. Here we use this representation for investigating entanglement related questions, since a spin-j state can be understood as a symmetric state of $2j$-qubits.

In the case of $j = 1$, the Bloch tensor reduces to an ordinary matrix, which we call "Bloch matrix". We show that the geometric entanglement of two qubits can be given as an analytic function of the smallest eigenvalue of the Bloch matrix. For more than two qubits, the situation is more complex. We employ the formalism of tensor eigenvalues that was developped recently in the mathematical literature [3], and investigate to what extent they contain information about the multipartite entanglement (or, equivalently, the quantumness) of the state [4]. Furthermore we construct a matrix from the tensor representation of the state and show that it is similar to the partial transpose of the density matrix written in the computational basis. We explicitly construct the unitary transformation that underlies this similarity and find that it generalizes Wootter's magic basis that allowed him to derive an explicit formula for concurrence of two qubits. The matrix itself can be interpreted in terms of spin-correlations and allows for a more transparent experimental interpretation of the PPT criteria for an arbitrary spin-j state [5].

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Foundational importance of device-independent approaches in quantum physics

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Dirac sought an interpretation of mathematical formalism in terms of physical entities and Einstein insisted that physics should describe "the real states of the real systems". While Bell inequalities put into question the reality of states, modern device-independent approaches do away with the idea of entities : physical theory may contain no physical systems. Focusing on the correlations between operationally defined inputs and outputs, device-independent methods promote a view more distant from the conventional one than Einstein's 'principle theories' were from 'constructive theories'.

We discuss several contemporary examples of device-independent methods, including indefinite causal orders and almost quantum correlations. For quantum information, their import extends to the new areas of causality and postquantum models. They also pose a puzzling foundational question : if physical theory is not about systems, then what is it about ? The answer given by the device-independent models is that physics is about languages. We explain the mathematical and conceptual content of this statement. In moving away from the information-theoretic reconstructions of quantum theory, it marks a new conceptual development in the foundations of physics.

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General conditions for maximal violation of non-contextuality in discrete and continuous variables

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In classical mechanics systems have intrinsic properties that are later revealed by the measurements. In particular the result of one measurement does not depend on the subsequent measurements performed. We say that classical mechanics is non-contextual. It is possible to demonstrate the contextual nature of quantum mechanics by the violation of inequalities based on correlation measurements of well chosen observables. Surprisingly it is possible to find inequalities that are violated by any state [1]. These inequalities have been designed separately for both discrete and continuous variable measurements [2]. In this talk I show how to test contextuality in the Peres-Mermin scenario with measurements of observables acting on Hilbert spaces of arbitrary dimension. By unifying these two strategies we are able to derive general relations that must be obeyed by the observables to have a state independent maximal violation of the inequality [3]. Using these relations we can characterize the spectral decomposition of observables that are suitable for maximal state independent violation of the non-contextual bound. A consequence of our results is that in the discrete case, in order to have a state independent maximal violation, one must use observables of even dimension. In the continuous case we study various observables that can be used to demonstrate contextuality and show how previously known observables are special cases of our results.

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Generalized spin-squeezing inequalities for particle number with quantum fluctuations

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Particle number fluctuations, no matter how small, are present in experimental setups. One should rigorously take these fluctuations into account, especially for entanglement detection. In this context, we generalize the spin-squeezing inequalities introduced by G. Tóth et al. [Phys. Rev. Lett. 99, 250405 (2007).]. These new inequalities are fulfilled by all separable states even when the number of particles is not constant and may present quantum fluctuations. These inequalities are useful for detecting entanglement in many-body systems when the superselection rule does not apply or when only a subspace of the total system Hilbert space is considered. We also define general dichotomic observables for which we obtain a coordinate-independent form of the generalized spin-squeezing inequalities. We give an example where our generalized coordinate-independent spin-squeezing inequalities present a clear advantage over the original ones [1].

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Light-matter interfacing with quantum dots : a polarization tomography approach.

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The development of future quantum networks requires an efficient interface between stationary and flying qubits. A promising approach is a single semiconductor quantum dot (QD) embedded into a micropillar cavity : such a device can act as a bright emitter [1] as well as an excellent interface for single photons. In the latter case, the QD state can be coherently manipulated with few incoming photons [2]. Reciprocally, we have recently demonstrated that a giant rotation of photon polarization can be induced by a single spin qubit confined in a QD [3].

Here, we investigate the polarization rotation of coherent light interacting with a single QD, deterministically coupled to a micropillar cavity. Our experimental setup enables the complete analysis of the photon polarization density matrix in the Poincaré sphere. The devices we use (see Fig. 1(a)) were primarily intended to work as sources of indistinguishable single photons. Thanks to the brightness of these sources, the superposition of emitted single photons (H-polarized) with reflected photons (V-polarized) leads to a giant rotation of the output polarization, by 20° both in latitude and longitude [4]. The evolution of the resulting superposition state $\alpha|H\rangle + \beta|V\rangle$ can be illustrated in the Poincaré sphere while varying the excitation laser wavelength (λ) around the QD transition wavelength (see Fig. 1(a)). We experimentally and theoretically demonstrate that the coherent part of the QD emission contributes to polarization rotation, whereas its incoherent part contributes to degrading the polarization purity. This provides crucial information regarding the ability of our light-matter interface to coherently convert quantum information from a stationnary qubit to a photonic one.

These results open the way to numerous experiments whereby the evolution of a single electron spin, described in the Bloch sphere, can be monitored by or entangled with the evolution of a photon polarization qubit, described in the Poincaré sphere.

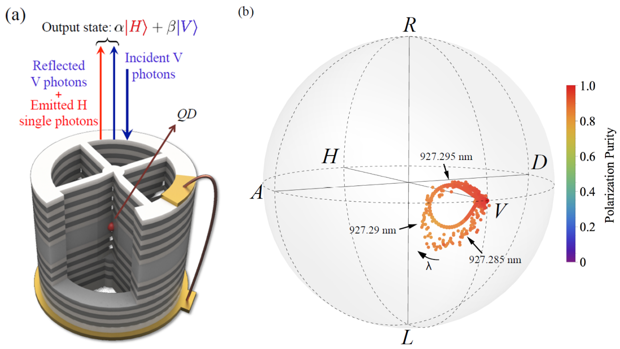

Figure 1 : (a) Scheme of the electrically-controlled QD-cavity device and the input-output fields. (b) Representation of the polarization state in the Poincaré sphere for varying excitation laser wavelength λ. The colorscale represents the purity of the polarization density matrix which is kept above 84% at all wavelengths. Line : simulations. Dots : experimental data.

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Near-optimal Single Photon Sources in the Solid State

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Bright sources of single and indistinguishable photons are crucial for the scalability of linear optical quantum computing. Recent works have shown that semiconductor quantum dots (QDs) are very promising to fabricate such sources : QDs deterministically emit true single photon states which can be efficiently collected if the QD is inserted in an optical structure.
Here we report on the fabrication and study of electrically tunable bright sources of fully indistinguishable single photons. We propose a cavity design which permits to apply an electric field while maintaining a 3D confinement for the photons. It consists of a micropillar cavity surrounded by Bragg mirrors doped in a p-i-n diode configuration, and connected to a larger ohmic-contact frame with four 1D-bridges (Fig.1a). A single QD is deterministically positioned at the center of the pillar by means of an advanced in-situ optical lithography [1, 2]. A strong Purcell effect is obtained with such a device when the QD transition is tuned into resonance with the CM, which in turn results in a very high brightness of the single-photon source, exceeding 0.6. We study the device at first by mean of non-resonant excitation and report a photon indistinguishability in the 0.7-0.8 range. Subsequently we demonstrate that performing strictly resonant pumping we can suppress completely any dephasing process thus obtaining near-unitary indistinguishability 0.998 ± 0.0086 of the emitted single photons ($g^{(2)}(0) = 0 \pm 0.0034$) (Fig.1b) [3]. High indistinguishability values around 0.9 are also observed at large timescales, i.e. for two photons separated by 430 ns, showing the ability of the present solid-state sources to provide long streams of highly pure photons, required for quantum information processing protocols (Fig.1c) [4].

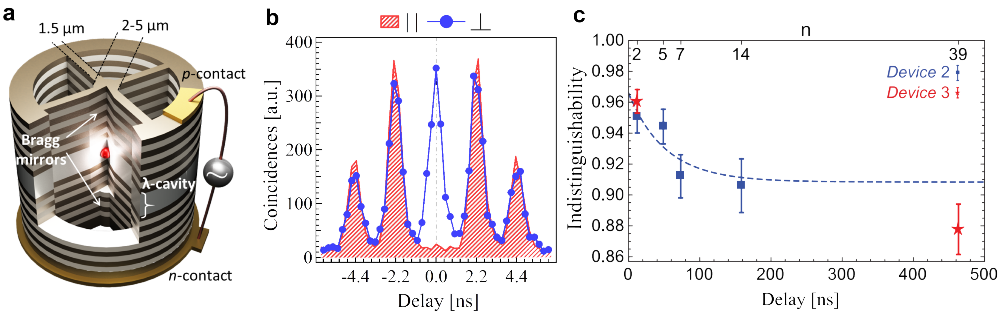

FIGURE 1: a) Schematic representation of the devices under study. b) Second order autocorrelation function in a Hong-Ou-Mandel experiment. The vanishing counts at zero delay show perfect single photon purity and full indistinguishability (0.998 ± 0.0086) of the source. c) Indistinguishability values between a first and n-th consecutive emitted photon for two different devices indicating purity robustness in the temporal domain.

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Optoelectronic detection of donor electron spins using bound excitons in ^{28}silicon.

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Enriched ^{28}Si is a prime candidate for semiconductor-based quantum information research, since the absence of nuclear spin leads to very long coherence times for impurity electron or nuclear spins. It also has another unique property - the almost complete elimination of inhomogeneous broadening for a wide variety of optical transitions, leading to improvements in spectral resolution of over an order of magnitude, and to linewidths which are almost lifetime-limited. Since the first observation of this effect in 2001 [1], there have been a number of new discoveries and applications. Among the most important is the ability to convert spin information into charge using donor bound exciton transition, providing an opto-electronic means of manipulating and reading out donor electron spins. These new methods has allowed electronic read-out of donor spin in highly enriched ^{28}Si very lightly doped with ^{31}P, resulting in the observation of long T_2 at 4 K [2]. This lays the foundation for realizing a single-spin readout with relaxed magnetic field and temperature requirements compared with spin-dependent tunnelling [3], enabling donor-based technologies such as quantum sensing.

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Phase transition of the two-photon Dicke model in the ultrastrong coupling regime

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We investigate, in the ultrastrong coupling regime, the presence of a phase transition in the two-photons Dicke model, which describes the interactions between a chain of qubits and a single bosonic mode [1]. The model is first analyzed through a mean-field analysis, which highlights the presence of a phase transition that impacts the field squeezing properties ; in contrast to the one-photon case, however, the field does not acquire macroscopic mean value. Additionally, the transition is not observed for all sets of parameters, due to the presence of a spectral collapse. In a further analysis, we use a method based on the decoupling of pseudospins eigenspaces [2] that allows us to obtain effective low energy physics and to characterize more precisely the state of the qubits and of the field. The qubit excitation spectrum, as well as the critical exponents of several observables, are also computed.

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Phase-sensitive amplification based on coherent population oscillations in metastable helium

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Phase-sensitive amplification (PSA) has been a subject of wide research over the last few years as it amplifies a weak signal without degrading its signal-to-noise ratio [1, 2]. It is further linked to the generation of squeezed states of light, which is of great interest in quantum optics and quantum information [3]. PSA can be realized either through three wave mixing process in non-linear crystals [1] or through four wave mixing (FWM) process in fibers or alkali vapors [2, 3]. In this work, we present our results on PSA in metastable helium (^{4}He) at room temperature [4]. The underlying physical process in this case is coherent population oscillations (CPO) which enhance the non-linearity in the system. The experiment is based on D1 transition in metastable helium and the Λ structure is extracted using linear polarization of signal-idler, orthogonal to pump polarization. This results in all the beams acting on both arms of the Λ (see fig. 1(a)) giving rise to coupled CPOs aiding in multiple FWM processes. In comparison to other alkali vapors, helium provides several advantages as it is free of hyperfine levels resulting in a simplified energy level structure and eliminates the possibility of unwanted FWM processes which could add extra noise and degrade the possible squeezing [3]. Thus, contrary to alkali vapors, we achieve high gain near the optical resonance. The set up is shown in fig. 1(b) : we detect the amplified signal at photodiode 2 and perform heterodyne measurement to measure the relative phase between the beams at photodiode 1. As the relative phase is scanned using a piezo actuator in the pump path, the signal undergoes amplification and de-amplification. The maximum PSA gain (G_{max}) depends mainly on the input pump power and the relative phase between the beams. In fig. 1(c), we have plotted (G_{max}) and minimum PSA gain (G_{min}) as a function of pump power. G_{max} of nearly 7 can be achieved for 40 mW of pump power and pump-signal detuning (δ) of 2 kHz. Further, G_{min} correspond very well to $1/G_{max}$, as expected for an ideal PSA [1]. Such large gains should lead to high degree of squeezing and high efficiency in the twin-beam generation.

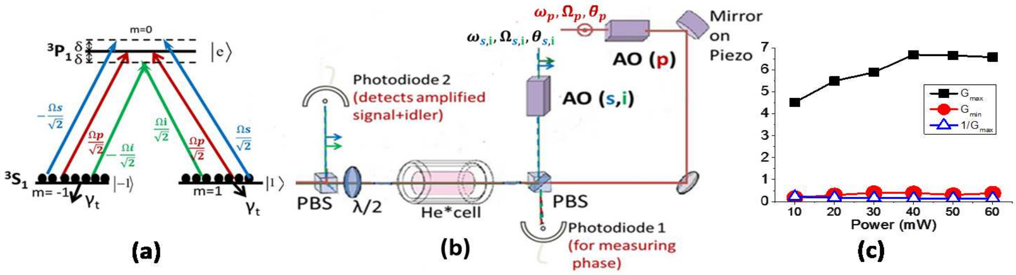

FIGURE 1: (a) Schematic of Λ structure, (b) experimental set up : the beams are derived from same laser and their frequencies and amplitudes are controlled by two acousto-optic (AO) modulators and are recombined before the cell using a polarizing beam splitter (PBS). The amplified signal is detected by photodiode 2. (c) Variation of G_{max} (squares) and G_{min} (circles) as a function of the pump power. $1/G_{max}$ (triangles) corresponds to the ideal value of G_{min}

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Quantum Zeno Dynamics in 3D circuit-QED

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We present our observation of the quantum Zeno dynamics (QZD) [1] in a 3D circuit-QED [2] system, where an artificial atom, consisting of a superconducting circuit called a transmon [3], is coupled to the electric field of a microwave cavity resonator. The transmon and resonator energy levels are aligned in a novel way enabling the manipulation of individual Fock states of the cavity, while minimizing its transmon-induced Kerr non-linearity [4]. We induce the QZD as in [5] by displacing classically the cavity field while continuously driving strongly a transmon transition specific to a particular Fock state, which keeps this Fock state population at zero. The QZD is then observed by measuring the Wigner function of the fields at regular time intervals, by standard quantum tomography and reconstruction of the density matrix. We observe three examples of QZD proposed in [6], and analyze the observed decoherence with the help of quantum simulations of the system.

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Quantum control of spin chains disturbed by chaotic noises

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A quantum system has the remarkable property of being in several states in the same time unlike a classical system. However, real quantum systems are never isolated, interactions with its environment induce quantum decoherence, i.e. transitions from quantum state superpositions into incoherent classical mixtures of eigenstates. In other words, the state superposition of quantum system is lost.

A quantum system often studied, the spin chain, is composed of spins which interact with each other. A spin can be viewed as a qubit which can be controlled to perform quantum calculations as logic gates. The spin chain control will be realised by trains of ultrashort pulses (kicks). Before to reach the spins, these pulses are disturbed by a classical environement, such as each spin views a different train. The environment generates a noise on the control which can produce decoherence and relaxation of the population [1]. The classical environment is choosen to be chaotic. A chaotic dynamics has the property of sensitivity to initial conditions. This one stipulates that two points initially really close will become exponentially separated from the horizon of predictability. In our model, the pulses are chaotically disturbed. Initially, those having an effect on two different spins will be really close (the spins are kicked in the same way) and will be separated from the horizon of predictability (the spins are kicked differently). The phenomenon induces a spin decoherence after the horizon of coherence ([2]) which is larger than the horizon of predictability. Before the horizon of coherence, it is possible to conserve the coherence in the spin chain

The spins conserving their coherence, it is possible to realise a control during the horizon of coherence ([3]). The control can act on two different ways. The first one uses the information transmission of the spins betwen them (due to their interaction) to induce a specific final state to the spins. The second one realises a total control on one or more spins. It is often with this last case that we can realise logical gates and more especially the "not" gate allowing to invert the spin states whatever their initial state. The importance of the control appears because the logic gate is the source of current conmputers but also of quantum computers.

Using this time characterizing the horizon of coherence, it is also possible to control other kind of materials as a spin ice. Spin ices are materials which have some exotic magnetic properties ($Dy_2Ti_2O_7$ or $Ho_2Ti_2O_7$) and particularly a magnetic monopole ([4]). This one can be controlled in order to periodically reborn. It is also possible to change the kind of control and using an adiabatic variation [5].

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Quantum dots under resonant excitation as efficient indistinguishable photon sources

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Developments in quantum information processes require the use of solid state quantum bits that would emit on demand single and indistinguishable photons. Semiconductor quantum dots (QDs) show an atom-like energy structure which makes them attractive in this regard. Though, the control of a 2-level system needs high coherence systems, which means that decoherence processes in the solid state have to be understood and controlled. Indeed, a single quantum dot (QD) constitutes an open quantum system coupled to its surrounding solid-state environment, the phonon bath and the fluctuating electrostatic environment. This has important consequences on the coherence properties of the electronic system and the QD is a probe to study these fundamental interactions.

Using an original geometry, we have demonstrated the possibility to address and coherently control a single exciton state in InAs/GaAs self-assembled QDs embedded in a one-dimensional waveguide with a strictly resonant pulsed laser excitation [1]. Photon correlation measurements show that a single QD is an on demand single photon emitter, without filtering or post-selecting the collected photons [2]. Performing Hong-Ou-Mandel experiments with two pulses separated by 2 ns, two-photon interferences (TPI) with a visibility around 85% have been demonstrated recently [2]. Our aim is to address the issue of dephasing experienced by the dot due to two main decoherence processes : the spectral diffusion which is a consequence of the charge (or spin) noise and the interaction with the phonon bath. Using Fourier spectroscopy and temperature-dependent resonant HOM experiments we show that these two mechanisms occur on very different time scales : spectral diffusion is a slow dephasing process acting on microseconds, while phonon interaction takes place in less than one ns. Then, the loss of indistinguishability in HOM measurements is only related to dephasing induced by the coupling to the phonon bath. The TPI visibility is preserved around 85 % at low temperature, followed by a rapid loss of coherence at a critical temperature of about 13 K. Temperature-dependent TPI can also reveal the influence of non-Markovian effects in the electron-phonon interaction. These new results are consistent with recent theoretical studies [3] where a fully microscopic model treating on an equal footing the electron-phonon and electron-photon interaction is used to explain decoherence.

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Quantum optical nonlinearities with Rydberg atoms

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In this poster, we theoretically investigate the quantum statistical properties of the light transmitted through or reflected from an optical cavity, filled with an atomic medium whose strong optical nonlinearity is induced by the van der Waals interactions between highly excited (the so-called Rydberg) atoms. Atoms in the medium are driven on a two-photon transition from their ground state to a Rydberg level via an intermediate state by the combination of a weak signal field and a strong control beam. Using three different approaches, from the simpler (semi-phenomenological) to the more sophisticated (many-body physics), we get perturbative numerical and analytic results which allow us to quantitatively explore new features of the response of the system.

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Quantum steering inequality with tolerance for measurement-setting-errors : experimentally feasible signature of unbounded violation

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Quantum steering is a relatively simple test for quantumness of correlations, proving that the values of quantum-mechanical measurement outcomes come into being only in the act of measurement. By exploiting quantum correlations Alice can influence – steer – Bob's physical system in a way inaccessible in classical world, leading to violation of some inequalities. Demonstrating this and similar quantum effects for systems of increasing size, approaching even the classical limit, is a long-standing challenging problem. Here we provide experimentally feasible signature of unbounded violation of a steering inequality. We derive its universal form where tolerance for measurement-setting-errors is explicitly build-in by means of the Deutsch–Maassen–Uffink entropic uncertainty relation. Then, generalizing the mutual unbiasedness, we apply the inequality to the multi-singlet and multi-particle bipartite Bell-state. However, the method is general and opens the possibility of employing multi-particle bipartite steering for randomness certification and development of quantum technologies, e.g. random access codes.

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Quantum synchronization and super/sub-radiance

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Collective phenomena in quantum systems induced by the interaction of their components with a common environment have been widely studied theoretically [1] in the last decades and are nowadays commonly experimentally investigated in many-body systems [2]. In this talk I report some analytical results about the connection between two such phenomena as spontaneous synchronization and super/sub-radiance.

Synchronization is one of the paradigmatic phenomena in the study of complex systems. It has been explored theoretically and experimentally mostly to understand natural phenomena, but also in view of technological applications. Although several mechanisms and conditions for synchronous behavior in spatially extended systems and networks have been identified, the emergence of this phenomenon has been largely unexplored in quantum systems until very recently. In particular, the emergence of spontaneous synchronization (i.e. in absence of a driving source) for coupled harmonic oscillators [3, 4] and for spins [5] in a common environment has been recently reported. It has been shown that spontaneous synchronization is based on the fact that the eigenmodes of the Redfield tensor, governing the system's evolution, decay on different time scales inducing the survival of single eigenmodes in some time windows.

The modification of the emission rates in a suitable collective basis is also responsible of the collective phenomenon of super and sub radiance for which a group of N emitters may interact with the environmental field in a collective and coherent way, emitting light with a pulse of large intensity scaling with N^2 [1, 2]. The phenomenon of super and sub radiance seems then to have physical roots similar to those of quantum synchronization.

In order to get an analytical insight about their connection, we have reexamined the dynamics of two detuned atoms coupled to a common environment using a formalism (Liouville representation) allowing to directly compare the two phenomena. We have found that in our model synchronization and super- and sub- radiance are two sides of the same coin. Indeed, we have found that the synchronization between averages of arbitrary single atom operators is due to the presence of long standing coherences between the ground state and a given one-excitation state $|A_R\rangle$ playing the role of the sub-radiant state. The decay rate of the total radiation rate starting from $|A_R\rangle$ is twice the decay rate of the coherence responsible of the synchronization, clearly showing that the two phenomena are intimately related. On the other hand, through this analysis we have identified the equivalent of the super-radiant state, $|S_R\rangle$. We have shown that the condition to have long standing coherences able to synchronize the two atoms is the same of having a strong super-radiant state.

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Quantum thermal transistor

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Harvesting or managing heat loss in energy transformation processes is becoming a very important challenge due to global warming issues and limited energy resources. While heat can be guided and transported by good thermal conductors and heat pipes, there is nothing to modulate or amplify, as it is the case for electricity. From a historic point of view, electricity has been managed through the development of two main components : the diode and the transistor. These components have changed everyday life starting the second half of the 20th century. Recent researches have shown that it is possible to achieve the so-called thermal rectification (Asymmetric exchanged heat flux between two bodies when their temperatures are inverted) in conduction [1], radiation [2] or even quantum systems [3]. Some of these concepts have been proved experimentally [4] and have paved the way to passive temperature control. Researches about thermal transistors are much recent. They have been conducted theoretically in thermal radiation using phase change materials. So far obtained results are very encouraging, which makes realization of logical thermal circuits a very optimistic perspective [5]. The question that naturally arises is whether it is possible to conceive such thermal transistors with elementary quantum objects such as quantum dots embedded in a material.

We show in this work that it is indeed possible to conceive a thermal transistor with three coupled two-level systems (TLS), each of them being attached to a thermal bath [6]. Following the work of Werlang et al. [3], we introduce a Hamiltonian of the coupled system and obtain Lindbladians on the basis of the eigenstates of the full system. We solve the master equation in the steady state in order to have all level populations and life times that allow us obtaining the currents that go from the three reservoirs to the coupled TLS. We show that the three latter coupled TLS play the analogue role of the emitter, base and colector in a bipolar electronic transistor. A case, particularly interesting to understand the process, consists of three degenerated TLS being coupled two by two except two of them. In this situation, the current coming from the reservoir playing the role of the gate is always much smaller than the two other currents. Whatever is its temperature, we introduce a transistor gain and show that this gain remains much higher than 1 in a wide temperature range for the gate, when the transistor components (emitter, base and collector) temperatures remain lower than the typical energy coupling. We also determine an regime where the transistor properties could be optimized.

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Shaping of single photons enabled by entanglement

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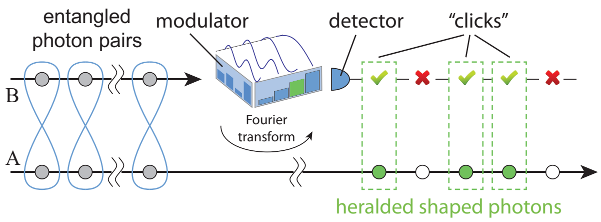
The ability to produce shaped single photons, i.e. photons in a desired spatial-temporal optical mode, is the crucial prerequisite in many modern research areas, particularly, in quantum information science [1].

Methods for photon shaping can be tentatively split into two groups. Methods of the first group shape the photons during the photon generation process by controlling the properties of quantum emitters. The corresponding experimental setups are rather complex, expensive and have limited flexibility. Methods of the second group shape the photons after the photon generation process, and rely either on reshaping or post-selection. They are experimentally simpler, but unavoidable losses that accomplish the photon manipulations lead to probabilistic and non-scalable production of shaped photons.

In this work we propose generic single-photon shaping method [2] which is both conditionally lossless, scalable, practical and overcomes the above mentioned limitations. The main idea is schematically illustrated in Fig. 1 and briefly outlined below.



As the main resource the method uses pairs of photons A and B that entangled with respect to the degree of freedom which is subject to shaping. Photons B probabilistically pass through a modulator which forms a required single-photon shape. A single photon detector is placed after the modulator and detects photons B in the basis which is Fourier conjugated to the modulation basis. Clicks of this detector deterministically herald the shaped photons A (marked green), while the "no-click" cases are discarded (marked white).

The proposed method has several distinctive features. First of all, it is very versatile and can be used to shape single photons with respect to any degree of freedom (particularly, temporal shaping [3]). Moreover, the method allows for shaping photons with respect to several degrees of freedom simultaneously, e.g. joint shaping of amplitude and polarization. Second, the method does not use any direct manipulation with the signal photon, but only with the idler one. As a consequence of such indirect heralded shaping, shaped photons are produced in a conditionally lossless way. This aspect makes the method scalable for producing many shaped single photons, which is vital for quantum information processing tasks. Last but not least, the method is absolutely feasible to realize in experiment since all the required ingredients are readily accessible.

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Statistical Signatures of Boson Sampling

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The complexity of a quantum system drastically increases with its number of particles, which gives rise to many conceptual, analytical and computational difficulties. A well-known source of such difficulties is the interaction between particles. Nevertheless, also the indistinguishability of particles as such can lead to dynamical interference effects which go well beyond mere quantum statistics, even in absence of interactions. Recently, these many-particle interference effects became the centrepiece of the debate on boson sampling, connecting them to quantum supremacy. As a core message, it was explicitly stressed that such interference patterns are computationally intractable. As a consequence, we are confronted with apparent difficulties upon certification of many-particle interferometers. However, from a complex systems perspective, the lack of deterministic features in a physical system is a common problem which can often be overcome via statistical treatment. In this contribution, we present statistical signatures of different types of many-particle interference by studying correlation functions combined with techniques from random matrix theory [1, 2].

In particular, we focus on the setup sketched in Fig. 1, where photons are transmitted through a linear optics circuit to ultimately be detected by an array of photon counters. The arrival times of the different photon wave packets govern the degree of indistinguishability. In the case where all photons arrive at exactly the same time, this scenario becomes a case of ideal boson sampling. The statistical signatures of many-particle interference are obtained through the two-point correlations $C_{ij} = \langle \hat{n}_i \hat{n}_j \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_j \rangle$ between different pairs of detectors. They offer a powerful tool for the evaluation of the degree of indistinguishability and for the certification of boson sampling.

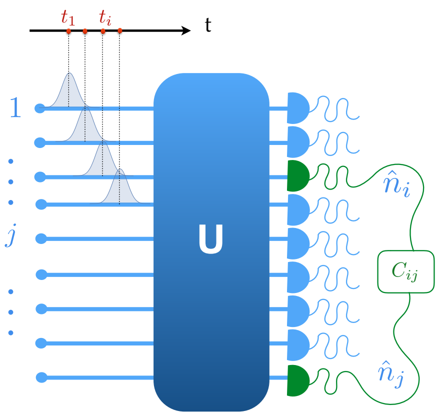

FIGURE 1. Sketch of the setup. m input modes are connected by a linear optical circuit to m output modes, on each of which a photon counter is mounted. The initial state consists of n (here four – topmost modes on the left) photons which are described by wave packets. The photons are injected at possibly distinct times t_j.

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The Big Bell Test – A Bell inequality test driven by human randomness
30$^{\mathrm{th}}$ November 2016

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The unambiguous demonstration of the existence of entanglement has remained a long-standing quest. In 1935, Einstein, Podolsky and Rosen (EPR) pointed out the question whether the quantum-mechanical description of physical reality be considered complete, or if local hidden variables predetermine measurement outcomes [1]. Almost 30 years later, Bell developed the theoretical framework allowing researchers to design experiments for answering the EPR question – the Bell inequalities [2]. If these inequalities are violated, then measurement outcomes cannot be predetermined by local hidden variables. As a consequence, entanglement and its spooky interaction at a distance must exist. First experimental results have been demonstrated in 1972 by Freedman and Clauser [3], favouring the existence of entanglement. Ever since then, an almost infinite amount of experiments has been carried out, all favouring the existence of entanglement.

However, it was only until 2015, when unambiguous violations of the Bell inequalities have been demonstrated [4–6]. One critical issue in these experiments has been the totally random choice on the measurement basis settings for the two particles under test. This is necessary to prevent that the particles can know beforehand how they are going to be measured. The three above mentioned experiments have therefore relied on quantum random number generators.

In The Big Bell Test, we will use human beings as random number generators. Initiated by Prof. Morgan Mitchell, several research teams from around the world have teamed up to perform the first Bell inequality test powered by human randomness. The following groups are participating : ICFO Barcelona (Spain), CQC2T Brisbane (Australia), DIE Concepción (Chile), ISY Linköping (Sweden), University of Sevilla (Spain), DFS Rome (Italy), CAS and USTC Shanghai (China), EQUS Brisbane (Australia), IQOQI Vienna (Austria), LMU Munich (Germany), LPMC Nice (France), QUDEV and ETH Zurich (Swiss).

All the groups will run, at the same time, a 48-hour long Bell inequality test in which human beings from all around the world can choose the random measurement settings in real-time via smartphones, tablets, and computers.

Random numbers, that will be streamed to the different research laboratories, can be generated on The Big Bell Test internet webpage, www.TheBigBellTest.org. In order for this experiment to be a success, at least 30 000 people have to contribute at least 30 000 sequences of random bits.

Besides introducing general framework of The Big Bell Test, we will also detail the particular entanglement source that we have developed in our laboratory in Nice. It is based on a highly-reliable fully fibred Sagnac interferometer, generating polarization entangled photon pairs at 1559 nm and 1561 nm. The random basis settings from the human beings are implemented using electro-optic phase modulators. With our setup, we will be able to perform $\sim 30 \cdot 10^6$ measurements per hour.

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The excitonic qubit coupled with a phonon bath on a star graph : anomalous decoherence and coherence revivals

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Based on the operatorial formulation of perturbation theory, the dynamical properties of a Frenkel exciton coupled with a thermal phonon bath on a star graph is studied. Within this method, the dynamics is governed by an effective Hamiltonian which accounts for exciton-phonon entanglement. The exciton is dressed by a virtual phonon cloud whereas the phonons are dressed by virtual excitonic transitions. Special attention is paid to the description of the coherence of a qubit state initially located on the central node of the graph. Within the nonadiabatic weak-coupling limit, it is shown that several time scales govern the coherence dynamics. In the short time limit, the coherence behaves as if the exciton was insensitive to the phonon bath. Then, quantum decoherence takes place, this decoherence being enhanced by the size of the graph and by temperature. However, the coherence does not vanish in the long time limit. Instead, it exhibits incomplete revivals that occur periodically at specific revival times and it shows almost exact recurrences that take place at particular super-revival times, a singular behavior that has been corroborated by performing exact quantum calculations.

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Will the qubits of the quantum computer remain mesoscopic ?

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Quatorze ans après la réussite de l'ordinateur à 7 qubits de Chuang et l'arrêt de son développement [1], nous proposons une réflexion sur les fondements de l'ordinateur quantique. Nous discutons en particulier la réalité physique des qubits individuels tant au niveau expérimental que théorique.

Au niveau expérimental, il y a une forte différence dans les réalisations entre

1) fabriquer, maintenir et observer des qubits individuels

2) fabriquer un ordinateur quantique qui réalise un microprogramme avec ses qubits.

Or expérimentalement, on réalise effectivement le cas 1 avec des qubits individuels qu'on maintient et qu'on observe comme l'on montrait en particulier Serge Haroche et David Wineland.

Mais pour le cas 2, les seuls ordinateurs quantiques actuels qui réalisent des opérations effectives, sont des ordinateurs avec des qubits mésoscopiques. Cela était déjà le cas des différents ordinateurs développés en 1997, 1999 et 2001 par Chuang : pour chaque qubit, il utilise un ensemble de 100 millions de molécules avec la technique RMN. Et comme il est passé d'un ordinateur avec 2 qubits, puis 4 qubits, puis 7 qubits, il a pu montrer que sa mesure est un signal qui décroit d'un facteur 2 à chaque qubit supplémentaire. C'est pour cette raison qu'IBM et Chuang ont arrêté ce type de développement. C'est aussi le cas des ordinateurs quantiques basés sur la jonction Josephson : chaque qubit est représenté par un milliard d'atomes d'aluminium [2]. C'est aussi le cas de ordinateurs basés avec des qubits photoniques sur des chips photoniques [3].

Au niveau théorique, l'ordinateur quantique parallèle est basé sur l'interprétation de Copenhague et des mondes multiples d'Everett où la mécanique quantique est considérée comme un modèle complet de la réalité et où on identifie la particule physique avec sa fonction d'onde (qubit). Dans la théorie de de Broglie-Bohm-Bell (dBBB), la fonction d'onde ne suffit pas pour représenter complètement la réalité du système quantique et il faut lui ajouter la position de la particule (variable cachée). Cette théorie est non locale et n'est pas invalidée, comme le rappelle Laloë [4], par les inégalités de Bell et les expériences d'Aspect. Au contraire, la théorie de dBBB explicite clairement la non-localité de la mécanique quantique. L'évolution du système quantique (fonction d'onde + position) est alors déterministe. C'est ce que l'on montre l'analyse mathématique de l'expérience de Stern et Gerlach [5]. Dans cette théorie, un qubit est représenté par la fonction d'onde et par au moins deux particules pour représenter les deux alternatives. La théorie dBBB explique simplement pourquoi les seuls ordinateurs quantiques implémentant actuellement des algorithmes quantiques sont des ordinateurs basés sur des qubits mésoscopiques. Elle permet aussi de donner une réponse simple au problème de Chuang pour qui les signaux magnétiques qui mesurent l'orientation des spins et déterminent les états quantiques deviennent excessivement faibles à mesure que le nombre de qubits augmentent, faiblissant d'un facteur voisin de 2 pour chaque qubit supplémentaire.

Finalement, la faisabilité de l'ordinateur quantique parallèle (avec des qubits individuels) dépend de l'interprétaion de la mécanique : faisable dans l'interprétation des univers parrallèles d' Everett, mais impossible dans la théorie de dBBB.

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Quantum Communication & Cryptography (QCOM)

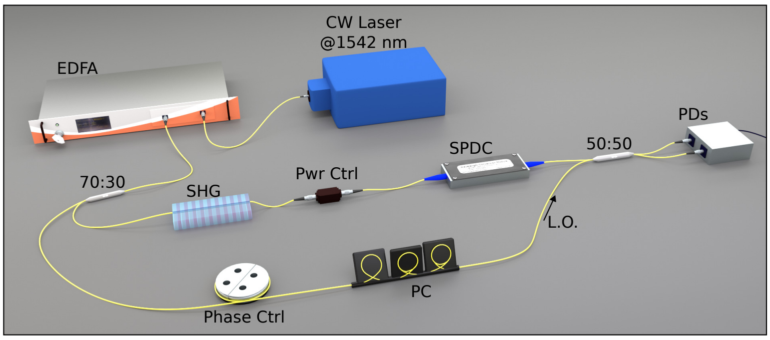

FIGURE 1. Schematic experimental setup

A fully guided-wave approach to the generation and detection of squeezing at a telecom wavelength

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In the last years, the application of squeezed light to quantum information science has experienced. In order to comply with out-of-the-lab realizations of CV quantum optics and their application to quantum communication in optical fibers, we demonstrate, for the first time, the feasibility of a full guided-wave approach for both the generation and measurement of squeezed light at a telecom wavelength [1]. The experimental setup is represented in Fig.1 : it is entirely based on plug-and-play components fully compatible with existing telecom fiber networks. In our scheme, single-mode squeezing at 1542 nm is generated via single pass degenerate spontaneous parametric down conversion (SPDC) in a periodically poled lithium niobate ridge-waveguide (PPLN/RW). The SPDC is pumped by a continuous wave laser at 1542 nm, whose frequency is previously doubled to 771 nm via second harmonic generation (SHG) in a dedicated PPLN waveguide. At the output of the SPDC stage, squeezed light is collected by a butt-coupled optical fiber and measured with a fiber homodyne detector based on a 50 :50 fibre beam splitter (50 :50) whose outputs are connected to two InGaAs photodiodes (PDs). The overall detection efficiency, including the coupling and detection efficiencies, is $\eta = 0.54 \pm 0.01$. We measured the squeezing and anti-squeezing as functions of the LO phase for different SPDC input pump powers. Experimental data for both squeezing and anti-squeezing correctly follow the quadratic behavior predicted by the theory as expected in the absence of unwanted excess noise on anti-squeezed quadratures. At the highest input pump power (28 mW at 771 nm) we measured a raw squeezing of -1.83 ± 0.05 dB. By correcting this value for η, we can infer at the output of the waveguide a squeezing of ≈ -3.3 dB, which is among the best values reported to date for CW-pumped squeezing.

To conclude note that compared to bulk implementations, the fully guided-wave approach offers multiple advantages. Efficient single pass SPDC in waveguides offers high compactness and stability and allows obtaining a broad squeezing emission bandwidth. At the same time, besides the miniaturization of the setup, the fiber homodyne allows achieving a high degree of spatial mode matching between the LO and the signal without optical adjustment [2]. These advantages make our approach a valuable candidate for real-world quantum communication based on CV quantum optics.

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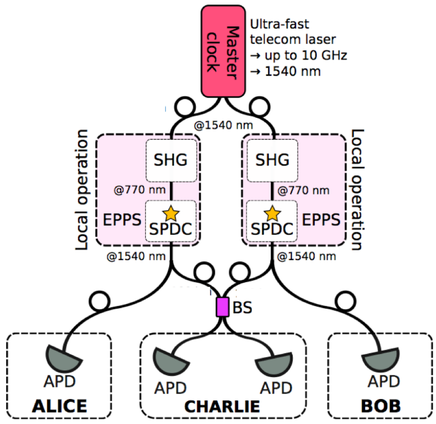

FIGURE 1. Schematic experimental setup

All-optical synchronization for quantum networks

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Entanglement based quantum communications and quantum networking protocols are today considered as main tools to address the urgent problem of secure communications. In this context, the architecture know as *quantum relay* plays a crucial role for long distance realizations where the propagation losses combined with detector imperfections can severely limit the link performances. The basic idea is to break a long channel into shorter subsections, each spanned by a pair of entangled photons, and then to use the protocol of entanglement teleportation to link the subsections together [1]. The success of the protocol relies on the perfect indistinguishability of the photons interfering at the relay stations : in particular, the time uncertainty on the photon arrival times must be smaller that their coherence time. Experimentally, a major bottleneck is represented by the synchronization of the remote entangled photon pairs sources (EPPS) which are usually pumped by independent lasers that must be locked together [2]. In our experiment, we show how to circumvent this problem by employing a single master clock laser at telecom wavelength that is distributed to the different EPPS. This configuration allows providing an all-optical, jitter free synchronization, compatible with long distance propagation in optical fibers and pump high repetition rates.
The experimental setup is represented in Fig. (1). The master clock laser generates ps pump pulses at 1540 nm at a repetition rate of 2.5 GHz that are distributed towards two remote sources. Here they are locally frequency doubled to 770 nm (SHG) and used to pump periodically poled lithium niobate waveguides so as to generate via spontaneous parametric down conversion entangled photons at telecom wavelengths (SPDC). A wavelength division multiplexing stage allow separating idler photons at 1543 nm to the outer channels (Alice and Bob), and signal photons at 1537 nm towards the relay station (Charlie) where they interfere on a 50 :50 beam-splitter (BS). Four-fold coincidences are measured. The quality of the synchronization is measured via a Hong Ou Mandel interference (HOMI) measurement : when the inner photons are perfectly indistinguishable, coincidence counts are expected to drop to zero. Our experimental results show a HOMI raw visibility greater than 99% clearly validating the quality of our synchronization scheme.

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Ambiguity–Losses Trade-Off for State Discrimination

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Given a set of non-orthogonal linearly independent quantum states, unambiguous discrimination is only possible at the price of some losses. On the other hand the ambiguity of a lossless measurement can be evaluated by different figure of merits, depending on the application. Many of these figure of merits can be mapped to conditional Rényi entropies of various coefficients α. Using their parent quantity — the α-z-relative Rényi entropy $D_{\alpha,z}(\rho\|\sigma)$ introduced by Audenaert and Datta — we find here, for a set of equally likely symmetric states, the minimal value of these conditional entropies as a function of losses.

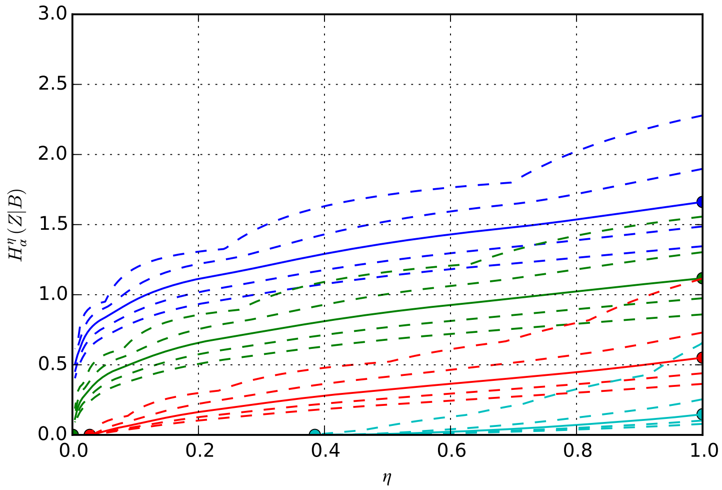

FIGURE 1. Each beam of curve corresponds to same constellation of 8 coherent states states, with an average photon number $\mu \in \{.5, 1, 2, 5\}$ from top to bottom. In each beam is plotted the α-z-conditional Rényi entropy $H^{\uparrow,\eta}_{\alpha,z}(Z|B)$, with α describing $\{\frac{1}{2}, 1, 2, \infty\}$ upwards, as a function of the success probability of η of the measurement. The $\alpha = 0$ curve is hidden, since it corresponds to $H_2^{\downarrow,\eta}(Z|B) = \widetilde{H}_\infty^{\downarrow,\eta}(Z|B) = 0$.

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Coherent Population Oscillation-Based Light Storage

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Optical quantum information processings need devices able to store quantum states of light and retrieve them on demand with high fidelity and efficiency. Λ-type three-level atomic systems have received particular attention (Electromagnetically Induced Transparency (EIT), Photon Echo, Frequency Combs...) because the coherence between the ground states – the Raman coherence – may have a long lifetime and can thus be used for storage. Nevertheless, since these protocols rely on the excitation of this coherence, they are quite sensitive to dephasing effects.

Recently, it was experimentally shown that coherent population oscillations (CPO) can be a support for classical light storage in Λ-system using metastable helium vapor at room temperature [1], as well as in cold and warm cesium [2, 3]. CPO occur in a two-level system when two δ-detuned coherent electric fields of different amplitudes drive the same transition. When δ is smaller than the decay rate of the upper level, the dynamics of the saturation opens a transparency window in the absorption profile of the weak field. The CPO lifetime may be increased using a Λ-system where two CPO resonances may occur in opposite phase on the two transitions, resulting in a global CPO resonance between the two lower states [4]. This implies an ultranarrow transmission resonance for the weak field broadened by the ground states decay, which can be used for storage. Moreover, since it involves only populations, CPO-based light storage protocol is then robust to dephasing effects.

We theoretically explore the propagation of a weak field in a Λ-atomic medium excited by an intense field driving the two transitions. We show that the four eigenmodes of propagation have propagation features (group velocities and transmission coefficient) that strongly relate to the two CPO excitation modes of the system. When the CPO in each arm are in phase (antiphase), it yields a global CPO mode between both lower states and the upper state (between the lower states while the upper state population remains constant). In each case, the CPO mode couple to a specific quadrature of an eigenfield of propagation, and is damped by the upper level or lower levels decay rates respectively. These eigenfields have strongly reduced group velocities and good transmission coefficient, as required for storage protocols. We then introduce a new field that we call « populariton », mixture of the populations – matter component characterizing the CPO mode – and its eigenfield coupled quadrature – light component –, by analogy to the dark state polariton put forward in EIT-storage protocols [5]. This allows us to qualitatively understand CPO-based light storage sequence. The existence of two CPO excitation modes suggests that both quadratures of the signal field might be simultaneously stored in populations, with robustness to decoherence effects, as required for quantum memories.

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Demonstration of EPR steering using single-photon path entanglement and displacement-based detection

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Single photon entanglement is the simplest and natural form of entanglement; it appears when a single photon is sent on beam splitter [1]. During a long time, this type of entangled state was controversial due to the fact that we are not able to analyze it with non-local measurements. Today it lies at the heart of key quantum information protocols, such as quantum repeaters, and is the essential resource for heralded photon amplification. This approach offers a promising alternative to standard two-photon entanglement, with the advantage of heralding and scalability.

Here, we report the violation of quantum steering inequality by a delocalize single-photon entangled state using a heralded single photon source and an all-fiber displacement-based measurement scheme featuring high-efficiency superconducting nanowire single photon detector [2]. Our setup is inherently post-selection free, with global efficiency sufficiently high allowing us to conclusively demonstrate single-photon path entanglement in a one-sided device-independent scenario. Moreover, our approach is directly extensible to a loophole-free Bell-inequality test, and thus to the implementation of fully device-independent protocols [3]. This approach can also be combined with an heralded single photon amplifier, which already demonstrated a gain greater than 100 [4], to overcome the propagation losses and perform device-independent quantum key distribution protocoles over long distance.

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Entanglement distribution across a quantum peer-to-peer network

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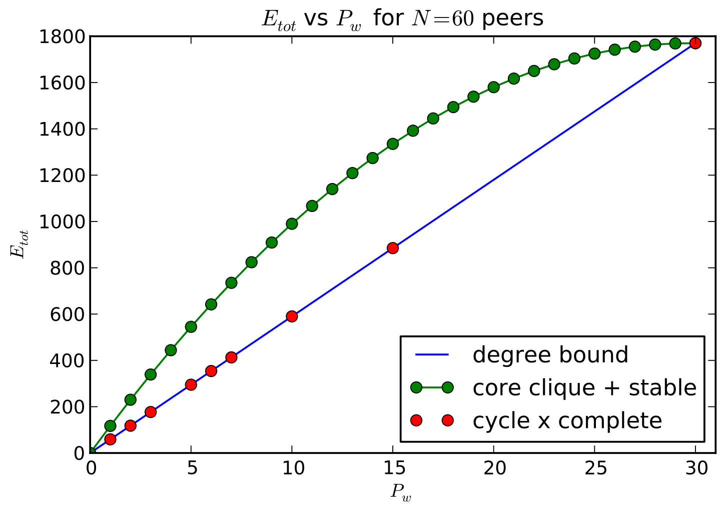
Quantum repeaters have been proposed to overcome the practical distance limit of quantum communication between two parties. My work was to go beyond this linear scheme and explore the possibilities offered by an arbitrary network of such repeaters, connecting N clients. We model these networks by graphs where each vertex corresponds to a client and each edge to a quantum repeater sharing a maximally entangled pair between the two connected peers. A client can either perform a Bell measurement between two qubits or keep only one qubit; all the other qubits owned by the client are thrown away. In a single time step, two vertices (the sender and the receiver) can share entanglement if they are connected by a continuous path in the graph: the vertices along the path have to perform a Bell measurement and classically communicate their results to the sender and the receiver.

Furthermore, the above strategy allows to simultaneously share EPR pairs between several pairs of clients if the corresponding paths are vertex disjoint. If the main cost of such a network is proportional to the number of repeaters, the efficiency of a network is obtained by comparing the number P of EPR pairs that can be shared simultaneously to the resources used to generate the graph *i.e.* the total number of edges E_{tot}. We have studied two figures of merit: P_w the maximum number of EPR pairs that can be shared simultaneously in the worst case, where clients are chosen by an adversary; P_a the average number of EPR pairs that can be shared simultaneously across the network when the client are chosen at random.

P_w is upper bounded by the minimum degree δ: $P_w \leq \frac{\delta}{2} \leq \frac{E_{tot}}{N}$ and also by the non-orientable genus of the graph g: $P_w \leq g+1$. We construct two graph families (almost) saturating this degree bound: one is a complete bipartite graph with a clique of order $2P_w$ on one side and a stable of order $N-2P_w$ on the other side; the other is a Cartesian product of a cycle and a complete graph.

If the range l (in terms of physical distance) of a repeater is small compared to the size D of the network, it is relevant to investigated networks lying in a region of diameter D in a d-dimensional space ($d = 2$ or 3). For the average case when the client spatial density is uniform, P_a is upper bounded $\frac{P_a}{E_{tot}} = O(\frac{l}{D})$ meaning that keeping the ratio $\frac{P_a}{E_{tot}}$ and the client density constant implies a maximum distance of communication in this model. When the range limitation l is the only connectivity limit, P_a is also lower bounded: $\frac{P_a}{E_{tot}} = \Omega[(\frac{l}{D})^d]$.



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Experimental realization of equiangular three-state quantum key distribution

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Quantum key distribution (QKD) is a cryptographic technique whose security is based on the laws of quantum mechanics. Relevant QKD schemes include the BB84, which uses four states in two non-orthogonal bases and is secure up to a bit error rate of about 11% [1], and the B92, using just two non-orthogonal states but with a security threshold dependent on channel losses [2]. The security of B92 can be enhanced by adding a third state. The optimal three state protocol, introduced in 2000 by Phoenix-Barnett-Chefles (PBC00) [3], uses states that form an equilateral triangle in the X-Z plane of the Bloch sphere and is secure, in the asymptotic case, up to an error rate of 9.81% [4]. An improvement of this protocol, introduced by Renes in 2004 (R04) [5], allows to estimate the error rate directly from the number of inconclusive events, thus avoiding the public transmission of part of the key for error estimation.

We aim to present our recent experimental demonstration of an entanglement-based version of the R04 protocol [6]. We use a source of polarization-entangled photons based on a Sagnac interferometer and two identical POVMs for Alice and Bob that use only passive optical elements in a linear scheme. With this setup, we obtain an asymptotic secure key rate higher than $10\,\mathrm{kbit/s}$ and a mean quantum bit-error rate (QBER) of 1.6% for at least 2 hours of continuous acquisition. We then extend a recent study of the finite key security of the PBC00 [7] to the R04, evaluating the secure key rate for both collective and general attacks.

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Experimental temporal ghost imaging with twin photons

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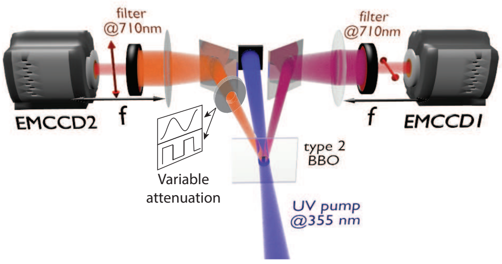
We propose an experiment that aims at reconstructing a temporal signal, acquired with a camera that totally integrates the signal, i.e. acquired without any temporal resolution.

This experiment of temporal ghost imaging can be realized with the use of two twin series of random events. These events can be patterns generated by a computer [1], intensity fluctuations of an incoherent source [2], or in our case, twin images of fluorescence emitted by spontaneous parametric down conversion [Figure 1].
The patterns of one series (signal images) are first weighted by a variable density whose value is given by the temporal signal. The patterns are then summed by a camera (here EMCCD2) to form a single picture with random events, so that the temporal signal seems to be completely lost in the image. However, the unweighted patterns of the other series (idler images) are acquired by a second camera (EMCCD1), as reference patterns.
A comparison of the integrated image with each reference pattern, performed by computing the cross-correlation of the pictures, allows the reconstruction of the shape of the signal.

The complexity and the length of the signal that can be reconstructed depend on the degree of correlation of the twin patterns, and on the number of independant resolution cells in the images. A degree of correlation of 28% between two twin images [3] allowed us to reconstruct a temporal signal made of eight binary values, with 4% errors on the values interpretation. Each reconstruction is operated only once, with an acquisition time below a half second, and does not need any a-priori information on the hidden signal.
This method can be used to hide a full signal, or subdivisions of a much longer signal, making it unreadable for those who don't have the reference patterns.



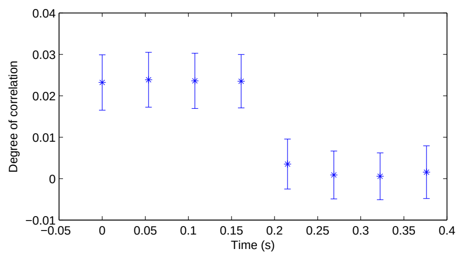


FIGURE 1. Left : Experimental setup. Right : Mean on 1000 reconstructions of the same binary signal.

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Generation of temporally multiplexed pairs of photons with controllable delay in a crystal

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Entanglement of remote systems is at the core of quantum communication protocols, and the distribution of this entanglement remains one of the main challenge in this field. Especially, as the distance between the parties increases, the amount of entanglement diminishes due to channel imperfections, and devices as quantum repeaters have to be used [1]. A possible way of implementing these devices is to use the DLCZ protocol [2], in order to store entangled excitations in spatially separated media and thus distribute the entanglement.

We show here the first implementation of the DLCZ protocol in a rare-earth ion doped crystal, which allowed us to store correlated pairs of photons for 1 ms. Amongst others, using such devices as quantum repeaters provides the interest of long coherence times and high multimode capacity due to the very large inhomogeneous broadening. As the electric dipole of these material is very weak, the control pulses (write and read pulses) must be applied on resonance, so that the write photons (Stokes photons) are spontaneously emitted from the excited state of the lambda system. Due to the very large inhomogeneous linewidth of the optical transition, we use a technique initially designed for quantum memories application in order to rephase the atoms after the emission of this Stokes photon : the atomic frequency comb (AFC) technique [3, 4]. In this method, the inhomogeneous profile is shaped with a comb-like structure with teeth spacing Δ, so that any photon absorbed on the tailored structure will create a coherence that will rephase after a time $1/\Delta$. In the DLCZ experiment, this relates to the fact that the anti-Stokes photon (read photon) will be emitted at a very precise instant, when the atomic coherence is rephased. In addition, this protocol allows for the emission of the anti-Stokes photon on demand, as the optical coherence is frozen in a spin transition, like in the spin-wave storage protocol [5].

We implemented this experiment in an isotopically pure $^{151}Eu^{3+}:Y_2SiO_5$ crystal with europium concentration of 1000 ppm, and we work on the visible 4f $:^7F_0 \longrightarrow$ 4f $:^5D_0$ transition at 580.04 nm. The nuclear quadratic hyperfine splitting of the ground state is used to define the two ground states of the lambda system. By using an AFC time of $1/\Delta = 20$ μs and a spin storage time of 1 ms, we could retrieve photons with a cross-correlation function of $g_{si} = 4$, giving a strong intuition of the non-classical correlations between the two temporally separated photons. In addition, the photons have a temporal width of 400 ns and are detected on a temporal gate of 10 μs, which means that the temporal multimode capacity of our protocol is of more than 10 modes.

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High quality entanglement from a silicon chip in wavelength demultiplexed channels

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Integrated quantum photonics has already proven its suitability for high-performance photon-pairs source realisations [1]. Silicon platform has recently found huge interest in photonics, and more particularly for generation of entangled photons-pairs [2] thanks to their outstanding properties, such as high integration density, CMOS compatibility, and efficient nonlinear optical properties, associated with well-established and mature technology. This photonics platform stands as one of the most promising for dense functionality integration, such as integrated ring resonators which already enable producing entangled photons thanks to enhanced third-order nonlinear processes [3].

Here, we report an efficient energy-time entangled photon-pair source based on four-wave mixing occuring in a silicon ring resonator. The source shows a large spectral brightness of 400 pairs of entangled photons /s/MHz for 500 μW pump power, compatible with standard telecom dense wavelength division multiplexers. We demonstrate high-purity entanglement, *i.e.* free of photonic noise, with near perfect raw visibilities (> 98 %) between various channel pairs in the telecom C-band.

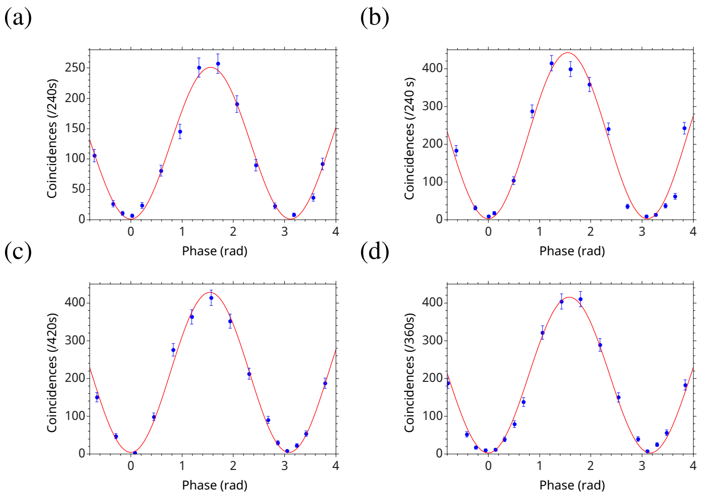

FIGURE 1: Two-photon interference fringes obtained with energy-time entangled photons. The curves show the coincidence counts for the ITU paired channels 48/52 (a) 45/55 (b) 43/57 (c) and 41/59 (d) as a function of the interferometer phase.

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Large-bandwidth entanglement distribution for high-rate wavelength division multiplexed quantum key distribution

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Quantum key distribution (QKD) provides a unique tool to establish communication with known security [1]. QKD systems are already commercially available, and many laboratories are performing research towards improving both, the speed and communication distance of those systems. One of the most promising routes in the race for increasing QKD bit rates lies in dense wavelength division multiplexing (DWDM) of independent signals in and out of a single fiber link [2, 3]. In this sense, QKD based on entangled photon pairs, generated via spontaneous parametric downconversion or four-wave mixing, is a very interesting candidate, as the conservation of the energy naturally generates a flux of multiplexed and correlated photon pairs (see FIGURE 1(a)).

Here, we answer to the question of how many wavelength multiplexed signals can be analysed simultaneously using the commonly used configuration for revealing energy-time entanglement [4], *i.e.* two unbalanced fibre interferometers [5]. Using two equally unbalanced analysers at Alice's and Bob's locations allows performing DWDM QKD with a quantum bit error rate (QBER) below 0.5% in 16 ITU channel pairs (100 GHz grid) simultaneously. However, the standard telecommunication C-band ($1530\,\mathrm{nm} - 1565\,\mathrm{nm}$) spans 44 channels. Therefore, exploiting the entire C-band requires either dynamically adapting the interferometers as a function of the wavelength, and/or employing multiple pairs of interferometers, all of them actively phase stabilized at the same time. Both of these strategies increase significantly the resource overhead.

We will demonstrate that the situation is significantly improved by using two non-identical interferometers, allowing to analyse energy-time entanglement simultaneously in up to 46 channel pairs (see FIGURE 1(b)). The key towards upstanding our strategy lies in the influence of chromatic dispersion in the fibre interferometers. QKD necessitates the following condition for the summed up phase shift that Alice's and Bob's photon experience in the interferometers : $\phi_\mathrm{A} + \phi_\mathrm{B} = 0 \bmod \pi$. Due to chromatic dispersion in the fibre analysis interferometers, this condition is hard to fulfil over a large spectral range. It turns out that the optimal configuration is characterized by the following equation : $\frac{\Delta L_\mathrm{A}}{v_\mathrm{A}} = \frac{\Delta L_\mathrm{B}}{v_\mathrm{B}}$. Here, $\Delta L_\mathrm{A,B}$ represent the physical path length difference of Alice's and Bob's interferometer. $v_\mathrm{A,B}$ denote the average photon group velocities of Alice's and Bob's photons, respectively.

Our results can be directly applied to almost all experiments based on energy-time entanglement, therefore representing a significant step forward towards realizing high-speed QKD links.

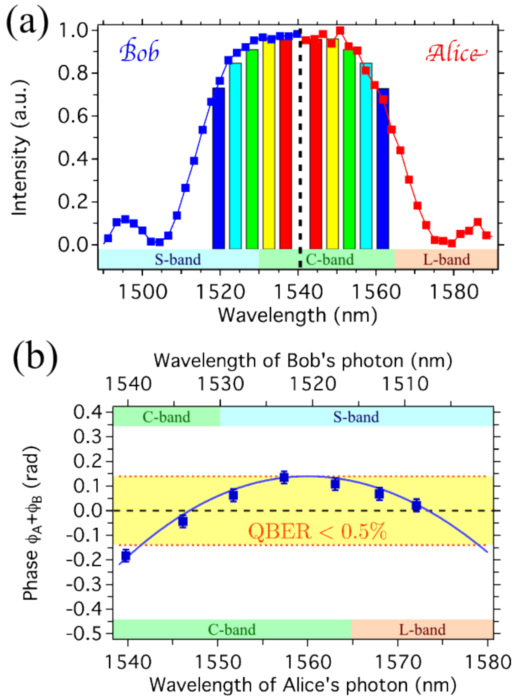

FIGURE 1: (a) Typical emission spectrum of a photon-pair source based on a periodically poled lithium niobate waveguide. Symmetrically around the degenerate wavelength of 1540 nm, we find entangled photon pairs in wavelength channels labelled with identical colors. (b) Two-photon phase shift measurements for non-identical analysis interferometers at Alice's and Bob's locations. The spectral bandwidth over which QBER<0.5% corresponds to 46 pairs of standard 100 GHz ITU channels.

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Liquid Filled Photonic Crystal Fiber Photon-Pair Source For Quantum Information

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We study the generation of photon pairs by spontaneous four-wave-maxing (SFWM) in liquid-filled hollow-core photonic-crystal fiber (LF-HCPCF). We show that they offer the possibility to reduce the Raman Scattering noise by three orders of magnitude and to engineer the two-photon states spectral correlations allowing to produce both : i) pure heralded single photons without resorting to spectral filtering ii) polarization-entangled photon pairs.

Fibered sources of photon pairs would be easily integrable into future quantum communication networks. However, in silica-core fibres, the broadband spectrum of spontaneous Raman Scattering strongly contributes to uncorrelated noise photons degrading the quality of the source. To overcome the problem of the silica Raman Scattering, a new architecture was proposed with LF-HCPF in which the core and the cladding are filled with a non-linear liquid. As opposed to the Raman scattering spectrum of silica which is broadband and continuous, the Raman scattering spectrum of liquids is composed of narrow lines. Thus, generating photons pairs between these narrow lines permits to avoid the spectral overlap between the SFWM pairs and the Raman Scattering. A near infra-red LF-HCPCF photon pair source was demonstrated, with a three orders of magnitude suppression of the Raman noise [1]. We also demonstrate the first non-linear LF-PCF with a transmission band and a zero-dispersion-wavelength (ZDW) in the telecom wavelength range combined with a non-linearity of the same order of magnitude as the one of silica, as a first step towards a Raman-free photon pairs source in the telecom band [2]. Injecting light on both side of this source in a Sagnac loop scheme is a way to obtain entangled photons.

Photon pairs can be used as on-demand single-photons with one of the two photons detected to give a heralding signal. However, for this purpose one has to make sure that the two photons share no spectral correlation. Otherwise, the heralded photon would be in a statistical mixture of the allowed spectral modes which would be deleterious as many quantum protocols rely on the Hong-Ou-Mandel interferometry between single photons from different sources. Solutions have been proposed [3] in order to produce factorable SFWM pairs by satisfying the symmetric : $2\,\beta_1(\omega_p) = \beta_1(\omega_s)+\beta_1(\omega_i)$ or the asymmetric : $\beta_1(\omega_p) = \beta_1(\omega_s)$ group velocity matching, β_1 being the inverse of the group velocity $\beta_1(\omega) = \frac{1}{v_g(\omega)}$. In standard hollow core photonic crystal fiber (HCPCF), fulfilling these conditions require the presence of several ZDWs or birefringence. Based on finite difference frequency domain simulation, we present a straightforward approach to design a HCPCF or a LF-HCPCF with three different bands. From a standard commercial HCPCF (NKT Photonics), a widening of 20% of the core thickness shifts inside the band two surface modes which normally lie outside the band. This results in a splitting of the band into three, leading to three differents ZDWs and possible fulfillements of the group velocity matching for both symmetric and asymmetric cases.

In conclusion, offering the possibility to engineer both the Ramam scattering and the spectral correlations, LF-PCF is a flexible source for the generation of entangled-photons and pure heralded single photons.

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Modification of phonon processes in nanostructured rare-earth-ion-doped crystals for quantum memory applications

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Quantum memories for light are key elements for quantum networks, especially operating at a wavelength compatible with standard telecom fibre infrastructure. Among rare-earth-ion (REI) doped materials, erbium doped systems are attractive because of their transition around 1.5 μm, but performing efficient optical pumping, required for many quantum memory protocols, is challenging in these materials [1]. Alternatively to the recent demonstration of quantum storage in a weakly doped erbium-doped silica fiber [2] limited by short coherence lifetimes, our approach is here nano-structuring impurity-doped crystalline systems, which naturally exhibit long optical coherence lifetimes [3] to affect the phonon density of states and thereby modify the atomic dynamics induced by interaction with phonons. We propose the use of nanostructured materials in the form of powders or phononic bandgap crystals to enable or improve frequency selective optical pumping and coherence properties for inhomogeneously broadened absorption lines in rare-earth-ion-doped crystals [4].

For the case of Er^{3+}:Y_2SiO_5, we simulated the improvement in terms of spin-state lifetime and homogeneous linewidth due to phonon restriction (see Fig.1(a)), as well as the phonon density of states of nano-sized powders and phononic crystals. With the geometry shown in Fig.1(b), the phononic crystal presents a band gap (see Fig.1(c)) at a frequency corresponding to the spin transition of the erbium ions, inhibiting any direct phonon absorption or emission. Then, we will report on experimental investigation towards the realization of impurity-doped nanocrystals with sufficiently good properties for quantum memory applications [5]. Indeed, nuclear spin or optical coherence lifetimes are strongly affected by mechanical treatment, and spectroscopic techniques can serve as a sensitive method to characterize the quality of REI doped powders. Different methods for obtaining powders were compared and we demonstrated micrometer-sized crystals with performances comparable to the ones of bulk crystals.

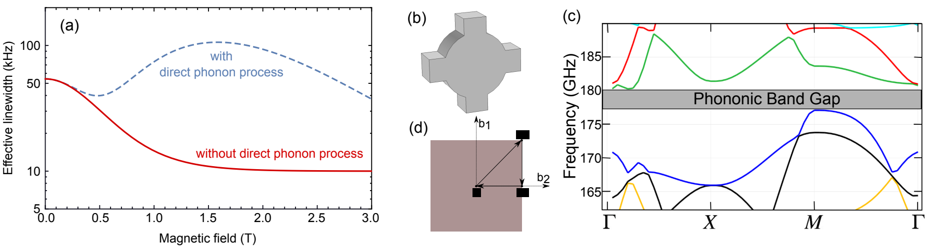

Figure 1: (a) Effective homogeneous linewidth as a function of magnetic field in the case of Er^{3+}:Y_2SiO_5 with and without phonon restriction via nano-structuring. (b) Unit cell, (c) band structure and (d) reciprocal lattice of the phononic crystal.

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Multi-user quantum key distribution with a semiconductor source of entangled photon pairs

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Quantum cryptography with entangled photon pairs can be more powerful than protocols based on single photons or weak coherent pulses : they can tolerate higher losses and thus allow the distribution of quantum secret keys (QKD) over longer distances [1], and they also open the way towards device-independent quantum cryptography [2]. However, in order to enable a wide use of entangled photon pairs in future quantum telecommunication systems, further developments are needed to demonstrate high performance sources that can be easily fabricated and integrated into Telecom fiber networks.

Here we present a source consisting of an aluminium gallium arsenide waveguide generating photon pairs in the Telecom band by type II spontaneous parametric down-conversion [3]. Such a device has already been proven to work under electrical pumping [4]. Thanks to the very small birefringence of the guided modes, the pairs are directly generated in a polarization-entangled Bell state, without the need for any post-compensation. Moreover, as the photons are emitted over a large bandwidth (about 100 nm) with a joint spectrum that exhibits frequency anticorrelation, the same source can be used to simultaneously distribute keys among multiple pairs of users by using standard Telecom wavelength demultiplexers [5]. Here, we experimentally show the distribution of quantum secret keys with the BBM92 QKD protocol [6] between four different pairs of users with a commercial 100 GHz demultiplexer (0.8 nm channel width and spacing). Under CW pumping conditions, using free-running InGaAs single-photon detectors, we achieve a secret key rate of 0.21 bits/s and a qubit error rate (QBER) of 6.9% over 50 km of standard optical fiber.

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Optical addressing of the erbium spin in Y_2SiO_5 crystal for quantum memories

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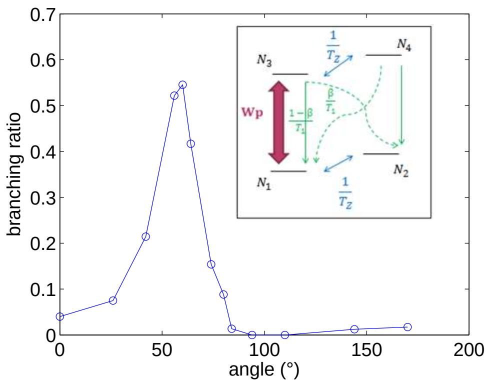
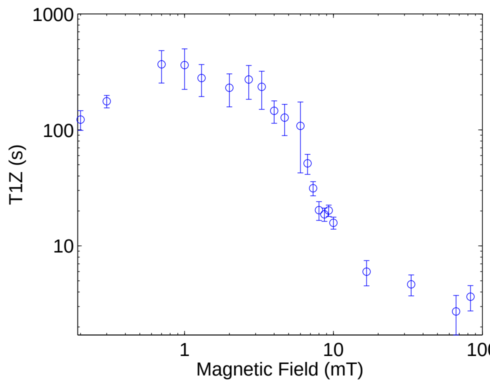
Among rare-earth-doped materials, erbium-doped crystals are good candidates to implement optical quantum memories that will operate directly in the telecommunication band [1, 2], but also to interface microwave fields using the electron spin transition of the erbium ions[3]. To realize such a device, the optical addressing of the erbium spin is an important step [4], because it allows to perform frequency selective optical pumping [5], in order to shape the inhomogeneously broadened optical linewidth as a pre-requirement for many quantum storage protocols.

In a Er^{3+}:Y_2SiO_5 crystal, we have studied two critical parameters: the branching ratio, characterizing the ability to optically manipulate the spin state, and the spin Zeeman lifetime, giving the relaxation rate between the spin states. The ground and the excited Zeeman doublets are split by the magnetic field (fig. 1a, insert). The branching ratio strongly depends on the orientation of this applied field relative to the crystal axis, as showed in figure 1a as expected from the strong anisotropy of the spin properties. We also observe an important modification of the spin relaxation time when an increasing magnetic field is applied (fig. 1b).

We specifically use a low concentration erbium sample (10 ppm), so that interactions between erbium ions are minimized [1]. As a consequence the mutual spin flip-flops between erbium ions are strongly reduced, which leads to the observation of Zeeman lifetimes of the order of minutes at low magnetic field (a few mT). This latter corresponds to an orientation of the magnetic for which the branching ratio is weak (135°, see fig. 1a). Further investigations of the spin relaxation at orientations where the branching ratio is much, as well as study of the optical coherence lifetimes are currently in progress.



(a) Branching ratio as a function of the angle of the magnetic field relative to the D_2 axis of the crystal. Insert : Scheme of the four level system we use



(b) Zeeman lifetime T_{1Z} as a function of magnetic field strengh.

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Proof-of-principle study of self-coherent continuous-variable quantum key distribution

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CV-QKD systems allow the generation of secret keys between two parties as follows: Alice randomly generates states following a certain distribution (for instance, Gaussian in GMCS [1]) and transmits them through an insecure quantum channel; and Bob recomposes the original state making the signal transmitted by Alice interfere with a powerful, classical signal - the local oscillator (LO). In order to have a good reconstruction of the original state, the LO at Bob's must have the same frequency and phase as the signal generated by Alice. This is difficult in practice, since two lasers do not typically have exactly the same characteristics and the channel can affect the original signal.

One option to obtain a signal of identical frequency and phase at Bob's is to send the LO along the insecure quantum channel, as done in [2]. This assures a good match in terms of frequency and phase at Bob's side, but also opens the way to side-channel attacks [3, 4]. Several proposals have been introduced recently in order to allow the generation of the LO locally at Bob's side. In particular, Refs. [5] and [6] propose the transmission of reference pulses between the quantum signal in order to estimate the phase difference between Alice and Bob. The reference is used only for estimation and does not contribute to the secret key rate. These Refs. as well as [7] also provided proof-of-principle demonstrations of such proposals.

Although the aforementioned methods can deal with certain levels of phase noise, they typically require the use of very reliable lasers (in terms of high stability and narrow linewidth in particular) at both Alice's and Bob's sites. Ref. [8] has recently performed a theoretical analysis that studies the performance of these methods depending on parameters such as the laser linewidth. As narrow linewidth lasers remain a laboratory tool, it is interesting to extend the phase estimation methods to standard lasers. One possibility for that is to avoid the phase mismatch between two consecutive pulses obtaining them from the same original laser pulse using a Franson interferometer (self-coherent delay line scheme, or *LLO-delayline* in [8]). Doing this at both sides ideally guarantees that a consecutive reference-signal pair will have the the same phase, independently of the linewidth of the laser.

The purpose of this work is to assess the viability of this scheme. Alice splits the pulses of her laser (generated with a frequency f) to obtain two branches; one serves as a reference for the phase estimation at Bob's side and the other carries the quantum signal. The reference-signal pulse pair then share the same frequency and phase, since they come from the same original pulse, even if they are now separated in time by $1/(2f)$. At Bob's side the LO is generated locally and goes through the same Franson interferometry procedure. Both pairs of pulses have to be matched at Bob's side via a delay line that serves as a synchronization mechanism. Heterodyne detection is then performed using a 90° hybrid and two homodyne detectors. This allows the estimation of the phase from the reference pulses, difference that is then applied to the signal. Using this setup, we test the viability of the scheme in particular as a function of the linewidths of the lasers involved, mainly with respect to their capability to recover the phase of the original state, but also to their tolerance to possible differences in the optical delay lines.

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Quantum communication with remote mechanical resonators

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Mechanical resonators represent one of the most promising candidates to mediate the interaction between different quantum technologies, bridging the gap between efficient quantum computation and long-distance quantum communication. The interaction of mechanical resonators with travelling optical signals has been studied for the purpose of coherent frequency-conversion [1], qubit-to-light transduction [2], entanglement generation [3–5] and light-to-mechanical teleportation [6]. However, a complete protocol for transferring arbitrary quantum states between distant mechanical resonators is still missing.

In general, interconnecting remote quantum systems through propagating quantum signals is a highly challenging task, due to the pulse mismatch between the emission and absorption processes. So far, the exchange of quantum signals between stationary links has been realized for single atoms [7, 8], trapped ions [9], atomic clouds [12] and, most recently, with superconducting circuits [10, 11]. These implementations exploit a large atomic non-linearity, which is not available in cavity optomechanics.

In our work [13], we propose a novel optomechanical scheme to overcome the issue of temporal-envelope mismatch in the absorption and emission processes. We design protocols to implement mechanical-to-mechanical continuous-variable teleportation, or to directly transmit arbitrary quantum states between two remote mechanical resonators. This scheme is implementable with state-of-the-art technology and it can work at microwave and telecommunication wavelengths.

The proposed system consists of a two-cavity optomechanical system embedded in a single-path interferometer. A collective optical mode is used to mediate the interaction of the mechanical resonator with propagating quantum optical signals. This configuration naturally leads to a linear optomechanical interaction, without performing linear approximations on the relevant quantum modes. The nature of the optomechanical interaction, and the temporal shape of input/output optical pulses, can be controlled by tuning the frequency and intensity of an independent classical drive.

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Recent results in experimental satellite quantum communication

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In the next decades, Satellite Quantum Communications (QC) is expected to play a major role in the development of quantum information science. This is due to a double aspect : on one hand extending the QC reach beyond Earth atmosphere is necessary for testing fundamental aspects of quantum mechanic, as well as its interplay with special and general relativity. On the other hand, satellite QC is an essential requirement for the realization of a global quantum key distribution network. Within this context, Padua University in collaboration with the Matera Laser Ranging Observatory realized the first transmission of a quantum bit from an orbiting terminal in low Earth orbit (LEO) to a ground station [1]. This result has been followed by the realization of a single photon exchange between a medium Earth orbit satellite and a ground station, fostering the expansion of QC to the global navigation satellite system constellations, such as the forthcoming Galileo system [2]. Finally, in the last work, the collaboration has shown the interference of single photons retro-reflected from satellites in LEO, proving the persistence of photon coherence after more than 5000 km [3]. The presentation will give an overview of these recent results, highlighting challenges and perspective for the realization of orbiting quantum transmitters onboard of small satellites.

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Robustness of photon indistinguishability versus temporal delay and temperature for a quantum dot in a cavity

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A fundamental building block in the architecture of photonic quantum networks is a true single-photon source generating pure indistinguishable photons. We recently reported on such sources [1], fabricated by deterministically inserting quantum dots in electrically controlled micropillar cavities [2], see a schematic representation of the device in Fig. 1(a).

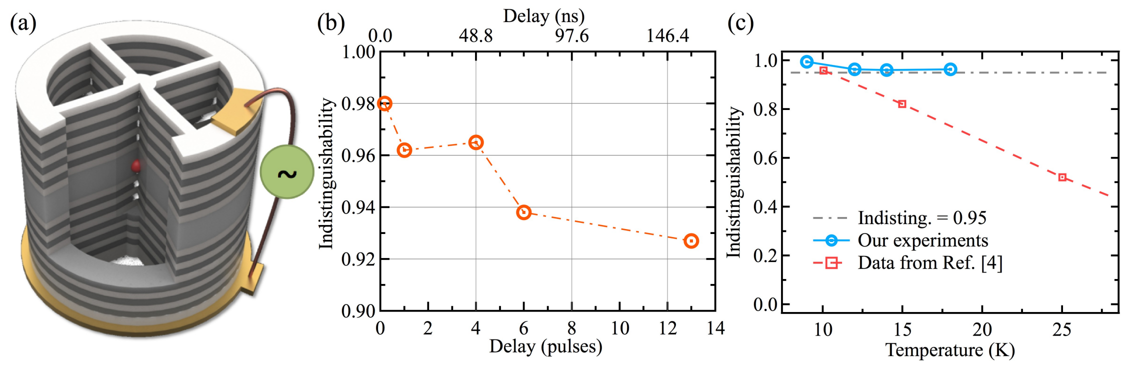

Figure 1: (a) Sketch of the quantum dot-micropillar cavity device, with electric contacts to apply a bias voltage on the quantum dot. (b) Indistinguishability versus temporal delay (in laser pulses, bottom axis, or in nanoseconds, top axis) between the two interfered photons. (c) Indistinguishability of the zero phonon line versus temperature in our experiments (blue circles, 12 ns delay), compared to data from Ref. [4] (red squares, 2 ns delay).

Photonic quantum computing at large scale demands to perform operations with many indistinguishable single-photons. To this purpose, we study the photon indistinguishability versus the time-delay between two successively emitted photons [3], which reveals how many identical photons can be generated by a single source and eventually temporally demultiplexed and used in quantum operations. In Fig. 1(b) we show that the photon indistinguishability is almost independent of the time difference between the two photons, going from 0.98 at 2.2 ns to 0.92 at 150 ns delay. This result shows that one could use a 1 GHz laser excitation rate and generate a train of more than 100 single-photons with an indistinguishability exceeding 90%.

Then we also study the dependence of the indistinguishability of the zero phonon line versus temperature in a regime of strong Purcell effect. The voltage tuning allows keeping the quantum dot in resonance with the cavity for all the measured temperatures. We observe an almost negligible decrease of the indistinguishability with temperature up to 20 K [Fig. 1(c)]. Furthermore, our results show that the strong Purcell effect cancels the influence of pure dephasing of the zero phonon line.

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Security and performance issues in post-quantum cryptography

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Introduced more than twenty years ago, quantum computation and the dream of the so-called « quantum computer » hold the promise of a drastical speed-up of computation, based on the rules of quantum physics. The introduction of this new way of computing taking avantage of quantum phenomena such as superposition of states and entanglement is a real change of paradigm in the field of security. The impact of a plausible quantum computer on cryptography is indeed huge. The universal quantum computer is able to execute Schor algorithm in polynomial time, hence ruins the security fundations of both RSA and ECC at the same time.

The research community is thus actively researching from alternatives. Regarding digital signature, they can be broadly classified in four classes : hash-based, code-based, based on lattices, and based on polynomial systems. Recently, hash-based signatures have been put forward. Their principle has been known from long : Lamport one-time signature (OTS [3]) date back from 1979. However, the initial complexity was linear with the number of messages to sign. Many improvements have been carried out, such as the use of Merkle trees, to trade key sizes for computation. Some schemes have emerged which have security proofs and which are fully instanciated. For instance, SPHINCS runs in a reasonable time on servers [1] and can be even be tweaked into embedded systems [2].

Still, we notice that the performance is at least two orders of magnitude less than state-of-the-art digital signature schemes (compared with same security parameter against an attacks led by a classical computer). There is therefore a challenge to both optimize the speed while keeping the implementation secure against implementation-level attacks, such as timing and cache attacks.

In this respect, hardware implementations will prove useful. It is possible to obtain a tenfold speedup by trading software by hardware, in terms of hash function execution. Next, another tenfold speedup can be obtained by parallelization : hash-based signatures are amenable to tree-hashing, which can be executed in batch by a swarm of dedicated cryptoprocessors.Besides, hardware implementations are easily made constant time, hence resistant against timing attacks, and are natively protected against cache-based attacks, since the hardware behavior can be made deterministic.

In conclusion, this talk will emphasize that the next post-quantum world will also significantly allow a redesign of efficient and secure cryptographic modules.

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Self-coherent phase reference sharing for continuous-variable quantum key distribution

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CV-QKD protocols rely on coherent detections and, as such, require the sharing of a reliable phase reference. In most implementations of CV-QKD performed so far [1–3], the phase reference, known as the local oscillator (LO), is transmitted through the optical channel as a bright optical pulse. Such approach raises practical issues in terms of integration over existing optical networks and is vulnerable to attacks manipulating the LO [4–6] on the optical channel. These important issues can however be lifted by locally generating the LO at reception.

A major challenge in this regime is then to share a reliable phase reference despite the relative phase drift between emitter and receiver lasers. This can be done by exchanging optical pulses carrying phase reference information in addition to quantum signal pulses. Simultaneous quantum signal and phase reference transmission in CV-QKD implies constraints on the amplitude modulator (AM) dynamics and we show that this is a key parameter in order to compare performances of realistic CV-QKD implemented with a local LO (LLO).

Recent works have been done in this direction and proof-of-principle implementations of a new LLO CV-QKD design have been proposed [7–9]. This design relies on the sequential transmission of quantum signal and phase reference pulses from emitter to receiver. Due to the time delay between signal and reference pulses at emission, the phase reference sharing of [7–9] is however intrinsicly limited to low phase noise regimes and requires the use of expensive low noise lasers as well as large AM dynamics. This is a strong limitation in terms of CV-QKD cost and system integration.

In this work [10], we introduce the idea of self-coherence in phase reference sharing for CV-QKD implementations with a local LO. A self-coherent design consists in ensuring optical coherence between quantum signal and phase reference by deriving both of them from the same optical wavefront at emission. This allows to perform phase reference sharing beyond the intrinsic phase noise limitation of [7–9]. We investigate the feasibility of such self-coherent protocols in realistic regimes by introducing an explicit design based on two matched delay line inteferometers placed at emitter and receiver sides. This design is practically implementable and we demonstrate that it is highly resilient to phase noise. For instance, our simulations show that it allows to produce secret key at a distance of 50 km with a repetition rate of 50 MHz, laser linewidths of 400 kHz and AM dynamics of 40 dB while the design of [7–9] is limited to 20 km in this regime. As such, it is a promising design suitable for next-generation LLO based CV-QKD implemented with standard optical components.

We also investigate the possibility of implementing CV-QKD with a LLO based on minimal hardware requirements by introducing a design that relies on an extremely simple setup both at emission and reception. This self-coherent design is based on performing logical multiplexing using displacement so that quantum signal and phase reference information can be simultaneously transmitted within the same optical pulse. Simultaneous transmission of quantum and phase reference information had not been studied so far and our results provide a simple approach to multiplex classical and quantum communications [11], opening a practical path towards the development of ubiquitous coherent classical-quantum communications systems compatible with next-generation network requirements.

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Stark Echo Modulation for Quantum Memories

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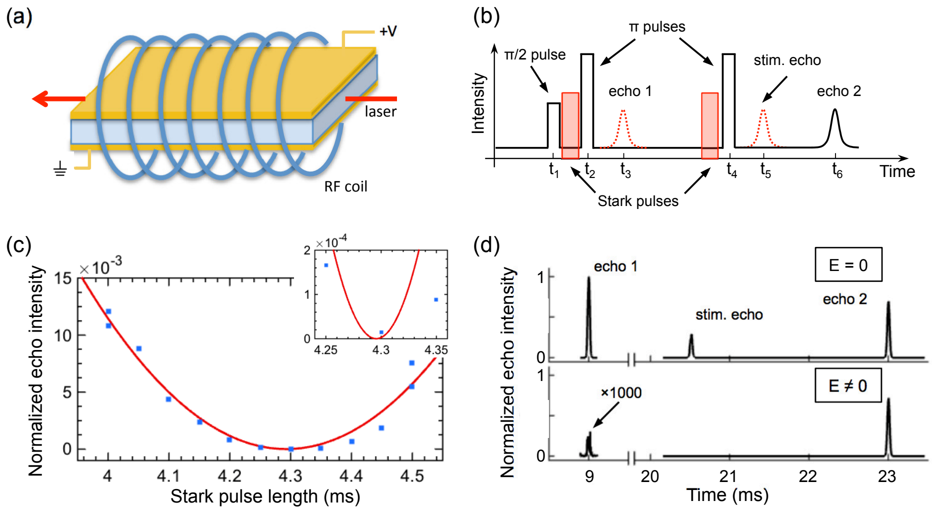
Quantum memories for optical and microwave photons provide key functionalities in quantum processing and communications. Here we propose a protocol well adapted to solid state ensemble based memories coupled to cavities [1]. It is called Stark Echo Modulation Memory (SEMM), and allows large storage bandwidths and low noise. This is achieved in a echo like sequence combined with phase shifts induced by small electric fields through the linear Stark effect. We investigated the protocol for rare earth nuclear spins and found a high suppression of unwanted collective emissions that is compatible with single photon level operation. Broadband storage together with high fidelity for the Stark retrieval process is also demonstrated. SEMM could be used to store optical or microwave photons in ions and/or spins. This includes NV centers in diamond and rare earth doped crystals, which are among the most promising solid-state quantum memories.



Measurements on $^{151}Eu^{3+}:Y_2SiO_5$ nuclear spins. (a) scheme of the sample with attached electrodes to create electric fields. The coil is used to produced rf pulses and the laser to detect spin coherences. (b) Experimental SEMM scheme. (c) Normalized echo 1 intensity as a function of the length of the Stark pulse. (d) Echoes observed with or without electric field in the SEMM sequence.

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Towards optical connection between solid state and atomic quantum memories

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The realization of a quantum network is an important challenge of quantum information science [1]. A quantum network is composed of nodes where the quantum information is generated, processed and stored. The nodes are linked by quantum channels transferring the information. Many applications are possible such as quantum simulation, distributed quantum computing, and communication. A realistic quantum network will likely be heterogeneous, composed of very different types of nodes for different purposes. Compatibility and interface between these technologies are a key point for future realisation of quantum networks. Furthermore these interfaces have to be compatible with the telecommunication wavelengths needed for long distance communication through the quantum channels.
In this work we show the storage of single photon level light pulses compatible with Rubidium atomic memories in a Praseodymium doped crystal using frequency conversion. A 150 ns long weak coherent state at 780 nm is first down-converted to a C-band telecom pulse in a PPLN waveguide. In a second non-linear waveguide (PPKTP), the telecom photons are up-converted to 606 nm, resonantly with the Praseodymium transition. The resonant 606 nm photons are then stored in the solid state memory for 3 μs using the Atomic Frequency Comb protocol [2]. The retrieved echo is measured in a noise-free temporal mode [3], thus enabling high Signal to Noise Ratio (up to 30 for one photon per pulse at 780 nm). We finally show the conversion and storage of a time bin qubit at single photon level with 85% fidelity. This result is an important step towards the quantum state transfer between an emissive atomic ensemble and an absorptive solid state quantum memory.

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Towards storage of quantum dot single photons in a cold atomic ensemble*

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Single photon sources and quantum memories are key resources to implement quantum networks for computation and simulation [1]. The hybrid system we are investigating combines a semiconductor quantum dot (QD) as a deterministic source of single photons with a frequency-matched memory based on a cold ensemble of ^{87}Rb atoms. As a first step, we have characterized a promising sample of droplet GaAs/AlGaAs QDs which emit lifetime-limited single photons at 780 nm, the wavelength of the Rb D2 line [2]. Fine-tuning of the QDs emission is achieved using a PZT to induce biaxial strain in the sample. The scanning range covers all the hyperfine structure of the D2 line, as the spectroscopy of a room temperature Rb vapor shows in Figure 1. Independently, our new light-atom interface allows us to prepare cold and dense ensembles of ^{87}Rb atoms (OD > 2000). By combining the two systems we are now developing an EIT-based memory that predicts storage-and-retrieval efficiency exceeding 30% [3]. Such a memory will form the basis for experiments on hybrid entanglement and quantum networks.

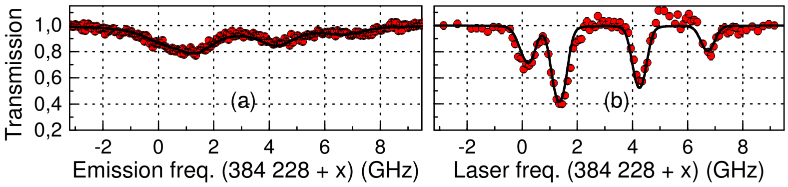

Figure 1. Spectroscopy of the Rb D2-transitions using QD photons. (a) The QD is excited non-resonantly and the QD resonance is swept through the Rb transitions via strain coupling. (b) The QD is driven at resonance in the coherent scattering regime, while the frequency of the driving laser is scanned across the Rb transitions.

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Tunable single photon source with carbon nanotubes

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Carbon nanotubes have emerged as original light-emitters in the last decade with intriguing properties that trigger both fundamental investigations and technological developments. They are promising candidates as single photon emitters : they can be electrically injected, and single photon emission has been recently demonstrated up to room temperature and at telecoms wavelength [1]. In addition to their low cost and high integrability, they are also attractive since their transition energy can cover a large part of the near infrared spectrum from $\lambda = 850$ nm to $\lambda = 2000$ nm. Moreover their unique 1D geometry deeply enhance the exciton phonon coupling which can be used to reach very large single photon source tunability.

In this work, we present an original approach, where the nanotube is fully characterized by regular micro-photoluminescence spectroscopy and where a fiber-based micro-cavity (adapted from cold atoms physics) is subsequently adjusted to its location and spectral characteristics. Photons are then efficiently funnelled into the cavity mode. We demonstrate a Purcell enhancement factor up to 35. Thanks to the intrinsic spectral tunability of fibered-cavities, the emission can be tuned in the whole PL spectrum, over several THz, while keeping a strong antibunching ($g^{(2)}(0) \leq 0.05$) [2].

From the 1D geometry, where elementary excitation have to be described in the polaron picture (mixed exciton-phonon particle), our results show that the strongly coupled tripartite system (exciton-photon-phonon) is at reach unravelling a novel physics related to Kosterlitz-Thouless phase transition.

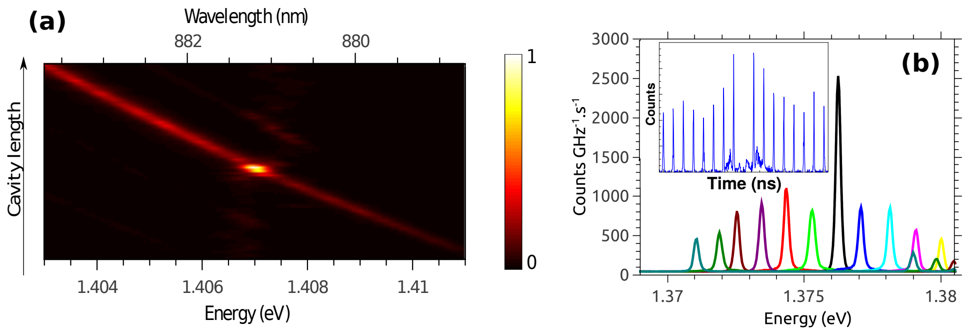

FIGURE 1. (a) 2D plot of the emission spectrum of a carbon nanotube embedded in a fibered cavity . (b) Emission spectrum of the cavity coupled to a single nanotube for several cavity lengths. Inset : Intensity correlation measurements $g^{(2)}(\tau)$.

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cQED-like description for quantum plasmonics

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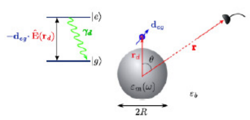
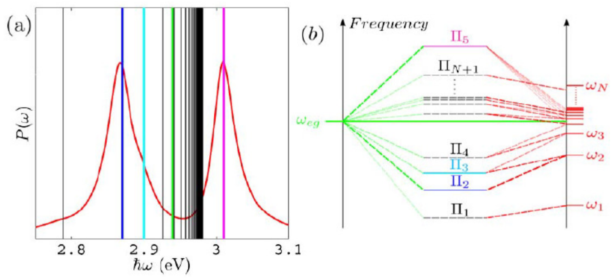
Light matter interaction is generally extremely weak and strategies have to be developed to enhance this coupling. In a simple picture, the coupling strength depends on the quality factor Q and the effective volume V of the involved mode by the ratio Q/V. High Q/V ratio, hence efficient light–matter interaction, is achieved in cavity-based systems, where large modal volumes are easily compensated by extremely narrow resonances[1]. It has been also proposed to work with diffraction limited volumes by coupling a single-atom to an elongated fiber [2]. Another downscaling step is made with plasmonics [3]. Surface plasmon polariton (SPP) results from coupling electromagnetic wave to a surface density of charges. They are therefore naturally confined near a metal surface and are not diffraction limited, offering thus a new tool for interfacing light and matter at the nanometer scale, but at the price of strong losses [4]. Strong effort have been done since a decade to transpose cavity quantum electrodynamics (cQED) concepts to quantum plasmonics. This opens a new way to realize original nano-optical devices integrated on chip.

In this work, we present an effective model that fully transposes cQED concepts to quantum plasmonics, with particular attention devoted to the role of losses[5]. We apply this formalism to a quantum emitter strongly coupled to a metal nanoparticle. Specifically, we show that the coupled plasmon-emitter system behaves like an emitter in a multimodal lossy cavity and determine the structure of the emitter states dressed by the plasmon modes [7].





a) Spectrum calculated for an emitter coupled to a silver nanoparticle. The vertical lines indicate the dressed states resulting from the strong coupling. b) Energy diagram of the atomic states dressed by the plasmonic cavity modes.

Finally, we show that strong coupling in quantum plasmonics can be used to mediate efficiently the interaction between emitters via a decoherence-free channel, immune to the strong plasmon dissipation. Efficient and robust population transfer, as well as the deterministic generation of entanglement between emitters are numerically shown. These results pave the way for an efficient use of the quantum plasmonic platform beyond its inherent losses[6].

Finally, although relying on a different paradigm (mode confinement instead of mode lifetime), this formalism permits a direct transposition of cQED concept to the nanoscale and constitutes therefore a powerful tool to propose and design original nanophotonics or plasmonics devices

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Quantum Sensing & Metrology (QMET)

About a connection of temporal correlations and invasiveness of measurements to quantum metrology

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The Leggett-Garg inequality (LGI) is a widely used test of the "quantumness" of a system, and involves correlations between measurements realized at different times. According to its widespread interpretation, a violation of the LGI disprooves macroscopic realism and non-invasiveness. Nevertheless, recent results point out that macroscopic realism is a model dependent notion and that one should always be able to attribute to invasiveness a violation of a LGI. This opens some natural questions : how to provide such an attribution in a systematic way ? How can apparent macroscopic realism violation be recast into a dimensional independent invasiveness model ? We introduce an operational model where the effects of invasiveness are controllable through a parameter associated with what is called the *measurability* of the physical system. Such a parameter leads to different generalized measurements that can be associated with the dimensionality of a system, measurement errors or back action. Using this model, we provide a connection of temporal correlations to quantum metrology. This ultimately allows the discussion about the connection between the notions of invasiveness and the later. Within our model, invasiveness is also connected to a definition of macroscopic coherence given by the quantum Fisher information.

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Absolute laser-probe stabilization protocol for quantum clocks

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High-precision atomic clocks based on neutral atoms in optical lattices and trapped ions are reaching today relative accuracies in the 10^{-18} range requiring new techniques in very precise control of external systematic corrections.
Unconventional spectroscopic probing protocols manipulating the laser phase with modified or generalized (Hyper) Ramsey-type schemes have been studied to fully eliminate one of them: the light-shift perturbation by off-resonant atomic states [1–5].

We will present new interrogation schemes based either on a combination of measured frequency-shifts with different Ramsey times [6] or a direct combination of $\pi/4$ and $3\pi/4$ phase-modulated resonances [7] to efficiently stabilize the probe laser on ultra-narrow atomic transitions. Quantum engineering of these protocols is investigated to generate synthetic and robust clock frequency-shifts to reduce or eliminate imperfect correction of probe induced light-shifts when decoherence, relaxation by spontaneous emission or even collisions are present simultaneously during the entire laser pulse sequence.

A new generation of hyper-stable optical clocks with exceptional metrological performances may become accessible.

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Atom chip based guided atom interferometer for rotation sensing

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The physical aspects as well as the experimental progress towards the realization of a rotation sensor using cold atoms magnetically guided on an atom chip are presented. The design and derivation of the magnetic guiding potential, the expected sensitivity, and the study of a highly efficient matter-wave beam splitter are in detail analyzed. This device is designed taking into account the stringent requirements of inertial navigation. Besides the usual constraints imposed on the physical dimensions and power consumption for the aforementioned application, we also investigate here the on-chip incorporation of keys elements needed in the realization of a cold atom interferometer. In particular, we discuss different strategies to overcome the fundamental limitations of guided [1] and free falling atom interferometer inertial sensors [2]: wire roughness induced decoherence, cloud fragmentation, interrogation time and quantum projection noise.

The working principle of this inertial sensor is based on a magnetic polarized cloud of cold ^{87}Rb atoms coherently split by a π/2 pulse that creates a superposition of two opposite wave-packet propagation modes. Both wave-packets will be constrained to propagate along a circular guide of a few millimeters diameter. At the output of the guide, the application of a second π/2 pulse produces an interference signal sensitive to rotation via the Sagnac effect, measured as an atom number imbalance. If, for example, we fix the interrogation time to 1s, and the atoms are launched via a Bragg process ($v/v_{recoil} = 2$) on a guide of 500μm radius then the expected sensitivity is 3×10^{-8} rad.s^{-1}/ $\sqrt{Hz}$ (6×10^{-3} deg/hr/ $\sqrt{Hz}$) for 10^6 atoms. Such a sensitivity is already close to the navigation grade bias stability requirement for a gyroscope which is on the order of 10^{-4} deg/hr.

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Coherence of an interacting atomic ensemble in a trapped matter-wave sensor

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The FORCA-G project aims to develop a quantum-sensor for probing short range forces, *i.e* forces at length scale of typically few micrometers. The sensor relies on a trapped atom interferometer using an ultra-cold cloud of ^{87}Rb trapped in a vertical optical lattice. For shallow depths of the lattice, stimulated Raman transitions are used to induce a coherent coupling between different lattice sites, allowing us to realize atom interferometers capable of probing with very high sensitivity and accuracy the local potential undergone by the atoms. By using a symmetrized interferometer configuration, our force quantum-sensor reaches a state-of-the-art relative sensitivity of 1.8×10^{-6} at 1 s on the Bloch frequency, and thus on the local gravitational field [1, 2].

In a recent work [3], we studied the impact of atomic interactions arising from the use of a dense and small ultra-cold atomic cloud as a source for our trapped interferometer. The purpose of using such an atomic source is to reduce inhomogeneous dephasing and to obtain better addressability of the lattice sites and ultimately to populate only one of them. At densities of typically 10^{12} atoms/cm^3, we observe an unexpected behaviour of the interferometer's contrast when applying a π-pulse to symmetrize the interferometer. These results are interpreted as a competition between the spin-echo technique and a spin self-rephasing (SSR) mechanism based on the identical spin rotation effect (ISRE). Originating from particle indistinguishability, SSR has been observed in trapped atomic clocks, where it can enhance the clock's coherence up to several seconds [4, 5]. The study of these mechanisms due to atomic interactions seems thus to be of great interest for metrology and for developing more compact quantum sensors based on trapped atomic ensembles.

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Controlled transport of an elongated BEC over large distances : a 3D numerical study

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Since the development of laser cooling and trapping of atoms, a multitude of cold-atom-based devices and sensors were realized. From time keeping to measurements of fundamental constants, these devices are pushing the boundaries of explored quantum phenomena. A very common technique put in practice in these experiments involves atom interferometry, where the wave nature of matter is predominant close to absolute zero temperatures. Atom interferometers reached a level of precision allowing to test fundamental principles and predictions at the heart of modern physics controversies such as Einsteins weak equivalence principle, the detection of gravitational waves, or probing the quantum superposition principle at macroscopic scales. Going beyond state-of-the-art performance in these experiments requires long interferometer durations, of the order of several seconds, and optimized matter-wave sources whose dynamics is extremely well controlled. We present here a detailed 3D realistic numerical study of the transport of an elongated Bose-Einstein Condensate (BEC) on an atom chip. The aim is to test recent proposals of fast and controlled transport of BECs over large distances, of the order of 1 to 2 mm. The limits of these protocols will be investigated in terms both of residual oscillations and residual breathing of the final quantum state.

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Electron spin resonance from NV centers in diamonds levitating in an ion trap

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The negatively charged Nitrogen Vacancy (NV^-) center in diamond has emerged as a very efficient source of single photons and a promising candidate for quantum control and sensing via its electron spin. Recently, there has been much interest in the electronic spin of the NV^- center in levitating diamonds [1, 2]. This interest is partly motivated by proposals for hybrid optomechanics [3], and implications in ultrahigh force sensitivity [4] where the NV center's spin response to magnetic fields is exploited to read-out the motion of the diamond with high spatial resolution under ambient conditions [5]. Amongst the many levitation schemes, optical traps are the most widely used [1, 6–8]. They provide efficient localisation for neutral and charged particles and can work under liquid or atmospheric environnements. However the trap light that is scattered from the object means that excessive heating can be at work [6, 7, 9, 10] and result in a lower optomechanical read-out. Furthermore, optical traps may quench the fluorescence of NV centers [7] and affect the electronic spin resonance contrast.

Being able to trap diamonds hosting NV centers without light scattering could thus offer a better control of the spin-mechanical coupling and enlarge the range of applications of levitating diamonds. Levitation techniques such as ion traps [11] or magneto-gravitational traps [12] are tentalizing approaches for reaching this goal. Ion traps could not only provide an escape route for scattering free trapping, but also enable a high localisation of the particles together with large trap depths as demonstrated by the impressive control over the motion that have been developped with single ions in the past [13].

We will report our observations of the Electron Spin Resonance (ESR) of Nitrogen Vacancy (NV) centers in diamonds that are levitating in an ion trap. Using a needle Paul trap operating under ambient conditions, we have shown efficient microwave driving of the electronic spin and that the spin properties of deposited diamond particles measured by the ESR are retained in the Paul trap. We also exploit the ESR signal to show angle stability of single trapped monocrystals, a necessary step towards spin-controlled levitating macroscopic objects.

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Fast BEC transport with atoms chips for inertial sensing

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Recent proposals in the field of fundamental tests of foundations of physics assume Bose-Einstein condensates (BEC) as sources of atom interferometry sensors [1]. Atom chip devices have allowed to build transportable BEC machines with high repetition rates as demonstrated in the QUANTUS project [2]. The proximity of the atoms to the chip surface is, however, limiting the optical access and the available interferometry time necessary for precision measurements. In this context, a fast and perturbation-free transport of the atoms is required. Shortcuts to adiabaticity protocols [3] were proposed and allow in principle to implement such sequences with well defined boundary conditions. In this theoretical study, one can engineer suitable protocols to move atomic ensembles trapped at the vicinity of an atom chip by tuning the values of the realistic chip currents and external magnetic fields. Experimentally applicable trajectories of the atomic trap optimizing the transport time and reducing detrimental effects due to the offset of atoms positions from the trap center are found using a reverse engineering method. We generalize the method of reverse engineering in order to optimize the size evolution and the center of a Schrödinger or a BEC wave packet in phase space. This allows an efficient delta-kick collimation (DKC) [4, 5] to the pK level as observed in the Quantus 2 experiment. With such low expansion rates, atom interferometry experiments with seconds of drift time are possible.

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Ion microtraps for precision spectroscopy and quantum information

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We design, realise and operate micro-fabricated ion surface traps made of gold electroplated electrodes deposited on silica substrates. We load the traps with single $^{88}\mathrm{Sr}^+$ ions that are Doppler cooled by addressing the $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2}$ transition ($\nu = 711$ THz, $\lambda = 422$ nm). We characterise the heating-rate of the trap by applying the Doppler re-cooling method [1] and use surface science diagnostics and Ar-ion bombardment to obtain reliable information about limits to miniaturisation imposed by the fluctuating electric fields ("anomalous heating") [2].

We also demonstrated that these micro-devices are well suited for precision spectroscopy.

In a first experiment we measured the branching fractions for the decay of the $5p\ ^2P_{1/2}$ state of $^{88}\mathrm{Sr}^+$ by applying a recently demonstrated photon-counting sequential method [3]. The branching fraction for the decay into the $5s\ ^2S_{1/2}$ ground level was found to be $p = 0.9449(5)$, in good agreement with recent theoretical calculations but in disagreement with previous experimental measurements [4].

In a second series of experiments we developed and implemented a laser spectroscopy technique that allows for probing a single ion laser-cooled in a radio frequency trap in the absence of the artefacts that are usually generated by the mechanical action of light (i.e. laser heating). We compare the experimental results obtained probing the $^{88}\mathrm{Sr}^+$ dipole-allowed "cooling" against a simple Monte-Carlo simulation based on a two-level atom / harmonic-oscillator model in order to clarify the applicability conditions of the method. This strategy allowed us to measure the 436.5(5) MHz frequency-shift of the "cooling" transition with respect to the $5s\ ^2S_{1/2}(F = 2) \rightarrow 6p\ ^2P_{1/2}(F' = 3)$ transition of neutral $^{85}\mathrm{Rb}$ [5] , obtaining an improved absolute referencing. We also demonstrate that this technique is able to catch the rich spectral line-shape obtained in the presence of dark states that shows-up when a "repumping" laser beam addresses the $4d\ ^2D_{3/2} \rightarrow 5p\ ^2P_{1/2}$ ($\nu = 275$ THz) transition in order to avoid accumulation of populations in the $4d\ ^2D_{3/2}$ metastable state. In particular, the experimental spectra containing narrow features are in excellent agreement with the calculated fluorescence spectra obtained by solving the optical Bloch equations describing the system. This relatively simple-to-implement technique opens the way to a more precise and reliable measurement of experimental parameters in experiments involving laser-cooled and laser-manipulated trapped ions, in particular in the field of quantum information processing.

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Magnetic domains imaging with a scanning NV magnetometer at cryogenic temperatures

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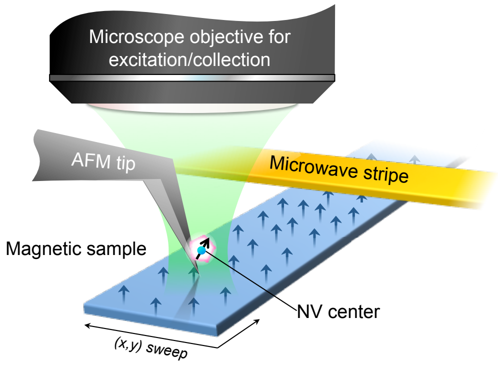
The ability to map magnetic field distributions with high sensitivity and nanoscale resolution is of crucial importance for fundamental studies ranging from material science to biology, as well as for the development of new applications in spintronics. Recently, it has been shown that these problems can be tackled by scanning NV magnetometry [1]. This technique relies on the optical detection of the electron spin resonance (ESR) associated with a single Nitrogen-Vacancy (NV) defect in diamond attached to an AFM tip (see Figure). With this system, we have demonstrated quantitative imaging of magnetic nano-structures at room temperature [2]. In particular, it has been shown that it was possible to image domain walls in ultrathin ferromagnetic films, providing a useful tool to study the interactions in this type of materials [3].



Extending this technique to cryogenic environment, we aim at studying new materials that display magnetism only at low temperatures. In this regard, we present our recent realization of a scanning magnetometer based on NV centers in a nanodiamond, working at low temperature. We have imaged magnetic domains in GaMnAsP, a semiconductor displaying a diluted ferromagnetism at cryogenic temperature. The opportunity to understand the structure and properties of magnetic domain-walls in this model material will constitute an important step toward the development of domain-wall based memory. In addition, these first results obtained by scanning NV microscopy at cryogenic temperatures pave the way to the observation and study of novel magnetic phenomena in condensed matter systems, such as superconductivity or strongly correlated electrons systems.

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Magnetic Resonance with Squeezed Microwaves

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Although vacuum fluctuations appear to represent a fundamental limit to the sensitivity of electromagnetic field measurements, it is possible to overcome them by using so-called squeezed states. In such states, the noise in one field quadrature is reduced below the vacuum level while the other quadrature becomes correspondingly more noisy, as required by Heisenberg's uncertainty principle. At microwave frequencies, cryogenic temperatures are required for the electromagnetic field to be in its vacuum state and reach the quantum limit of sensitivity [1]. Here we report the use of squeezed microwave fields to enhance the sensitivity of magnetic resonance spectroscopy of an ensemble of electronic spins beyond the standard quantum limit [2]. Our scheme consists in sending a squeezed vacuum state to the input of a cavity containing the spins while they are emitting an echo, with the phase of the squeezed quadrature aligned with the phase of the echo. We demonstrate a total noise reduction of 1.2 dB at the spectrometer output due to the squeezing. These results provide a motivation to examine the application of the full arsenal of quantum metrology to magnetic resonance detection.

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Near quantum-limited amplification and conversion based on a voltage-biased Josephson junction

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Josephson parametric amplifiers[2], have proven to be an indispensable tool for a wide range of experiments on quantum devices in the microwave frequency regime, because they provide the lowest possible noise[1]. However, parametric amplifiers remain much more difficult to use and optimize than conventional microwave amplifiers.

Recent experiments with superconducting circuits consisting of a DC voltage-biased Josephson junction in series with a resonator have shown that a tunneling Cooper pair can emit one or several photons with a total energy of $2e$ times the applied voltage[3]. We present microwave reflection measurements on the device in [3], indicating that amplification is possible with a simple DC voltage-biased Josephson junction. We also show that this amplification adds noise close to the limit set by quantum mechanics for phase preserving amplifiers[1]. For low Josephson energy, transmission and noise emission can be explained within the framework of $P(E)$ theory of inelastic Cooper pair tunneling and are related to the fluctuation dissipation theorem (FDT). We also experimentally demonstrate, by controlling the applied DC voltage, that our device can act as both an amplifier and a frequency converter.

Combined with a theoretical model, our results indicate that voltage-biased Josephson junctions might be useful for amplification near the quantum limit, being powered by simple DC voltage and providing a different trade-off between gain, bandwidth and dynamic range, which could be advantageous in some situations[4].

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Nitrogen-Vacancy Centers in Diamond for Current Imaging at the Redistributive Layer Level of Integrated Circuits

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We present a novel technique based on an ensemble of Nitrogen-Vacancy (NV) centers in diamond to perform magnetic current imaging (MCI) at the redistributive layer of an integrated circuit [1]. The experimental set-up relies on a standard optical microscope, and the measurements are performed at room temperature and atmospheric pressure. The presence of four possible NV center orientations in the 100 oriented diamond crystal allows to simultaneously measure the three components of the magnetic field generated by a mA range current in an integrated circuit structure over a field of 50 x 200 μm^2 with sub-micron resolution. Obtaining all the vector components enables the use of an algorithm more robust than those used for magnetic current imaging using Giant Magneto Resistance (GMR) or Superconducting Quantum Interference Device (SQUID) sensors [2] that only give access to the magnetic field component that is perpendicular to the circuit. The magnetic current imaging derived from our measurements shows a very good agreement with the theoretical current path. In addition, acquisition time is around 10 sec, which is much faster than scanning measurements using SQUID or GMR.

These early experiments, as yet not optimized for integrated circuits, show that NV centers in diamond could become a realistic alternative for magnetic current imaging in integrated circuits.

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Novel optophononic confinement strategies studied by Raman scattering

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The manipulation of the phononic environment of nanostructures appears as a new active and challenging field of research. The spatial and spectral confinement of high frequency acoustic phonons (tens of GHz up to THz) using acoustic nanocavities is a milestone in the quest of ultimate phononic and optomechanical devices [1] [2].

Based on the concept of Fabry-Perot resonators, an acoustic cavity can be fabricated by enclosing a GaAs spacer by two GaAs/AlAs phononic distributed Bragg reflectors (DBRs). The mirrors are fabricated by stacking materials layers presenting an acoustic impedance contrast [3]. By adjusting the thickness of the DBRs layers and of the spacer, we optimize the confinement of the fundamental mechanical mode inside the cavity [1] [3] [4]. In this work we design, fabricate and characterize new kinds of acoustic nanocavities with a resonant frequency around 200 GHz. For this frequency range high resolution Raman scattering appears as a suitable technique to study the acoustic phonon confinement. In order to amplify the Raman signals, the studied structures were grown between two optical DBRs, constituting an optical microcavity [3]. This configuration concentrates the electromagnetic field in the acoustic cavity, allowing to increase the spatial overlap of the incident field with the confined mechanical mode and of the optical mode in which the scattered photons are coupled to [1] [3]. This technique allows an enhancement of the detected signal by a factor of 106 [1] [3].

In this work we explored three GaAs/AlAs based phononic resonators : a standard cavity constituted by a GaAs spacer and two GaAs/AlAs DBRs, and two nanocavities able to confine phonons in the absence of a spacer. One of such cavities relies on the adiabatic variation of the layer thicknesses in a periodic system. These structures are known in optics for the robustness of their quality factor, and have the potential of similar performance in nanophononics. The last cavity is based on the concatenation of two acoustic DBRs to create an interface mode. By engineering the symmetry of the acoustic band structure in the two superlattices, it is possible to confine a mode at their interface [5] [6]. These represent new platforms allowing the control of the phonon confinement and manipulation, expanding the set of existing building blocks to study complex phonon dynamics.

We present an experimental study of the MBE grown samples, and we simulate the results based on a photoelastic model. The explored strategies to confine phonons open exciting perspectives for nanoptomechanics.

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Prospects for sub quantum projection noise stability in strontium optical lattice clocks

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Optical lattice clocks, which use a narrow inter-combination transition in alkaline-earth atoms like Sr as a frequency reference, have become the best frequency standards to date, both in terms of frequency stability and control of perturbing systematic effects. They rely on the interrogation of about 10^4 atoms trapped in an optical lattice by an ultra stable laser. These clocks, now connected by stabilised optical fibre links [1], will soon contribute to international time scales [2], and put bounds on physics beyond the standard model [3].

The frequency stability of optical lattice clocks is currently limited by technical noise sources, mainly the sampling of the frequency noise of the clock laser used to probe the atoms – or Dick effect. However, these technical limits are expected to be overcome by current progresses on optimisations of the clock cycle and on laser stabilisation, including low mechanical loss coatings, cryogenic silicon cavities, or spectral hole burning in rare earth doped cryogenic crystals. The frequency stability of optical lattice clocks is therefore expected to reach the fundamental quantum projection noise limit.

In [4], we proposed a detection system of the transition probability based on the measurement of the phase-shift induced by the atoms with a Mach-Zehnder interferometer. This detection, which features a signal-to-noise ratio at the quantum projection noise, enabled the classical non-destruction of the atoms, *i.e* the recycling of the atoms from clock cycle to clock cycle, and thus the reduction of the clock dead time.

In this paper, we describe a new generation of this non destructive detection under development at SYRTE, which uses an optical cavity to measure the phase shift induced by the atoms. This detection is expected to have an enhanced signal-to-noise ratio, which would then lie in the quantum regime where spin-squeezing can be used to improve the clock stability. We propose theoretical strategies to achieve a shot-noise limited detection, and present experimental challenges in its realisation.

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Quantum temporal imaging with squeezed light

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Temporal imaging is a technique that enables manipulation of temporal optical signals in a manner similar to manipulation of optical images in spatial domain. The concept of temporal imaging uses the notion of space-time duality [1] with dispersion phenomena playing the role of diffraction and quadratic phase modulation in time acting as a *time lens*.

Spatial quantum imaging investigates ultimate quantum limits of imaging techniques in regimes where quantum fluctuations cannot be neglected [2]. On one hand it would be desirable to bring the experience from spatial quantum imaging into temporal imaging and to establish its ultimate limits imposed by the quantum nature of the light. On the other hand the quantum description of temporal imaging is relevant in the context of long-range quantum communication. Indeed this technology relies on the efficiency of quantum repeaters for which the temporal mode matching between the quantum emitters, the communication network and the quantum memories is critical. Few steps in this direction have been already made in the literature such as quantum optical waveform conversion [3] or spectral bandwidth compression of single photons [4].

In this work we make a new step towards the theory of quantum temporal imaging [5]. Precisely, we address the problem of temporal imaging of a temporally broadband squeezed light generated by a traveling-wave optical parametric amplifier [6] or a similar device. We consider a single-lens temporal imaging system formed by two dispersive elements and a parametric temporal lens, based on a sum-frequency generation (SFG) process. We derive a unitary transformation of the field operators performed by this kind of time lens. This unitary transformation allows us to evaluate the squeezing spectrum at the output of the single-lens imaging system and to find the conditions preserving squeezing in the output field. As figure 1 shows, when the efficiency factor of the temporal lens is smaller than unity, the vacuum fluctuations deteriorate squeezing at its output. For efficiency close to unity, when certain imaging conditions are satisfied, the squeezing spectrum at the output of the imaging system will be the same as that at the output of the OPA in terms of the *scaled frequency* $\Omega' = M\Omega$ which corresponds to the scaled time $\tau' = \tau/M$. The magnification factor M gives the possibility of matching the coherence time τ_c of the broadband squeezed light to the response time of the photodetector.

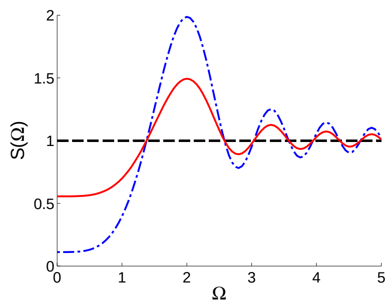

Fig. 1 Squeezing spectrum of broadband squeezed light at the output of the OPA (dash-dotted) and after the temporal lens with efficiency factor $\eta = 1/2$ (solid) ; $\exp[r_{\mathrm{m}}] = 3$, and frequency Ω is in units of Ω_c.

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Real time quantum-limited detection of interacting spins

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Alkali atoms are a robust platform for the realization of a wide range of practical devices, from atomic clocks and magnetometers to quantum memories. Of particular interest is their interaction with other spin species for the implementation of hybrid quantum technologies and enhanced sensing, for instance. One requirement for such applications is quantum-limited detection, i.e. the ability to resolve stochastic fluctuations in the spin orientation. We have implemented a versatile setup to optically prepare and detect alkali vapors using Faraday rotation with both classical and non-classical light [1]. We have experimentally shown the advantages of using non-classical light in power spectral analysis of the recorded signal [2]. Here we extend this work to the time domain, which is necessary for control applications. Using a similar setup we are exploring optimal filtering techniques to track the stochastic motion of spins in real time, and in a regime where spin-exchange collisions couple different spin species. Spin-exchange coupling allows spin-state initialization and probing of atomic species that are not optically addressable [3]. It also plays a key role in the most sensitive (i.e. SERF) [4] and miniaturized (i.e. chip-scale) [5] alkali-based magnetometers to date. Here we report our current results and discuss the extension of our approach to detecting spin correlations in mixtures of alkali atoms.

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Single photon radiation scheme based on inelastic Cooper pair tunneling

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Usually, Cooper pair tunneling through a Josephson junction is elastic: the dc voltage across the junction has to be zero. Nonetheless, tunneling can also occur at non-zero bias if the difference of potential can be dissipated somewhere [1]. By coupling the junction to a transmission line, it can be dissipated as photons [2]. At first sight, the photons have the same statistics as the tunneling Cooper pairs: poissonian, i.e. tunneling events are independent. We show that photons statistics can also be non-classical [3]: by designing the electromagnetic environment, we are able to emit antibunched photons on demand.

Our project is built around a voltage-biased Josephson junction and a quarter-wave resonator as the electromagnetic environment. Cooper pair tunneling can occur inelastically at non-zero bias, leading to photons dissipated through a transmission line. This phenomenon has been explained by P(E)-theory [4, 5] in the early nineties and some experiments have measured Cooper-pair current at non-zero voltages [1]. More recently, experiments have also probed the emitted radiation [2]. Our project is focused on the question whether the emitted radiation can be non-classical [3], that we investigate using an Hanbury Brown and Twiss scheme [6].

In this scheme, each time a Cooper pair tunnels, a photon is created in the resonator, so the statistics of photons will be the same as that of the Cooper pairs: Poissonian. To go below this statistics, we block tunneling events before the resonator relaxes. To do so we use a high-impedance RC circuit slower than the resonator, so that the second tunneling event has to pay a higher energy than the first one, resulting in single photon statistics. Using tunable Jospehson energy, this blocking mechanism can be transformed into a latching mechanism alowing us to obtain a very bright on demand single photon source.

Moreover, we build this source from niobium nitride, a wide gap superconductor, which should allow us to scale this source to mm-wave or THz frequencies.

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Single-pass quantum source of multimode squeezed states

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In a multimode squeezed state of light the noise reduction of one of the field quadrature can be used together with an intense beam allowing to perform space-time positioning beyond the standard quantum limit[1]. Furthermore these highly entangled states can be used as a quantum network in order to accomplish measurement based quantum computing[2] using a continuous variable approach[3]. Our group has already demonstrated the generation of this multimode quantum resource using a femtosecond-frequency comb as a seed for an optical parametric oscillator[4].

Here we present a new quantum source able to produce a multimode squeezed state of light in a single pass configuration. A synchronously pumped optical cavity, a cavity allowing all the frequency of a comb to resonate, is resonant for the pump beam of a non-collinear type I parametric downconversion process. It produces after the non-linear crystal a signal and an idler pulse travelling in two different directions symmetric to the pump $\vec{k}$ vector. Each pair of pulses produced by this source is a quantum state with multipartite entanglement in the frequency domain. Furthermore, one can show that it is always possible to find a mode basis that diagonalize the interaction Hamiltonian whose evolution gives the quantum output-state. In this basis each mode, called supermode, is found to be independently squeezed. A first application of this quantum source will be to use the produced beam to perform a space-time positioning beyond the standard quantum limit. Such an experiment requires increasing resolution over large distances. It has been shown that a multimode squeezed state will give an ultimate precision in estimation of space-time distances if the two most squeezed supermodes have the same value for the squeezing parameter[5].

A femtosecond oscillator produces a Fourier Transform limited frequency comb centered around 795nm with a full-width-half-maximum (FWHM) of 40nm ; these pulses are frequency doubled on a 350μm BiBO crystal in order to set the frequency of the pump beam for the downconversion. All the teeth of the 4nm FWHM pump frequency comb resonates in an optical cavity with a free spectral range that exactly matches the repetition rate of the femtosecond oscillator. A 800μm BBO crystal is positioned where the linear cavity has its waist and is slightly tilted in order to maximize the phase-matching for a non-collinear downconversion. This BBO crystal is seeded along the signal direction ; state analysis is then performed with pulse shaped homodyne detection in pulse-to-pulse regime.

Since the number of squeezed modes and their squeezing parameter depends on the pump spectrum and on the non-linear crystal thickness, this source can be later engineered in order to generate big cluster states with hybrid entanglement. Exploiting the presence of two separated beams, this source is indeed able to entangle the squeezed supermodes in the time domain. By delaying one of the two multimode pulse by an interpulse delay and combining it with the second pulse on a beam splitter entanglement between the different time bins can be produced. Since the downconversion process already provides multipartite entanglement between the signal and idler pulses the final quantum state will exhibit entanglement in both time and frequency components.

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State-of-the-art cold atom gyroscope without dead time

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Since the pioneering experiments of 1991, atom interferometry has established as a unique tool for precision measurements of fundamental constants and of gravito-inertial effects. Atom interferometry covers multiple applications such as metrology, inertial navigation, geophysics, fundamental tests of gravity, and has been proposed for gravitational wave detection.

One important limitation of cold atom interferometers is dead times between successive measurements, corresponding to the preparation of the atom source prior to the injection in the interferometer zone. The dynamics during this preparation period is lost, which is a major drawback for many applications. We will report on the first operation of a cold atom inertial sensor without dead times [1]. Using a cold atom gyroscope setup, we achieve continuous operation of an atom interferometer which features a Sagnac area of 11 cm^2. We show that the continuous operation does not prevent from reaching state of the art inertial sensitivity levels, by demonstrating a sort term rotation sensitivity of 90 $\mathrm{nrad.s}^{-1}/\sqrt{\mathrm{Hz}}$ and a long term stability of 1 $\mathrm{nrad.s}^{-1}$ after 10000 s of integration time. Extension of our method to multiple interleaved atom interferometers as we demonstrated in Ref.[2] represents a major step forward for applications of quantum sensors.

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Towards a quantum electrical multimeter in the new International System of units (SI)

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The International System of units (SI) has always progressed following the scientific knowledge with the aim of being universal and of reducing the measurement uncertainties. In a very near future it is planned to base the SI on seven defining constants, among which are the Planck constant h and the elementary charge e. This modernization will allow the SI conform realizations of the electrical units, the volt and the ohm, from the Josephson effect and the quantum Hall effect, with unprecedented low uncertainties only limited by their implementation. This will benefit to measurements. Another advantage is that the ampere, once defined from *e*, can be realized using quantum effects, either by using single electron tunneling devices or by applying directly Ohm's law to the quantum voltage and resistance standards. In this context, we aim at exploiting the solid-state quantum effects by extending the limits of their applications, for instance, towards relaxed experimental conditions and lower uncertainties. Here we present two recent developments of our group.

The quantum Hall resistance standards (QHRS) usually used in National metrology Institutes (NMIs) are based on GaAs/AlGaAs semiconductor heterostructures that typically work at temperatures of 1.5 K, at magnetic fields above 10 T and at bias currents that cannot exceed tens of μA imposing the use of cryogenic amplifiers based on SQUIDs to reach uncertainty levels of 1 part in 10^9. Consequently, the use of QHRS is mainly limited to NMIs. The unexpected solution to relax these experimental conditions came from the massless and relativistic character of charge carriers in graphene that leads to a more robust quantum Hall effect. We have demonstrated that devices made of high-quality graphene grown by chemical vapour deposition on silicon carbide can operate in extended and significantly relaxed experimental conditions compared to state-of-the-art GaAs/AlGaAs devices[1, 2]. The Hall resistance can be accurately quantized to within 1 part in 10^9 down to 3.5 T at a temperature of up to 10 K or with a current of up to 0.5 mA. This experimental simplification highlights the great potential of graphene in the development of user-friendly and versatile quantum standards that are compatible with broader industrial uses beyond those in NMIs. More recently, we have developed an original implementation[3] of Ohm's law applied to a special circuit combining the PJVS, the QHRS and an highly-accurate superconducting amplifier to realize a programmable quantum current generator (PQCG). We have demonstrated the accuracy of the generated current in the milliampere range to 1 part in 10^8[4]. This new quantum current standard can generate currents down to the microampere range with such accuracies and we have shown that it can be used to efficiently calibrate digital ammeters. It competes seriously with the electron pumps reaching only 2 parts in 10^7 at 90 pA [5] at the expense of big research efforts over the last two decades.

More fundamentally, the PQCG will become a direct realization of the future definition of the ampere from the elementary charge with an uncertainty at the level of 1 part in 10^8 in the new SI. Moreover, the availability of graphene-based quantum resistance standards allow the implementation of the quantum voltage, resistance and current standards, as well as their combination, in a unique compact cryogen-free setup. This would constitute a major step towards the realization of a quantum multimeter based on the combination of the solid-state quantum effects.

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Towards bulk crystal coherence times in Eu^{3+} :Y_2O_3 nanocrystals

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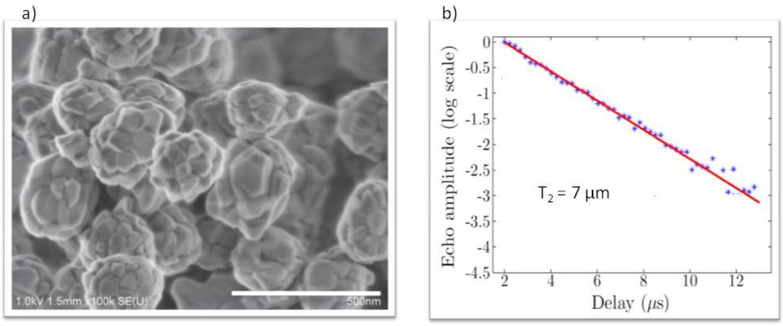
Rare-earth-ion-doped crystals have been extensively studied for quantum information applications because of their excellent coherence properties. Despite the very promising properties of the materials, development of quantum hardware is hindered by difficulties to access single ions and to couple several interacting units together, to create a scalable system in a bulk crystal.

Nanoparticles containing rare-earth ions open up opportunities for high contrast single-ion optical detection [1, 2], and optical coupling to ensembles through access to optical cavities with small mode volumes [3]. One key question is to what extent it is possible for the linewidths in nanocrystals to approach the sub-kHz linewidths achieved in bulk crystals.

Optical homogeneous linewidths of Eu^{3+} dopants in Y_2O_3 nanoparticles below 100 kHz have been previously reported for 60 nm crystallites [4, 5], and we now present homogeneous linewidths below 50 kHz for 100 nm crystallites.

By performing hole burning and coherent spectroscopy on powdered nanoparticle samples we determine the broadening contributions of interactions between europium ions and dynamic disorder modes, phonons, and magnetic fluctuations within the host lattice. We explore the possibilities to extend the coherence times of sub-micron particles towards the bulk crystal values.



a) Scanning electron microscope image of Eu^{3+} :Y_2O_3 nanoparticles. The particles are about 450 nm large, and contain several single crystallites of about 100 nm. b) The particles show an optical coherence time of 7 μs, which corresponds to a homogeneous linewidth of 45 kHz.

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Two-photon rotational spectroscopy with hertz-level resolution on trapped HD^+

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Precision measurements with hydrogen molecular ions were proposed for metrology of nuclear to electron mass ratios [1]. Doppler-free frequency measurements of two-photon rovibrational transitions with narrow linewidths in trapped hydrogen molecular ions allow to improve the accuracy of the determination of the mass ratios at the 10^{-11} level [2]. The longest lifetimes (>1 s) of the rotational energy levels of the HD^+ ions are found in its ground vibrational state [3]. Moreover, the dipole moments of the one-photon rotational transitions in the ground vibrational level are by an order of magnitude greater than the dipole moments of the one-photon rovibrational transitions of the HD^+ ions [4]. The two-photon rotational transitions are therefore interesting for increasing the resolution of the Doppler-free frequency measurements [5].

Frequencies, transition rates, lineshapes and lightshifts are calculated for two-photon rotational transitions on the basis of the experimental setup [6] with 10^2 trapped HD^+ ions that are sympathetically cooled at 10 mK with 10^3 laser-cooled Be atoms. The calculations, based on the two-photon operator formalism [7], are using dipole moments from [4] and accurate HD^+ ion energy levels from [8]. The detection of the two-photon transition (v,J)=(0,1)->(0,2)->(0,3) at 3.268 THz is based on resonance-enhanced multiphoton dissociation (REMPD) with the two-photon rovibrational transition (v,J)=(0,3)->(4,2)->(9,3) at 1.4 μm followed by the photodissociation of the (v,J)=(9,3) level. A THz quantum cascade laser (THz QCL) with an intensity of 1 mW/(1 mm^2) may allow a transition rate as high as 2×10^3 s^{-1}. Interaction with the blackbody radiation recycles continuously the HD^+ ions in the (v,J)=(0,0)-(0,5) rotational levels contributing thus to the two-photon transition signal. The photodissociated signal with the REMPD scheme is described with a rate equation model. It corresponds to the broad profile of the two-photon rovibrational absorption on which is superposed a two-photon rotational signal with FWHM linewidth of 1.31 Hz leading to a resolution in the THz range of 4×10^{-13}. The detection of a fraction of 0.31 HD^+ trapped ions can be done in a relatively short (2 s) measurement time. The Allan variance of the THz QCL laser locked on the two-photon rotational line at the limit of quantum projection noise is estimated at 1.6×10^{-14} $(\tau/s)^{-1/2}$. Intensity stabilisation of the THz QCL at 0.1 allows to calculate an uncertainty of the lightshift of 2.3×10^{-14}.

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Vectorial near-field coupling on the nano-scale

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Dipole-dipole coupling is ubiquitous in nanoscale systems and accounts for phenomena such as inter-molecular level splitting [1] or the high efficiency of light harvesting complexes [2] due to ultrafast coherent exchange of energy. As dipole-dipole coupling sensitively depends on the separation as well as relative orientation of dipole moments, it is however experimentally challenging to fully characterize a coupled system of dipole moments and their associated optical modes simultaneously on both the relevant length scales below 5 nanometers (nm) and over a broad spectral bandwidth.
To address this challenge, we implemented a novel type of Scanning Near-Field Optical Microscope (SNOM) based on the adiabatic nanofocusing of Surface Plasmon Polaritons (SPPs) [3], which are grating-coupled onto the shaft of a metallic nanotaper. In this way, a bright, spatially isolated and spectrally broad nano light source is excited at the 10nm sized apex of the taper [4, 5], which is then used as a probe for virtually background-free high resolution near-field spectroscopy.

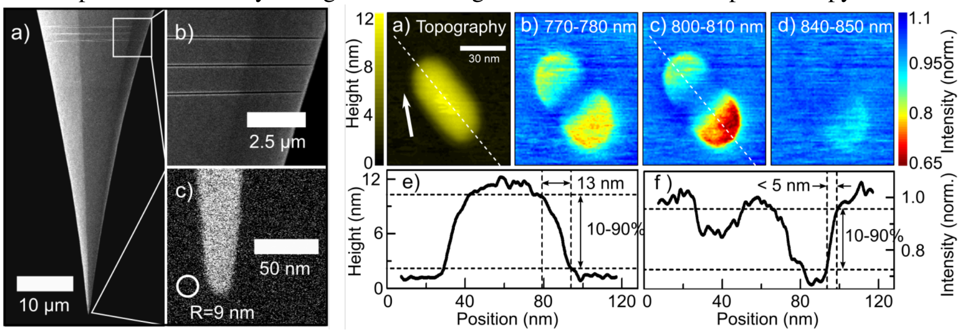

Figure 1 : (left) Nanofocusing SNOM taper with a 9nm sized apex is equipped with a grating coupler. (right) Normalized optical scattering images of an individual gold nanoparticle a) AFM topography, b)-d) scattering intensities integrated over 10nm spectral width showing dipolar patterns and coupling-induced absorption. e)-f) Cross-sections through a) and c) along the dashed lines showing 5nm optical resolution.

Here, we use this novel microscope to investigate dipole-dipole coupling in a prototypical system of the tip antenna and small 10nm×40nm metallic nanorods (cf. Figure 1). By systematically varying both the relative position and configuration - and hence the coupling strength - of the rod and tip in all three dimensions, we find clear spectral signatures of coupling-induced absorption from dipolar plasmon modes, coupling-induced spectral shifts of plasmonic resonances, as well as coupling-induced broadening in plasmon line widths. All these effects are found to vary dramatically on exceedingly short few-nanometer length scales.
In conjunction with coupled dipole model calculations these measurements demonstrate how the systematic variation and spectroscopic study of vectorial coupling in nanoscale systems paves the way toward a new wealth of information in near-field spectroscopy since coupling energies, mode profiles and the associated coherent dynamics become fully accessible on the relevant length scales. We will argue that our approach presents a fundamentally new way to interrogate dipole-dipole couplings in a variety of nanosystems in the spatial-, spectral- and temporal domain.

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Quantum Simulation (QSIM)

An atom-by-atom assembler of 2d atomic arrays for quantum simulation

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Large arrays of individually controlled atoms trapped in optical tweezers are a very promising platform for quantum engineering applications [1]. However, to date, only disordered arrays have been demonstrated, due to the non-deterministic loading of the traps. I will present how we succeeded in the preparation of fully loaded, two-dimensional arrays of up to ~ 50 microtraps each containing a single atom, and arranged in arbitrary geometries [3]. Similar results have been obtained in one dimension in a group at Harvard [3].

Starting from initially larger, half-filled matrices of randomly loaded traps, we obtain user-defined target arrays at unit filling. This is achieved with a real-time control system and a moving optical tweezers that performs a sequence of rapid atom moves depending on the initial distribution of the atoms in the arrays.

These results open exciting prospects for quantum engineering with neutral atoms in tunable geometries.

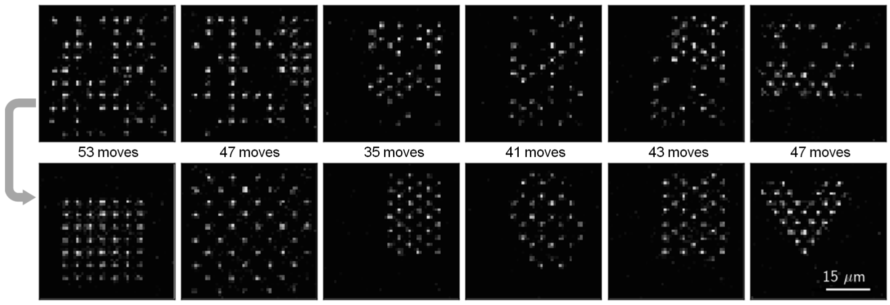

FIG 1 : Gallery of fully loaded arrays (bottom images) obtained from the initial configurations shown in the top images. All images are single shots. The number of elementary moves needed to achieve the sorting are indicated.

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Exploring Ultrastrong Coupling Effects Using a Josephson Mixer

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We use the Josephson Ring Modulator (JRM) to demonstrate new signatures of the ultrastrong coupling between two bosonic modes [1]. The JRM implements a three wave mixer between two microwave modes a and b. When pumping the JRM at a red (blue) frequency $f_R^{(0)} = f_a - f_b$ ($f_B^{(0)} = f_a + f_b$), we realize frequency conversion between modes at a rate G_R (two mode squeezing at a rate G_B). The effective ultrastrong coupling is obtained when the JRM is pumped by these two tones simultaneously so that $G_B = G_R$ is larger than the relaxation rate of the modes a and b. In this experiment, we reach this regime by weakly coupling the modes of a Josephson mixer to measurement transmission lines compared to the rates $G_{B,R}$. As expected, by detuning the blue pump at a frequency $f_B = f_B^{(0)} + 2\delta$, two peaks appear in the spectral density of each mode output, separated by 2δ. A key signature of ultrastrong coupling corresponds to the splitting of each of these peaks into two other peaks whose separation is set by G_R. We present preliminary experimental results that demonstrate this behavior and reach the regime where a strong (20 dB) peak appears in the spectral density of each mode output at $G_R = G_B = \delta/2$. In this regime, we should be able to demonstrate both two-mode and single mode squeezing of the output fields.

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Heteronuclear controlled–NOT quantum gate for single neutral atoms using the Rydberg blockade

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Quantum information processing with mixed–species architectures shows advantages in avoiding crosstalk and in quantum non–demolition detection [1, 2]. Implementing the C–NOT gate with these architectures is still a challenge. The C–NOT gate between two different ions has been demonstrated recently [3, 4]. However, for trapped neutral atom systems, which are unique in controlling the interaction strength [5] and in forming tunable arrays for simulations [6], the C–NOT has only been realized with two identical atoms [7]. We experimentally demonstrate the first heteronuclear C–NOT gate, using a single ^{87}Rb atom and a single ^{85}Rb atom. First, we realize a strong heteronuclear Rydberg blockade by exciting ^{87}Rb to the 79D Rydberg state to suppress the Rydberg excitation of ^{85}Rb which is 3.8μm away. Then, we transfer this blockade to the heteronuclear C–NOT gate with the fidelity of 0.73 $\pm$ 0.01. We model the Rydberg blockade theoretically and point out the important impact of the temperature on the blockade strength. Our work paves the way towards the use of multi-element neutral atoms in quantum computation, quantum simulation, and quantum metrology.

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Measurements of spectral function of ultra-cold atoms in disordered potentials

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We present our work on ultracold atoms in a disordered potential created by a laser speckle. This allows us to study phenomena of Anderson localization known in condensed matter physics [1]. For this purpose, a BEC of ^{87}Rb is initially prepared in a spin state $|1\rangle$ insensitive to the disorder and is transferred using a radio-frequency spin flip to state $|2\rangle$ which is sensitive to the disorder. By measuring the transfer rates of atoms to the state affected by a spatially disordered potential, we obtain the so-called *spectral functions* of the disordered system [2].The disorder amplitude can be tuned from attractive one to repulsive one by changing the laser speckle's frequency. Such technique has been employed in Fermi gas experiment [3]. We will also discuss two regimes of disorder : the ”classical” disorder where the fluctuations of the potential mainly shape the atomic states and the ”quantum” disorder where tunneling effects between the potential minima play major roles. Finally, we will discuss the possibility to produce energy-resolved matter wave states. This work provides the venue to explore metal-insulator Anderson phase transition and to measure the critical exponents.

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Multimode circuit QED : Towards many-body physics

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The study of light matter interaction represents a key topic in fundamental physics. Over a decade ago this study got to another stage with the introduction of artificial atoms made of superconducting circuits. Because of their mesoscopic size they can couple much strongly to light than natural ones. This gave rise, for example, to the first observation of the ultra strong light-matter coupling regime in a cavity system [1].

In our work we follow a new approach consisting in coupling a superconducting artificial atom (namely a transmon qubit) to a meta-material made of thousands of SQUIDs. The latter sustains many photonic modes and shows a characteristic impedance close to the quantum of resistance. Thanks to this high characteristic impedance, we observe a coupling an order of magnitude higher than previously reported in multi-mode systems [2].

Thus, in our circuit the artificial atom is simultaneously coupled to many photonic modes, which, in return, all interact together. With this experiment we were able to push quantum optics towards the realm of many-body physics, where strong interactions between many particles is the norm. As a direct application, we use this circuit to explore quantum optics in the ultrastrong coupling regime, where new phenomena arise [3–5]. Moreover it provides a fully-tunable platform for the quantum simulation of the spin-boson model in the strong dissipative regime [6] ; this is of prime importance since this model has remained so far a theoretical concept, despite its central role in condensed matter physics.

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Quantum simulation of a time-dependent ultrastrong coupling between two bosonic fields in Circuit Quantum Electrodynamics

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We show how a three-wave mixing interaction achieved in a Josephson ring modulator [1] can be used to simulate a time-dependent ultrastrong coupling between two bosonic modes. The simulation requires the physical coupling strength to be at least comparable with the dissipation rates of the bosonic modes, and the pump mode to be driven by a two-tone radiation. First, we show that the simulation enables to retrieve the typical behaviour of a genuinely ultrastrongly coupled bosonic system [2]. Second, we find that one consequence of the simulation is the emission of exotic states, namely states whose noise is squeezed under the standard quantum limit in both the single mode and the two-mode pictures. Additionally, we show that tuning one of the drivings allows us to study a transition between a regime where the system emits a standard two-mode squeezed state that can be generated in an OPO, and a regime where the emitted state is both single mode and two-mode squeezed. Finally, preliminary experimental results [3] indicate the first measured signature of this simulation.

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Quantum simulation of spin systems using 2D arrays of single Rydberg atoms

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Quantum spin Hamiltonians can describe a large variety of condensed matter systems such as quantum magnets, topological insulators, or high-temperature superconductors. During the last decade several platforms, including cold atoms/ions, superconducting circuits or polar molecules, have been explored to simulate those models that are otherwise difficult to solve analytically, and cannot generally be treated numerically, even for a few tens of particles.

Here we report on a novel scalable platform for quantum simulation of spin systems [1]. In our experiment, we exploit van der Waals [2] and dipole-dipole interactions [3, 4] between single Rydberg atoms in fully configurable 2D arrays (see Figure 1) to engineer different types of spin Hamiltonians. For arrays of up to thirty spins (approaching the currents limit for numerical simulations), we measure the coherent evolution of the particles interacting under an Ising-type Hamiltonian in a transverse field after a quantum quench [1]. We show that the dynamics are accurately described by parameter-free theoretical models and we analyze the role of the small remaining experimental imperfections.

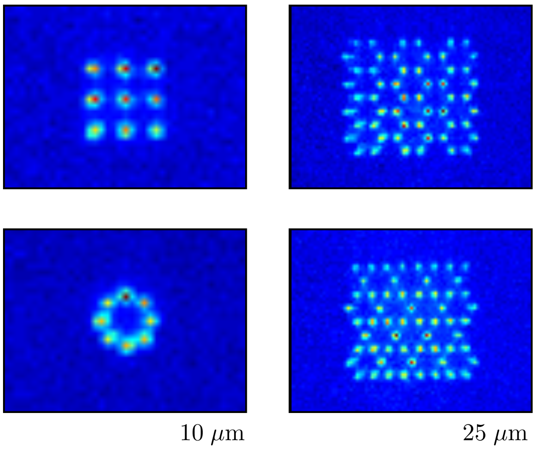

FIGURE 1. Examples of 2D atomic arrays : average fluorescence emitted by up to fifty atoms in different configurations.

We recently implemented an atom-by-atom assembler [5] to create fully loaded 2D arrays of atoms. Our set-up will allow us to study for example geometrical frustration in systems of about fifty spins.

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Engineering quantum transport and exotic materials with cold atoms and hot molecules

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The ability to control and modify inter-particle interactions using external electric, magnetic and electromagnetic fields has proven an outstanding tool to cool and stabilize gases of atoms and to harness novel quantum many-body phases in these systems. In this talk we review recent results for alkali atoms prepared in their absolute ground-state, where long-ranged inter-particle interactions are obtained by weakly dressing the ground-state by laser light with a highly-excited Rydberg state. We demonstrate theoretically that novel exotic quantum materials can be engineered with these types of interactions, where, for example, frictionless superfluid flow of particles can coexist with disordered glassy phases [2] or where the bosonic ground state can break no symmetry - a Bose metal [**?**]. Lessons learned in the cold atom world can sometimes be transferred back to room temperature materials and devices : We demonstrate that charge transport in disordered molecular materials can be substantially enhanced by coupling organic molecules to the vacuum field of a cavity or of a properly tuned two-dimensional plasmonic structure [3] [4]. This may have interesting consequences for the design of optoelectronic devices at room temperature.

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Spin exchange dynamics in chromium quantum gases

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Chromium atoms have a large s=3 spin in the ground state. They therefore have a large permanent magnetic moment, and the resulting dipolar interactions between atoms confer to chromium quantum gases specific properties as this interaction is long range, and anisotropic. Chromium atoms also exhibit large spin dependent contact interactions. Therefore, when chromium atoms are prepared in an excited spin state, they do not undergo a simple precession around the magnetic field : these different interactions lead to a spin exchange dynamics, generating correlations between atoms [1]. Recent experimental results showing spin exchange dynamics in a chromium Bose Einstein Condensate are presented. The dynamics is initiated by a spin rotation of all the atoms. Comparison with numerical simulations provides an insight on the origin of the dynamics, both in the superfluid and in the Mott regimes. In particular, beyond mean field dynamics is evidenced in an optical lattice, resulting from dipolar intersite interactions [2].

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Spreading of Quantum Correlations in Short- and Long-Range Interacting Systems

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The out-of-equilibrium dynamics of correlated quantum systems is attracting considerable attention sparked by the emergence of new quantum devices that combine long coherence times, slow dynamics, and precise control of parameters. They concern a variety of systems including ultracold atoms, artificial ion crystals, electronic circuits, spin chains in organic conductors, and quantum photonic systems for instance. One of the most fundamental features of the dynamics of quantum systems is the existence of so-called *Lieb-Robinson bounds* to the propagation of correlations. Such bounds have fundamental implications on propagation of information, spreading of quantum correlations, and the dynamics of thermalization processes.

Here, we study the dynamics of quantum correlations in various lattice systems using a combination of numerical and analytical many-body approaches. For quantum systems with short-range interactions, our results confirm ballistic spreading of quantum correlations in 1D and 2D Bose-Hubbard models and allow for accurate determination of the cone-like velocity [1]. In dimension higher than two, we show that the correlation pattern is determined by many-body interference effects and that the wave front is characterized by a ballistic spreading within the *Manhattan metrics* rather than *Euclidian metrics*, hence producing a square rather than circular correlation front.

In long-range interacting systems, various extensions of the Lieb-Robinson bounds have been proposed. For interactions decaying algebraically in space like $1/R^\alpha$ in a square lattice of dimension D, universal bounds predict super-ballistic spreading for $\alpha > D$ and no bound for $\alpha < D$. While compatible with those bounds, our results show that (i) the quantum speed limit set by Lieb-Robinson bounds is most often not reached, (ii) the spreading of quantum correlations is often sub-ballistic, and that it is both (iii) model-dependent and (iii) observable-dependent [2]. These conclusions are based on the systematic numerical study of the dynamics of two models characterized by the same universal bounds but that show completely different behaviors and on the study of various observables. These two models, namely the extended Ising and Bose-Hubbard models, are realizable within ultracold atom or ion systems. The numerics are both qualitatively and quantitatively supported by an analytical approach based on exact dynamics of many-body excitations [3].

Our results shed new light on the dynamics of quantum correlations in short- and long-range interacting systems. They pave the way to future experimental investigations and application to quantum communications in new engineered quantum devices.

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Quantum Processing, Algorithm, & Computing (QPAC)

A direct approach to measurement-based quantum computing

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Measurement based quantum computation (MBQC) is a quantum computational model equivalent to the circuit model in terms of computational power, but based on a different setting. In its traditional formulation, the manipulation of the input state to be processed is achieved by entangling it to a highly entangled resource state, the cluster state, and by performing suitable local projective measurements on the nodes of the cluster state, thereby projecting the remaining nodes onto the desired computation result [1, 2]. In this work we introduce a different scheme for measurement based quantum computation in Continuous Variables. Our approach does not explicitly rely on the use of ancillary cluster states to achieve its aim, but rather on the detection of input state and ancillary squeezed states in a suitable mode basis, followed by digital post-processing. Practically speaking, we provide a recipe to optimize the adjustable parameters that are employed at the detection level to obtain the relevant statistics of the measurement outcomes, corresponding to the desired computation [3].

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Atomic scale Quantum Hamiltonian Boolean Logic gates

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Abstract

The new Quantum Hamiltonian Computing (QHC) quantum engineering approach for implementing Boolean logic gates at the atomic scale will be presented. With QHC, the complex functionality of a Boolean logic gate is embedded inside the quantum system by inputting the logical information directly on the Hamiltonian and by measuring the logical output using the Heisenberg-Rabi oscillation of the quantum system between always the same initial and final quantum states [1]. In QHC and contrary to the Feynman-Deutch quantum computing qubit approach [2], those initial and final states running the gate are carrying no direct information on the implemented Boolean function.

Without embedding rectifiers, switches, transistors and without using qubits along the quantum structure, a QHC molecule can compute in a quantum way even if the data inputs are classical, the classical to quantum conversion occurring directly on the molecule using for example the picometer precision of a low temperature scanning tunneling microscope (LT-UHV-STM). The atomic scale quantum measurements at work to measure the logical output will also be discussed [3]. A quantum graph technique for designing QHC gates will be described leading for example to a very simple 6 quantum states QHC Boolean ½ adder quantum gate [4]. We will detail the advantages and limitations of the QHC quantum control approach in term of computing power, clock frequency and interconnects. QHC NOR, XOR single molecule gates [5] and a surface NOR/OR atomic scale circuits [6] have been experimentally demonstrated with an LT-UHV-STM and can be now generalized to 4 LT-UHV STM in parallel.

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Optical and Electron Paramagnetic Resonance Spectroscopy of $Yb^{3+}:Y_2SiO_5$

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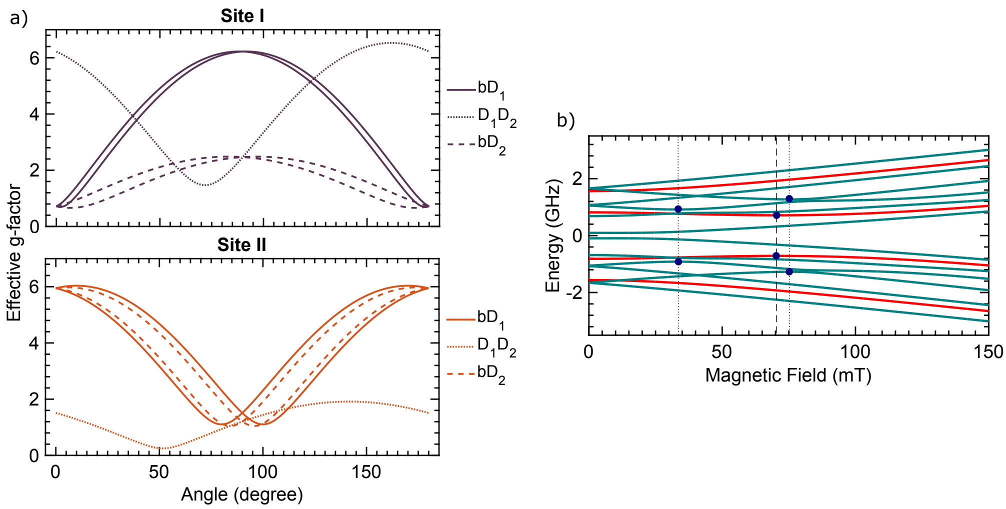
Crystals doped with paramagnetic rare earth (RE) ions are promising materials for quantum information processing because they can be coupled to microwave photons [1] or provide large bandwidth memories [2]. We also recently demonstrated that coherence transfer with high fidelity was possible between electron and nuclear spins in these materials, opening the way to long storage time capability [3].

In this paper, we report on the optical and paramagnetic spectroscopic properties of $Yb^{3+}:Y_2SiO_5$ at low concentration. In particular, we determined the ground state spin Hamiltonian (**g** and **A** tensors) for isotopes with I=0, I=1/2 and I=5/2 nuclear spins for ions in sites 1 and 2 [4]. As it has been done for $Er^{3+}:Y_2SiO_5$ [5], we also determined optically the **g**-tensor of the excited state $^2F_{5/2}$ of $Yb^{3+}:Y_2SiO_5$. This allows one to determine energy level structure of both the ground state ($^2F_{7/2}$) and the excited state ($^2F_{5/2}$) for an arbitrary magnetic field, which may be useful to minimize decoherence processes caused by Yb^{3+}-Yb^{3+} interactions [6].



a) Calculated ground-state effective g factors in the bD_1, bD_2,and D_1D_2 planes for sites 1 and 2 in $Yb^{3+}:Y_2SiO_5$. b) Calculated energies E of the ground state hyperfine levels of $^{171}Yb^{3+}$ (I=1/2, red) and $^{173}Yb^{3+}$ (I=5/2, blue) in site 2 as a function of the magnetic field strength. The field is oriented along D_1. The vertical dashed (dotted) line denotes partial clock transitions (dE/dB=0) for I=1/2 (I=5/2)

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Quantum Observables for Binary, Multi-Valued and Fuzzy Logic : Eigenlogic

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We propose a linear algebraic method, named Eigenlogic [1], for two-, many-valued and fuzzy logic using observables in Hilbert space. All logical connectives are represented by observables where the truth values correspond to eigenvalues and the atomic input propositional cases, i.e. the "models" of a propositional system, to the respective eigenvectors. In this way propositional logic can be formalized by using combinations of tensored elementary quantum observables. The outcome of a "measurement" of a logical observable will give the truth value of the associated logical proposition, and becomes "interpretable" when applied to vectors of its eigenspace, leading to an original insight into the quantum measurement postulate. Recently the concept of "quantum predicate" has been proposed in [2] leading to similar concepts.

We develop logical observables for binary logic and extend them to many-valued logic.

For binary logic and truth values $\{0, 1\}$ logical observables are commuting projector operators [1].

For truth values $\{+1, -1\}$ the logical observables are isometries formally equivalent to the ones of a composite quantum spin $\frac{1}{2}$ system, these observables are reversible quantum logic gates.

The analogy of many-valued logic with quantum angular momentum is then established using a general algebraic method, based on classical interpolation framework suggested by the finite-element method. Logical observables for three-valued logic are formulated using the orbital angular momentum observable L_z with $\ell = 1$. The representative 3-valued 2-argument logical observables for the ternary threshold logical connectives Min and Max are then explicitly obtained [3].

Also in this approach fuzzy logic arises naturally when considering vectors outside the eigensystem. The fuzzy membership function [4] is obtained by the quantum mean value (Born rule) of the logical projector observable and turns out to be a probability measure. Fuzziness arises because of the quantum superposition of atomic propositional cases, the truth of a proposition being in this case a probabilistic value ranging from completely false to completely true.

This method could be employed for developing algorithms in high-dimensional vector spaces for example in modern semantic theories, such as distributional semantics or in connectionist models of cognition [5]. For practical implementation, due to the exponential growth of the vector space dimension, adapted logical reduction methods must then be used. LSA (Latent Semantic Analysis) algorithms are often used in quantum-like approaches, this was done in [6] using the HAL (Hyperspace Analogue to Language) algorithm.

Our approach is also of interest for quantum computation because several of the observables in Eigenlogic are well-known quantum gates (for example CONTROL-Z) and other ones can be derived by unitary transformations. Ternary-logic quantum gates using qu-trits lead to less complex circuits, our formulation of multi-valued logical observables could help the development of new multi-valued quantum gate architectures.

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Quantum information processing in phase space : A modular variables approach

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Quantum information can be processed in two fundamentally different ways, using either discrete or continuous variable representations. Each one of them, provides different practical advantages and drawbacks. In [1] it was shown that by combining both realms one can encode binary quantum information fault tolerantly in states defined in infinite dimensional Hilbert spaces and thereby permit a perfect equivalence between continuous and discrete universal operations. However, a practical difficulty is the extremely challenging experimental production of such logical states in terms of the quadratures of the electromagnetic field, which has not been realized yet.

In this talk, I use the modular variables formalism to show that, in a number of protocols relevant for quantum information and for the realization of fundamental tests of quantum mechanics, it is possible to loosen the requirements on the logical subspace without jeopardizing neither their usefulness nor their successful implementation [2, 3]. Thereby, modular variables are defined by dividing the spectrum of two canonically conjugate observables into a discrete and a modular part, respectively, allowing for the definition of a new basis that is characterised solely by the bounded values of the corresponding modular eigenvalues. In particular, we consider protocols that involve measurements of appropriately chosen logical observables enabling the readout of the encoded discrete quantum information from the corresponding logical states.

To demonstrate the applicability of our framework we show how to violate a discrete variables Bell inequality in terms of continuous variables states expressed in the modular variables basis [4]. Our work is strongly motivated by the experimental ability to produce and manipulate the corresponding logical states in photonic systems that exploit the transverse distribution of single photons as continuous-variables degree of freedom.

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Quantum walking in curved spacetime : $(3+1)$ dimensions, and beyond

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A Quantum Walk (QW) is essentially a unitary operator driving the evolution of a single particle on the lattice. Some QWs admit a continuum limit, leading to familiar PDEs (e.g. the Dirac equation), and thus provide us with discrete toy models of familiar particles (e.g. the electron). We study the continuum limit of a wide class of QWs, and show that it leads to an entire class of PDEs, encompassing the Hamiltonian form of the massive Dirac equation in $(3+1)$-dimensional curved spacetime. Therefore a certain QW, which we make explicit, provides us with a unitary discrete toy model of the electron as a test particle in curved spacetime, in spite of the fixed background lattice. This means that the metric field can be represented by a field of local unitaries over a lattice. Mathematically we have introduced two novel ingredients for taking the continuum limit of a QW, but which apply to any quantum cellular automata : encoding and grouping.

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Robust quantum gate by single-shot shaped pulses

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We present a new method to design robust quantum processes hybridizing the technique of shortcut to adiabaticity based on an analytical formulation and an inverse engineering design [1] with an optimal control calculation. Contrary to standard optimal control algorithm, this technique allows the selection of a few relevant parameters that are next optimized for designing robust process of control. The technique is applied for the construction of a robust NOT gate for which smooth and simple pulses shaped in phase an in amplitude are designed. These pulses feature oscillations reminiscent to the composite pulse sequence technique [2, 3] but with a time-dependent phase. We demonstrate the remarkable efficiency of these pulses on experimental rephasing of atomic coherence in Pr3 :Y2Si05 crystal [3]. Our technique achieves a better efficiency than the composite methods with a smaller pulse area.

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Shaping the Pump of a Synchronously Pumped Optical Parametric Oscillator for Continous-Variable Quantum Information

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Our group has developed a setup able to produce highly multimode entangled states of light exploiting the downconversion of an optical frequency comb inside an optical parametric oscillator (OPO) [1]. Our main goal is to use this entanglement to implement quantum information protocols.

The evolution of the field inside the OPO is described by a symplectic transformation on the quadratures of the field. It is thus always possible to find a set of modes, called supermodes, which are independently squeezed by the OPO. The supermodes will generally be linear superpositions of frequency modes. The quantum properties of the output state are fully determined by the degree of squeezing and the spectral profile of the supermodes [2]. These are in turn governed by the phase-matching conditions of the crystal and the spectral profile of the pump. If they are fixed, the output state is fixed and the only experimental freedom comes from the choice of the measurement modes. If one needs a specific entanglement structure, the corresponding measurement modes may happen not to be physically separable, for example because they are overlapping superpositions of frequency modes. As a consequence, the entanglement may not be available for actual realizations of quantum information protocols.

To change the structure of correlations in the output mode in order to make it more suitable for quantum information, one could either change the phase matchng condition or change the shape of the pump. The first option is less versatile, because it would involve changing the experimental setup everytime one needs a new output state. Instead, one could use a pulse-shaper before the OPO to change the pump and obtain many different output states with no modification to the experimental setup. This motivates our theoretical study of how the output state can be engineered to create multimode entangled states using pump-shaping techniques. Starting from the Hamiltonian for the evolution of the field inside the crystal, we have developed a method to compute how the shapes and the squeezing spectrum of the supermodes change when an arbitrary field pumps the OPO.

We then used a genetic algorithm to find the pump shape that optimizes specific properties of the output state. We mainly concentrate on the production of continuous-variable cluster states, which are used in several quantum information protocols, such as measurement-based quantum computation [3] and quantum secret sharing [4]. We show that pump-shaping can improve the properties of the cluster states and could allow to produce cluster states whose nodes are on physically separable modes (frequency band modes). We also show how the same optimization procedure can be used to target other properties of the output state, for example the spectrum of the squeezing parameters of the supermodes.

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Single photon Fock state filtering with an artificial atom

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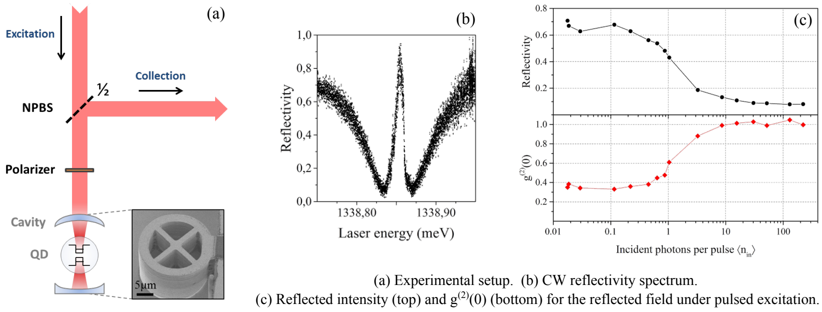
The probabilistic operation of a quantum gate based on linear optics is a fundamental limitation for the scalability of a photonic quantum network or a quantum computer. Pioneering works towards the achievement of deterministic gates for optical photons have been demonstrated exploiting a single natural atom as a nonlinear medium [1].

Demonstrating such nonlinearities with a solid-state artifical atom would offer the advantage of scalability and integration. The intrinsic anharmonicity of a semiconductor quantum dot energy spectrum allows engineering effective photon-photon interactions where the absorption of a first photon changes the transmission probability for a second one. Moreover, by coupling the quantum dot to an optical cavity we can make sure that every photon sent on the cavity interacts with the artificial atoms and vice versa [2]. Here we report on the observation of an optical nonlinearity at the sub-photon scale in a micron-scale solid-state device and the routing of light pulses based on their photon number.

We study a micropillar cavity deterministically coupled to a single QD using the in-situ lithography technique. The cavity is doped to electrically tune the spectral resonance of the QD to the cavity mode [3]. A pulsed linearly polarized laser of controlled temporal profile resonant to the mode of the cavity is sent on the device. Monitoring the directly reflected signal as a function of the excitation power, we observe the saturation of the quantum dot transition for an average incident photon number as low as 0.3 incident photons per pulse, evidencing the excellent light matter interface provided by the structure. The photon statistics of the reflected field evidences a clear antibunching : measurements of the second and third order correlation functions $g^{(2)}$ and $g^{(3)}$ shows how the two and three photons component of the field are strongly suppressed compared to the single photon one. The device behaves as a single photon Fock state filter, converting a coherent pulse into a highly non-classical wavepacket, consisting of 80% single photons.



(a) Experimental setup. (b) CW reflectivity spectrum.
(c) Reflected intensity (top) and $g^{(2)}(0)$ (bottom) for the reflected field under pulsed excitation.

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Tomography of mode-tunable coherent single-photon subtractor

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Single-photon annihilation operator $\hat{a}$, $\hat{a}|n\rangle = \sqrt{n}|n-1\rangle$, plays important roles in an optical quantum information processing. For example, it enables distillation of entanglement, noiseless amplification of a quantum state, and enhancement of measurement precision. In particular, the non-Gaussian nature of the operator provides genuine speed-up of quantum computing based on continuous variable quantum information. Until now, implementation of a single-photon annihilation operator has been limited on a single mode [1] or two modes [2], but recently, extension to multiple modes was proposed [3, 4] based on nonlinear interaction with a strong laser [5].

A crucial step for properly implementing and controlling such operation is to investigate its complete characteristics. Coherent-state quantum process tomography provides a method to characterize an unknown quantum process by probing it with various coherent states and measuring the responses [6, 7]. This method has been used to characterize a quantum process up to two modes [8], but extension to multiple modes requires much efforts because the output states from the operation, which are generally in multiple modes, should be investigated by homodyne detection.

In this work, we implement and characterize mode-tunable coherent single-photon subtractor operating on multiple time-frequency modes. In contrast with conventional coherent-state quantum process tomography [6, 8], we found that characterization of single-photon subtractor does not require information of the output state, but the success probability of the operation is sufficient. We characterize the mode-tunable coherent single-photon subtractor by probing it with weak coherent states for multiple modes. The tomography results show that the single-photon subtractor can be tuned to subtract a single-photon at a single mode exclusively or at multiple modes coherently. This mode-tunable coherent single-photon subtractor will play a key role for building a scalable optical quantum system [9].

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ZX-Calculus and Extension for Real Matrices

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Quantum circuits are commonly used when a representation of a quantum evolution is wanted, without the pain of dealing with matrices of exponentially growing size. But they suffer one major downside : different quantum circuits may represent the same matrix, and there is no proper formalism on which transformations are allowed – i.e. on which transformations preserve the represented matrix.

The ZX-Calculus has been introduced by Bob Coecke and Ross Duncan [1]. It may be seen as a generalisation of the quantum circuitry, and comes with a set of axiomatic equalities between its diagrams. These equalities preserve the represented matrix – the language is *sound* –, and showing that two diagrams are equal amounts to transform one into the other using a succession of locally-applied axioms.

The ZX-Calculus is powerful not only because of its set of authorized transformations, but also because of the paradigm “only topology matters” which means that the wires – the edges in the diagrams – can be bent at will, without changing the represented matrix. Moreover, the diagrams are universal, meaning that for any quantum transformation, a zx-diagram can be found to express it.

Some nodes in the language hold angles, and restricting the language – the diagrams and the set of rules – to only a finite set of these angles allow us to represent the *real stabiliser quantum mechanics* – the multiples of π –, the *stabiliser quantum mechanics* – the multiples of $\pi/2$ –, or the *Clifford+T quantum mechanics* – the multiples of $\pi/4$. It has been shown (R. Duncan, S. Perdrix (2013), M. Backens (2014) [2, 3]) that the language is complete – i.e. the formalism captures all the possible authorised transformations – for the two first restrictions – π and $\pi/2$. The completeness for the last one however – the Clifford+T group – is still an open question, especially since this fragment is *approximately universal* whilst the other two are not i.e. any quantum evolution can be approximated with arbitrarily good precision using the fragment $\pi/4$.

This language was created to manipulate qubits, but does not directly handle *rebits*, and quantum evolutions with real coefficients. These evolutions are as powerful as there counterparts, and some models rely on their use. Hence, it would be interesting to modify the formalism to allow us to only manipulate real transformations. Part of the work to do so was to develop a new language : new nodes in the diagrams, and an adapted set of transformation rules. We have also shown a bridge between the two languages, showing in the process that quantum evolutions on reals efficiently simulate usual quantum evolutions, and we have shown that in the new language as well the $\pi/2$ fragment was complete, using a completeness result in the ZX-Calculus.

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