GDR 3322
⟨IQ|FA⟩
CNRS

8th *Colloquium* OF THE CNRS GDR № 3322 ON QUANTUM ENGINEERING, FOUNDATIONS & APPLICATIONS

INGÉNIERIE QUANTIQUE, DES ASPECTS FONDAMENTAUX AUX APPLICATIONS – IQFA

Université Côte d'Azur – Campus Nice Saint-Jean d'Angély
November 29 - December 1 2017

BOOK OF ABSTRACTS

UNIVERSITÉ CÔTE D'AZUR

Université Nice Sophia Antipolis

INPHYNI
INSTITUT DE PHYSIQUE DE NICE

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advancing the frontiers

Contents

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 twofold: 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.cnrs.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).

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[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 8th Colloquium – Scientific Information

2.1 Welcome !

IQFA's 8th colloquium is mainly organized by the Institut de Physique de Nice (INPHYNI[6]) at the Univesrité Côte d'Azur (UCA[7]).

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:

- 6 tutorial talks, having a clear pedagogical purpose, on the very foundations and most advanced applications of the field;
- 18 contributed/invited talks on the current hot topics within the strategic thematics (ARTs) identified by the GDR IQFA (see online the ARTs[8] for more details);
- and 2 poster session gathering ∼50 posters, again within IQFA's strategic thematics (ARTs).

In total this year, **IQFA's Scientific Committee (see Sec. 1.2) has received 67 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.

Olivier ALIBART (President of the colloquium IQFA 8),
& **Sébastien TANZILLI** (IQFA's Director),

On behalf of IQFA's Scientific Committee.

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[6] http://univ-cotedazur.fr/labs/inphyni/
[7] http://univ-cotedazur.fr/
[8] http://gdriqfa.unice.fr/spip.php?rubrique2

2.2 Program of the colloquium

	Wednesday 29/11/2017	Thursday 30/11/2017	Friday 1/12/2017
8:30	Welcome – S. Tanzilli		
9:00	QMET-tuto: Exploring condensed matter physics with a single spin microscope – V. Jacques	QCOM-tuto: Optical realization of info and com complexity protocols – N. Lutkenhaus	QCOM/FQA-tuto: Q communication in free-space, fiber and eventually to a satellite – R. Ursin
10:00	QMET: Overcomplete Q tomography of a spatially encoded 2-photon N00N state – O. Krebs	QCOM: 1-D atomic chains around a nanoscale waveguide – N. Corzo-Trejo	QCOM: Coherent control of the silicon-vacancy spin in diamond – B. Pingault
10:30	Coffee Break	Coffee Break	Coffee Break
11:00	QMET: Towards electron spin hyperpolarization via radiative cooling – B. Albanese	QCOM: Photonic quantum state transfer between a cold atomic gas and a crystal – N. Maring	QCOM: Dense wavelength division multiplexed hyperentanglement for high capacity quantum information processing – P. Vergyris
11:30	QMET: Resolution of Q ghost imaging and quantum Fourier ptychography – P.-A. Moreau	QCOM: All-optical synchronization for quantum networks – B. Fedrici	FQA-tuto: Multi-time states, multi-time measurements and pre- and post-selection – S. Popescu
12:00	European Flagship, Coordination & Support Actions – T. Debuisschert	QCOM: Correlations with on-chip detection for continuous-variable QKD – L. Trigo Vidarte	
12:30	Lunch	Lunch	Lunch
14:00	QPAC-tuto: Quantum low density parity-check codes – G. Zémor	QSIM-tuto: Quantum simulation – C. Salomon	FQA: Statistical signatures of photon-added and -subtracted states of light – M. Walschaers
14:30			FQA: Fluctuation theorems in a hybrid optomechanical system – J. Monsel
15:00	QPAC: Golden codes, regular Q codes built from regular tessellations of hyperbolic 4-manifolds – Vivien Londe	QSIM: Observing the growth of correlations in dynamically tuned synthetic Ising antiferromagnets – V. Lienhard	FQA: Frequency-entangled qudits in AlGaAs waveguides – G. Maltese
15:30	Coffee Break	Coffee Break	Closing session – S. Tanzilli
16:00	QPAC: Spin detection of natural and artificial atoms in a CMOS device – E. Chanrion	QSIM: Single-atom-resolved probing of lattice gases in momentum space – H. Cayla	
16:30	QPAC: Autopsy of a quantum electrical current – B. Roussel	QSIM: Controlling symmetry and localization properties with an artificial gauge field in a disordered Floquet system – J-F. Clément	
17:00	Poster session 1	Poster session 2	
19:00		Banquet	

2.3 The Université Côte d'Azur, the INPHYNI, and their scientific environment

The Université Côte d'Azur (UCA)[9] is a recently created cluster of higher education establishments on the French Riviera that brings together the major players in higher education and research on the Côte d'Azur. UCA aims at developing a new, 21^{st}-century model for French universities, based on new interactions between disciplines, a new form of coordination between research, teaching, and innovation, and strong partnerships with the private sector and local authorities. UCA gathers, over the entire Côte d'Azur:

- the Université Nice Sophia Antipolis (UNS[10]), research-intensive, present in all international rankings;
- two National Research Organizations, namely the CNRS and INRIA Sophia Antipolis, multidisciplinary and emblematic in digital sciences, respectively;
- the Observatoire de la Côte d'Azur (OCA), one of the three French establishments in Earth and Universe Sciences, with a strong commitment to international projects;
- the Centre Hospitalier Universitaire (CHU) of Nice, a leading national center for simulation and innovation in hematology, biological resources and therapies;
- EDHEC and SKEMA, two Business Schools present in all international rankings;
- as well as a consortium of six Art Schools, active at the international level: the Centre National de Création Musicale, the Ecole Nationale Supérieure d'Art Villa Arson, the Ecole Supérieure de Réalisation Audiovisuelle (ESRA), the Sustainable Design School (SDS), the Ecole Supérieure de Danse de Cannes Rosella Hightower, and the Conservatoire National à Rayonnement Régional de Nice (CNRR).

In January 2016, UCA won the prestigious "IDEX" label from the French government for its UCA^{JEDI} project, placing it among the top 10 world-class, comprehensive universities in France.

Research at UCA is outlined along 5 academies of excellence:

- **Academy 1**: Networks, Information and Digital society;
- **Academy 2**: Complex systems;
- **Academy 3**: Space, Environment, risk and resilience;
- **Academy 4**: Complexity and diversity of living systems;
- and **Academy 5**: Human societies, Ideas and Environments.

The Institut de Physique de Nice (INPHYNI[11]) is an Unité Mixte de Recherche (UMR 7010), associated with the Université Nice Sophia Antipolis (UNS) and the Centre National de la Recherche Scientifique (CNRS), through the Institut de Physique (primary) and the Institut des Sciences de l'Ingénierie et des Systèmes (secondary). Within the local context, the INPHYNI is a member of the Université Côte d'Azur, mainly through the Academies of Excellence #1 - Networks, Information and Digital Society, and #2 - Complex systems.

In terms of positioning, the INPHYNI gathers the majority of the research activities that are carried out in Physics over the Côte d'Azur. The INPHYNI is strucutred along 3 main scientific axis, *i.e.*, Waves and Quantum Physics, Photonics, as well as Nonlinear Physics, Complex Fluids, and Biophysics. The projects developed through those axis cover both theoretical and experimental aspects, and range from fundamental physics to applications. Research projects also take advantage of the capabilities of several performant technological platforms: a Laser and Detection center for Light-Matter Interaction, a center for Optical Fiber Fabrication, a center for Integrated Optics on Lithium Niobate, a Clean Room facility for Complex Fluids and Biophysics, as well as a center for Micro- and Nano-Rheometry.

Within the context of supporting scientific research & colloquiums, the UCA and the INPHYNI support and welcome IQFA*'s 8th colloquium In Nice Campus Saint-Jean d'Angély.*

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[9] http://univ-cotedazur.fr/

[10] http://unice.fr/

[11] http://univ-cotedazur.fr/labs/inphyni/

3 IQFA's 8th Colloquium – Practical Information

3.1 Venue

The exact location of the Colloquium is Campus Nice Saint-Jean d'Angély 1, in the building of the Institut Supérieur d'Économie et de Management (ISEM).
The exact address is ISEM, Rue du 22ieme B.C.A., 06300 Nice, see Fig. 1. Note that "ISEM" is written on the front wall of the building, and that a banderole, on which IQFA 8 @ UCA will be also hanged.

All the tutorial and invited talks will be given in the "Amphitheater #3" inside the ISEM building. Moreover, the poster sessions will be held in the Hall next to the Amphitheater, in the same building.

3.2 Access to the Campus Nice Saint-Jean d'Angély 1

You can join us on the Campus Saint-Jean d'Angély 1 using the following means, see also the Local Map on Fig. 1 and the Tramway line on Fig. 2:

- *By public transportation*:
  From the aiport: two Bus lines can bring you to Nice downtown from the Aéroport Nice Côte d'Azur, namely the 98 (up to Place Massena), and the 99 (up to the main railway station).
  From Nice downtown: take the Tramway line T1 and stop at "Saint-Jean d'Angély Université". Then it's 3 minutes walking, see also Fig. 2.
  Nice public transportation website can be reached online at Lignes d'Azur[12].
- *By Vélo Bleu*: see online the map of available stations Vélo Bleu's map[13].

Figure 1: Localization map of the Nice Saint-Jean d'Angély campus area.

For more details on how to reach the place of the colloquium, please refer to its webpage at: Practical information[14], or refer to the Faculté des Lettres, Arts, Sciences Humaines @ Nice Saint-Jean d'Angély[15].

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[12] https://www.lignesdazur.com
[13] https://www.velobleu.org
[14] https://iqfacolloq2017.sciencesconf.org/resource/acces
[15] http://unice.fr/faculte-des-lettres-arts-sciences-humaines/presentation/les-campus/saint-jean-dangely

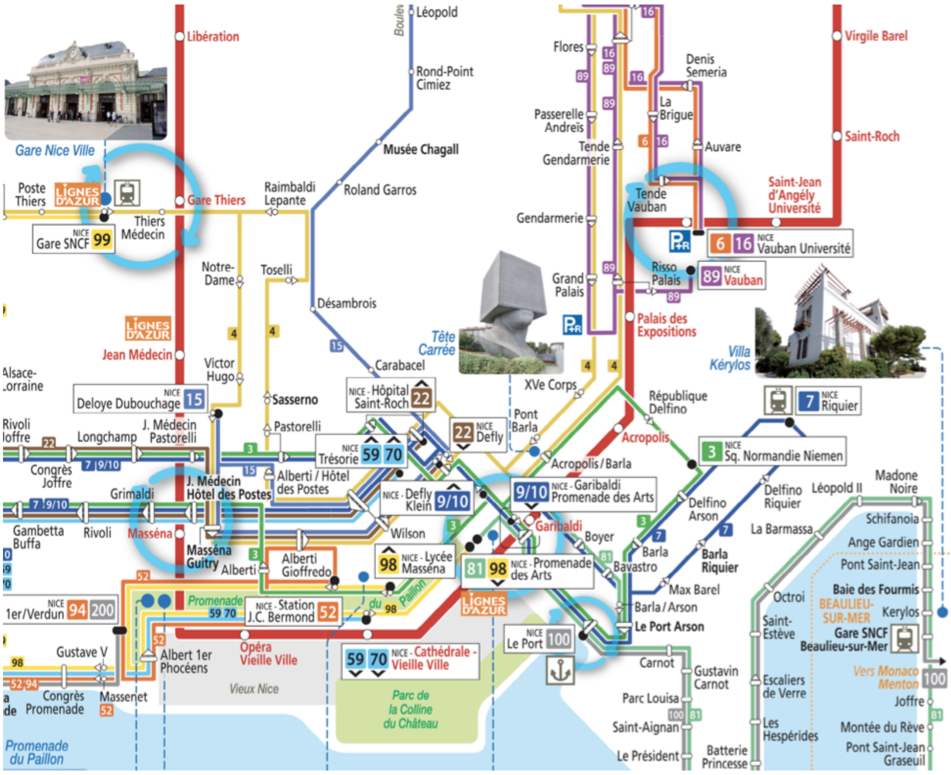

Figure 2: Tramway line T1 that goes from Nice downtown to the Campus Nice Saint-Jean d'Angély. The Tramway stop to reach the Colloquium is "Saint-Jean d'Angély Université".

3.3 Registration & badge

The participants' venue will be made available from Wednesday the 29th of November at 7:30 am, in the Hall of the ISEM building. Once the building reached and its entrance passed, you'll discover both the Hall and the Amphitheater #3, where the colloquium takes place.

For security reasons, please make sure to attend the Colloquium with a valid ID card or passport. Upon your arrival, a nominative badge will be provided to all registered participants, to ease security check.

3.4 Internet Connection

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

3.5 Coffee breaks, lunches & buffet

During the colloquium, all coffee breaks and lunches will be taken on site in the Hall in front of the Amphitheater #3. Coffee breaks and lunches are free of charge for all registered participants.

The banquet of the colloquium is organized on Thursday the 30th of November, 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.

3.6 Organization & financial supports

This colloquium is organized by: the GDR IQFA,
& the Institut de Physique de Nice (INPHYNI),
at the Université Côte d'Azur (UCA),

and with the financial supports of: the CNRS, through the Institutes INP and INSIS,
the Université Côte d'Azur (UCA),
the Université Nice Sophia Antipolis (UNS),
the Institut de Physique de Nice (INPHYNI),
and ID QUANTIQUE,
that are warmly acknowledged.

3.7 Local organization committee for this colloquium at the INPHYNI

President: Olivier Alibart,

Members: Sébastien Tanzilli,
& the Q. Photonics & Information group,

with the precious help of: Nathalie Koulechoff,
& Bernard Gay-Para.

4 Abstracts of the contributions

In the following, you can find, after the tutorial lectures and the Flasghip seesion, all the contributions given per ART.
In each ART, the abstracts that are tagged on the top with the mention “iqfacolloq2017 - Amphitheater - Day - start time / end time (30min)” correspond to contributions that have been selected as oral invited talks (see the Program in Sec. 2.2).
All the other abstracts correspond to poster contributions.

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Tutorial Talks

Exploring condensed matter physics with a single spin microscope

Vincent Jacques*
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Detecting and imaging magnetic fields with high sensitivity and nanoscale resolution is a topic of crucial importance for a wealth of research domains, from material science, to mesoscopic physics, and life sciences. This is obviously also a key requirement for fundamental studies in nanomagnetism and the design of innovative magnetic materials with tailored properties for applications in spintronics. Although a remarkable number of magnetic microscopy techniques have been developed over the last decades, imaging magnetism at the nanoscale still remains a challenging task.

In the past years, it was realized that the experimental methods allowing for the detection of single spins in the solid-state, which were initially developed for quantum information science, open new avenues for high sensitivity magnetometry at the nanoscale. In that spirit, it was proposed to use the electronic spin of a single nitrogen-vacancy (NV) defect in diamond as an atomic-sized magnetic field sensor [1, 2]. This approach promises significant advances in magnetic imaging since it provides non-invasive, quantitative and vectorial magnetic field measurements, with an unprecedented combination of spatial resolution and magnetic sensitivity under ambient conditions [3].

In this talk, I will illustrate how scanning-NV magnetometry can be used as a powerful tool for exploring condensed-matter physics, focusing on (i) domain walls and magnetic skyrmions in ultrathin ferromagnets [4, 5] and (ii) antiferromagnetic order in multiferroic materials [6].

[1] J. R. Maze *et al.*, "Nanoscale magnetic sensing with an individual electronic spin in diamond", Nature **455**, 644 (2008).

[2] G. Balasubramanian *et al.*, "Nanoscale imaging magnetometry with diamond spins under ambient conditions", Nature **455**, 648 (2008).

[3] L. Rondin *et al.*, "Magnetometry with nitrogen-vacancy defects in diamond", Rep. Prog. Phys. **77**, 056503 (2014)

[4] J.-P. Tetienne *et al.*, "The nature of domain walls in ultrathin ferromagnets revealed by scanning nanomagnetometry", Nature Communications **6**, 6733 (2015)

[5] I. Gross *et al.*, "Skyrmion morphology in ultrathin magnetic films", preprint arXiv :1709.06027 (2017).

[6] I. Gross *et al.*, "Real-space imaging of non-collinear antiferromagnetic order with a single spin magnetometer", Nature **549**, 252 (2017)

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Optical Realization of Information and Communication Complexity Protocols

Dave Touchette[1], Juan Miguel Arrazola[1], Ben Lovitz[1] and Norbert Lütkenhaus[1]*
[1]*Institute for Quantum Computing, University of Waterloo, Canada*

Quantum communication can offer qualitative and quantitative advantage over classical communication. Quantum Key Distribution provides a qualitative advantage, and is now widely known. Less known is the potential of quantitative adavantage, although it has been explored for about 20 years. [5] These protocols have been viewed more of theoretical conceptional value, but recently progress has been made to push these protocols into the more practical domain using simple optical implementations.

In this tutorial I will lay out the background motivation of communication and information complexity protocols, including secure multi-party communication. I will do this in the context of the tasks of quantum fingerprinting [6] (comparison or large sets of classical data) and of the scheduling problem (finding common time slots in multiple large calendars). For both problems we have by now implementation proposals based on coherent laser pulses. [1, 4] I will make the connection between the quantum optical protocols and the abstract quantum protocols and will discuss some experimental demonstrations. [2, 3]

[1] J. M. Arrazola nd N. Lütkenhaus, Phys. Rev. A **89**, 062305 (2014).
[2] F. Xu et al, Nature Comm. **6**, 8735 (2015).
[3] J.Y. Guan et al, Phys. Rev. Lett **116**, 240502 (2016).
[4] N. Kumar, E. Diamanti, I. Kerenidis, Phys. Rev. A **95**, 032337 (2017).
[5] H. Buhrman, R. Cleve, S. Massar and R. de Wolf, Rev. Mod Phys **82**, 665 (2010).
[6] H. Buhrman, R. Cleve, J. Watrous, R. de Wolf, Phys. Rev. Lett **87**, 167902 (2001).

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Multi-time states, Multi-time measurements and pre- and post-selection

Sandu Popescu*
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In my talk I will give an introduction to pre- and post-selection, a method that allows one to prepare quantum systems with two independent time-boundary conditions, an initial one and a final one. I will then discuss the concepts of multi-time states and multi-time measurements and I will present a number of surprising quantum effects associated with them. The talk is intended to be at a very pedagogical level.

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Quantum simulation

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CNRS, Université Pierre et Marie Curie, Paris, France

Quantum simulators are one of the four pillars of the Quantum Technology flagship of the European Union. In this presentation we will first review the basic concepts of quantum simulation as introduced by Richard Feynman in a 1981 visionary paper. We will discuss the various platforms which are being developed for this task and give a few examples of recent results. Open questions and challenges in this field will finally be outlined.

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Quantum communication in free-space, fiber and eventually to a satellite

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We all know quantum communication conceptually work on table top experiments in laboratories all over the world on a daily. To investigate the circumstances the use-cases and the techniques for their efficient implementation in the real world are still subjected to research.

Satellites are the efficient way to achieve global scale quantum communication (QC) because unavoidable losses restrict fiber based QC to a few hundred kilometers. We demonstrate the feasibility of establishing a QC uplink with a tiny 3U CubeSat (measuring just $10\times10\times32\,\mathrm{cm}^3$) using commercial off-the-shelf components, the majority of which have space heritage. We demonstrate how to leverage the latest advancements in nano-satellite body-pointing to show that our 4 kg CubeSat can provide performance comparable to much larger 600 kg satellite missions. A comprehensive link budget and simulation was performed to calculate the secure key rates. We discuss design choices and trade-offs to maximize the key rate while minimizing the cost and development needed. Our detailed design and feasibility study can be readily used as a template for global scale QC [1, 2].

The unification of the theory of relativity and quantum mechanics is a long-standing challenge in contemporary physics. Experimental techniques in quantum optics have only recently reached the maturity required for the investigation of quantum systems under the influence of non-inertial motion, such as being held at rest in gravitational fields, or subjected to uniform accelerations. Here, we report on experiments in which a genuine quantum state of an entangled photon pair is exposed to a series of different accelerations. We measure an entanglement witness for g-values ranging from 30 mg to up to 30 g – under free-fall as well on a spinning centrifuge – and have thus derived an upper bound on the effects of uniform acceleration on photonic entanglement. Models of quantum systems on curved space-times lack sufficient experimental verification. Some speculative theories suggest that quantum properties, such as entanglement, may exhibit entirely different behavior to purely classical systems. By measuring this effect or lack thereof, we can test the hypotheses behind several such models. As predicted by Ralph and coworkers [T. Ralph et al. PRA, 79(2) :22121, (2009)], a bipartite entangled system could decohere if each particle traversed through a different gravitational field gradient. We propose to study this effect in a ground to space uplink scenario. We present a detailed mission design of the European Space Agency's (ESA) Space QUEST (Space - Quantum Entanglement Space Test) mission, and study the feasibility of the mission schema [3].

Quantum entanglement is a fundamental resource in quantum information processing and its distribution between distant parties is a key challenge in quantum communications. Increasing the dimensionality of entanglement has been shown to improve robustness and channel capacities in secure quantum communications. Here we report on the distribution of genuine high-dimensional entanglement via a 1.2-km-long free-space link across Vienna. We exploit hyperentanglement, that is, simultaneous entanglement in polarization and energy-time bases, to encode quantum information, and observe high-visibility interference for successive correlation measurements in each degree of freedom. These visibilities impose lower bounds on entanglement in each subspace individually and certify four-dimensional entanglement for the hyperentangled system. The high-fidelity transmission of high-dimensional entanglement under real-world atmospheric link conditions represents an important step towards long-distance quantum communications with more complex quantum systems and the implementation of advanced quantum experiments with satellite links [4].

[1] $https://arxiv.org/abs/$1704.08707
$https://arxiv.org/abs/$1711.01886

[2] in preparation (2017).

[3] https ://arxiv.org/abs/1703.08036

[4] doi :10.1038/ncomms15304

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Quantum LDPC Codes

Gilles Zémor[1],*
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Classical Low Density Parity-Check (LDPC) codes are subspaces of discrete vector spaces defined by a set of linear equations of low weight. They come with efficient decoding algorithms and are some of the oldest members of the classical theory of error-correction. They have been the subject of extensive study, that ultimately lead to constructive versions of Shannon's channel capacity Theorem, and as such have few rivals both in theory and in practice.

Their quantum analogues are defined by a stabiliser group that is generated by elements of low weight. They have a number of analogies with their classical counterparts and could be expected to ultimately play a similarly important role as in the classical setting. They are however far less well understood, they are not as easy to construct, and decoding them efficiently requires more sophisticated approaches. In particular their constructions typically involve a strong topological connection.

We will give an introduction to the topic of quantum LDPC coding, highlight similarities and fundamental differences with the classical theory, survey recent progress and remaining challenges.

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Flagship session

European Flagship, Coordination & Support Actions

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Fundamental Quantum Aspects (FQA)

Efficient quantum pseudorandomness with simple graph states

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Measurement based (MB) quantum computation allows for universal quantum computing by measuring individual qubits prepared in entangled multipartite states, known as graph states. Unless corrected for, the randomness of the measurements leads to the generation of ensembles of random unitaries, where each random unitary is identified with a string of possible measurement results. We show that repeating an MB scheme an efficient number of times, on a simple graph state, with measurements at fixed angles and no feed-forward corrections, produces a random unitary ensemble that is an ε-approximate t-design on n-qubits. Unlike previous constructions, the graph is regular and is also a universal resource for measurement based quantum computing, closely related to the brickwork state.

Randomness plays a prominent role in quantum computing, quantum information processing and physics in general. In particular, random unitaries chosen from the Haar measure [1] on the unitary group U(N) find applications in randomized benchmarking [2] , noise estimation [3], quantum metrology [4], as well as modeling thermalization [5] and even black hole physics [6]. Unfortunately, genuine Haar distributed unitaries are hard to create as the scaling required is exponential in the number of qubits [7]. On the other hand efficient substitutes of Haar distributed unitaries were shown to exist [8], [9], [10], [11], [12], [13], [14]. These substitutes are known as unitary t-designs [9] - ensembles over subsets of U(N) which mimic exactly [9], [10] , [14] or approximately [8], [11], [12],[13],[14] choosing from the Haar measure up to order t in the statistical moments.

Following [14] our approach is to harness the quantum randomness arising from applying a measurement based (MB) scheme to produce approximate designs. In MB computation [15], unitary determinsitic computation is achieved by making sequential, adaptive measurements on an entangled multipartite state, known as a graph state [16]. Without these adaptive feedforward corrections, the inherent randomness of the measurements effectively samples from ensembles of unitaries. In [14] it was shown that starting with a fixed graph state, applying fixed angle measurements (with no need for feedforward corrections), effectively samples from an approximate t-design. Furthermore this process is efficient in the number of qubits, preperation and measurements, following from the efficiency of the construction of Brandao et al. [8]. Indeed the construction of the graph state essentially mimics the random circuit construction of Brandao et al. [8]. However, in doing so, the graph itself is rather complicated, and moreover is not a simple regular lattice. A natural question is then, can simple, regular lattices (such as those useful for universal measurement based computation [15], [17]) applied to generate t-designs ? As well as being more convenient from a practical point of view (in terms of generating the graph state), this connects the question of optimal generation of ensembles to standard measurement based quantum computation. Furthermore it requires a new proof that it is an approximate t-design (though the techniques also follow along the lines of [8] it does not follow directly from their results).

In this work we show that it is possible. In particular we show that running fixed measurement MB scheme on a regular graph with poly-log (in n, t and $\frac{1}{\varepsilon}$) number of qubits, with no feed-forward, results in an ensemble of random unitaries which forms a ε-approximate t-design ensemble. The graph we use is very similar to the brickwork graph known to be a universal resource for MB quantum computation [17]. Our proofs rely principally on the G-local random circuit construction (GLRC) of Brandao et al. [8], the detectability lemma (DL) of Aharonov et al. [18] as well as a theorem [19], [13], [8] on the equivalence between tensor product expanders (TPE s) and approximate t-designs.

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Shaping spatial entanglement of photon-pairs

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Entanglement is one of the most intriguing features of quantum theory and is at the heart of quantum information processing and quantum imaging. During the last decades, a growing interest has been devoted to the development of photonic sources generating entangled states of light in high dimensions. High-dimensional entanglement has then been demonstrated and exploited using different type of degrees of freedom, such as orbital angular momentum [1] or frequency modes [2]. Spatially entangled photon-pairs, such as those generated by Spontaneous Parametric Down Conversion (SPDC), exhibit correlations between many spatial modes [3]. This large amount of entanglement is interesting from a fundamental point of view but it also offers new perspectives for applications in quantum information processing [4], quantum cryptography [5] or quantum imaging [6].

Taking advantage of such a high-dimensional platform requires the capacity to **generate**, **manipulate** and detect **entanglement**. In this work, we demonstrate the use an Electron Multiplying Charge Coupled Device (EMCCD) camera together with a spatial light modulator to respectively detect and manipulate high-dimensional entanglement of spatially entangled photon-pairs.

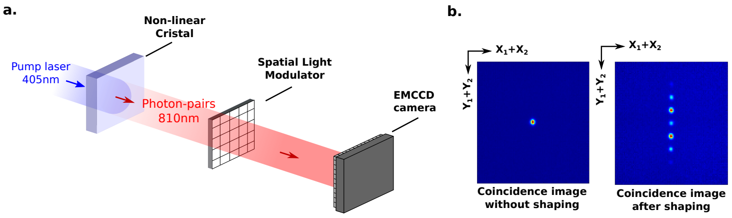

FIGURE 1. a. Simplified experimental scheme of spatial entanglement shaping composed by a non-linear crystal (Beta-Barym Borate) where photon-pairs are generated, a spatial light modulator that shapes the wavefront of the pairs and a EMCCD camera that images the resulting two-photon wavefunction. b. Examples of correlation images reconstructed without (left) and with (right) wavefront shaping using a cosine phase mask.

For this purpose, we have develloped an imaging technique that uses an EMCCD camera to measure the amplitude of the two-photon wave function of photon-pairs entangled over more than 10^6 spatial modes [7]. This new imaging capability is applied to reconstruct the joint probability distribution of photon-pairs previously shaped using a spatial light modulator (Figure 1). For the first time, we then demonstrate deterministic manipulation of spatial entanglement between photon-pairs. Applications range from the development of structured-entanglement approaches for imaging to adaptive optics for quantum communications.

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Fluctuation theorems in a hybrid optomechanical system

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Irreversibility is a fundamental concept of thermodynamics quantified by entropy production. When defined at the level of single realizations, the fluctuations of entropy production verify the celebrated fluctuation theorems such as Jarzynski's equality [1, 2]. To measure entropy production, the usual strategy is to monitor the trajectory of the small system under study. If it gave rise to successful experimental demonstrations in the classical regime [3, 4], this strategy can become problematic in the quantum regime.

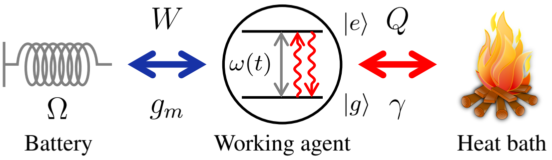

FIGURE 1. Hybrid optomechanical system : a two-level system is coupled to a heat bath on the one hand, and, on the other hand, to a mechanical oscillator. In a thermodynamic perspective, the mechanical oscillator plays the role of the battery exchanging work with the two-level system that corresponds to the working agent. The two-level system also exchanges heat with the thermal bath in the form of photons.

Here we propose another strategy to measure fluctuation theorems within a hybrid optomechanical system, i.e. a two-level system coupled to a mechanical oscillator on the one hand, and to optical photons on the other hand (see Fig. 1). It was shown in [5] that the mechanical oscillator plays the role of a battery, exchanging work with the two-level system. Work exchanges can be obtained by measuring the mechanical energy at the beginning and at the end of the transformation. Here we go beyond these first results and show that mechanical fluctuations can be related to work fluctuations, offering direct access to stochastic entropy production.

We consider two different perspectives. In the one of the total optomechanical system, we show the presence of absolute irreversibility, while in the one of the two-level system, we evidence Jarzynski's and Crooks' equalities.

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Statistical signatures of photon-added and -subtracted states of light

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Quantum entanglement, one of the key resources for quantum information processing, can be deterministically generated in a scalable manner in continuous variable (CV) systems. However such CV entangled states typically display Gaussian statistics, which limits their use for quantum computing. It is experimentally feasible to overcome this problem by the mode-selective subtraction of photons from multimode Gaussian states and thus make them non-Gaussian [1]. Furthermore, both photon addition and subtraction are known to enhance the entanglement between modes.

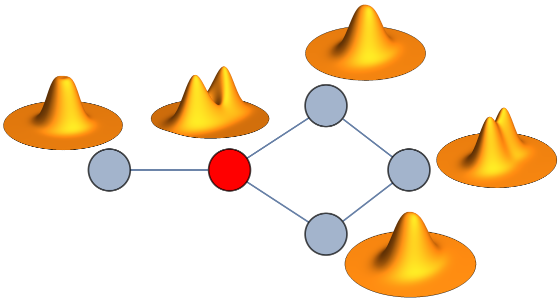
In multimode setups, however, the theoretical properties of the resulting non-Gaussian states are still surrounded by open questions. In the present contribution we use techniques from quantum statistical mechanics [2] to develop a new characterisation scheme for such multimode photon-added and -subtracted states of light [3].

As a key result, we obtain the multimode *Wigner function* for photon-added and -subtracted states using *truncated correlation functions* [2] :

$$W_{\pm}(\beta) = \frac{1}{2}\Big((\beta, V^{-1}A_g^{\pm}V^{-1}\beta) - \mathrm{tr}(V^{-1}A_g^{\pm}) + 2\Big)W_G(\beta), \tag{1}$$

where $W_G(\beta)$ is the Wigner function of the initial Gaussian state to/from which the photon was added/subtracted, and V is the covariance matrix of this Gaussian state. All non-Gaussian features are introduced by the matrix $A_g^{\pm}$, which depends on the mode g in which the photon was added or subtracted, and which can be expressed analytically [3].

From the expression for $W_{\pm}(\beta)$ we directly deduce an elegant condition for the negativity of the Wigner function. For pure states, we showed that coherent subtraction or addition of a photon can enhance enhance entanglement between modes. Moreover, we prove [4] that this entanglement can persist in *all* mode bases, contrary to the Gaussian case. As an application, we consider photon-added and -subtracted cluster states (see figure of a five-mode small cluster state, with a photon subtracted in the red vertex).



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Indefinite Causal Relations in Multipartite Scenarios

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If the physical world obeys a classical notion of causality, correlations between events should have a causal explanation. Reichenbach's principle famously asserts that any such correlations should either have a direct causal relation (i.e., one event causes the other) or a common cause. Recently, there has been a growing realisation that the violation of Bell's inequalities – traditionally interpreted as a proof of quantum nonlocality – implies a breakdown of such a notion of causality [1]. In a Bell scenario, special relativity prohibits two space-like separated parties from directly influencing one another, and yet quantum mechanics allows them to generate correlations that cannot be explained by a common cause. Quantum mechanics thus seems to transcend classical causality.

Bell inequalities are meaningful only in no-signalling scenarios (where parties are unable to communicate), so it is important to consider scenarios where parties have more general causal relationships in order to better understand the relationship between quantum mechanics and causality. This problem has notably been tackled within the process matrix formalism [2], which represents parties as closed laboratories in which quantum mechanics is locally valid, and the process linking the parties (in a possibly indefinite causal order) is modelled by a *process matrix* W, which generalises both the notions of quantum states and channels, and allows the probabilities for parties to produce certain outputs to be calculated via a generalisation of the Born rule.

It has been shown that not only can one indeed find causally indefinite process matrices, but some of these, such as the quantum switch [3], are even physically implementable. A stronger certification of noncausality can be obtained by violating *causal inequalities* [2] – which are satisfied by any correlation which has a causal explanation – and while some process matrices do violate such inequalities, no known implementation of such a process is yet known.

Extending the notions of causal processes and correlations – initially defined only in the bipartite scenario – to multipartite scenarios is crucial, as multipartite settings permit more freedom and are perhaps more promising for finding physical processes exhibiting noncausal correlations. However, properly defining notions of causal definiteness in such settings is more complicated due, in particular, to the possibility of dynamical causal orders [4].

In this submission, we will show how such notions can be properly formulated and interpreted, and consider the possibility for quantum mechanics to exhibit multipartite causal indefiniteness. In particular, we show how multipartite causal correlations can be defined in a rigorous, recursive fashion, and how this allows such correlations to be characterised in practice to obtain multipartite causal inequalities that all causal processes must obey [5]. We present examples of some such inequalities of interest which have natural interpretations as "causal games" played by the parties. Moreover, we see that many of these inequalities can be violated by process matrices, but their physicality remains unknown.

We then consider what it means for a multipartite process matrix to be causally indefinite (or "non-separable"), for which violating a causal inequality is only a sufficient but not necessary condition. The definition of such process matrices contains several subtleties which we discuss, in the process giving a physical interpretation to any "causally separable" process matrix. Finally, we consider whether (and how) such processes matrix can be efficiently characterised using semidefinite programming techniques.

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Photonic Cooper-like Pairs

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Photons are the elementary particles carrying light. Contrary to electrons, which carry electric current, photons do not interact with each other in vacuum. However, when propagating in a material, for example water, photon pairs may effectively interact through the medium. For example, in Raman processes[1], an incident photon is typically converted into a lower frequency one, the remaining energy being converted into a vibration of the illuminated material. This is called a Stokes process. Another possibility is that the incoming photon absorbs a vibration and is converted into a blue-shifted (anti-Stokes) one. Since the first process may happen spontaneously while the second requires population in the vibrational degree of freedom, Stokes processes are much more likely than anti-Stokes, at least in low temperatures, where low is to be understood regarding the vibrational energy.

Sometimes, these processes can combine into a single scattering event in which the vibration created by a Stokes conversion is the one that generates an anti-Stokes photon. While such a combined Stokes–anti-Stokes process is often obfuscated by the usual single scattering mechanisms, this second-order effect dominates the anti-Stokes production in the absence of native thermal quanta of vibration [2, 3]. In this case, both events can be understood as a single energy preserving scattering process in which two incoming photons of frequency ω_L effectively interact through the medium to generate a pair of outcoming photons, one red and one blue-shifted from the incident light. This phenomenon has been observed in materials as diverse as diamond and water[4], and should be present as long as Raman resonances are available.

In this work [5] we demonstrate theoretically and experimentally that photon pairs may also interact via a virtual vibration, meaning that the energy exchanged in the process is outside the spectral energy range of normal vibrations in the medium. In this case, the interaction is mediated by the vacuum of the quantized vibrational degree of freedom and the outuput field is composed of twin photons of different tunable frequencies.

The same process occurs for electrons in a metal at very low temperatures, where virtual vibrations of the medium attractively couple them, forming the so-called Cooper pairs. In fact, the Hamiltonian derived in our work is the bosonic counterpart of the standard BSC Hamiltonian in the mean field approximation. For electrons, this phenomenon changes a normal metal into a superconductor. Cooper pairs are the supercurrent carriers and we have shown here their photonic counterparts. Whether this analogy can be extended to a photonic equivalent of superconductivity is a challenging and intriguing question for future investigation.

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Heralded generation of maximal entanglement in any dimension via incoherent coupling to thermal baths

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Entanglement is a key phenomenon distinguishing quantum from classical physics, and is the paradigmatic resource enabling many applications of quantum information science. Generating and maintaining entanglement is therefore a central challenge. Decoherence caused by unavoidable interactions of a system with its environment generally degrades entanglement, and significant effort is invested in minimising the effect of such dissipation in experiments. However, dissipation can also be advantageous, and may indeed be exploited for the generation of entangled quantum states under the right conditions [1].

In this work [2], we present a scheme for dissipatively generating maximal entanglement in a heralded manner. Our setup requires incoherent interactions with two thermal baths at different temperatures, but no source of work or control. A pair of $(d+1)$-dimensional quantum systems is first driven to an entangled steady state by the temperature gradient, and maximal entanglement in dimension d can then be heralded via local filters. This model for quantum thermal machines is emblematic to illustrate how quantum thermal machines outperform their classical counterparts by achieving genuine quantum tasks, here generating entanglement in arbitrary dimension.

I will also present experimental prospects considering an implementation in superconducting systems, given that a collaboration with the group of Prof. B. Huard at ENS Lyon has recently be established.

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Toward Inductive-detection ESR spectroscopy with single spin sensitivity

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Electron spin resonance (ESR) is a well-established spectroscopic method to analyze paramagnetic species, utilized in materials science, chemistry and molecular biology to characterize reaction products and complex molecules [1]. In a conventional ESR spectrometer based on the so-called inductive detection method, the paramagnetic spins precess in an external magnetic field B_0 radiating weak microwave signals into a resonant cavity, whose emissions are amplified and measured. Despite its widespread use, ESR has limited sensitivity, and large amounts of spins are necessary to accumulate sufficient signal. Most conventional ESR spectrometers operate at room temperature and employ three-dimensional cavities. At X-band, they require on the order of 10^{13} spins to obtain sufficient signal in a single echo [1]. Enhancing this sensitivity to smaller spin ensembles and eventually the single spin limit is highly desirable and is a major research subject. This has been achieved by employing alternative detection schemes including optically detected magnetic resonance [2], scanning probe based techniques [3] and electrically detected magnetic resonance [4].

Recently, there has been a parallel effort to enhance the sensitivity of inductive ESR detection, triggered by the progress made in the field of circuit quantum electrodynamics, where high fidelity detection of weak microwave signals is essential for the measurement and manipulation of superconducting quantum circuits. In particular, it has been theoretically predicted that single-spin sensitivity should be reachable by combining high quality factor superconducting micro-resonators and Josephson Parametric Amplifiers, which add minimal noise as allowed by quantum mechanics to the incoming spin signal. In the ongoing work, we have built on our previous efforts [5] to show that, by optimizing the resonator design, the sensitivity can be enhanced to the level of 65 spins/$\sqrt{\mathrm{Hz}}$.

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Controlled generation of multimode squeezed states

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Synchronously Pumped Optical Parametric Oscillator (SPOPO) is a very promising source of quantum states [1]. It produces a multimode squeezed vacuum state, whose spectro-temporal shape is determined by the crystal's phase matching condition and the spectrum of the pump beam. In our lab, we demonstrate the experimental implementation of pump shaping and its ability to control the multimode quantum state generated by the SPOPO.

The original pump beam is a strong coherent beam generated by frequency-doubling the output of a Ti :Sa oscillator, which is a femtosecond frequency comb with a central wavelength of 795 nm. To this purpose, we use a 350 μm-long BiBO crystal, which allows a conversion rate as high as 50% and a maximum output power of 300 mW. We then select the up-converted light (397.5 nm centered) and directly send it to the crystal inside the SPOPO cavity. The aim of our work is to allow for a new degree of control over this beam, and subsequently over the produced quantum state. Instead of being directly led towards the SPOPO, the blue light will undergo a pulse-shaping, i.e. its spectrum will be tailored in amplitude and phase.

To do so, we use a pulse shaper based on the $4f$ configuration : light is dispersed by a grating, recollected by a cylindrical mirror onto a spatial light modulator (SLM) where every wavelength is separately adressed. The SLM is computer-controlled so that the spectrum of the output beam can be easily modified, both in amplitude and phase.

We know from the theory [2] that the spectral shape of the squeezed mode directly depends on the spectrum of the pump, so that the pump shaping opens wide possibilities. A first example is the parity of the pump and its influence over the repartition of the squeezing level inside the multimode squeezed vacuum. We have performed the following experiment to test it : one half of the spectrum was added a phase of π, which makes the pump spectrum odd. We will present the effect of this change to the covariance matrices.

Other spectral shapes can be designed for producing a squeezed state in a target spectral mode, or to maximize squeezing in one mode. This will be used in future experiments to optimize cluster states for measurement-based quantum computing protocols [3].

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Bouncing oil droplets : manifestation of wave-particle duality at the macroscale

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Walkers, also called bouncing oil droplets, are at the center of recent works and could be a gateway to a better understanding of quantum properties. It has been shown by Fort and Couder [1] that walkers can exhibit quantum behavior in the following sense : their average trajectory apparently obeys the pilot wave dynamics introduced by de Broglie in 1927. In the de Broglie-Bohm [2] pilot-wave theory, a single quantum particle is not only described by its wave-function, but also by an actual position, which is guided by the wave-function in a deterministic way. A quantum ensemble, on the other hand, is described by a wave-function and by a distribution of particle positions. The pilot-wave theory reproduces the predictions of standard quantum mechanics for ensembles in which the positions are distributed according to the Born law, but it also opens a door to new physics [3] for ensembles in which the positions are not distributed according to the Born law (quantum non-equilibrium).

We consider modifications of the pilot-wave theory [4] *à la* Nelson [5] in which the motion of the particle is not deterministic anymore, and how they affect the process of relaxation to quantum equilibrium. Such stochastic terms could be helpful to model the trajectories of bouncing droplets [6].

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Intensity correlations of a 1550 nm near-threshold optical parametric oscillator

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Optical parametric oscillator (OPO) makes use of cavity enhanced parametric down-conversion in $\chi^{(2)}$ crystals, and is of crucial importance in high quality quantum optical states generating. The state-of-arts in generating high purity single photons, squeezing state with high squeezing rate and Schrödinger kitten state with high negativity in its Wigner function relay on this technique. To either define or make use of the quantum optical states generated with the OPO, one has to investigate the temporal and spatial mode of the OPO cavity [1–3].

The spatial mode of a cavity can be easily measured by, for example, camera or slit beam profiler, but the temporal mode of a cavity can only emerge by intensity correlation $\Gamma(\tau) = \langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t)\rangle$ or its normalized form $g^{(2)}(\tau)$ function : $g^{(2)}(\tau) = \frac{\Gamma(\tau)}{\Gamma(\infty)}$. For an OPO working far below threshold, it is well known the intensity correlation function is exponentially decay with coupling constants for single frequency mode case, and comb function spaced by the cavity round-trip time with a negative exponential envelop for multimode case [4]. For an OPO with higher gain, the theoretical study shows the photon created by parametric down conversion is likely to be further amplified by stimulated parametric process, thus the correlation function of a higher gain OPO is broader in time than the one with lower gain [5].

Here we report an experimental study of the intensity correlation of a 1550 nm near-threshold bow-tie OPO cavity with type-zero phase matched PPKTP crystal as nonlinear gain medium. The output of the OPO is directly coupled to single mode fiber with coupling efficiency 94%, which followed by a 50 :50 beam splitter and two fiber-coupled superconducting nanowire single photon detectors (SSPD). The output signal of the detectors are send to a time-to-amplitude converter (TAC) to measure the intensity correlation function. The result of the measurement consistent with the theory [4, 5]. Thanks to the pico-second precision of the TAC, the comb structure of the correlation function is sharply presented and the width of the comb structure is only confined by the 40 ps jitter of the SSPD. With the intensity correlation result, we can calibrate the OPO cavity parameters, such as free spectral range, cavity temporal mode and threshold, in high precision, and this could further help for high quality quantum optical state generating.

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Continuous-variable entanglement of two bright coherent states that never interacted

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Quantum information can be encoded in many different degrees of freedom with either a discrete or a continuum (continuous variables, CV) spectrum. CV encoding is of main importance since near-unit efficiency detectors and unconditional operations are available, and entanglement can be produced on demand by efficient nonlinear optical interactions achieving high-rate performances. Information encoded in CV entangled states is all the more powerful/useful that these states are generated on chip, bright and multipartite.

In our work we theoretically demonstrate continuous-variable entanglement of bright quantum states in a pair of evanescently coupled nonlinear waveguides operating as down-converters [1]. We show that this device, when operated in the depletion regime -i.e. optical parametric amplification-entangles the pump fields through a nonlinear cascade effect. This is highly interesting since we only consider energy exchange between the signal modes, but not between the pump modes. We further show that two-colour quadripartite entanglement -i.e. pumps-signals entanglement- is obtained with appropriate system parameters.

Our proposal differs significantly from others on three fronts [2, 3]. (i) In contrast with other theoretical proposals dealing with entanglement of bright waves, our work is to the best of our knowledge the first where those bright waves never interact directly, i.e. linear coupling between the pumps is not considered. (ii) The proposed device is not a doubly-resonant optical cavity, but a nonlinear directional coupler of traveling waves. It is thus much simpler and broadband. (iii) It can be fabricated with current technology. Therefore, the proposed device is a good candidate for a source of bipartite and multipartite entangled states for optical continuous-variables and hybrid quantum information processing.

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

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Photon-number states are an important resource for quantum information science [1]. Producing them on demand and at a high rate are critical issues to be solved to guarantee their applicability. With this goal, we implemented three synchronous cavities, the first two to enhance nonlinear effects, the third one to store the state (fig. 1a).

Pulses from a mode-locked Ti:sapphire laser (850 nm, 3 ps, 76 MHz repetition rate) are frequency-doubled in a synchronous bow-tie cavity via second-harmonic generation with a BiB_3O_6 crystal [2]. Photon pairs are then produced using the frequency-doubled beam to pump an optical parametric amplifier placed in a second bow-tie cavity. The non-collinear regime allows an easy separation of the twin beams and two avalanche photodiodes placed along one beam herald single photon and two-photon states in the other arm [3]. The states are characterized with a homodyne detection: the fidelities (corrected from detection losses) reach 91% for the heralded single photon state and 88% for the two-photon state.

To overcome the probabilistic nature of the source, we have implemented a quantum memory. It consists in a cavity in which a Pockels cell allows the non-classical states to be extracted once they are required in the rest of the experiment. After a given number of round-trips into the cavity, the states are extracted and characterized: lifetimes of several round-trips have been reached for the single and two-photon states (fig. 1b). These results pave the way towards the efficient production of more complex states such as Schrödinger cat states [4]: the quantum memory can serve as a platform for their production and for increasing their amplitude.

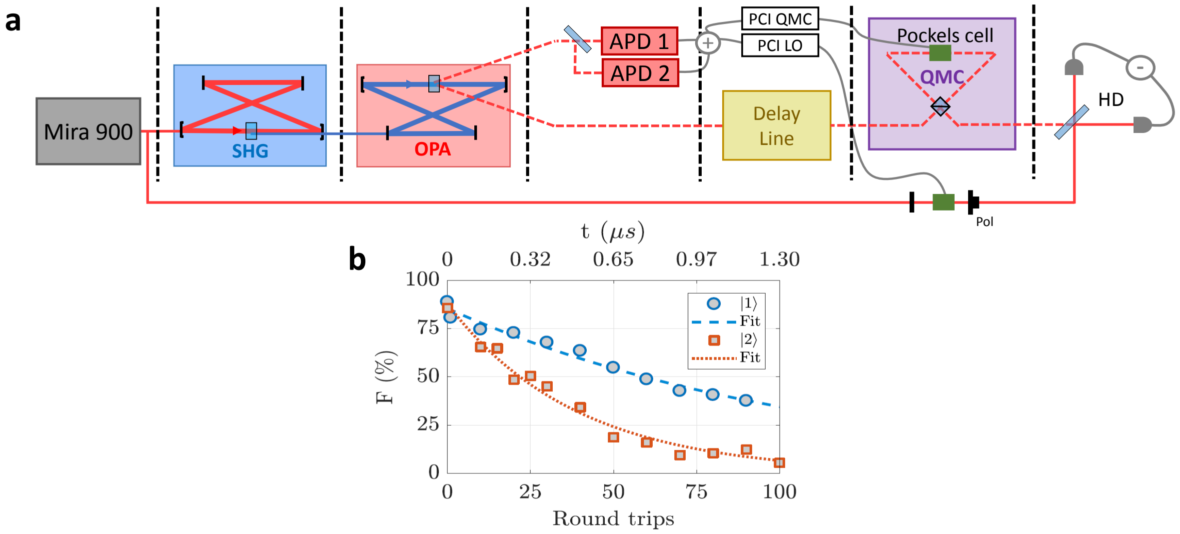

FIG. 1: a: Experimental set-up. b: Fidelity versus number of round-trips into the quantum memory cavity when heralding a $|1\rangle$ or $|2\rangle$ state (corrected from detection losses). SHG: Second Harmonic Generation, OPA: Optical Parametric Amplifier, APD: Avalanche Photodiode, LO: Local Oscillator, QMC: Quantum Memory Cavity, HD: Homodyne Detection.

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Frequency-entangled qudits in AlGaAs waveguides

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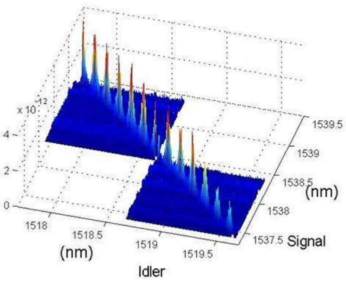
The generation, manipulation and detection of non-classical states of light on a miniaturized chip is a major issue for future quantum information technologies. Among the different material platforms explored in these last years AlGaAs attracts a particular interest due to its compliance with electrical injection [1] and electro-optic effect. Here we demonstrate AlGaAs waveguides with high rate of biphoton generation (2.37 MHz) and signal-to-noise ratio (SNR) up to 5×10^4. This potentially brings us in the condition of achieving a 0.99 fidelity for the generation of entangled states. Our devices, based on a modal phase-matching scheme, include two Bragg mirrors providing both a photonic band gap confinement for a TE Bragg pump mode around 780 nm and total internal reflection claddings for the twin photons TE and TM modes centered at 1560 nm. Furthermore, the dispersion properties of our devices, together with the modal reflectivity on the waveguide facets, allow engineering the joint spectrum of the emitted biphoton state to get comb-like spectral correlations, corresponding to frequency-entangled qudits. Indeed the facets create a Fabry-Perot cavity for both output modes, inducing regular time-delays between photons directly transmitted through the waveguide facet and photons having experienced one or more round trips [2]. Taking this into account, the expression of the joint spectral density $|\Phi(\omega_s,\omega_i)|^2$ of the emitted biphoton state is : $|\Phi(\omega_s,\omega_i)|^2 = N^{-1}|\alpha_p(\omega_s,\omega_i)|^2|A(\omega_s,\omega_i)|^2 f_{TE}(\omega_s,\omega_i) f_{TM}(\omega_s,\omega_i)$. Here $\alpha_p(\omega_s+\omega_i)$ is the spectral amplitude of the pump beam, $A(\omega_s,\omega_i)$ is the three-wave-mixing phasematching function, f_{TE} and f_{TM} describe the effect of the reflection on the waveguide facets for the generated TE and TM polarized photons, respectively and N is a normalization constant.



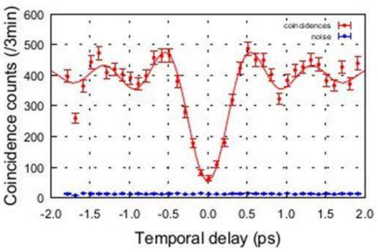


Figure 1 reports the measurement of a portion of the JSD for the biphoton state emitted by our device under CW pumping, as well as a Hong-Ou-Mandel measurement. The amplitude of the biphoton wavefunction is distributed along $\omega_s+\omega_i=\omega_p$ and oscillates with peaks at $\omega_s-\omega_i$. This suggests that the generated state is an entangled qudit structure $\Phi=\sum_i^n \alpha_i|\omega_i,\omega_{n-i}>$ as pointed out also in [3]. Contrary to recent experiments that required spectral filters and/or modulators, or external cavities to engineer the target state, our devices represent a miniaturized source, working at room temperature and telecom wavelength.

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Will the qubits of the quantum computer remain mesoscopic ?

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In 2001, after the success of his 7-qubit computer, Chuang did not develop quantum computer any further [1]. Fifteen years later, we propose a reflection on the foundations of quantum computer. We discuss in particular the physical reality of individual qubits both experimentally and theoretically.

Experimentally, there is a strong difference between :

1. realizing, maintaining and observing individual qubits
2. realizing a quantum computer that implements effective operations with qubits.

The case 1 is actually performed with individual qubits as shown by Serge Haroche and David J. Wineland. But in case 2, the only existing quantum computers that perform effective operations, are computers with mesoscopic qubits. The different computers developed in 1997, 1999 and 2001 by Chuang were with mesoscopic qubits : each qubit was simulated by a set of 100 million molecules with the NMR technique. And as he had used a computer with two qubits, then with 4 qubits, and finally with 7 qubits, it shows that the measure decreases by a factor 2 with each additional qubit. That's why IBM and Chuang have stopped this type of development. This is also the case of quantum computers based on the Josephson junction : each qubit is represented by a billion aluminum atoms [2]. This is also the case of computers based on photonic qubits in photonic chips [3].

Theoretically, the parallel quantum computer is based on the Copenhagen interpretation and on the many-worlds of Everett where quantum mechanics is complete and where the physical particle is identified with its wave function (qubit). In the de Broglie-Bohm-Bell theory (dBBB), the wave function is not sufficient to fully represent the reality of the quantum system and it is necessary to add the position of the particle (hidden variable). This interpretation is not local and is not invalidated, as recalled by Laloë [4] Bell's inequalities and Aspect's experiments. On the contrary, the dBBB theory clearly expresses non-locality of quantum mechanics [5]. The evolution of the quantum system (wave function + position) will now be deterministic. This is shown by the mathematical analysis of the Stern and Gerlach experiment [6]. In this interpretation, a qubit is represented by the wave functions and two particles (to take account of the two alternatives). The dBBB theory simply explains why the only quantum computers currently implementing quantum algorithms are based on computers with mesoscopic qubits. It also helps to give a simple answer to Chuang's problem whereby the magnetic signals, that measure the orientation of the spins and determine the quantum state, become excessively weak when the number of qubits increases, weakening by a factor of 2 for each additional qubit.

Finally, the feasibility of a parallel quantum computer (with individual qubits) depends on the interpretation of mechanics : feasible in the Everett's parallel universes interpretation, but impossible in the dBBB theory.

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Optimal entanglement witnesses in a split spin-squeezed Bose-Einstein condensate

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While Bell correlation witnesses have been proposed and used recently to successfully detect Bell-correlated states in a Bose-Einstein condensate [1], the device-independent detection of non-classical correlations remains to be demonstrated in many-body systems. The main problem is that Bell tests requires one to address the constituent bodies individually, which is challenging in many-body systems. A natural approach to circumvent this problem consists first in a bipartite splitting of the constituent bodies and then, in applying collective measurements on each party. A first step toward this goal is to find efficient entanglement witnesses using these collective measurements.

This work adresses the question of finding entanglement witnesses in bipartite scenarios using a split many-body system and collective measurements on each party. We address this question by deriving entanglement witnesses using either only first or first and second order moments of local collective spin components. We use a numerical approach in order to derive optimal entanglement witnesses with respect to local white noise which can be adapted to a set of experimental data. As an example we derive optimal witnesses for spatially split spin squeezed states in the presence of local white noise. We find that the corresponding witnesses to be the criteria of [2] for first order and [3] for second order of moments of local collective spin components.We then compare the two optimal witnesses with respect to their resistance to various noise sources operating either at the preparation or at the detection level. We finally evaluate the statistics required to estimate the value of these witnesses when measuring a split spin-squeezed Bose-Einstein condensate.

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Graphene quantum dots : a new quantum emitter

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In the condensed matter area, graphene plays a central role as a main material for nanoelectronics. Nevertheless, graphene is a zero-gap semiconductor. Therefore, a lot of efforts are being made to develop semiconductor materials compatible with the hexagonal lattice of graphene. In this perspective, little pieces of graphene such as graphene quantum dots and nanoribbons have a lot of assets. First, the so-called bottom-up synthesis that have been developed for more than a decade allows a precise control of the size, shape and edges of these objects [1]. In principle, it should allow to design the desired properties needed for a specific technology. In order to take advantage of the variety of their properties, a key point is to be able to isolate these objects, and in particular to prevent them from aggregation. In this poster, we will present our preliminary results on the study of single graphene quantum dots by means of optical spectroscopy. In particular, the spectrum of a single quantum dots as well as the first results of Hanbury Brown and Twiss experiments will be discussed.

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The orbital angular momentum of light for quantum applications

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Optical vortices which are light beams with wave-fronts shaped as a helix are known to be donut shaped and to carry an orbital angular momentum. The donut shape finds many applications in physics from spectroscopy to cold atom manipulation [1].

The orbital angular momentum is a quantized quantity with a signed integer ℓ related to the helix period. This quantum variable of light (qOAM), also called the third momentum of light, is exchanged with matter via quantum rules.

Because the qOAM explores a large range of values of ℓ, it is a quantum variable usable for quantum encoding and quantum information. In the context of quantum memory and quantum computing, we explore the relevance of the qOAM for the transfer to the matter and its retrieval.

In this context we study atom-vortex interaction and will present two examples : (i) qOAM conversion with a frequency change (from red to blue) realized in a rubidium vapor by using a two-photon transition [2] and (ii) qOAM storage and retrieval at the same color realized in a cold cesium cloud by using a lambda-3-level configuration [3, 4].

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Quantum Communication & Cryptography (QCOM)

Long distance and long duration quantum information manipulation in a solid-state ensemble

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The ability to manipulate the qubits of information over long distances and for long durations is at to core of the possibility to implement a quantum network. A major challenge to distribute the entanglement over long distances is that the quantum channel eventually degrade the quality of the state, and a quantum repeater must be used [1]. Then, the storage duration of the information is ultimately limited by the coherence properties of the system that is used [2]. In this work, I present two recent works that open promising perspectives to tackle both these issues, in a rare-earth ion doped crystal.

In order to distribute the entanglement at long distances, a possible way to implement the quantum repeater is to use the DLCZ protocol [3]. We adapted this protocol to rare-earth ion ensembles, which have a large inhomogeneous broadening a weak electric dipole interaction, by working with resonant field and by using a rephasing scheme : the Atomic Frequency Comb (AFC) [4, 5]. The main strength of this new protocol is its multimode capacity, namely the number of temporal modes that can be simultaneously stored and retrieved from the ensemble. We performed with this scheme the simultaneous heralding of more than 10 modes for 1ms of storage time on an isotopically pure $^{151}\mathrm{Eu}^{3+}:\mathrm{Y}_2\mathrm{SiO}_5$ crystal with europium concentration of 1000 ppm. We additionally revealed the quantum nature of the correlations by showing a violation of the Cauchy-Schwarz inequality of 2.88>1 [6].

Then, the storage duration is limited in our case by decoherence processes in our crystal, which can in principle be reduced by the application of a constant magnetic field. In the case of Eu^{3+} however, the application of a magnetic field will split the states into two and change the coupling strengths, thanks to the Zeeman effect. In order to identify a new efficient lambda system for the implementation of the spin-wave storage AFC, we then identified the Zeeman tensor for both the electronic ground and excited states [7].

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Phase Sensitive Amplification Enabled by Coherent Population Trapping

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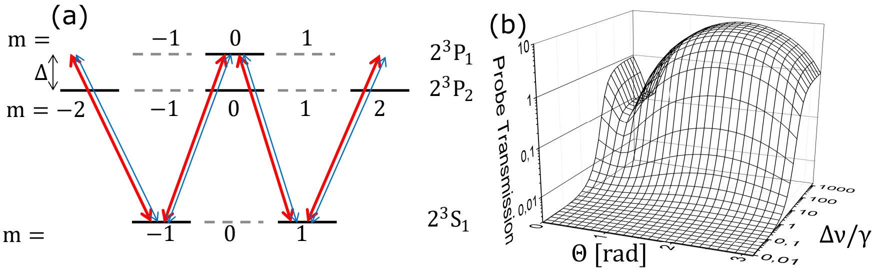
Recently, phase-sensitive amplification (PSA) has been a subject of wide research in a variety of fields due to its unique noise properties [1]. It enables amplification of a quantum light field without adding any extra noise. This is associated with the generation of non-classical squeezed states of light, used in some quantum information and telecommunication processing protocols. Usually, such non-linear processes are far-detuned from optical transitions to avoid noise from spontaneous emission.

Nevertheless, we have recently reported the observation of a strong and highly pure PSA (8 dB) using a resonant excitation of the D1 transition in metastable Helium at room temperature [2] of moderate optical depth (about 3). In this present work, we demonstrate theoretically how this PSA builds up and discuss the physical underlying processes ensuring its purity.

The $2^3S_1 \rightarrow 2^3P_1$ (D1) transition of Helium is resonantly excited by a strong linearly-polarized pump and a weak cross-polarized probe. This Λ-type double excitation creates a coherence between the lower states : the atoms are pumped into a superposition of the lower states, which is a dark state that is not coupled to the upper state level by the lasers. This coherent population trapping (CPT) induces full transparence of the D1 transition for both fields. This enables the interaction of the fields to far-detuned transition, in that case the $2^3S_1 \rightarrow 2^3P_2$ (D2, 2.29 GHz detuned) transition : we show that several four waves mixing occurs from the dark state, leading to a global PSA behavior.

As experimentally observed, this PSA is quite original because it does not explicitely depend on the pump field strength, but only on how the CPT is efficiently created on the D1 transition. As a consequence, the more resonant the fields are on the D1 transition, the stronger this PSA is, as opposed to usual PSA schemes.

So far, metastable Helium has been shown to be an operating device for light storage [3, 4]. This work suggests that it can also be used to generate non classical states of light, opening up the possibility of quantum information processing protocols in this system.



(a) : D1 and D2 transition of metastable Helium, excited by a (red) pump and a (blue) probe. Due to selections rules, dashed levels can be forgotten. **(b)** Simulation of the probe transmission, as a function of its relative phase Θ with the pump, and $\Delta\nu/\gamma$ where $\Delta\nu$ is the saturation broadening due to the pump and γ the ground levels coherence decay rate. As soon as the CPT is efficient ($\Delta\nu \gg \gamma$), the probe experiences a phase dependant amplification (PSA).

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Semi-device-independent quantum random number generation based on unambiguous state discrimination

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The generation of random numbers is of paramount importance in modern science and technology, e.g. for Monte Carlo simulation, statistical sampling, cryptography, and gaming applications. Here, we develop a new approach to quantum random number generation based on unambiguous quantum state discrimination. We consider a prepare-and-measure protocol, where two non-orthogonal quantum states can be prepared, and a measurement device aims at unambiguously discriminating between them. Because the states are non-orthogonal, this necessarily leads to a minimal rate of inconclusive events whose occurrence must be genuinely random and which provide the randomness source that we exploit. Our protocol is semi-device-independent in the sense that the output entropy can be lower bounded based on experimental data and few general assumptions about the setup alone. It is also practically relevant, which we demonstrate by realising a simple optical implementation achieving rates of 16.5 Mbits/s. Combining ease of implementation, high rate, and real-time entropy estimation, our protocol represents a promising approach intermediate between fully device-independent protocols and commercial QRNGs.

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A QD-based light-matter interface : from polarization tomography to spin-photon mapping

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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) deterministically coupled to a micropillar cavity : such a device performs as a bright single photon emitter [1] and the QD state can be coherently manipulated with a few incoming photons [2]. Here we focus on another exciting perspective : the development of polarization-based photonic gates, whereby the polarization state of a single incoming photon is manipulated through its interaction with the artificial atom.

In this framework, we first investigate the polarization rotation of coherent light interacting with a neutral QD-cavity system, by analyzing the polarization density matrix of the reflected photons in the Poincaré sphere. The superposition of emitted single photons (H-polarized) with reflected photons (V-polarized, cf. Fig.1(a)) leads to a rotation of the output polarization by 20° both in latitude and longitude [3]. The evolution of the output state is illustrated in the Poincaré sphere as a function of the excitation laser wavelength, scanned across the QD transition wavelength (see Fig.1(b)). We demonstrate that the coherent part of the QD emission contributes to polarization rotation, whereas its incoherent part contributes to degrading the polarization purity. In addition, this technique is sensitive to the noise mechanism and provides a promising tool to study decoherence processes in cavity-QED devices.

In addition, we show that this polarization-based approach is particularly interesting for the development of an efficient spin-photon interface, using a resident hole in a charged QD as a stationary qubit with long coherence time. Indeed, we have recently demonstrated a large rotation of photon polarization induced by a single hole spin qubit [4]. We will discuss ongoing developments aiming at perfect spin-photon mapping : a situation where a single spin qubit, described in the Bloch sphere, is mapped into a single polarization qubit described in the Poincaré sphere.

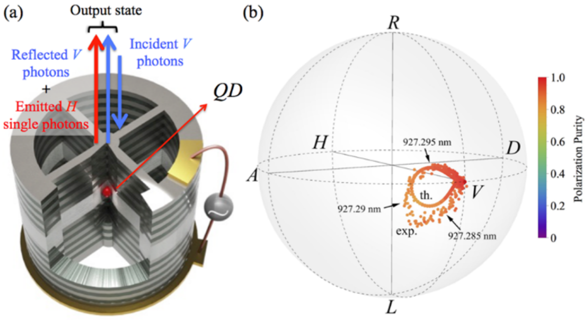

Figure 1 : (a) Scheme of the electrically-controlled QD-cavity device and the input-output fields. (b) Representation of the polarization state in the Poincaré sphere for varying excitation laser wavelengths. The colorscale represents the purity of the polarization density matrix, kept above 84% at all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

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Optical Hybrid Entanglement of Light for Remote State Preparation and Quantum Steering

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Optical hybrid quantum information processing [1] bridges the gap between the traditionaly separated discrete- (DV) and continuous-variable (CV) tools and concepts. In this approach, DV states, such as single photons, and CV states, for example Schrödinger cat states $|cat\pm\rangle \propto |\alpha\rangle \pm |-\alpha\rangle$, are used in conjonction to exploit the benefits of both encodings. Having succeeded in generating hybrid entanglement of light [2], we now report on the use of this resource in two hybrid protocols : the remote preparation of arbitrary CV qubits $|\alpha\rangle + qe^{i\phi}|-\alpha\rangle$ as well as the demonstration of Einstein-Podolsky-Rosen steering, using in both cases high-efficiency homodyne detection setups.

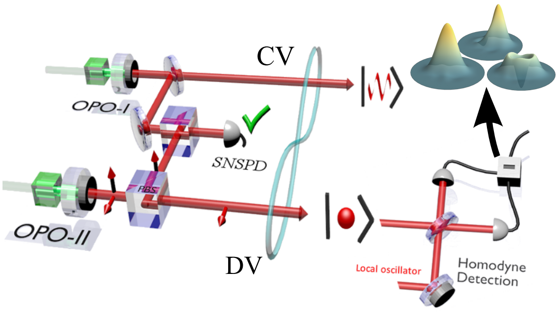

FIGURE 1: Hybrid entanglement is generated using two non-classical sources (optical parametric oscillators) and single photon heralding via superconducting nanowire single-photon detectors (SNSPD). By conditionning on the results of homodyne measurements made on the DV side, we can remotely create arbitrary CV qubits as well as a set of conditionned states that violate an EPR steering inequality by five standard deviations.

Our experimental setup, shown in figure 1, uses two optical parametric oscillators (OPO) and high-efficiency superconducting nanowire single-photon detectors (SNSPD) to herald the generation of non-gaussian light fields in well-defined spatiotemporal modes [3] : high purity single photons [4] as well as large-amplitude squeezed Schrödinger cat states, with $|\alpha|^2 \approx 3$ at high preparation rates [5]. Joining the two heralding paths allows us to generate the hybrid entangled state $|0\rangle_{DV}|cat-\rangle_{CV} + e^{-i\Phi}|1\rangle_{DV}|cat+\rangle_{CV}$. Recently, we used this resource to perform remote state preparation of CV qubits. By conditionning on the result of homodyne measurements made on the DV side, the CV system is projected to any desired qubit $|\alpha\rangle + qe^{i\phi}|-\alpha\rangle$. We experimentally obtained states presenting more than 80% fidelity with the targeted CV qubits, including odd cat states presenting negative values of the Wigner function without correction.

In the broader context of hybrid quantum networks, we then evaluated the steerability of our resource. Performing six different homodyne measurements by changing the local oscillator relative phase on the DV side, and then sign-binning the result, we remotely generated a set of 12 conditionned CV states, or assemblage, demonstrating EPR steering. Testing our experimental data against an optimal steering inequality found through semi-definite programming, we find a violation by more than five standard deviations, for the first time using hybrid entangled states of light [6]. Along with confirming the suitability of hybrid states for one-sided device independant scenarios, these results pave the way to the realisation of hybrid quantum teleportation from DV to CV and vice versa —a crucial stepping stone for the realisation of hybrid quantum networks.

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Modelling EIT-based quantum memory : effect of multiple excited levels

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In the context of quantum information networks, quantum memory enables to implement the controllable and reversible mapping of a quantum state of light onto a quantum state of matter [1]-[2]. In recent years, the physical implementation of such interfaces in free space has been at the focus of a very intense research. In spite of significant advances and realization of efficient optical memory, the storage-and-retrieval efficiency of demonstrated quantum memory for a qubit had been below 30%. The memory efficiency is determined by technical losses and the storage efficiency, and depends on the storage mechanism and matter properties. One of the strong requirement to obtain a large storage-and-retrieval efficiency is a large optical depth (OD). In addition, a low decoherence rate for the long-lived matter state is another crucial requirement. However, some nonlinear optical effects become significant at a large OD and lead to reduce the storage-and-retrieval efficiency.

Here we present the theoretical description of the recently implemented faithful and high efficient quantum memory for polarization qubits demonstrated in our group [3]. This memory relies on electromagnetically induced transparency (EIT) in a single spatially-multiplexed ensemble of cold cesium atoms featuring a very large OD. Our theoretical model is based on the Maxwell-Bloch equations and takes into account the interaction of the probe and the control fields with the full D_2-line structure of ^{133}Cs atoms. In addition to all the excited levels, we also include the Zeeman sublevels to compare implementations with and without optical pumping. We show that at a large OD, as required, the non-resonant coupling of the control field with hyperfine sublevels of the excited state results in significant modification of atomic response compared to the standard Λ-scheme approximation. This non-resonant coupling leads to additional effective atomic ground state decoherence and limits the storage efficiency.

Our model allows to estimate the highest storage-and-retrieval efficiency for chosen polarization configuration and atomic transitions. Moreover, our results are in perfect agreement with the highest efficiency memory (70%) demonstrated for optical qubits in a large-OD elongated atomic ensemble, which can be achieved in this configuration [3]. The achieved efficiency opens the way to first tests of advanced quantum networking tasks where the storage node efficiency plays a critical role.

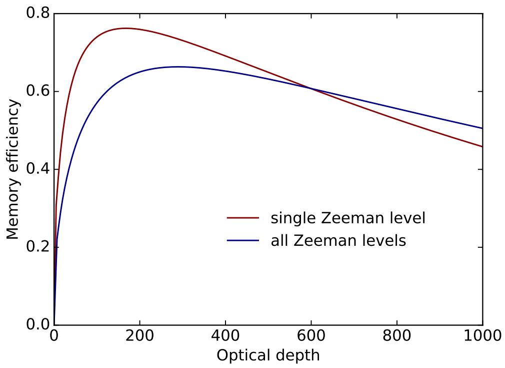

FIGURE 1: Storage-and-retrieval efficiency as a function of the OD using the Cs D_2 line. The brown line corresponds to one populated Zeeman sublevel in the ground state $|F_g = 3, m = 3\rangle$, while the blue line corresponds to equally populated Zeeman sublevels.

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Highly Efficient Quantum Memory for Polarization Qubits in an Elongated Atomic Ensemble

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Quantum memory for flying optical qubits is a key enabler for a wide range of applications in quantum information science and technology, such as long-distance optical communication and all-optical quantum computation [1]. In this context, our group focuses on the demonstration of such interfaces based on large cold atom ensemble. In recent years, we demonstrated for instance the implementation of a quantum memory for quantum bits encoded in the orbital angular momentum (OAM) degree of freedom, which provide an essential capability for future networks with multimode capability [2]. We also realized multiple-degree-of-freedom memory, which can find applications in classical data processing but also in quantum network scenarios where states structured in phase and polarization have been shown to provide promising attributes [3].

In all these realizations, critical figure of merit is the overall storage-and-retrieval efficiency. Theoretically, the retrieval efficiency can be improved with the increase of the optical depth (OD). Efficient optical memory has been demonstrated with large OD, however, high efficiency qubit storage had not been demonstrated. Here we report on a quantum memory for polarization qubits that gathers an average fidelity above 99% and an efficiency equal to 68 ± 2%, thereby demonstrating for the first time a reversible qubit mapping where more information is retrieved than lost [4]. The memory is based on electromagnetically-induced transparency in an elongated laser-cooled ensemble of cesium atoms spatially multiplexed for dual-rail storage (see Fig.1). This implementation preserves high optical depth on both rails, without compromise between multiplexing and storage efficiency. This novel platform is compatible with our recent work on the storage of spatially structured photons, and provides an efficient node for future tests of quantum network functionalities and advanced photonic circuits, where efficiency plays a critical role.

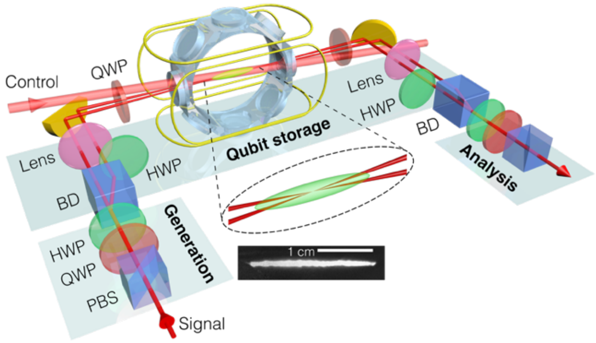

Fig.1. A two-dimensional ^{133}Cs magneto-optical trap is prepared by using a pair of rectangular-shaped magnetic coils. The cigar-shaped atom cloud has a longitudinal length of 2.5 cm and a temperature of 20 μK. A polarization qubit is encoded via a quarter (QWP) and a half wave plate (HWP) and converted into a dual-rail qubit with a beam displacer (BD). The orthogonally polarized beams, separated by 4 mm, are then mapped into an elongated ensemble of laser-cooled cesium atoms prepared in a 2D magneto-optical trap in a glass chamber.

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Theoretical threshold for quantum expander codes

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Quantum error correction is a technique used in order to prevent the decoherence of quantum states. A quantum error correcting code encodes some logical qubits into a larger number of physical qubits in such a way that it is possible to recover an initial state when some small errors have been applied on it. We study quantum expander codes ([1]) and in particular we prove that there exists a threshold for them. These codes have several nice properties : they are LDPC, they have a strictly positive rate, their minimal distance is good and there is an efficient decoding algorithm to decode them. We prove that these codes can almost surely correct random errors (in the so called locally stochastic noise error model) assuming that the probability of error is below some strictly positive constant called “threshold”. This is the first construction of a constant-rate quantum LDPC code with an efficient decoding algorithm that can correct a linear number of random errors.

Three parameters are of particular interest for a quantum error correcting code : n the number of physical qubits, k the number of logical qubits and d the minimal distance which is such that any Pauli operator of size less than d can be corrected by the code. Such a code is called a $[[n, k, d]]$ quantum-code and we are particularly interested by LDPC codes which are expected to be implementable. In classical coding theory, the goal of constructing $[n, k, d]$ classical LDPC codes with k and d linear in n has been achieved. However, the best known minimal distance of a quantum LDPC code is of order $\sqrt{n}$. Physically, errors come with a constant rate and thus are of size $\Theta(n)$. That’s why we study the behaviour of quantum expander codes against random errors with a constant rate. We use the same kind of tools than [2] and [3] and in particular percolation theory. A standard result of percolation theory states that if we pick randomly and independently vertices in a degree bounded graph then the induced sub-graph has small connected components. We study a generalised version of percolation, namely α-percolation, and following [2] we prove that with high probability, the size of the largest connected α-subset of a random set W is of size $\Theta(log(n))$. Here X is an α-subset of W means $|X \cap W| \geq \alpha|X|$. Going back to error correcting codes, we represent a random error on physical qubits by running the process of percolation on a graph whose vertices represent qubits. Since the largest connected α-subset of the error is of size $\Theta(log(n)) = o(\sqrt{n})$ and since quantum expander codes have a minimal distance in $\Theta(\sqrt{n})$, they can correct each of these connected α-subset and thus the entire error is corrected.

Future work : we would like to prove the existence of a threshold when there are errors on the syndrome measurement too. This result would have applications in efficient fault-tolerant quantum computation with constant overhead, using a previous work of Gottesman ([3]). Fault-tolerant quantum computation is an essential tool in the designing of a quantum computer since it allows us to fight against the noise in quantum circuits.

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All-optical synchronization for quantum networks

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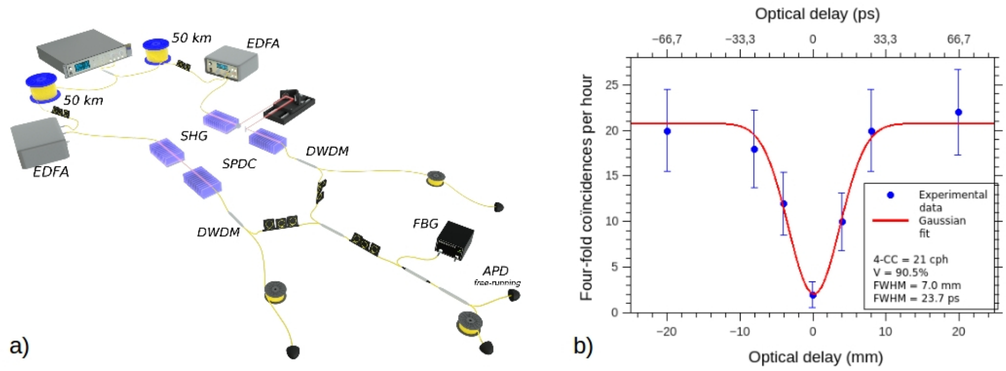
A major bottleneck in the implementation of a quantum relay link is represented by the synchronization of (at least) two remote entangled photon pair source (EPPS) which are usually pumped by two independent lasers[**?**]. To answer this challenge, a first approach consists in synchronizing the emission times of the pairs by using two fs lasers locked in a master/slave configuration. The use of fs pump pulses has the double advantage of reducing the uncertainty on the photon creation times and introducing an intrinsic time-binning. However, this regime requires synchronizing the two pump lasers within 10 fs accuracy, a condition which is particularly hard to meet. Moreover, for long distance applications the initial synchronization has to be transfered to the created photons, meaning that the propagation lengths from the EPPS to the relay station have to be controlled with a precision of a few fs, i.e. ∼mm. To date, configurations using fs pump lasers remain restricted to short distances, essentially below 30 km [2]. An alternative approach is based on continuous operation regime and on the post-selection of random two-photon events by means of detection . In this case, issues linked to pump laser synchronization are completely relaxed. However, since no intrinsic time-binning is provided by the continuous lasers, detector timing jitters become the main source of time uncertainty. It is thus mandatory to push the coherence time of the generated photons well above this jitter. To this end, narrowband filters must be inserted in the setup, drastically reducing its performances in terms of detection rates [3].



a) Schematic representation of the experimental setup. **b)** Hong-Ou-Mandel dip with four photons. The number of 4-fold coincidence counts (4-CC) per hour is shown as a function of the relative delay between the two interfering photons.

To circumvent these issues, we have demonstrated an all-optical method for synchronizing quantum relay scenarios connecting at least two sources emitting pairs of photons at telecom wavelengths. Our experimental setup is based on a pulsed telecom fibre laser operating at 2.5 GHz that pumps, after frequency doubling, two nonlinear waveguide photon-pair sources. Our synchronization scheme is validated via the implementation of a two-photon interference experiment performed at the relay station, i.e. where the Bell state measurement takes place. We show a raw visibility greater than 90%, obtained in the 4-fold coincidence counts, for a separation distance of 100 km between the photon-pair sources. This result demonstrates the relevance of our approach.

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One-Dimensional Atomic Chains around a Nanoscale Waveguide : Generation, Storage and Controlled Transport of Single Photon Pulses

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Reversible light-matter interfaces are crucial elements in quantum optics and quantum information networks. In particular, the coupling of one-dimensional bosonic nanoscale waveguides and cold atoms appears as a promising pathway to build strong light-matter interaction thanks to the tight transverse confinement of light.

Recently, our group has developed an interface where light, tightly guided by a subwavelength-diameter optical fiber (nanofiber), strongly interacts with atoms near its vicinity. In this setting, a single atom close to the surface of the nanofiber can absorb a non-negligible fraction of the guided light, as the effective area of the mode is comparable with the atomic cross-section. Moreover, using this configuration, it is possible to generate an in-fibered dipole trap and create 1D atomic chains around the nanoscale waveguide.

Here, I present three of our most recent results using this light-matter interface. The first result is the realization of an optical memory at the single photon level [1]. Using the process of Electromagnetically Induced Transparency (EIT), we store a single-photon pulse with a total storage-retrieval efficiency of 10%, and a signal-to-noise ratio in the retrieved pulse larger than 20.

The second result is the storage and retrieval of a single excitation in an atomic ensemble composed of the 1D atomic chains, and the subsequent generation of strongly correlated photon pairs out of the system. Due to the strong light-atom interaction , the correlated photons are directly collected into the nanofiber and are easily transfered to commercial optical fiber. Measurements of the high-quality and purity of the heralded single photons are presented where we observe their non-classicality [3].

And finally, I will report on the observation of a large Bragg reflection from a 1D lattice made of trapped atoms around the nanofiber [2]. Contrary to previous experimental results with atoms around nanofibers which were obtained with a disordered or incommensurate array of atoms, and only relied on the resulting optical depth of the medium, in this experiment we realize collective effects arising from atoms trapped in a close-to-commensurate optical lattice. By engineering the atomic distance in the chains to be almost half of the atomic transition wavelength, we create conditions to observe a large Bragg reflection. Using configuration, a strong Bragg reflection as high as 70% for single-photon pulses is achieved with only 2000 atoms in the 1D atomic chains [2].

Our results represent interesting new capabilities for strong and coherent atom-photon interaction in an all-fibered quantum network. It paves the way to the generation of remote entanglement of all-fibered ensembles and dynamical control of the transport properties down to the few photon level.

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Coherent control of the silicon-vacancy spin in diamond

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Spin impurities in diamond have emerged as a promising building block in a wide range of solid-state-based quantum technologies. The negatively charged silicon-vacancy centre combines the advantages of the high quality of its photonic properties for optical networks [1] with a ground state spin which can be read out optically [2]. However, for this spin to be usable in a quantum network, full quantum control is essential.

Here, we report the measurement of optically detected magnetic resonance and coherent control of a single silicon-vacancy centre spin with microwave field [3]. Using Ramsey interferometry, we directly measure a spin coherence time exceeding 110 ns at 3.6 K. Furthermore, we show that this coherence time is consistent with dephasing of the spin arising from single phonon-mediated excitation to the upper orbital branch of the ground state. Our results make the spin a usable resource to establish the silicon-vacancy centre as a spin-photon interface.

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Do micro- and nanolasers actually have thresholds ?

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Nanolasers are key components of future photonics integrated circuits, and their impact on the rapidly evolving field of information technology is already taking shape in the form of devices which promise ever faster transmission and better integration levels. Yet, the physics of their lasing transition remains comparatively poorly understood.

Indeed, their response to pumping combine : a) the memory effects introduced by the slow material response in "Class B" devices [1], b) a high sensitivity to spontaneous emission [2], the fraction of spontaneous emission coupled into the lasing mode ranging from $\beta \quad 10^{-4}$ in microlasers to $\beta \quad 10^{-2}$ in nanolasers, and c) an operation at low photon flux levels that complicates the exploration of their extended threshold region.

We have thus performed, through photon counting measurements in a standard Hanbury-Brown & Twiss (HBT) configuration, a systematic characterization of the threshold region of a commercial VCSEL microlaser (Thorlabs @980 nm). This choice represents a happy compromise between a significant $\beta \quad 10^{-4}$ and a large enough cavity size to also observe the temporal dynamics through fast photodetectors (10 GHz) and detection chain (6 GHz analog bandwidth LeCroy oscilloscope, 10^6 points per trace). These two combined sets of measurements yield several unexpected observations and conclusions :

- *Values of $g^{(2)}(0)$ in excess of 2* : while $g^{(2)}(0) = 2$ is the upper limit for a *stationary* chaotic signal, small-size lasers sensitivity to spontaneous emission invalidate this approximation by spontaneously inducing a spiked, time-dependent dynamics. Theoretically, $g^{(2)}(0)$ in then inversely proportional to the duration of the pulses, thus unbounded.

- *The signature of a (fluctuating) coherent signal at very low pump intensities*, down to one tenth of the conventionnal, full coherence threshold. This signature is obtained by inserting a Mach-Zender interferometer before the HBT beamsplitter [3].

- Evidence that, while the photon statistics can theoretically be equivalently described either by the probability density function (PDF) of the laser's output signal or by the measurement of coincidences in the arrival times, *the equivalence of these typical "classical" and "quantum" approaches does not hold* when measurements are limited to the second moments ($g^{(2)}$).

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Dense wavelength division multiplexed hyperentanglement for high capacity quantum information processing

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The performance of quantum information protocols increases exponentially with the size of the accessible Hilbert space [1]. Most intuitively, such high-dimensional spaces are accessed by superposing multiple quantum objects in a coherent manner. However, especially for photons this strategy is extremely challenging due to the intrinsic multipair emission of commonly used spontaneous parametric downconversion sources. This issue is overcome when entangling less quantum objects over more degrees of freedom simultaneously, *i.e.* they become hyperentangled [2]. Key achievements of hyperentanglement are superdense coding, complete photonic Bell state analysis, deterministic entanglement purification, and the realisation of efficient quantum repeaters [1].

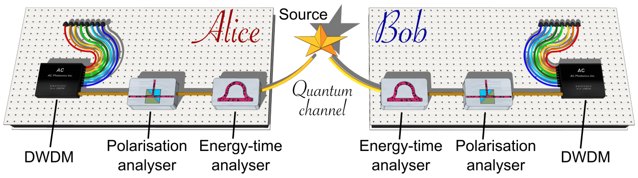

FIG. 1. Experimental schematic. Photons from the source are sent to Alice and Bob who analyse hyperentanglement and demultiplex the signal into wavelength anticorrelated channel pairs.

In this work, our target is to maximise the quantum channel capacity of fibre optic communication links. We show a one order of magnitude enhancement compared to standard entanglement distribution by combining two strategies:
first, we increase the Hilbert space from 4 to 16 dimensions by entangling our photon pairs simultaneously in the polarisation and energy-time degrees of freedom;
second, in analogy to standard fibre optic telecommunication systems, we use dense wavelength division multiplexing to distribute entanglement in 5 independent wavelength channel pairs simultaneously.
Our experimental schematic is shown in FIG. 1. We use a fully guided wave Sagnac type source [3], producing photon pairs in the maximally hyperentangled state

$$|\Psi\rangle_k = \frac{\left(|H\rangle_a|H\rangle_b+|V\rangle_a|V\rangle_b\right)_k \otimes \left(|E\rangle_a|E\rangle_b+|L\rangle_a|L\rangle_b\right)_k}{2}. \qquad (1)$$

Here, H and V are vertical and horizontal photon polarization modes, E and L are early and late time creation times of energy-time entangled photon pairs, a and b denote photons propagating to Alice and Bob, respectively, and k indicates the wavelength channel pair.

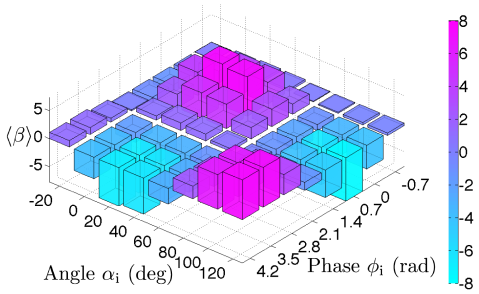

FIG. 2. Violation of a generalised Bell inequality. For the optimal settings of, we obtain $\langle\beta\rangle = 7.73 \pm 0.12$.

We first analyse the quantum state in energy-time and polarisation using suitable analysers. Additionally, before detection, we demultiplex the paired photons into 5 telecom wavelength channel pairs. An exemplary result for the violation of a generalised Bell inequality [2] in one of those channel pairs is shown in FIG. 2. We obtain a maximum Bell parameter of $\langle\beta\rangle = 7.73 \pm 0.12$, which is 31 standard deviations above the classical bound ($\langle\beta\rangle \leq 4$). In all other channel pairs, our results are at least 27 standard deviations above the classical limit. Thus, our high-quality results demonstrate clearly that hyperentanglement and dense wavelength division multiplexing in fibre networks is compatible.

Note that, by exploiting standard 12.5 GHz telecom demultiplexers, our strategy can be easily boosted towards 368 channel pairs. This promises a 3 orders of magnitude enhancement of the quantum channel information capacity, and dynamically connecting hundreds of users in a large scale quantum network. Strikingly, it has already been demonstrated that this is possible without increasing the number of quantum state analysers which makes our strategy extremely resource efficient [4]. We therefore believe that our approach will find its applications in future high capacity quantum information processing, potentially in combination with suitable quantum memories.

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Random numbers with only one qutrit

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We aim to produce randomness using a single quantum system, and to certify it by quantum only behavior [2]. In this sense, we imagine the following theoretical setting which produces randomness that could be certified by Homogenuous Bell Inequalities [3].
Assume a physical system and a single ternary measurement apparatus whose results are denoted $1, \omega, \omega^2$ (with $\omega^3 = 1$) for commodity. We also set a transformation V, between the system and the device, which could represent a change of orientation for the apparatus, with the property $V^3 = \mathrm{Id}$.

Quantum system
The system is a qutrit. We choose :

$$V = \frac{\omega - \omega^2}{3} \begin{pmatrix} \omega & 1 & 1 \\ 1 & \omega & 1 \\ 1 & 1 & \omega \end{pmatrix} \quad \text{hence} \quad V^2 = \frac{1}{\omega - \omega^2} \begin{pmatrix} \omega & 1 & 1 \\ 1 & \omega & 1 \\ 1 & 1 & \omega \end{pmatrix}.$$

Observables associated to measurements in the three possible configurations are : $A_i := V^i Z V^{\dagger i}$ (with $0 \leq i \leq 2$) :

$$A_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} = Z; \quad A_1 = \begin{pmatrix} 0 & 0 & \omega \\ \omega^2 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} = \omega Z X; \quad A_2 = \begin{pmatrix} 0 & \omega^2 & 0 \\ 0 & 0 & 1 \\ \omega & 0 & 0 \end{pmatrix} = \omega^2 Z X^2.$$

Classical behavior
With a system having a classical description, we show that the elements of reality a_i associated to measurements A_i verify inequalities $\mathrm{Im}(B) \leq \sqrt{3}/2$ where B is any of the following expressions :

$$(\omega + x + x^2) \qquad (1 + \omega x + x^2) \qquad (1 + x + \omega x^2)$$

$$-(\omega^2 + x + x^2) \quad -(1 + \omega^2 x + x^2) \quad -(1 + x + \omega^2 x^2)$$

or those obtained multiplying them by ω or ω^2. Here x stands for $a_1/\omega a_0 = a_2/\omega a_1$.

Quantum Violations
For the quantum system described above we can observe violations of these inequalities (up to a factor 1.88). Such violations certify quantum behavior. They could be used to certify randomness in the sequence of the issues obtained.

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Quantum frequency conversion for photonic polarisation qubits: towards interconnected quantum information devices

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Quantum technology is on the edge to revolutionise our lives in all aspects dealing with science and application of information [1]. In this perspective, quantum computers and simulators [2], high-precision quantum sensors [3], and quantum key distribution [4] are the most promising candidates to replace today's state-of-the-art approaches. To turn such promises to reality, those quantum technology pillars have to be made compatible with each other to combine individual system advantages. One major obstacle here is the wavelength discrepancy between different systems. Telecom wavelength photons ($\lambda \sim 1.55\,\mu$m) are generally preferred for quantum communication purposes, while quantum computation, storage and metrology are usually performed with matter based systems at shorter wavelengths ($\lambda \sim 600 - 900\,$nm). To bridge this gap, the solution lies in *quantum interfaces* [5] that coherently convert photons back and forth between the different wavelength bands. Unfortunately, today's quantum interfaces for photonic polarisation qubits do not achieve adequate performances in terms of efficiency, flexibility and fidelity [6, 7].

In this presentation, we will discuss a novel quantum interface in which single photon polarisation qubits are converted via sum frequency generation in two nonlinear crystals from 1560 nm to 795 nm (see FIG. 1). Our device is therefore adapted for quantum networking scenarios in which telecom photons are distributed in a fibre network and subsequently stored in stationary quantum systems based on hot and cold atomic ensembles, as well as solid state quantum memories. One key feature of our approach is a high photon conversion efficiency (currently 4%, straightforwardly extendible to $\sim$ 25%). Additionally, we achieve high quantum state transfer fidelities (currently 0.95, straightforwardly extendible to 0.99) which we demonstrate through near perfect single photon state transfer tomography and observation of high-fidelity entanglement after conversion. As we will outline in the talk, these results are mainly due to the fact that our device operates essentially noise-free over a spectral bandwidth of $\sim 250\,$MHz which is compatible with the above-mentioned stationary quantum systems. We mention further, that for our experimental setup, we choose a design based on nonlinear guided-wave optics to increase robustness and facilitate integration into existing systems. Therefore, our work represent a significant step towards interconnecting the pillars of quantum communication, storage and computation.

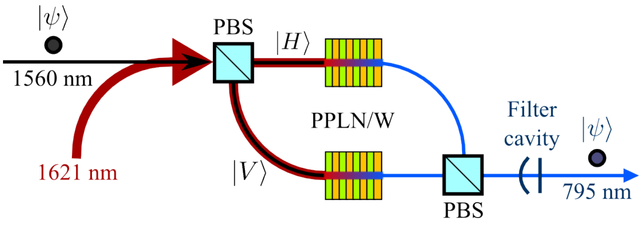

FIG. 1. Experimental schematic. Incoming single photon polarisation qubits at 1560 nm are mixed with a 1621 nm pump laser and their polarisation components are wavelength converted in two periodically poled lithium niobate waveguides (PPLN/W). A cavity based filter is used to remove undesired anti-Stokes noise originating from the PPLN/Ws.

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Multimode Spectral Bosonic Encodings for Practical High-Dimensional Quantum Cryptographic Protocols

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In recent years, high-dimensional quantum states (qudits) have shown great promise as highly efficient tools to aid the development of future quantum technologies, as higher dimensionality can be exploited to effectively encode several qubits without increasing the physical resources (e.g. encoding several qubits into a single photon). In particular, when compared to qubits, the higher dimensionality of qudit states is associated with benefits such as more bits per signal for quantum communications and cryptography [1], tolerance to higher error rates for quantum key distribution protocols [2,3] and the parallelization of operations in quantum computing [4].

Owing to these benefits, there has been a growing interest in the optical/photonic realization of high-dimensional quantum states. Although most of the recent work has focused on time-frequency encoding [5], encoding quantum information over frequency modes has also been proposed as a promising method of achieving high-dimensionality [6, 7]. Toward this end, recent work by Lukens and Lougovski [7] proposes and theoretically develops a photonic computing platform that could, in principle, provide a powerful paradigm for the experimental realization of quantum cryptographic protocols. The spectral linear optical quantum computation (spectral LOQC) scheme employs the principle of dual-rail encoding to code photonic qubits over two spectral modes. Physical operations can be realized by an alternating sequence of Fourier transform pulse shapers and electro-optic phase modulators. While this arrangement of optical components can be used to physically realize a universal set of quantum gates [7], here we are primarily concerned with the efficient implementation of single qubit gates that are necessary for practical cryptographic schemes.

Consequently, in this presentation, we discuss our current efforts aimed at extending this protocol towards a simultaneous (one-shot) implementation of several Hadamard gates on a qudit (dimension d = 2^n, and therefore, also encoding for n qubits) with limited resources (two pulse-shapers and two electro-optic phase modulators). Such an implementation is desirable as the required building blocks are available as standard telecom components, and because this scheme would allow for parallelization of quantum gate synthesis on a significant scale. Furthermore, the ability to realize non-diagonal gates such as the Hadamard is expected to be a key enabling technique that we investigate through numerical simulations for the efficient implementation of high-dimensional quantum communication protocols.

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Telecom down-conversion of spin-selective single photons from a nitrogen-vacancy defect in diamond

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The demonstration of an inter-metropolitan quantum network is currently a great challenge for quantum communications [1]. This architecture relies on connecting many optically active qubit-hosting nodes, separated by dozens or hundreds of kilometres, while keeping a high inter-node entanglement rate [2]. Nitrogen-vacancy (NV) defect in diamond stands out as a promising platform for realizing such networks due to its multi-qubit character combined with a solid-state spin-photon interface. First steps in the creation of these networks have already been demonstrated with the recent realization of a km-scale entanglement between two distant NV centres [3]. Nevertheless, the wavelength of the NV centre zero-phonon line (ZPL) photons (637 nm) used in the remote entanglement protocol [4] exhibit high photon loss during propagation in the optical fibres, which currently prevents the application of these defects for inter-metropolitan quantum connections.

Here, we will present the first telecom conversion of single photons emitted by an individual NV defect in diamond. By means of the non-linear process of difference frequency generation, NV center ZPL spin-selective photons are down-converted to the target wavelength of 1588 nm in the L-telecom band, corresponding to the range of minimal loss in optical fibres. This one-step frequency conversion reaches a maximal efficiency of 17%, along with a signal-to-noise ratio of $\sim$7, limited by detector dark counts and pump-induced noise, and preserves the single photon light statistics. This result constitutes the first step towards the realization of telecom photon-spin interface based on NV centers in diamond in the prospect of implementing future quantum communication networks.

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Measurement back-action in a spin-photon interface

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Measuring and controlling a single spin state in solid-state devices is of high interest for quantum information technologies. These operations have been implemented in a variety of systems such as single donor impurities in diamond or silicon, or spins of a semiconductor quantum dots doped with an electron or hole. If such a doped quantum dot is embedded into a microcavity, the efficiency of the light-matter interaction can be improved by several orders of magnitude [1].

The interaction between the circularly polarized light and matter in such a structure depends on the orientation of the electron spin. Because of the angular momentum conservation, the right-polarized (σ^+) photons interact only with the spin-up states ($S_z = +1/2$), while if the spin is down ($S_z = -1/2$), light passes as if the cavity were empty.

In this work we study a quantum dot, doped with an electron and embedded into a microcavity. We consider the strong coupling regime: the coupling strength between the quantum dot and the field in the cavity g is much larger than the decay rates of both the trion and the photons in the cavity. This allows finding an experimental configuration where light is fully transmitted or fully reflected, depending on the spin state

We analyze the second-order correlation function of the transmitted light, investigating its behavior under continuous laser excitation and in a weak magnetic field for different detunings. We separate long and short time-scales that are related to different impacts on the system: the short time-scale covers the dynamics governed by the interaction of the quantum dot with the laser through the cavity, and the large time-scale embraces the spin precession in magnetic field and the spin decay, that are normally slower.

The correlation function is calculated analytically for the low-power limit, and numerical simulation is performed to investigate higher powers and to check the validity of the analytical results and the limits of this approach.

We found that the correlation function of the transmitted light contains information not only about the dynamics of the electron spin, but also about the strength of the back-action of a photodetection on a spin orientation. This result can be used to prepare spin in a target state and to monitor its precession in a magnetic field.

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Efficient quantum communications with coherent state fingerprints

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Communication complexity is an ideal model for testing quantum mechanics and for understanding the efficiency of quantum networks. This model studies the amount of communication required by separate parties to jointly compute a task. There are several examples where communicating quantum information can result in considerable savings in the communication overhead [1, 2]. Nevertheless, it is in general difficult to test these results experimentally and demonstrate quantum superiority in practice since the quantum protocols typically necessitate large, highly entangled states, which are out of reach of current photonic technologies.

Recently, Arrazola and Lütkenhaus proposed a mapping for encoding quantum communication protocols involving pure states of many qubits, unitary operations and projective measurements to protocols based on coherent states of light in a superposition of optical modes, linear optics operations and single-photon detection [3]. This powerful model was used to propose the practical implementation of coherent state quantum fingerprints, leading to two experimental demonstrations: a proof-of-principle use of such fingerprints for solving the communication task of Equality asymptotically better than the best known classical protocol with respect to the transmitted information [4]; and a subsequent implementation beating the classical lower bound for the transmitted information [5]. Following these demonstrations that have focused on Equality and on transmitted information, an important question remains: is there a realistic model for proving and testing in practice that quantum information is asymptotically better than classical for communication tasks with respect to *all* important communication and information resources?

We answer in the affirmative by proposing the *first example of a communication model and a distributed task, for which there exists a realistic quantum protocol that is asymptotically more efficient than any classical protocol, both in the communication and the information resources*. For this, we extend a recently proposed coherent state mapping for quantum communication protocols, study the use of coherent state fingerprints over multiple channels and show their role in the design of an efficient quantum protocol for estimating the Euclidean distance of two real vectors within a constant factor.

Our communication model is as follows. Alice and Bob possess large data sets x and y respectively, which are unit vectors in $\mathcal{R}^n$. They would like to allow a Referee to check how similar their data is by estimating the Euclidean distance. We call this the Euclidean Distance problem. Alice and Bob can transmit their entire data to the Referee, but this is non-optimal. The idea is to send fingerprints of the data, which are much shorter but still allow the Referee to approximate their Euclidean distance within some additive constant. Such a model also requires the Referee to receive the fingerprints of data of both players at the same time.

We come up with a new scheme for experimental implementation of the quantum fingerprinting protocol for estimating the Euclidean distance. In our implementation Alice and Bob follow separate paths. This is in contrast to previous implementations involving a sagnac loop setup where Alice's pulse passes through Bob's path and vice-verca. Although the sagnac loop makes sure that the pulses of the two players arrive to the Referee at the same time, a possibility of communication between the two players during the protocol run might arise in this case. We overcome this issue by carefully adjusting the path lengths of Alice and Bob. We give preliminary results based on this setup for Equality and Euclidean distance protocols. Further details on our model and the scheme can be found on[6].

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Correlations with on-chip detection for continuous-variable QKD

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Despite the great progress in quantum key distribution (QKD) implementations in the recent years, QKD remains a technically demanding and costly technology, which hinders its widespread use for high-security applications. To this end, the photonic integration of QKD devices can play a crucial role by reducing size and cost by several orders of magnitude. Recent efforts in this direction include the development of chip-based devices using various integrated technologies for QKD protocols relying on single-photon detection [1].

Here we report on the on-chip demonstration of the main functionalities of continuous variable (CV) QKD, which requires standard telecommunication technology and in particular no photon counting [2]. Our demonstration is based on silicon chips, which comprise all the components of a CV-QKD system, including attenuators, amplitude and phase modulators, and homodyne detectors. Silicon photonics [3] allows for CMOS compatible technology and wide scale production of the developed devices, and has been used extensively in classical optical communications. Device requirements, however, differ significantly for CV-QKD operation, where for instance high extinction ratio and low loss modulators are necessary. In addition, homodyne detectors based on Si-integrated Ge photodiodes must be optimized to reach shot noise limited performance, which is more challenging than for the InGaAs photodiodes typically used in bulk systems [2].

Two different chips of roughly 0.7 x 0.5 mm^2 each are used for the preparation of states (Alice) and the measurement (Bob). The performance of the homodyne detection at Bob's side has been evaluated using an Alice made of bulk components. In particular, the linearity of the homodyne detector as a function of the local oscillator power has been verified in the shot noise limited regime (SNL). The clearance of the expected photon noise with respect to the electronic noise is between 10 and 20 dB depending on the chip. The excess noise ξ of the setup has been estimated to be below 10%. This is a pessimistic value since the coupling is not yet optimized and it is expected to be drastically improved increasing the achievable secret key rate distance.

Our results were obtained under typical CV-QKD system operation conditions (100 ns pulses at 1550 nm and 0.5 MHz repetition rate [2]) and are compatible with the generation of secret keys; hence, they illustrate the potential of Si-integrated CV-QKD for the widespread use of this technology in communication networks.

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Integrated filters for quantum photonics applications

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Among all the platforms that have already demonstrated their ability to generate entangled photon-pairs, Silicon is one of the most promising thanks to its outstanding properties. Beyond the well-established and mature technology, this platform shows very efficient non-linear properties, CMOS compatibility and high integration density. Here, we present a technological challenge of fully integrated silicon chip entangled photon-pairs source. This contains all the optical functions as the photon-pairs generation, the pump beam filtering and the entangled photons distribution through ITU channels.

The first function has already been done using a micro-ring resonator [1]. We will mainly focus on the second one that is based on an innovative integrated Bragg filter illustrated in figure 1. The sub-wavelength engineered Bragg filter relies on a double-periodicity with a differential width configuration. Such a structure exhibits 1.1 nm rejection bandwidth as well as an extinction ratio exceeding 40 dB [2]. Further investigations based on other subwavelength geometries have shown even better rejection rate reaching 55 dB. Also the use of an photonics crystal approached for the design of the Bragg filter has led to improved performance which gives promising results. All this done without increasing the fabrication constrains.

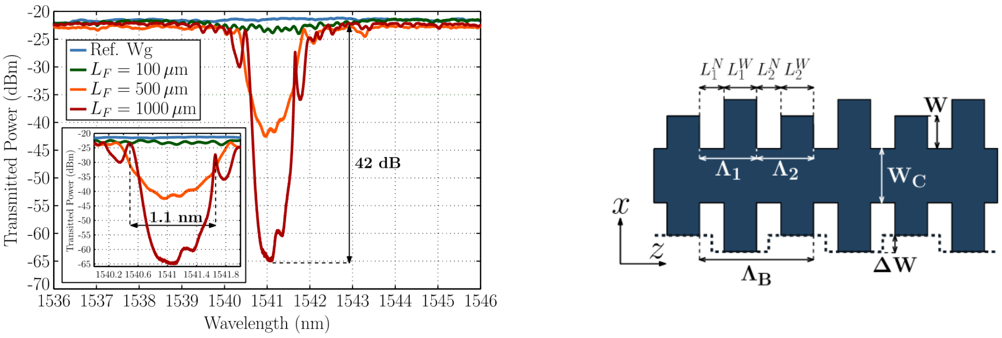

FIGURE 1: (left) Measurement transmission spectrum of the filter. (right) Design of the engineered Bragg filter.

Finally, we will show how to distribute the entangled photons over ITU channels using demultiplexed wavelength filters. These add/drop filters consist in fully controllable cascaded micro-ring resonators.

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Photonic quantum state transfer between a cold atomic gas and a crystal

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The interconnection of fundamentally different quantum platforms via photons is a key requirement to build future hybrid quantum networks [1]. Such heterogeneous architectures hold promise to offer more powerful capabilities than their homogeneous counterparts, as they would benefit from the individual strengths of different quantum matter systems.

We report on interfacing a cold atomic ensemble of Rubidium atoms with a rare-earth ion-doped crystal. The first one, beside being an excellent quantum memory (QM) and single photon source [2], also gives access to quantum processing via Rydberg excitation, while the second system offers multiplexed long-lived quantum state storage [3].

In this experiment we demonstrate storage in the solid state memory of a paired single photon, emitted from the atomic cloud (to appear in Nature 2017). As both systems exhibit very different optical transitions, we apply cascaded frequency conversion techniques to bridge the wavelength gap and moreover transmit the single photon at telecom wavelength, favorable for long distance communication. We demonstrate that the coherence of the single photon is preserved through frequency conversion, storage and retrieval. Finally, we show time-bin qubit transfer between the two fundamentally different QM systems with a conditional fidelity of 85 %, surpassing the classical threshold.

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On-chip III-V monolithic integration of heralded single photon sources and beamsplitters

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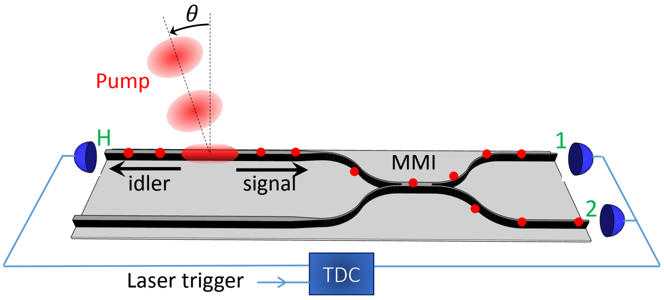
Nonclassical light sources and linear optical components are essential tools for quantum information ; the integration of these elements in a single chip is a key issue for future quantum processors. Among the different platforms for quantum photonics AlGaAs is particularly attractive, since it combines high second order nonlinearity, direct bandgap and electro-optics effect. These properties have already led to the demonstration of electrically driven two-photon sources based on spontaneous parametric down-conversion [1], to the generation of biphoton states with high level of entanglement [2,3] and to photonic circuits manipulating quantum states [4].

Here, we report the first realization of a monolithic GaAs/AlGaAs photonic circuit combining a parametric heralded single-photon source with a beamsplitter, operating at room temperature and telecom wavelength. The sample is grown by molecular beam epitaxy using a (100)-oriented GaAs substrate, and processed by reactive ion etching to design a beamsplitter having straight waveguides as input and output ports. This beamsplitter is a multimode interferometer, which has been characterized in terms of optical losses, splitting ratio and sensitivity to polarization. Photon pairs are generated in an input waveguide through type II spontaneous parametric down conversion, in a transverse pump configuration. Among the two photons generated, one of them is used to herald the injection of its twin into the beamsplitter. This configuration allows to realize an integrated Hanbury-Brown and Twiss experiment, yielding a heralded second-order correlation $g^{(2)}_{\mathrm{her}}(0) = 0.10 \pm 0.02$ that confirms single-photon operation.



The used transverse pump configuration circumvents the usual issue of pump filtering (required in collinear injection schemes), allows a direct spatial separation of the heralding and heralded photons, as well as a tuning of the joint spectral intensity to obtain a nearly separable state ($K \sim 1$) ensuring high single-photon purity. The demonstrated scheme can be extended to more complex photonic operations : for instance, pumping both input waveguides of the device would allow to perform an integrated Hong-Ou-Mandel experiment, to test the indistinguishability between remote parametric sources, a key requirement for scalability. Furthermore, depositing electrodes should enable the implementation of fast phase shifters to manipulate the produced quantum states, and progress towards optical quantum computing tasks on the GaAs platform.

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Quantum Sensing & Metrology (QMET)

Resolution of quantum ghost imaging and quantum Fourier ptychography

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Quantum ghost imaging uses photon pairs produced from parametric down-conversion to enable an alternative method of image acquisition [1] : information from either one of the photons does not yield an image, but an image can be obtained by harnessing the correlations between them. We report an examination of the resolution limits of such ghost imaging systems and show how the same systems can be used to implement a quantum version of the Fourier ptychographic imaging technique.

It has been claimed that quantum ghost imaging may present advantages in terms of resolution compared to both conventional imaging and classical ghost imaging [2]. We show that there is no such advantage : the resolution is limited not only by the resolving power of the optics between the object and the imaging detector but also the resolution can be further degraded by reducing the strength of the spatial correlations inherent in the down-conversion process.

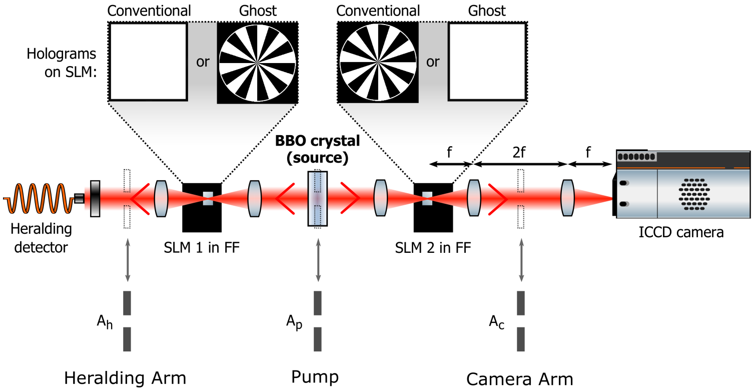

Figure 1 : Unfolded experimental setup.

However, a more surprising result appears when one introduces a very stringent spatial filter in the heralding arm of the ghost imaging setup (cf. Fig. 1). Indeed, in such conditions one observes an apparent degradation of the resolution in the acquired images which at first glance is not expected. We will explain this phenomenon and show how we were able to use this to acquire both phase and amplitude of an object through a quantum version of the Fourier ptychography technique [3].

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Quantum description of timing-jitter for single photon ON/OFF detectors

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Discrete variable quantum optics stands as one of the most prominent platform for quantum cryptography with an increasing number of promising out-of-the-laboratory implementations [1, 2].

The quest for competitive systems, compatible with future practical applications, has promoted huge developments concerning both photonic sources [3, 4] and detection systems [5, 6]. Nevertheless, a critical point is still represented by experimental operation rates. Time multiplexing techniques allows in principle to pump photonic sources at rates in the gigahertz regime [7]. However, a strong limitation to ultra-fast operation lies in timing errors at the detection stage. Detection timing-jitters introduce random variations in the time delay between the photon arrival time and the time at which the output electrical signal is delivered : important jitters can thus lead to counts associated with a given optical clock cycle to appear as temporally indistinguishable from those corresponding to neighbouring ones [6]. Accordingly, limited resolution directly affects the quality of any time-correlated single photon counting or quantum state engineering operations [7].

In anticipation to further technological advances as well as in the perspective of promoting future conceptual developments on existing quantum communication protocols, it is thus extremely pertinent to correctly describe the effects of detectors' timing performances. Despite a huge number of papers reporting the experimental time response of photon-counting devices [6], to our knowledge, no quantum description taking into account these effects has been developed so far.

We explicitly address this point by providing a theoretical model able to describe the temporal behaviour of standard single photon detectors affected by non negligible timing-jitter and in presence of dead-time.

We will adopt the formalism of positive operator-valued measurements (POVM) [8]. This approach has already been employed to describe detector with photon-number abilities and has been successfully used to experimentally investigate the characteristics of unknown single photon detectors [9]. A first step towards the description of timing-effects in terms of POVM has been recently performed by including dead-time effects in the description of standard single-photon detectors [10].

We propose a new model exploiting a multi-mode formalism to describe temporal degrees of freedom to fully describe timing-resolution effects in ON/OFF detector by a POVM, taking into account the effect of dead-time and finite detection efficiency. Based on the analysis of probability distribution for the measurement results in the case of different temporal distribution for the photons at the detector input we reconstruct by linearity the POVM. We then apply our results to the quantitative study of timing-jitter effect on some usual quantum optics experiments, such as coincidence measurements. As for an example, this fully quantum approach allows expressing the density matrix of a heralded photon explicitly, and taking into account the imperfections of the heralding detector.

Our study can be easily generalized to detection systems involving multiplexing strategies where different detectors are used in parallel such as in photon number resolving schemes.

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Schroedinger-Newton equation : from theory to experiments.

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The status of gravitation in the quantum regime is still today a controversial subject [1]. It is not clear whether, in order to provide a correct formulation of the gravitational interaction in the quantum formalism, it is necessary to quantize space-time or, following Penrose's words [2] to gravitize quantum mechanics, an idea that can be traced back to Rosenfeld [3] according to who the coupling between gravity and (quantum) matter ought to be treated in the mean field limit. In this approach, where the source of gravity is the quantum-averaged stress-energy tensor, the Schroedinger-Newton equation naturally appears in the non-relativistic limit. In addition to the usual, linear, Schroedinger equation, it contains a non-linear potential that expresses the (self) gravity exerted by a quantum system on itself [4]. As has been shown by Diosi [5] in the 80's, self-gravity can consistently be neglected at the microscopic scale (fundamental particles, atoms, molecules) but this is no longer true at the mesoscopic scale. In our talk/poster, we shall present some features of self-gravity as well as the possibility to reveal its existence experimentally.

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Towards electron spin hyperpolarization via radiative cooling

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Electron spin resonance (ESR) spectroscopy is widely employed for the detection and characterization of paramagnetic species and their magnetic and chemical environment [1]. In ESR the spins precessing around an applied static magnetic field are first excited by microwaves and subsequently emit a signal into an inductively coupled resonant cavity. A high degree of polarization is essential to maximize the signal. Here, we are interested in increasing the polarization beyond thermal equilibrium. In the present work we propose a new universal hyperpolarization scheme based on the coupling of the spins to a colder electromagnetic bath via Purcell-enhanced radiative relaxation.

For spins in solids, radiative relaxation is completely negligible. The dominant process is relaxation to phonons. However, by coupling the ensemble to a high Q resonant cavity with a small mode volume, the spontaneous emission rate can be enhanced up to the point where the radiative relaxation dominates. This enhancement is called Purcell effect [2]. The goal of our experiment is to demonstrate Purcell enhanced thermalization of a spin ensemble to a colder radiation bath while the crystal lattice remains at higher temperature.

The spin system under study is an ensemble of bismuth donors implanted into a host silicon crystal. The spins are inductively coupled to a high Q superconducting niobium resonator. The silicon crystal is installed at the 1 K stage of a dilution cryostat while the resonator is coupled to a 10 mK black body. In this configuration, the electronic spins thermalize to 10 mK via radiative relaxation while the silicon crystal remains at 1 K. We expect an increase of the ESR signal by a factor 5 compared to the case without hyperpolarization.

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Generation and manipulation of squeezed light on chip

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Squeezed light exhibits reduced noise properties with respect to «classical light »such as that emitted by standard laser sources [1]. Its peculiar quantum properties make it a good candidate for a wide variety of applications, encompassing quantum metrology [2], processing [3] and communication [4].

The ongoing growth of these technologies implies a need for stable and efficient squeezing experiments, relying on compact (integrated) setups. In particular, the miniaturisation concerns the squeezing generation stage, typically relying on bulk optical parametric oscillators in a cavity, as well as its detection, based on bulk homodyne-like interferometers [5]. Integrated optics provides many of these requirements. The high confinement of light in waveguides allows obtaining compact and efficient generation of squeezing [6], even in a single pass (cavity-free) configuration [7]. On the other hand, the traditionnal issue of spatial mode matching of homodyne interferometers can be greatly simplified with single-spatial-mode splitters and combiners [8]. A fully fibered configuration has been recently demonstrated [9] opening the way to plug and play devices.

Until now, squeezing implementations [6, 7, 9] always separate the generation from the detection of squeezing which limits their compactness and integration possibilities. In this contribution, I will adress the miniaturisation of squeezing experiment by discussing a novel and home-made lithium niobate chip fully integrating for the first time, the generation and the detection (optical part) stages on the same component. The chip includes a periodically poled waveguide for the generation of squeezing by spontaneous parametric down conversion (SPDC) at telecommunication wavelengths (1540nm), followed by an integrated tunable beam-splitter for the homodyne detection. The SPDC occurs in one arm of the beam-splitter, while the other serves for the injection of the local oscillator (LO). Thanks to an integrated optical switch, we can choose at the end of the SPDC either to make interfere the squeezed beam with the LO or to collect it for any dedicated application... The ratio of the beam-splitter and the optical switch can be electro-optically adjusted wih precision by applying the appropriate voltage on the electrodes. In this contribution, I will present some details on the chip fabrication as well as preliminary results on the chip characterization.

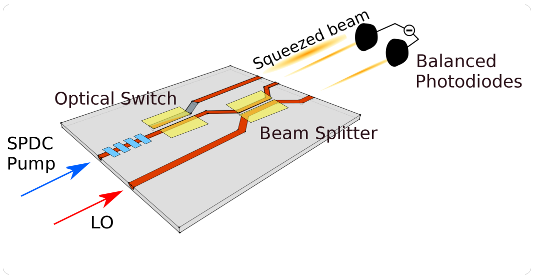

FIGURE 1. Schematic of the chip
The waveguides are fabricated by protonic exchange on a lithium niobate substrate. They are single mode at 1540 nm. The upper one is periodically poled (blue rectangles) and is using for the SPDC process, while the lower one guides the local oscillator. The ratio of the optical switch and the beam splitter can be adjusted with electrodes (yellow rectangles).
Chip area is 5 times 1 cm^2.

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Towards microwave detection of a single spin

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Our project aims at detecting a single spin using magnetic resonance techniques by coupling it to a high quality factor superconducting resonator, following a recent proposal [1]. The electron spins of choice are shallow (15 nm) implanted single Nitrogen-vacancy (NV) centers in an ultrapure diamond layer isotopically enriched in the nuclear-spin-free ^{12}C isotope. After characterization at room temperature using a confocal microscopy, an Aluminium microwave resonator is fabricated on top with a nanometric constriction (width 40 nm) carefully aligned to a pre-selected NV center. The constriction enhances the magnetic field generated by the microwave frequency current, and therefore allows to increase the spin-resonator coupling strength to a range of 15 kHz. Microwave-only measurements in a dilution refrigerator at 20 mK should then allow to observe a spin-echo signal from a single spin. Here we report on a novel method to characterize the location of the spin with respect to the superconducting circuit with nanometric precision, based on the dependence of the optically detected magnetic resonance signals at room-temperature on a dc current passing through the circuit.

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Overcomplete quantum tomography of a spatially encoded 2-photon $N00N$ state

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Multi-photon entangled states are at the heart of quantum metrology, where the property of quantum entanglement can be exploited to go beyond the measurement accuracy allowed by classical approaches. This field has strongly benefited from the advances in the production and manipulation of single and entangled photons, and a very interesting resource is represented by so-called $N00N$ states. When used in interferometric protocols, these states allow to achieve super resolved measurements and a precision beyond the Standard Quantum Limit [1]. The creation of up to $N = 5$ photons $N00N$ states has been demonstrated through the observation of the enhanced phase dependence [2], while most of the multi-photons state reconstruction techniques employed so far relied on polarization encoding protocols [3]. The quantum tomography of path-entangled indistinguishable photons has been scarcely addressed because it requires multiple phase estimations increasing rapidly with N. Here we implement a novel method to derive the density matrix of a two-photon state in the spatial mode basis requiring to control/measure a single optical phase.

Using the Hong-Ou-Mandel (HOM) effect, commonly employed to quantify the indistinguishability of single photons, we create a path-entangled 2-photon $N00N$ state, and characterize it by means of an overcomplete tomography. In the present work, the single photon source consists of a semiconductor quantum dot coupled to an electrically controlled semiconductor micropillar cavity [4]. Under resonant excitation, this quantum dot provides a stream of highly indistinguishable single photons used for the generation of the 2-photon $N00N$ state. The output state of the HOM interference between two of these photons can be described by a 3-level system, whose basis is constituted by the three possible distributions of the two photons on the two output spatial modes : $|20\rangle$, $|11\rangle$, $|02\rangle$. To reconstruct the 3×3 density matrix of such state, we developed a measurement scheme based on a split Mach-Zehnder configuration whose phase delay evolves freely and which is coupled to an ancilla spatial mode. Two-photon correlation measurements between the interferometer output modes and ancilla mode for a selection of 20 phase delays of the interferometer provide an overcomplete set of 79 measurements enabling the full quantum state tomography in the spatial-mode basis [5]. This notably allows us to observe the phase enhanced-resolution coming from the biphoton interference. Our results show that even with limited or noisy statistics we can optimally reconstruct the density matrix of our state, which reveals spatial coherences terms that could be otherwise hidden using a standard tomography protocol based on a minimum set of only 9 measurements. Finally, we extend our analysis to extract the truly indistinguishable part of the density matrix, allowing us to identify the main origin for the imperfect fidelity to the ideal $N00N$ state.

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Quantum Simulation (QSIM)

Optical control of the resonant dipole-dipole interactions between Rydberg atoms

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Long-range dipolar interactions giving rise to spin-exchange dynamics have recently been observed between molecules [1] and Rydberg atoms [2]. In the latter, qubits (or spin-1/2 particles) are encoded between two Rydberg levels of a ^{87}Rb atom, with transition frequencies ν_0 identical for each atom, and are thus resonantly coupled by the dipole-dipole interaction between the Rydberg states.

We report in [3] on the local control of the transition frequency of a single qubit by applying a state-selective light shift using an addressing beam. With this tool, we first study the spectrum of an elementary system of two spins, tuning it from a non-resonant to a resonant regime, where "bright" (superradiant) and "dark" (subradiant) states emerge. We observe the collective enhancement of the microwave coupling to the bright state.

We then show that after preparing an initial single spin excitation and letting it hop due to the spin-exchange interaction, we can freeze the dynamics at will with the addressing laser, as shown in Fig.1, while preserving the coherence of the system. In the context of quantum simulation, this scheme opens exciting prospects for, e.g., engineering inhomogeneous XY spin Hamiltonians or preparing spin-imbalanced initial states.

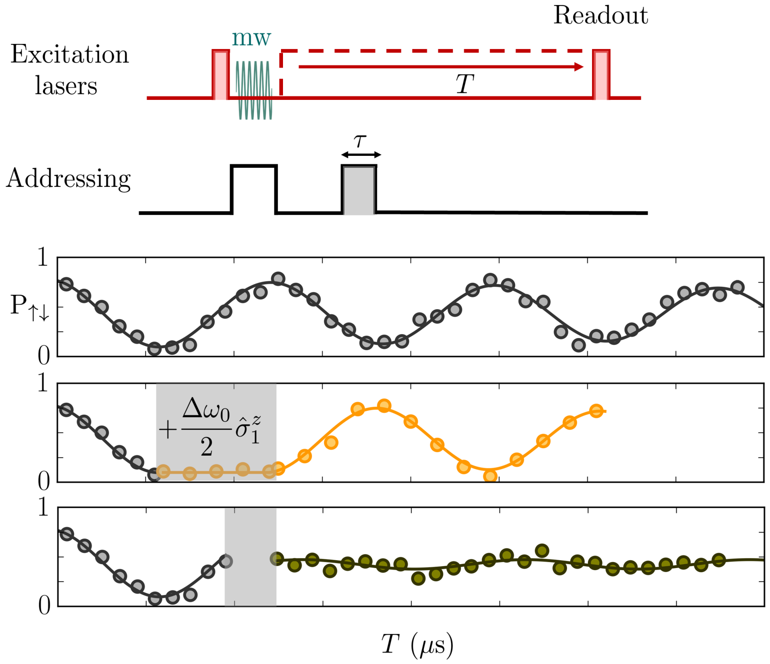

Fig 1 : An initial spin-excitation ($|\uparrow\downarrow\rangle$) hops coherently between the two atoms. The dynamics can be controlled by applying the addressing beam on one atom (shaded grey area).

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Excitonic qubit dynamics on complex networks in presence of a local phonon environment : perturbative approach vs. exact calculations.

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A method combining perturbation theory with a simplifying ansatz is used to describe the dynamics of an excitonic qubit on complex networks in presence of a local phonon environment. This method, called PT^* [1], is compared to exact calculations based on the numerical diagonalization of the exciton-phonon Hamiltonian for eight small-sized networks [2]. It is shown that the accuracy of PT^* depends on the nature of the network, and three different situations were identified. For most graphs, PT^* yields a very accurate description of the dynamics. By contrast, for the Wheel graph and the Apollonian network, PT^* reproduces the dynamics only when the exciton occupies a specific initial state. Finally, for the complete graph, PT^* breaks down. These different behaviors originate in the interplay between the degenerate nature of the excitonic energy spectrum and the strength of the exciton-phonon interaction so that a criterion is established to determine whether or not PT^* is relevant. When it succeeds, our study shows the undeniable advantage of PT^* in that it allows us to perform very fast simulations when compared to exact calculations that are restricted to small-sized networks.

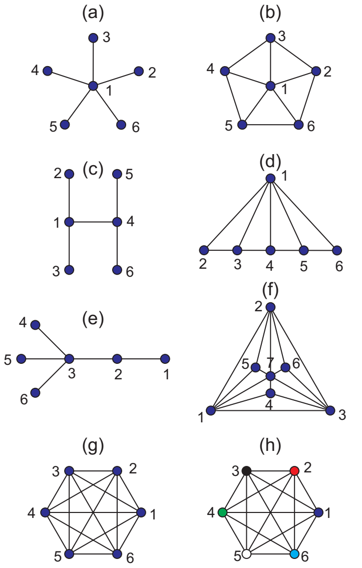

FIGURE 1. Representation of the different networks considered in our study. (a) The star graph, (b) the wheel graph, (c) the H graph, (d) the hat graph, (e) the fork graph, (f) the Apollonian network, (g) the complete graph, and (h) the random complete graph.

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Quantum gases in rf-dressed adiabatic potentials : from fundamental aspects to quantum simulation

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Radio-frequency dressed adiabatic potentials are highly versatile traps for cold atoms [1]. The trap geometry is defined by a static magnetic field landscape and by the dressing wave frequency, amplitude and polarisation. In a particular configuration, the trap center spreads over an isomagnetic surface of the static field, allowing highly anisotropic profiles of the atomic cloud [2].

In the following we will describe how our group takes advantage of the adiabatic potentials to study problems of fundamental nature, but also to design a system useful for quantum simulation.

We can routinely produce a degenerate gas of bosons in a quasi-2D harmonic configuration [3] where the trap parameters can be dynamically modified. We have then characterized some fundamental dynamical properties of the quasi-2D condensate through the study of its collective oscillations [4]. In particular, we have identified the local normal to superfluid crossover in a finite temperature 2D cloud. By selectively exciting the so-called "scissor modes" and using a local average analysis of the surface dynamics we have been able to locate the Berezinskii-Kosterlitz-Thouless transition boundary in the cloud and extract information about the damping mechanism [5].

One of our goals is to use the tunable ultracold-atom system trapped in adiabatic potentials to investigate the complex phenomenon of superfluidity, with strong analogies with superconductivity in electronic devices, in the spirit of the quantum simulator proposed by Feynman. Our current project is to study the superfluid flow of low-dimensional quantum gases in a ring geometry. Due to its superfluid character, the circulation of the velocity of the atomic flow around a loop is quantized : the analog phenomenon in condensed matter physics is the quantization of the magnetic flux in a superconducting loop. Using a vertical confinement produced by an optical potential and a radial one by the adiabatic potential [6] we are able to produce a flat ring potential into the 2D regime, which could sustain metastable persistent currents when set into rotation. We have implemented different ways to rotate the ring cloud of atoms : rotating trap anisotropy, optical potential stirring and phase imprinting, all these techniques being independently controlled. In the fundamental aspect, we want to study the superfluid dynamics in this configuration, identify the possible decay mechanisms with different perturbations. In a quantum simulation spirit, we would like to increase the ring confinement to reach a quasi-1D regime where the dimensional reduction enhances the effects of correlations and makes it possible to explore the precursors of strongly interacting Bose gases. This regime offers also the possibility to study strong interactions beyond the strictly one-dimensional limit. It would allow to simulate dynamical properties of quasi-1D gases of conduction electrons in solid state physics as well as to address the physics of multi-component coupled 1D atomic gases.

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Single-atom-resolved probing of lattice gases in momentum space

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Measuring the full distribution of individual particles is of fundamental importance to characterize many-body quantum systems through correlation functions at any order. Real-space probes of individual quantum objects – ions, superconducting qbits, Rydberg atoms or neutral atoms through a quantum gas microscope – have indeed paved the way to unprecedented investigations of many-body physics. Here I will present an experiment that provides the possibility to reconstruct the momentum-space distribution of three-dimensional interacting lattice gases atom-by-atom [1]. This is achieved by detecting individual metastable Helium atoms [2, 3] in the far-field regime of expansion, when released from an optical lattice. We benchmark our technique with Quantum Monte-Carlo calculations, demonstrating the ability to resolve momentum distributions of superfluids occupying 10^5 lattice sites. It permits a direct measure of the condensed fraction across phase transitions, as we illustrate on the superfluid-to-normal transition. Our single-atom-resolved approach opens a new route to investigate interacting lattice gases through momentum correlations.

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Ultrastrong coupling regime of two-photon interactions

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Two-photon processes have so far been considered only as effective models to describe quantum optical systems subjected to strong classical drivings. In this case, two-photon interactions (TPI) arise from second- or higher-order effects, and so they are limited to extremely small coupling strengths. However, a variety of novel physical phenomena emerges in the strong or ultrastrong coupling regime, where such coupling values become comparable to dissipation rates or to the system bare frequencies, respectively. For instance, in the ultrastrong coupling regime of TPI a spectral collapse [1] can take place, i.e. the system discrete spectrum can collapse in a continuous band.

In this contribution, I will present different schemes to implement TPI using current quantum technologies and recent theoretical analysis on the physics of such models. First, I will present a quantum-simulation protocol [2, 3] where a trapped-ion system is used to implement ultrastrong TPI between a chain of qubits and a single bosonic mode. We analyzed the phase diagram in the many-body limit of such system, showing that there exists a parameter regime where two-photon interactions induce a superradiant phase transition, before the spectral collapse occurs. [4]. Then, we designed a superconducting circuit scheme to implement genuine TPI in a solid-state device [5]. An open quantum system analysis shows that fundamental quantum optical phenomena are qualitatively modified with respect to standard dipolar interactions. We show that realistic parameters allow to reach the spectral collapse, where extreme nonlinearities are expected to emerge at the few-photon level.

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Observation of $1/k^4$-tails in an expanding Bose-Einstein condensates : a beyond-mean field effect

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Quantum depletion is a paradigmatic beyond mean-field effect expected to occur in Bose-Einstein condensates at zero temperature. In 1947, Bogoliubov provided a theoretical approach to quantitatively describe how repulsive interaction deplete particles from the BECs in weakly interacting systems [1]. At large momenta k, this theory predicts that quantum depletion leads to a finite population of the momentum distribution, decaying as $1/k^4$. The amplitude of these $1/k^4$-tails is the celebrated contact constant C introduced by S. Tan [2].

We have tested this theory in weakly interacting gaseous BECs of metastable Helium atoms [3], for which a single-atom detection method allows us probing extremely dilute distributions after a time-of-flight [4, 5]. We have investigated the time-of-flight distributions for various temperatures and clearly separated two contributions to the depletion of the condensate by their k-dependence. The first one is the thermal depletion. The second contribution falls off as $1/k^4$, it can not be captured by at the mean-field level and its magnitude increases with the in-trap condensate density as predicted by the Bogoliubov theory. These observations suggest associating it with the quantum depletion but with two caveats : the measured contact C exceeds the predicted one by a factor 6 and how this contribution can survive the expansion of the released interacting condensate remains an intriguing open question [6]. Here I will report on our early experiments [3] as well on new experimental data aiming at further investigating the phenomenon of quantum depletion, both in a harmonic trap and in the presence of an optical lattice.

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Observing the growth of correlations in dynamically tuned synthetic Ising antiferromagnets

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For a few decades, several research groups have been able to isolate and manipulate single quantum objects, such as atoms or ions. Controlling interactions between those objects allows engineering specific Hamiltonians, which can be then studied with this kind of experimental platforms. In our experimental set-up, we exploit the van der Waals interaction between Rydberg atoms to engineer an Ising-like Hamiltonian [1].

I will present our latest work on the quantum simulation of the Ising model on systems of up to 36 atoms, assembled in various geometries [2]. We access different states of the Ising phase diagram by dynamically changing the parameters of the Hamiltonian, as previously done in [3, 4]. The 36-atom system shows correlations, characteristic of an antiferromagnetic phase, in a specific region of the parameters space, see Fig. 1. We study the dependence of the contrast of the correlations on the duration of the preparation, and how the correlation length grows during the preparation.

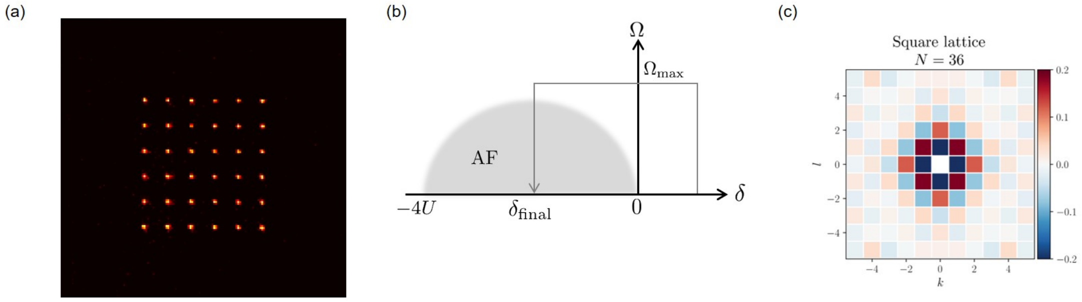

FIG. 1. Preparation of an antiferromagnet with a 36-atom system. (a) : Fluorescence image of 36 Rubidium atoms assembled in a 6×6 matrix of micro optical traps. (b) : By changing the parameters of the Hamiltonian, the amplitude Ω and detuning δ of the Rydberg excitation laser, the atomic system follows the grey arrow to reach the antiferromagnetic phase (grey shaded area). The energy U is the interaction between neighbouring atoms (c) : Rydberg density-density connected correlation function measured when we follow the path shown in (b). Two nearest neighbouring atoms are in different states (negative correlations, one is in the ground state, the other in the Rydberg one), and next nearest neighbouring atoms are in the same state (positive correlations). The alternative sign of correlations from site to site is a characteristic of an antiferromagnetic phase.

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Light scattering by cold interacting two-level atoms

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We study the problem of light scattering by a dense ensemble of cold atoms. When the medium is dense and the frequency of the light is tuned close to an atomic resonance, the light-induced dipoles interact. These resonant dipole-dipole interactions in turn modify the way the light is scattered. Besides being an interesting problem on its own, these studies are motivated by their potential applications. For example, these interactions may limit the accuracy of atomic based sensors (such as optical clocks).

We have shown recently that in the presence of these interactions, the *incoherent* response of a wavelength-sized and dense atomic cloud is no longer proportional to the number of atoms but is rather strongly suppressed [1]. The near-resonance *coherent* optical response of cold atomic gases is also modified by dipole-dipole interactions and has been at the focus of recent investigations by several groups including ours, both experimentally [2] [3] and theoretically [4] [5]. When comparing to the state-of-the-art coupled-dipole model, significant discrepancies between theory and experiment remain, possibly due to the multi-level structure of rubidium being improperly accounted for in the model.

Here, I will present our latest measurement of the coherent optical response of our microscopic dense ensemble but this time isolating a closed transition thanks to the application of a strong magnetic field. We thus realize a clean situation where the atoms are two-level systems. We developed a new model based on the Maxwell-Bloch equations (accounting for the propagation of light through the cloud of interacting atoms and the time-dependent evolution of the atomic coherences), which now shows good agreement with the data at low density and confirms the approach of the coupled-dipole model in this regime.

These promising results motivated us to upgrade the experimental setup. Indeed, as the collective response of a dense cold atomic cloud is supposed to depend dramatically on its geometry, we have added a second high resolution microscope axis in our setup, orthogonal to the first one. The goal of this second axis is to be able to control the geometry of our cloud by superimposing on it an interference pattern with adjustable interfrange distance, also called accordion [6]. This will allow us to generate spherical samples, as well as slabs. Here, I will present how we aligned and characterized the performance of these two confocal high resolution microscopes.

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Broadband beam splitting using Multiple Recipient Adiabatic Passage

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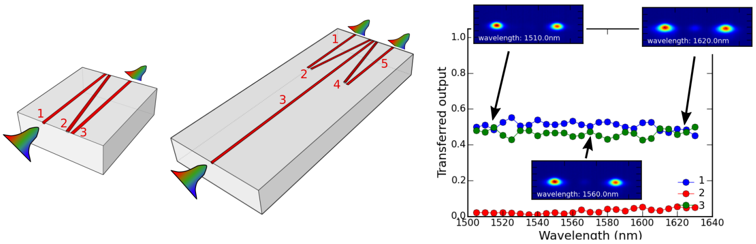
Integrated optics is often used as an emulator for quantum effects in atomic and condensed matter systems. For example, STImulated Raman Adiabatic Passage (STIRAP) allows to transfer the population from an initial state 1 to a target state 3 through the passage for an intermediate state 2. By dynamically tuning the coupling 1-2 and 2-3 the population transfer is efficient and robust against experimental imperfections. The spatial analogue to STIRAP, called Coherent Tunnelling Adiabatic Passage (CTAP), attracts interest in the integrated optics community since it provides a set of tools leading to innovative applications in classical and quantum optics such as beam splitting, interaction free-measurements and quantum gates via long-range coupling [1]. In an optical CTAP, a light beam is initially confined in waveguide 1 and transferred into the target waveguide 3. Waveguides 1 and 3 are coupled only through an intermediate waveguide 2. By tuning the couplings 1-2 and 2-3, the transfer is efficient and robust against variations of the beam characteristics. In practice, these 3-waveguide couplers feature broadband operations covering up to hundreds of nanometers. A typical architecture of a 3-waveguide coupler is shown in Fig.1 (a).

Building on this idea, we fabricated a new class of beam splitters consisting of 5 waveguides on $LiNbO_3$ substrates. Our approach, similar to the one theoretically proposed in [3], is based on Multiple Recipient Adiabatic Passage (MRAP). The structure consists on two, symmetrically folded, 3-waveguide couplers (see Fig. 1(b)) sharing the same central waveguide. Light from a tunable laser is initially injected in waveguide 3. While propagating through the MRAP, the optical beam is split and adiabatically driven to the external waveguides. The key signature of this process is that no light can be found in the central waveguides (2-3-4). We characterize the robustness of this 5-waveguide couplers by imaging the output beam while scanning the wavelength. The device features a constant splitting ratio and efficiency over more than 130 nm while all the light exits in the external waveguides. This proves the correct operation of the MRAP. This device allows for efficient generation of spatially delocalized entangled states and it is immediately integrable with nonlinear quantum sources based on $LiNbO_3$. In the poster we will provide more information on the theoretical frameworks at the basis of these structures and on their fabrication procedure. We will also provide full optical characterizations.



(a) (b) (c)

Figure 1 : (a) Integrated photonic CTAP architecture. (b) desig of the MRAP photonic emulator. (c) Ratio of the optical power on waveguides 1, 2, 3 at different wavelengths. Insets show the output beams at 3 different wavelengths.

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Controlling symmetry and localization properties with an artificial gauge field in a disordered Floquet system

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Anderson localization, which has long been a paradigm of condensed matter physics [1], has been observed and studied in the last decades in many different disordered systems, both classical and quantum. The symmetry characteristics of the disordered system are expected to greatly affect its localization and transport properties, yet few experiments are available in this direction. Here we report upon the experimental realization of an artificial gauge field in a synthetic (temporal) dimension of a disordered, periodically driven (Floquet) quantum system [2].

Our remarkably simple technique is used to control the Time-Reversal Symmetry (TRS) properties, and leads to two experimental observations representing smoking-gun signatures of this symmetry breaking. The first consists in the first observation of the Coherent Forward Scattering (CFS), a novel genuine interferential signature of the onset of the (strong) Anderson localization, recently predicted [3]. The second is a measurement of the celebrated $\beta(g)$ function, with a direct test of the one-parameter scaling hypothesis, and its universality in two different symmetry classes.

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Imaging and trapping cold atoms using a multimode fiber

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A high imaging resolution, or a tight focus of a laser beam impose a certain minimal numerical aperture (NA) of the optical system in question. Since a higher NA is usually achieved by placing larger lenses closer to the object, one can quickly be limited by spatial constraints on the experiment. This is true, amongst other scenarios, when imaging or trapping cold atoms inside a vacuum chamber. Multimode fibres, in conjunction with spatial light modulators [1], offer an interesting alternative to the standard approach of high NA lenses, as they are a flexible optical waveguide with very small transverse dimensions ($\sim 100\mu m$), and a reasonably high NA (up to 0.5). For those reasons, the use of multimode fibres for imaging purposes has been widely studied in the past years, especially with bio-medical applications in mind [2, 3] .

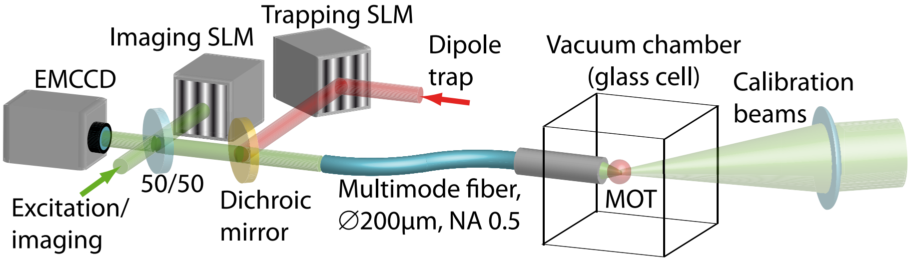

Figure 1. Trapping and imaging experimental setup.

I will present our work in progress, which aims at transferring this technique to the field of cold atoms. We will collect light from the atoms for imaging, and send light towards the atoms for trapping, all with a NA of 0.5. Inherent in this approach is a correction of optical aberrations, meaning that the spot size will attain the theoretical diffraction limit given by the NA ($\lesssim 1\mu m$).

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Quantum Processing, Algorithm, & Computing (QPAC)

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(Dated: October 9, 2017)

Belonging to theQuantum Hamiltonian Computing (QHC) branch of quantum control [1, 2], atomic-scale Boolean logic gates (LGs) with two inputs - one output (OR, NOR, AND, NAND, XOR, NXOR) and - two outputs (half-adder circuit) were designed on a Si(100)-(2 1)?H surface following the experimental realization of a QHC NOR gate [3] and the formal design of an half-adder with 6 quantum states in the calculating block [4]. The logical inputs are determined by two nearest neighbour crossing surface Si dangling bonds, which can be, for example, activated by adding or extracting two hydrogen atoms per input. QHC circuit design rules together with semi-empirical full valence K-ESQC transport calculations were used to determine the output current intensity of the designed LGs when interconnected to the metallic nano-pads by surface atomic-scale wires. We represent the process also for the measurements of the Rabi-Heisenberg oscillation of the our designed calculating block explaining the quantum to classical information conversion [5]. Our calculations demonstrate that the proposed devices can reach a ?0? to ?1? logical output ratio up to 10 000 for a running current in the 0.2 μA range for 50 mV to 150 mV bias voltage around the nano-pads Fermi level. We also show that the minimum number of quantum state to have a functioning Boolean half-adder is 4 states.

Keywords: Quantum Computing, Quantum Hamiltonian Computing, Quantum Boolean Logic gates, Quantum Performances.

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Continuous Variable Sampling from Photon-Added or Photon-Subtracted Squeezed States

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In the recent years we have witnessed an increasing interest in quantum circuits that define sub-universal models of quantum computation [1–5]. These models lie somewhere in-between classical and universal quantum computing, in the sense that, although not possessing the full computational power of a universal quantum computer, they allow for the outperformance of classical computational capabilities with respect to specific problems. Beyond their conceptual relevance, the reason for this interest is that these models require less experimental resources than universal quantum computers do. Therefore, they may enable experimental demonstration of *quantum advantage*, i.e. the predicted speed-up of quantum devices over classical ones for some computational tasks.

These models are often associated with sampling problems for which the task is to draw random numbers according to a specific probability distribution. Some of these probability distributions are likely to be hard to sample for classical computers, assuming widely accepted conjectures in computer science, for example with the celebrated Boson Sampling [1].

In parallel, Continuous-Variable (CV) systems are being recognized as a promising alternative to the use of qubits, as they allow for the deterministic generation of unprecedented large quantum states, of up to one-million elementary systems [6, 7], and also offer detection techniques, such as homodyne detection, with high efficiency and reliability.

We introduce a new family of quantum circuits in continuous variables and we address the corresponding sampling problem, that we call CVS [8]. We show that, relying on the widely accepted conjecture that the polynomial hierarchy of complexity classes does not collapse, their output probability distribution cannot be efficiently simulated by a classical computer. These circuits are composed of input photon-subtracted (or photon-added) squeezed states, passive linear optics evolution, and eight-port homodyne detection. We address the proof of hardness for the exact probability distribution of these quantum circuits by exploiting mappings onto different architectures of sub-universal quantum computers. We obtain both a worst-case and an average-case hardness result in the case of exact sampling. Hardness of Boson Sampling with eight-port homodyne detection is obtained as the zero squeezing limit of our model.

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Single Pass Squeezing and Spatio-Temporal Modes

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A multimode squeezed state of light can be used as a quantum network in order to accomplish measurement based quantum computing[1] using a continuous variable (CV) approach[2]. Our group has already demonstrated the generation of such quantum state using a synchronously pumped optical parametric oscillator (SPOPO)[3]. Here we characterize a new quantum source able to produce a multimode squeezed state of light in a single pass configuration. This source has highly promising applications in cluster-state preparation for CV quantum computation.

The source is based on a non-collinear type I parametric downconversion (PDC) process pumped by a frequency comb. Each pair of pulses produced by this source is predicted to be a quantum state with multipartite entanglement in the frequency domain because of the non-collinear configuration. Furthermore, there is a mode basis that diagonalize the interaction Hamiltonian in which each mode is found to be independently squeezed along the phase or the amplitude quadrature.

Since the squeezing is obtained in a single-pass configuration, the spatial mode of the squeezed light is not determined by a cavity, as in usual OPOs. For this reason we performed a complete theoretical analysis of the PDC process when the pump is a frequency comb. Our analysis shows that the output state of light is highly multimode and that spatial and temporal modes cannot be treated separately. Following the theoretical approach presented in [4] we are able to show the three-dimensional spatio-temporal shape of the eigenmodes of the non-linear interaction that result to be squeezed in the amplitude or phase quadrature.

Experimentally this source is realized using a femtosecond oscillator which produces a Fourier Transform limited frequency comb centered around 795 nm with a full-width-half-maximum (FWHM) of 40 nm ; these pulses are frequency doubled on a 1 mm BBO crystal in order to set the frequency of the pump beam for the downconversion. All the teeth of the 2 nm 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 2.8 mm 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.

A remarkable advantage of the non-collinear process is the presence of two separated beams that can be used to entangle the eigenmodes also 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. The geometrical structure of the cluster state in the time domain corresponds to a dual rail CV cluster state where the squeezed qumodes exhibit entanglement in time as reported in[5].

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Autopsy of a quantum electrical current

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Electron quantum optics is an emerging branch of electronic transport aiming at generating, manipulating and characterizing elementary excitations of the electronic fluid, similarily to what is done in photon quantum optics [1].

The key question in electron quantum optics is to determine which single-electron and more generally many-electron wavefunctions are propagating within the conductor. This is encoded within the electronic coherences defined similarly to the Glauber correlation function of order n. In the electronic case, this quantity contains all information about the n-particle wavefunctions present in the electronic fluid. This raises the question of the best elementary electronic signals describing the electronic coherences for a periodically-driven electronic source [2].

In this work, we introduce the spectral decomposition of the electron and hole parts of the first-order coherence. From this we compute the elementary signals (or "atoms of signal" as introduced by M. Devoret [3]) describing a periodic source. Whenever interactions can be neglected, we can reconstruct the whole many-body state. We then define a many-body notion of entanglement spectrum giving a many-body criterion for pure electron or hole emission. Notably, it allows us to assess quality of single-electron sources and to obtain realistic wavefunctions emitted by these sources in the optimal regime. We also study the case of an experimental quantum electrical current, and fully describe it in terms of namely electron and hole wavefunctions and the coherence between them, conducting the autopsy of a quantum electrical current wavefunction by wavefunction. This work is a first step towards the development of quantum signal processing techniques in electron quantum optics.

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Solid-State based Multi-Photon Quantum Photonics

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Optical quantum technologies lie at the forefront of a forthcoming second quantum revolution, with advances in quantum photonics at the single-photon level enabling new technologies—from applications for secure quantum communication [1], to the realization of quantum simulation and quantum computation protocols [2]. The scaling of quantum photonics, however, has been long restrained by low efficiencies in current photon sources based on parametric scattering—limiting the complexity of the protocols being demonstrated. Quantum-dots in photonic structures [3, 4], on the other hand, have recently shown potential for scalable multi-photon generation, they can produce long streams of highly indistinguishable single-photons with large emission yields [5, 6], whose active temporal-to-spatial demultiplexing [7] enables multi-photon sources with generation rates orders of magnitude larger than current alternatives [8].

Here we report our advances in multi-photon manipulation with solid-state based photon sources. First, we report the implementation of a BOSONSAMPLING device operated with a bright demultiplexed source of three highly-pure single-photon Fock states from the emission of a deterministic quantum dot-micropillar system [9]. A high source brightness allows us to implement multi-photon sources markedly more efficient than their downconversion counterparts, completing the BOSONSAMPLING protocol faster than in previous implementations. Secondly, we implement efficient and active temporal-to-spatial photon demultiplexers, resonantly-enhanced electro-optic modulation allow us to drive our demultiplexers with low amplitude signals, and at timescales similar to photon-production. In combination with our resonantly pumped single-photon sources [4], these implementations anticipate efficient resonantly-addressed multi-photon manipulation for quantum optics and photonics.

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Spin detection of natural and artificial atoms in a CMOS devices

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Over the last fifty years, the CMOS (Complementary-Metal-Oxide-Semiconductor) electronics industry has been continuously scaling down transistors in size, to increase performance and reduce power consumption. Nowadays, the smallest transistors in industry can obtain features 5nm in size. As a result, those silicon structures tend to exhibit undesirable quantum effects for a classical transistor which appear to be new research opportunities for quantum information processing.

In particular, it is nowadays possible to trap a single electron spin in quantum dots, also called artificial atoms, or in natural atoms such as donors implanted in silicon. These structures combined with the intrinsic properties of the silicon lattice (low spin orbit and hyperfine interaction) make CMOS devices excellent candidates for scalable quantum architectures. We will show how we can detect a single spin in a CMOS device thanks to a single-shot charge detector. For this purpose, we will present two strategies : either the integration of a single electron transistor in the device [1] or the use of a reflectometry technique [2]. Finally, we will present a new mechanism of spin-dependent photoionization in silicon [3] that may offer great perspectives for single-spin detection and scalability of a CMOS based quantum architecture.

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Coherent spin manipulation in silicon quantum dots arrays

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Qubits can be made out of a large variety of material systems. However, when it comes to a crucial issue such as large-scale integration, the range of possible choices becomes much narrower. To this respect, solid-state qubits are in principle well positioned. A possible approach relies on semiconducting structure with elementary bit of quantum information encoded in an electron-spin degree of freedom [1, 2]. Furthermore, silicon devices have demonstrated quantum bit (qubit) characteristics which make them extremely promising for future quantum technologies (QTs). In particular, it has been shown in the past few years that an electron spin qubit defined in an isotopically purified ^{28}Si crystal exhibits exceptionally long coherence times, T_2, ranging between 30 ms to 0.5s [3, 4]. So, as for most potential QT platforms, the next key step is identifying ways to scale up control and interactions between qubits.

In the present project, we explore spin qubit based architecture in which single electrons are isolated in silicon quantum dots (QD), in collaboration with a state of the art microelectronic foundry (CEA-LETI). Based on recent achievement with single qubit system [5, 6], we will develop chain and arrays of QDs in order to perform basic quantum operations on multi-qubit system. An important effort will be dedicated to automatically tune the dot arrays in order to increase the number of dots under control. The demonstration of such operation on a fully CMOS compatible devices will open up strong perspective toward the realization of a large scale quantum computer.

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Golden codes, regular quantum codes from regular tessellations of hyperbolic 4-manifolds

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Quantum information is fragile. Quantum error correcting codes offer a promising solution to protecting quantum information. LDPC (low density parity check) stabilizer codes are of particular interest because they lead to efficient decoding algorithms. Three parameters summarise the properties of such a code. The number of physical qubits of the code is n. The number of logical qubits of the code is k : it gives the quantity of quantum information that the code can carry. The minimal distance of the code is d. It is proportional to the number of physical qubits that can be corrupted without loss of information.

Geometry offers an efficient way to construct LDPC stabilizer codes. From a tessellation and a dimension i, a code is constructed by identifying qubits with i-faces, and stabilizers with $(i-1)$-faces and $(i+1)$-faces of the tessellation. It is then possible to understand n, k and d geometrically. The number of physical qubits n is proportional to the volume of the tessellated manifold. The number of logical qubits k equals the i^{th} Betti number of the manifold. The minimal distance d is proportional to the minimum of the i^{th}-systole and the $(m-i)^{th}$-systole of the manifold, m being the dimension of the manifold. Such codes coming from geometry are called homological codes.

We present an improvement over a construction of Guth and Lubotzky [1] of a family of homological codes whose parameters satisfy the following asymptotic relations : k is linear in n and d grows at least like $n^{0.2}$. Such parameters are beyond the reach of tessellations of two-dimensional manifolds such as the toric code and other surface codes. Our construction exhibits the same excellent asymptotic relations as [1] and benefits from a regular local structure. More precisely a building block of our construction is the regular tessellation of hyperbolic 4-space by 4-cubes, i.e. the tessellation with Schläfli symbols {4,3,3,5}.

The regularity of the local structure is exploited to design explicit and efficient decoding algorithms.

[1] Larry Guth and Alexander Lubotzky. Quantum error correcting codes and 4-dimensional arithmetic hyperbolic manifolds. *Journal of Mathematical Physics*, 55(8) :082202, 2014.

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