9th Colloquium of the CNRS GDR № 3322 on Quantum Engineering, Foundations & Applications

Ingénierie Quantique, des aspects Fondamentaux aux Applications – IQFA

Université de Montpellier – Campus Triolet

November 14 - 16, 2018

Book of Abstracts

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]), Systems & Engineering Sciences (INSIS[3]), and Computer Sciences & their interactions (INS2I[4]), 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[5]) is two-fold: first, to establish a common base of knowledge, and second, to use this platform to emulate new knowledge.

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

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

IQFA is organized along the 4 newly identified thematics - ART[6] - 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] http://www.cnrs.fr/
[2] http://www.cnrs.fr/inp/
[3] http://www.cnrs.fr/insis/
[4] http://www.cnrs.fr/ins2i/
[5] French acronym for "Ingénierie Quantique, des aspects Fondamentaux aux Applications.
[6] In French: Axes de Réflexion Thématiques.

1.2 Scientific Committee of the GDR IQFA

Members:	Alexia Auffèves (CNRS, Uni. Grenoble Alpes), Patrice Bertet (CEA, Uni. Paris Saclay), Antoine Browaeys (CNRS, Inst. d'Optique Graduate School, Uni. Paris Saclay), Thierry Chanelière (CNRS, Uni. Grenoble Alpes), Eleni Diamanti (CNRS, Sorbonne Uni., Paris), Anaïs Dréau (CNRS, Uni. Montpellier), 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), Nicolas Treps (Secretary, ENS Paris, Sorbonne Uni., Paris),
Administration manager:	Nathalie Koulechoff (CNRS, Uni. Côte d'Azur).

2 IQFA's 9^{th} Colloquium – Scientific Information

2.1 Welcome !

IQFA's 9^{th} colloquium is mainly organized by the Laboratoire Charles Coulomb (L2C[7]) at the Univesrité de Montpellier(UM[8]).

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, as well as 2 invited talks;
- 17 contributed/invited talks on the current hot topics within the strategic thematics (ARTs) identified by the GDR IQFA (see online the ARTs[9] for more details);
- and 2 poster session gathering ∼40 posters, again within IQFA's strategic thematics (ARTs).

In total this year, **IQFA's Scientific Committee (see Sec. 1.2) has received 60 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.

Anaïs Dréau (President of the colloquium IQFA 9),
& **Sébastien Tanzilli** (IQFA's Director),

On behalf of IQFA's Scientific Committee.

[7] https://www.coulomb.univ-montp2.fr/
[8] https://www.umontpellier.fr
[9] http://gdriqfa.unice.fr/spip.php?rubrique2

2.2 Program of the colloquium

IQFA'9 - University of Montpellier

	Wednesday the 14th of November 2018	Thursday the 15th of November 2018	Friday the 16th of November 2018
08:30	**Welcome - A. Dréau & S. Tanzilli**		
09:00	***Tutorial* - QSIM - J. Bloch (CNRS, Univ. Paris Saclay, FR): *Polariton fluids in semiconductor lattices***	***Tutorial* - QPAC/QSIM - D. Poulin (Univ. Sherbrooke, CA): *Quantum algorithms for simulation of quantum systems***	***Tutorial* - FQA/QPAC - D. Horsman (Univ. Grenoble Alpes): *The Logic of Quantum Error Correction***
09:30			
10:00	QSIM - M. Bellec (CNRS, Univ. Côte d'Azur, FR): *Superfluidity of light in a bulk nonlinear crystal*	QPAC - A. Luongo (Univ. Paris Diderot, CNRS, FR): *Quantum algorithms for classification*	FQA/QPAC - J.D. Bancal (Univ. Basel, CH): *Certifying the building blocks of quantum computers from Bell's theorem*
10:30	Coffee break	Coffee break	Coffee break
11:00	***Tutorial* - FQA/QSIM - T. Giamarchi (Univ. Geneva, CH): *Cold atoms and condensed matter: a love story***	***Tutorial* - QPAC - C. Eichler (ETH Zurich, CH): *Quantum Information Processing with Superconducting Circuits***	***Invited Talk* - QCOM - O. Fawzi (ENS Lyon, CNRS, FR): *An algorithmic approach to quantum communication***
11:30			QCOM - A. Cavaillès (ENS, Sorbonne Univ., FR): *Optical Hybrid Entanglement of Light for Remote State Preparation and Q Steering*
12:00	QSIM - A. Olivo (INRIA, FR): *Investigating the optimality of ancilla-assisted linear optical Bell measurement*	QPAC - I. Jakobi (Univ. Stuttgart, DE): *Addressing of Nanoscale Spin Quantum Registers*	QCOM - M. Bozzio (CNRS, Sorbonne Univ., Télécom ParisTech, FR): *Implementation of practical unforgeable quantum money*
12:30	Lunch	Lunch	Lunch
14:00	***Invited Talk* - QMET - F. Schopfer (LNE, FR): *Advances in quantum electrical metrology***	***Tutorial* - QCOM - W. Tittel (TU Delft, NL): *Quantum Repeaters***	QMET/FQA - Q. Ficheux (ENS Lyon): *Dynamics of a qubit while simultaneously monitoring its relaxation and dephasing*
14:30	QMET - L. Toraille (CNRS, Univ. Paris Sud, FR): *Magnetic Imaging at High Pressure inside Diamond Anvil Cells using Ensembles of NV*		QMET/FQA - T. Delord (ENS, CNRS, Sorbonne Univ., FR): *Particles levitating in Paul traps for spin-mechanics*
15:00	QMET - A. Reigue (CNRS, Univ. Grenoble Alpes, FR): *Cavity nano-optomechanics in the ultra-strong coupling regime*	QCOM - A. Boaron (Univ. Geneva, CH): *Secure quantum key distribution over 421 km of optical fiber*	QMET - R. Richaud (ENS, Sorbonne Univ., FR): *Quantum sensing using circular Rydberg states*
15:30	Coffee break	Coffee break	Closing session - S. Tanzilli
16:00	QMET - S. Garcia (ETH Zurich, CH & Collège de France, FR): *Single-shot Non-destructive Detection of Ensembles of Rydberg Atoms with Microwave Cavity Transmission Measurements*	QCOM - F. Kaiser (Univ. Stuttgart, DE): *Spin-optical investigations on single vacancy centres in silicon carbide, a particularly robust system for quantum networking applications*	
16:30	QMET - R. Canon (CNRS, Univ. Côte d'Azur, FR): *High-accuracy measurement of refractive index difference in dual-core fibers*	QCOM - S. Wengerowsky (IQOQI, Vienna, AT): *Quantum Communications Network Based on Polarization Entanglement at Telecom Wavelength*	
17:00	Poster session 1	Poster session 2	
19:00		Banquet	

2.3 The University of Montpellier, the I-Site MUSE, the L2C, and their scientific environment

Created in 2015 through the merger of the University Montpellier 1 and the University Montpellier 2, **the University of Montpellier (UM)**[10] draws from the excellence and synergy of these two institutions. It is reminiscent of the multi-disciplinary approach taken by the first university established in Montpellier in 1289 as a secular and international university.
For eight centuries, renowned scholars and scientists, from Rabelais and Curie, to Renaudot, Chaptal and Grothendieck, have been shaping this open university. It is deeply embedded into the city's life and committed to the key challenges of its time.
Today, the University of Montpellier brings together an extensive community of knowledge, from science, technology, medicine and environmental sciences, to educational sciences, economics, management, law and political science. It is involved in a strategic global initiative aiming at making Montpellier one of the European capitals for Health and Agro-environment.

The "Montpellier University of Excellence" (MUSE[11]) project gathers the forces of 19 institutions towards a common ambition: create in Montpellier a thematic research-intensive university that will be internationally recognized for its impact in the fields of agriculture, environment, and health. For all its consortium members, this university strives to act as the academic partner they can establish strong ties with, and on which they can fully rely. In 2017, the MUSE project received the Initiative - Science - Innovation - Territories - Economy (I-Site) certification.

The Laboratoire Charles Coulomb (L2C[12]) is an Unité Mixte de Recherche (UMR 5221), associated with the University of Montpellier (UM) and the Centre National de la Recherche Scientifique (CNRS), through the "Institut de Physique" (primary) and the "Institut de Chimie" (secondary). The L2C gathers more than a hundred researchers in Physics, nearly 50 technical and administrative staff members, and about 80 other personnel (emeriti, PhD students, post-doctoral fellows, etc.). The L2C covers a wide range of fields, from the most mathematical theoretical Physics to Chemical Physics and Biophysics, with a solid background of theoretical and experimental research devoted to Condensed Matter and Nanosciences. The investigations performed at the L2C are often at the interface with Chemistry, Life Sciences and Electronics.

The L2C possesses an ensemble of high-level experimental techniques, in particular, a unique set of optical spectroscopy facilities. Mainly concerned with Basic Physics, the L2C is nevertheless at the center of numerous collaborations with industrial partners, and of applied research leading to the filing of several patents and to the creation of start-ups.

Within the context of supporting scientific research & colloquiums, the UM, the I-Site MUSE, and the L2C support and welcome IQFA*'s 9th colloquium in UM's Triolet Campus.*

3 IQFA's 9th Colloquium – Practical Information

3.1 Venue

The colloquium takes place on the campus Triolet at the Faculty of Sciences of the University of Monpellier. The exact address is Université de Montpellier, Campus Triolet, Place Eugène Bataillon, 34095 Montpellier Cedex 5. Note that a banderole, with IQFA'9 @ UM will be hanged at the pedestrian entrance of the campus, rue Truel, as depicted in Fig. 1.

All the tutorial and invited talks will be given in the "Amphitheater Dumontet" inside the building 7 of the campus. Moreover, the poster sessions will be held in the Hall next to the Amphitheater, in the same building.

3.2 Access to the Campus Triolet - Faculty of Sciences

The Faculty entrance is located close to the tramway stop station "Universités des Sciences et Lettres" of the Line 1 (the blue line). From there, leave the tramway and follow the street in front of you with a big red sculpture on a roundabout in the back (see Fig. 1). At the roundabout, cross the street

[10] https://www.umontpellier.fr/
[11] http://muse.edu.umontpellier.fr/en/muse-isite/
[12] https://www.coulomb.univ-montp2.fr/

on your right and follow the campus boarder until the pedestrian entrance of the campus in rue Truel. You can plan your itinerary on the TAM[13] website (French only, sorry).

You can join us on the campus Triolet of the Faculty of Sciences 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 - To join the Faculty of Sciences, you can take the airport shuttle to “Place de l’Europe” in Montpellier, then the tramway line 1, direction Mosson, until the station “Université des Sciences et Lettres”. Tickets combining the shuttle and the tramway can be purchased directly with the airport shuttle driver.
  From the station “Montpellier Saint Roch” - You can directly take the tramway line 1, direction Mosson, stop at “Université des Sciences et Lettres”.
  From the new station “Montpellier Sud de France” - You have first to take the bus to “Place de l’Europe” in Montpellier, then the tramway line 1, direction Mosson, stop at “Université des Sciences et Lettres”.
- *By car* - Leave the highway through the exit “Montpellier Est - Fréjorgues”. Take direction “Montpellier Centre” and follow it up to the indication “Castelnau-le-Lez - Pompignane”. At the large roundabout, do not take right (Castelnau Center) but in front, down the “Avenue de la Justice”. Follow this avenue to the “Rue du Truel” (6th road-light on the right). The Rue du Truel leads to the “Place Eugène Bataillon”. The entrance to the Science University is on the right.

Figure 1: Access map to the colloquium location in building 7 of the Campus Triolet of the Faculty of Science, from the tramway Line 1, stop “Universités des Sciences et Lettres”.

For more details on how to reach the place of the colloquium, please refer to its webpage at Practical information[14] or to the L2C[15] access map webpage.

[13]http://www.tam-voyages.com/
[14]https://iqfacolloq2018.sciencesconf.org/resource/acces
[15]https://www.coulomb.univ-montp2.fr/-Localisation-

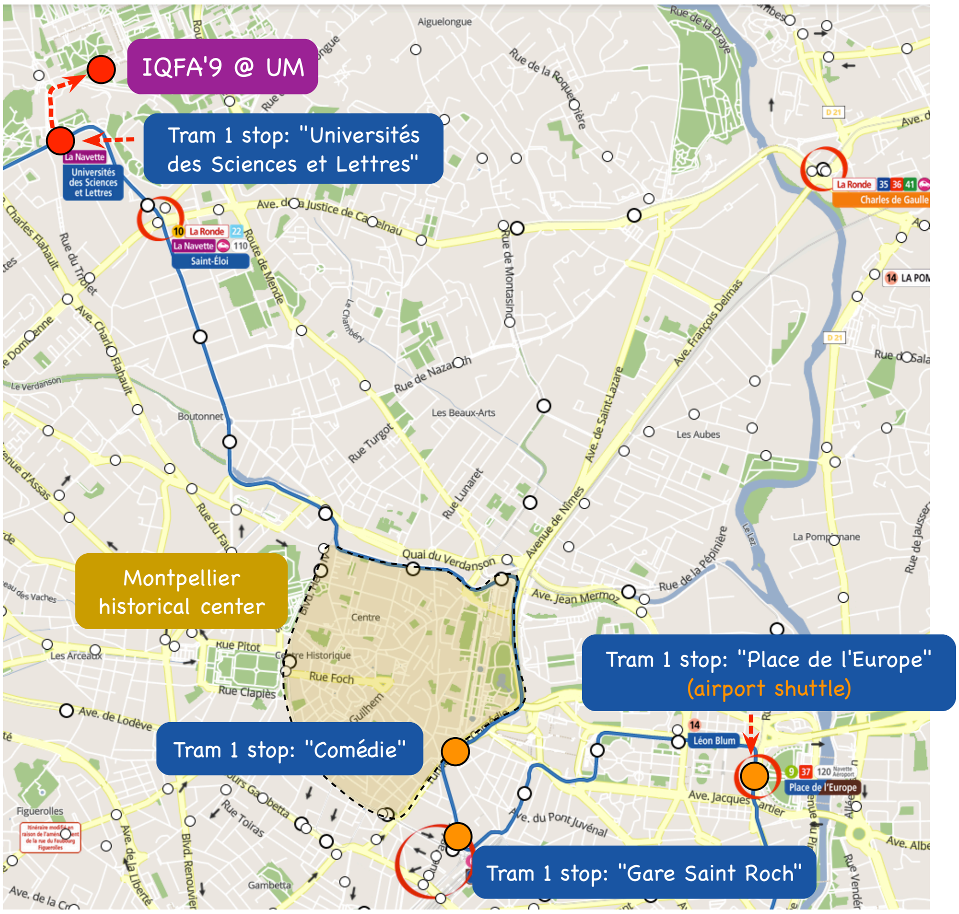

Figure 2: Map of the tramway TAM line 1 with all important stops, notably the stop "Universités des Sciences et Lettres" which is the closest to the place where IQFA'9 is organized.

3.3 Registration & badge

The participants' venue will be made available from Wednesday the 14^{th} of November at 8:00 am, in the Hall of the building 7, at the Campus Triolet of the Faculty of Sciences. Once the building reached and its entrance passed, you'll discover both the Hall and on your right the Amphitheater Dumontet, where the colloquium takes place.

3.4 Internet Connection

A Wi-Fi connection will be available inside the building, with dedicated login and password for each registered participant. Logins & passwords will be delivered on site.
Otherwise, the EDUROAM network will also be available for all participants who have already installed the necessary profile (from their respective university) on their computers, before they attend the colloquium.

3.5 Coffee breaks, lunches & buffet

During the colloquium, all coffee breaks and lunches will be taken on site on the 1st floor of the building, while exiting the Amphitheater Dumontet. Coffee breaks and lunches are free of charge for all registered participants. The banquet of the colloquium is organized on Thursday the 15^{th} 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 Laboratoire Charles Coulomb (L2C),
at the Université de Montpellier (UM),

and with the financial supports of: the CNRS, through the Institutes INP, INSIS, and INS2I,
the Université de Montpellier (UM),
the Montpellier University of Excellence (I-Site MUSE),
the Laboratoire Charles Coulomb (L2C),
and ID QUANTIQUE,
that are warmly acknowledged.

3.7 Local organization committee for this colloquium at the L2C - Uni. Montpellier

President: Anaïs Dréau,

Members: Isabelle Robert-Philip,
Vincent Jacques,
Guillaume Cassabois,
Christelle Eve (Admin),
Jean-Christophe Art (Admin),
& the NPQO team members;

With the remote help of (from the Nice Physics Institute): Sébastien Tanzilli,
Nathalie Koulechoff,
& Bernard Gay-Para.

4 Abstracts of the contributions

In the following, you can find, after the tutorial lectures, all the contributions given per ART.
In each ART, the abstracts that are tagged on the top with the mention "iqfacolloq2018 - Theater Dumontet - 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

Quantum Information Processing with Superconducting Circuits

Christopher Eichler[1]*
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The high level of control achievable over quantized degrees of freedom has turned superconducting circuits into one of today's most promising physical systems for quantum information processing. In this talk, I shall give an overview of recent advances in superconducting circuit technology and the use of intermediate-scale quantum devices for studying the concepts of quantum error correction and for exploring near-term applications. In particular, I will present our own progress in the design and fabrication of superconducting quantum processors [1], the engineering of cryogenic systems [2], and the coherent control and readout of superconducting qubits. We have developed an architecture that allows for fast, multiplexed dispersive readout and have demonstrated the simultaneous measurement of five qubits using a single readout channel [1, 3]. Our scheme features low readout crosstalk and enables the selective measurement of individual qubits without perturbing all others. This is expected to be useful in algorithms, in which subsets of qubits are measured while other qubits evolve coherently. Furthermore, by combining high fidelity qubit readout with controlled photon-qubit gates, we demonstrate the quantum non-demolition measurement of single itinerant microwave photons [4]. Such photon detectors in the microwave regime could e.g. be interesting to herald entanglement between remote qubits. Finally, I discuss nonlinear, parametrically tunable coupling schemes and their use in realizing circuit analogs of optomechanical systems [5], for studying novel quantum states of light in nonlinear resonators arrays [6] and for realizing two-qubit gates.

[1] J. Heinsoo, C. Kraglund Andersen, A. Remm, S. Krinner, T. Walter, Y. Salathe, S. Gasparinetti, J-C. Besse, A. Potocnik, A. Wallraff, and C. Eichler, Phys. Rev. Applied 10, 034040 (2018).

[2] S. Krinner, S. Storz, P. Kurpiers, P. Magnard, J. Heinsoo, R. Keller, J. Luetolf, C. Eichler, and A. Wallraff, arXiv :1806.07862.

[3] T. Walter, P. Kurpiers, S. Gasparinetti, P. Magnard, A. Potoćnik, Y. Salathe, M. Pechal, M. Mondal, M. Oppliger, C. Eichler, and A. Wallraff, Phys. Rev. Applied 7, 054020 (2017).

[4] J-C.. Besse, S. Gasparinetti, M. C. Collodo, T. Walter, P. Kurpiers, M. Pechal, C. Eichler, and A. Wallraff, Phys. Rev. X 8, 021003 (2018)

[5] C. Eichler and J. Petta, Phys. Rev. Lett 120, 227702 (2018)

[6] M. C. Collodo, A. Potoćnik, S. Gasparinetti, J. - C. Besse, M. Pechal, M. Sameti, M. J. Hartmann, A. Wallraff, and C. Eichler, arXiv :1808.00889 (2018)

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Polariton fluids in semiconductor lattices

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Semiconductor microcavities have recently appeared as a versatile platform for the study of quantum fluids of light. They enable confining both light and electronic excitations (excitons) in very small volumes. The resulting strong light-matter coupling gives rise to hybrid light-matter quasiparticles named cavity polaritons. Polaritons propagate like photons but strongly interact with their environment via their matter part : they are fluids of light and show fascinating properties such as superfluidity or nucleation of quantized vortices. Sculpting microcavities at the micron scale, we fabricate at C2N lattices of various geometries and use this photonic platform for the emulation of different Hamiltonians [1].
After a general introduction, I will illustrate the potential of this photonic platform describing a few recent experiments where we have emulated different Hamiltonians and imprinted on the photon field the properties of the Hamiltonian eigenstates.
1) Synthesizing an effective spin orbit coupling for polariton modes, we have realized a microlaser which lasing mode presents a finite orbital angular momentum. Time reversal symmetry is obtained by optically spin polarizing the polariton population so that the chirality of the lasing mode is optically controlled [2]. 2) A topological SSH chain of coupled micropillars is emulated using a 1D chain of coupled resonators : the band structure and edge states are directly accessible in the photon emission. When lasing is triggered in the topological edge states, the lasing mode present topological robustness to disorder and imperfections[3]. 3) Finally I will describe how Dirac physics can be uniquely investigated in honeycomb lattices of coupled semiconductor microcavities. In addition to the usual Dirac cones and edge states[4], these photonic structures present additional interesting bands and edge states emerging from higher orbitals [5]. Manipulation of these bands when emulating strain reveal the appearance of exotic Dirac cones emerging from a flat band[6].
These works open a lot of perspectives in particular making use of the polariton-polariton interaction to explore many body effects in a driven dissipative context.

[1] "Exciton-polaritons in lattices : A non-linear photonic simulator", A. Amo and J. Bloch, Dossier Polariton Physics, Comptes Rendus de l'Académie des Sciences 8, 805 (2016) (Elsevier)
[2] "Optically controlling the emission chirality of microlasers", N. Carlon Zambon, P. St-Jean, M. Miliceviv, A. Lemaître, A. Harouri, L. LeGratiet, O. Bleu, D. Solnyshkov, G. Malpuech, I. Sagnes, S. Ravets, A. Amo, J. Bloch, arXiv :1806.04590
[3] "Lasing in topological edge states of a 1D lattice", P. St-Jean, V. Goblot, E. Galopin, A. Lemaître, T. Ozawa, L. Le Gratiet, I. Sagnes, J. Bloch, and A. Amo, Nature Photonics 11, 651 (2017)
[4] "Direct observation of Dirac cones and a flatband in a honeycomb lattice for polaritons", T. Jacqmin, I. Carusotto, I. Sagnes, M. Abbarchi, D. Solnyshkov, G. Malpuech, E. Galopin, A. Lemaître, J. Bloch, A. Amo, Physical Review Letters 112, 116402 (2014)
[5] "Orbital Edge States in a Photonic Honeycomb Lattice", M. Milicevic, T. Ozawa, G. Montambaux, I. Carusotto, E. Galopin, A. Lemaître, L. Le Gratiet, I. Sagnes, J. Bloch, and A. Amo, Physical Review Letters 118, 107403 (2017)
[6] "Tilted and type-III Dirac cones emerging from flat bands in photonic orbital graphene", M. Milicevic, G. Montambaux, T. Ozawa, I. Sagnes, A. Lemaître, L. Le Gratiet, A. Harouri, J. Bloch, A. Amo, arXiv :1807.08650

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Cold atoms and condensed matter : a love story

Thierry Giamarchi*

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In the recent years tremendous progress have been made in the preparation, trapping and cooling of atomic gases to abysmally low temperatures.

This has allowed to realize with an unprecedented level of control systems of many quantum particles interacting with each other. The nature of the particles, the lattice in which they move and even their interactions can be controlled at will. This has allowed to create in the laboratory systems that are close realizations of phenomena ranging from the ones found in solids, to neutron stars, such as superconductivity. Cold atomic gases can thus be used as quantum simulators, namely experiments that reproduce so perfectly a phenomenon or a given model, that measuring the experiment “solves” the model.

This has not only allowed to address some of the major questions that were present in quantum many body physics, but also opened new avenues to study phenomena hard to tackle previously, in particular concerning non-equilibrium physics, disorder or very large magnetic fields.

I will present in this talk some of the examples of this success story, as well as some of the concepts that emerged from this new field. I will also discuss how cold atomic gases and condensed matter started to go hand in hand in addressing some of the major issues of the field, as well as some of the challenges that put some spices in this otherwise idyllic love story.

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Quantum algorithms for simulation of quantum systems

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The simulation of quantum mechanical systems is one of the most prominent foreseen application of quantum computers. While analogue simulations are already being realized experimentally, this presentation will focus on digital simulations, which employ an error-corrected computer to realize simulations of arbitrary precision. I will review some of the challenges and opportunities of this field, and briefly describe some of the recent innovations.

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Quantum repeaters

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Despite many theoretical and experimental efforts since more than a decade, the building of a quantum repeater, allowing the efficient distribution of entangled photons over in principle arbitrarily long distances and through channels of arbitrarily high loss, remains an outstanding challenge. After introducing the general goal of a quantum repeater and providing some insights into the underpinning principle, I will discuss a specific solution [1] that employs sources of entangled photons pairs, quantum memories for light based on cryogenically-cooled rare-earth crystals, and Bell-state measurements.

[1] N. Sinclair, E. Saglamyurek, H. Mallahzadeh, J.A. Slater, M. George, R. Ricken, M.P. Hedges, D. Oblak, C. Simon, W. Sohler, and W. Tittel, Phys. Rev. Lett. **113**, 053603 (2014).

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The Logic of Quantum Error Correction

Dominic Horsman[1*]
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Quantum error correction is a key element in the development of a programmable quantum computer that performs significantly better than existing classical technologies. Once devices are capable of operating at a given degree of precision (known as the error correction threshold), active error correction techniques enable computations to be performed to arbitrary precision.

The overheads required for full-scale quantum error correction are known but often not fully appreciated. Several thousand physical qubits will be required per logical qubit in an algorithm. On top of that, dynamic and networked connectivity means that potentially tens of thousands of operations per error correction cycle will be required. All this puts severe strain on the current model for representing quantum computing. Circuit diagrams describe individual physical qubit gates rather than structures at scale, and have no status as a formal language (so cannot be used for example within a compiler chain).

In this talk, I will introduce the basic operations of the quantum surface code, and show how the diagrammatic ZX calculus of observables enables us to represent both physical and logical operations in encoded and unencoded spaces. I will demonstrate its functionality as a formal language, including diagram re-writing that can be automated.

As well as the standard calculus, I will also introduce the scalable calculus of observables. This is capable of representing arbitrary structures, and is not limited by qubit number. This calculus enables us to represent broad classes of stabilizer codes (including the surface code) and perform diagrammatic calculations. I will end by looking at the challenges that remain in finding appropriate logical and design tools for deployable quantum error correction.

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Fundamental Quantum Aspects (FQA)

Quantum microwaves with a DC-biased Josephson junction

Ambroise Peugeot[1], Chloé Rolland[1], Olivier Parlavecchio[1], Marc Westig[1], Iouri Moukharski[1], Björn Kubala[2], Carles Altimiras[1], Max Hofheinz[1], Pascal Simon[3], Patrice Roche[1], Philippe Joyez[1], Patrice Bertet[1], Denis Vion[1], Joachim Ankerhold[2], Daniel Esteve[1] and Fabien Portier[1]*

[1]*SPEC, CEA, CNRS, Université Paris-Saclay, CEA-Saclay, 91191 Gif-sur-Yvette Cedex, France*
[2]*Institute for complex Quantum Systems, University of Ulm, 89068 Ulm, Germany*
[3]*Laboratoire de Physique des Solides, Université Paris-Saclay, 91405 Orsay, France*

Tunneling of a Cooper pair through a dc-biased Josephson junction is possible only if collective excitations (photons) are produced in the rest of the circuit to conserve the energy. The probability of tunneling and photon creation, well described by the theory of dynamical Coulomb blockade, increases with the coupling strength between the tunneling charge and the circuit mode, which scales as the mode impedance. Using very simple circuits with only one or two high impedance series resonators, we first show the equality between Cooper pair tunneling rate and photon production rate [1]. Then we demonstrate a blockade regime for which the presence of a single photon blocks the next tunneling event and the creation of a second photon [2]. Finally, using two resonators with different frequencies, we demonstrate photon pair production [3], two-mode squeezing, and entanglement between the two modes leaking out of the resonators.

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Quantum advantage from dynamic contextuality.

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Overview : Contextuality is a key non-classical phenomenon exhibited by quantum systems, which was first considered by Bell and by Kochen and Specker. It has been the subject of renewed interest recently, as a range of results have established it to be the essential ingredient for enabling quantum advantages over classical implementations. These results concern Bell-Kochen-Specker (BKS) contextuality, a feature which can arise in the outcome statistics of measurements performed jointly in contexts. It can only be present in quantum systems with Hilbert space dimension at least three, and thus in particular it cannot be present in single qubit systems. Nevertheless, single qubit resources have also been found to be sufficient to enable quantum advantage. This raises the important question of which precise non-classical feature could be at play if not contextuality of the BKS kind.

Here we introduce a notion of contextuality for transformations performed in sequential contexts that we call dynamic contextuality. Our transformation contextuality is inequivalent to the notion introduced by Spekkens (see appendix of [1]). The present kind of contextuality will be shown to be the crucial feature enabling quantum advantage in a specific single qubit example of [3], provided the computational assumptions are reflected in any underlying ontology. The setting for that example is a transformation-based model of quantum computing, which we call here $l2$-TBQC, that was shown to be useful in achieving secure delegated computing. In the model, a classical control computer, whose power is limited to $\mathrm{mod}2$-linear computation, may interact with a quantum resource, by which its computational power may be enhanced. $l2$-TBQC turns out to be a useful testing ground for identifying the roots of quantum advantage. In this setting we will see that dynamic contextuality is necessary to enable quantum advantage over classical resources for the task of probabilistically computing any non-linear function, under appropriate ontological assumptions. Moreover, the degree of contextuality can be related to the probability of success, and in particular strong (i.e. maximal) contextuality is necessary for deterministic computation of any non-linear function.

In particular, as shown in [2], one can implement a protocol with minimal quantum communication - a single qubit - where the client promotes efficiently and securely its computational power to full classical computation. The multi-qubit counterpart relies on the traditional notion of contextuality and cannot meet these security requirements. The question of implementing non-linear functions that require adaptivity - from a classical point of view - has also been addressed and we propose different solutions.

Our results set the stage for future consideration of where else dynamic contextuality arises and how it relates to quantum advantages, speedups and the onset of universality in other settings (e.g. shallow circuits).

Main result : This culminates in our main result (further details and proof of which can be found in [1]). If an $l2$-TBQC probabilistically computes a function $f : (\mathbb{Z}_2)^r \to \mathbb{Z}_2$ with an average failure probability $\bar{\varepsilon}$ over all 2^r possible inputs, then

$$\bar{\varepsilon} \geq \mathsf{NCF}(e)\,\tilde{\nu}(f)\,,$$

where e is the resource empirical model. The empirical model e is a description of the empirical behaviour of the resource part of the $l2$-TBQC. The quantity $\mathsf{NCF}(e) \in [0,1]$ is a measure quantifying the degree to which the empirical model can be said to exhibit classical behaviour. Finally, $\tilde{\nu}(f) \in [0,1]$ is a measure of the non-linearity of function f, given by the minimum over all linear functions $g : (\mathbb{Z}_2)^r \to \mathbb{Z}_2$ of the Hamming distance between $f(\mathbf{i})$ and $g(\mathbf{i})$ averaged over all inputs $\mathbf{i} \in (\mathbb{Z}_2)^r$.

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Parametric instabilities in a 2D periodically-driven bosonic system: Beyond the weakly-interacting regime

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Engineering new, complex states of matter is an important area, impacting both our fundamental understanding and practical applications. One promising approach is to rapidly oscillate some parameters, so-called Floquet engineering. Under the right conditions, new properties can emerge that are not present in the static system. Such oscillations carry energy which can be absorbed, and one might generally expect heating. Energy absorption in interacting many-body systems, unlike in non-interacting systems, is an interesting open question with practical implications for quantum engineering. Recently, theoretical work [1] predicted that interacting Floquet systems can be inherently unstable, which would be visible as fast heating. We experimentally confirm this prediction [2]. We also report an unexpected additional heating, pointing to effects beyond current theories.

We study a Bose-Einstein condensate in a periodically shaken optical lattice, where the position of the lattice is the oscillating parameter. In the presence of the drive, Bogoliubov modes spontaneously grow and deplete the condensate, and we experimentally investigate the effects of these parametric instabilities on the short-time heating process of bosons in 2D optical lattices with a continuous transverse (tube) degree of freedom. We analyze three types of periodic drives: (i) linear along the x-lattice direction only, (ii) linear along the lattice diagonal, and (iii) circular in the lattice plane. In all cases, we demonstrate that the BEC decay is dominated by the emergence of unstable Bogoliubov modes, rather than scattering in higher Floquet bands, in agreement with recent theoretical predictions [1–3]. The observed BEC depletion rates are much higher when shaking both along x and y directions, as opposed to only x or only y. We also report an explosion of the heating rates at large drive amplitudes, and suggest a phenomenological description beyond Bogoliubov theory. In this strongly-coupled regime, circular drives heat faster than diagonal drives, which illustrates the non-trivial dependence of the heating on the choice of drive.

Future work will investigate the unexpected super-instability to better inform our theoretical understanding. Another research path is the possibility of suppressing the instability at high shake frequency when confining the system to limit the density of states.

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The Ou-Mandel experiment revisited: producing delocalized Schrödinger cats by local frequency-time filtering

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In the OM experiment [1], spatial beating was observed in a photon coincidence measurement which comes from the interference of two paths containing two frequency filters at different centered frequencies. We propose a new interpretation of the fringe pattern observed in this experiment: a frequency-time cat state is post-selected out of the state produced by a SPDC source, and this structure can be revealed using the generalization of the HOM experiment proposed in [2]. Hence, we present a new way of engineering and detecting time-frequency entanglement by post-selection using frequency-time filtering. Finally, we propose a tomography for the post-selected state thanks to this scheme.

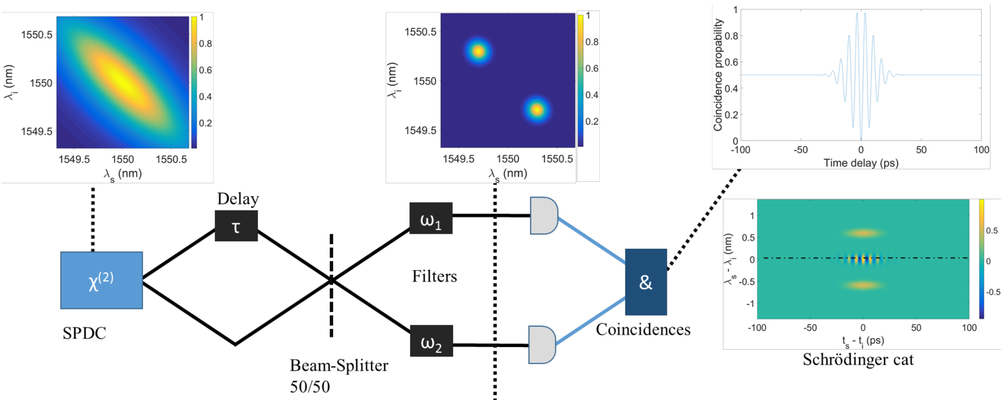

Figure 1: Anti-correlated photons (on the left) created by SPDC cross time shifter, beam-splitter and two Gaussian frequency filters. (On the right) The measure of coincidence shows a fringe pattern and the interference part of the Wigner function $W_{-}(\tau = t_s - t_i, 0)$ of a frequency-time cat state is matching which means that post-selection thanks to frequency filtering permits to select only the cat part from the wave function generated by SPDC process.

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Une expérience cruciale pour tester la faisabilité de l'ordinateur quantique et l'interprétation de la mécanique quantique

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"***Et si la théorie quantique finissait par être réfutée, de sorte que des barrières plus fondamentales empêchent la construction d'ordinateurs quantiques ?***" s'interroge David Deutsch en 2016 [1]. Montrer que de telles barrières existent (non dans la réfutation de la théorie, mais dans sa complétude) et en proposer une validation est l'objectif de cette communication.

En information quantique [2], le qubit n'est pas représenté par un **spineur complet** en espace et en temps comme le spineur en x et z ci-dessous :

$$\Psi^0(x,z) = (2\pi\sigma_0^2)^{-\frac{1}{2}} e^{-\frac{(z^2+x^2)}{4\sigma_0^2}} \begin{pmatrix} \cos\frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin\frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{pmatrix}$$

mais par **un spineur tronqué sans extension spatiale** $\Psi^0 = \left(\begin{smallmatrix} \cos\frac{\theta_0}{2} e^{-i\frac{\varphi_0}{2}} \\ \sin\frac{\theta_0}{2} e^{i\frac{\varphi_0}{2}} \end{smallmatrix}\right)$. Cette troncature est à la base d'une première interrogation sur la fiabilité de l'ordinateur quantique. En effet, les démonstrations expliquant le gain des algorithmes quantiques de Deutsch, Glover et Shor reposent sur une factorisation des calculs utilisant les qubits intriqués, cf. [2]. Ces factorisations sont exactes pour des spineurs sans extension spatiale, mais seulement approchées pour des spineurs avec extension spatiale : erreur habituellement attribuée à l'environnement et que l'on essaye de corriger par des codes détecteurs d'erreurs. La seconde interrogation est plus fondamentale car elle lie la faisabilité de l'ordinateur quantique à **la complétude ou non de la mécanique quantique** et donc à son interprétation. Dans l'interprétation de De Broglie-Bohm, le qubit statistique existe, mais non le qubit individuel. Pour représenter les deux états du spin,il faut ajouter à la fonction d'onde (qubit statistique) au moins deux particules comme en mécanique classique. Or expérimentalement, les seuls ordinateurs quantiques qui réalisent des opérations effectives sont des ordinateurs avec des qubits mésoscopiques (statistiques) : ainsi chaque qubit est représenté par 100 millions de molécules avec la technique RMN et un milliard d'atomes d'aluminium avec la jonction Josephson. Nous avons montré [3] que l'interprétation de Broglie-Bohm permet d'expliquer la décroissance d'un facteur 2 pour chaque qubit individuel (2 qubits en 1987, 4 en 1999, 7 en 2001) des ordinateurs basés sur la technique RMN développée par Chuang *et al*. La encore, c'est l'extension spatiale qui permet de prendre en compte la position initiale de la particule et de montrer que l'évolution du système quantique (fonction d'onde + position) va être déterministe. [4] Ainsi, la validité de l'interprétation DBB, qui n'était qu'un problème théorique, devient lié à la faisabilité de l'ordinateur quantique.

Dans la suite de la communication, nous présentons **une expérience qui permet de tester l'interprétation DBB** par rapport aux interprétations où la mécanique quantique est complète. C'est une expérience de fentes de Young asymétrique avec des fullerénes ou des atomes de Rydberg : une grande fente par laquelle l'atome peut passer et une grille de petites fentes par lesquelles l'atome ne peut pas passer.

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Multipartite causally (non)separable quantum processes

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Our conventional view of causality is that events are ordered according to some global time parameter, with past events influencing future events, but not vice versa. It has been found that, in quantum theory, the situation is not so clear and the causal order between events can be indefinite (e.g., in a superposition of different orders). The investigation of such quantum causal relations is a new research program that is not only of great importance for the foundations of physics, but also of crucial interest for quantum information theory, since new resources for quantum information processing become available when the assumption of a definite causal structure is relaxed.

A particular model used to investigate quantum causal relations is the process matrix formalism [1]. In this framework, quantum events are described as local operations that are subject to the laws of quantum theory, but that are not assumed to be embedded into a global causal order a priori. The physical resource relating the local operations is described by a *process matrix*, which, broadly speaking, is a generalisation of a multipartite density matrix allowing also for the description of signalling scenarios, such as quantum channels, and more general possibilities. Some process matrices are compatible with a definite background causal structure between the operations—these are called causally separable. However, there exist also causally nonseparable process matrices, for which the causal order between the parties is indefinite.

In the bipartite case, the concept of causal (non)separability is clearly defined and well understood [1–3]. Its generalization to the multipartite case, however, involves several complications. In particular, for more than two parties, dynamical causal orders need to be taken into account, and the possibility to extend process matrices with ancillary quantum states has nontrivial implications for the definition of causal (non)separability [4]. In recent works, several definitions for multipartite causal (non)separability have been proposed [2, 4]. In this submission we present our recent work [5], in which we compare them and show that they are not equivalent. We then propose our own definition of causal (non)separability for the general multipartite case, which we argue is a more natural definition for general multipartite scenarios. Although a priori slightly different, it turns out to be equivalent to the concept of "extensible causal (non)separability" introduced before [4], which does not allow for the activation of causal indefiniteness by shared entanglement.

We then study how causally separable process matrices can be characterized in terms of simple conditions, and we derive a sufficient and a necessary condition for multipartite process matrices to be causally separable. This allows us to generalize the technique of *witnesses of causal nonseparability* [2, 3], a method similar in concept to entanglement witnesses with which one can determine the causal (non)separability of process matrices via semidefinite programming.

A natural question is whether causally separable process matrices correspond to physically realizable situations [4]. We show that the process matrices satisfying our sufficient conditions for causal separability have an operational interpretation as *quantum circuits with classical control*, where one has probabilistic operations with several outcomes between the parties, permitting a dynamical control of the causal order [6]. We also characterize a class of processes corresponding to *quantum circuits with quantum control*, which are causally nonseparable in general and which can be realized by a superposition of orders with a quantum system controlling the order of the operations.

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Non-dipolar light-matter interactions in quantum technologies

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Until very recently, two-photon interaction (TPI) processes have been considered only as arising from second- or higher-order effects in driven systems, and so limited to extremely small coupling strengths. However, a variety of novel physical phenomena emerges in the strong and ultrastrong coupling regimes, where such coupling values become comparable to the dissipation rates and to the system bare frequencies, respectively. In this contribution, we present different schemes that make it possible to reach the ultrastrong coupling regime of TPI with atomic and solid-state devices. Then, we analyze novel fundamental quantum-optical phenomena that could be observed in such systems, and we show how they could overcome fundamental limitations of current quantum technologies.

The most striking feature of the ultrastrong coupling regime of TPI models is the collapse [1] of the system discrete spectrum into a continuous energy band. Furthermore, in the many-body limit a rich interplay emerges between this spectral collapse and the superradiant phase transition [2]. These theoretical results prompted various efforts to design implementations of TPI models in different quantum platforms such as trapped ions [3] and cold atoms [4], using quantum-simulation schemes. However, the implementation of a genuine TPI requires an interaction more complex than dipolar.

We have recently shown that, in the context of circuit-QED, a nondipolar interaction can be implemented between a superconducting flux qubit and a quantum microwave resonator [5]. We have shown theoretically that an improved version of this scheme makes it possible to realize a genuine non-dipolar interaction in the ultrastrong coupling regime [6]. By means of an input-output analysis, we have unveiled high-order quantum nonlinearities that can be applied to implement two-qubit gates on qubits encoded in propagating photons.

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Work extraction exploiting thermalization with a single bath

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Here we study a physical implementation of the tools provided by the thermodynamic resource theory [1]. We first propose a protocol, named *thermalization protocol*, which exploits the collective thermalisation of a bipartite system to extract work from another system. The protocol is based on a recently proposed work definition, based on concepts from thermodynamic resource theory, not requiring measurements and involving the presence of a single bath [2]. A general description of the thermalization protocol is provided without specifying the characteristics of the bipartite system. We quantify both the extracted work and the ideal efficiency of the process also giving a maximum bound to the extracted work [3]. The strength of this protocol relies on its simplicity because it only requires processes of thermalization and the possibility of turning on and off an interaction Hamiltonian term without noticeably changing the state of the systems involved.

We then apply the protocol to the case when the bipartite system is governed by the Rabi Hamiltonian, which has been recently analytically solved [4, 5], while using a zero temperature bath. For very strong coupling, an extraction of work comparable with the typical energies of the subsystems and an efficiency greater than one half can be obtained [3]. Moreover, we found some hints of a possible connection between the entanglement between the two subsystems and the extracted work.

The thermalization protocol is not iterable and can lead to states whose utility is not evident by itself. To address this problem, we add finally a second protocol, named *transfer protocol*, which makes use of the final state obtained within the Rabi model after the thermalization protocol to charge an external system in a way such that the external system plays the role of a battery. Furthermore, this transfer protocol makes the whole protocol, composed by thermalization and the transfer protocols, iterable. All of this shows that the results obtained with the thermalization protocol could be useful as a part of a larger process, even when they are not useful standalone.

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Interaction of light and matter : tracking the gauge to get the expected result

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In a canonical formulation of the quantum-optics theory, the modeling of light-matter interaction starts with the knowledge of a hamiltonian. For the minimal-coupling hamiltonian, the light-matter interaction occurs through the coupling $\hat{\mathbf{p}}.\hat{\mathbf{A}}(\hat{\mathbf{r}},t)$ where $\hat{\mathbf{p}}$ is the charge momentum-operator and $\hat{\mathbf{A}}(\hat{\mathbf{r}},t)$ the potential vector. For a single electric charge q it reads :

$$\hat{H} = \frac{1}{2m}[\hat{\mathbf{p}} - q\hat{\mathbf{A}}(\hat{\mathbf{r}},t)]^2 + V(\hat{\mathbf{r}},t) + \int_{\mathbb{R}3} d\vec{x}[\frac{1}{2}\varepsilon_0\hat{\mathbf{E}}(\vec{x},t) + \frac{1}{2\mu_0}\hat{\mathbf{B}}(\vec{x},t)]$$

where $\hat{\mathbf{E}}(\vec{x},t)$, $\hat{\mathbf{B}}(\vec{x},t)$ are respectively the electric-field and the magnetic-field operators. $V(\hat{\mathbf{r}},t)$ is a general potential energy.

For neutral emitters, such as atoms or quantum dots, it might be more convenient to describe the coupling through their multipole moments. In a series of seminal papers, Power and Zienau [1] and Woolley[2] have exhibited a hamiltonian $\hat{H}_{pzw}$ for which the light-matter coupling arises through the coupling of the displacement field $\hat{\mathbf{D}}(\mathbf{x},t)$ with multipole moments included in the polarization field $\hat{\mathbf{P}}^{\perp}(\hat{\mathbf{r}},\mathbf{x},t)$.

$$\begin{aligned}\hat{H}_{pzw} = \frac{1}{2m}[\hat{\mathbf{p}} + q\hat{\mathbf{r}} \times \int_0^1 sds\hat{\mathbf{B}}(s\hat{\mathbf{r}},t)]^2 + V(\hat{\mathbf{r}},t) + \int_{\mathbb{R}^3} d^3x[\frac{1}{2\varepsilon_0}\hat{\mathbf{D}}^2(\mathbf{x},t) + \frac{1}{2\mu_0}\hat{\mathbf{B}}^{\mathbf{2}}(\mathbf{x},t)] \\ - \frac{1}{\varepsilon_0}\int_{\mathbb{R}^3} d^3x\hat{\mathbf{D}}(\mathbf{x},t).\hat{\mathbf{P}}^{\perp}(\hat{\mathbf{r}},\mathbf{x},t) + \frac{1}{2\varepsilon_0}\int_{\mathbb{R}^3} d^3x\hat{\mathbf{P}}^{\perp}(\hat{\mathbf{r}},\mathbf{x},t)^2\end{aligned}$$

The Power-Zienau-Woolley hamiltonian $\hat{H}_{pzw}$ is said to derive from the minimal-coupling hamiltonian with the help of a unitary transformation [1, 3] or a gauge transformation [2, 3]. Consequently, since its introduction in 1959, the Power-Zienau-Woolley hamiltonian has been widely used particularly for modeling quantum-optics phenomena in solid-state environments [4–6]. It is also taught in many textbooks [3, 4].

Whereas the foundations of the Power-Zienau-Woolley hamiltonian appears to be strongly established, we have recently shown [7] that it is not equivalent to the minimal-coupling hamiltonian. The Power-Zienau-Woolley hamiltonian is actually not correct because of a gauge-fixing error. We have shown that (i) it does not reproduce the expected equations of motion and (ii) it generates non-physical photons. Our study highlights the fundamental role of the gauge-fixing conditions and the quantization of constraint hamiltonians[8] that is, in our opinion, underestimated in most of the textbooks devote to quantum optics.

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Mode-dependent losses on multimode photon-subtracted states

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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, thus rendering them non-Gaussian [1]. Furthermore, photon subtraction is known to enhance the entanglement between a pair of modes.

However, the interesting non-Gaussian features of such states tend to be fragile due to the presence of decoherence. In quantum optical systems, losses are the most important source of such detrimental effects. In this contribution, we focus on the interplay between mode-selective photon subtraction and mode-dependent losses. We use an open system model [2] to describe the action of a loss-channel Λ on a photon subtracted state ρ_- that is obtained by subtracting n photons in modes $g_1, \dots, g_n$ from a state ρ :

$$\rho_- = \frac{a(g_1)\dots a(g_n)\rho a^\dagger(g_n)\dots a^\dagger(g_1)}{\mathrm{tr}[a^\dagger(g_n)\dots a^\dagger(g_1)a(g_1)\dots a(g_n)\rho]}.$$

The main result is that the action of the loss channel Λ on the state ρ_- always results in

$$\Lambda(\rho_-) = \frac{a(\tilde{g}_1)\dots a(\tilde{g}_n)\Lambda(\rho) a^\dagger(\tilde{g}_n)\dots a^\dagger(\tilde{g}_1)}{\mathrm{tr}[a^\dagger(\tilde{g}_n)\dots a^\dagger(\tilde{g}_1)a(\tilde{g}_1)\dots a(\tilde{g}_n)\Lambda(\rho)]},$$

where $\Lambda(\rho)$ describes the action of the loss-channel on the state ρ. This means that losses transform an n-photon subtracted state into another (less pure) n-photon subtracted state. Note that in the state $\Lambda(\rho_-)$ the photons are subtracted in a different set of modes $\tilde{g}_1, \dots, \tilde{g}_n$. Hence, mode-dependent losses and photon-subtraction do not necessarily commute, even though this is the case in single-mode systems.

To highlight the impact of this result on quantum systems that are relevant for quantum information processing, we apply our result to photon-subtracted graph states [3] as shown in Figure 1.

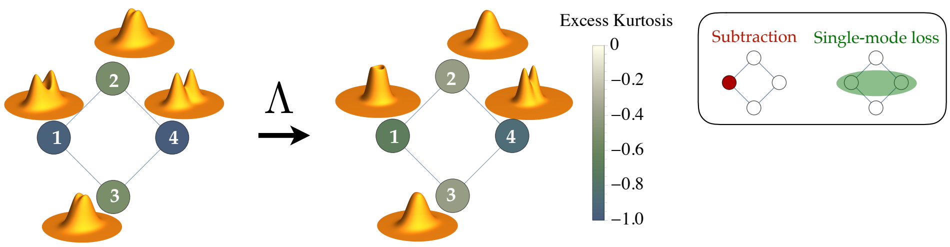

FIGURE 1. Action of a loss-channel on a photon-subtracted graph state [3].

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Quantifying measurement incompatibility of mutually unbiased bases

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Contrary to classical physics, different measurements in quantum mechanics can be incompatible, meaning that one cannot have access to their results simultaneously. Motivated by the question of finding the measurements that are "maximally incompatible", Schwinger and others [1–4] discussed the concept of mutually unbiased (bases) measurements. Formally, in a complex Hilbert space of dimension d, two orthonormal bases $\{|\varphi_a\rangle\}_{a=1,\dots,d}$ and $\{|\psi_b\rangle\}_{b=1,\dots,d}$ are called *mutually unbiased* if $|\langle\varphi_a|\psi_b\rangle| = 1/\sqrt{d}$ for all a and b. That is, if a system is prepared in any eigenstate of one of the bases, then performing a measurement in the other basis gives a uniformly random outcome. In the simplest case of qubits ($d = 2$), there are three mutually unbiased bases (MUB) which are given by the eigenstates of the three Pauli observables. In arbitrary dimension d, however, the construction of MUB is a difficult task. It is proven that $k \leqslant d + 1$ [5], and an explicit construction of complete sets of $k = d + 1$ MUB is only known when the dimension is a power of a prime, i.e., $d = p^r$ with p prime and r positive integer [4]. More generally, MUB play a central role in quantum information processing [6], and have been used in a wide range of applications such as quantum tomography [2, 4], uncertainty relations [3, 7, 8], quantum key distribution [9, 10], quantum error correction [11], as well as for witnessing entanglement [12–17] and more general forms of quantum correlations [18–20].

Given the general significance of MUB, it is important to characterize their properties. While MUB represent intuitively the most incompatible quantum measurements, the goal of our work is to precisely quantify the degree of incompatibility of arbitrary sets of MUB. As a measure of incompatibility we determine the noise robustness η^* [21–24], namely the minimal amount of white noise required to make a given set of k MUB in dimension d jointly measurable [25–31], i.e., compatible. More precisely, joint measurability of a set of POVMs amounts to the existence of a parent POVM from which the initial POVMs can be recovered by taking the marginals. Then the noise robustness of the POVMs $\{\{A_{a|x}\}_a\}_x$ can be expressed as a semidefinite program (SDP)

$$\begin{aligned}
\eta^* = \max_{\eta,\{\mathcal{G}_{\vec{j}}\}_{\vec{j}}} \quad & \eta \\
\text{s.t.} \quad & \sum_{\vec{j}} \delta_{j_x,a}\mathcal{G}_{\vec{j}} = \eta A_{a|x} + (1-\eta)\operatorname{tr} A_{a|x}\frac{\mathbb{1}}{d} \quad \forall a, x, \\
& \mathcal{G}_{\vec{j}} \geqslant 0 \quad \forall \vec{j}, \quad \eta \leqslant 1.
\end{aligned}$$

With arbitrary sets of POVMs, we use SDP duality theory to get a general bound on η^*. Interestingly, with MUB, this upper bound turns out to be tight in many cases, in particular for $k = d$ and $k = d+1$ as we show analytically when d is a prime power. Together with the proof we provide an explicit parent POVM reaching the optimum in these cases. For any set of MUB, we also construct a parent POVM relying only on the unbiasedness ; this gives us a lower bound on η^*, which is however rarely tight.

Moreover, these results highlight some interesting properties of MUB. In particular, we find that there exist operationally inequivalent sets of k MUB in dimension d, in the sense that they feature a different noise robustness. For instance, for triplets of MUB in dimension five, we can find two different values for η^* depending on the choice of the $k = 3$ MUB out of the $d + 1 = 6$ available. Based on numerical computations, lower bounds on the number of inequivalent sets are obtained for $k \leqslant 8$ and $d \leqslant 32$. In fact, we observe that this phenomenon becomes very frequent in high dimensions. Finally, our results also have direct implications for Einstein-Podolsky-Rosen steering [32]. Exploiting the strong connection existing between joint measurability and steering [33–35], we characterize the noise robustness of a broad class of entangled states in steering experiments. An interesting open question is then whether complete sets of $d + 1$ MUB are the most robust among all sets of $d + 1$ measurements, as conjectured in Ref. [36].

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Particles levitating in Paul traps for spin-mechanics

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Quantum control of macroscopic mechanical oscillators could enable tests of fundamental quantum theory and find applications in ultra-high precision measurements. It could also be used as a transducer in quantum information when coupled to other qbits [1]. To achieve these goals, there is a growing research effort for realizing high quality mechanical oscillators coupled to well-controlled quantum systems. Among the various experimental platforms under investigation, our team focuses on the possibility to couple the electronic spin of diamond NV centers to the motion of micro-particles levitating in Paul traps. On the one hand, particles levitated under vacuum can form isolated, high quality factor, mechanical oscillators. On the other hand, electronic spin of NV centers have excellent spin properties, with a full quantum control and a ms lifetime at room temperature and high fidelity read-out at cryogenic temperature. Spin-mechanics proposes to combine these two systems using the magnetic force or torque to couple an NV spin to the center of mass [2] or angular degree of freedom [3] of a mechanical oscillator.

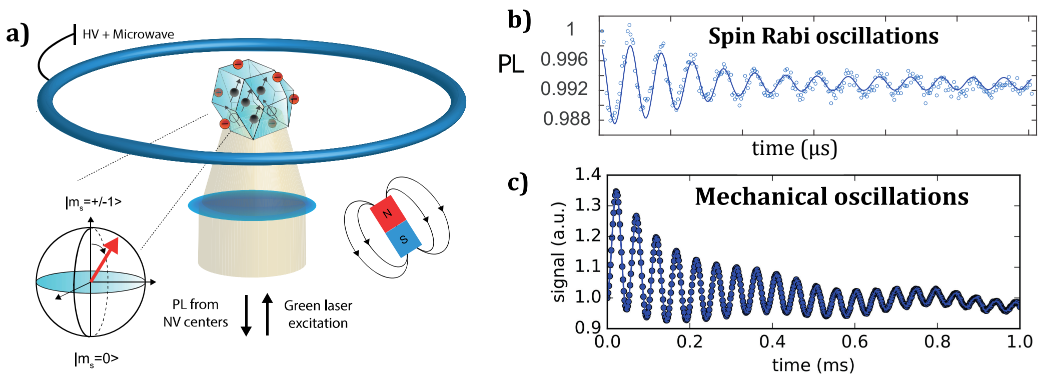

FIGURE 1: **a)** schematic of the setup. **b)** Spin Rabi oscillations from a levitated diamond. **c)** Relaxation of the angular motion of a magnetically stabilised iron particle following the excitation of the angular mode.

Recently, we demonstrated full coherent manipulation of the electronic spin of NV centers hosted in micron-size diamonds levitating in a Paul trap, realizing Ramsey interferences and spin echoes [4]. At present, the rotational confinement lies in the kHz range, which is too low to contemplate coupling the motion to the NV centers spins. The frequency and the Q-factor can however be boosted using levitating magnet, exploiting the large torque exerted by an external magnetic field. Magnetic coupling NV centers can then be realized with fixed NV centers sitting a few microns away. This new technique should enable reaching angular trapping frequency in the MHz range and bringing the spin-mechanical coupling within the resolved sidebands regime. In this work, we trapped micron-sized iron particles in a Paul trap and measured magnetic angular confinement exceeding 100 kHz under hundreds of Gauss. We also show that hybrid iron/diamond particles can be stably levitated and manipulate the NV spins in this system. Those results represent important steps toward the realization of spin-mechanical coupling using diamond NV centers magnetically coupled to levitated particles.

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Hong-Ou-Mandel effect under partial time reversal : a destructive interference effect in the amplification of light

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In the usual, predictive approach of quantum mechanics, one deals with the preparation of a quantum system, followed by its time evolution and ultimately its measurement. In the retrodictive approach of quantum mechanics, one postselects the instances where a particular measurement outcome was observed and considers the probability of the preparation variable conditionally on this measurement outcome. This can be interpreted as if the actually measured state had propagated backwards in time to the preparer. Here, we present an intermediate picture, called partial time reversal, where a composite system is propagated partly forwards and partly backwards in time. As a striking application, we focus on the simplest two-mode linear-optical component, namely a beam splitter, and show that it transforms into a two-mode squeezer under partial time reversal [1]. More generally, by building on the generating function of the matrix elements of Gaussian unitaries in Fock basis, we prove that the multiphoton transition probabilities obey simple recurrence equations. This method applies to Gaussian unitaries effecting both passive and active linear coupling between two bosonic modes [2]. The recurrence includes an interferometric suppression term which generalizes the Hong-Ou-Mandel effect to more than two indistinguishable photons impinging on a beam splitter of transmittance 1/2. It also exhibits an unsuspected 2-photon suppression effect in an optical parametric amplifier of gain 2 originating from the indistinguishability between the input and output photon pairs which we coin “timelike" indistinguishability (it is the partial time-reversed version of the usual “spacelike" indistinguishability which is at work in the Hong-Ou-Mandel effect).

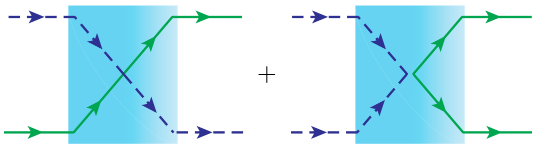

Figure 1. The optical parametric amplification of two single photons with gain 2 exhibits a destructive interference effect between both photons simply crossing the nonlinear medium, on the one hand, and the stimulated annihilation of the input photon pair accompanied with the stimulated emission of a distinct output pair, on the other hand. The “timelike" indistinguishability between the input and output photon pairs is responsible for the full suppression of the coincidence term (1,1) at the output.

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Tunable two-photon quantum interference of structured light

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Structured photons are nowadays an important resource in classical and quantum optics due to the richness of properties they show under propagation, focusing and in their interaction with matter. Vectorial modes of light in particular, a class of modes where the polarization varies across the beam profile, have already been used in several areas ranging from microscopy to quantum information. In quantum communication in particular, vectorial modes allow to encode qubits in rotational-invariant single photon states and thus, to overcome the need of a reference frame shared by the users [1–3]. One of the key ingredients needed to exploit the full potential of complex light in the quantum domain is the control of quantum interference, a crucial resource in fields like quantum communication, sensing and metrology. Here [4] we report a tunable Hong-Ou-Mandel interference between vectorial modes of light. We demonstrate how a properly designed spin-orbit device can be used to control quantum interference between vectorial modes of light by simply adjusting the device parameters and no need of interferometric setups. We believe our result can find applications in fundamental research and quantum technologies based on structured light by providing a new tool to control quantum interference in a compact, efficient and robust way.

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Quantum Communication & Cryptography (QCOM)

NanoBob : Quantum Communication using a CubeSat

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Quantum Key Distribution (QKD), i.e., the quantum secure exchange of secret keys between two parties usually identified as Alice and Bob, provides a level of communication security that cannot be obtained by classical cryptographic means, including those based on numerical algorithms. Quantum information can be coded into polarization states of single photons. In a properly designed experiment, an eavesdropping attempt by a third party ('Eve'), would necessarily lead to detectable errors, since the no-cloning theorem states that an arbitrary unknown quantum state cannot be copied perfectly. Given our ever-growing reliance on secure data communication, the intrinsic security of quantum communication largely outweighs the disadvantages of additional complexity and cost. QKD has already been demonstrated to be a practical way to distribute secret keys between two parties in a number of fiber networks. However, losses limit the maximum distance between two parties to a few hundreds of km, as the no-cloning theorem prohibits the use of standard optical amplifiers. Much progress has been made in the development of quantum repeaters, but this remains an extremely challenging solution. For the foreseeable future, satellites are the only option enabling to go beyond the limits posed by fiber absorption or Earth′s curvature for exchanging secret keys on a global scale. In this scheme, the satellite exchanges different secure keys with different optical ground stations (OGSs). Performing bitwise XOR operations on the keys, the different OGSs can be connected securely, with the satellite acting as a trusted node. NanoBob will demonstrate optical quantum communication between an OGS and a nanosatellite in an uplink configuration. Placing the entangled photon source ('Alice') on the ground, the space segment contains BobÕs detection system only : less power consuming, smaller and less complex, thus increased reliability. The space segment payload is also versatile : the receiver is compatible with multiple QKD protocols and other quantum physics experiments, such as investigating entanglement decoherence in a gravitational potential. To our knowledge, NanoBob, having completed its Mission Definition Review following CNES/ESA guidelines, is so far the most advanced European project focusing on the use of entangled photons and a CubeSat platform in Low Earth Orbit [1]. In order to extend the geographical reach of the OGSs at the metropolitan scale we will design a synchronized quantum network, thus demonstrating a complete infrastructure for global and metropolitan scale QKD. A size, mass and power analysis has shown that the payload is compatible with the 12U CubeSat standard form factor. Using conservative estimates of the relevant experimental parameters a detailed analysis of the typical encounter between satellite and OGS enables the calculation of the atmospheric attenuation and the rate at which secure keys can be constructed. With expected rates well over 100 kbits per encounter we can estimate that with current technology a single CubeSat can already distribute secure keys globally at a price level below 100€/kbit.

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Integrated pump rejection filter for high-quality photonic quantum communication

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Integrated photon sources are a fundamental building block of any quantum circuit. One such components is the ring resonator, which is already used in a variety of platform such as Silicon-on-Insulator (SOI) or Silicon Nitride. We have already demonstrated its promising properties in SOI for signal/idler pairs generation [1]. Where we shown high visibility and brightness for multiple pairs simultaneously. However the non-linear process used, which is spontaneous four wave mixing (SFWM), has the disadvantage of requiring a pump close to the generated photon pairs in terms of wavelength. This makes the rejection of the pump challenging as a large rejection must be applied (>100dB) on a relatively small bandwidth ($\sim$ 10 nm). This has been demonstrated using active devices [2, 3] but at the expense of a high complexity, due to the control of all the filters, as well as large coincidence rate losses.

We have demonstrated thanks to a new strategy using cascaded Bragg filters such rejection. This integrated filter combined with a ring yields a rate of 480 pairs per seconds for simultaneously two signal/idler pairs with a raw visibility higher than >95 %, and a brightness of $390\,\mathrm{pairs/s/M\,Hz}$. This was achieved by adding only a 20dB-crosstalk de-multiplexing after the chip. On top of the integrated filter which uses multi-mode effects to break the coherence between filters. A rejection of 70dB was measured for the on-chip filter.

This all passive system made by a single lithographic step is very promising for an integrated heralding source. Thanks to its simplicity and low loss, it does not increase the fabrication process while keeping the rate of generated pairs high. Moreover as many strategies already exist for the de-multiplexing on-chip, it is not a limitation. Finally as this strategy is compatible with standard deep-UV lithographic, we hope to implement it in larger scale systems.

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Quantum Communications Network Based on Polarization Entanglement at Telecom Wavelength

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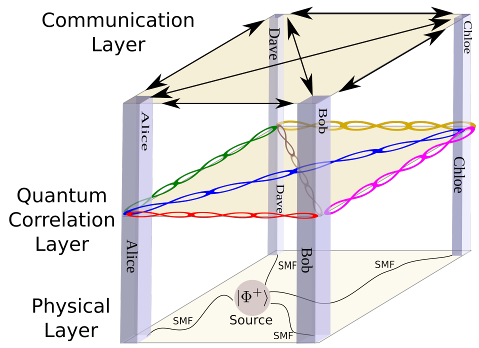
Here we implement a novel network architecture which enables scalable quantum communication networks at telecommunication wavelengths. More information about this experiment can be found in [1]. Our simple scheme uses wavelength multiplexed polarization entangled photon pairs [2, 3] to share 6 two-photon entangled states between each pair of clients in a mesh-like network topology using only one fiber per client. Using only one source of polarization entangled photon pairs and wavelength multiplexing, every client shares entanglement via several wavelength channels using only one single mode fiber each. Clients need minimal resources – only one polarization detection module and time tagger each.



Scheme of our network architecture : Different layers represent different levels of abstraction. *Physical connections layer :* contains all tangible components. Each of the 4 clients receives a combination of 3 channels via a solitary single mode fiber. Thus, the source distributes 6 bi-partite entangled photon states to the four clients Alice, Bob, Chloe and Dave. *Entanglement distribution layer :* shows the 6 entangled states (each corresponding to a different secure key) that link the 4 clients. *Communications Layer :* Entanglement-based two-party QKD protocols like E91 can be used to generate secure keys between all pairs of clients.

We successfully implemented a 4 client network with uncorrected polarization correlation visibilities $> 85\%$ in both bases and for all pairs of clients. These visibilities and count rates are sufficient to obtain secure key rates between 2 and 17 bits/s.

Distributed computation tasks or problems like the millionaire's problem could be easily implemented on this network.

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Generation and manipulation of entangled frequency combs on an AlGaAs chip

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The development of miniaturized chips for the generation, manipulation and detection of entangled states of light is one ofthe key issue on the way towards a large diffusion of quantum information technologies. Among different platforms AlGaAspresents a strong case for integrability thanks to its compliance with electrical injection, allowing to monolithically integrate active and passive components [1], and to its large electro-optic effect that can be exploited for the manipulation of photonic states.In recent years, growing attention has been devoted to generate hih-dimensional entangled states space enabling high-capacity and robust quantum information protocols [2]. An interesting way to achieve this is to use quantum frequency combs where photons are frequency-entangled over a large bandwidth.

In this work we present an AlGaAs waveguide emitting entangled photon pairs through spontaneous parametric down conversion displaying a frequency comb-like spectrum thanks to an intrinsic cavity effect. We demonstrate that in the CW pumping regime, a fine tuning of the pump wavelength allows for the generation of resonant and anti-resonant two-photon states.

Our source consists of an AlGaAs non-linear waveguide that emits two-photon states in the telecom range at room temperature with a generation rate of 2,37 MHz and a SNR up to 5x104. The dispersion properties of the devices, combined to energy and momentum conservation, lead to the generation of photon pairs which are entangled in polarization and frequency.

Moreover, due to the reflectivity of its facets, the waveguide acts as a Fabry-Perot cavity and the two-photon spectrum takes the form of a frequency comb spanning several tens of nanometers. The measured biphoton joint spectral intensity in Fig. a) presents a strong frequency anti-correlation with peaks spaced of around 20 GHz. Furthermore, we use Hong-Ou-Mandel (HOM) two-photon interference as a proof for quantum state manipulation. The central HOM dip in Fig. b) has a visibility of 85% and a width corresponding to a biphoton bandwidth of around 150 nm; this excludes the generation of a frequency-correlated classical mixed state or of a quantum-classical mixed state. Fine tuning of the pump frequency switches the HOM interference signal form bunching c) to anti-bunching d) [3]. These results demonstrate the ability of our chip to generate and manipulate high-dimensional entangled states and open the way to its utilization in quantum information protocols.

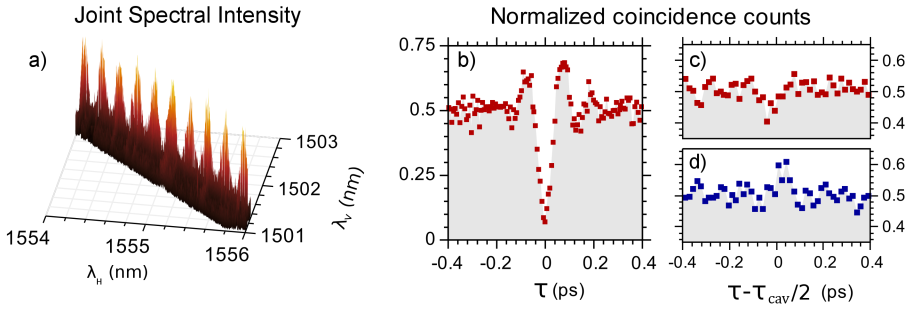

Figure 1 : Characterization of the biphoton state emitted by our device: Joint Spectral Intensity (a), HOM interference at zero delay (b) and for a time delay of the half of the cavity roundtrip for two different pump beam frequencies (c,d).

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On the possibility of classical client blind quantum computing

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The recent interest in quantum technologies has brought forward a vision of *quantum internet* that could implement a collection of known protocols for enhanced security or communication complexity. Quantum internet could not only be used to share secret keys, but we also know that combined with full quantum computers, it could be used to blindly delegate a quantum computation on a more powerful server from a weaker device, and even allow him to verify that this computation has been done honestly [1]. However, there exist some challenges in adapting widely the above vision : a reliable long-distance quantum communication network connecting all the interested parties might be very costly, and for this reason it is of high interest to remove this requirement [2–6].

In this work [a] we define a classical client - quantum server protocol called *QFactory* that can be used to simulate a quantum channel by using only purely classical communication. It is believed [7] that such functionality cannot be achieved in an unconditional secure way, so unsurprisingly, this protocol has computational security. At the moment, the security of this protocol is proved in a model known as *Honest-but-curious* and we are currently working on the proof of security in the fully malicious setting.

The QFactory protocol, viewed as a resource, has a wide range of applications. It enables fully-classical parties to participate in many quantum protocols using only public classical channels and a single (potentially malicious) quantum server. The first type of applications concerns a large class of delegated quantum computation protocols, including *blind* quantum computation and *verifiable* blind quantum computation. These protocols are of great importance, enabling secure (and verifiable) access to a quantum cloud. Concretely, we can use QFactory to implement the blind quantum computation protocol of [8], as well as the *verifiable* blind quantum computation protocols (e.g. those in [9, 10]) giving classical-client, secure and verifiable access to a quantum cloud.

Moreover, it seems [b] that QFactory has a still wider range of application : not only, it can be used to replace quantum clients by classical clients, but it can also be used to boost the security and efficiency of existing protocols. Indeed, a number of protocols (including multi party protocols [11]) need quantum communication between parties, but in order to make sure that all parties send honest qubits, it is needed to test all the communications through an expensive and inefficient process (the security grows only linearly with the number of tests). However, by replacing those communications with QFactory, all the exchanged messages become now classical. Therefore the sender can now use classical Zero-Knowledge proofs to certify that all the classical messages were sent honestly, leading to a security that grows exponentially fast with the security parameter.

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[a] Further details can be found in the full paper [12].
[b] This last claim is not included in our paper and is a work in progress

Implementation of practical unforgeable quantum money

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Wiesner's unforgeable quantum money scheme is widely celebrated as the first quantum information application. The principle is to ensure unforgeability of tokens, banknotes or credit cards by encoding them with qubit states prepared in one of two possible conjugate bases [1]. The no-cloning theorem then ensures that a malicious party willing to duplicate the money cannot copy the unknown qubit state perfectly. Despite quantum money's central role in quantum cryptography, its experimental implementation has remained elusive because of the lack of realistic protocols adapted to practical quantum storage devices and verification techniques. Here, we experimentally demonstrate a quantum money protocol that rigorously satisfies the security condition for unforgeability, using a practical system exploiting single-photon polarization encoding of highly attenuated coherent states of light for on-the-fly credit card state generation and readout. Our implementation includes classical verification with a trusted terminal and is designed to be compatible with state-of-the-art quantum memories (both single-emitter type and atomic ensemble type), which have been taken into account in the security analysis, together with all system imperfections. Recently, we have also extended the analysis to an untrusted payment terminal, and established a time-dependent security proof which deals with decohering quantum memories. Quantum banknotes have been implemented "on-the-fly" but also shown to be forgeable [4]. Unforgeable quantum credit cards, on the other hand, have not been implemented to date, and no protocol has ever been fully demonstrated taking into account the effect of a quantum memory.

Our protocol is based on [3] and [5], and has a number of desirable features, including single-round classical verification, credit card re-usability, and information-theoretic security with exponentially good parameters. Ideally, the bank stores an amount of money into a credit card using a unique secret string and gives the card to the client. When a transaction is to be made, the client first gives the credit card to a trusted vendor, who chooses at random one out of two challenge questions and accesses the credit card (*i.e.*, performs a measurement on the card states) in order to get an answer to the challenge. Then, the vendor classically sends the challenge and answer to the bank, who, using its initial secret string, verifies the authenticity of the credit card.

In order to test in practice the protocol's security conditions, it is necessary to generate blocks of photon pairs randomly chosen from the set $S_{\text{pair}} = \{|0+\rangle, |0-\rangle, |1+\rangle, |1-\rangle, |+0\rangle, |+1\rangle, |-0\rangle, |-1\rangle\}$, where $|0\rangle$, $|1\rangle$ and $|+\rangle$, $|-\rangle$ are the Pauli σ_z and σ_x basis eigenstates, respectively, and estimate the probability c of successfully answering some challenge questions. We do so by chopping a continuous 1564nm laser into pulses with an acousto-optic modulator, encoding the polarization information with a polarization controller, and measuring a block of pairs either in the $\sigma_z \otimes \sigma_z$ or $\sigma_x \otimes \sigma_x$ basis with a 50/50 beamsplitter, a half-wave plate, and two Id201 single photon avalanche detectors.

Our results, described in detail in [6], allow us to determine the range of average photon number per pulse μ that satisfy the practical security condition of our on-the-fly protocol, anticipating the use of either a single-emitter type quantum memory or an atomic ensemble type quantum memory. Our data points satisfy the strictest and most general theoretical security threshold provided that $\mu = 0.025$ to 0.200. We are now currently running the protocol and testing such conditions including a highly-efficient cold cesium cloud quantum memory [7] in our setup.

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A Metropolitan Quantum Network with Hand-held and Integrated Devices

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Quantum key distribution, together with one time pad (OTP) encryption, is an information-theoretically secure way of communicating, however imperfections in the implementation must also be considered with regards to overall security. [1, 2]. This initial challenges have been dealt with and there now exist several protocols that have been proposed and demonstrated in real world scenarios, such as decoy-state QKD and measurement-device-independent (MDI) QKD. However, other challenges remain for a large-scale adoption of QKD in our modern networks [3] ; there is still a lot of work to be done on how to integrate various QKD systems into a key management framework so they can be practically included as part as an IT infrastructure. Classical networks are usually built from physical devices like servers and networking hardware that are dedicated to specific tasks, using data handling rules within the firmware. One drawback of this model is the lack of flexibility, which naturally drove the research towards the development of software defined networks (SDNs). The SDN rules deployed as software modules allowing the control plane and the forwarding plane to be separated in such a way that permits global reconfiguration of the network from a single location. For QKD to be useful in near future, it must be compatible with next-generation communication models. Considering this outlook of interoperability with a QKD tailored SDN [4], we have designed a software suite flexible enough to be used as part of a standard framework such as Transport Layer Security (TLS). The software can be used for a number of different purposes and devices. The key interfaces allow for several different sources of pre-shared key to be used via standard interfaces thus isolating the application from the specifics of QKD. The tools have been designed with clear separation of components to allow customisation of the tool with future devices. Once a key is produced it is passed to the key store where it can be managed. Custom QKD devices can be incorporated into the system from a lower level by implementing a driver. The device can then make use of the post-processing layers and thus produce key. The pluggable nature of the post-processing pipeline allows for different modules to be applied to the device, providing a tool for experimental environments as well as security. This will facilitate the integration of the latest chip-based QKD devices [5, 6], produced by QETLabs, with our next-generation Bristol metropolitan QKD network.

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Feasibility study of satellite continuous-variable QKD

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Achievable distance remains one of the main limitations for the practical deployment of quantum key distribution (QKD) systems. Quantum repeaters will provide a flexible solution for this problem in the future, but for the moment the performance of these systems is well below the requirements of practical QKD scenarios. One alternative is to extend the range using trusted nodes, but this would require a network of nodes that is perhaps not flexible or scalable. In the short term, satellite communications is the most promising technology to extend QKD over intercontinental distances. A decoy-state Discrete-Variable (DV) QKD protocol link of 1200 km has been recently achieved using a low Earth orbit (LEO) satellite [1] proving the feasibility of this approach, but many challenges remain to be solved before QKD over satellite becomes a commercial reality.

Continuous-variable QKD is an alternative to DV-QKD that uses the quadratures of the electromagnetic field to encode the information. The similarities with classical communications make it a very interesting candidate, since most of the components are available off-the-shelf from telecom industry. Additionally, its reception technique (homodyne or heterodyne detection), acts as a natural filter to undesired components, and could allow the use in free-space under Sun-light conditions. CV-QKD is a mature technology which has been successfully implemented in fiber [2] and in real scenarios [3], but satellite communications present new challenges to CV-QKD technologies.

The main difference with respect to fiber is the attenuation in the channel. In practical scenarios (LEO and above) the attenuation will typically exceed 20 dB, but the fact that it increases quadratically with the distance instead of exponentially allows the communication over higher distances. The minimum attenuation depends only on the involved optics, so it could be improved by technical means (e.g.: bigger telescopes). Another special characteristic of mobile free-space communications is the inevitable variation of the attenuation with time that will be a function of the slant distance between the transmitter and the receiver. Also, as the optics have to be aligned during the communication, the fluctuations due to pointing will introduce a fading effect in the received signal.

In our work we propose a feasibility analysis of CV-QKD considering a satellite-to-ground communication for different satellite perigees using an auxiliary classical beacon to recover the local oscillator reference and estimate the transmittance. For each satellite passage we calculate the evolution of the expected channel transmittance as well as the expected fading considering realistic experimental parameters for the optics and the pointing systems. We propose a method to measure the effect of those errors (fading excess noise) in the generated secret key. We show that without further processing no key could be achieved. To solve this problem we classify the received quantum symbols into sets (bins) in function of the transmittance ($\pm\Delta$) of their corresponding classical beacons. Assuming that we have enough symbols in each bin to obtain reliable statistics, they can then be treated as independent CV-QKD sessions. We recalculate the expected excess noise after applying this binning and we show that we can overcome the fading (even in LEO orbits where pointing is more critical) and generate secret key over a passage. As we ascend to MEO orbits we show that the effect of fading is reduced and the limiting factor is the excess noise introduced in the local oscillator recovery. The whole analysis assumes realistic technological parameters and we consider it a useful tool to dimension a CV-QKD satellite-to-ground link.

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Quantum communication advantage with coherent states and one beam splitter

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A long-standing goal in quantum information science is the ability to demonstrate in practice an advantage in the use of communication resources with respect to any classical protocol. The field of quantum communication complexity, which is interested in the optimization of such resources, has stimulated the proposal of many theoretical protocols ; however to date none of them has been amenable to experimental implementation with state-of-the-art technology. This is typically due to the fact that large input sizes are required to demonstrate a quantum advantage. When the information is encoded on entangled qubit states, this becomes rapidly prohibitive.

Recently, it was shown that several qubit based protocols can be mapped into a coherent state framework [3], which is particularly convenient for practical demonstrations. Indeed, this mapping was successfully used for quantum fingeprinting experiments. Here, we are interested in applying this framework to a protocol proposed by *Aaronson et al.* [1] and subsequently analyzed in a linear optics setting [2]. The protocol enables the verification of NP-complete problems, for example, the verification of whether a boolean formula is satisfiable or not. We propose a protocol that can achieve this with coherent states and a small number of linear optics components, hence opening the way to an experimental demonstration of a quantum advantage for this task.

The 2-out-of-4 SAT is a satisfying formula over N binary variables consisting of a conjugation of many clauses, each of which consists of four variables. The clauses are satisfiable if exactly two variables are equal to 1. The problem is to decide if there is a truth assignment $x = x_1 x_2 .. x_N$ to the formula. When Merlin (the prover) and Arthur (the verifier) use a quantum channel, the verification task can be done with $K = O(\sqrt{N})$ unentangled proofs, each revealing $O(\log N)$ bits of information. This can be verified in polynomial time by Arthur, whereas, in the classical case, any verification proof revealing $O(\sqrt{N} \log N)$ bits of information still requires exponential time for Arthur to verify. Ref. [2] showed recently that the quantum proof states can be implemented with single photon states in an equal superposition over many optical modes. The verification tests can be performed using linear-optical transformations consisting of permutation of modes, interferometers and measurement using single-photon detectors, and it was shown that an advantage over the classical proof requires $N \geq 512$. Although such an experimental demonstration is in principle possible, the creation of a large number of identical single photon proof states and the maintenance of large superposition states is a challenging task and out of the reach of current photonic technologies.

We simplify considerably the practical requirements for this problem while also improving its soundness by using the aforementioned coherent state framework and by introducing a novel technique, which we call Sampling Matching [4] and which reduces the complex experimental requirements of the Hidden Matching problem - one of the main verification tests required in the original protocol [1, 2]. Indeed, with respect to the original protocol that consisted in three separate tests to check Satisfiability, Uniformity and Symmetry, we reduce the verification task to one single test. For this, we require two coherent state sources (one for Merlin and one for Arthur), a small, fixed number of optical components, including a single beam splitter, and two single photon threshold detectors. In our test, instead of several copies of the same state, we simply increase the average photon number of the coherent states to $O(\sqrt{N})$, leading to the same information leakage as in the qubit case. This leads to a further simplification of the computational complexity, the drop of the unentanglement promise, and an increase in the probability of detecting Merlin's hacks.

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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] joins 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 two recent implementations of hybrid protocols using this resource : the remote preparation of arbitrary CV qumodes $|\alpha\rangle + qe^{i\phi}|-\alpha\rangle$ [3] as well as the demonstration of quantum steering [4].

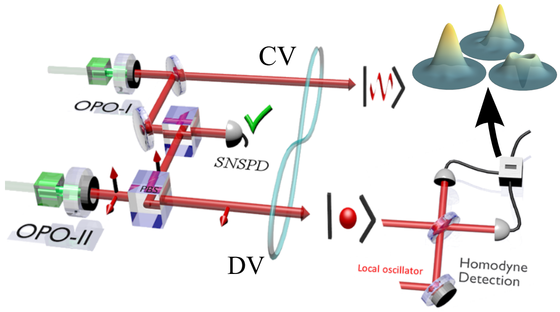

FIGURE 1: Hybrid entanglement is generated using two non-classical sources (optical parametric oscillators) and single photon heralding via superconducting nanowire single-photon detectors (SNSPD). By conditionning on the results of homodyne measurements made on the DV side, we can remotely create arbitrary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

Our experiment, 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 [5] : high purity single photons [6] as well as Schrödinger cat states at large preparation rates. Joining the two heralding paths allows us to generate the hybrid entangled state $|0\rangle_{DV}|cat-\rangle_{CV} + e^{-i\Phi}|1\rangle_{DV}|cat+\rangle_{CV}$. We first 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 prepared at a distance 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 security in hybrid quantum networks, we then evaluated the steerability of our resource. Quantum steering is a key requirement for one-sided device independent quantum information protocols where one party can be trusted. Performing six different homodyne measurements by changing the local oscillator phase on the DV side, and then sign-binning the result, we generated a set of 12 conditionned CV states, 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. These results pave the way to the realization of hybrid quantum teleportation from DV to CV and vice versa as well as entanglement swapping between DV, CV and hybrid entangled states—both crucial stepping stones for the realization of hybrid quantum networks.

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Secure quantum key distribution over 421 km of optical fiber

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Quantum key distribution (QKD) allows two remote users to exchange secret keys. Since the first experimental demonstration over a short distance of 32 cm, there has been continuous progress such that nowadays the maximum distance has been pushed up to 400 km.

We present a QKD experiment that takes advantage of state-of-the-art performance on all fronts to push the limits to new heights. We rely on a new 2.5 GHz clocked setup, low-loss fibers, in-house-made highly efficient superconducting detectors [1] and last but not least a very efficient one-decoy state scheme [2]. See [3] and references therein for a detailed description of the system.

We use a protocol based on time-bin encoding with decoy-state method. We employ only three quantum states and two decoy levels. This allows us to have a simple experimental setup, with only one electro-optic modulator. The secret key rate (SKR) is obtained by performing a complete security analysis, taking into account finite-statistics effects [4].

Figure 1 shows the SKR as a function of the distance. We exchanged 0.25 bps at a transmission distance of 421 km, which is the maximal transmission distance reported for a QKD system in fiber. We achieve an improvement of the SKR by 4 orders of magnitude with respect to the only comparable experiment over 400 km (which was using a measurement-device-independent QKD configuration).

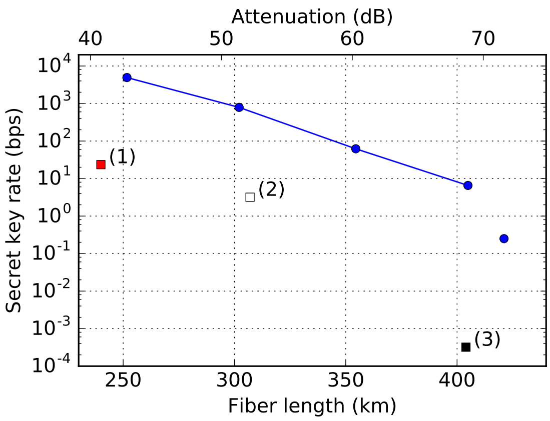

FIGURE 1: Circles : experimental final SKR versus fiber length. Squares : results of other long-distance QKD experiments using finite-key analysis : (1) BB84, B. Fröhlich *et al.* [5] ; (2) Coherent one-way, B. Korzh *et al.* [6] ; (3) Measurement-device-independent QKD, H.-L. Yin *et al.* [7]. The upper axis indicates the overall attenuation based on a fiber loss of 0.17 dB/km.

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Simple and high-speed polarization-based QKD

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Quantum key distribution (QKD) allows two distant parties, Alice and Bob, to generate a secret key in the presence of an eavesdropper Eve. This secret key can be used for information theoretically secure communication, e.g. with the One-Time-Pad [1].

We present a simplified implementation of the polarization-based BB84 protocol in optical fiber [2]. We employ a three state protocol [3] with weak coherent pulses. The pulses are carrying more than a single photon with non-negligible probability. These multiphoton states pose a security risk which can be handled by using the decoy method [4]. In practice three different intensities (one signal and two decoys) are commonly used [5, 6]. However, to keep the implementation simple, we developed a new approach based only on one signal and one decoy. We showed that for most practical experimental settings this method achieves higher performance than the two-decoy one [7].

A single gain-switched laser is used by Alice to create weak coherent pulses at 625 MHz repetition rate. Then the pulse intensity gets modulated to either the signal or decoy level. The three polarization states are encoded with a electro-optic phase modulator. Bob uses a time-multiplexed readout scheme to detect all the three states with only two Stirling cooled InGaAs detectors. Polarization fluctuations in the transmission channel are compensated with a feedback loop controlled by the quantum bit error rate (QBER).

Figure 1 shows the secret key rate (SKR) and QBER as a function of the distance. The maximum distance over which we could exchange a secret key is 200 km at a rate of 23 bps. To our knowledge, this is the fastest polarization-based implementation of a BB84 protocol.

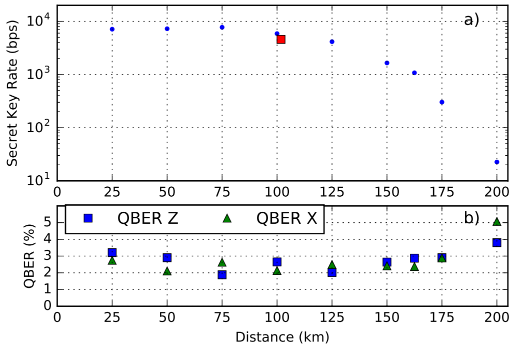

FIGURE 1: SKR (a) and QBER (b) as a function of the transmission distance. The measurements were done using a quantum channel composed of 12.16 km of real fiber and attenuation to simulate additional distances. The red square indicates a measurement done with more than 100 km of real fiber.

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Polymorphic Photon-Pair Spectral Correlations

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Photon-pair states, whether spectrally entangled or separable, can all be very useful in quantum technology applications. For example, the former are used for improving the security of quantum key distribution, whilst the latter are the backbone in heralded single photon sources. It has been shown that the amount of spectral entanglement is well-described by the shape of the Joint Spectral amplitude function (JSA), which mostly depends on the relative group velocity relation between the pump, signal and idler photons within the source medium [1].
We demonstrate that gas-filled inhibited coupling hollow-core photonic crystal fibers (IC-HCPCF) provide a highly versatile integrated platform for generating photon pair states with tailored phase- and group velocity relations and possibly at any given wavelength from the UV to infrared [2]. Furthermore active parameters (gas pressure, pump spectral properties) can be tuned to access various JSA shapes.
Within a single IC-HCPCF source, we experimentally demonstrate an unprecedented high degree of JSA manipulation (see Fig. 1) featuring (i) two dimensional spectral tuning $\Delta\nu > 14$ THz of the JSA central position through gas pressure or pump frequency tuning and (ii) a control of entanglement through change of pump spectral width or fiber length. Moreover, the broad spectral width of the pump (~ 9 nm) makes it compatible with pulse shaping technique, allowing to access much more complexe photon pair spectral correlations such as the one given in (d) paving the way to spectro-temporal mode encoding [3] in such a media.

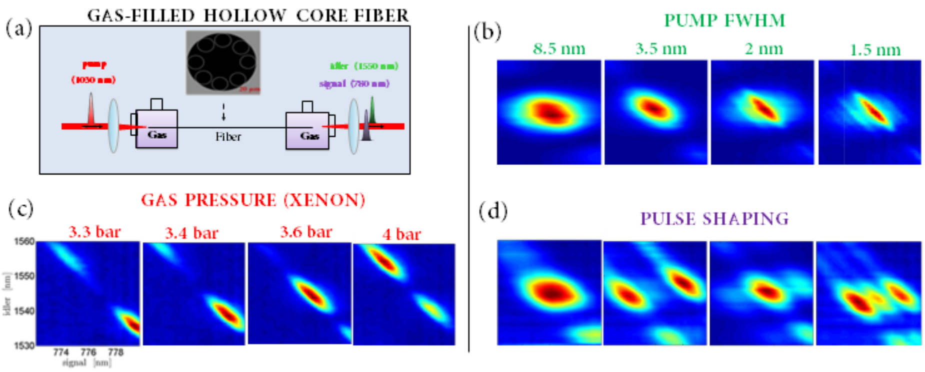

Figure 1: (a) Schematic of the Gas-filled hollow core fiber with its cross section in inset. (b)-(d) Effect of a change of one parameter on the JSA , either the pump full-width at half maximum, the gas pressure or the pump spectral envelope. All joint spectral amplitudes have been measured by stimulated emission tomography technique.

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Spin-optical investigations on single vacancy centres in silicon carbide – a particularly robust system for quantum networking applications –

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Optically addressable single spins in solids are a promising basis for establishing a scalable quantum information platform [1]. Pivotal landmark demonstrations have been achieved with the nitrogen-vacancy (NV) centre in diamond, whose key asset is excellent electron spin coherence. However, implementation of NV centres into scalable nanophotonics structures has proven to be challenging as environmental influences severely compromise spin and optical stability. In this regard, the silicon vacancy defect in diamond shows high optical stability due to inversion symmetry and implementation into nanostructures has recently been demonstrated [2]. However, the pronounced spin-phonon coupling necessitates millikelvin temperatures for practical spin coherence times. Here we show that the silicon vacancy (V_{Si}) centre in the 4H polytype of silicon carbide (SiC) combines, in the same system, excellent spin and optical stability and coherence at standard cryogenic temperatures. Some key results are shown in Fig. 1. The V_{Si} level structure is a spin quartet ($S = \frac{3}{2}$) with low spin-orbit coupling, leading to millisecond spin coherence times even at room temperature. All optical transitions are spin conserving, and nearly transform limited at low excitation intensities. Importantly, spectral diffusion is not observed at all, even after about one hour of repeated excitation scans. Thanks to low strain-coupling, multiple defects are spectrally distributed over a very narrow range, making it easy to observe defects with overlapping spectra. Those smoking-gun results show that spin-to-photon interfaces that connect several V_{Si} centres are in reach.

We will further demonstrate near deterministic optically-assisted electron spin initialisation, and coherent coupling to nearby nuclear spins. Both features are primordial for guaranteeing high-fidelity quantum state transfer via error correction and quantum state distillation [3].

Our results promise that integration of V_{Si} centres into scalable photonic nanostructures will be successful, which will have a great impact the development of quantum network applications using integrated semiconductor-based spin-to-photon interfaces.

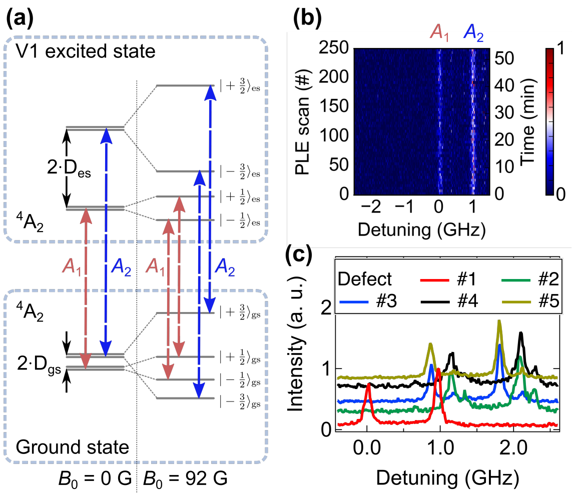

FIGURE 1. (a) Ground and excited state level structure at zero magnetic field ($B_0 = 0$ G), and with $B_0 = 92$ G. Optically allowed transitions are spin conserving and labelled A_1 and A_2. (b) Repeated resonant excitation scans for almost one hour at $B_0 = 92$ G show no signs of spectral diffusion. (c) Excitation spectra of five V_{Si} centres, showing several ones with overlapping lines.

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An algorithmic approach to quantum communication

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Quantum Shannon theory aims to quantify the information that can be stored or transmitted over a noisy quantum medium. However, unlike the classical case where Shannon's noisy coding theorem gives a very satisfactory answer, the quantum setting presents significant difficulties. In fact, a version of Shannon's noisy coding theorem is unknown for quantum channels, even for transmitting classical information. In this talk, I will give an overview of the state of affairs in quantum Shannon theory and propose an algorithmic approach to tackle the question of optimal communication over a noisy medium. I will also present preliminary results in this direction, namely a hierarchy of semidefinite programs to quantify the optimal achievable fidelity [1].

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Quantum Sensing & Metrology (QMET)

High sensitivity quantum-limited electron spin resonance

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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 [5] 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 [6, 7] to show that, by optimizing the resonator design [8], the sensitivity can be enhanced to the level of 10 spins/$\sqrt{\text{Hz}}$.

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Dynamics of a qubit while simultaneously monitoring its relaxation and dephasing

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Measuring a spin-1/2 along one direction projectively maximally randomizes the outcome of a following measurement along a perpendicular direction. Here, using either projective or weak measurements, we explore the dynamics of a superconducting qubit for which we measure simultaneously the three components x, y and z of the Bloch vector.

The x and y components are obtained by measuring the two quadratures of the fluorescence field emitted by the qubit. Conversely the z component is accessed by probing an off-resonant cavity dispersively coupled to the qubit. The frequency of the cavity depends on the energy of the qubit and the strength of this last measurement can be tuned from weak to strong in situ by varying the power of the probe.

In this experiment, the tracked system state diffuses inside the Bloch sphere and performs a random walk whose steps obey specific rules revealing the backaction of incompatible quantum measurements. The associated quantum trajectories follow a variety of dynamics ranging from diffusion to Zeno blockade. Their peculiar dynamics highlight the non trivial interplay between the backaction of the two aforementioned incompatible measurements.

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Cavity nano-optomechanics in the ultra-strong coupling regime

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We report on the recent developments of a novel cavity-nano-optomechanical scheme realized by inserting an ultrasensitive force sensor, a suspended silicon carbide nanowire of sub-wavelength diameter, in a high finesse fibre microcavity (from J. Reichel's group at LKB). The combination of the small mode volume of the cavity, of the large optomechanical interaction strength that can be achieved, both in the dispersive and dissipative regimes, and of the extremely large zero point fluctuations, permits to achieve novel regimes in cavity-optomechanics. In particular we operate largely in the ultrastrong coupling regime, where one single cavity photon can displace the oscillator by more than its zero point fluctuations, achieved when the single photon coupling rate ($g_0/2\pi \sim 3\,\mathrm{MHz}$) largely exceeds the nanoresonator frequency ($\Omega_m/2\pi = 20\,\mathrm{kHz}$).

We have developed a versatile experiment in which the nanowire can be micro-positioned in the optical mode of a fiber microcavity. Collecting the scattered light using a lateral objective, and exploiting an independent readout laser provides multiple measurement channels for both the intracavity field and the nanowire motion. It allows to evaluate the coupling strength of our optomechanical system by measuring the perturbation of the intracavity field (optical frequency and linewidth changes) caused by the nanowire. Furthermore by employing pump-probe experiments, we have been able to investigate and map the optical force exerted by the intracavity field on the nanowire. Those measurements thus permits to evaluate simultanesouly both counterparts of the optomechanical interraction. Force measurements permit to investigate in great detail the intracavity field and represent a measurement strategy which is complementary to more common approaches based on light scattering analysis.

It is interesting to extrapolate this experiment to an operation at dilution temperatures (to suppress unwanted thermal noise) where we have already demonstrated the extreme force sensitivity of the nanoresonators, at the $10\,\mathrm{zN}/\sqrt{\mathrm{Hz}}$ level at $20\,\mathrm{mK}$. In that condition, we should be be able to largely enter the novel regime where one single intracavity photon render the cavity entering the static ally bistable (defined by $g_0^2/\kappa\Omega_m > 1$), which provides avenues for implementing optical non-linearities at unprecedented low light levels (few picoWatts). This opens numerous perspectives in quantum optics and represents a long lasting goal for cavity nano-optomechanics.

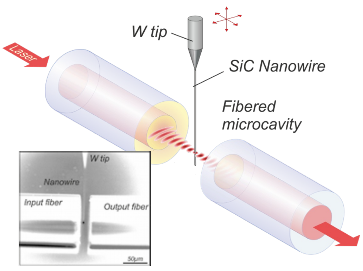

FIGURE 1. Scheme of the experiment.

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An Ultrasensitive Force Sensor for Quantum Applications

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Force measurements based on mechanical oscillators such as AFMs provide single atom precision and are important scientific tools in multiple fields of science. However, their size and geometry imposes limitations such as restriction towards 1d measurements and a relatively low force sensitivity. We present a novel technique for realizing ultrasensitive vectorial force field sensing based on suspended nanomechanical oscillators and an advanced optical read out scheme. The oscillator in the form of a sub-μm diameter SiC nanowire has due to its aspect ratio (>200) and high stiffness a good intrinsic force sensitivity up to $1aN/\sqrt{Hz}$ at room temperature which for instance has been used to perform noise based force field cartography [1]. We implemented an improved technique realizing ultrasensitive vectorial force field sensing by optically probing the excited vibrations of a suspended oscillating nanowire and simultaneous tracking of its eigenfrequencies and eigenmode orientations, which are modified in presence of an external force field. This development dramatically increases the measurement rate, its precision and its robustness and clears the way towards the exploration of novel phenomena. Firstly, our current research aims to measure a repulsive Casimir force which has been predicted in novel geometries [2], in our case the nanowire is expected to experience a repulsive force when approaching a sub-μm hole in a conducting plate. Secondly, a magnetic functionalization of the nanowire's oscillating extremity together with the developed measurement technique will permit non-perturbative exploration of magnetic micro- and nanostructures. Furthermore, local magnetic gradient of the nanowire will couple its mechanical motion with an electronic spin NV center in diamond [3]. Thanks to the high sensitivity of $1aN/\sqrt{Hz}$ of our measurement we can mechanically read out the spin state whose change gives rise to a difference in force of about 20 aN in a 1 $T/\mu m$ field gradient. Thus, the presented experimental platform represents a hybrid spin qubit-nanomechanical system for both sensing applications and fundamental exploration of the hybrid coupling between both components.

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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 technologies with an increasing number of encouraging out-of-the-laboratory implementations [1, 2]. The quest for competitive quantum photonic systems, compatible with future engineered systems, has promoted huge developments concerning both source [3, 4] and detection devices [5].

To date, a critical point lies in experiments' operation rates. Time multiplexing technics allow in principle to pump photonic sources at rates on the order of the GHz [6]. However, a strong limitation to ultra-fast operation lies in timing errors at the detection stage. Limited resolution directly affects the quality of any time-correlated single photon counting or quantum state engineering operations [6]. In particular, single photon detector's timing-jitters lead counts associated with a given optical clock cycle to appear as temporally indistinguishable from those corresponding to neighbouring ones [5].

Fast and accurate time-tagging is mandatory in multiple operations, such as quantum teleportation [1], quantum state engineering [6] and quantum random number generation. In anticipation to further technological advances, as well as in the perspective of promoting novel conceptual developments on existing quantum communication protocols, it is thus of the utmost importance to correctly describe the effects of detectors' timing performances. Temporal uncertainties at the detection stage are somehow treated in multiple works on quantum key distribution exploiting time-bin encoding where they are discussed in the context of communication security [7–9]. However, in all these works, detection description does not represent the paper principal scope and reported models are extremely basic and mostly restricted to the case of only one photon at the detector input.

In our work, we explicitly address the problem of detection temporal uncertainties by means of an original theoretical model able to describe the temporal behaviour of standard single photon detectors, with no photon-number resolving abilities [5], affected by non negligible timing-jitter and in presence of dead-time. Our model exploits a multi-mode formalism to describe timing-resolution effects in ON/OFF detectors by a fully operational POVM description, taking into account the effect of dead-time and finite detection efficiency, without any *a priori* restriction on the number of photons impinging on the detector.

We then apply our results to the quantitative study of timing-jitter effects on some usual quantum optics experiments, such as direct photon detection, coincidence measurements, as well as heralded quantum state preparation. As an example, for a time correlation experiment, considering a source of simultaneous twin photons, our model allows expressing explicitly the delay probability density function. As an other example, this fully quantum approach allows expressing the density matrix of a heralded photon explicitly, by taking into account the imperfections of the heralding detector.

In conclusion, we believe that our work fills a gap in the discussion on practical quantum technologies by providing a full operational POVM description of practical detection stages. Full derivation and details are available in [10].

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Persistent spectral hole burning with SiV$^-$ centers in nano-pyramids

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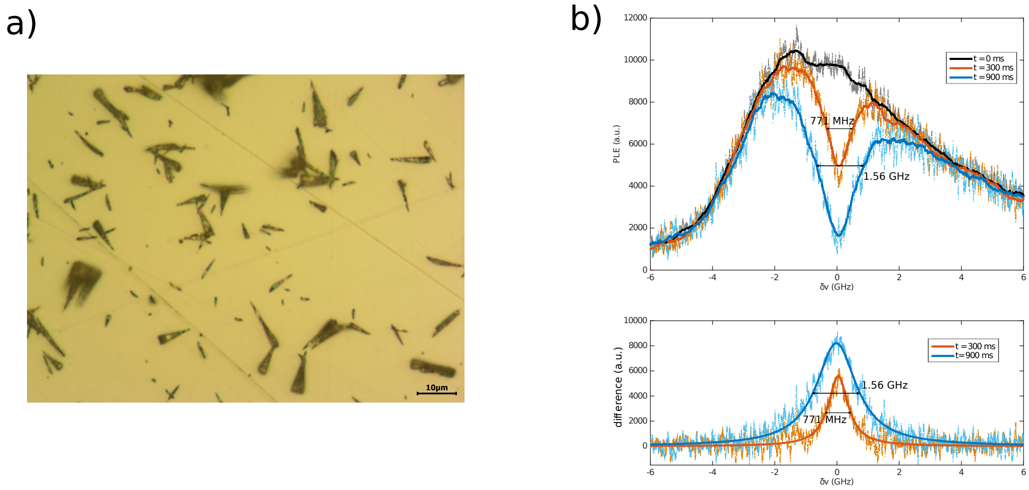

a) Microscope picture of the sample : diamond pyramids are deposited on a silicium substrate. b) Top : photoluminescence excitation spectra recorded after different exposure times under resonant excitation. Bottom : Difference between PLE spectra without hole burning and after two different expsore times. The resulting peaks is fitted by a lorentzian curve which allows us to measure their linewidth.

Efficient interfaces between emitters and photons form the basis of quantum networks and fundamental applications. Diamond negatively charged silicon vacancy centers (SiV$^-$) can be used for such applications as they are photostable and reveal a huge emission in the zero phonon line. Nanostructures are required in order to ensure a strong coupling between the emitters and the light field.

In our search for a suitable sample, we have studied in detail and at cryogenic temperature sharp single crystal diamond AFM probes from Artech Carbon. Due to the growth conditions, a lot of SiV$^-$ centers are present at the apex of such a tip whose radius of curvature is as low as 10 nm [1]. They exhibit very interesting optical properties at low temperature. We have shown that the inhomogeous linewidth of the ensemble of emitters is 15 GHz at 6 K [2]. That means that the structure has very low strain which is probably due to the slow and controlled CVD growth along the <001> axis.

Moreover, when NV centers are also present, resonant excitation leads to the trapping of SiV$^-$ centers into a dark state. It is likely to be due to a transfer into an other charge state. Its lifetime is very long (more than several minutes). Illumination with a green laser is needed to recover the photoluminescence. It enables persistent spectral hole burning which unveils the homogeneous broadening width. The smallest hole linewidth observed is 771 MHz which means that the emitters are close to be lifetime limited. These results are promising for quantum optics experiments and paves the way to sub-wavelength microscopy technics such as ground state depletion microscopy [3].

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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 (1560nm), followed by an integrated beam-splitter for the optical part of 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). With such a device, we recently measured a squeezing level corresponding to a noise reduction of - 2 dB with respect to the classical limit. During this contribution, I will present these results.

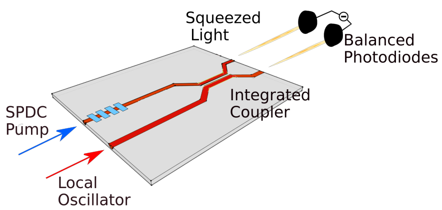

FIGURE 1. Schematic of the chip
The chip consists of an integrated coupler made of 2 lithium niobate waveguides single mode at 1560 nm. The upper arm is periodically pooled (blue rectangles) and is using for the SPDC process while the lower one guides the local oscillator. Chip area is 5 times 1 cm^2.

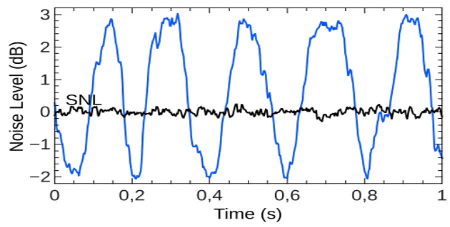

FIGURE 2. Normalized noise variances at 2 MHz of the squeezed vacuum state (blue trace) and the vacuum state (dark trace) as a function of the local oscillator phase (proportional to the time).

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Advances in quantum electrical metrology

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The quantum Hall effect and the Josephson effect have revolutionized the electrical measurements by providing universal and highly reproducible resistance and voltage references related to the elementary charge e and the Planck constant h. These quantum electrical standards culminate in the imminent revision of the International System of units SI based on fixing the exact value of several fundamental physical constants : e, h, the Boltzmann constant k and the Avogadro constant N_A. The quantum Hall resistance standard and the Josephson voltage standard can serve the realizations of the new definitions of the ampere based on e and of the kilogram based on h, as well as the realizations of the ohm and of the volt, with unprecedented accuracy. The next challenges for the quantum standards concern the simplification of their use for broadening their dissemination towards industrial end-users, the extension of their applications, and their integration in more complex systems.

At LNE, we have recently made significant progress towards these objectives. By the use of graphene, we have demonstrated the operation of the quantum Hall resistance standard with state of the art accuracy ($< 10^{-10}$) in relaxed experimental conditions (magnetic field down to 3.5 T, temperature up to 10 K or current up to 0.5 mA), much easier than those required by GaAs/AlGaAs devices [1]. These conditions are compatible with integration of the standard in compact, simple-to-operate and lower-cost cryogen-free cryomagnetic setup. Besides, by combining the quantum Hall resistance standard, the Josephson voltage standard and a SQUID-based cryogenic transformer arranged in an original circuit, we have demonstrated a programmable quantum current generator related to e and that realizes the new definition of the ampere with record accuracy (10^{-8}) [2]. This realization outperforms the alternative approach based on single electron devices, regarding its accuracy and the broad range of generated current (μA - mA). These advances constitute major steps towards the realization of a universal and highly accurate quantum electrical multimeter (Ω, V, A, F) gathering the quantum electrical standards in a unique and compact system. Such a device would contribute to realize and disseminate the advantages of the revised SI and would considerably improve electrical measurements.

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A band-gap engineered Josephson traveling wave parametric amplifier

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Josephson Parametric Amplifiers (JPA) are key to research fields involving microwave signals in the quantum regime, such as superconducting quantum bits or nano electromechanical systems. Their elementary building block, the Josephson junction, is at the the same time strongly non-linear and non-dissipative. Therefore they provide both large gain [1], [2] and noise performances close to the quantum limit [3], [4]. To obtain reasonable gain (typically $20\,\mathrm{dB}$), the interaction time between the weak signal, the strong pump and the non-linear medium must be maximized. Up to now, this interaction time was increased by coupling the Josephson element to a resonant cavity, but at the expense of a reduced bandwidth. Despite continuous improvement [5–7], these resonant amplifiers still display a bandwidth below $1\,\mathrm{GHz}$.

Increasing this interaction time is also possible using distributed non-linear media, similar to non-linear optical fibers, thus overriding the limitations due to resonant cavities. This new class of devices is called Josephson Traveling Wave Parametric Amplifier (J-TWPA). It requires long arrays of Josephson junctions, at least one thousand unit cells. Fabricating such amplifiers is now technically possible [8, 9]. However, these traveling-wave amplifiers suffer from what is known as phase-matching issue : not only energy conservation must be fulfilled but k-vector (or equivalently propagating phase) must also be conserved.

Here we present a device, which solves this phase-matching problem. Contrary to previous implementations [8, 9], we engineer the non-linear medium by periodically modulating the size of the Josephson junctions of the array, leading to the opening of a gap in the dispersion relation. This opening allows to compensate the k-vector dispersion (both due to linear and non-linear effects). Our device shows gain greater than $15\,\mathrm{dB}$ while having bandwidth larger than $3\,\mathrm{GHz}$.

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Metrological advantage at finite temperature for Gaussian phase estimation

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The precision of an optical phase estimation protocol is limited by the quantized nature of light. In the absence of nonclassical correlation, the accuracy is bounded by the so-called standard quantum limit [1]. It is well-known that some quantum features like (mode) entanglement can be used to surpass this limit ; however, we lack a general characterization of the resources allowing to achieve such a metrological advantage. Moreover, the standard quantum limit itself can be unattainable at the classical level due to noise in the preparation procedure. To adress these issues, we introduce a quantifiable measure of metrological advantage that takes into account preparation noise. We study this quantity for a broad class of Gaussian states [2]. We show that squeezing is not only necessary, but sufficient, to have an advantage. Finally, we discuss our results in the framework of resource theory [3] ; interestingly, we find that some, but not all, properties of our metrological advantage measure can be interpreted in this language.

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High-accuracy measurement of refractive index difference in dual-core fibers

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High-precision index measurements are important for high-density energy transport in large mode area optical fibers. The conception of such fibers is a very challenging technological issue and a precise index control on the order of 10^{-5} is now needed. Here, we use entangled photon pairs to observe higher order interference, Hong-Ou-Mandel, to perform quantum optical coherence tomography. As opposed to classical methods, our quantum approach is insensitive to optical phase and dispersion. This allows us to measure relative index changes of 10^{-5}. Our work is a step forward to break down the barriers of essential technologies for developping the future generation of telecommunication systems.

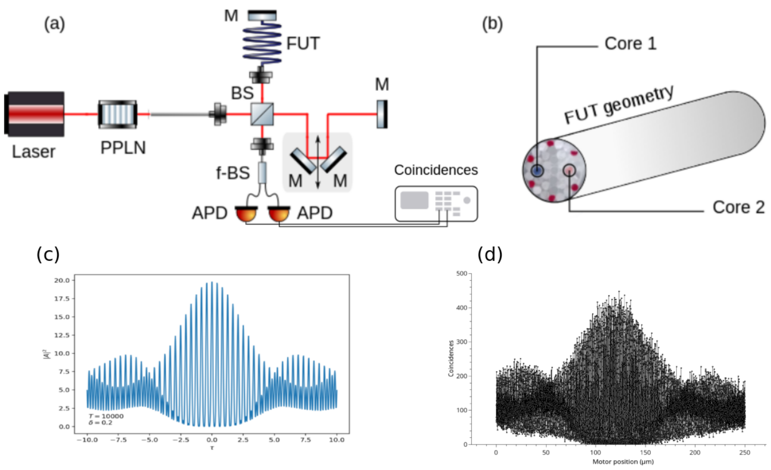

FIGURE 1: **(a)** Scheme of the experimental setup composed by the laser, the PPLN waveguide and the Michelson interferometer. **(b)** Illustration of the special fiber geometry with the double-core engineering. **(c)** Quantum theoritical model. The curve shows the coincidence count versus the nano-positionner position. **(d)** Quantum measurement showing coincidence counts versus the nano-positionner position.

The experimental setup is shown schematically in Figure 1 (a). We generate entangled photon pairs in a periodically poled lithium niobate (PPLN) waveguide. The photons are directed to a Michelson interferometer in which one arm is the length-tunable free-space reference, and the other comprises the fibre under test (FUT).

In our experimental arrangement, we observe quantum interference of two kinds. First, when indistinguishable photons return back to the beam-splitter (BS), they bunch together via Hong-Ou-Mandel (HOM) interference. In our case, this leads to the observation of a HOM peak. In addition, we observe Franson-type interference where the signature is sinusoidal oscillations within the HOM peak.

In order to measure refractive index differences, we use a double-core FUT where each core was produced with slightly different parameters. By recording subsequent interferograms for each core, and measuring the shift of the envelope function, we can deduce the refractive index with high precision. In Figures 1 (c) and 1 (d), we show, respectively, the simulated and the measured interference patterns at the output of the interferometer. These figures show that an excellent agreement is obtained between experimental data and theory. From our particular fibre, we extract an index difference of $1,66 \cdot 10^{-4} \pm 6 \cdot 10^{-6}$.

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Magnetic Imaging at High Pressure using Nitrogen-Vacancy Centers in a Diamond Anvil Cell

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The diamond anvil cell (DAC) is the tool that allows scientists to create pressures comparable to those existing in the Earth core, above the megabar range. These conditions lead to new states of matter with specific magnetic and superconducting properties. However, the minute size of the sample and the constraints associated to the DAC make the implementation of magnetic diagnostics highly challenging. We will report the realization of an optical magnetometry technique that can detect the sample magnetic behavior through the diamond anvil. The sensing is achieved with Nitrogen-Vacancy (NV) centers located at the surface of the diamond anvil, created by nitrogen implantation with a focused ion beam.

The NV center has a spin-dependent photoluminescence. By combining a microwave excitation and an optical excitation/readout, we reconstruct the full vector magnetic field inside the diamond anvil cell at pressures as high as 30 GPa so far.

As a proof-of-principle, we detected the $\alpha - \epsilon$ phase transition of iron with pressure through the monitoring of its magnetization. We plan to synchronize this experiment with an x-ray diffraction measure in order to finally determine whether the crystalline transition or the magnetic transition happens first.

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Single-shot Non-destructive Detection of Ensembles of Rydberg Atoms with Microwave Cavity Transmission Measurements

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Rydberg atoms are used in an increasing number of experiments, in particular due to their large dipole moment that induces finite range interactions which allows controlled simulations of interacting quantum systems. The usual techniques to detect Rydberg atoms are based on ionization followed by detection of ions or electrons on an avalanche detector, or, in systems of trapped atoms, on detection of presence or absence of atoms. Both methods are very efficient but destructive. Cavity quantum electrodynamics (QED) provides a powerful tool to realize quantum non-demolition measurements of either part of the system, emitter or photon, by observing the effect of the interaction on the other part. Ideal projective measurements allow to detect, to prepare and to manipulate quantum states in a controlled and coherent manner. They are used with atomic or solid-state emitters in the optical or microwave domains. So far, Rydberg atoms in cavity QED systems have mainly been used to measure or create quantum states of light. Using a microwave cavity to detect Rydberg atoms is less explored. It also constitutes a step towards the application of the long coherence time of Rydberg atoms as quantum memories for microwave-based quantum information processing.

Detecting the change in phase $\delta\phi$ of a weak probe tone transmitted through a superconducting 3D microwave cavity [1] allows us to measure the dispersive shift χ induced by an ensemble of helium Rydberg atoms. The system is quantitatively described by the dispersive Tavis-Cummings hamiltonian, as the atom-cavity coupling is dominated by the transition between the 42s and 42p states which has a small detuning Δ from the cavity resonance. Thus, the dispersive shift is given by $\chi = g_1^2 N/\Delta$, where the single atom coupling to the cavity g_1 is calculated from the cavity field distribution and the transition dipole moment of the atom. The detuning Δ is measured by intra-cavity spectroscopy and N is the number of Rydberg atoms.

We measured the scaling of the collective dispersive shift with the atom-cavity detuning and the number of Rydberg atoms [2]. The latter provides a non-destructive measurement of the number of Rydberg atoms which we compare to the destructive detection by ionization and collection of electrons on a microchannel plate. The technique also offers non-destructive measurements of the internal state of an ensemble of Rydberg atoms by detecting its pseudo-spin polarization. By calibrating the dependence of the response on the probe power, the sensitivity of our atom detector allows to reach a single shot non-destructive detection of ensembles of 500 atoms with an uncertainty of 13%. We discuss possible improvements of this type of non-destructive detector for Rydberg atoms.

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Nanoscale thermometry with NV centers in diamond

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Precise measurement of temperature with ultrahigh sensitivity and spatial resolution at ambient conditions in a variety of environment is becoming decisive and critical, from exploratory research to prototyping and manufacturing, in various areas : nanomaterials science, nanoelectronics, nanophotonics, nanochemistry, nanobiology, nanomedicine... Nanoscale thermal imaging techniques encompass presently a wide variety of approaches, including radiation-based thermometry, electron beam induced plasmons in transmission electron microscopy, atomic force microscopy equipped with thermocouples or resistive thermometers or SQUIDS deposited on nanoscale tips to name a few. However, all these probes still present some limitations in terms of sensitivity, spatial resolution or operation environment.

One emerging strategy in this context, that could enable to surpass the performance of current nanoscale thermal sensors, rely on thermal probes based on single spins associated to a single deep defect in a diamond (an NV center). The resonance of such spin depends on the temperature due to thermal expansion and vibronic interactions in the diamond lattice. Moreover, such spin resonance can be probed optically. These features have already been exploited for thermal sensing at nanoscale, revealing sensitivities down to $mK/\sqrt{Hz}$ in bulk diamond and 100 $mK/\sqrt{Hz}$ in nanodiamonds [1].

Various practical sensing configurations can be envisioned depending on the sensor geometry : (i) wide-field or confocal imaging with bulk diamond or (ii) confocal imaging with nanodiamonds. The operational capability of these two configurations has been here investigated numerically and corroborated experimentally, assessing the benefits of the nanodiamond-based geometry. In such experiments, temperature gradients at microscale have been produced by use of thermoplasmonic arrays of gold nanoparticles deposited on a substrate [2]. When excited by a laser, such arrays induce temperature gradients with a spatial distribution and an amplitude that can be controlled respectively by the array's geometry and the laser intensity. The high thermal conductivity of diamond reveals to be a strong hurdle for bulk configurations, for which the diamond substrate acts as a very efficient thermal sink. On the contrary, it reveals to be a huge advantage for the nanodiamond-based geometry, insuring a perfect thermalization of the sensor with the hot sample to probe.

In order to push the sensor's sensitivity, one recently-implemented strategy builds on a hybrid architecture, exploiting a conversion of temperature variations on magnetic field variations [3]. It takes advantage of the high sensitivity of the electronic spin to magnetic fields (down to $nT/\sqrt{Hz}$) and the efficient transduction of temperature changes on magnetic field provided by ferromagnetic or ferrimagnetic coatings deposited on the nanodiamond hosting the probing spin. Such hybrid strategy promises to reach sensitivities down to sub-$mK/\sqrt{Hz}$.

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Quantum sensing using circular Rydberg states

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Rydberg atoms are highly excited states of an atom, in which the electron is located far from the nucleus. These states exhibit enhanced properties such as electric or magnetic dipoles, making them very sensitive to their electromagnetic environnement and thus good candidates for quantum metrology. Using microwave and radio-frequency fields, our team is able to engineer the quantum state of the atoms to probe electric and magnetic fields with a measurement accuracy below Standard Quantum Limit (SQL).

The measurement of small electric field is done using Ramsey interferometry involving states with very different dipoles [1]. We prepare the atom in a superposition of states with different sensitivity to the electric field. Measuring the quantum phase between the two states allows us to probe the varations of the field. We reach a sensitivity of $0.3\mathrm{mV/cm}$ for a $200\mathrm{ns}$ interrogation time. For shorter interrogation time, the single-atom sensitivity is below the SQL by $-14.8\mathrm{dB}$.This electrometric technique could have applications for detection of individual charged particles in mesoscopic physics.

Following the same principle, Rydberg atoms are used to measure magnetic field using a quantum superposition of two opposite angular momentum circular states [2]. This non-classical state corresponds to an electron rotating in two differrent directions in the same circular orbit, with a dipole difference of the order of $100\mu_\mathrm{B}$. This single-atom magnetic probe is able to perform a detection of $13\mathrm{nT}$ field in $20\mu\mathrm{s}$. These results could lead to even better sensitivities by improving the experimental scheme.

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Quantum Simulation (QSIM)

Phase transition and quantum engineering in modulated optical lattices

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We propose to discuss three recent experiments that we have performed with a Bose Einstein condensate in a 1D modulated optical lattices.

— For a phase modulated optical lattice at a frequency below interband transition resonance, we have investigated the dynamical phase transition from a spatially periodic state to a staggered state with alternating sign in its wavefunction. We have observed the crossover from quantum to thermal fluctuations as the triggering mechanism for the nucleation of the new phase. We obtain a good quantitative agreement with numerical simulations based on the truncated Wigner method [1].

— We have also investigated optical lattices in the presence of phase or amplitude modulation in a frequency range resonant with the first bands [2]. We study the combined effect of the strength of interactions and external confinement on the 1 and 2-phonon transitions. We identify lines immune or sensitive to atom-atom interactions. Experimental results are in good agreement with numerical simulations. Using the band mapping technique, we get a direct access to the populations that have undergone n-phonon transitions for each modulation frequency.

— Using amplitude modulation, we have setup a new technique to cool directly atoms trapped in optical lattices [3]. For this purpose, we use a proper frequency sweeping. This technique removes the most energetic atoms, and provides, with the onset of thermalization, a cooling mechanism reminiscent of evaporative cooling. However, the selection is here performed in quasi-momentum space rather than in position space. Interband selection rules are used to protect the population with a zero quasi-momentum. The Bose Einstein condensate therefore remains unaffected by the modulation. Direct condensation of thermal atoms in an optical lattice is also achieved with this technique. Our approach offers an interesting complementary cooling mechanism for quantum simulations performed with quantum gases trapped in optical lattices.

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Controlling frequency correlations and biphoton statistics in a semiconductor photonic chip

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Nonclassical states of light are key components in quantum information science; in this domain, the maturity of semiconductor technology offers high potential in terms of ultra-compact devices including the generation, manipulation and detection of photonic quantum bits. Among the different resources under development, on-chip entangled photon sources play a central role for applications spanning quantum communications, computing and metrology [1]. The technological maturity and optoelectronic capabilities of III-V materials make them an ideal platform to develop integrated quantum light sources. In particular, employing a transverse pump geometry (see Fig. 1a) enables a high control on the frequency correlations of the emitted states, hardly achievable in a collinear geometry [2].

In this work, we demonstrate that tailoring the spatial profile of the pump beam in intensity and phase enables the control of the frequency correlations and the symmetry properties of the spectral wavefunction, without post-manipulation. Fig. 1b) and Fig.1c) report the joint spectrum of the biphoton state emitted by an AlGaAs ridge waveguide under transverse pump illumination, measured with a fiber spectrograph. Using a spatial light modulator, we add a phase shift between the two halves of the pump beam, leading to a splitting of the joint spectrum into two distinct lobes (Fig. 1c). These results enable the study of new effects linked to the parity control of the biphoton wavefunction. As example, Fig. 1d) and Fig. 1e) report the result of a Hong-Ou-Mandel experiment performed with the biphoton states presented before. The coincidence probabilities feature a clear change from a bunching behavior, typical of bosonic statistics, to an anti-bunching behavior, typical of fermionic statistics. These findings open interesting perspectives for the utilization of our platform to perform quantum simulation of fermionic and bosonic statistics by simple frequency correlation engineering of photon pairs [3].

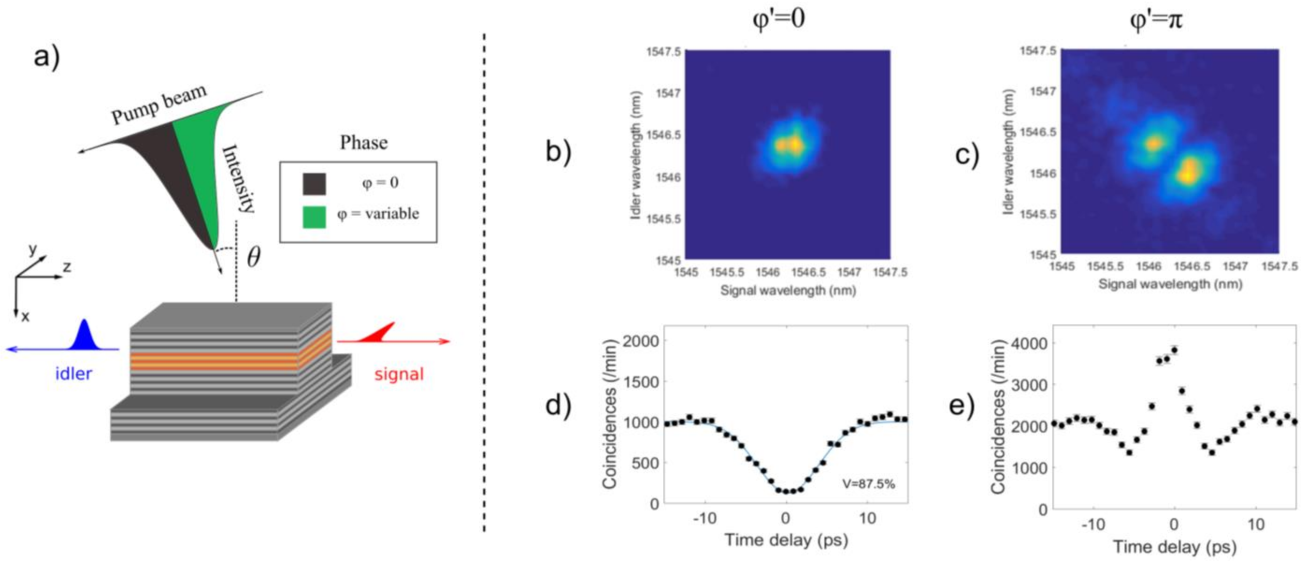

Figure 1: a) Sketch of the working principle of the device under transverse pump illumination. On the right: experimentally measured joint spectrum with a flat phase (b) or a π phase shift (c); corresponding two-photon interference measured in a Hong-Ou-Mandel experiment (d-e)

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Investigating the optimality of ancilla-assisted linear optical Bell measurement

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Due to its experimental and theoretical simplicity, linear quantum optics has proved to be a promising route for the early implementation of important quantum communication protocols [1]—including quantum teleportation, dense coding and entanglement swapping. An essential step in these protocols is the *Bell measurement* (BM), a projective measurement onto a basis of two-qubit maximally entangled states, the Bell states. Here we are concerned with *unambiguous* BM, i.e. a measurement that correctly identifies some the Bell states without errors, but gives an inconclusive answer with a non-zero probability. Lütkenhaus *et al.* [2] showed long ago the impossibility of perfect linear optical Bell measurement for dual-rail photonic qubits. In a following result, Calsamglia and Lütkenhaus bound the success probability P_{succ} of the no-ancilla case to 50% [3]. However in the last decade Grice [4] and Ewert and van Loock [5] found linear optical networks achieving near-unit efficiency unambiguous Bell state discrimination, when fed with increasingly complex ancillary states. However, except for the vacuum ancilla case [3], the optimality of these schemes is unknown.

Here, the optimality of these networks is investigated through analytical and numerical means. We show an analytical upper bound to the success probability for interferometers that preserve the polarization of the input photons. While this restriction is not motivated by experimental realities, instead being a consequence of the proof technique, we show that the bound is saturated by both Grice's and Evert-van Loock's strategies. Furthermore, we obtain a link between the complexity of the ancilla states and the scaling of the performances of the discrimination. Among other states, we compute this bound for networks with k ancillary single photons, or equivalently $\frac{k}{2}$ ancillary Bell pairs. We bound the success probability of these cases to $P_{\text{succ}} \leq 1 - O(\frac{1}{\sqrt{k}})$, giving interesting insights into the reason why the big GHZ-like states that appear in the schemes of [4] are needed to attain their linear $P_{\text{succ}} \leq 1 - O\left(\frac{1}{k}\right)$ scaling.

In the second part of the work, we show a computer-aided approach to the optimization of such measurement schemes for generic interferometers (not constrained to be polarization-preserving), by simulating an optical network supplied with various kinds of ancillary input states. For each ancilla we want to analyze, and for each input Bell state, we generate a symbolic expression for the probability amplitudes of all output events in terms of the unitary matrix U representing the network. Those functions, along with their gradient with respect to the U entries, are symbolically optimized exploiting physical and mathematical symmetries in order to reduce the number of operation needed. Then, a constrained numerical optimization using a nonlinear method is performed. With this program we numerically confirm the optimality of known small schemes. We also numerically investigate the usefulness of single photons, additional Bell pairs and GHZ and W states, obtaining $P_{\text{succ}} = \frac{3}{4}$ as the highest success probability we achieve with small (≤ 10 modes, ≤ 6 photons) networks.

Associated paper pre-print : arXiv :1806.01243 . *Source code available at :* arxiv.org/src/1806.01243/anc

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Ultra-compact fiber-based system for cold atom trapping and manipulation

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We developed an ultra-compact system for trapping and manipulating cold atoms, replacing traditional centimeter-scale aspherical lenses with a multimode optical fiber presenting a similar numerical aperture of $NA = 0.5$ but a diameter of only $225\ \mu m$. The strong distortions of optical wavefronts transmitted through the fiber are compensated with an spatial light modulator (SLM). Despite the sensitivity of the fiber's transmission matrix to external parameters, the system proves sufficiently stable for practical applications, in particular in UHV setups with little optical access. We demonstrated the ability of this system to form an optical conveyor belt with a $20\ \mu m$ waist and a contrast sufficient to horizontally transport a cloud of cold ^{87}Rb atoms over 5 mm, starting from the location of a magneto-optical trap and bringing it to $\approx 100\ \mu m$ from the fiber end. We are now working towards the realization of micron-sized single-atom traps with a geometry fully controllable by the SLM.

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Generation of non-Gaussian quantum states of multimode light field

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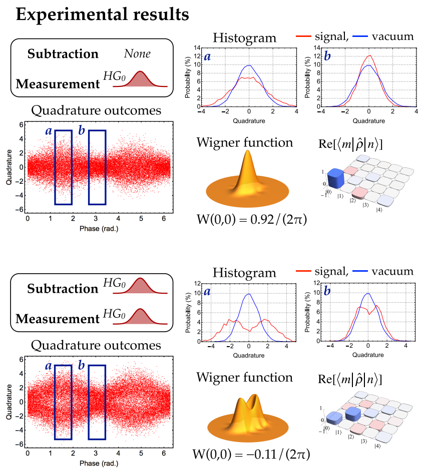
Continuous-variable quantum information encoded on the electromagnetic fields of light plays a pivotal role in quantum technologies. It enables to build a large-scale entangled quantum state for quantum computing and quantum communication based on standard optical resources : a squeezed vacuum state of light, linear optics, and homodyne detection. However, a quantum state produced by those resources always exhibits a Gaussian distribution, which is generally insufficient for quantum technologies [1, 2]. Subtracting a single photon from a squeezed vacuum state can introduce a non-Gaussian distribution [3, 4], but the conventional method [5] of photon subtraction works only for a single-mode quantum state, which significantly limits the range of application. Here we present tailored generation of non-Gaussian quantum states of multimode light by employing a single-photon subtractor compatible with multimode light [6]. We first prepare a multimode squeezed vacuum state [7, 8] and then subtract a single photon at a desired mode or at a superposition of desired modes.



The resultant multimode quantum state exhibits a non-Gaussian distribution (negativity of the Wigner function in best cases) when measured at the mode(s) of photon subtraction. Furthermore, when a single photon is subtracted from a multimode entangled state, we observe that the induced non-Gaussianity is distributed to other modes via entanglement between modes. Such non-Gaussian multimode quantum states will have broad applications for universal quantum computing, entanglement distillation, and nonlocality test.

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Superfluidity of light in a bulk nonlinear crystal

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Quantum fluids of light merge many-body physics and nonlinear optics, revealing quantum hydrodynamic features of light when it propagates in nonlinear media [1]. One of the most outstanding evidence of light behaving as an interacting fluid is its ability to carry itself as a superfluid.

Here, we report a direct experimental detection of the transition to superfluidity in the flow of a fluid of light past an obstacle in a bulk nonlinear crystal [3, 4]. In this cavityless all-optical system, we extract a direct optical analog of the drag force exerted by the fluid [5] of light and measure the associated displacement of the obstacle. Both quantities drop to zero in the superfluid regime characterized by a suppression of long-range radiation from the obstacle.

The experimental capability to shape both the flow and the potential landscape paves the way for simulation of quantum transport in complex systems.

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Hybrid cavity-Rydberg platform for quantum engineering of light

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We are setting up a new experimental platform for quantum engineering of light, which will allow us to create and to control strong coherent interactions between optical photons. At its core, a cold cloud of ^{87}Rb atoms is placed inside a single-end non-planar running-wave optical resonator. Photons injected into this resonator will be converted into collective Rydberg excitations using two independent cavity-enhanced control laser beams. The resonator's parameters are adjusted in such a way that the presence of a single Rydberg "blockade sphere" switches its optical impedance from over-coupled to under-coupled, leading to a π phase shift on the reflected light. This mechanism will allow us to implement a recently proposed control-Z gate between optical photons [1] and deterministically generate free-propagating optical "Schrödinger's cat" states for precision measurements. Ultimately, it will give access to a yet unexplored regime where intracavity photons form a strongly correlated quantum fluid, with spatial and temporal dynamics ideally suited to perform real-time, single-particle-resolved simulations of non-trivial topological effects appearing in condensed-matter systems [2, 3].

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Quantum Processing, Algorithm, & Computing (QPAC)

Efficient pseudorandomness and hardness of classical simulability of simple graph states

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Measurement based (MB) quantum computation [5] 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 [1, 2]. In this work [1], we show that repeating an MB scheme an efficient number of times, on a simple graph state, with measurements at fixed angles and no feedforward corrections, produces a random unitary ensemble that is an ε-approximate t design on n input qubits. Unlike previous constructions, the graph is regular and the graph state is also a universal resource for measurement based quantum computing, closely related to the brickwork state [6]. We will frequently refer to a graph state with an MB scheme applied to it as a graph gadget.

As an application to the above mentioned graph gadget, we show that when t=2 (or greater) sampling from the probability distribution over the measurement results of qubits constituting this gadget (up to a constant l_1-norm error) is classically intractable provided two complexity theoretic conjectures hold [3]. Hence, our gadget may be viewed as an architecture for quantum simulation showing a quantum advantage [7–9, 16]. The total number of qubits needed to implement this gadget scales as $O(n^2)$.

Our gadget combines the property that it samples from a t-design- which provides a provable anti-concentration [8, 10], along with the fact that it is universal under post-selection [1]- which provides instances of output probabilities which are ♯P-hard to approximate (so-called worst-case hardness). Note that worst-case hardness is guaranteed in our case in depth $O(n)$ (same order of depth as our gadget) as a direct consequence of Theorem 7 in [8]. We also present an argument for an average-case hardness conjecture in 2 ways, one of which stems from the worst-case hardness of approximating Ising partition functions along the lines of [7–9, 16, 17]. And another which stems from the worst-case hardness of approximating the Jones polynomial ascossiated to random braids [18] as in [10]. Anti-concentration along with worst-case hardness, and a conjecture on average-case hardness, provide all the ingredients needed for a standard hardness of approximate classical sampling proof [7–10, 16] .

Furthermore, our gadget differs from the previous MBQC gadgets [7–9] in the sense that it is the first architecture to combine fixed state preparation and fixed measurement angles with a provable anti-concentration. As previous MBQC gadgets with fixed state preparation and fixed measurement either conjecture anti-concentration [7] , or use some weaker assumption [9]. On the other hand, previous gadgets with a provable anti-concentration [8] inject classical randomness into the system.

Finally, as shown in [8] , hardness of approximate classical sampling holds for any quantum circuit which is an ε-approximate $t \geq 2$ - design and which is universal under post-selection. Our construction shows that such a circuit can be implemented in MBQC using fixed angles and measuring non-adaptively on a regular lattice graph state.

The implementation of our gadget requires initializing $O(n^2)$ qubits in the $|+\rangle$ state , followed by applying a fixed, translationally invariant Ising interaction for a given fixed time, and finally performing non-adaptive fixed angle single-qubit measurements on all the qubits simultaneously. Our gadget can be readily implemented via cold atoms using the same techniques discussed in [7–9]. It is also possible to efficiently certify the functioning of our gadget [7, 9, 11, 12]. Our hardness result, however, suffers from the usual limitations as in [7, 8, 16] and is not robust against a constant amount of independent noise applied to each qubit, mainly because of its anti-concentration property [13].

In light of recent results concerning worst- to-average case hardness reduction for random quantum circuit sampling with gates chosen from the Haar measure (RCS) [14], and because our gadgets t-designness comes from the fact that its construction is based on a G-local random circuit construction [4] (a finite set equivalent of an RCS). This RCS result may provide insight into finding a theorem nescessarily needed for proving our average - case conjecture as is done for RCS in [14] . Since a full proof of average-case hardness conjectures seems to require non-relativizing techniques [15]. Thereby promoting our architecture to the first experimentally feasible architecture with such a theorem concerning average-case hardness.

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Addressing of Nanoscale Spin Quantum Registers

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Engineering and scaling of quantum registers, i.e. networks of coupled qubits, lies at the core of quantum information processing. The expansion of quantum algorithms to useful applications depends on computational resources. However, while the physical scaling of such networks is by itself challenging, executing algorithms on a large quantum register comes with its own scaling challenges. Particularly, individual qubits need to be controllable in order to retain a universal set of gate operations. As the qubits are typically instances of the same particles, they might not be easy to distinguish in high densities. This is especially the case for spin-based solid-state quantum registers, since the range of spin-spin interactions is typically on the nanoscale [1, 2].

Here, we show how a potential quantum processor based on dipolar coupled nitrogen-vacancy defect (NV) spins could be implemented and present how individual spins in dense clusters can be manipulated and read out. Moreover, the same NV structures can be used as sensing arrays to obtain nanoscale spatial information on environmental interactions.

Our work involves two techniques, using magnetic field gradients and optical super-resolution methods. On the one hand magnetic gradients can encode spatial information on spin-states through their Zeeman interaction. In our work we use the write head of a modern hard-disk drive to produce the necessary strong gradients on the order of 10^5 T/m to split the resonances of single spins within nanometer distances [3, 4]. On the other hand we use charge-state depletion microscopy to localize individual NVs beyond the diffraction limit [5]. This super-resolution method further allows us to deliberately switch off NV defects and single out individual spins for manipulation and read-out.

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Certifying the building blocks of quantum computers from Bell's theorem

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Experimental research on quantum computing is progressing at an unprecedented rate [1]. Five-qubit quantum computations combining around a dozen of quantum logical gates can nowadays be performed with a mean gate fidelity of $\sim$98% using trapped ions [2] or superconducting circuits [3]. However, for implementing large-scale quantum computation, it is crucial to proceed in a scalable way and certify that each new component is qualified for use in a quantum computer, independently of the purpose for which that larger device is used.

Such a certification must be device-independent, that is, it cannot rely on a physical description of the actual implementation. Indeed, an exhaustive model of the setup is challenging, if not impossible, to establish. Relying on any particular model therefore amounts to making assumptions about the functioning of blocks. But seemingly harmless assumptions can have dramatic consequences when they are not perfectly satisfied. An assumption on the Hilbert space dimension for example can completely corrupt the security guarantees of a network of small quantum computers used to communicate securely [4, 5]. Blocks certified in a device-dependent way thus cannot be used safely for arbitrary purposes.

Bell's theorem [6] has lead to device-independent certification schemes for components either producing quantum states or performing quantum measurements [7–18]. But these are just some of the elementary blocks needed to build a quantum computer. In particular, a robust device-independent method that can be used in present-day experiments for assessing the quality of components in charge of the transfer, processing and storage of quantum information is still missing. Together with existing techniques, such a method would in principle allow for the certification of all kinds of elementary building blocks needed in a quantum computer.

Building on the work of Magniez et al. [19], we present a framework for the device-independent certification of quantum channels. We apply our methods to individual elements of quantum computers, including single qubit identity channels and two qubit controlled unitary operations. Our technique does not certify the proper functioning of composite circuits but it constitutes a first necessary verification step that is relevant given the status of on-going experiments. In the long term, our technique coud be used to identify the elements causing the failure of a quantum computation.

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Quantum algorithms for classification

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Quantum machine learning carries the promise to revolutionize information and communication technologies. In supervised machine learning, classification is the task of finding the correct label for a new sample given a training set of N elements, each one associated with one of K possible labels. In clustering, the task is to group elements of the training set that are deemed similar according to some measure of similarity.

We present two new algorithms [1, 2] for supervised and unsupervised classification. For supervised learning we developed two subroutines : QSFA and QFD. QSFA is a dimensionality reduction algorithm that maps the dataset in a lower dimensional space, where classification can be performed with higher accuracy. Dimensionality reduction is often a necessary while performing classification in high dimensional spaces due to the curse of dimensionality. QFD is a supervised classifier which assign a new point to the cluster with minimum average square distance between the vector and the points of the cluster. Being simple to implement, it can be used to target NISQ-architectures. For unsupervised clustering we developed Q-means : the quantum version of δ-k-means, a classical algorithm. Being an iterative algorithm, Q-Means has convergence and precision guarantees similar to the classical variants of the k-means algorithm. All the algorithms presented here are polylogarithmic in the number of vectors in the dataset, thus with an exponential separation with respect to classical algorithms. SFA and QFD provide exponential separation also in the number of features. We introduce carefully the toolbox used in quantum machine learning : procedure to perform quantum linear algebraic operations, the QRAM circuit as an access model on the data, and routines to calculate distances - which we refined.

Finally, we provide positive evidence that quantum computer can be useful to solve real-world problem, by testing our algorithms on real data. We simulated QSFA and QFDC (including errors) on the MNIST dataset of hadwritten digits - a common dataset used to benchmark classification algorithms - and show that their combination can provide an accuracy around 98.5%, as the classical case. We estimated the running time of all the quantum algorithms by analyzing the parameters on which the running time depends on real data. They scale favorably, thus ascertaining the efficiency of our algorithms.

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GDR - IQFA Abstract
Control of the Fluxonium qubit at $\frac{\Phi_0}{2}$

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Superconducting qubits are a subject of intense research as a platform for scalable quantum computing. While transmon qubits have received a lot of attention, currently all experiments with multiple transmons suffer from surface loss, small anharmonicity and flux noise. The principal issue is the qubit's single transition, which on the one hand has to be extremely coherent and on the other hand has to undergo strong interactions. The less ubiquitous fluxonium qubit, consisting of a transmon shunted by a super-inducting loop, has been shown to solve the second and third issues. The goal of our project is to show that surface loss impact can be mitigated by lowering the frequency of the fluxonium by an order of magnitude, which will increase its lifetime while keeping the desired strong interactions. To do this we will concentrate on the half flux quantum sweet spot where T_2 is greatly enhanced thanks to first order insensitivity to flux noise and decay channels (dielectric losses, Purcell effect among others) are suppressed because of the low transition frequency. Necessarily, such low frequencies mean that the thermal excitation of the qubit is high, so a key part of the project will be to efficiently cool the fluxonium by reservoir engineering. Our poster will be focused on characterising our qubit : we will present its spectrum as well as Rabi oscillations, T_1 and T_2 measurements at the sweet spot. We will also detail strategies for ground state cooling and a qubit reset faster than the T_1 decay. A short introduction to the key properties of the fluxonium qubit and the elements to keep in mind to understand current research will also feature.

Single shot high fidelity qubit readout using a transmon molecule in a 3D cavity

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Using the transverse dispersive coupling between a qubit and a microwave cavity is the most common read-out technique in circuit-QED. However, despite important progresses, implementing a fast high fidelity readout remains a major challenge. Indeed, inferring the qubit state is limited by the trade-off between speed and accuracy due to Purcell effect and unwanted transitions induced by readout photons in the cavity. To overcome this, we introduce a transmon molecule circuit design coupled to a 3D-cavity [1, 2]. This system presents one transmon qubit with a large direct cross-Kerr coupling to a weakly anharmonic mode, called polaron mode. This polaron mode results from the hybridization between the microwave cavity and the second mode of the transmon molecule circuit and is used to readout the qubit state. Direct cross-Kerr coupling is a key point to our readout scheme since such a coupling is immune to Purcell effect.
We will present qubit readout performance with fidelity as high as 97%. We will also present quantum trajectories with high time resolution and discuss the quantum non-demolition properties of this novel readout.

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Production of multimode squeezed states of light in a single pass configuration

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We propose the experimental generation of multimode squeezed states of light in a single-pass configuration via noncollinear-type-I Spontaneous Parametric Down Conversion (SPDC). These states exhibit spatio-spectral correlations and would be the building blocks of cluster states [1]. The latter are quantum complex networks displaying multipartite entanglement, which is of great interest for continuous-variable-quantum computation [2].

We use a mode-locked Titanium-Sapphire laser, which delivers a train of 25-fs pulses at a rate of 156 MHz. In the frequency domain, this corresponds to a 45-nm-spectrum frequency comb centered at 795 nm. Part of the main laser source is used as a reference while the rest is frequency doubled in a 1-mm long BBO (β-baryum-Borate) crystal, thus producing a frequency comb centered at 397 nm. Then, the up-converted pulses are injected into an optical cavity where they pump a type-I-noncollinear SPDC process through a 2.8-mm long BBO crystal placed at the beam waist. In this configuration, two-mode squeezed vacua (TMSV) are generated. Differently from the Optical Parametric Oscillator, signal and idler pulses do not resonate in a cavity thus preserving the multimode structure of the quantum states. After the nonlinear crystal, signal and idler beams are superimposed on a balanced beamsplitter. This corresponds to a basis change, after which the outgoing quantum states are eigenstates of the squeezing operator $\hat{S}$. The modal structure of the quantum states can be accessed via single value decomposition of the coupling matrix $\mathcal{K}$ associated to the nonlinear process. Mathematical analysis shows that their spectral shape can be approached by Hermite Gaussian functions [3]. Therefore, to access the multimode structure of the produced light, we use a homodyne detection, in which the spectrum of the local oscillator (LO) is shaped with a Spatial Light Modulator (SLM). This allows to separately measure squeezing in choosen eigenstates. With this protocole, we have been able to measure squeezing in up to four spectral modes (HG_0 to HG_3) (fig. 1).

We later studied the spatio-temporal features of the TMSV by simulating the spatial and spectral shapes of squeezing eigenmodes at given phase-matching conditions in our crystal. Thus, by using spatial and spectral shaping of the LO we were able to measure the covariance matrix associated to four spatio-temporal modes and to witness the presence of correlations which are mode dependent. These results give an overview of the rich and complex structure of the generated quantum states.

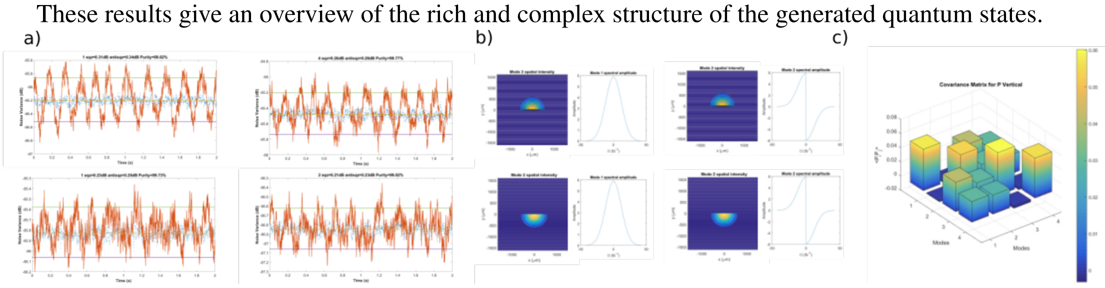

FIGURE 1: a) Squeezing-measurement curves. b) Experimental spatio-spectral modes. c) Covariance matrix associated to the spatio-spectral modes.

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Quantum Entanglement involved in Grover's and Shor's algorithms

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Quantum information and quantum algorithms are on their way to revolutionize our conception and implementation of calculus and computations. In the last twenty years, many quantum algorithms have emerged, to solve different problems. However, we are not yet able to explain precisely what caracterizes quantum algorithms and quantum computations, and what are the reason that some computational speed-up is observed.

One quantum phenomenon was proposed as a candidate for explaining such computational speed-up, but we do not understand fully its role and how it is involved in quantum algorithms. In this work, we focused on two of the most famous quantum algorithms : Grover's and Shor's algorithms.

Most of the latest works focused on studying, from a quantitive point of view, the amount of entanglement throughout the iterations and steps of these algorithms. Our goal is to give some qualitative results about which entanglement class can appear in Grover's and Shor's algorithms. By using tools coming from the fields of Algebraic Geometry and Invariant Theory [1–3] we are able to characterize quantum entanglement for the 3 and 4-qubits systems versions of these two algorithm, and give a generalization of several results for the general n-qubit case. We also been able to explain and comment other quantitative results, and investigate this question by using the hyperdeterminant as a measure of entanglement.

For Grover's algorithm, we focused on the first iteration of Grover's algorithm (as it was done in [4]), mainly the Oracle gate, but also the Diffusion gate which can modify entanglement in the "critical case". For Shor's algorithm, we were interested in the entanglement of periodic states generated during the period-finding algorithm. We studied entanglement of periodic states before and after the application of the Quantum Fourier Transform, depending on the shift and the period of these states. Finally, we tried to deal with the influence of the Quantum Fourier Transform on entanglement of general quantum states.

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Entanglement Analysis for a First-Order Quantum Programming Language with Inductive Datatypes

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Quantum entanglement is a very important resource in quantum information processing. For example, many quantum algorithms produce entanglement during their execution and many quantum information protocols use entanglement for a variety of goals. In this work, we consider the problem of detecting whether quantum entanglement is produced by quantum programs by statically analysing their source code. This has applications in verification – if an automated tool guarantees that no entanglement can be generated by a specific program, but the considered algorithm or protocol is known to require it, then this means that the program is not correct. Moreover, static analysis could also be used to optimize the quantum compilation of programs.

First, we describe a first-order functional quantum programming language which supports inductive datatypes such as natural numbers and lists of arbitrary types. The language has a formal operational semantics, which describe the steps taken in the execution of quantum programs, and denotational semantics, which finds a mathematical interpretation for every well-formed quantum program. In detail, the denotational semantics is described as follows: every program type is interpreted as a W*-algebra and every program is interpreted as a normal completely positive subunital map. These operator algebras were introduced by von Neumann himself, and motivated by his study of quantum mechanics. The theory of operator algebras has found direct application in various fields such as quantum information theory and quantum field theory.

We identify some relevant categorical properties of W*-algebras and show they form a suitable setting for the mathematical interpretation of a first-order programming language with inductive datatypes. Since qubits are easily representable in a W*-algebra, the denotational semantics supports many features relevant to quantum programming languages.

Then, using techniques from theoretical computer science, we design the language, its operational and denotational semantics such that soundness holds: the interpretation of a program as a completely positive map is invariant with respect to the execution of the program (as specified by its operational semantics).

Moreover, since the denotational semantics is described in a natural category of quantum computation, this allows us to elegantly reason about quantum phenomena such as entanglement, within a mathematical language which is familiar to the working quantum computer scientist. The naturality of the model then allow us to perform quantum entanglement analysis on programs written in the programming language using methods from abstract interpretation. Abstract interpretation is a technique which allows one to gain information about the executions of programs and is used by formal tools for the static analysis of programs. Hence, our project lays the theoretical foundation for the development of software tools which can detect potential (lack of) entanglement in quantum programs based on their source code. In other words, we aim to certify the correctness of quantum programs against some of the bugs related to the use of quantum entanglement.

This abstract describes work-in-progress by the four authors.

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Towards Optically Controlled Qubits in Rare Earth Doped Nanoparticles

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Nanoscale systems offer new functionalities in quantum technologies, like single qubit control and detection, or extremely localized sensing. The ability to couple qubits with light is an attractive feature for these systems to enable interfacing with photonic qubits, creating light matter entanglement or fast processing of quantum information. Rare earth ions are promising candidates for this purpose [1-3], as they can show record long optical and spin coherence lifetimes in bulk crystals [4]. However, maintaining these properties at the nanoscale can be challenging, as surface effects for example can cause strong dephasing. In this paper, we will discuss recent results obtained in our group on europium doped nanoparticles. These materials show optical and spin coherence lifetimes of 7 μs [5] and 1.3 ms at low temperature [6]. Moreover, spin dephasing can be controlled by trains of optical pulses, resulting in coherence lifetimes up to 8 ms [6]. This is the highest reported value for optically addressable spins in any nano-material. These particles could be placed in high-finesse fiber-based cavities to achieve efficient optical control and readout of nuclear spin qubits [7]. Combined with rare earths unique coherent properties, this scheme opens the way to quantum memories with single ion processing capabilities, single photon sources or highly scalable quantum processors.

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